Interactive comment on "TanDEM-X PolarDEM 90 m of Antarctica: Generation and error characterization"

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Referee comments are shown in *black*, our response in blue. Line numbers refer to the manuscript version (pdf) of 21 January 2021.

Authors' response to anonymous Referee#2

This paper describes the generation of a new 90 m resolution DEM, with virtually complete coverage of Antarctica, from TanDEM-X acquisitions. This DEM features gap filling with new acquisitions, a treatment of noisy areas, and the authors describe a new technique for delineating the Antarctic coastline. The DEM is then extensively evaluated against a series of datasets from different sensors.

Overall I found this study to be very well written – it's clear the authors have put in a lot of effort to make sure the methods and validation are thoroughly described and that the paper is well presented. The DEM agrees very well with the chosen validation datasets; the methods implemented are new and the DEM features several improvements over previously existing InSAR DEMs making it worthy of publication.

Response: First, we want to thank the Referee for the time and effort put in this detailed and thorough review. We are impressed about the deep understanding and careful reading of the reviewers. We thoroughly evaluated all comments and suggestions, which are very valuable in improving this paper and we are glad about the positive feedback.

We particularly value the Referee#2's appreciation of the following main aspects that we will incorporate into the manuscript: 1a) a better explanation of the reflective surface of X-Band SAR DEM for ice/firn areas; 1b) more explanations and examples of the benefits of the presented DEM; and 2) some more IceBridge comparisons will be discussed here, also why the authors think that these are not useful for an error characterization.

General comments

My only general comments are regarding (1) the surface actually represented by the DEM and (2) the comparison between the laser altimetry (both ICESat and IceBridge):

(1) While I appreciate the author's decision to not raise the DEM to ICESat elevations, it leaves me with questions regarding which surface the DEM represents, as my understanding is that it's not the true surface (i.e. air-firn interface) but somewhere below in the firn pack (with spatial variations depending on scattering properties). This unfortunately limits it's use for applications in e.g. ice flow models. It would be helpful to add some text explaining this more clearly to the reader and for what applications this DEM is appropriate for.

Response: (1a - surface of X-Band SAR DEMs for ice/firn areas) Many thanks for stressing this topic. We recognized that the physical scattering surface for X-Band SAR for ice/firn surfaces was not well enough explained, also, both reviewers raised this topic. In fact, the scattering surface is not air-ice but

somewhere in the ice resp. in the firn varying due to the ice/firn characteristics, what makes it variable and complicated.

First of all, the measured InSAR height represents an elevation corresponding to the average penetration when firn is present. Over pure dry firn (no melting or physical effects present) the radar waves at X-band penetrate inside the snow pack and are gradually absorbed with increasing depth, while only a fraction is backscattered toward the SAR instrument. The individual scattered returns stem from varying depth, that are aggregated to a mean "scattering phase center". In Antarctica as well as on the Greenland ice sheet no more "mean scattering depth" than 10m below the air-ice surface were observed (ICESat-1 as reference) in case of TanDEM-X. Compared to Greenland ice sheet, the InSAR penetration bias in Antarctica is smaller, because the ice masses are affected by strong wind effects that changes the microstructure and density of the snow and ice layer. Such densified layers influence the backscattering as they often act like a strong backscatter layer for X-band SAR, where a large part of the scattering takes place. In general, the layer-structure and therewith the corresponding X-band penetration bias is unknown. A hint about the reflective surface is given by the amplitude image (Fig. 10). Strong backscatter indicates the presence of such densification processes which lead to a predominant reflection at this layer. To improve the usability of the TanDEM-X DEM in the future, this relationship will be further investigated by the authors to be able to model the penetration bias to achieve a corrected version that represents at least an approximation of the surface (Abdullahi et al. 2019).

Response: (1b - Use of the DEM)

We agree that the use of the TanDEM-X DEM over ice sheets is therefore not straight forward. However, SAR sensors are well established and widely used in cryosphere applications. They all have in common that the SAR signal penetrates and the derived information is not related purely to the upper surface. From that point of view the TanDEM-X DEM could serve as an ideal basis DEM e.g. for applications like the interferometric SAR velocity estimation and also the ortho-rectification of SAR data. Theybenefit from a similar penetration bias as well as from a complete, gap-free coverage that is prerequisite for these applications. The almost gap-free coverage of TanDEM-X is also a big plus. Compared to REMA the Polar Whole is covered and there are no data gaps at the Peninsula.

