Responses to Editor and Reviewers' comments (minor revision)

We thank editor and two reviewers for the constructive comments and suggestions.

Editor

Line 43: Capitalize 'Salar'

Done.

Line 63: change to 'capability for the estimation of volume changes...' since part of the changes of the firn are unrelated to mass changes

Done.

line 204-205: the description of the RGT here is confusing, unclear what 'they' refers to. Your description seems to imply that there's one RGT for each beam pair, but that is not the case. See https://doi.org/10.5067/ATLAS/ATL06.003 for a description of the RGTs: "The Reference Ground Track (RGT) refers to the imaginary track on Earth at which a specified unit vector within the observatory is pointed. Onboard software aims the laser beams so that the RGT is always between ground tracks 2L and 2R (i.e. coincident with Pair Track 2)."

It is revised: "*…… Furthermore, the reference ground track (RGT) is defined as an imaginary track between the nadir ground track pair (2L and 2R). All six laser beams then have laser spot IDs (1, 2…, 6)……*"

Line 324-325: could you add information here about which beam track passed over the CCRs, as you did for Zhongshan station?

The information is added: "*…… On the other hand, ICESat-2 passed across the CCR line array near Taishan Station along the weak beam track of 2L of RGT 0424 at 12:37 UTC on January 23, 2020 (green dots in Fig. 6b)……*"

line 407: 'location, environmental conditions, and time'

Done.

line 438 'attributed to': do you mean 'contributed to'?

It is changed to "*contributed to*".

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The authors have answered all my questions sufficiently and after restructuring the manuscript now is very clear and easy to follow. I have only a few remaining minor comments:

l.166 „GNSS data … were handled“: Please modify, e.g. „GNSS data ...were processed“

Done.

l.174 „These crossovers are the intersections of tracks by the snowcat during instrument installations, observations, and overnight breaks.“ To clarify, I suggest a little modification: “...are the intersections of tracks by the snowcat which occurred usually during...”

Accepted and done.

l.188 „Tide-free“ elevations are a convention. Applying all tidal corrections do not necessarily mean that the elevations are tide-free. However, Neumann et al. 2019 (p.111) informs that the elevations are given as „tide-free“.

The sentence is changed to: “*…… Thus, the reduced ice surface elevations are given as “tide-free” (Neumann et al., 2019) and the permanent crustal deformation is removed (Schröder et al., 2017; Brunt et al., 2021)*”

l.253 Why did you choose 30 as a number of sufficient pairs? If the ICESat and GNSS profiles are perpendicular, there can be 2 GNSS points and ~11 photon locations within a radius of 4 m around the exact crossover location, which gives only 22 pairs. In this case, a perpendicular crossover would never be sufficient.

The threshold of 30 is adopted from Brunt et al., 2019b. In our study there are ~11 pules (instead of photons) within a radius of 4 m of a crossover, which gives 22 to 44 pairs of ICESat-2 – GNSS comparisons. The minimum case of 22 pairs may correspond to a perpendicular intersection. However, the most intersection angles between the ICESat-2 and GNSS traverses are around ~30 degrees, with the maximum of ~52 degrees. In fact, there is no ICESat-2 – GNSS pairs eliminated because of this 30 - pair threshold.

l.338 Please add a short notice about the reason for the significantly lower accuracy at Taishan here.

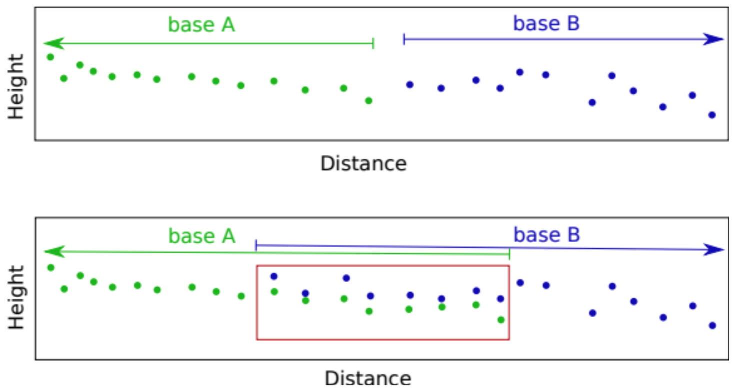
The sentence is changed to: “*…… Due to logistic difficulties, CCR positions were surveyed using the* *single-point positioning technique at ~1 m accuracy level in both the horizontal and vertical directions.*"

Furthermore, I have two suggestions for future works but I do not expect them to be included in this manuscript:

1. Concerning crossovers in the kinematic profiles, those mentioned at l.174 are within very short time differences, which implies that temporally correlated errors are similar in both segments. Do you also have any crossovers between the inbound and the outbound profiles? If not, this could be considered when planning such traverses in the future. Furthermore, you could install GNSS equipment an 2 independent snowcats and analyze crossovers between them.

Thanks for these are very good suggestions. We will take them into account when planning the future campaigns.

2. You did a quite interesting analysis in response to my suggestion to use overlapping sections to access the accuracy. However, there seems to be a misunderstanding. To make my suggestion more clear I will explain it with a small drawing:



The upper part shows how you processed a section of the profile with a specific base station. I suggest to include some more observations to each section as in the lower part. This means that there is some overlap between the profiles (the observations in the red box) of different base stations. Now you can use the resulting coordinates in this overlap to analyze the accuracy and precision by calculating the mean offset and standard deviation between these different coordinate solutions.

Thanks for the clarification and the figures. We will look into this in a future extended analysis.

