Final response to "TanDEM-X PolarDEM 90 m of Antarctica: Generation and error characterization"

Authors: Wessel, B., Huber, M., Wohlfart, C., Bertram, A., Osterkamp, N., Marschalk, U., Gruber, A., Reuß, F., Abdullahi, S., Georg, I., and Roth, A., The Cryosphere Discuss., https://tc.copernicus.org/preprints/tc-2021-19/

Referee comments are shown in *black*, our response to the interactive communication are in blue and updates to the final response to the referees in oliv. Line numbers refer to the manuscript version (pdf) of 21 January 2021.

Authors' response to Referee#1 Ted Scambos

General comments:

The study describes the assembly and processing of a new DEM of Antarctica produced by X-band interferometry using the TanDEM-X and TerraSAR-X satellites, with a gridding scale of 90 m. The DEM is exceptionally complete (99.991% of the continent mapped) and has a new derived ice sheet edge (coastline). Validation of the DEM over blue ice areas shows that in regions of near-zero radar penetration into the snow-ice surface (and little surface elevation change), the new DEM matches ICESat data very well. The paper is fairly well-written and well-described, and the authors are very clear about how they build the DEM.

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#1's appreciation of the following main aspects that we will incorporate into the manuscript: 1) a better explanation of the reflective surface of X-Band SAR DEM for ice/firn areas; 2) some more glaciological processes but also some explanations, why the authors think that these are not in detailed needed for an error characterization; 3) more explanations and examples of the benefits of the presented DEM; and 4) the insertion of some selective profiles plots.

However, the DEM is intentionally ***left unadjusted for X-band penetration*** *below the snow surface, although the offset between ICESat and the TanDEMX DEM is well described and has interesting regional variations. However,* ***it's unclear what surface is being measured*** *– how would this surface be described? Firn level at which a large fraction of X-band radar energy is scattered back?*

Response: (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).

Response1: We added some explanations in the introduction about “what surface is being measured”:

1) a better explanation of the reflective surface of X-Band SAR DEM for ice/firn areas:

“For the cryosphere, it provides an up-to-date high-resolution elevation of glaciers and ice sheets in high latitudes. It allows, for example, the comprehensive and contemporary high-resolution delineation of glaciers and ice sheets in high latitudes. The SAR signal can permeate up to a few meters (Rott et al., 2021; Fischer et al., 2020; Dehecq et al., 2016; Wessel et al., 2016). For Antarctica the mean penetration bias is 3 m, which is varying on a larger scale depending on the ice and firn characteristics. The measured InSAR height represents an elevation corresponding to the average penetration into the firn or ice surface. The different backscattered returns stem from varying depth and are aggregated to a mean “scattering phase center”. Over pure dry firn (no melting or40physical 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. 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 “

This makes the DEM hard to use for things not related to radar studies.

Response2: We added some explanations and examples of the benefits of the presented DEM in the conclusions:

“In cryosphere applications, different SAR sensors are well established and widely used. They all have in common that the SAR signal penetrates and the derived information is not related purely to the upper surface. Therefore, 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. They benefit from a similar penetration bias as well as from a complete, gap-free coverage, which is prerequisite for these applications. 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. (2018) 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 as it comprises just few meters. For

X-band DEM to X-band DEM comparisons the penetration bias could be regarded as an uncertainty assuming similar biases (Floricioiu et al., 2016)."

It also calls into question the nature of the local topography (scales of 1 – 5 ice thicknesses, horizontally) that is being measured. In many areas of East Antarctica, this is unlikely to be parallel to the air-snow interface because of strong variations in backscatter associated with local variations in deposition and sublimation.

Resonse3: 3 new sentences addressing the local topography are added at the end of the ICESat section (Sec. 5.1), in the description of the new profile plots (Sec. 5.4) and in the conclusions:

"The assumption could be confirmed that these differences are stable over large areas with homogeneous backscatter (compare to Figure 11 and Figure 10)."

"The profiles in Fig 19b), d), and e) illustrate the capability of the DEMs to capture fine-scale topography"

"Aside from the subsurface, the InSAR DEM captures local and regional relief quite well, as evidenced by the well-matching local heights with the REMA DEM."

The authors need to consider some glaciological processes that they may not be aware of

– sub-glacial lake drainages in the Recovery Ice Stream explain some of the shifts they see; Thickening in the LarsenC and thnning along the George VI southern coast and Amundsen Sea coast should be discussed as indicators of major mass balance changes --- also the Dotson Ice Shelf region.