Nevertheless, elevation change or mass balance change are important topics that require two or more DEMs. For DEM to DEM comparison the penetration bias should be handled adequately. For example (Huber et al. 2020) used the TanDEM-X DEM of Greenland in comparison with aerial photogrammetric DEMs over a 28-years period and therefore decided to neglect the penetration. In contrast, Malz et al. used the TanDEM-X DEM for a comparison with SRTM and roughly estimate the different penetration biases in advance. In both cases, the (residual) unknown penetration bias was regarded and modelled as an additional uncertainty for the heights. For X-band DEM to X-band DEM comparisons the penetration bias could be regarded as an uncertainty assuming similar biases or- for higher accuracies – has to be compensated first (Abdullahi et al. 2019). We will add these aspects and the examples.

(2) *I find the author's approach inconsistent in that they omit addressing temporal differences between the ICESat data and the DEM, but use them as a justification to remove the majority of IceBridge data available in Antarctica. The well characterised pattern of dynamic ice sheet thinning across West Antarctica is clearly visible in the largest ICESat-DEM differences (Fig 11) but is not addressed. As presented, I feel the reduced spatial distribution of the IceBridge comparison make it not as useful as some the other comparisons in*

characterising the DEM accuracy. Regarding the IceBridge data – there have been (to my knowledge) contemporaneous IceBridge acquisitions between 2013-2017 across Antarctica which could be included as they would minimise this temporal difference. It may also be possible to address this using rates of elevation change (many datasets are available) to adjust for the temporal difference between both datasets.

Response: (2- more IceBridge comparisons) For a DEM error characterization, we chose stable regions in height and over time for a prober absolute height validation. This was the reason to select the stable blue-ice areas (ICESat comparisons) or the Recovery glacier or South Pole comparisons with IceBridge. Areas with larger height variations were excluded from a detailed analysis as the height differences can be attributed to both "real" change phenomena caused by height variations during the time-span between ICESat (-2009) and TanDEM (2013-2014) or to calibration errors. The latter are of main interest here. As the reviewer states, for the selection of IceBridge data we therefore evaluated its availability with areas where height change occurs. So, we finally decided to take just two campaigns closest in time and with the potentially lowest change rate (Recovery glacier or South Pole).

