Evaluation of Slope Correction Methods to Improve Surface Elevation Change Estimation over Antarctic Ice Sheet using SARAL/AltiKa

Priyanka Patel[1,*], Purvee Joshi[2], Tarang Patadiya[3], Sushil Kumar Singh[2], Kunvar Yadav[1], Sandip R Oza[2]
[1] Ganpat University, Mehsana
[2] Space Applications Center, ISRO, Ahmedabad
[3] Gujarat University, Ahmedabad
*Correspondence E-mail: pyankap@gmail.com

(Received: 30 December 2022; Accepted: 9 July 2023)

DOI: *https://doi.org/10.58825/jog.2023.17.2.23*

Abstract: Antarctic Ice Sheet (AIS) surface elevation change plays a crucial role in understanding the ice sheet mass balance. The present study focuses on improving AIS surface elevation estimations by incorporating slope correction methods called Direct Method (DM) using SARAL/AltiKa 40 Hz geophysical data record for 2013 (Exact Repeat Mission) and 2020 (Drifting Phase) with terrain slope ranges from 0° to 0.85°. The NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) Digital Elevation Model (DEM) has been utilized as a priori topography model to retrieve slope of the AIS terrain. While comparing the two direct methods (DM1 & DM2) based slope corrected elevations with Operation Ice Bridge (OIB) elevation data of November 2013, the RMSE resulted in 0.35 and 0.37 m and biases of the order of 0.26 and 0.28 m for DM1 and DM2 respectively. Moreover, comparison with ICESat DEM showed the RMSE of the order of 1.81 and 2.09 m, and biases of the order of 0.95 and 0.99 m for DM1 and DM2, respectively. It has been observed that DM1 is the most suitable method for correcting terrain slope with the lowest RMSE and bias. Moreover, the slope induced error correction methods show utmost importance in estimating accurate elevation, especially over undulating terrain of AIS.

Keywords: SARAL/AltiKa, Antarctic Ice Sheet, Surface Elevation, Slope Correction Method

1. Introduction

The study of changes in Antarctic Ice Sheet (AIS) surface elevation serves as a significant response of ice dynamics and is crucial for understanding global climatic variations (Helm et al., 2014; Felikson et al., 2017; Suryawanshi et al., 2019). A satellite altimetry is a key measurement tool for monitoring polar ice sheets (Remy et al., 1989). Zwally et al. (1975) first proposed the use of the satellite altimetry to measure ice sheet surface elevation changes. Several studies used altimeter due to its capability to provide almost complete and homogeneous coverage of the ice sheets, which makes it useful for understanding and analysing elevation over ice sheets (Bamber, 1994; Davis et al., 2004; Roemer et al., 2007; Pritchard et al., 2009; Flament and Remy, 2012; Helm et al., 2014; Mcmillan et al., 2019; Suryawanshi et al., 2019; Hai et al., 2021).

Both laser and radar altimeters have been widely used to observe polar elevations remotely (Pritchard et al., 2009; Smith et al., 2009; Sorensen et al., 2011; Ewert et al., 2012). For example, to examine the AIS elevation changes between 1995 and 2000, Davis et al. (2004) used ERS-2 radar altimeter data. Another study by Pritchard et al. (2009) utilized ICESat laser altimeter data to monitor AIS elevation changes. However, there are certain advantages and disadvantages of both laser and radar altimeters. For instance, in a laser altimeter the divergence of the beam is narrow, resulting in a fine resolution footprint. Due to this the slope-induced error in estimating elevation can be ignored (Fricker et al., 2005; Brenner et al., 2007). On the other hand, the processing of radar altimeter data over ice sheet surface is complicated due to its large radar footprint, causing the slope-induced error (SE) in elevation estimations. This requires slope correction in radar altimeter as the essential data processing step for correcting the range of the satellite for the corresponding ground location (Bamber, 1994; Schroder et al., 2019; Hai et al., 2021).

