Authors response to the comments of referee #1

We thank Johan Nilsson for the thorough, fast and helpful evaluation of the manuscript. Especially the comments concerning the additional IceBridge dataset helped to get further confidence in the absolute accuracy of the results. Also the smaller edit recommendations in the supplement helped us a lot to further clarify some statements and improve the language. We would like to mention that the correction of a small inconsistency in our variance propagation of the GNSS profiles and the variable ICESat campaign precisions (recommended by reviewer #2) slightly changed the results for the campaign biases. However, this does not change anything in the general messages of the manuscript. In the following we will respond the comments one by one.

(1) One can clearly see that the inter-campaign biases differ from each other depending on the surface type or region used to derive them. What is the sensitivity of your or other solutions to surface type or possible location bias? I would like, if possible, some more discussion about this. This as the estimation of the inter-campaign bias I find to be the main outcome of this study.

We agree that inter-comparisons of ICESat biases obtained with different methods and in different regions are needed, although this is beyond the scope of the present paper. Towards the application of this set of biases in other glaciated regions, especially in Greenland, further investigations should be carried out. Assuming that these biases are laser-energy-related (Schutz et al., 2011) those corrections would be applicable for surfaces with similar albedos (Hofton et al., 2013) as Lake Vostok.

(2) The choice of the crossover methods for the validation procedure, though very accurate and mature, has the limitations of limited spatial coverage and data density. It would be useful to include, or at least compare, the use of another method to judge the stability of the distribution used to derive the statistics. A small-scale study using the "average footprint method", which was initially discussed in the paper and applied in Wouters et al. (2015), might be of interest?

Wouters et al. (2015) validate the CryoSat-2 elevation change grid using IceBrigde ATM derived dh/dt, gridded to a similar resolution. However, ATM measures a swath of elevations and dh/dt can be considered uniform over longer distances (e.g. a beam limited radar altimeter footprint), which is not the case for the elevation itself. Thus, for computing elevation grids, we would need not just linear profiles but a good 2-D coverage, preferably an array of profiles (Phillips et al., 1998). Our dataset does not include such arrays and thus does not provide for such an analysis, although it would indeed be very interesting.

(3) The application of the 67 cm elevation bias in the CryoSat-2 Baseline C products I think needs to be discussed in a bit more detail, as this is one of the main differences between the two ESA baselines. One can clearly see that the application of the bias pushes the radar horizon closer to the reference surface. For full-waveform retrackers, like ESA's, this has no major effect as they usually show high surface penetration. However, leading edge retrackers, which track closer to the surface (not using the entire waveform), will in many cases produce positive biases. This could, for example, be seen in your presentation at ESA living planet. As it forces the radar-laser surface bias to be positive, which is unphysical for radars, it begs the question: should the bias be applied?

On Lake Vostok, there are no positive biases for any dataset. The cause for the shift of the biases towards the positive direction has been explained for the Envisat data and is exactly the same for CryoSat-2 LRM. It is the sampling of the local topography maxima by the POCAs (point of closest approach) of the radar altimeter, compared to the full topography sampling for the kinematic data. Thus, with increasing slope and increasing roughness too, the biases grow towards positive. This is discussed in section 3.3.1.

(4) Stated in the manuscript is the preference for threshold retrackers over model based ones, as they are less affected by volume scattering, which has also been proven in other studies. However, I can't find any information about which threshold is used for the OCOG retracker for Envisat (25% for CryoSat-2)? It would be good to state them clearly in the manuscript.

Done. This information was very difficult to find. It is defined in the auxiliary processing file 'RA2_ICT_AX: Ice1/Sea Ice Configuration'. Finally, with the help of the ESA support, we found out that the threshold is set to 30%.

(5) Figure 6 shows the relation between the relative change in elevation and backscatter at crossover locations over Lake Vostok. It would be interesting to see the effect of other waveform parameters, like LeW and TeS, in the same type of plot (preferably for both Envisat and CryoSat-2). Remy et al. (2012) suggested that the addition of these parameters would be more valuable understanding snow characteristic fluctuations using Envisat and CryoSat-2 derived time series. These parameters are already available or can be easily computed for the two products. I think the inclusion of these parameters in your analysis would provide heavier weight to your argument.

This would indeed be interesting, but it goes beyond the scope of this validation. What we want to show is, that the seasonal variation is an order of magnitude larger for functional fits and that this signal is highly correlated to backscatter. As our final recommendation is to use low-threshold retrackers (where no LeW and TeS exist) we left those parameters out of our analysis.

(6) I might be misunderstanding you, but what is the crossover time-span used to derive your validation statistics? I'm guessing you use all crossovers independent of time-span, as your elevation change signal is very small? If so, it would be good to state this in more detail in the manuscript, as crossover difference of less than 30 days has been the norm for previous validation studies, see (Khvorostovsky 2012).

You are guessing right. Except for the validation of ICESat, we do assume that the surface is stable and thus, that the elevation change is negligible. This is described more in detail now in Sect. 2.5.

(7) The Bernese software has been used for the processing of the GNSS data. How does this software compare to the other available packages, like GIPSY? I think it would be good to discuss the impact (or differences) of different software packages on the results, maybe in sentence or two? Further, maybe direct the reader to a set of references for the curious.

Such a survey has been performed by Dietrich et al. (2001) for static observations. In a comparison of the results from six groups using four different software

packages (including Bernese and GIPSY) the results showed a very good agreement. However, we would like to emphasize, that even within the same software package the results strongly depend on the strategy, the algorithms and the models and products used. Kohler et al. (2013) use Precise Point Positioning (PPP) which does not require reference stations but instead needs precise satellite clock information for every epoch. Usually these clock offset data have a rate of 30s. Prior to 2004, the rates were even more sparse (5min). Only after 2008, the Center for Orbit Determination in Europe (CODE) publishes a 5s high rate product but this would not be applicable for the early profiles. Here, the significantly decreasing number of observations would lead to much larger errors in a PPP-solution.

However, our results are very similar to the results of Kohler et al. (2013). They process two seasons with two profiles each. From crossovers between these profiles they calculate a mean offset of -4.1 cm and a standard deviation of 8.6 cm. We divide our average crossover difference by $\sqrt{(2)}$ to obtain our accuracy measure $\overline{RMS_X}$, which is in the range from 4–9 cm. Thus we conclude that the accuracy and precision of both types of solutions is very similar.

(8) Has there been any attempt to validate or compare elevations over Lake Vostok using NASA's Operation IceBridge, to acquire another reference surface? If so how do they compare?

Very good point! Has been done in section 2.4 now and included in Tab. 1.

(9) The difference between the Bamber et al. (2009) DEM and Bedmap-2 is very interesting! Clearly the rounding will have an effect on the precision, but the -1 m bias is surprising? Is this bias spatially dependent, as different datasets have been merged together?

This bias exists all over Antarctica where the Bamber-DEM is the data source for Bedmap-2. It varies mainly between -0.5 to -1.5 m along bands which look like waves. Hopefully this bug will be found and fixes in case of a new version of Bedmap.

References

Dietrich, R., Dach, R., Engelhardt, G., Ihde, J., Korth, W., Kutterer, H.-J., Lindner, K., Mayer, M., Menge, F., Miller, H., Müller, C., Niemeier, W., Perlt, J., Pohl, M., Salbach, H., Schenke, H.-W., Schöne, T., Seeber, G., Veit, A., and Völksen, C.: ITRF coordinates and plate velocities from repeated GPS campaigns in Antarctica – an analysis based on different individual solutions, J. Geod., 74, 756–766, 2001.

Hofton, M., Luthcke, S., and Blair, J.: Estimation of ICESat intercampaign elevation biases from comparison of lidar data in East Antarctica: Estimating ICESat elevation biases, Geophys. Res. Lett., 40, 5698–5703, doi: 10.1002/2013GL057652, 2013.

Kohler, J., Neumann, T., Robbins, J., Tronstad, S., and Melland, G.: ICESat Elevations in Antarctica Along the 2007–09 Norway-USA Traverse: Val-

idation With Ground-Based GPS, IEEE Trans. Geosci. Remote Sens., 51, 1578–1587, doi:10.1109/TGRS.2012.2207963, 2013.

Phillips, H., I., A., Coleman, R., Hyland, G., Morgan, P., and Young, N.: Comparison of ERS satellite radar altimeter heights with GPS-derived heights on the Amery Ice Shelf, East Antarctica, Ann. Glac., 27, 19–24, 1998.

Schutz, B., DiMarzio, J., Luthcke, S., Hancock, D., and Urban, T.: Notice Concerning Detection of ICESat/GLAS Inter-Campaign Elevation Biases, Tech. rep., 2011.

Wouters, B., Martin-Español, A., Helm, V., Flament, T., van Wessem, J., Ligtenberg, S., van den Broeke, M., and Bamber, J.: Dynamic thinning of glaciers on the Southern Antarctic Peninsula, Science, 348, 899–903, doi: 10.1126/science.aaa5727, 2015.

Authors response to the comments of referee #2

We thank the reviewer for the thorough and very fast evaluation of the manuscript. The reviewers comments concerning accuracy helped us to improve the wording in the manuscript and to include another dataset (IceBridge) to provide further confidence in our results. We would like to mention that the correction of a small inconsistency in our variance propagation of the GNSS profiles and the variable ICESat campaign precisions (recommended by the reviewer) slightly changed the results for the campaign biases. However, this does not change anything in the general messages of the manuscript.

We respectfully disagree with the main scope of the review to withdraw two thirds of the paper, which is also not supported by the other two reviews. We will justify our opinion in the following detailed comments.

[RC] ICESat intercampaign biases: *I am very concerned about the presentation of these ICESat intercampaign biases, which are a tricky thing to determine. My concern lies here: 1) the intercampaign biases presented here (Table 3) are determined based on kinematic, traverse–based GPS data, which generally has decimeter–scale accuracy; 2) the GPS traverse data are processed via DGPS methods, using 5 different base–station sites (Vostok, Mirny, Progress, Casey, and Davis), with baselines that can exceed 800 km, and therefore, I question the accuracy of these DGPS results, especially when considering that the troposphere (and ionospheric) corrections have to span that spatial scale; 3) the authors claim to assess the accuracy of the traverse data by comparing the DGPS results of the various baselines; while comparing various baselines is a good strategy for beating down the noise in the solution, this strategy represents an assessment of the spread of the result, or the PRECISION, not the accuracy, thus, the authors have no assessment of accuracy, or ground 'truth'; 4) to develop intercampaign biases, you have to make an assessment of ICESat vs 'truth', and given the comments I have made about accuracy/precision, I do not believe that the authors have done this adequately; 5) to develop intercampaign biases, you also need to do this using relatively coincident (with respect to time) data, or you have to show that the surface is not changing; from Figure 2a, the surface being used as ground 'truth' (which is a substantial percentage of the East Antarctic Ice Sheet) is changing at decimeter scales, yet the authors obtain cm–level bias corrections. Given that they are using GPS data from a changing surface, with a gap in time associated with the first half of the ICESat campaign (2003 – 2006), I again do not believe that the authors have adequately defended their set of intercampaign biases. Therefore, overall, this method does not represent the rigorous attention to detail needed to determine cm–level intercampaign biases. Yet casual users of ICESat data will take Table 3 as 'truth'.*

(1) The accuracy of a single epoch is not much better than a decimeter, but we have to consider that in the bias estimation we use more than 80,000 crossovers in the Lake Vostok region from 15 profiles spanning 14 years. Furthermore, the GNSS-processing was performed on a daily basis, i.e. each day can be considered as an independent estimate and each profile consists of several days, even in this region. This high number of individual results gives us the confidence that our biases are very well constrained.

(2) In the processing, the ionospheric effect is eliminated as we use the ionosphere-

free linear combination L3. The troposphere is fixed for the reference station in a preprocessing step and then estimated together with the coordinates for the kinematic sites. This means that for each single baseline solution, the noise includes the uncertainty of the tropospheric estimate, which is summarized as $\overline{RMS_{BL}}$.

(3) This is the most important misunderstanding we hope to resolve with this response. The terms accuracy and precision have indeed not been used with sufficient severity in the manuscript. This has been corrected now throughout the paper.

Apart from this, the reviewer's notion that we just compare multiple baseline results and claim that they reflect the accuracy is a misunderstanding. We assess our surface elevation data using crossovers between different profiles of one season, as practiced also in other peer-reviewed works (e.g. Siegfried et al., 2011; Kohler et al., 2013). These profiles are independent to a very high degree. We agree that an external independent dataset could help to further pinpoint their accuracy. Therefore, we now included crossovers with an IceBridge ATM track crossing Lake Vostok. There are relatively few crossovers (between 1 and 9 per profile) and surely some of them may be affected by local peculiarities but in sum, they show, that $\overline{RMS_X}$ is a realistic estimate. We conclude therefore, that within the given confidence intervals our data are indeed ground 'truth'.

(4) see (3).

(5) We do not determine our biases over the whole area. We only use the Lake Vostok region (100–108.5 E, 76–79 S). We now make this more clear in the manuscript. Elevation change is accounted for by the term $\dot{h}$ in Eq. (4).

[RC] DEM assessments: *A DEM represents a snapshot of the ice surface at some specific time. The DEMS that the authors are assessing are from about 2006 and 2009, while the validation data (from the traverses) generally spans the subsequent 6 to 8 years (Table 1). The result they find is that near the coast, where the surface is steeper, the DEM elevations deviate from the GPS data. However, steep–slope areas around the coast of Antarctica are also where the ice sheet is changing the most (Pritchard, et al 2009); their result is probably at least partially associated with real surface change. The DEM comparison, in my mind, is pointless.*

The elevation changes in the area of our profiles do hardly exceed 10 cm/yr, even in the margins. For the mentioned time span this affects the assessment by less than 1 m. In contrast, the differences of the elevation models are in the order of 20 m in this area. We agree that the mentioned effect exists, but we show in this paper that its magnitude is insignificant compared to the observed elevation differences.

I suggest that the authors remove the intercampaign bias and DEM assessment sections of this manuscript.

We respectfully disagree for the reasons mentioned above.

Specific Comments:

– line numbers are needed

They have existed in the submitted document (Copernicus Latex template, compiled with the 'manuscript' option), but disappeared in the type setting step for the discussion paper.

– abstract lists accuracy of in situ data, but not precision. What is accuracy based on?