Response: (glaciolgical processes) The reviewer's observation is correct and we intentionally avoided to attribute the affects to glaciological processes. For a DEM error characterization, we chose stable regions in height and over time for a proper 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. Nevertheless, we agree to mention regions with some well-known effects like the most obvious explanation for the differences at the Peninsula down to Getz glacier or the thickening in LarsenC (zoom here in the review). Also, in the inner Antarctica different snow characteristics play a mayor role for the variations between ICESat and TanDEM-X DEM. Here, we are very pleased about the hint of the Referee regarding an explanation for the inner ray-like structure (Scambos et al., 2016)

Recovery Glacier: We investigated your assumption that subglacial drainage might be partly responsible for the height differences over the Recovery glacier in more detail. We added to Figure 16 (height differences TanDEM-X minus IceBridge) the outlines of the known subglacial lakes (source Quantarctica3, Smith et al. 2009). The subglacial lakes deliver no clear indication for the larger height errors present at this glacier. So, we had a closer look at the TanDEM-X input data, the TanDEM-X DEM mosaic represents mean values of May 2013 and May 2014 at this part; IceBridge was taken in October 2014. In the TanDEM input data there are indeed mayor differences at some locations outside the lakes, these are marked with a red star in the updated Figure 16, indicating, the same depression like

IceBridge does. These might stem from potentially active subglacial lakes, but could also be caused by other effects (wind, incidence angle, change of ice characteristics). For us, the reason remains unclear, but there really seem to exist some depressions that explain the larger discrepancies between TanDEM-X mosaic and Icebridge. Apart of these spots, most of the Recovery Glacier main trunk shows the expected correlation between the amplitude backscatter (which is related to ice characteristics) and the measured penetration bias: high amplitude values = no/small penetration bias, low amplitude values = high penetration bias (Floricioiu et al, 2016).

Response4: As discussed above, this area is quite complicated and show that active areas that are the observing goal of IceBridge are not well suited for a DEM validation, even if the time span covers just 1.5 years. As this point is described in the online-answer and is mentioned in Sec. 2.4 IceBridge measurements,

Sec. 2.4 "*Furthermore, the IceBridge program's focus are active glacier areas (Koenig et al., 2010) which lead to temporal changes. Therefore, regarding our validation purpose, we carefully examined the IceBridge data set and selected IceBridge data from the same period and from the most stable regions like the South Pole and the Recovery glacier, both acquired in October 2014.*"

We only added a reference that deeper analyzed this problem (Floricioiu et al. 2016).