There are certain slope correction methods such as Direct Method (DM), Intermediate Method (IM) and Relocation Method (RM). The IM (Remy et al., 1989) does not deal with correcting the range of the satellite, instead, it focuses on finding the exact location so that the measured range becomes accurate. The RM (Brenner et al., 1983; Roemer et al., 2007; Hai et al., 2021) locates the closest point to the satellite using surface slope magnitude and direction and calculates the correction required to determine surface elevation. The DM (Brenner et al., 1983) calculates the corrected range to the nadir position using the surface slope magnitude between the closest point and nadir. Based on the previous studies (Brenner et al., 1983; Cooper, 1989; Bamber, 1994; Roemer et al., 2007; Hurkmans et al., 2012; Helm et al., 2014; Hai et al., 2021), two mathematical approaches of the direct method have been noticed, which helps in retrieving the elevation in a more accurate manner. Here, the approaches have been termed as Direct Method 1 (DM1) (Roemer et al., 2007; Hai at al., 2021) and Direct Method 2 (DM2) (Brenner et al., 1983; Suryawanshi et al., 2019).

DM1, a study by (Brenner et al., 1983; Bamber, 1994; Roemer et al., 2007) have introduced the consideration of quadratic function to fit the varying DEM surface as the effective surface. This function helps in calculating the local slope angle and direction, which further minimizes much of a slope-induced error in estimating elevation (discussed in detail in section 4). DM2 incorporated by (Brenner et al., 1983; Suryawanshi et al., 2019) measured the elevation impacted due to terrain slope. Therefore, the present study aims to implement slope correction methods (DM1 and DM2) for further improving the elevation and elevation change over AIS. SARAL/AltiKa, a radar altimeter has been used in this study, which is principally a nadir-looking altimeter that transmits and receives microwave pulses (Ka-band frequency, 35.75 GHz) as backscattered signals (Suryawanshi et al., 2019; Verron et al., 2021). In the present study, the surface elevation has been estimated for 2013 from the Exact Repeat Mission (ERM) and 2020 from the Drifting Phase (DP) of SARAL/AltiKa (discussed in section 3) over AIS. In addition, a-priori available Digital Elevation Model (DEM) from NASA's Ice, Cloud and Land Elevation Satellite (ICESat) was then used to apply slope corrections on the retrieved elevations mainly for regions having slope less than or equal to 0.85°. The limit on the slope has been applied to avoid vertical error which can reach more than 80 m above the surface slope 0.85° (Brenner et al., 1983; Hurkmans et al., 2012; Fei et al., 2017). In order to deduce the best approach out of the two methods (DM1 and DM2), the estimations obtained from SARAL/AltiKa have been compared with NASA's Airborne Topographic Mapper (ATM) of the Operation Ice Bridge dataset for the period 26 November, 2013 and ICESat DEM for the period 2003-2005 over Vostok subglacial lake. The paper also includes the estimation of elevation change between 2013 and 2020 of SARAL/AltiKa slope-corrected datasets over entire AIS, obtained using the best approach out of two (DM1 and DM2).

2. Study Areas

The Antarctic Ice Sheet has been chosen to implement direct method-based slope correction for estimating corrected elevation as shown in Figure 1. A green colored rectangle over East Antarctic Ice Sheet covering Vostok subglacial lake has been selected for finding range correction magnitude (ΔR) associated with terrain slope (θ) for comparison of two methods DM1 and DM2, respectively.

3. Data used

The joint altimetry mission of ISRO and CNES, called as SARAL (Satellite with ARgos and AltiKa) followed initially 35-day repeat cycle, known as Exact Repeat Mission mode (ERM) from launch i.e. February 2013 to July 2016. Thereafter it entered into a new orbit called the Drifting Phase (DP) on July 4, 2016. Both, ERM and DP phases acquisition of SARAL/AltiKa have been depicted for one cycle in Figures 2a and 2b. SARAL/AltiKa 40Hz geophysical data records have been utilized from the FTP link ftp://avisoftp.cnes.fr/AVISO/pub/saral/gdr_f for the years 2013 and 2020 in ERM mode and DP mode respectively as listed in Table 1 to estimate the AIS surface elevation change. The 500 m high resolution NASA's, ICESat DEM (1 February 2003 to 30 June, 2005) downloaded from the US National Snow and Ice Data Centre (NSIDC) website http://nsidc.org/data/nsidc-0304 to estimate the terrain slope of AIS. Further, the ATM of OIB data for the year 2013 have been downloaded from https://nsidc.org/data/ilatm2/versions/2 to compare the slope-corrected dataset of SARAL over Vostok Lake.