Reference

Brunt, K. M., Neumann, T. A., and Smith, B. E.: Assessment of ICESat-2 ice sheet surface heights, based on comparisons over the interior of the Antarctic ice sheet, Geophys. Res. Lett., 46(22), 13072-13078, https://doi:10.1029/2019GL084886, 2019b.

tc-2020-330-referee-report-2
General Reviewer Comments:

Thank you for providing the revised manuscript. I believe it to be much improved from the original submission. However, I do have some comments for minor revisions to this version.

I believe figure 6 and the explanation of the CCR signals should be improved for more clarity to the reader.

- **For 6b: The two CCR streaks at multiple elevations are explained by the different in height between #6 and #7. It would be better to plot them as different colors or label which signal returns are attributed to which optical component.**

  In Fig. 6b we labelled CCR IDs (#6 and #7) individually to each of the two layers.

- **For 6b: It is still unclear why there is a bump in the middle of the streak and the authors comments about high signal levels at nadir are not the reason unless they intend to imply that higher signal-to-noise levels make for higher elevations. Is it the slant range variation between t-approaching and t-nadir that is the difference? That can be calculated and compared to the apparent elevation increase for #6.**

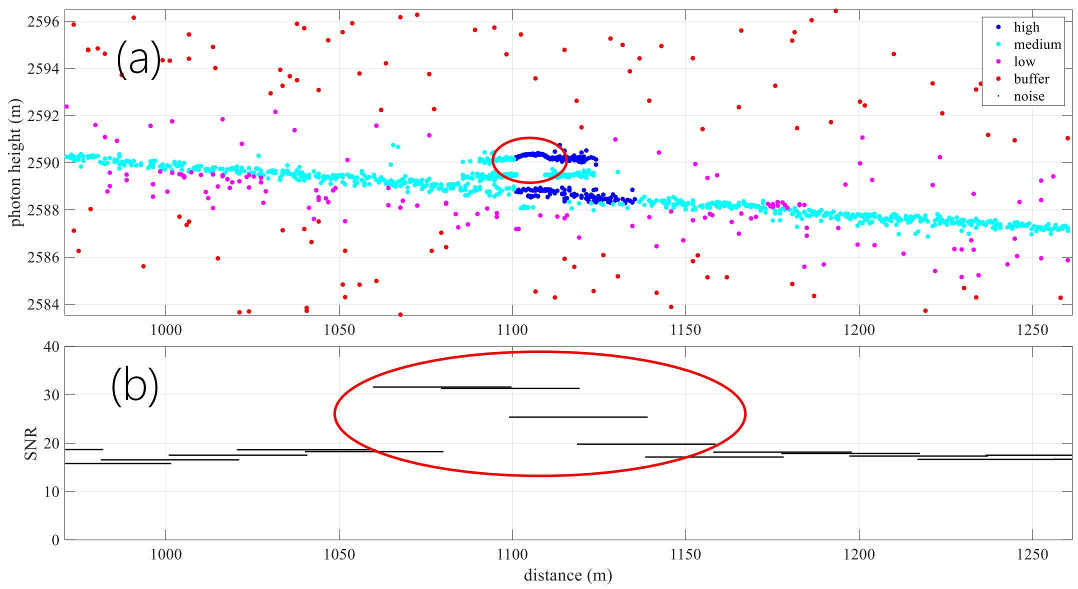
  Our calculation indicated that the elevation difference caused by the slant range variation between t-approaching (20 m from nadir) and t-nadir, without considering the complex factors such as atmospheric, scattering, and other effects, is 0.8 mm, which would not make the bump height of 22.5 cm. With the data available at this point we do not have a clear answer as why this bump exists in Fig. 6b. It may also exist in Fig. 6a, but blended by the photons from the two neighboring CCRs. One possible reason, in addition to a "specific" atmospheric condition at that site and time etc., is that the large aperture may have created it. But this bump is symmetric at nadir position and with the averaged photon elevations the estimated peak position agreed with the precision GNSS position in this study (near Zhongshan Station). We will design a future experiment with different CCR aperture sizes to investigate the possible relationship between the aperture size and the bump (and other parameters).

- **Can the authors confirm that the higher SNR at t-nadir is truly the reason why returns were rejected from #7 during that central 9 m along track section?**

  We have examined the SNR values given in the ICESat-2 ATL06 data. "*SNR (estimated signal-to-noise ratio for the segment)*" flag accounts for the number of higher quality photons used for elevation fitting in each 40 m segment (Smith et al., 2020;

/gtx/land_ice_segments/fit_statistics/snr). In Fig. b the three segments that contain photons of the central 9 m “single layer” section of the nadir CCR position near Taishan Station have the SNR of 31.61, 31.32, and 25.39, in comparison to the average SNR of 16.89 of the nearby firn surface. The SNR differences are significant, although they cannot be used to directly confirm the rejection of the photons from the neighboring CCR (#7).

Given the orbital configuration, CCR size and ground setting, and CCR streak data, the Fraunhofer refraction pattern analysis we have provided in the last round of responses to reviewers’ comments showed a theoretical conclusion of the absence of CCR #7 photons in the central 9 m section due to the high SNR. However, based on the above analysis a numerical confirmation would have to come from additional signals in the original data that may or may not be saved onboard and stored in the mission data beyond ATL03. We hope to have in-depth discussions with the mission team and plan to conduct a future CCR experiment to achieve a numerical confirmation.



- **Why isn’t the same signal bump present in figure 6a?**

Please see response to the second comment.

Reference

Smith, B., Hancock, D., Harbeck, K., Roberts, L., Neumann, T., Brunt, K., Fricker, H., Gardner, A., Siegfried, M., Adusumilli, S., Csathó, B., Holschuh, N., Nilsson, J., and Paolo, F.: Algorithm

Theoretical Basis Document (ATBD) for Land Ice Along-Track Height Product (ATL06), Goddard Space Flight Center Greenbelt, Maryland, 2020.