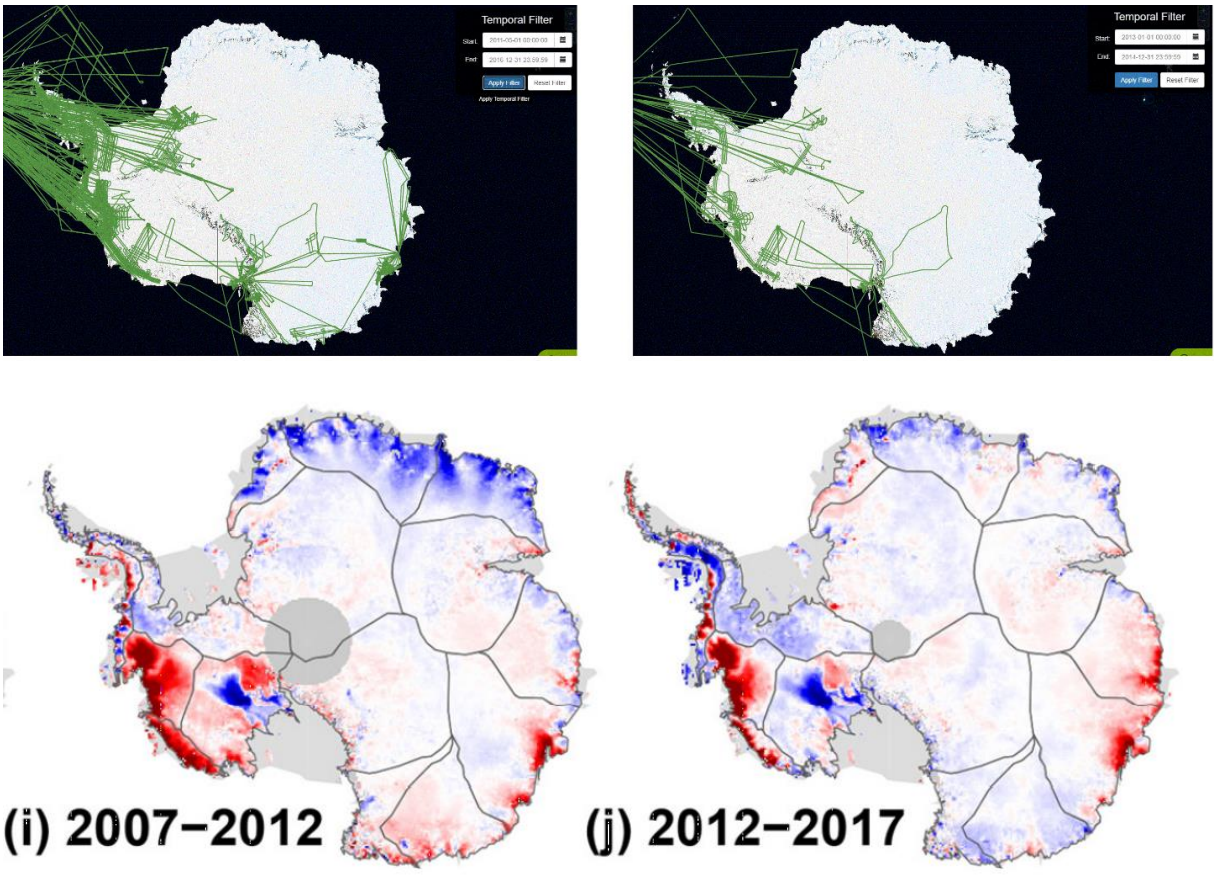


Figure A: Availability of IceBridge, upper left between 2011 – 2016; upper right between 2013 - 2014 (for reference: TanDEM-X acquisitions 2013 – 2014). In the bottom row: estimated elevation change from Schröder et al 2019.

Nevertheless, the Recovery Glacier shows some larger height discrepancies. Due to the comment of Referee#1 we investigated his assumption in detail that subglacial drainage might be partly responsible for the height differences over the Recovery glacier. It turned out, that some active regions are within the main trunk. In summary, even a time span of just 0.5 to 1.5 years is not well suited for a DEM validation in this area. Anyhow, the comparison with IceBridge shows some nice details about the data set, and that in general the expected correlation between the amplitude backscatter (which is related

to ice characteristics) and the measured penetration bias is confirmed: high amplitude values = no/small penetration bias, low amplitude values = high penetration bias (Floricioiu et al, 2016).

In contrast, the the value of ICESat data lies in its well-distribution over whole Antarctica. On the one hand, the differences to ICESat give a good overview of the penetration bias in general. And for the blue ice areas, where the heights of ICESat and TanDEM-X are most comparable, a true validation is possible. On the other hand, due to the time lag between ICESat (< 2009) and TanDEM-X (2013-2014) the differences indicate the same elevation change presented in Figure A. So, we agree the need to mention the regions with some well-known effects that can be observed by the ICESat differences like the most obvious explanation for the differences at the Peninsula down to Getz glacier.

Specific comments

L4 – Suggest explicitly stating the time period the DEM covers somewhere in the abstract.
A: Thanks for this comment. We will add the acquisition period of April 2013 to October 2014 in the abstract.

L9 – I suggest rewording this sentence as it implies an error characterisation was carried out continent wide for IceBridge, which is not the case.
A: We agree and will omit IceBridge in the abstract as it plays a minor role. (REMA and CryoSAT-2 DEM aren't mentioned either)

L25 – Helm et al., 2014 is not based on 2010-2016 data so I suggest rewording here.
A: Thanks. We will rephrase to "or CryoSat-2 DEMs *based on data as of 2010* with a spatial resolution of 1 km"

L39 – Suggest 'Futhermore' instead of 'Furtheron'.
A: Thanks.