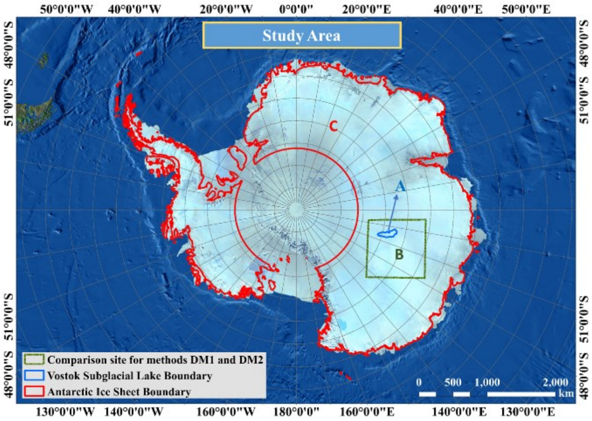

Figure 1: A) Region selected for Comparison of Direct Methods (DM1 & DM2) derived using SARAL/AltiKa with ATM and ICESat DEM over Vostok Lake (shown in blue color), EAIS, B) Region selected for depicting graph of Slope induced elevation correction (ΔR) (metres) vs. Slope (Degrees) (shown in green color) and C) Antarctic Ice Sheet (red color boundary) selected for estimating elevation change by incorporating DM1 based slope correction method

Table 1: Details of altimeter data utilized for applying slope correction methods and improving surface elevation estimations over AIS.

Sr. No.	Acquisition Duration	Data
1	(i) cycles 136 to 146 (16 Dec 2019 - 04 Jan 2021) (ii) cycles 01 to 09 (14 March 2013 - 23 Jan 2014)	SARAL/AltiKa
2	2003-2005	ICESat DEM
3	26 November, 2013	Airborne Topographic Mapper (ATM)

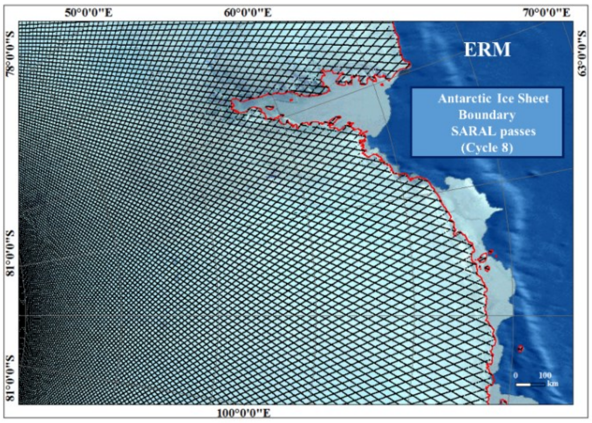

Figure 2a: SARAL/AltiKa passes of cycle 008 (14 Nov-19 Dec, 2013) in ERM mode

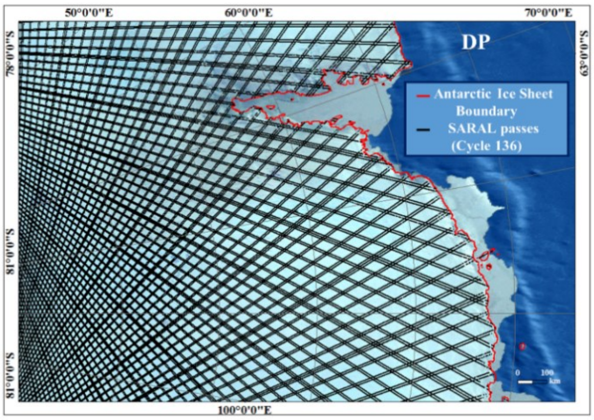

Figure 2b. cycle 136 (16 Dec-20 Jan, 2020) in DP mode over EAIS

4. Methodology

4.1 Ice Surface Elevation Estimation over AIS

The formula suggested by Helm et al. (2014) has been applied to derive the elevation over AIS.

$$\text{Elevation}=H-R_m-DTC-WTC-IC-SETC-PTC \quad (1)$$

where,
H is altitude of a satellite,
R_m is measured range of a satellite,
DTC and WTC are Dry and Wet Troposphere Corrections
IC is Ionosphere Correction
SETC is Solid Earth Tide Correction
PTC is Pole Tide Correction

Ice-2 is a physical retracker on board SARAL, which adapts brown model (Brown, 1977) with slight modification, where the concept is to fit the return waveform especially for the ice sheet region to coincide with the brown shape model. In the present study, elevation change between 2013 [cycles 01 to 09 (14 March 2013 - 23 Jan 2014)] and 2020 [cycles 136 to 146 (16 Dec 2019 - 04 Jan 2021)] have been derived using ice-2 retracker range.