As mentioned in (3), on intra-season crossover differences ($\overline{RMS_X}$), now on IceBridge profiles too.

– "A crossover analysis with three different Envisat..." this sentence is so specific and doesn't allow the abstract to stand–alone. Consider edit.

Edited.

– Baseline B, to the best of my knowledge, is no longer available, thus, these results are not reproducible.

Unfortunately this is true. However, as most of the recent publications (e.g. Armitage et al., 2014; McMillan et al., 2014; Simonsen and Sørensen, 2017) still use Baseline B, we think that these are very important results regarding the interpretation of those results.

– give example(s) for 'systematic effects'

Done.

– "One crucial step in the processing of surface elevations from satellite radar altimetry... is the slope correction": this is not unique to radar; this was a big problem for ICESat, which had smaller, 70–m footprints. I believe what the authors are getting at is the large error in the radar. But this error is not negligible in the laser altimetry, when significant mass change in east Antarctica is associated with cm–level surface change. An edit is needed here.

At this point in the introduction we are not talking about laser altimetry at all. The slope error is much more crucial for radar altimetry as for laser. For radar retracking, the retracking point in the leading edge corresponds to the point of closest approach (POCA). In contrast, the gaussian fit in the ICESat laser signal retracking refers to the middle of the return signal and thus the footprint average. Schutz et al. (2005) state, that 'an error of 1 arcsec in laser pointing knowledge, combined with a surface slope of 1°, will introduce an effect of 5 cm on the inferred spot elevation'. Thus we agree, that the slope has to be considered when it comes to accuracy but we think, there is no 'slope correction' as for SRA.

– Author needs to verify proper mission naming conventions throughout (e.g., CryoSat–2, NOT Cryosat–2; Ice, Cloud, and land Elevation Satellite, NOT Ice Cloud and Land Elevation Satellite)

Checked and changed.

– "...(ICESat) mission these effects do not arise..." be more specific here. The slope issue does arise in steeper terrain. I believe you mean volume scattering, which is NOT necessarily mitigated by the use of laser altimetry (as opposed to radar altimetry); certain wavelengths of light could potentially volume scatter.

See answer concerning slope above. We are aware that the slope causes an additional uncertainty. However, when calculating elevations at crossover locations, we believe the interpolation error is much larger than the slope error due to a non-uniform slope in the footprint (which would cause an asymmetric return waveform). This is discussed in Sect. 3.3.3. A comment on slope effects has been added.

– write out GPS and GLONASS here in the last paragraph of the Intro. You write them out in section 2.2, but THIS is the first instance...

This has been changed in the manuscript.

– "This set of surface–elevation profiles..." Processed? Raw data?

We do not see an ambiguity in our wording. The previous sentence states that the surface elevation profiles are derived from kinematic GNSS observations. We think when mentioning "surface–elevation profiles" it should be clear, that those are the final profiles, no raw data.

– "The profiles acquired on snowmobiles provide accuracies of only a few centimeters..." Based on what? Are you comparing the snowmobile data to the static site?

To detect possible biases between a static site and a kinematic rover, a very detailed knowledge of the topography (including microtopography) around the static site would be necessary. As stated by Richter et al. (2014), "Crossovers between the profiles acquired during the same field season (usually within a few days) are not affected by long-term surface height changes and are therefore used to assess the accuracy of the surface height determination." A similar comparisons between two profiles during the same day have been performed by Siegfried et al. (2011). They find a mean elevation bias of 9 mm. Also King et al. (2009) state that in their profiles "Uncertainties of the GPS-derived heights are 0.05 m with effectively zero bias". References have been added.

– "...and are thus well suited for precise studies on local elevation and elevation changes..." Only if their precision (again, compared to what) is also small/good. Given that you don't use these data, I'm inclined to tell you to remove this text (and the accuracy text).

This paragraph explains the differences between kinematic GNSS on lightweight snow mobiles and heavy tractors. We find it important to mention this to explain the reader the additional difficulties related to the correction of the offset between antenna and snow surface.

– regional peculiarities: like what? Slope? Surface compaction? What else?

Kohler et al. (2013) subdivide their area and relate different mean offsets to topographic peculiarities but furthermore to different driving constellations of the two vehicles as well. As we measured the antenna–snow-surface offset repeatedly, we expect such effects to be of minor importance. However, especially topographic features play an important role in the slope correction. Thus, only long-range profiles allow a statistically significant analysis involving larger areas.

– Figure 1: a colorbar is not useful for capturing the date detail. Make a legend or label them in the figure.

Details about the dates are given in Tab. 1. Figure 1 intends to give an overview and thus we think (together with the area column in Tab. 1) this figure gives a good overview over the times and locations.

– Processing: 800 km baselines are long. Did you try looking at PPP solutions? Kohler et al 2013 used PPP specifically for this reason. You could use the DGPS method when close to the stations and compare your results.

We added some sentences in the GNSS data processing section. Geng et al. (2010) compare the two processing methods and found quite comparable results even over longer baselines. Compared to the results of this work we think that our DGPS results are even more reliable as we use a combination of several baselines.
Kohler et al. (2013) use Precise Point Positioning (PPP) which does not require reference stations but instead need precise satellite clock information for every epoch. Usually these clock offset data have a rate of 30s. Prior to 2004, the rates were even more sparse (5min). Only after 2008, the Center for Orbit Determination in Europe (CODE) publishes a 5s high rate product but this would not be applicable for the early campaigns. Here, the significantly decreasing number of observations would lead to much larger errors in a PPP-solution.
However, comparing the crossover differences between profiles of the same season, our results show even smaller differences compared to Kohler et al. (2013). We suppose that this is a result of our improved antenna offset correction and thus assume, that both GNSS processing schemes are comparable (when applicable).

– IGS08: is this appropriate for comparison with both ICESat and CryoSat–2? What frame are those data in?

It was not mentioned in previous manuscript versions. This is not very well documented for most of the datasets but finally we found the information and included it in the manuscript.

– Perhaps Table 1 could capture which kinematic traverses that included GLONASS

Included in Table 1.

– "Therefore, in this case we used the Melbourne–Wübbena and the Quasi–Ionosphere–Free Linear Combination only" this needs more description or references

Reference added.

– The last part of this paragraph needs more elaboration/clarity. This is important, given my previous statement about PPP. Your troposphere and ionosphere corrections won't hold up over these length scales. So what does this technique (with which I am not familiar) do to address this critical issue?

As mentioned in (2), the tropospheric correction from a preprocessing step is fixed for the reference stations. Thus the correction for the kinematic receiver is independent from the baseline length. The ionospheric effect is eliminated as we use the ionosphere-free linear combination (see Dach et al., 2015) in the final step.

– "Altimetric elevations, in contrast, refer to the "mean tide" system..." I believe

that ICESat has tide–free (WGS–84/ITRF) height as well as TPX 'mean–tide' heights. If so, this statement is not entirely accurate. How does your conversion compare to what's on the ICESat data product?

The field "deltaEllip" in ICESat is "Surface Elevation(T/P ellipsoid) minus Surface Elevation (WGS84 ellipsoid)." To our understanding, this only refers to the ellipsoidal parameters a and f but does not correct for different conventions in the reference system such as the handling of the permanent tide.

– "A more realistic measure is found by comparing multiple baseline solutions." What about comparing to PPP solutions?

See comments above concerning PPP for older datasets.

– Further, comparing GPS solutions from multiple baselines does not compare these GPS data to 'truth'. Without 'truth', you cannot get at an overall bias/accuracy assessment of your GPS data. Instead, your RMS_BL informs you about the reproducibility, or spread, of the results; this is the precision of the solution, not the accuracy/bias, which is the difference between the measurement and truth. RMS_BL may be a meaningful error assessment, but not as described.– Same of RMS_S

– Same for RMS_X. These are all spreads of the data.

As mentioned above, we agree that RMS_{BL} is precision, not accuracy. However, Shuman et al. (2006) call intra-campaign crossovers a "relative accuracy". Our crossovers between different profiles of one season (RMS_X) are independent measurements to a very high degree. The antenna/snow-surface offset is independent, satellite constellation is completely different, the equipment used is different. The only common thing among those profiles is the use of the GNSS technique. As GNSS measurements are used to define the IGS/ITRF reference system, we assume the technique itself to be free of offsets.

– For RMS_X, a useful value would be the number of crossovers per traverse. How large is the dataset 'N'?

This table is already very large and contains very much information. Besides K08C, the smallest amount of RMS_X crossovers is 26 between K11A and K11B. Usually there are several hundreds up to several thousands (more than 21,000 between K12E/F) of crossovers. We do not believe, that this number of crossovers contains any significant information here.

– "While crossover differences within one expedition are used for accuracy estimates, the elevation differences in crossovers between profiles of different years allow to assess temporal rates of surface elevation changes (h_dot)." The first part of this statement is not accurate: again, RMS_X is an assessment of precision, not accuracy. The second part of this statement is true, as a differential assessment (h_dot) does not require absolute 'truth'.

As discussed above towards RMS_X, we believe, that this is a good measure for accuracy.

– "are found on the traverse to Mirny. In the lower parts..." lower = elevation?

Yes, changed.

– "Our profiles shall be used nevertheless for the validation of SRA, which is..." You will be comparing this to ICESat as well, yes? Then perhaps SRA is not the best term to use. Perhaps 'SA'?

The whole paragraph has been rewritten.

– From section 2.4 to section 3, these are really results. And then other datasets are introduced in section 3... It might be good to reorganize the paper a bit to have all of the data introduced early (then perhaps questions associated with, e.g., IGS/WGS84 are answered immediately).

We had many discussions about the structure of the manuscript and decided against introducing all datasets together due to the very different nature of these types of data and thus the methods applied.

– "Above steeper terrain, the altimeter is switched to SARIn Mode..." 'Above'?

The altimeter is "flying above" the terrain.

– Fricker et al., 2005, Shuman et al., 2006, Kohler et al., 2013, Siegfried et al., 2011 should all be cited in the ICESat accuracy assessment section. Most of these were 'on–ice' or 'ice–like' surface assessments. Schutz et al, 2005 is an ICESat overview paper, not an assessment based on in situ data.

Schutz et al. (2005) defined the mission requirements of "a series of points on the ice sheet with vertical accuracy at the decimetre level". We agree that a validation is even more convincing than mentioning the mission goals. Thus we changed the reference to Fricker et al.(2005) and Shuman et al.(2006). However, as they relate to very early releases of the ICESat data the results are not comparable any more and we did not relate to them in the further assessment. A section comparing the results of Kohler et al. (2013) and Siegfried et al. (2011) has been added.

– "Our validation approach is the following: We assess how accurately the altimetry data reflects the actual surface elevation at the nominal positions of the altimetry data." This assumes that the in situ data are 'truth' and error–free, which is probably never the case. It's reasonable to make that assumption, it just has to be stated, with the caveats.

See above. This "validation" is exactly the same as Siegfried et al. (2011) or Kohler et al. (2013) did. The much higher amount of independent profile makes our ground 'truth' even significantly more reliable.

– "On the other hand, in this zone typically the largest elevation can be expected" this is not clear to me.

This comment seems to refer to an older version of the manuscript where "changes" was missing. In the discussion paper it is "elevation changes".

– "ICESat surface elevations are less sensitive..." 'Relatively' less sensitive. This is still an issue. For cm–level surface change, the effect of slope on ICESat data is still significant, especially in your 'zone 1'.

We are writing "less sensitive", not "not sensitive", so we think, this is correct.

– "Including the unbiased GNSS profiles..." The authors are trying to present a new set of ICESat intercampaign biases. The community may cite these widely.

My concern is that theauthors haven't truly provided and accuracy to their kinematic data (they instead provide precision). I am strongly against presenting a new set of bias corrections this way. See my comments above.

See comments above. Even if all our datasets would have an offset (e.g. of 34 cm to match the average Zwally et al. (2015) biases), the relative biases would still be correct, which would still be sufficient for the detection of elevation change rates from ICESat. But nevertheless, now by comparing the ICEBrige data too, we are even more confident, that this is not the case.

– "For the ICESat elevations, in contrast, we assume a homogeneous accuracy and adopt a standard deviation of 10 cm..." also not a good idea. The spread (standard deviation) of ICESat data increased (got worse) with extended laser life. It was not static.

We completely agree with the reviewer. We have changed this towards the use of intra-campaign RMS_X now, which slightly changed the resulting biases.

– Figure 4: "4 ... 9" must mean 4 – 9?

Was already changed in the final discussion paper.

– Table 2: Are statistics with an 'N' of 2 (or 3 or 6) really meaningful? I know you acknowledge this in the text, but it jumps out at you in the table.

We agree. This has been marked more obviously and mentioned in the caption, too.

– Fig 5: What are the 'N's associated with each assessment?

'N's added.

– Prior to the validation of ICESat elevation data, we first determine the ICESat laser campaign biases as described in Sect. 3.2.2." Again, I express my concern on how this is being presented, given that a more rigorous accuracy assessment needs to be made for the ground–based data. Note that for many of the other assessments of the intercampaign bias, the timing of the in situ data and the ICESat data was taken into consideration (e.g., Fricker et al., 2005, Borsa et al., 2014, Siegfried et al., 2011). These GPS data have very little overlap with ICESat overpasses.

We take the timing into consideration as we estimate $\dot{h}$ together with the biases.

– "...not surprising that our biases are very similar to the set presented by Richter et al. (2014) for R33 including the Gaussian–Centroid (G–C) correction" What does this mean? Did you remove the G–C correction from the R33 data to make the comparison?

Perhaps the wording was a bit ambiguous. We have changed this in the manuscript.

– "we perform an absolute calibration..." I don't believe this to be true, given what I have said about the RMS method of determining 'accuracy'.

This point has already been discussed towards RMS_X above.

– Fig 7b: what are the 'N's? Also, right–most panel shows that slope has an impact on ICESat (comments above)

'N's added. It was never said, that the slope has no influence. We just say, that there is no slope correction, as the elevations refer to the footprint average (gaussian), not the POCA. The increased standard deviation is discussed in the text.

– *Section 4: Why are we validating the 2007 and 2009 DEMs (which are snapshots of the ice surface at some specific time) with these GPS datasets, which generally (from Table 1) span the subsequent 6 to 8 years? This is not meaningful.*

See discussion towards "DEM assessments" above.