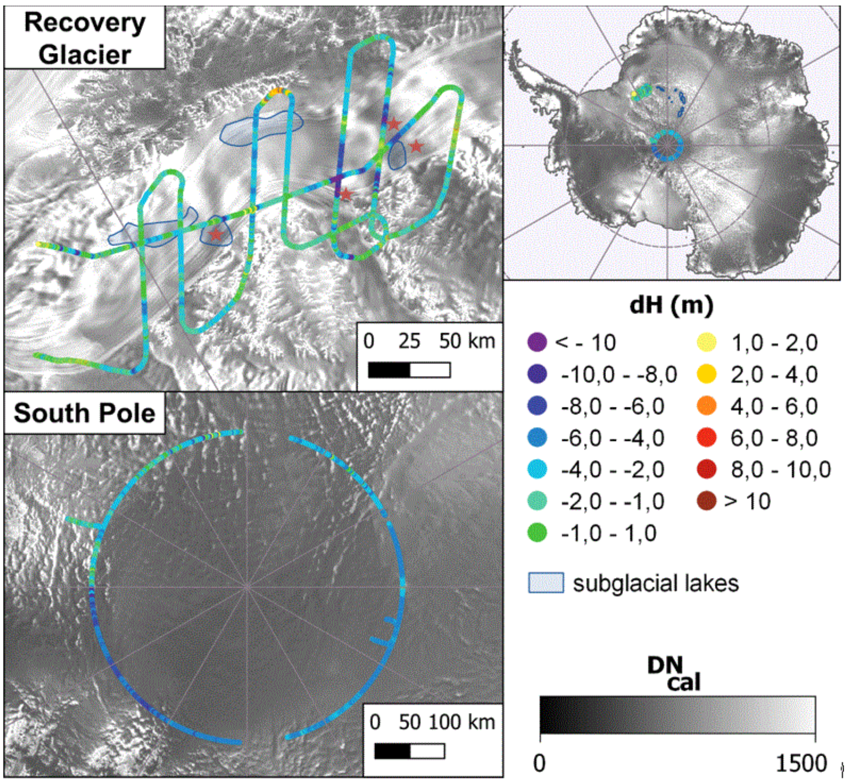
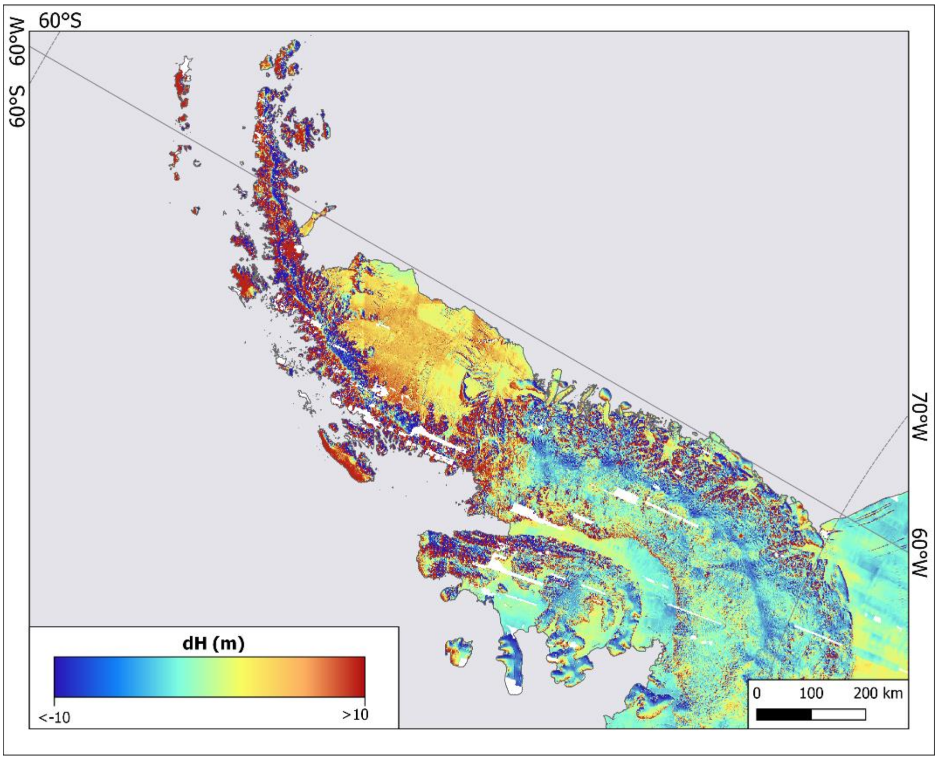


Fig. 16 updated here, but not in the paper: Height differences TanDEM-X PolarDEM 90m minus IceBridge; with subglacial lakes outlines for the Recovery glacier and spots where TanDEM-X input data from 05-2013 and 05-2014 differ marked with a red star.

The paper is fine as it stands, with minor edits; but the authors need to make clear how the DEM can be used. It is not suitable for mass-balance related change detection studies, because of the fuzzy nature of the correlation surface measured in the DEM; even a comparison with a repeat DEM by TanDEM-X would be more a study of backscatter changes *at depth than elevation. Also not suitable for determining the surface slope for ice velocity studies, at least not in detail.*

Response: (Use of the DEM)

We agree that the use of the TanDEM-X DEM over ice sheets is 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. They benefit 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. In the zoom you see the gaps in the REMA DEM at the Peninsula, which are filled with valid values in the TanDEM-X DEM).



Zoom: Difference TanDEM-X minus REMA for the Antarctic Peninsula, in white no data areas in REMA.

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).

Response5: We added the aspects of the use of the DEM in the conclusions. See also Response2 for the new paragraph.

It would be good to see detailed profile comparisons between this DEM and ICESat elevations, REMA elevations, CryoSat-2 elevations in several key areas – a good figure to add.