4.2 Slope Induced Elevation Correction Methods

Due to complicated and non-linear surface topography, the altimeter measures range from the Point Of Closest Approach (POCA) instead of nadir view, which makes it difficult to process altimeter data for retrieving the correct estimation of surface elevation. Several hundred meters of vertical error can be introduced by a slope of 0.85° when measured at 800 km altitude of satellite (Brenner et al.,1983). In order to estimate correct elevation over such surfaces, it becomes very crucial to incorporate terrain slope information. This can be achieved by applying slope correction methods. Slope correction methods can be broadly categorized as (i) Direct Method (DM) (ii) Intermediate Method (IM) and (iii) Relocation Method (RM).

In present study, we have employed direct methods in order to incorporate the slope information and thereby improved surface elevation. Direct method for correcting slope induced error calculates the corrected range from the Center Of Gravity (COG) of satellite to the nadir point, which is normal to the local ellipsoid surface. The assumption for the direct method is such that the terrain surface between the originally measured position (P) and satellite nadir point (S) is a simple inclined plane as shown in Figure 3. Plane slope angle θ has been used for the range correction estimation.

The two direct methods suggested by (i) Hai et al. (2021) (here after named as Direct Method 1 (DM1)) (ii) Brenner et al. (1983) (here after named as Direct Method 2 (DM2)) have discussed in detail in subsequent sub sections for the terrain slope range 0 to 0.85°. A python based module has been developed to implement the slope correction methods over AIS surface elevation and ESRI's ArcGIS was used to analyze the outputs of the study.

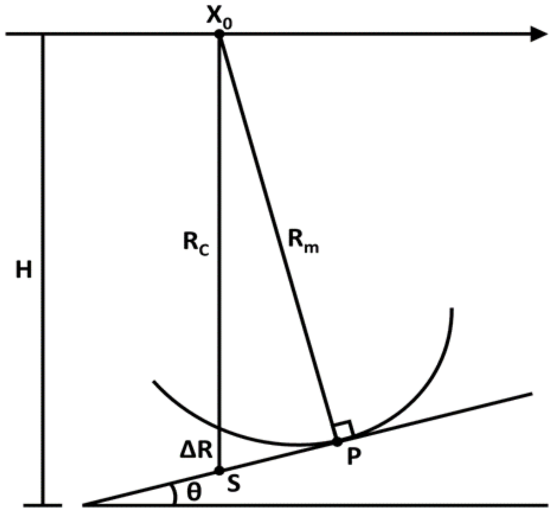

Figure 3: Schematic diagram of direct method.

4.2.1 Direct Method 1 (DM1)

Within the radar Pulse Limited Footprint (PLF), the topography surface can either be complex or flat region. In the present case we have utilized the first study approached by Hai et al. (2021) for the terrain slope range 0 to 0.85°. In this case, a quadratic function has been introduced to fit the varying DEM surface as the effective surface. Explicitly, the method was expressed by Roemer et al. (2007) as follows:

$$h_i = \bar{h} + \theta_x x_i + \theta_y y_i + \theta_{xx} x_i^2 + \theta_{xy} x_i y_i + \theta_{yy} y_i^2 \quad (2)$$

$$\theta = \sqrt{\theta_x^2 + \theta_y^2} \quad (3)$$

$$c = \frac{2(\theta_x^2\theta_{xx} + \theta_x\theta_y\theta_{xy} + \theta_y^2\theta_{yy})}{\theta^2} \quad (4)$$

$$R_c - R_m = \Delta R \quad (5)$$

$$\Delta R = \frac{R_m\theta^2}{2\left(1 - R_m\left(c - \frac{1}{r_E + \bar{h}}\right)\right)} \quad (6)$$

In the final expression of correct elevation, the R_m (measured range) will be replaced by the corrected range R_c (measured from eq. 5) in the equation 1.