– *"However, with increasing slope the standard deviation of this DEM grows..." High slope areas around the coast of Antarctica are also where the ice sheet is changing the most (Pritchard, et al 2009). Thus, some of these differences are probably associated with real surface change. I ask again why are the authors validating a 2007 and 2009 DEMs with these GPS datasets, which generally span the subsequent 6 to 8 years?*

Yes, some part of the differences might be related to elevation changes, as discussed in the end of Sect. 3.3.3. However, those results also pinpoint the magnitude of those effects. In the "$> 0.5°$"-zone ICESat-Kin is -0.13$\pm$ 0.35 m. For the ICESat-DEM, this is -7.67$\pm$ 28.12 m. The significant difference shows, to what extent elevation changes might have played a role here.

– *"The comparison of the CryoSat–DEM with the ICESat–based models proves that SRA with advanced instrument design provides excellent elevation information over all zones" Note that the traverses are more coincident with the CS–2 time period. Again, this comparison ispointless.*

We do not think so. All evaluated DEMs rely mainly on ICESat, except the CryoSat-DEM. This comparison shows the influence of the interpolation error in ICESat-based DEMs. The CryoSat-DEM, even if not as accurate at the data locations itself, does not have this weak point.

– *"We resolved the challenges of the GNSS processing, such as the very long baselines and ..." I do not think that you have characterized the accuracy, therefore, I do not feel that this statement is valid.*

See discussion above.

References

Armitage, T., Wingham, D., and Ridout, A.: Meteorological Origin of the Static Crossover Pattern Present in Low-Resolution-Mode CryoSat-2 Data Over Central Antarctica, IEEE Geosci. Remote Sens. Lett., 11, 1295–1299, doi:10.1109/LGRS.2013.2292821, 2014.

Dach, R., Lutz, S., Walser, P., and Fridez, P., eds.: Bernese GNSS Software Version 5.2, Astronomical Institute, University of Bern, Bern Open Publishing, Bern, doi:10.7892/boris.72297, 2015.

Geng, J., Teferle, F., Meng, X., and Dodson, A.: Kinematic precise point positioning at remote marine platforms, GPS Solut., 14, 343–350, doi: 10.1007/s10291-009-0157-9, 2010.

King, M., Coleman, R., Freemantle, A.-J., Fricker, H., Hurd, R., Legrésy, B., Padman, L., and Warner, R.: A 4-decade record of elevation change of the Amery Ice Shelf, East Antarctica, J. Geophys. Res., 114, F01 010, doi:10. 1029/2008JF001094, 2009.

Kohler, J., Neumann, T., Robbins, J., Tronstad, S., and Melland, G.: ICESat Elevations in Antarctica Along the 2007–09 Norway-USA Traverse: Validation With Ground-Based GPS, IEEE Trans. Geosci. Remote Sens., 51, 1578–1587, doi:10.1109/TGRS.2012.2207963, 2013.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A., and Wingham, D.: Increased ice losses from Antarctica detected by CryoSat-2, Geophys. Res. Lett., 41, 3899–3905, doi:10.1002/2014GL060111, 2014.

Richter, A., Popov, S., Fritsche, M., Lukin, V., Matveev, A., Ekaykin, A., Lipenkov, V., Fedorov, D., Eberlein, L., Schröder, L., Ewert, H., Horwath, M., and Dietrich, R.: Height changes over subglacial Lake Vostok, East Antarctica: Insights from GNSS observations, J. Geophys. Res. Earth Surf., 119, 2460–2480, doi:10.1002/2014JF003228, 2014.

Schutz, B., Zwally, H., Shuman, C., Hancock, D., and DiMarzio, J.: Overview of the ICESat Mission, Geophys. Res. Lett., 32, L21S01, doi:10.1029/ 2005GL024009, 2005.

Shuman, C., Zwally, H., Schutz, B., Brenner, A., DiMarzio, J., Suchdeo, V., and Fricker, H.: ICESat Antarctic elevation data: Preliminary precision and accuracy assessment, Geophys. Res. Lett., 33, L07 501, doi: 10.1029/2005GL025227, 2006.

Siegfried, M., Hawley, R., and Burkhart, J.: High-Resolution Ground-Based GPS Measurements Show Intercampaign Bias in ICESat Elevation Data Near Summit, Greenland, Geoscience and Remote Sensing, IEEE Transactions on, 49, 3393–3400, doi:10.1109/TGRS.2011.2127483, 2011.

Simonsen, S. and Sørensen, L.: Implications of changing scattering properties on Greenland ice sheet volume change from Cryosat-2 altimetry, Remote Sens. Environ., 190, 207–216, doi:10.1016/j.rse.2016.12.012, 2017.

Authors response to the comments of referee #3

We thank the reviewer for the thorough, fast and helpful evaluation of the manuscript. His suggestions, including also the minor comments, helped substantially to improve clarity. We would like to mention that the correction of a small inconsistency in our variance propagation of the GNSS profiles and the variable ICESat campaign precisions (recommended by reviewer #2) slightly changed the results for the campaign biases. However, this does not change anything in the general messages of the manuscript.

[RC] *1. Presentation: A major component of this paper is the derivation of inter-campaign biases in the ICESat data. The authors present a series of histograms showing the residuals between the ICESat-derived heights and those derived by kinematic GNSS in Figure 7b. It would be useful to also have a third panel in the figure showing residuals between ICESat and kinematic GNSS prior to the inter-campaign bias correction, so the reader can see the effect of the correction in improving the height residuals.*

We decided not to include the suggested histograms as they would look very similar to those for the corrected data. In the time invariant treatment of the data (Fig. 7b), the crossover statistics of the uncorrected data will mainly differ in its mean values. This is a result of the mean value of the biases. The standard deviations will not be significantly larger (e.g. 11.1 cm for the uncorrected, 10.7 cm for the corrected data over Lake Vostok) as most of the corrections are in the order of only a few centimetres. The main effect of correcting the biases is to remove the spurious trend before the calculation of temporal changes from the data. We added a sentence towards this comparison in the discussion of the results.

[RC] *Figure 7a needs to be presented with error bars.*

We followed this suggestion and modified Figure 7a accordingly.

[RC] *All histograms shown in this paper should be presented with the number of measurements that go into it (this could be added to all the legends along with the mean and standard deviations).*

OK, this was included for the crossover histogram statistics. For the validation of the DEMs, such a number would not be very meaningful. Here elevations were interpolated and differences calculated for each kinematic GNSS position. Hence, this would just reflect the number of GNSS elevations in a specific zone but say nothing about their spacial coverage of a sufficient area of this zone.

[RC] *2. Stability of reference surface: There can be issues with height changes in the reference surface between the time of acquisition of the GNSS data and the time of the altimetry-derived height measurement (i.e. the reference surface is not always stable). Toward this, the authors should include a time series of GNSS data over Lake Vostok to demonstrate the variability in the observed height over the reference surface and provide statistics on the time difference between GNSS and altimetry datasets at crossovers.*

This point is discussed in section 2.5. For radar altimetry, the errors of the slope correction (up to 10 m and more in the margins) exceed the possible elevation change rate (maximum around 10 cm/yr) in this region by at least an order of

magnitude. As elevation changes are important when determining the ICESat campaign biases, we included $\dot{h}$ in Eq. (4).
However, we agree that a time series helps to get a deeper view into the temporal variations and their origins. Therefore we added Fig. 7c.

[RC] *3. Precision of GNSS estimates: The mean baseline differences presented here are only one potential source of error in the GNSS estimate. In this paper, however, there is no mention of the precision of GPS measurements. To estimate this, the authors could look at GPS data collected by a tractor/trailer in a single place for an extended period (hours) and present the noise in the determined height (see Borsa et al, 2007 Modeling long-period noise in kinematic GPS applications). This is important if the authors include Table 3 in the final version, since this can be a major source of uncertainty. If this cannot be included, the authors should add a note about this in the discussion.*

We use the terms precision and accuracy now in a more precise way. We have already done the suggested analysis for measurements acquired during the stops of the vehicles. The elevations vary within 1–2 cm. However, we did not include this in the paper, as it provides only information about white noise. But there are further possible sources of errors as, for example, the ambiguity resolution, which are not detectable in this way. We think, solving the same epoch as a differential solution using multiple baselines is a rigorous estimate for the repeatability of the epoch solution.
In contrast, the RMS of the final surface elevation is determined from crossovers between different profiles of one season. These profiles are considered independent and thus, this RMS is a realistic estimate for accuracy. In addition, now we include also an independent dataset (ICEBridge) which confirms our accuracy estimate. However, the small amount of crossover points here does not provide sufficient statistical significance.

[RC] *4. Residuals through time: The authors show residuals through time between ICESat and GNSS (Figure 7a). It is not clear if the trend in the residuals is unique to the ICESat period. Since the authors already have the data for Envisat and CryoSat-2, I suggest that the authors also plot residuals between each those missions and the GNSS, with time on the x-axis. One way of doing this would be to bin the GNSS-altimeter residuals into yearly (or other) intervals and plot them over the whole time period.*

There might be a misunderstanding here. Fig. 7a does not show residuals over time between the two datasets, it shows the result of the bias estimation using Eq. (4). The trend is not a true elevation change, it is the apparent trend introduced by these biases. The results of Eq. (4) suggest that $\dot{h}$ is 0.0 $\pm$ 0.2 cm/yr.

[RC] *Furthermore, there is an offset (5 cm) in the residuals between ICESat and GNSS. Through the caption over Table 3, the authors imply that the ICESat elevations need to be corrected for that offset. However, there is no evidence that ICESat-derived heights are biased by 5 cm (this would be a major finding if this is real), and this is likely a bias in GNSS-derived heights. The authors need to discuss potential causes of this discrepancy.*

Yes, the mean value of our biases is 5 cm and we believe this is real. This result is not exceptional: Other authors even calculate much bigger mean offsets

(Zwally(2015): -28.8 cm). We know, that the accuracy of our profiles is only some centimeters (see answer on question 3.). Nevertheless, by comparing different profiles of one season and even ICEBridge, we can limit this uncertainty to below 10 cm. Using profiles from 9 different seasons we think that in average we come very close to what is the 'true' surface elevation.
Besides this, the biases are usually used when calculating elevation CHANGES from ICESat data, where any possible mean offset vanishes.

[RC] *5. DEM analysis: The section on DEM validation detracts from the major substance of the paper, i.e., validation of L2 heights derived using various altimeters. The comparison of the ICESat and CryoSat-2 DEM's could be useful in terms of the assessment of their accuracies, but I suggest the authors consider removing the comparisons with the Bamber-DEM and the Bedmap2-DEM.*

We do not think, that there is a conflict between the L2 elevations and the DEMs (or so called L3 grids). They are just a step further to what most end users need. As these grids are created from satellite altimetry data, this nicely matches the scope of this paper. We think there are some very interesting coincidences between the DEMs and the datasets which have been used to create them. Furthermore, especially the Bamber-DEM and the Bedmap2-DEM are widely used products and importand to include in this study.

[RC] *6. Crossover analysis: Section 3.2.1 (Paragraph 4) This paragraph mentions that the crossover method is outlined in Section 2.4, but there is no mention of how altimeter-GNSS crossovers are defined (which is a major aspect of the manuscript). Does the altimeter footprint need to overlap with the GNSS track, or are the authors interpolating the altimeter track crossing the GNSS traverse to obtain a measurement on the traverse? A further technique one could use would be to fit a line to a few altimeter measurements in the along track direction around the crossover point - the prediction of the line fit at the crossover location would be the altimeter-derived height. The technique the authors use should be discussed and justified.*

This is now explained in more detail in the manuscript.

Minor comments:

1. Section 3.1.3 - Include reference for the saturation correction.

Done.

2. Section 3.2.1 (Paragraph 3) This whole paragraph is confusing, with no citations or anything of substance. Maybe the entire paragraph can be rephrased as "some studies that used GNSS data for satellite altimeter calibration/validation use a 2-D gridded reference DEM (cite studies), but we do not adopt this here due to observational limitations". If not, this paragraph can be deleted, since it does not add too much to the discussion.

The whole paragraph has been tightened.

3. Section 3.2.1 (Paragraph 4) I think the along track sampling is around 290 m for CryoSat-2. Check (Wingham 2006) or the CryoSat-2 product handbook for details.

Changed.

4. Section 3.2.2 (Paragraph 1) Consider replacing "Between the campaigns systematic biases exist. If not corrected carefully, these biases corrupt the inference of temporal surface-elevation changes and estimates of height change" with "If not accounted for carefully, any systematic biases between campaigns can corrupt the inference of temporal surface-elevation changes and estimates of height change"

Changed.

5. Section 3.2.2 (Last Sentence) Provide reference for or justify using this value (10 cm).

Modified according to review #2 to use campaign specific values now.

6. Section 3.3.1 (Paragraph 2) Replace "For the GSFC product those errors are even significantly larger." with "For the GSFC product those errors are significantly larger."

Changed.

7. The conventions used are inconsistent (CryoSat vs. CryoSat-2 vs. Cryosat-2; SARIn mode vs. SARIn Mode vs. SARIN; 18.000 vs 18,000.

Changed.

8. There is no punctuation in the caption for Figure 1.

Changed

9. Units are inconsistent (sometimes m sometimes cm).

We are aware that this is not consistent, but e.g. in Fig. 7 we do this for good reason. As the campaign biases are very small, they are easier distinguished in cm. However, for better visual comparability of the histograms, Fig. 7b uses meters. We are confident that this does not lead to confusion as the units are stated clearly everywhere.

Validation of satellite altimetry by kinematic GNSS in central East Antarctica

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Abstract. Ice-surface elevation profiles of more than ~~30.000~~ 30,000 km in total length are derived from kinematic GNSS (GPS and the Russian GLONASS) observations on sledge convoy vehicles along traverses between Vostok station and the East Antarctic coast. ~~The~~ These profiles have accuracies between 4 and 9 cm. They are used to validate elevation datasets from both radar and laser satellite altimetry as well as four digital elevation models. A crossover analysis with three different processing versions of Envisat radar altimetry ~~datasets~~ elevation profiles yields a clear preference for the relocation method over the direct method of slope correction and for threshold retrackers over functional fit algorithms. The validation of ~~Cryosat-2~~ CryoSat-2 low-resolution mode and SARIn mode datasets documents the progress made from baseline B to C elevation products. ICESat laser altimetry data are demonstrated to be accurate to a few ~~decimeters over~~ decimetres over a wide range of surface slopes. A crossover adjustment ~~above~~ in the region of subglacial Lake Vostok combining ICESat elevation data with our GNSS profiles yields a new set of ICESat laser campaign biases and provides new, independent evidence for the stability of the ice-surface elevation above the lake. The evaluation of the digital elevation models reveals the ~~importance of radar altimetry for the reduction of interpolation errors~~benefits of combining laser and radar altimetry.