L48 – I feel it is misleading to characterise Laser/InSAR measurements as 'the same' because there will be other sampling factors beyond the penetration bias, so would suggest rewording – happy for this to be explained to me if I'm wrong and the authors disagree!
A: This sentence will be rephrased to *"BIAs consequently should have near-identical elevations in both X-band InSAR and laser altimetric measurements."*

L54 – Are there major differences between these baselines? It may be beneficial for the reader new to this data to go into a little bit more here.
A: The different baselines are mainly acquisition-related and not relevant here. We will omit the phrase "with larger heights of ambiguity". Anyway, details can be found in (Borla Tridon et al. 2013)

L77 – Are these data removed for block adjustment or for validation? If for validation this seems circular to me as the authors would be removing IceSAT data based upon comparisons to their DEM before using it as a validation dataset – can the authors provide more justification as to why this is appropriate to remove the ICESat data if this is the case? Apologies if I've misunderstood.
A: Thanks for noting, indeed it seems a bit circular. What is missing in the explanation is that ICESat-1 contains several points that are reflected on clouds in some few hundred meters height above the surface. These are really gross errors that should be eliminated for any evaluation of the data. TanDEM-X wouldn't have to be used necessarily, any more or less 10-meter accurate DEM would be appropriate. For Antarctica and elsewhere at that moment, the TanDEM-X input scenes seemed good enough for this gross error detection. We will rephrase this passage addressing the gross errors caused by clouds.

L80/L86 – It's not clear to me from this section how the 'best 10' or 'most 1000 reliable' ICESat data points are selected. I'd suggest editing the text slightly to help the reader out.

A: In fact, we haven't described it clear enough. We will revise this and the paragraph before in the final manuscript. (For all ICESat points, first the standard deviation TanDEM-X minus ICESat is calculated and stored as a quality measure for the ICESat points. Higher standard deviations indicate on the one hand higher slopes, i.e. unreliable ICESat heights or on the other hand, higher local relief or noise in the TanDEM-X DEM. Both should be avoided for reliable validation or calibration points, which should be located on relatively flat terrain.)

L93 – Suggest rewording this sentence to make it clearer.

A: Thanks for noting. -> rewording: "They (blue ice areas) are scattered throughout the continent, mostly near inland mountain ranges and nunataks, and in coastal regions with strong katabatic wind influence."

L106/throughout – there are lots of locations referenced in the text with no indication of where they are. I feel it would be helpful to the reader to illustrate where some of these locations are to an existing figure or elsewhere.

A: We agree with this. We think some locations can be integrated with abbreviations into Figure 4, showing the calibration blocks. In other cases it will be possible to refer to a region by its coordinates, as we annotated every Figure with coordinate frames for this purpose.

L114 – Suggest changing 'bridging' to 'bridged'.

A: Thanks.

L122 – As I said previously in my general comment – I think better treatment and justification is required here as to why the vast majority of the available IceBridge data in Antarctica have not been used here.

A: See response above (2- more IceBridge comparisons).

L153 – I feel this sentence is unclear – it is implied that ICESat has a penetration bias when it is taken to return from the surface.

A: We agree. Will be reworded to: "In contrast, Antarctica's coast is mostly covered by ice and therefore, the ICESat and radar elevations do not represent the same elevation *because of the radar data's penetration bias*."

L155 – namend 'therewith'.

A: not fully clear what the reviewer means. We think this improves the sentence: "… we developed a new innovative approach relying on areas with homogeneous backscattering characteristics and thus primarily *homogeneous penetration bias (HPB)*, …"

L158 – I'm not sure what is meant by 'probably' in this sentence?

A: Thanks, we will remove it.

L166 – I feel this sentence is unclear as to what is meant by 'difficult conditions'.

A: Thanks, we will remove it. *"~~Due to the difficult conditions on ice sheets~~ For Antarctica only offsets a were determined."*

Fig 5 – A colour scale and indication of where this is in Antarctica might be helpful for the reader.

A: Sure, we will add a color scale in the final version of the manuscripts for Fig. 5.

Fig 6 – it looks to me like there could be new acquisitions used to fill gaps in regions in the Bellingshausen Sea where rates of thinning are high – is this accounted for when the DEM scenes are re-mosaicked, or is it not a factor on the DEM accuracy in these areas?

A: You are right, at the Peninsula there are some additional acquisitions for specific experimental tests, therefore, these were not used for global DEM generation. Only dedicated operational scenes were included in the update. In Figure 6 the geocells updated by gap-filling are plotted. The most southern tip of the Peninsula still has some minimal DEM gaps. An update is not foreseen at the moment.