where,
h_i,x_i , y_i are vertical & horizontal Cartesian coordinates of each DEM pixel
$\bar{h}$ is fitted model elevation in meters (m)
θ_x, θ_y,θ_{xx},θ_{xy},θ_{yy} are 1st and 2nd order coefficients of topography (need to be estimated)
c is curvature is measured in (m^{-1})
θ is slope angle measured in radians
R_c is corrected range measured in meters (m)
$\Delta R = R_c - R_m$ measured in meters (m)
r_E is mean radius of Earth that is equal to 6371 km = 6371000 m

To implement the direct method 1, there are two key points which need to be noted. First, determining the fitting area within the nadir (S) and POCA (P) points. A technique called the Euclidean distance, is used to search a fitting area within the footprint between the COG of the satellite and DEM cells. Secondly, a linear least-square technique is adopted to successfully estimate at least six DEM cells ($\bar{h}, \theta_x, \theta_y, \theta_{xx}, \theta_{xy}, \theta_{yy}$). Also, in this method, the slope angle is estimated by PLF (Pulse-Limited Footprint) which is determined using the quadratic and spatial scale fitting. This improves the quality of slope and curvature parameters (Roemer et al., 2007).

4.2.2 Direct Method 2 (DM2)

Initially, this method was introduced by Brenner et al. (1983) with the assumption that terrain slope θ is very small. Using this approach Suryawanshi et al. (2019) have shown the slope-induced elevation correction over AIS for the terrain slope range 0 to 1°. We have incorporated the slope-induced elevation correction (Brenner et al., 1983) using ICESat DEM-derived slope (θ) information for the terrain slope range 0 to 0.85°. The formulae used in the calculations are given below:

$$\Delta R = H - H cos\theta \quad (7)$$

$$\Delta R = H(1 - cos\theta) \quad (8)$$

If θ (measured in radians) is small, then

$$\Delta R = \frac{H\theta^2}{2} \quad (9)$$

where,
ΔR is slope induced elevation correction magnitude

$$Correct\ Elevation = Elevation - \Delta R \quad (10)$$

5. Results and Discussion

From the study, it has been observed that in radar altimetry data, slope-induced elevation correction is important. This is because the radar altimeter does not measure the distance between the satellite and the sub-satellite point (nadir), instead, it measures from the POCA in case of an inclined surface, where the measurement taken is shifted upward, resulting in an error, which depends on the square of the slope (Hurkmans et al., 2012). The relationship between correction magnitude (ΔR) and surface slope (θ) has been shown in Figure 4. The statistical trend of the graph shown in Figure 4 has been aligned with the previous studies (Brenner et al., 1983; Suryawanshi et al., 2019; Hai et al., 2021). For example, Brenner et al. (1983) mentioned as "For a radar altimeter with an altitude of 800km and surface slope of 0.8° can cause up to 80 m of vertical error". Therefore, the slope-induced elevation correction has been applied for regions having a slope less than or equal to 0.85° over AIS. However, the graph of (ΔR) vs. slope (θ) has been displayed for the East Antarctic Ice Sheet (EAIS) shown in Figure 1, which shows that the correction magnitude (ΔR) is smaller in DM1 compared to DM2.

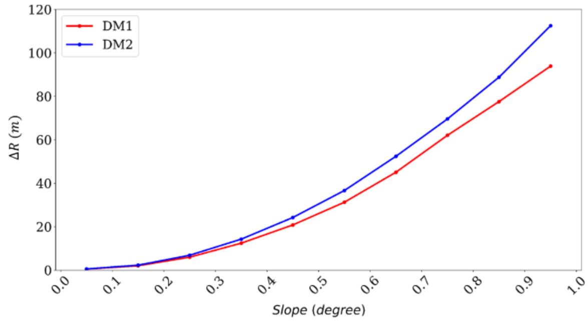

Figure 4: Slope induced elevation correction (ΔR) vs. Slope (Degrees)