1 Introduction

Surface elevation data is crucial for a broad range of applications in polar sciences. Only satellite altimetry is able to provide this information with a high and nearly uniform accuracy and precision for almost the entire Antarctic ~~ice sheets~~Ice Sheet. This high accuracy also allows to infer temporal changes in ice surface elevation, which is of prime scientific interest in the context of ongoing climate change (Shepherd et al., 2012; Groh et al., 2014). However, systematic effects (as varying surface properties or measurement biases) can deteriorate the derived elevation trend $\dot{h}$ and - if not corrected thoroughly - they might lead to misinterpretation of the observations (Arthern et al., 2001; Lacroix et al., 2009).

One crucial step in the processing of surface elevations from satellite radar altimetry (SRA) over ice sheets is the slope correction (Brenner et al., 1983). Due to the size of the beam-limited footprint of about 20 km in diameter the first reflection

can originate from a location up to several ~~kilometers~~ kilometres away from the nadir point in a sloping surface. Different approaches exist to correct for this effect (e.g. Bamber, 1994; Roemer et al., 2007) but, as the corrections can exceed 100 m (Brenner et al., 2007), remaining model errors may introduce height errors of up to several ~~meters~~metres. This is the major factor limiting the application of SRA in the steep and rugged coastal areas (Flament and Rémy, 2012).

Another issue when deriving ice-surface elevations from SRA data is the penetration of the ~~electromagnetic~~ microwave signal into the upper firn layers. This results in a mixed return signal consisting of surface reflection and volume reflection (Ridley and Partington, 1988). Here, the selection of an appropriate retracking algorithm is essential. One approach to minimize the influence of the volume echo on the observed surface elevations is to retrack at the very beginning of the waveform (Davis, 1997). Another method is to apply appropriate corrections using parameters of the radar ~~return~~ waveform shape (Wingham et al., 1998; Flament and Rémy, 2012; Zwally et al., 2015).

For the Ice Cloud and ~~Land~~ land Elevation Satellite (ICESat) mission ~~these effects~~ the effects of topographic correction and signal penetration do not arise or are negligible as the onboard altimeter uses laser signals. Hence, significantly higher accuracies can be achieved. Nonetheless, also those measurements are not free of systematic errors. Pointing errors and orbital variations (Luthcke et al., 2005) or saturation effects (Scambos and Shuman, 2016) may cause laser campaign biases which induce spurious trends of up to 2 cm/yr (Hofton et al., 2013; Gunter et al., 2014) and introduce errors of more than 100 Gt/yr in mass balance estimates (Hofton et al., 2013).

In order to quantify the impact of these errors and to evaluate methods for their correction, independent elevation data of high precision and accuracy is crucial. Here, we make use of ice-surface elevation profiles in central East Antarctica ~~of more than 30.000 km of~~ comprising more than 30,000 km in total length. These profiles are ~~derived from~~ observed with kinematic GNSS (Global Navigation Satellite System, ~~GPS and GLONASS~~ which means the Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS) in this case) ~~observations~~ carried out over more than one decade on sledge convoy vehicles along continental traverses. This set of surface-elevation profiles is made available for download on the data server PANGAEA (https://doi.org/10.1594/PANGAEA.869761).

2 Surface elevations from kinematic GNSS-profiles

2.1 Kinematic GNSS observations

The Russian research station Vostok is located in the central part of East Antarctica (106.8° E, 78.5° S). It is the main base for a wide range of scientific fieldwork related to the subglacial Lake Vostok. Between 2001 and 2015 several kinematic GNSS profiles have been measured in the area of the lake as well as on the scientific traverses from Vostok station to the East Antarctic coast.

Geodetic dual-frequency GNSS receivers with external antennas were used for the kinematic profiling as well as on the reference stations. Two different types of profiles can be distinguished with respect to the vehicles onto which the GNSS antennas were mounted. The first type are observations performed on lightweight snowmobiles. With the help of such profiles Richter et al. (2014a) have shown that the surface elevation around Vostok station has been stable over the last decade confirming the

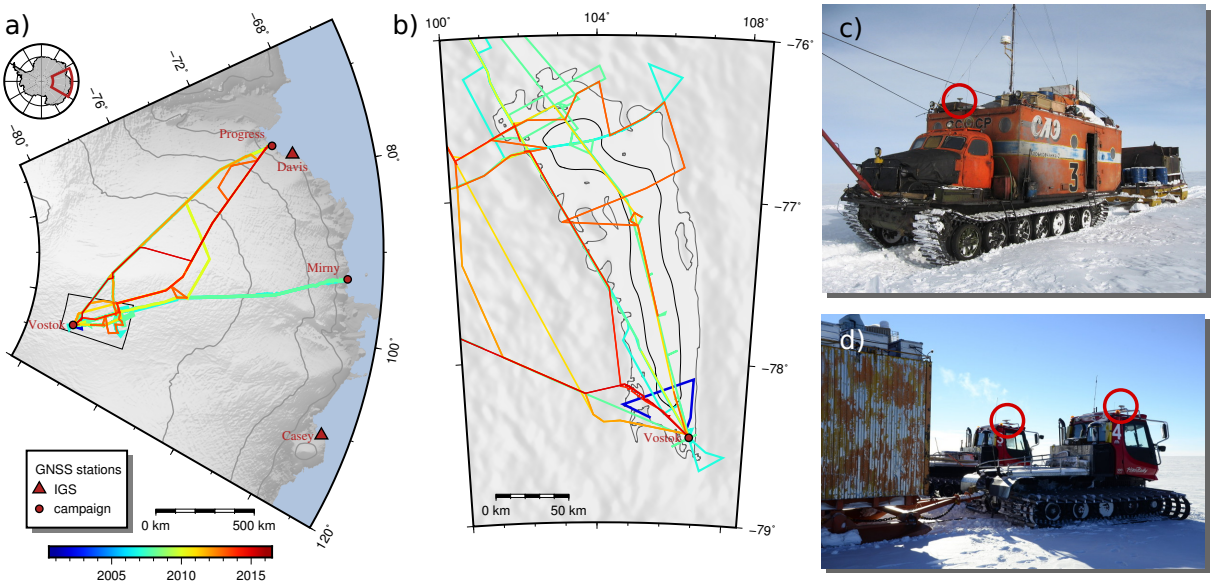

Figure 1. a) Overview of the kinematic GNSS profiles (~~color~~ colour coded by their chronological sequence) and the GNSS reference stations used in the differential processing. **b)** Detailed map of the profiles in the area of subglacial Lake Vostok (outline in ~~gray~~grey, hydrostatic equilibrium area in black). **c)** Convoy vehicle of type STT-2 Kharkovchanka-2 (profile K10B) with antenna mounted on the container above the cabin (red circle). **d)** Convoy vehicles Kässbohrer PistenBully (profiles K14A and K14B) with antenna mounted on top of the cabins.

results of permanent GNSS observations (Richter et al., 2008, 2014a). ~~The~~ Such profiles acquired on snowmobiles provide accuracies of only a few ~~centimeters~~ centimetres (cf. also King et al., 2009; Siegfried et al., 2011) and are thus well suited for precise studies on local elevation and elevation changes. However, due to logistic reasons they usually cover only a very limited area and are therefore not considered here.

The second type of observations are carried out on heavy convoy vehicles. Those are tractors on tracks, designed to pull sledges with containers for accommodation and fuel tanks (Fig. 1). Hence, they are ideal platforms for ~~the measurement~~ such measurements over very long distances. This is a precondition for the validation of satellite altimetry on a larger scale, as it helps to minimize the influence of regional peculiarities, especially due to specific topographic conditions (Kohler et al., 2013). The disadvantage of such heavy platforms, compared to snowmobiles, is that they sink into the soft upper snow layers ~~by~~ up to several ~~decimeters~~decimetres. The amount of the vehicle's subsidence, and thus of the height of the antenna above the snow surface, varies locally. Therefore, this antenna height has to be measured as often as possible along the traverse.

In the austral summer 2001/2002, our first surface elevation profile was acquired during a seismic convoy of the Russian Antarctic Expedition (RAE) along a 150 km transect in the southern part of Lake Vostok. During this traverse over 6 days a GNSS antenna was installed on the roof of a trailer, pulled by a traverse vehicle.

After this regionally limited campaign, much longer profiles were ~~observed~~ measured since 2006. In that time Mirny station (93.0° E, 66.6° S) was the coastal logistical hub for the supply of Vostok station by overland traverses. Several scientific obser-

vations were performed during these convoys ~~(Masolov et al., 2001; Richter et al., 2013; Popov, 2015; ?)~~(Masolov et al., 2001; Richter et a
In the austral summer 2006/2007 kinematic GNSS profiles between Vostok and Mirny were observed on two convoy vehicles. For the first time these profiles cover all the distance of about 1.600 km from the remarkably flat ice surface above Lake Vostok down to the rugged terrain at the coast. In the following season these profiles were repeated on two vehicles.
In 2009, Progress station (76.4° E, 69.4° S) became the main logistic hub for Vostok station. ~~A first~~ Further, an initial reconnaissance traverse from Progress to Vostok and back was performed in 2007/2008 that already included geodetic GNSS-equipment. Since austral summer 2009/2010, several profiles between these two stations were ~~observed~~ measured each season. A number of different routes were used according to the needs of ~~further~~ the participating scientific groups, snow conditions or logistical constraints. Fig. 1 gives an overview of the locations and ~~observation times~~ timing of the routes as well as two ~~impressions~~ examples of the types of vehicles used. Table 1 contains detailed information about each individual profile.

2.2 GNSS data processing

We used the Bernese GNSS Software 5.2 (Dach et al., 2015) for the differential post-processing of the kinematic observation data. ~~This processing yields~~ In such remote locations, other studies (Siegfried et al., 2011; Kohler et al., 2013) used the precise point positioning (PPP) technique, which does not require reference stations. However, PPP depends on precise high-rate satellite clock information, which is not available for our early campaigns. Geng et al. (2010) showed that both techniques are able to reach very high accuracies (~3 cm) for very long distances to reference stations. The processing provides a 3D coordinate of the GNSS antenna for each observational epoch in the terrestrial reference frame IGS08. Using those coordinates, a profile of ellipsoidal elevations ~~referring~~ referenced to WGS-84 ~~are~~ is derived. For ~~most~~ many of the profiles multi-system GNSS receivers were used, i.e. observations from the Russian ~~Global Navigation Satellite System (GLONASS)~~ GLONASS are logged in addition to ~~the Global Positioning System (GPS)~~GPS. The increased amount of ~~observation data~~ observations improves the reliability of the solution significantly. As kinematic reference ~~site~~ sites in this differential positioning we utilised static observations from campaign sites, for example in Mirny or Progress, from an own permanent receiver in Vostok installed in early 2008 (for details see Richter et al., 2014a) and additionally from the sites Casey and Davis of the IGS-network (see Fig. 1). To cope with the scarce sampling interval of the IGS-sites of 30 s, those static observations had to be interpolated to the rate of the kinematic receivers (mainly 5 s or 15 s, sf. Table 1). For that purpose we used WaSoft, a software tool developed by Wanninger (2000). We adopt the processing strategy of Fritsche et al. (2014), which corrects or parametrises the tropospheric and ionospheric delay, the antenna phase centre offsets and variations, solid earth tides and loading displacements. Special attention is paid to the resolution of the GNSS carrier phase ambiguities of the differenced observations. When the vehicle is halfway between Vostok and the coast, no baseline to a static reference station is shorter than 800 km. Then, only very robust ambiguity resolution strategies are able to produce satisfactory results. Therefore, in this case we used the Melbourne-Wübbena and the Quasi-Ionosphere-Free Linear Combination only (Dach et al., 2015). As this is the most critical step in processing, a thorough outlier screening of the fixed ambiguity solutions is essential. For this reason, we always used more than one, typically four to five, baselines to different reference sites. Undetected cycle slips lead to very large deviations of the affected baseline.

Thus, by processing each baseline independently and comparing the results to the combined solution, the baseline causing large deviations can be identified and the undetected cycle slip has to be introduced manually.

2.3 Derivation of surface elevation profiles

The antenna trajectory resulting from the GNSS positioning has to be corrected for the height of the antenna above the local snow surface in order to derive surface elevation profiles. This vertical offset is not constant as the amount to which the vehicle sinks into the snow depends on the regionally varying surface snow properties, but also on the vehicle type (e.g. track width). For example, Kohler et al. (2013) had to employ additional laser measurements on another vehicle in order to retrieve the amount of vehicle subsidence because the antenna height was not measured repeatedly along their profiles. During our traverses we measured this antenna height offset AH several times for each observation day and for each profile. However, the representativity of a single offset measurement may still be limited due to small-scale surface structures (sastrugi) at the locations of the measurements. Thus, to obtain a specific offset for each single epoch i, we use a regional average

$$AH_i = \frac{\sum_j (d_{ij}^{-1} \cdot AH_j)}{\sum_j d_{ij}^{-1}}, \tag{1}$$

where d_{ij}^{-1} is the inverse distance between the position at epoch i and the position of the antenna height measurement AH_j. The offset of profile K08C was measured only once. Here we model the subsidence from similar profiles with comparable vehicles.

Furthermore, a permanent tilt of the moving vehicles had to be considered. While driving in soft snow, especially when pulling heavy sledges, the nose of the vehicle gets lifted up while the rear buries deeper. This dynamic effect is not determined directly as our offset measurements are taken during stops when the vehicle stands upright. However, an instantaneous jump in antenna elevation from GNSS positioning is observed whenever the vehicle stops. Depending on the antenna's position on the vehicle, it can reach 20 cm. These jumps are used to correct the measurement AH for the vehicle dynamics. For this purpose we interpolate the *elevations in movement* (i.e. velocity > 1 km/h) to the position of the antenna height measurement by fitting a quadratic function within a distance of 100 m around this point and comparing it to the average *elevation in rest*.