Response: (Profile comparison) Thank you for this suggestion. We decided to introduce some elevation profiles of TanDEM, REMA and CryoSAT-2 in several key areas. The new Fig. 19 was included. In the first profile (Fig. Ya), there is a relatively homogenous penetration bias between TanDEM-X and REMA or CryoSAT-2, except for some crevasses. The profiles in Fig. Y b), d), and e) illustrate the capability of the DEMs to capture fine-scale topography and its limitations especially in the case of the 1km data set of CryoSAT-2. In the difference images TanDEM-X minus REMA in Fig. Y b) and c) some rectangular features from the REMA DEM can be observed, where REMA is close to or even below TanDEM-X DEM.

Response6: We incorporated a new Figure with 5 profile plots (→ Figure 19) and its description into the paper.

"For a more detailed comparison of the different DEMs, we plotted elevation profiles of TanDEM-X, REMA and CryoSAT-2 in some key areas (Figure 19). In the first profile (Fig. 19a),there is a relatively homogenous penetration bias between TanDEM-X and REMA or CryoSAT-2, except for some crevasses. The profiles in Fig 19b), d), and e) illustrate the capability of the DEMs to capture fine-scale topography and its limitations especially in the case of the 1 km data set of CryoSAT-2. In the difference images TanDEM-X minus REMA in Fig 19b) and c) some rectangular features from the REMA DEM can be observed, where REMA is close to or even below TanDEM-X DEM."

