Antarctic Ice Shelf Tide Modeling Using PALSAR Interferometry

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Abstract

The knowledge of ocean tides underneath permanently or seasonally sea ice covered ocean and ice shelves over Antarctica, is largely unknown. Significant amount of West Antarctic ice sheet melt is through the mechanism of basal melting and due to turbulent tidal mixing. Knowledge of the ice shelf grounding lines and their extent, are critical to accurately quantify ice sheet mass balance, and ocean tides are well known to significantly shift the grounding lines. Seasonal variability of ocean tides, especially underneath the ice shelves, adds to the complexity of the problem of accurate ice sheet mass balance studies. First, we demonstrate the feasibility of fine spatial scale (as fine as 100 m or less) O_1 barotropic ocean tide modeling undernearth the Sulzberger ice shelf, West Antarctica, using the VV-polarized C-band ERS-1/-2 tandem mission two-pass SAR interferometry time series. The tidal inversion is accomplished by first developing a 60-m resolution DEM over the ground ice and the adjacent ice shelves using ERS tadem InSAR and ICESat altimetry, thereby diminishing the stringent data requirement in four-pass InSAR for tidal analysis. Here we present a status report to use the ALOS PALSAR and other complementary data sets (ICESat laser and ENVISAT radar altimetry, GRACE) for multi-resolution (as fine as 100 m using InSAR) barotropic tide modeling and ice mass balance studies planned for and near the major Antarctic Ice Shelves, including the Filchner-Ronne, Ross, Larsen, and Amery Ice Shelves, and Antarctic Peninsula.

Keywords: Tide modeling, SAR (synthetic aperture radar), InSAR (SAR interferometry), ICESat, Antarctica

1. INTRODUCTION

In this study, two-pass differential InSAR (DInSAR) technique is applied for tidal signal modeling underneath the Sulzberger ice shelf, West Antarctica. The fine resolution (60-m) Digital Elevation Model (DEM) over grounded ice and ice shelf, obtained by combining ERS-1/2 tandem InSAR and ICESat laser altimetry, has been used to correct the topography phase from interferograms, resulting in a more accurate time series of vertical deformation measurements. Here, it is demonstrated for the first time, that observable tidal constituents can be estimated underneath an ice shelf (ice tongue) using an InSAR time series. In particular, it is shown that the time series of observed tidal differences from InSAR agrees well with a number of global/regional ocean tide models such as NAO.99b[1], TPXO.6.2[2], GOT00.2[3], CATS02.01[4], and FES2004[5] with the regional model, CATS02.01, having the best agreement. Once the ALOS PALSAR data are available and through data integration among various sensors passing over the study area, it is expected to improve tide modeling under the ice shelf. The technique developed here can be applied to other regions where tide modeling is poor in accuracy and resolution.

2. DEM GENERATION

It is an inherent requirement of an accurate, high-resolution digital elevation model (DEM) for ice mass balance, glacier dynamics, ocean and tidal dynamics and its modulation with the grounding line study. However, current DEMs available in this region, e.g., Radarsat Mapping Project (RAMP) DEM and Antarctic Digital Database (ADD) DEM are in poor accuracy. In addition, InSAR processing requires ground control points (GCPs), but GCPs are often unavailable. The extreme weather conditions and logistic difficulties in Antarctica are among the barriers hindering estimation of necessary ground control points for InSAR studies.

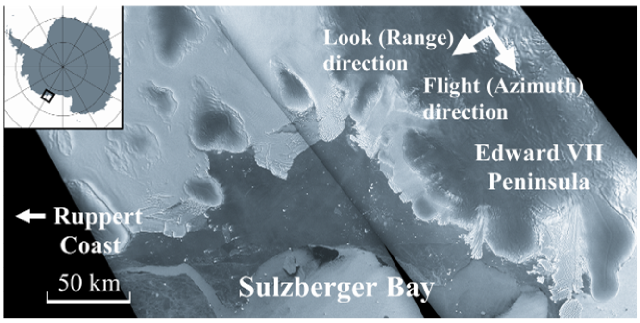


Figure 1. Study area

Our study area covers 76.5 °S to 77.5 °S and 153 °W to 159 °W by the Ross Sea, West Antarctica, and is one of the major drainage outlets of the West Antarctic Ice Sheet. SAR data used in this dissertation are all from ERS-1 and ERS-2 tandem missions in 1996. Interferograms generated between tandem combination was given on Table 1. Its perpendicular baseline falls between 5.8m and 194.9m in absolute distance and mean coherence ranges from 0.40 to 0.66.