To reduce the noise and ~~to make the along-track resolution more comparable to the altimetric elevations~~ the influence of sastrugi we applied a low-pass filter to the original antenna trajectory. ~~The typical along-track spacing of the radar altimeter data is several hundreds of meters. Furthermore, due to the diameter of the pulse limited footprint of about 2 km the measurement represents an average elevation of this area. In contrast, the GNSS profiles sample the elevation along their track with a very dense spacing.~~ Depending on the sampling interval (Table 1) and the velocity of the vehicles (about 7 km/h) the usual point distance is in the range of 10 to 30 m. We applied a Gaussian filter with a Gaussian sigma of 60 m and a total length of 180 m. ~~This reduces not only the measurement noise, but also variations due to vehicle dynamics or very small-scale topography (e.g. sastrugi).~~ In addition, the trajectory positions are thinned out to an equidistant interval of 30 m. This reduces substantially the data amount ~~without loss of information~~ (e.g. ~~data~~ when data was logged during overnight stops of the convoy) without loss of information.

A comparison between kinematic GNSS profiles and satellite altimetry products requires ~~a correction due to the different~~ consistency in the reference system used (King et al., 2009). ICESat (Schutz and Urban, 2014) and CryoSat-2 (Schrama et al., 2010) refer to ITRF08. This is identical to IGS08 within sub-mm level (Rebischung et al., 2012). Envisat GDR-C orbits refer to ITRF05 (Cerri et al., 2011) but as this affects the differences in the order of some millimetres only (Rebischung et al., 2012), it is considered negligible here, too. However, the treatment of the permanent tide in the reference systems underlying both techniques has a significant influence here. According to McCarthy and Petit (2004) the International Terrestrial Reference Frame (ITRF) and consequently IGS08 too, is a "conventional tide free" frame. Hence, all tidal effects including the permanent effect have been removed from the coordinates of the reference stations. Our elevation profiles are ~~consequently~~ henceforth also conventional tide free. Altimetric elevations, in contrast, refer to the "mean tide" system. The GNSS elevations are converted to this mean tide system using Eq. 7.14a of Petit and Luzum (2010), which is a function of ~~the~~ latitude and amounts to about -10 cm at 70°S.

2.4 Accuracy ~~estimates~~and precision

~~Accuracy~~ Precision estimates for the epochwise coordinates consist of estimates of the quality of the antenna positioning and an additional uncertainty due to the reduction to the snow surface. In a first step we assess the quality of the GNSS processing. The formal coordinate ~~accuracies~~ errors reported by the processing software are too optimistic as they do not account for non-white noise components. A more realistic measure is found by comparing multiple baseline solutions. As mentioned in Sect. 2.2, the ambiguity resolution is a critical step in the GNSS data processing. Unrecognized cycle slips can distort profile sections over several ~~kilometers~~ kilometres and are thus not removed by the low-pass filter. However, such instances are identified within independent solutions using different reference sites. The average baseline coordinate differences RMS_{BL} are used to derive realistic estimates for the ~~accuracy~~ precision of the kinematic positioning. Mean baseline differences in the vertical component are shown for each profile in column $\overline{RMS_{BL}}$ of Table 1 and are in general on the order of ~~3 cm~~a few centimetres.

An additional source of uncertainty is imposed by the reduction of the GNSS antenna elevation to the snow surface. This reduction varies regionally due to varying snow surface characteristics. Thus, besides the error of the offset measurements themselves, the offset corrections, obtained by Eq. (1), contain an additional interpolation error. We assess both types of errors using semivariograms. Here, we fit a linear function to the squared differences between the measurements of the antenna height offsets, with respect to the distances between those measurements. We obtain a constant part of 6 cm, which relates to the uncertainty of the antenna height measurement itself. It is potentially affected by local surface features (sastrugi) and residuals in the dynamic tilt correction. The distance related additional uncertainty is 0.25 cm/km and accounts for the specific distance between the location of the respective offset measurement and the location to be interpolated. Using these values, the ~~accuracy~~ precision of the antenna height reduction through inverse distance interpolation (RMS_{AH}) is derived. Hence, the total ~~accuracy~~ precision measure for a single surface elevation observation is obtained by

$$RMS_S = \sqrt{{RMS_{BL}}^2 + {RMS_{AH}}^2}. \quad (2)$$

To account for possible errors in the subsidence modeling for profile K08C, we add additional 10 cm to the uncertainty there.

Table 1. Overview of the kinematic GNSS-profiles. ~~Accuracy estimates are~~ Estimates of precision consist of the mean elevation error from GNSS processing (from differences between combined and single baseline solutions) $\overline{RMS_{BL}}$ ~~,~~ and the obtained mean formal ~~accuracy~~ precision of snow surface elevation $\overline{RMS_S}$ ~~and the~~ . The empirical mean crossover difference between independent profiles of one season $\overline{RMS_X}$ gives an estimate for the accuracy. Averages and (in case of more than one) the standard deviation of the crossover differences with Operation ICEBridge ATM at 2013-11-26 is given in the last column.

Profile	Vehicle ~~(Type)~~	Area ~~*~~ of operation*	Duration	Length [km]	~~Sampling~~ Samp. [s]**	$\overline{RMS_{BL}}$ [cm]	$\overline{RMS_S}$ [cm]	$\overline{RMS_X}$ [cm]
K01A	trailer (tracks)	V	2001-12-07 - 2001-12-12	150	30 (G)	5.0	5.0	-
K07A	~~tractor (Ishimbai)~~ Ishimbai	V→ M	2007-01-07 - 2007-03-05	2280	5 (G)	3.8	4.0	8.0
K07B	~~tractor (Ishimbai)~~ Ishimbai	V→ M	2007-01-09 - 2007-01-23	580	5 (G)	2.9	~~4.3~~ 4.7	6.4
K07C	~~tractor (~~STT-1 ~~)~~	V→ M	2007-02-04 - 2007-03-05	1270	5 (G)	~~3.3~~ 3.2	~~3.9~~ 3.8	8.6
K08A	~~tractor (Ishimbai)~~ Ishimbai	V→ M	2008-01-11 - 2008-02-18	1720	5 (G)	2.3	2.5	8.4
K08B	~~tractor (ATT)~~ ATT	M	2008-02-19 - 2008-03-13	400	5 (G)	1.9	~~3.3~~ 2.8	6.5
K08C	trailer (sledge)	P→ V→ P	2008-01-06 - 2008-02-07	2890	5 (G)	1.5	~~1.7~~ 10.2	-
K08D	~~tractor (~~STT-2 ~~)~~	V→ M	2008-02-08 - 2008-03-14	1960	5 (G)	~~2.4~~ 2.2	~~2.8~~ 2.5	6.7
K10A	~~tractor (ATT)~~ ATT	V→ P	2010-01-24 - 2010-03-18	1690	15 (G)	1.6	~~2.2~~ 2.0	6.1
K10B	~~tractor (~~STT-2 ~~)~~	V→ P	2010-01-31 - 2010-03-15	1460	15 (G)	2.2	~~2.5~~ 2.4	6.1
K11A	~~tractor (~~Kässbohrer ~~)~~	P→ V→ P	2011-01-07 - 2011-02-08	1690	15 (G)	1.7	~~2.3~~ 2.1	4.3
K11B	~~tractor (~~Kässbohrer ~~)~~	P	2011-02-13 - 2011-02-14	80	15 (C)	1.5	2.9	4.3
K12A	~~tractor (~~Kässbohrer ~~)~~	V→ P	2012-01-25 - 2012-02-11	1560	5 (C)	2.8	~~2.9~~ 3.0	8.4
K12B	~~tractor (~~Kässbohrer ~~)~~	V→ P	2012-01-25 - 2012-02-11	1560	5 (C)	2.2	~~2.4~~ 2.5	8.4
K13A	trailer (sledge)	V→ P	2013-01-20 - 2013-02-12	2140	5 (C)	2.4	2.6	6.2
K13B	~~tractor (~~Kässbohrer ~~)~~	V→ P	2013-01-20 - 2013-02-15	2220	5 (C)	2.2	2.3	6.2
K14A	~~tractor (~~Kässbohrer ~~)~~	V→ P	2014-01-22 - 2014-02-11	1480	5 (C)	2.6	~~3.1~~ 3.0	7.1
K14B	~~tractor (~~Kässbohrer ~~)~~	V→ P	2014-01-22 - 2014-02-11	1550	5 (C)	3.2	~~3.4~~ 3.5	7.1
K15A	~~tractor (~~Kässbohrer ~~)~~	V→ P	2015-01-21 - 2015-02-03	1560	15 (C)	1.5	~~2.0~~ 2.1	8.1
K15B	~~tractor (~~Kässbohrer ~~)~~	V→ P	2015-01-21 - 2015-02-03	1580	15 (C)	2.1	~~2.5~~ 2.8	8.1

* V..Vostok, M..Mirny, P..Progress

** G..GPS only, C..Combined of GPS and GLONASS

A rigorous empirical test for the ~~total~~ absolute accuracy estimate is performed by the calculation of height differences at crossover locations of two different profiles of the same season. The time elapsed between the two passes over this location is typically between a few minutes and some days, thus the surface elevation is assumed unchanged. We consider those profiles as highly independent measurements as the antenna/snow-surface offset is determined independently, the satellite constellations are usually completely different and the equipment used is different. During the procession also the tropospheric correction has been estimated individually for each profile. We assume the GNSS technique itself to be practically unbiased as it is used

to define the IGS08 reference system as well. As the differences Δh are calculated from two passes, the accuracy RMS_X of a single profile at the crossover location is given by

$$RMS_X = \Delta h / \sqrt{2}. \quad (3)$$

For our profiles we obtain RMS_X in the range of 4 ~~to~~ – 9 cm (see Table 1). This is slightly higher than the RMS_S because it includes also the effect of vehicle dynamics. Nevertheless, it is a conservative estimate as in these crossovers the elevations of the second profile are affected by the disturbances of the snow surface originating from the first vehicle pass.

As an additional independent validation, we compare our kinematic GNSS profiles to airborne elevation measurements from Operation ICEBridge (Studinger, 2014). Our region under investigation is very sparsely covered by flights, but on 26th November 2013 an Airborne Topographic Mapper (ATM) Lidar profile crossed Lake Vostok twice. Brunt et al. (2017) compared ATM measurements to ground-based GPS profiles in Greenland and found biases between -11 and 7 cm with precisions of less than 9 cm. After applying the correction for the mean tidal system, we calculated crossover differences Δh_{ATM} between the nadir measurements and our profiles (see Table 1, last column). The amount of crossover points of this validation is very low (maximum 9 with K07A), but still valuable to check RMS_X as an estimate for the overall absolute accuracy. The average offset from the 39 crossovers with all profiles is 4.9 cm and the standard deviation of the differences is 10 cm. Hence we find that our accuracy estimates are realistic. There are several other airborne profiles with a laser altimeter crossing the convoy route to Mirny, but with an average of 14 cm and a standard deviation of 36 cm, the crossover differences with these laser altimeter profiles are not adequate for such a comparison.

2.5 Elevation changes

Our kinematic GNSS profiles do not always coincide in their acquisition time with the satellite altimetry data to be validated. Therefore, when comparing the GNSS-derived elevations with altimetry products, it is crucial to know to what extent elevation changes occurred between their respective observation epochs. While crossover differences within one expedition are used for accuracy estimates, the elevation differences in crossovers between profiles of different years allow to assess temporal rates of surface elevation changes ($\dot{h}$). Figure 2a shows that the obtained surface elevation rates are very small over the whole area. In Fig. 2a they are averaged at 20 km-blocks to reduce random noise. However, the rates shown may still be affected by systematic errors effective over longer distances. One potential error source, in addition to those mentioned in Sect. 2.4, is the impact of human activities on the snow surface. The immediate vicinity of the stations is obviously heavily affected but this is not the only region which had to be handled with care. For five decades the convoy between Mirny and Vostok used the same route. Especially above 3000 m, the heavy convoy vehicles and cargo sledges had followed exactly the same track in order to cope with the soft snow. This resulted in enhanced snow compaction along the track and the accumulation of a continuous ridge of several ~~decimeters~~ decimetres in height which is even visible on satellite imagery. The elevations and elevation changes along this part of the traverse are not representative for this area and are thus excluded from all subsequent studies. The profiles acquired on the modern Kässbohrer tractors are not prone to this effect since their wider tracks and relatively small weight relieves these vehicles from the need to reuse a pre-existing track.

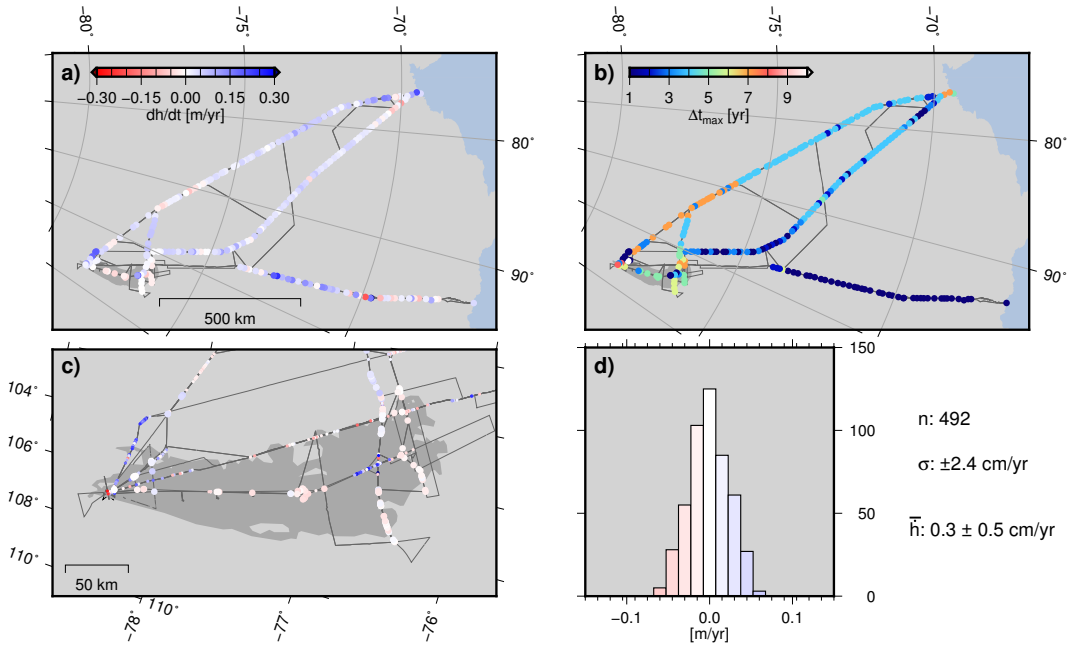

Figure 2. a) Elevation change rate from crossovers between different seasons (20 km block mean values). **b)** Maximum observation time span of crossover differences within each block. **c)** $\dot{h}$ in the Lake Vostok region. Crossovers on the convoy track or with $dt < 5$ yr are plotted half sized. **d)** Distribution of the valid (full sized) crossovers from c in the Lake Vostok region.