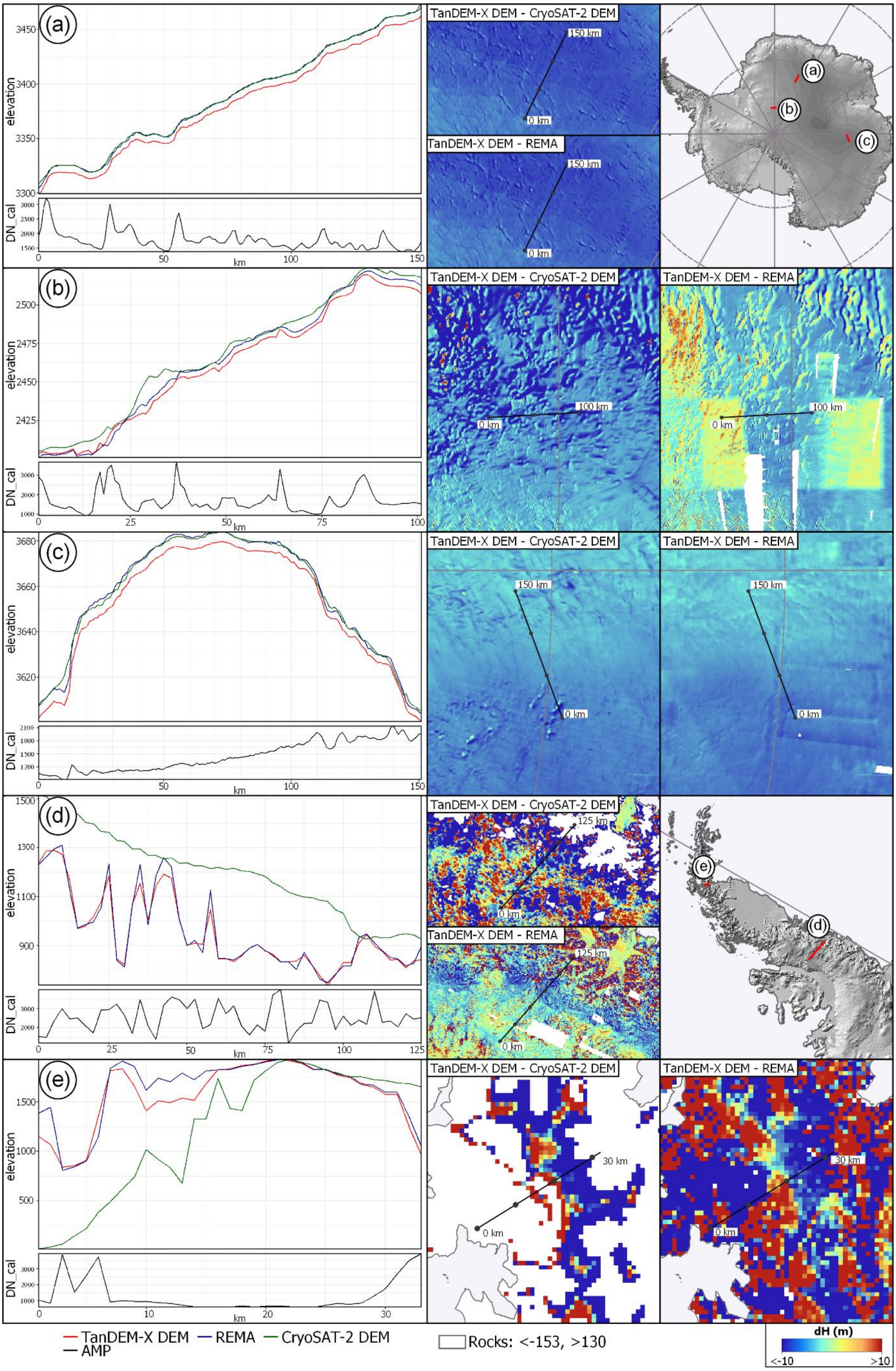


Fig. Y elevation profiles of TanDEM, REMA and CryoSAT-2 in several key areas

But the careful processing and blending of the data -do- make the data set useful. Figure 10 and 11 are worth more analysis and comparison with other backscatter data sets (e.g. Radarsat or ERS-1, 2 at C-band, PALSAR-2 at L-band)

The validation of the backscatter map is not the topic of this paper, but definitely interesting! We added your statement regarding comparison with other backscatter maps as a potential future research in the conclusions:

"Also, the amplitude mosaic itself could be further exploited in a more detailed analysis and in comparison with other backscatter data, e.g. Radarsat or ERS-1/2 at C-band or PALSAR-2 at L-band."

*I suggest that the paper could be acceptable with 'major' revisions, but mostly in terms of how the result is described and what it might be used for.Numerous short comments are in the annotated .pdf file uploaded with this review.Please also note the supplement to this comment:*https://tc.copernicus.org/preprints/tc-2021-19/tc-2021-19-RC1-supplement.pdf

Further Referee's comments from annotated pdf:

Thank you very much for taking the time and proposing so many improvements regarding minor remarks and wordings. All minor remarks or rewordings are accepted and are changed in the final manuscript. Where necessary, we provide some additional information below:

Line 5. suggest that you include the range of observations that are included in the DEM

A: We added the acquisition period of April 2013 to November 2014 in the abstract.

Line 180. I don't understand this paragraph. You determine the homogeneous bias in several regions, but then set the adjusted heights back to a mean InSAR height below the surface?

A: Correctly understood.

Line 188. would it have been better to complete the circle in both directions, re-unifying in East Antarctica and somehow averaging or blending the results?

A: Your suggestion of a double estimation and averaging the results would have been a technical easy solution to average out some errors. Unfortunately, we had some time constraints in processing as the goal of the TanDEM-X processing was the generation of a global DEM. At least a smoothing is applied on local scale in the range of some 200m, so no hard step was introduced.

Line 328. These ray-like areas around the pole are due to variations in net accumulation and the fraction of 'wind glaze' regions. Wind glaze is a high-altitude East Antarctic surface type that is formed in areas that have near-zero accumulation for decades or more, due to sublimation or wind transport off the surface. Megadunes are alternating bands of accumulation stripes (low backscatter) and wind glaze (high backscatter due to subsurface recrystalization). You may want to replace the pers. com. with this paper: Scambos et al., 2016, J. Glaciol, https://doi.org/10.3189/2012JoG11J232

A: Thank you very much for this explanation and the reference! We changed the reference to Scambos et al. 2012:

“Possibly wind dynamics, form together with the underlying topography ice with special characteristics, such as megadunes, snow-glaze areas and local accumulation highs (Scambos et al., 2012).”

Line 333. I am wondering, though, what the DEM is useful for, since you did -not- attempt to raise it to the level of the ICESat data -- what surface does it define? An unspecified surface of coherent backscatter at depth -- but what does that mean? How would someone use this DEM? Am I missing something?

A: The answer is given above (Use of the DEM), **Response2**

Line 375. “The higher variance in height differences at Recovery Glacier indicates a higher variability of signal penetration, which is also reflected in the higher variability of backscatter intensity (Fig. 16, lower right). “ *->sub-glacial lake drainage?*

A: The answer is given above (glaciolgical processes /Recovery Glacier)

References:

Abdullahi, S.; Wessel, B.; Huber, M.; Wendleder, A.; Roth, A.; Kuenzer, C. Estimating Penetration-Related X-Band InSAR Elevation Bias: A Study over the Greenland Ice Sheet. Remote Sens. 2019, 11, 2903. https://doi.org/10.3390/rs11242903

Floricioiu. D., Jaber, A.W., Baessler, M., Helm, V., and Jezek, K. (2016), Recovery ice stream: Synergy of satellite and airborne remote sensing for flow dynamics, Proceedings of IGARSS 2016, pp. 7098 – 7100.