Table 1. SAR dataset

Track	Orbits (ERS-1/-2)	Acquisition Dates	$B_\perp{}^*$, m	Mean Coherence
381	23916/4243	10/11 Feb 1996	-152.1	0.41
	24417/4744	16/17 Mar 1996	-147.4	0.40
	24918/5245	20/21 Apr 1996	-5.8	0.66
424	23959/4286	13/14 Feb 1996	-120.8	0.50
	24460/4787	19/20 Mar 1996	-194.9	0.40
	24961/5288	23/24 Apr 1996	-22.9	0.62

$^*B_\perp$: Perpendicular baseline at scene center

As can be shown from Table 2 and Figure 2, four InSAR DEMs are generated out of six tandem pairs and are averaged considering correlation between DEMs by taking coherence value of each interferogram as weighting factor to generate DEM. ICESat laser altimetry profile data was used in liu of ground control points in the process of DEM generation.

Table 2. Differential interferogram pairs

Image ID	Master pair (ERS-1/-2)	Slave pair (ERS-1/-2)	ΔB, m	Phase Error, deg	Height Error, m
1	23916/4243	24918/5245	-146.2	20.67	3.83
2	24417/4744	24918/5245	-141.6	21.16	4.05
3	23959/4286	24961/5288	-143.8	17.74	3.34
4	24460/4787	24961/5288	-217.8	21.65	2.69

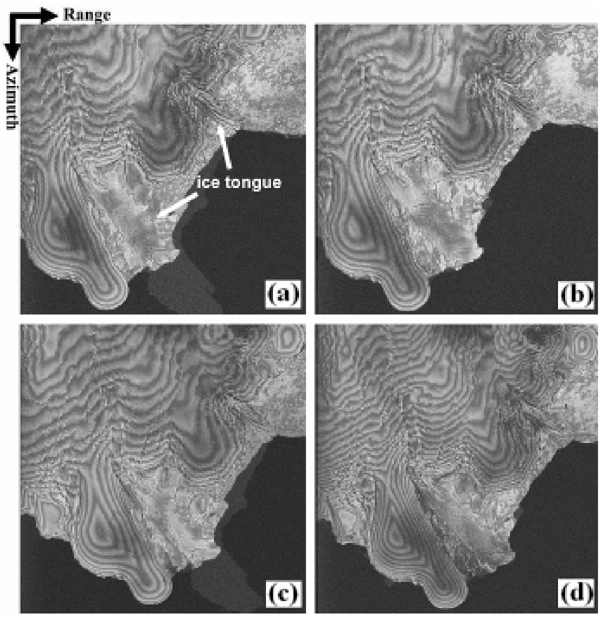
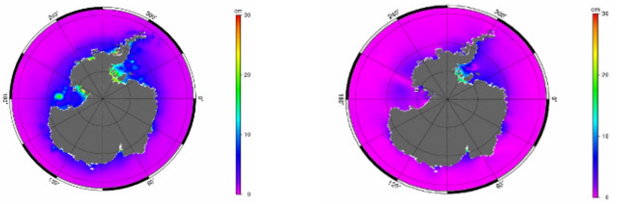


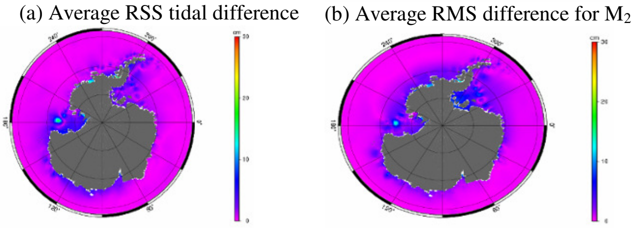
Figure 2. (a)–(d) Differential interferograms from image ID 1–4 of Table 2.

3. TIDE MODELING

Ocean tide is one of the major effects causing vertical deformation of the floating ice shelves in Antarctica, and ocean tide modeling which would allow to the removal of tides from space and in-situ measurements is critical for geophysical or glaciological studies such as those on the ice sheet mass balance. Several previous InSAR studies demonstrated that InSAR data are sensitive to tidal deformation and thus could validate tide models defined over Antarctica. The differences between GOT99.2b, NAO.99b, and CATS02.01 show that they possess about ±5 to ±6 cm RSS (Root Sum of Squares) error over the Southern Ocean (see Figure 3).



(a) Average RSS tidal difference (b) Average RMS difference for M_2



(c) Average RMS difference for K_1 (d) Average RMS difference for O_1

Figure 3. Differences between CATS02.01, GOT00, and FES2004 models around Antarctica

3.1 observation equation

The phase information in an interferogram consists of topography and deformation signals. To assess the vertical deformation from an interferogram, first, an InSAR DEM is generated, as described in the previous section, but by averaging two DEMs and with corrected topography signals. The ocean tidal signal can be expressed as a function of time, *t*, and location, (ϕ ,λ), as follows [6],[7]:

$$\zeta(t,\phi,\lambda) = a + b\cdot t + \sum_{i=1}^{n} f_i H_i(\phi,\lambda)\cos(\omega_i t + \Theta_i(t_0) + \chi_i + u_i - G_i(\phi,\lambda)) \tag{1}$$