The largest rates, but also the largest variations, are found on the traverse to Mirny. In the lower elevation parts this is not an effect of anthropogenic disturbance. As the snow is much harder there, the tractors do not repeat the exact tracks of their predecessors. Nevertheless, the rates obtained in this area rely ~~on only~~ solely on one year time ~~span between the measurement~~ spans between the measurements of those profiles and must therefore be treated with care. In the areas where the time span is longer, very small rates are obtained. Averaging all 18,000 $\dot{h}$ by introducing weights according to the time span results in a mean elevation change over the entire area of 4 cm/yr and a standard deviation (σ) of a single crossover rate of ±11 cm/yr.

A detailed look into the results in the Lake Vostok region is given in Fig. 2c and d. In order to avoid the limitations arising from short observation time spans, we used only crossovers spanning five years or more. The weighted mean $\bar{\dot{h}}$ of the 492 crossover differences in this area is 0.3 cm/yr with a standard deviation of a single rate of ±2.4 cm/yr. The $\dot{h}$ values are not uncorrelated, especially due to possible systematic biases (e.g. antenna height reduction) which affect multiple crossovers of a profile. Therefore, for the accuracy of the mean $\bar{\dot{h}}$ we only consider the number of combinations of independent profiles (27) in the estimation, resulting in a standard error of ±0.5 cm/yr. This comprises both, real variations in surface-elevation change rate and ~~observation~~ observational uncertainties. These results agree very well with the elevation changes observed by measurements on snowmobiles around Vostok station (Richter et al., 2014a, 0.1 ±0.5 cm/yr). The latter profiles have a higher accuracy but yield a smaller amount of crossovers which may be affected by higher spatial correlation.

We conclude that the elevation change rates are very small in the region under investigation, but their spatial pattern is not determined with homogeneous reliability due to the short observation time span in some areas. ~~Our profiles shall be used nevertheless for the validation of SRA, which is subject to much larger uncertainties, especially in coastal regions . Thus we consider the surface elevation over the entire region as stable and do not correct for elevation changes. This choice will be justified~~ For the following validations we consider the elevation change to be negligible. On the one hand we have chosen only missions which overlap in time with our profiles and thus the elevation changes due to the time differences are fairly small. On the other hand, at coastal regions where the rates might be larger, the errors of SRA are significantly larger too (metres for CryoSat-2 in SARIn mode, tens of metres for Envisat, see Sect. 3.3). As this is not the case for ICESat, elevation changes will be discussed further in Sect. 3.3.3.

3 Validation of satellite altimetry

3.1 Data

3.1.1 Envisat

We validate different altimeter missions to reveal characteristic effects of ~~the~~ their respective techniques and approaches to derive optimum results. Conventional altimeter systems usually use signals in Ku-band and have a beam limited footprint of 10 to 20 km. Over ice sheets their signals penetrate into the upper firn ~~layer, resulting in a return signal containing surface as well as volume scattering fractions~~layers. As an example for a conventional pulse limited radar we validate the Envisat mission, operated by the European Space Agency (ESA). We use the Ku-band measurements of its altimeter system RA-2 acquired during the entire operation period (May 2002 to April 2012). In the Level 2 product (SGDR V2.1) the slope induced error is corrected for using the relocation method (Bamber, 1994). This algorithm is designed to locate the measurement to the position where the first return signal comes from. The ESA dataset contains results from two types of ~~return~~ radar waveform retrackers applicable over ice sheets, ICE1 ~~(based on the Offset Centre Of Gravity (OCOG) retracker by Wingham et al., 1986)~~ (based on the Offset Centre Of G ICE2 (a functional fit developed by Legrésy et al., 2005). We use both retrackers ~~to~~ and compare their performance.

The Goddard Space Flight Center (GSFC) developed an ~~own~~ in-house processing chain for radar altimetry with slightly different approaches for ~~some steps in deriving the~~ deriving surface elevations. Here, the direct method of slope correction ~~is~~ was applied, which corrects the measurement ~~in the nadir~~ at the nadir position. This reprocessed Level 2 dataset is called Ice Data Record (IDR) and contains also different retrackers. We use the GSFC V4 β-retracker as Brenner et al. (2007) summarise that this algorithm provides more accurate absolute elevations than threshold based methods.

To remove potentially corrupted observations from the data, we used the *measurement confidence ~~flag~~flags* (which ~~is identical in ESA's~~ are identical in the ESA SGDR and GSFCs IDR datasets) to find recorded distances out of range and to identify problems ~~of~~ in the onboard processing and data handling, ~~of~~ the ultra stable oscillator, ~~of~~ the automatic gain control (AGC) or ~~of~~ in the waveform samples. In addition to these instrumental errors we removed shots where the GSFC retracking algorithm

failed as indicated by the *retracking problem flag*. In the SGDR data we furthermore used the ~~overall~~ *fault identifier* and the flag indicating that the ICE1 retracking in Ku-band was not successful.

3.1.2 CryoSat-2

Compared to the conventional SRA, ESA's CryoSat-2 has an improved resolution and accuracy due to its innovative design. In the smooth interior of the ice sheets the altimeter operates in the Low Resolution Mode (LRM) which is a conventional pulse limited observation mode as in the missions before. Above steeper terrain, the altimeter is switched to SARIn ~~Mode~~mode. In this mode, the Synthetic Aperture Radar (SAR) processing considerably improves the along track resolution utilizing the Doppler/delay shift. Hence, the beam limited footprint is subdivided in flight direction into stripes of ~~only~~ roughly 250 m in length. The interferometric processing of the reception times at the two antennas allows the determination of the ~~across track direction of~~ across-track angle to the point of closest approach (Wingham et al., 2006a).

We compare two different processing versions, Baseline B and C, of ESA's L2I dataset. The "I" in the product identifier stands for the In-depth dataset. It provides more parameters and flags and, over land, offers an additional feature relevant for our study. In the basic L2 product the *SARIn ambiguity flag* indicates an elevation difference between altimetry and a DEM exceeding 50 m. In this case the interferometric angle is considered as erroneous and the measurement position is set to nadir. In the L2I product, however, this is not applied. This product allows us, therefore, to validate the data also at the margins where the a priori DEM itself is prone to large uncertainties (see Sect. 4). As an alternative approach to identify outliers in the interferometric angle, we used the coherence flag and additionally excluded all measurements with a ~~cross-track direction~~ across-track angle exceeding 1° (corresponding to the very edge of the antenna beam). Furthermore, we exclude all data where the respective *retracker height error flag* indicates problems in the determination of the retracking point. For Baseline B, the waveform is processed using the CFI retracker (Wingham et al., 2006a). In Baseline C two additional retrackers have been applied on the LRM data: A threshold based OCOG-retracker and another functional fit retracker called UCL, which is based on the Brown-model (Brown, 1977).

3.1.3 ICESat

In contrast to radar altimeters, the ~~laser signal of the ICESat~~ ICESat laser altimeter mission has a ground footprint of only ~~65m~~ 65 m and does not penetrate into the snow pack. Hence, surface-elevation accuracies at the ~~decimeter~~ decimetre level can be achieved ~~(Schutz et al., 2005)~~ (Fricker et al., 2005; Shuman et al., 2006) which are almost comparable to our kinematic GNSS profiles. We use GLA12 elevation data from Release 34 (R34). We apply the saturation correction (Fricker et al., 2005) to the elevations and exclude all data where flags indicate off-nadir operation, orbit ~~maneuvers~~ manoeuvres or any other ~~degraded~~ factors degrading the orbit accuracy. We also remove data where the attitude flag indicates any problem with star trackers, gyro or the laser reference sensor. In order to exclude data affected by forward scattering in clouds or drifting snow (e.g. Siegfried et al., 2011), we reject all returns with a gain value exceeding 200, with a reflectivity below 10%, with a misfit between the received waveform and ~~a~~ the Gaussian model exceeding 0.03 V or ~~for which~~ where more than one waveform is detected (Bamber et al., 2009).

3.2 Methods

3.2.1 Crossover comparison

~~Our validation approach is the following: We assess how accurately the altimetry data reflects the actual surface elevation at the nominal positions of the altimetry data.~~

~~Our approach of referring the altimetry data to pointwise positions is a pragmatic choice. As a matter of fact, altimetry observes some average elevation over an extended footprint area. The footprint size amounts to tens of meters for ICESat, a few hundreds of meters for CryoSat-2 in SARIN mode, and a few kilometers for ENVISAT and CryoSat-2 in LRM mode. The LRM mode footprints additionally depend on surface roughness and on the applied retracker. The average altimeter footprint elevations will generally differ from the elevation at the nominal altimetry data position. For rugged terrain this discrepancy will be larger than for smooth terrain. Here we comprise this discrepancy under the altimetry error.~~

~~An alternative approach (not followed here) would be to observe, by kinematic GNSS, two-dimensional grids of the topography of the altimeter footprints. Then we could calculate a GNSS-based average footprint elevation and compare it to the altimetry data. This approach faces the theoretical problem of exactly defining what the altimeter footprint is. In other words, if we refrain from regarding altimetry as a pointwise measurement, we face the problem of exactly defining what altimetry ought to measure instead. The definition would need to be complicated. The alternative approach moreover faces the practical problem that the required two-dimensional observations are just not available along the 30,000 km of kinematic GNSS profiles.~~

We validate the surface elevation data derived from satellite altimetry by applying the crossover method, outlined in Sect. 2.4, to the intersections of the along-track altimetric profiles with our kinematic GNSS profiles. Therefore we interpolate the elevation of both profiles linearly if the distance between the two adjacent data points is less than 500 m. The along-track data point spacing amounts to 172 m for ICESat (Schutz et al., 2005), ~~250~~300 m for CryoSat-2 (Wingham et al., 2006a) and 400 m for Envisat (ESA, 2007). ~~Thus, in all cases the sampling interval exceeds by far that of the GNSS profiles. Because of the spatial averaging over the footprint area, the altimetry data represents smoothed profiles~~In fact, the altimetry measurements represent average elevations over the respective footprint area. As we did not measure 2D-grids but straight lines, this cannot be taken into account here. The smoothing of the ~~GNSS profiles (Sect. 2.3) allows thus for consistency in our comparison~~profiles with a filter length of 180 m, however, resembles the ICESat footprint at least in profile direction.

The largest error source for radar altimetry over a distinctive topography results from the slope correction. Brenner et al. (2007) found that crossover differences between ICESat and Envisat are less than 3 m for slopes below 0.1°, but up to 50 m and more for slopes above 0.7°. Hence, the validation of SRA needs to consider different surface slopes. Brenner et al. (2007) ~~or~~ and Helm et al. (2014) binned their elevation differences with ICESat with respect to the slope. The obtained quasi-continuous functions clearly depict the growing differences with increasing surface slope. The amount and spatial coverage of our crossovers does not allow a comparison in such a high sampling of slope. Instead, we investigate regions of different characteristic slope in separate histograms. This allows us not only to calculate a mean and standard deviation for each zone but also to identify

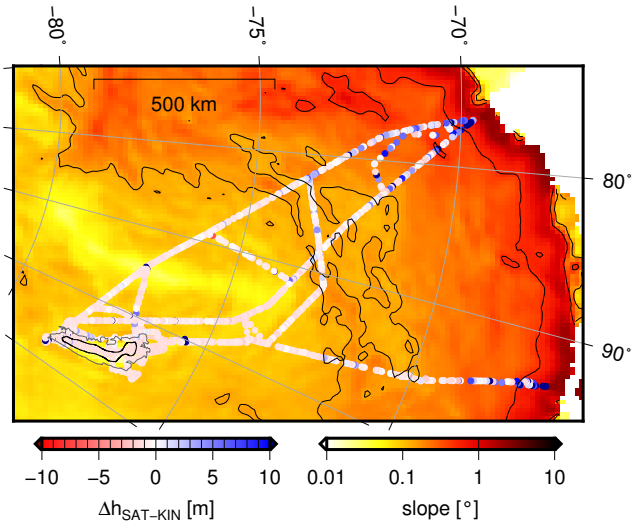

Figure 3. Crossover differences between Envisat (ESA, relocated, ICE1 retracker) and the kinematic GNSS profiles. The black contour lines mark the borders between the different zones of slope (0.15° and 0.5°) and the hydrostatic equilibrium area of Lake Vostok (outline in gray from Popov and Chernoglazov (2011)).

deviations from a Gaussian distribution. Those histograms display the full range of results including potential outliers. In order to reduce their impact, ~~however,~~ an iterative 5-σ filter is applied in the calculation of the mean and standard deviation.

We subdivide the region under investigation into four zones according to their mean surface slopes: >0.5°, 0.5 - 0.15°, <0.15° and, as a subset of the latter characterized by extremely little surface roughness, the hydrostatic equilibrium area of subglacial Lake Vostok. The ~~crossovers~~ crossover differences between Envisat data and the GNSS profiles (Fig. 3) clearly demonstrate the relationship between surface slope and SRA errors and motivates our subdivision. The first zone comprises the coastal areas. Outliers and large errors in the SRA elevations are frequent there due to the rugged topography. On the other hand, ~~in this zone typically~~ it is the zone where the largest elevation changes ~~can~~ would be expected. Hence, this zone introduces the largest uncertainties in ice-mass balance estimates based on SRA (Wingham et al., 2006b). The subsequent zone of intermediate slopes is still close to the coast and of low elevations. It may therefore also be subject to significant elevation changes. At the same time, SRA provides a ~~better~~ higher accuracy there compared to the first zone. The third zone comprises the flat interior of the ice sheet. ~~Elevation~~ Here, elevation changes are generally small ~~here~~ but, because of its vast areal extent, nevertheless important for mass balance studies. The ice above Lake Vostok, constituting ~~our~~ the fourth zone, floats in hydrostatic equilibrium (Ewert et al., 2012). Surface gradients are very small and homogeneous in this area. Thus, the influence of the slope induced error vanishes, offering a unique opportunity to study other effects such as the surface penetration of the radar signal.