Huber J., McNabb R., Zemp M. Elevation Changes of West-Central Greenland Glaciers From 1985 to 2012 From Remote Sensing Frontiers in Earth Science, 8, 2020, https://doi.org/10.3389/feart.2020.00035

Malz, P.; Meier, W.; Casassa, G.; Jaña, R.; Skvarca, P.; Braun, M. H. 2018. "Elevation and Mass Changes of the Southern Patagonia Icefield Derived from TanDEM-X and SRTM Data" *Remote Sens.* 10, no. 2: 188. https://doi.org/10.3390/rs10020188

Scambos, T., Frezzotti, M., Haran, T., Bohlander, J., Lenaerts, J., Van Den Broeke, M., . . . Winther, J. (2012). Extent of low-accumulation 'wind glaze' areas on the East Antarctic plateau: Implications for continental ice mass balance. Journal of Glaciology, 58(210), 633-647. https://doi.org/10.3189/2012JoG11J232

Smith, B. E., H. A. Fricker, I. R. Joughin, and S. Tulaczyk (2009), An inventory of active subglacial lakes in Antarctica detected by ICESat (2003-2008), J. Glaciol., 55(192), 573-595.

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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).

Response1: We added some explanations in the introduction about “what surface is being measured” :

1) a better explanation of the reflective surface of X-Band SAR DEM for ice/firn areas:

“For the cryosphere, it provides an up-to-date high-resolution elevation of glaciers and ice sheets in high latitudes. It allows, for example, the comprehensive and contemporary high-resolution delineation of glaciers and ice sheets in high latitudes. The SAR signal can permeate up to a few meters (Rott et al., 2021; Fischer et al., 2020; Dehecq et al., 2016; Wessel et al., 2016). For Antarctica the mean penetration bias is 3 m, which is varying on a larger scale depending on the ice and firn characteristics. The measured InSAR height represents an elevation corresponding to the average penetration into the firn or ice surface. The different backscattered returns stem from varying depth and are aggregated to a mean “scattering phase center”. Over pure dry firn (no melting or40physical 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. 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 “

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. They benefit 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).

Response2: We added some explanations and examples of the benefits of the presented DEM in the conclusions:

"In cryosphere applications, different SAR sensors are well established and widely used. They all have in common that the SAR signal penetrates and the derived information is not related purely to the upper surface. Therefore, 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. They benefit from a similar penetration bias as well as from a complete, gap-free coverage, which is prerequisite for these applications. 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. (2018) 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 as it comprises just few meters. For X-band DEM to X-band DEM comparisons the penetration bias could be regarded as an uncertainty assuming similar biases (Floricioiu et al., 2016)."

Resonse3: 3 new sentences addressing the local topography are added at the end of the ICESat section (Sec. 5.1), in the description of the new profile plots (Sec. 5.4) and in the conclusions:

"The assumption could be confirmed that these differences are stable over large areas with homogeneous backscatter (compare to Figure 11 and Figure 10)."

"The profiles in Fig 19b), d), and e) illustrate the capability of the DEMs to capture fine-scale topography"

"Aside from the subsurface, the InSAR DEM captures local and regional relief quite well, as evidenced by the well-matching local heights with the REMA DEM."

(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).