where ω_i is the angular frequency for the tidal constituent *i*; t is Universal Time measured in mean solar days from a reference epoch t_0 such as January 1, 0^h.000, 1900; $\Theta_i(t_0)$ is the astronomical argument at t_0 ; $H_i(\phi,\lambda)$ and $G_i(\phi,\lambda)$ are the amplitude and phase for the tidal constituent *i* at location (ϕ,λ) ; χ_i is the additive phase correction; f_i

and u_i are slowly varying functions to account for the longitude of the lunar node. The observation from InSAR is the range difference ΔR along the line of sight between times t_1 and t_2 such as $\Delta R = R(t_1, \varphi, \lambda) - R(t_2, \varphi, \lambda)$ and is converted to the surface elevation change to form an observation equation:

$$\begin{aligned} \Delta\zeta(t_1, t_2, \phi, \lambda) &= \zeta(t_1, \phi, \lambda) - \zeta(t_2, \phi, \lambda) \\ &= b(t_1 - t_2) + \\ &\sum_{i=1}^{n} [C_i(\phi, \lambda)(\cos\ \Omega_{i,1} - \cos\ \Omega_{i,2}) \\ &+ S_i(\phi, \lambda)(\sin\ \Omega_{i,1} - \sin\ \Omega_{i,2})] \end{aligned} \tag{2}$$

where the harmonic coefficients $C_i(\phi, \lambda)$ and $S_i(\phi, \lambda)$ are defined as:

$$C_i(\phi, \lambda) = f_i H_i(\phi, \lambda) \cos G_i(\phi, \lambda) \tag{3}$$

$$S_i(\phi, \lambda) = f_i H_i(\phi, \lambda) \sin G_i(\phi, \lambda) \tag{4}$$

Amplitude and phase are computed by the harmonic coefficients such as:

$$H_i(\phi, \lambda) = \frac{\sqrt{C_i^2(\phi, \lambda) + S_i^2(\phi, \lambda)}}{f_i} \tag{5}$$

$$G_i(\phi, \lambda) = \arctan\left(\frac{S_i(\phi, \lambda)}{C_i(\phi, \lambda)}\right) \tag{6}$$

3.2 O_1 constituent estimation

When comparing estimates from InSAR data with model values, it is reasonable to do this over freely floating points with several kilometers from the ground line [Rignot et al., 2000]. Two points have been selected for tidal signal analysis: one at the center and the other at the edge of the ice tongue. Then, harmonic coefficients have been estimated for the tidal constituents O_1. Table 4 shows the results for the O_1 only estimate of the tidal signal for both locations, with amplitude and phase about 17 cm and 155°. Their rms errors are about ±7 cm and ±34°.

Table 4. Estimates for the O_1 tidal constituent from InSAR measurements.

Location	Amplitude, cm	rms error, ±cm	Phase, deg	rms error, ±deg
Edge	17.4	7.8	155.7	34.8
Center	17.1	7.2	155.6	32.7

4. CONCLUSIONS

A high-resolution (60-m) DEM was generated over the Sulzberger ice shelf using differential InSAR and ICESat laser altimetry in lieu of GCPs. It is concluded that the differential InSAR technique incorporated with ICESat laser altimeter data is one of the best and cost-effective methods in generating DEMs in remote areas like Antarctica. The most dominant tide O_1 has been estimated (200m resolution) using InSAR time series with rms error ~±8 cm for amplitude and ±34° for phase, respectively. The integration of various datasets such as ALOS PALSAR data, ICESat laser altimetry, ERS/ENVISAT/GFO radar altimetry, and GRACE gravimetry is anticipated to improve our understanding of ocean tidal dynamics underneath the ice shelves, and their roles in the determination of ice sheet mass balances in Antarctica.

Acknowledgement

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References

[1] Matsumoto, K., T. Takanezawa, and M. Ooe, Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydrodynamical model: A global model and a regional model around Japan, J. Oceanogr., vol. 56, pp. 567-581, 2000.

[2] Egbert, G. D. and L. Erofeeva, Efficient inverse modeling of barotropic ocean tides, J. Atmos. Oceanic Technol., vol. 19, no. 2, pp. 183-204, 2002.

[3] Ray, R. D., A global ocean tide model from Topex/Poseidon altimetry: GOT99.2, NASA Tech. Memo. 209478, Goddard Space Flight Center, 1999.

[4] Padman, L., H. A. Fricker, R. Coleman, S. Howard, and S. Erofeeva, A new tidal model for the Antarctic ice shelves and seas, Ann. Glaciol., vol. 34, pp. 247-254, 2002.

[5] Lefevre, F., F. H. Lyard, C. Le Provost, and E. J. O. Schrama, FES99: A global tide finite element solution assimilating tide gauge and altimetric information, J. Atmos. Oceanic Technol., vol. 19, no. 9, pp. 1345-1356, 2002.

[6] McCarthy, D., ERS Conventions, IERS Technical note 21, 1996.

[7] Cartwright D. E. and R. J. Tayler, New computations of the tide-generating potential, Geophys. J. R. Astr. Soc. vol. 23, pp. 45-74, 1970.