3.2.2 ICESat campaign biases

Due to ~~the~~ its smaller footprint size, the ICESat surface elevations are less sensitive to surface slope ~~than~~ compared to SRA. However, the GLAS altimeter was operated in several laser operation campaigns due to laser degradation. Between the campaigns systematic biases exist (Fricker et al., 2005; Gunter et al., 2009). If not ~~corrected carefully, these biases~~ accounted for carefully, any systematic biases between campaigns can corrupt the inference of temporal surface-elevation changes ~~and estimates of~~ $\dot{h}$. To determine those biases, different ~~surfaces~~ surface types have been used, including the salt flat Salar de Uyuni (Fricker et al., 2005), the global oceans (Urban in Scambos and Shuman, 2016; Gunter et al., 2009), the ice surface above Lake Vostok (Ewert et al., 2012), the Antarctic low precipitation zone (Hofton et al., 2013; Gunter et al., 2014) or leads and polynyas in sea ice areas (Zwally et al., 2015). The estimated biases differ significantly between different data releases and, within the same release, depending on the surface type used for calibration.

Within the ~~shoreline of~~ region around subglacial Lake Vostok (Fig. 1b, 100–108.5 °E, 76–79 °S) Ewert et al. (2012) applied a least squares adjustment of crossover differences between elevation profiles of ascending and descending ICESat (I) ~~elevation profiles~~orbits, acquired during laser campaigns i and j (Δh_{ij}^{I-I}). To cope with the lack of an absolute reference, these authors introduced a zero-sum condition. As a consequence, the laser campaign biases were determined as relative biases, relating to their overall average. This method relies essentially on the assumption of a stable surface throughout the ICESat observation period. This assumption is justified by the observational results of Richter et al. (2008).

Using the same region of ice-surface ~~above~~ around Lake Vostok we derive a new set of laser campaign biases for release 34. In addition to the ICESat crossovers (I) used by Ewert et al. (2012) we ~~now~~ also include crossover differences between ICESat and our kinematic GNSS profiles (Δh_{iq}^{I-K}) and crossover differences between different GNSS profiles (Δh_{pq}^{K-K}). Including the unbiased GNSS profiles allows us to solve for the surface-elevation change rate $\dot{h}$ between the respective observation epochs t as an additional parameter and thus to overcome the assumption of a stable surface. ~~Instead, we~~ We are hence able to separate real elevation trends from the apparent trend implied by the laser campaign biases b. Furthermore, the incorporation of the unbiased GNSS ~~elevation profiles allows~~ elevations allows us to avoid the zero-sum condition and thus to determine absolute laser campaign biases. Combining all crossover differences results in three different types of observation equations:

$$\begin{aligned} \Delta h_{ij}^{I-I} &= b_i - b_j + \dot{h}\Delta t_{ij} + \epsilon \\ \Delta h_{iq}^{I-K} &= b_i + \dot{h}\Delta t_{iq} + \epsilon \\ \Delta h_{pq}^{K-K} &= + \dot{h}\Delta t_{pq} + \epsilon \end{aligned} \tag{4}$$

To account for the individual ~~accuracy~~ uncertainty of each GNSS profile, we introduce the epoch-wise surface elevation uncertainty RMS_S as weights for the elevations. As shown in Sect. 2.4 the empirical intra-expedition crossover differences RMS_X are about 5 cm larger. For this reason we add 5 cm to each RMS_S. For the ICESat elevations, ~~in contrast, we assume a homogeneous standard deviation of 10 cm~~we use campaign specific average $\overline{RMS_X}$ (Table 3), obtained from intra-campaign crossovers in the Lake Vostok region.

3.3 Results

3.3.1 Envisat

The validation of the Envisat data (Fig. 4) shows that in the flat interior all processing versions provide precise elevations. Nevertheless, the crossovers over Lake Vostok reveal significant differences between the three retracker versions. ~~With 51 and 44 cm the~~ The standard deviations of the two functional fit retrackers ~~(ICE2 and~~ yield similar results (51 cm for the β-retracker~~) yield similar results, while the precision of~~ , 44 cm for ICE2). In contrast, the precision or the ICE1-retracked data ~~with only 22 cm~~ is better by a factor of two (22 cm). This confirms the findings of Davis (1997)~~of a~~ , which argued for the superior precision of threshold retrackers. With respect to the kinematic GNSS profiles, the mean bias of all processing versions is negative. This can be explained by the penetration of the radar signal into the upper firn layers. However, significant differences between the retrackers are evident here~~too~~. Compared to the ICE1-retracker, the mean reference surface of the ICE2 functional fit is 90 cm lower. Thus the influence of variations in firn pack properties is much stronger ~~on~~ for this retracker. Between different datasets, a comparison of the biases of different retrackers should be treated with care. Here, elevation differences might also be caused by other ~~sources~~ factors as a different instrumental calibration value or alternative models for range correction.

Compared to Lake Vostok where the slope effect is negligible, significant differences can already be observed in the zone of least slopes (<0.15°). Even the smooth topography there introduces additional uncertainties of about 30 cm for the relocated ESA data and 1.5 m for the GSFC data corrected by the direct method. Furthermore, the mean biases are shifted in the positive direction. The histograms reveal that this is a consequence of a deviation from the Gaussian distribution of the crossovers. The increased amount of positive differences means that the GNSS-elevation is lower than the altimeter value. This is a consequence of the inability of the radar signal to observe depressions which are significantly smaller than the beam-limited footprint diameter (Brenner et al., 2007). For all versions, this effect increases progressively as the slope and hence also the magnitudes of the depressions gets ~~bigger~~larger. In the intermediate surface slope zone the standard deviations of the ESA datasets grow to 3 m and in the coastal zone up to 10 m. Here, the differences between the two ESA retrackers become negligible. For the GSFC product ~~those errors are even~~ these errors are significantly larger. ~~Thus~~Hence, our results support a clear preference for the relocation method. Nevertheless, in zones of larger slopes the error of the slope correction becomes the dominating uncertainty contribution.

To avoid loss of tracking, Envisat switched the tracking bandwidth from high resolution to two lower resolution modes when approaching steeper terrain. We analysed the performance of modes separately. Table 2 shows the results of each mode in the different zones. The number of crossovers indicates that the majority of data, even close to the coasts, was acquired in high resolution mode. In the central zone the accuracy of the lower resolution data is, as expected, worse. In the coastal zone, however, the other modes yield better results (if their small number of crossovers is considered as representative). The variations of the mean biases demonstrates in turn, that these mode switches induce offsets in the data. We agree therefore with Brenner et al. (2007) not to use the sparse data of the lower resolution modes for precise elevation change studies.

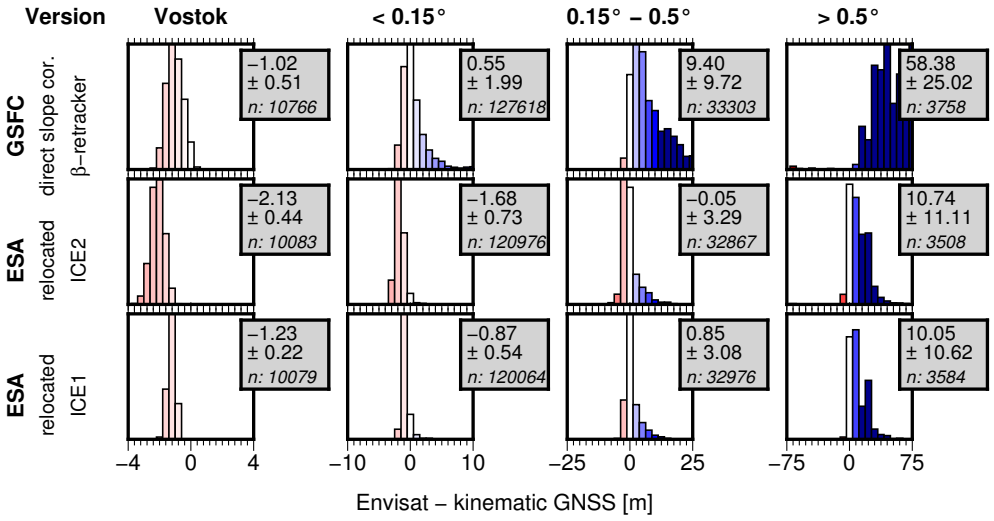

Figure 4. Histograms, means and standard deviations of crossover differences between different Envisat datasets and kinematic GNSS profiles for four zones of characteristic surface slope. The range of the histograms is adjusted according to the values found in each zone, the ~~color~~ colour scale is the same for all histograms. The displayed crossover differences contain uncertainties in the kinematic GNSS profiles (4 - 9 cm) and possible elevation changes between the observation epochs of both techniques in addition to the uncertainty in the Envisat data.

Table 2. Statistics of crossover differences between different Envisat resolution modes with kinematic GNSS profiles similar to Fig. 4. Outliers ($> 5\sigma_{\Delta h}$) are excluded iteratively. Each set of statistics contains $\overline{\Delta h} \pm \sigma_{\Delta h}$ and the number of valid crossovers (sums can differ from the total number due to outlier rejection). *Italic* values are considered to be not statistically significant.

Dataset	Vostok		< 0.15°		0.15° - 0.5°		> 0.5°	
	[m]	#n	[m]	#n	[m]	#n	[m]	#n
total (ESA, ICE1)	-1.25 ±0.22	10081	-0.89 ±0.54	120888	0.89 ±3.09	32524	9.62 ±10.61	3736
high res. (320MHz)	-1.25 ±0.22	10078	-0.89 ±0.54	120717	0.89 ±3.09	32470	9.89 ±10.62	3634
medium res. (80MHz)	*-0.86 ±0.22*	3	-0.62 ±1.01	136	1.29 ±3.33	48	-0.15 ±1.67	96
low res. (20MHz)	*2.20 ±0.12*	2	0.01 ±1.26	39	*-0.10 ±1.60*	6	*2.94 ±5.72*	6

3.3.2 CryoSat-2

The results of the validation of CryoSat-2 elevations are shown in Fig. 5. A comparison with those from Envisat (Fig. 4) clearly shows the advantage of the SARIn mode in zones of larger slopes. Furthermore, a comparison of the recent Baseline C version with the previous Baseline B documents the improvements made by solving several issues.

A primary issue solved from Baseline B to C was a range bias of 67 cm in SARIn and 20 cm in LRM data (Scagliola and Fornari, 2015). In the SARIn data this bias reduction is clearly visible in all zones. Besides that, no major changes are evident and also the standard deviations remain the same. Comparing the Baseline B LRM with the respective CFI-retracked version

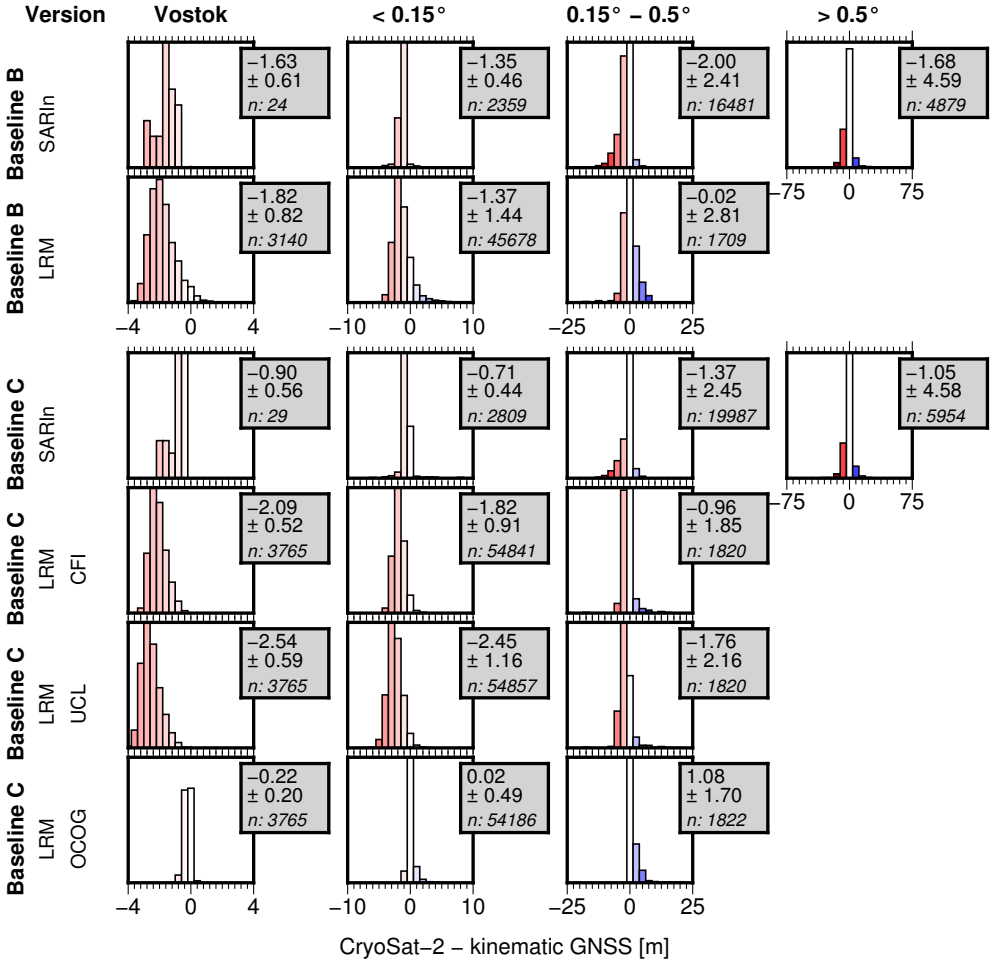

Figure 5. Histograms, means and standard deviations of crossover differences between different CryoSat-2 datasets and kinematic GNSS profiles for four zones of characteristic surface slope. The histogram ranges are the same as in Fig. 4 (Envisat) for comparability. The displayed crossover differences contain uncertainties in the kinematic GNSS profiles (4 - 9 cm) and possible elevation changes between the observation epochs of both techniques in addition to the uncertainty in the ~~Cryosat~~ CryoSat-2 data.

of Baseline C, we find a significant improvement in standard deviation. The refinements in the retracking procedure itself, described by Bouffard (2015), are probably responsible for those improvements. This holds especially true in the zones of stronger slopes where the retracking is more challenging. In the ~~practically~~ absence of slope related effects on Lake Vostok, the correction of the range bias is also evident in the LRM data.