5.1 Comparison of DM1 and DM2 over Vostok subglacial Lake

To realize the best approach between the two (DM1 and DM2) in terms of slope correction, slope-corrected surface elevation of SARAL/AltiKa cycle 008 (14 November – 19 December, 2013) data have been compared with the NASA's Airborne Topographic Mapper (ATM) (26 November, 2013) over Vostok subglacial Lake, EAIS (shown in figure 5) because of its flat topography (Richter et al., 2014). The ATM data available over AIS for the year 2013 is available from 18 to 28 November, but we have used 26 November, 2013 in order to compare and overlap the dataset in terms of temporal context with cycle 8 of SARAL/AltiKa over Vostok subglacial lake. The bias and root mean square error for DM1 and DM2 derived from the SARAL/AltiKa dataset with ATM and ICESat DEM are shown in Tables 2 and 3. While comparing DM2 with ATM resulted in RMSE of the order of 0.37 m. On the other hand, the comparison of DM1 with ATM resulted slightly better RMSE of the order of 0.35 m compared to DM2 over Vostok lake. Furthermore, the statistical comparison of DM1 and DM2 (for cycle 8 of SARAL) with DEM (2003-2005) also yielded better RMSE and bias of DM1 (1.81 and 0.95 m) compared to DM2 (2.09 and 0.99 m), respectively. It is to be noted that the above error estimations may also be partially contributed by interpolated products of SARAL/AltiKa. Moreover, Remy et al. (1989) demonstrated in their study that the results of the refined direct method which are termed here as DM1 significantly improve because it accounts for the surface curvature in addition to the slope of the surface. Therefore, based on the computations shown in Table (2, 3) and the graph shown in Figure 4, and also by considering an additional parameter "curvature" along with slope, it can be inferred that DM1 is better than DM2 in terms of RMSE and bias.

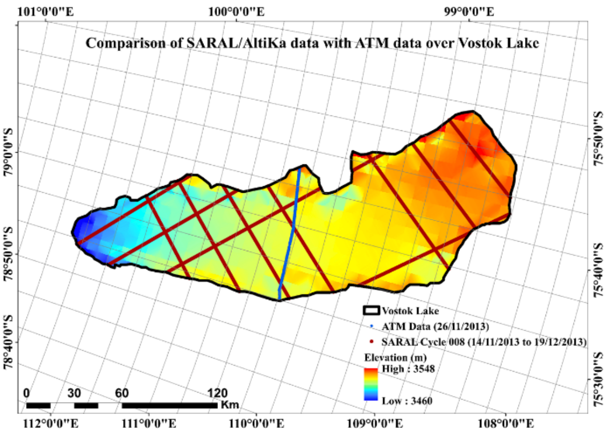

Figure 5: Comparison of Direct Method derived using SARAL/AltiKa with ATM over Vostok Lake

Table 2: Comparison of DM1 and DM2 with ATM over Vostok Lake

Direct Method	Bias (m)	RMSE (m)
DM1	0.26	0.35
DM2	0.28	0.37

Table 3: Comparison of DM1 and DM2 with ICESat DEM over Vostok Lake

Direct Method	Bias (m)	RMSE (m)
DM1	0.95	1.81
DM2	0.99	2.09

5.2 Estimation of elevation over Antarctic Ice Sheet

Figure 6 shows the slope-induced elevation correction map derived using DM1 with an elevation contour of 200 m over the AIS for the year 2020. The elevation has been found to vary between 0 and ~4092 metres. In the inner part of AIS, high elevation is observed (~4092 m) that keeps on decreasing towards the coast.

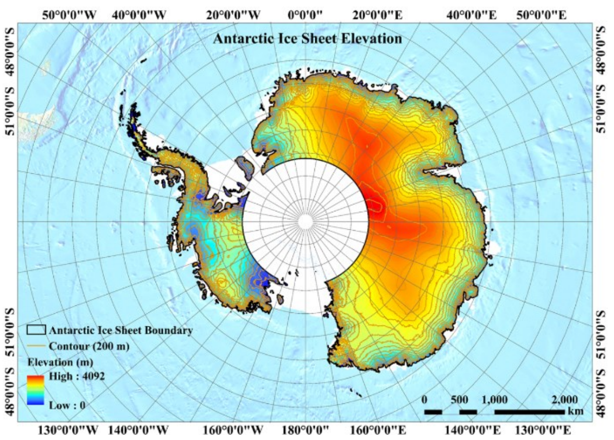

Figure 6: Direct Method 1 based slope corrected map of elevation over Antarctic Ice Sheet for the period 2020

5.3 Elevation change between 2013 and 2020 from SARAL/AltiKa dataset using the DM1 approach

To examine elevation change, the year 2020 [cycle 136 to 146 (16 Dec 2019 - 04 Jan 2021)] has been subtracted from year 2013 [cycle 1 to 9 (14 March 2013 - 23 Jan 2014)] over AIS. It has been observed that the elevation change ranges from -2 to 2 metres per year as shown in figure 7. Moreover, as observed in Figure 2, DP data (2020) represents higher geographic coverage, whereas in ERM mode (2013) same track has been repeated, limiting its capability to cover a larger area on the ground. This yields a higher number of distributed observations per 500m grid cell, which could provide a robust representation of elevation at 500m grid resolution.