L238 – I think 'Southern Ocean' instead of 'Antarctic Ocean' is the proper term here

A: Indeed. Thank you very much for this comment.

Fig 8 – It may be helpful to add the SCAR coastline to panel (d) to illustrate the difference.

A: We will try to integrate the initial SCAR, but it could be a bit tricky.

L303 – Fig 11 is referenced in the text before Fig. 10 – may be helpful to rearrange to improve readability.

A: Thanks. We will rearrange this.

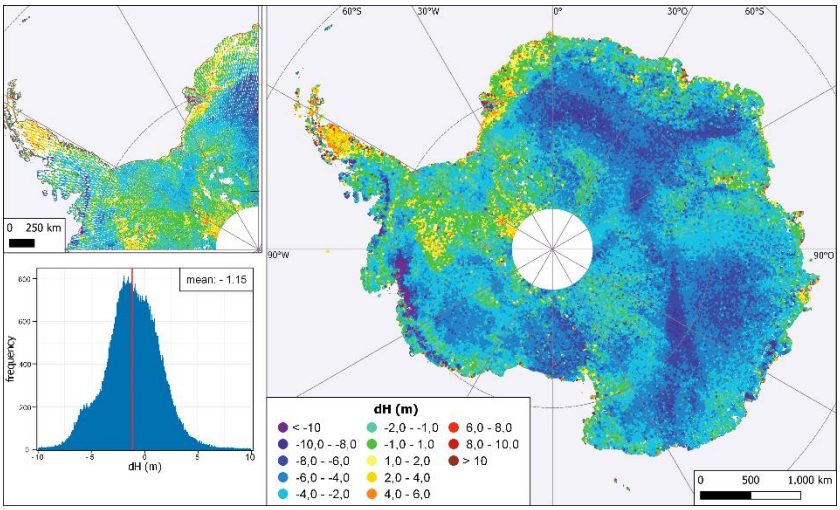
Fig 11 – As in my general comment – the pattern of dynamic thinning is clearly visible where the differences are purple from the Peninsula all the way across to the Getz region but is not addressed.

A: Thanks, as responded above, we will add the observation for this region.

L320 – It's not clear to me from the text which area is being referred to as 'West 90'.

coordinates were missing here, sorry.

A: We are sorry, because there were no coordinates in this image. We already updated it.



L323 – Suggest rephrasing this last sentence so it's clearer.

A: ok.

L324 – I'm not sure exactly what is meant by 'lower and stronger' here.

A: rephrases to "Here, deeper and shallower penetration biases alternate in a ray-structure…"

L327-328 – Suggest rewording this sentence to make it easier to read. These brighter amplitude areas look like they correspond to the Antarctic megadunes to me (in both Fig 10 and Fig 11) – it may be worth the authors commenting briefly on how these structures affect backscatter.

A: Exactly, this point was also mentioned by Referee#1. The megadunes represent 2 to 4 m amplitude waves of 2 to 5 km wavelength. This pattern is oriented perpendicular to the mean wind direction, as modeled in katabatic wind studies. Glazed surfaces cover the leeward faces and troughs; rough sastrugi cover the windward faces and crests. Leeward faces are characterized by glazed, sastrugi-free surfaces and extensive depth hoar formation. Here the grain size is increasing, which lead to an increasing backscatter (Scambos et al. 2012).

L330 – As in my general comment – apologies if I'm missing something here – I take this choice means the DEM does not represent the true surface height of Antarctica, but the X-band scattering horizon which seems to be variable in space/time. While the dataset is still very useful I feel this does limit it's potential use in e.g. ice flow models where the surface height is needed as a boundary condition and should be addressed in the paper.

We will add some lines about the use of the DEM, see response above.

L383 – CryoSat is used inconsistently throughout the text – suggest using 'CryoSat-2' everywhere.

A: We will use CryoSAT-2 for throughout the text. Thanks.

L400 – Would suggest rewording – it's clear there is an LRM/SARIn bias here but to me it's not clear whether it's due to penetration or other factors (e.g. footprint)

A: You are right, it is not fully clear where this LRM/SARin bias comes from. We will word it more carefully.

Best wishes,

Thanks again!

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