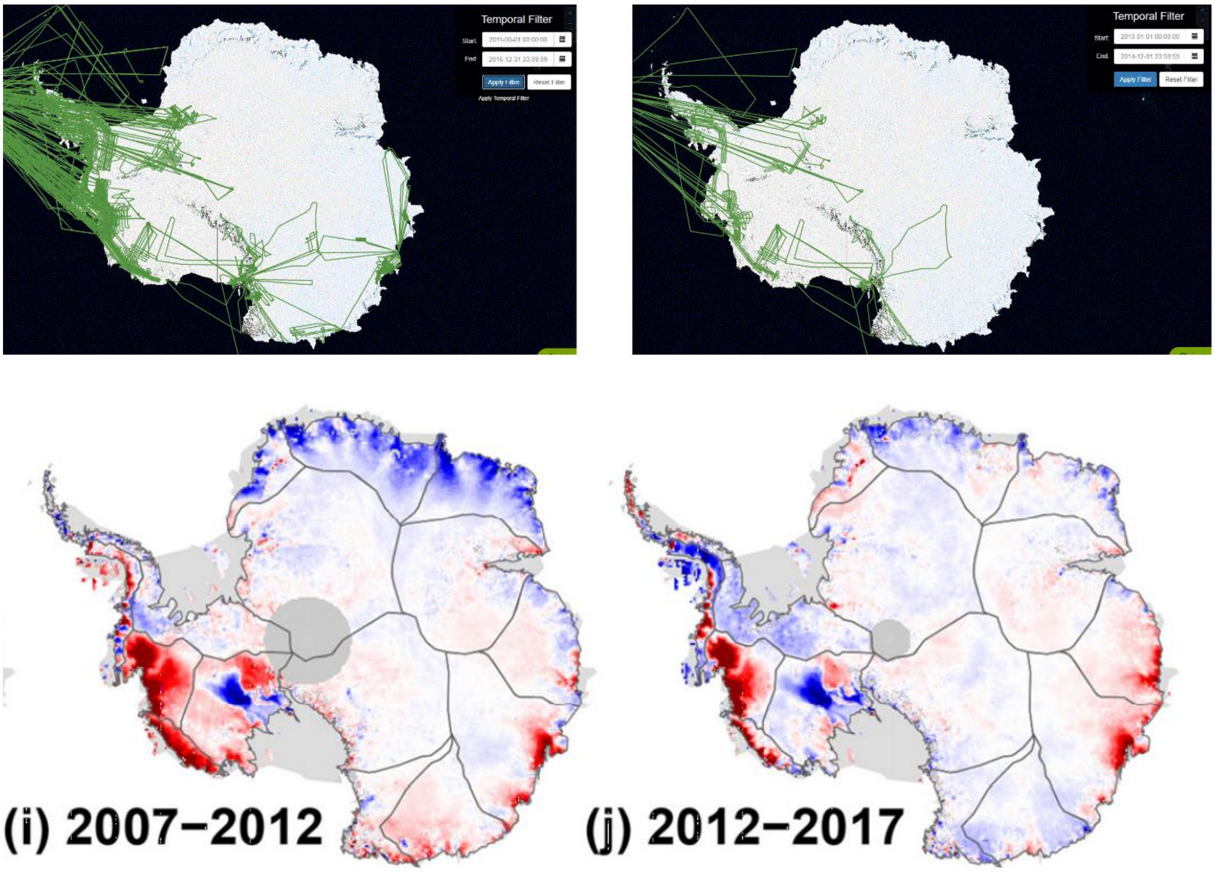


Figure A: Availability of IceBridge, upper left between 2011 – 2016; upper right between 2013 - 2014 (for reference: TanDEM-X acquisitions 2013 – 2014). In the bottom row: estimated elevation change from Schröder et al 2019.

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.

Regarding to your statement *" …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.":*

Response4: It is true that this looks contradictory at first sight. But the fact that IceBridge was recorded mainly in active areas is really disturbing for a classical height validation. With ICESat, on the other hand, the temporal dynamic component could be reduced by the relative stability of most points. After all, the Antarctic-wide coverage by ICESat generally gives a good overview of the spatial distribution of penetration bias. This is an important point for characterizing the heights. For a real validation, we find that the BIAs areas are best suited, and this is also where ICESat is most applicable.

We added one sentence to the temporal discrepancy of ICESat and TanDEM-X in Sec. 5.1:

"Note that the time difference between ICESat and TanDEM-X PolarDEM is the reason for some regional height differences in dynamic areas, e.g. the known decreases at Thwaites and Pine Island glacier as well as on the Peninsula are clearly visible in the height differences (Figure11)."

Specific comments

L4 – Suggest explicitly stating the time period the DEM covers somewhere in the abstract.
A: Thanks for this comment. We added 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 omitted 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 rephrased 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. Changed.

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 is rephrased to "*BIAs consequently should have near-identical elevations in both X-band InSAR and laser altimetric measurements.*" (Almost the same

but at least you are right and "the same" vanished and gets it clearer…)

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: We introduced the height of ambiguity in relation to the baseline and added a passage about the used heights of ambiguity.