It has been noted that in the coastal region, the thinning of ice is more compared to the inner part where the local surface topography is flat. Elevation change obtained between 2013 and 2020 of SARAL/AltiKa over AIS shows the mean loss of -0.26m/yr. It can be inferred from figure 7 that various parts of AIS show different elevation change behaviour. For example, Pine Island and Thwaites glaciers in WAIS show much of elevation loss, shown in blue colour in Figure 7. This may be due to the reasons mentioned by (Davies, 2020) and Darji et al. (2019) that mainly the ice stream is heavily crevassed and dangerous, which results in calving when studied using Sentinel-1A data. There are many other factors also responsible for the calving events, such as earthquakes, which occur at the plate boundaries of the Antarctica Plate (Winberry et al., 2020). In addition, grounding lines in WAIS extend down to 2000 metres below sea level, making the ice sheet intrinsically unstable and susceptible to melting, causing it to move quickly (Schoof, 2007; Davies, 2020). Moreover, stable elevation changes were observed in the EAIS. This may be due to the local surface topography which is the flat terrain, which is mostly located above sea level (An et al., 2022).

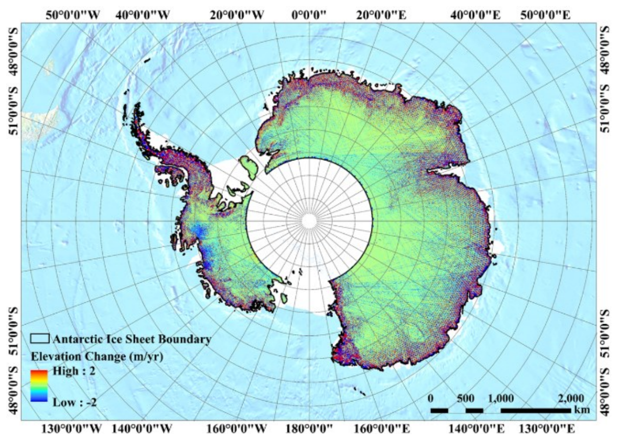

Figure 7: Elevation change between 2013 and 2020 of SARAL/AltiKa in metres per year over AIS

6. Conclusions

The current study is focussed on the detailed discussion and implementation of two approaches of direct methods (DM1 and DM2) to improve elevation and elevation change over the Antarctic Ice Sheet (AIS) for regions having slopes less than or equal to 0.85°. The ICESat DEM has been used as a priori topography model to retrieve the slope of the surface. Thereafter, in order to check the slope corrected dataset the DM1 and DM2 (for cycle 8 of SARAL) have been compared with ATM (for 26 Nov, 2013) and DEM (2003-2005) over Vostok subglacial Lake.

The study reveals the applicability of DP mode data to assess the average elevation change over ice sheet. Based on the RMSE and bias values obtained on the comparison, it has been observed that DM1 is the appropriate method for slope correction. Therefore, the DM1 method has been utilized to obtain elevation and elevation change between 2013 (Exact Repeat Mission) and 2020 (Drifting Phase) of the SARAL/AltiKa dataset over AIS. This resulted in a mean loss of -0.26 m/yr. Various parts of AIS show different behavior of elevation change. To observe and infer the detailed topography changes, we have to consider a long time series of radar altimeter data. Hence, the study can further continue to estimate and improve the elevation estimations over ice sheets by incorporating the most suitable slope correction technique.

Acknowledgement
We gratefully acknowledge Shri Nilesh M. Desai, Director, (SAC-ISRO) Ahmedabad, for his encouragement and support. We are also thankful to Dr. Parul Patel, Dr. S.P. Vyas and Dr. Sharad Chander from SAC providing the necessary technical support. Authors are also thankful to Dr. Amit Parikh, Head & Principal, MUIS College, Ganpat University for always motivating and supporting.

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