"A combination of two HoAs was considered in the acquisition planning to yield a better height error (Borla Tridon et al., 2013). At first a HoA between 50 m in the outer region and 90 m in the central region of Antarctica was chosen. The second acquisition was planned with 10 m to 20 m smaller HoA."

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.

"A gross error detection was necessary, because of reflections on clouds toexclude points with unrealistic heights of more than 100 m difference to TanDEM-X DEM."

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 revised this:

"The standard deviation to TanDEM-X serves as a quality measure for the ICESat points. Higher standard deviations indicate more unreliable points on slopes, local relief or noise. For block adjustment, in general only the best 10 ICESat points per 50 km long DEM scenes were used, and a much higher number was used as validation ground control points for the final DEM heights. For validation points, the standard deviation of the TanDEM-X DEM within the footprint still must be below 1 m. "

L93 – Suggest rewording this sentence to make it clearer.

A: Thanks for noting. -> reworded: "They (blue ice areas) are distributed across 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 integrated the mentioned locations with abbreviations into Figure 4, showing the calibration blocks.

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).

Sec. 2.4 "*Furthermore, the IceBridge program's focus are active glacier areas (Koenig et al., 2010) which lead to temporal changes. Therefore, regarding our validation purpose, we carefully examined the IceBridge data set and selected IceBridge data from the same period and from the most stable regions like the South Pole and the Recovery glacier, both acquired in October 2014."*

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. We reformulated to: "In contrast, Antarctica's coast is mostly covered by ice and therefore, the ICESat elevations differ from the radar elevations by the penetration bias."

L155 – namend 'therewith'.

A: 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 removed it.

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

A: Thanks, we 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 added a color scale and an overview to 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. But only dedicated operational scenes were included in the update, therefore, these were not used for global DEM generation. 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 updated Figure 8 with the initial SCAR.

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

A: Thanks. We re-arranged 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.

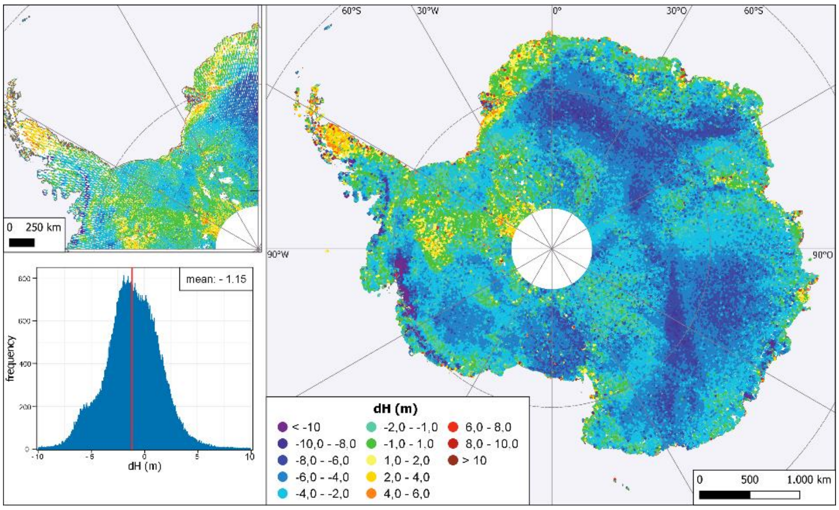
A: We added one sentence in Sec. 5.1:

"Note that the time difference between ICESat and TanDEM-X PolarDEM is the reason for some regional height differences in dynamic areas, e.g. the known decreases at Thwaites and Pine Island glacier as well as on the Peninsula are clearly visible in the height differences (Figure11)."

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 updated it in Fig. 11.



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

A: rephrased: *"These differences indicate that the DEM calibration in Western Antarctica is erroneous and an increase of the DEM by a few metres has occurred."*

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. 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).

A: …" such as megadunes, snow-glaze areas and local accumulation highs (Scambos et al., 2012). Glazed surfaces cover the leeward faces where the grain size is increasing, which lead to an increasing backscatter"

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.

A: We added some lines to the use of the DEM in the conclusions, see also response above.

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

A: Thank you for noticing. We replaced to CryoSat-2 for throughout the text.

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. → *"it seems that CryoSat-2 has also a penetration bias"*

Best wishes,

Thanks again!

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