The main improvement in performance of the Baseline C LRM data, ~~however,~~ has been introduced by adding two additional retrackers (UCL and OCOG). The OCOG retracker ~~reaches~~ shows standard deviations of about 20 cm over Lake Vostok, which is similar to the corresponding ICE1 retracker for Envisat. In contrast, the functional fit models show standard deviations of ~50 cm which is similar to the results of the ICE2 retracker of Envisat. For the entire low slope zone (<0.15°) we obtain similar

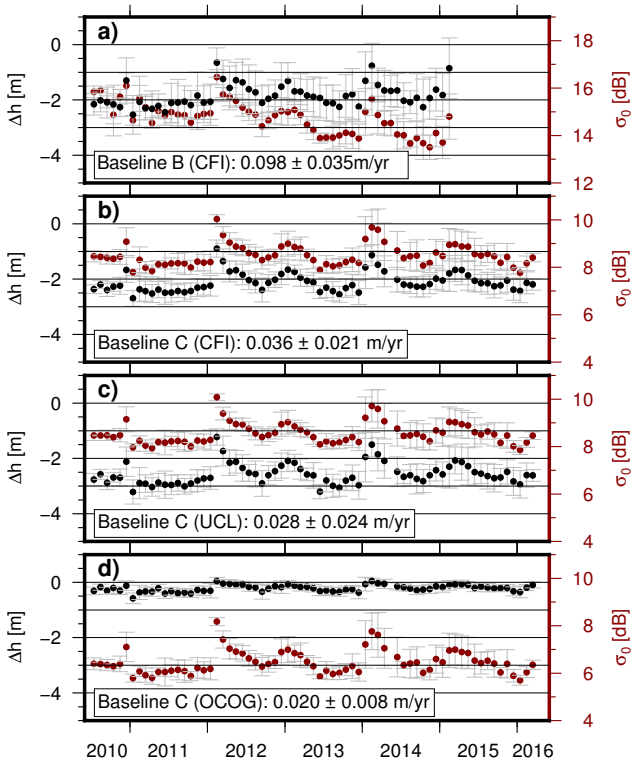

Figure 6. a-d) Monthly averages of crossover differences between different versions of CryoSat-2 data and kinematic GNSS profiles (black) and the corresponding backscatter σ_0 (red) within the hydrostatic equilibrium area of Lake Vostok. **a)** Baseline B dataset, **b-d)** Baseline C using the 3 different retrackers applied. The box at the bottom of each plot gives the overall elevation trend.

results when comparing ~~CryoSat~~ CryoSat-2 LRM to Envisat. In the intermediate zone (0.15°~~-0.5~~–0.5°) the two missions cannot be compared directly as the statistics for ~~CryoSat~~ CryoSat-2 only relate to the sub-zone where the LRM is applied, which covers only the gently sloping areas. It should be noted that even though SARIn mode is usually applied in coastal regions only, there is still some SARIn data available over Lake Vostok. On July 28th 2010 and the first week of June 2013 CryoSat-2 observed whole profiles across Antarctica in SARIn mode and ~~passed also~~ also passed our region under investigation (including Lake Vostok) several times. These profiles allow us to directly compare the different modes and in the case of Lake Vostok the performance of their retrackers. The first column of Fig. 5 shows that the accuracy of SARIn is quite similar to the CFI retracker in LRM.

Different ~~observation~~ observational techniques have substantiated the stability of the surface elevation above Lake Vostok over time scales of typical satellite altimeter mission life times (Richter et al., 2008, 2014a). This stability, together with the low precipitation and the continuous monitoring of relevant parameters at Vostok station, makes Lake Vostok an ideal area to examine apparent elevation variations in the altimetric time series. Spurious variations can be related to changes in surface backscatter and thus the backscattered power σ_0 of the altimetric signal (Wingham et al., 1998). Commonly, the relationship

is determined as a regression coefficient and its influence is removed from the elevation time series (Wingham et al., 1998; Davis and Ferguson, 2004; Zwally et al., 2015). Figure 6 displays monthly averages of the crossover differences between the kinematic GNSS profiles and different CryoSat-2 LRM datasets. The Baseline B product (panel a) yields a high correlation as well as trends of opposite sign in the elevations and the backscatter values. A trend derived from this elevation dataset suggests a surface increase of 9.8 cm/yr which clearly contradicts all results from other studies. For the three retrackers of the Baseline C product (Fig. 6 b-d) none of the backscatter curves shows a significant trend any more. Nevertheless, the retracking methods based on functional fits (CFI in b, UCL in c) still exhibit a high correlation between Δh and σ_0. Here, the retracking point is defined by the fit of the functional model to the whole waveform. Hence, it is more affected by volume scattering. In contrast the OCOG retracker uses a 25% threshold of the OCOG amplitude and thus locates the retracking point much closer to the first radar return. The results in Fig. 6 indicate that threshold retrackers (panel d) produce the most precise elevations, especially in terms of repeatability. This confirms similar findings by Davis (1997). The seasonal variation of the signal almost vanishes. However, there is still a very small remaining amplitude, which correlates quite well with σ_0. This indicates that there might still be some remaining effects of the snowpack properties superimposed on the elevation time series. Once the large variations disappeared, some jumps of a few ~~decimeters~~ decimetres are revealed. Apparent ~~height~~ elevation jumps in two winters (2011/2012 and 2013/2014) correspond to abrupt backscatter increase at the same time. Lacroix et al. (2009) detected a similar jump in Envisat data and referred it to changes in snow pack properties due to strong wind. However, the meteorological records from Vostok station (wind, precipitation, temperature; not shown here) do not show any significant peak at the times of the jumps. Inconsistencies in the applied correction models of the ionosphere, troposphere and tides can be ruled out as origin of these jumps. None of the time series of these features show variations exceeding a few ~~centimeters~~centimetres. Future studies including additional datasets will hopefully show whether these jumps are related to remaining processing issues or physical processes.

3.3.3 ICESat

Prior to the validation of ICESat elevation data, we first determine the ICESat laser campaign biases as described in Sect. 3.2.2. The resulting biases are given in Table 3. The simultaneously derived surface-elevation change rate $\dot{h}$ from Eq. (4) amounts to ~~0.1~~ 0.0 ± ~~0.1~~ 0.2 cm/yr. This is a new, independent evidence for the stability of the surface elevation above Lake Vostok. It confirms our results in Sect. 2.5 and those of previous studies (Richter et al., 2008, 2014a). It also justifies the assumption of a stable surface made by Ewert et al. (2012) ~~and Richter et al. (2014a)~~ as a precondition for the campaign bias determination. It is, therefore, not surprising that our biases are very similar to the ~~set presented by Richter et al. (2014a)~~ updated set of Ewert et al. (2012) for R33 including the Gaussian-Centroid (G-C) correction, presented by Richter et al. (2014a). The major difference is an offset of about 5 cm. This arises from the fact that in this study, we perform an absolute calibration.

The chronological sequence of the laser campaign biases implies a trend $\dot{h}_b$ which distorts any determination of surface-elevation rates if the biases are not applied. This trend over the entire ICESat operational period amounts to ~~1.08~~ 1.17 ± ~~0.35~~ 0.34 cm/yr. Table 4 and Fig. 7a compare the results of our new set of laser campaign biases with those of ~~different~~ recent publications. For consistency we limit this comparison to publications using either R33 data including G-C correction

Table 3. Intra-campaign RMS_X from crossovers within each ICESat laser campaign and biases (release 34) derived from a combined crossover adjustment of ICESat elevations and kinematic GNSS profiles ~~over~~ in the region of subglacial Lake Vostok (to be subtracted from the elevations for correction). The true surface elevation change $\dot{h}$, estimated simultaneously in Eq. (4) is 0.0 ± 0.2 cm.

Laser campaign	~~Δh~~ $\overline{RMS_X}$ [cm]	~~Laser~~ Δh ~~campaign~~ [cm]
L1A	~~1.8~~ 9.9	0.5 ± ~~0.8~~ 1.0
L2A	~~L3F~~ 7.0	~~3.7~~ 7.3 ± ~~0.6~~ 0.9
~~L2A~~ L2B	~~8.8~~ 6.7	3.6 ± ~~0.8~~ 0.9
L2C	~~L3G~~ 5.4	~~7.1~~ 8.9 ± ~~0.6~~ 0.8
~~L2B~~ L3A	~~4.9~~ 6.2	0.6 ± ~~0.7~~ 0.9
L3B	~~L3H~~ 7.1	~~4.6~~ 2.0 ± ~~0.5~~ 0.8
~~L2C~~ L3C	~~10.2~~ 4.8	1.6 ± 0.7
L3D	~~L3I~~ 4.9	~~4.6~~ 5.6 ± ~~0.5~~ 0.7
~~L3A~~ L3E	~~1.8~~ 5.5	3.9 ± ~~0.8~~ 0.7
L3F	~~L3J~~ 8.4	~~7.1~~ 2.7 ± ~~0.5~~ 0.6
~~L3B~~ L3G	~~3.2~~ 5.4	6.1 ± ~~0.7~~ 0.6
L3H	~~L3K~~ 5.7	~~8.2~~ 3.7 ± 0.6
~~L3C~~ L3I	~~2.7~~ 7.1	3.7 ± 0.6
L3J	~~L2D~~ 7.0	~~10.4~~ 6.2 ± ~~0.5~~ 0.6
~~L3D~~ L3K	~~6.6~~ 5.5	7.4 ± 0.6
L2D	~~L2E~~ 6.8	~~13.2~~ 9.6 ± ~~0.5~~ 0.6
~~L3E~~ L2E	~~4.9~~ 8.1	12.4 ± 0.6
L2F	~~10.5~~ 7.0	9.8 ± 0.6

or R34. Hofton et al. (2013) used an internal crossover adjustment over the low precipitation zone of the East Antarctic Ice Sheet (EAIS) as well as absolute calibration using an ICEBridge ~~lidar~~ Lidar profile along the maximum latitudinal extent of the ICESat mission (86°S). To account for any possible elevation changes, the authors apply corrections for glacial isostatic adjustment (GIA) and firn densification. It is interesting to note that in principle both sets of their biases are very similar to our results but ~~the artificial trends these biases imply~~ their artificial trends $\dot{h}_b$ are 0.2 ~~to –~~ 0.6 cm/yr larger than ~~our rates~~ ours (Fig. 7a, column ~~$\dot{h}$~~ $\dot{h}_b$ in Table 4). This might be due to some unmodeled effects in the firn densification model and/or GIA correction of Hofton et al. (2013). Nevertheless, both of their sets of laser campaign biases (obtained in different regions of Antarctica and with different methods) agree with our results within their stated accuracies.

In contrast, the trends obtained by Urban (in Scambos and Shuman, 2016) and Zwally et al. (2015) from calibrations over the ocean differ significantly from the results of calibrations over Antarctica. ~~Urban (in Scambos and Shuman, 2016), from a calibration over the global ocean, obtained significantly smaller biases.~~ Zwally et al. (2015) calculated offsets from open

Table 4. ~~Trends~~ Apparent trends $\dot{h}_b$ inferred from different sets of ICESat laser campaign biases weighted according to their standard deviation (if given). Results for Hofton (2013) differ from the originally given values as these authors applied unit weights. The trends in the second column have been calculated using only the laser campaigns Zwally et al. (2015) employed for their study.

set	~~$\dot{h}$~~ $\dot{h}_b$ [cm/yr]	~~$\dot{h}_{L2A-L2D}$~~ $\dot{h}_{b(L2A-L2D)}$ [cm/yr]
This study	~~1.08~~ 1.17 ± ~~0.35~~ 0.34	~~0.57~~ 0.68 ± 0.41
Richter (2014)	0.66 ± 0.45	0.33 ± 0.56
Hofton (2013) 86S	1.33 ± 0.36	1.11 ± 0.46
Hofton (2013) EAIS	1.72 ± 0.47	1.38 ± 0.53
Urban (2016)	0.01 ± 0.39	-0.44 ± 0.32
Zwally (2015)	-	-1.43 ± 0.44

water and thin ice in leads and polynyas in polar sea ice and used them to determine elevation changes over Antarctica. They obtain a $\dot{h}$ for Lake Vostok of 2.02 cm/yr. This contradicts the results of this study, but also those of two independent datasets in Richter et al. (2014a), i.e. static GNSS observations and kinematic GNSS profiles using snow mobiles (compare Richter et al., 2016). It is interesting to note, however, that the trends implied by our laser campaign biases and those of Zwally et al. (2015) differ by ~~2.00~~2.11 cm/yr. This explains the discrepancies of the elevation change rates obtained by Zwally et al. (2015) over Lake Vostok as a result of the applied set of laser campaign biases. The choice of these biases influences the derivation of elevation change rates from ICESat over the entire Antarctic ice sheet. Hence this also explains the disparity between their ICESat-derived mass budget and the mass-balance estimates of many other studies (e.g. Shepherd et al., 2012; McMillan et al., 2014; Martín-Español et al., 2016), especially in East Antarctica. Urban (in Scambos and Shuman, 2016) obtained significantly smaller biases. Here, the global ocean is used as a reference surface. They discuss that due to different sensor saturation those biases are not applicable over a high-albedo ice sheet surface.

After applying the laser campaign biases as corrections to the ICESat surface elevations we calculate the crossover differences with respect to the kinematic GNSS profiles. The results in Fig. 7b) show the very high accuracy of the ICESat data even in the coastal zone. The crossover differences in the less sloping regions indicate that both datasets have practically the same precision (compare Table 1). Here, the bias-corrections have only a minor influence on the standard deviations (e.g. 11.1 cm for the uncorrected, 10.7 cm for the corrected data over Lake Vostok) but become much more important when the temporal distribution of the data is analysed. Close to the coast we observe a small increase in standard deviation (approx. 30 cm for slopes exceeding 0.5°). This might be an effect of the increased surface roughness which affects the interpolation of the elevation to the crossover point. ~~Since we~~ A part of this increased noise could also be explained by topographic effects within the 65 m laser footprint.

To avoid the influence of surface elevation changes, previous studies as Siegfried et al. (2011) or Kohler et al. (2013) validated only laser campaigns in a very close temporal proximity (within some months) to their profiles. With a standard deviation of 10 – 20 cm in the majority of the area, we can confirm the results of Kohler et al. (2013). However, due to the different

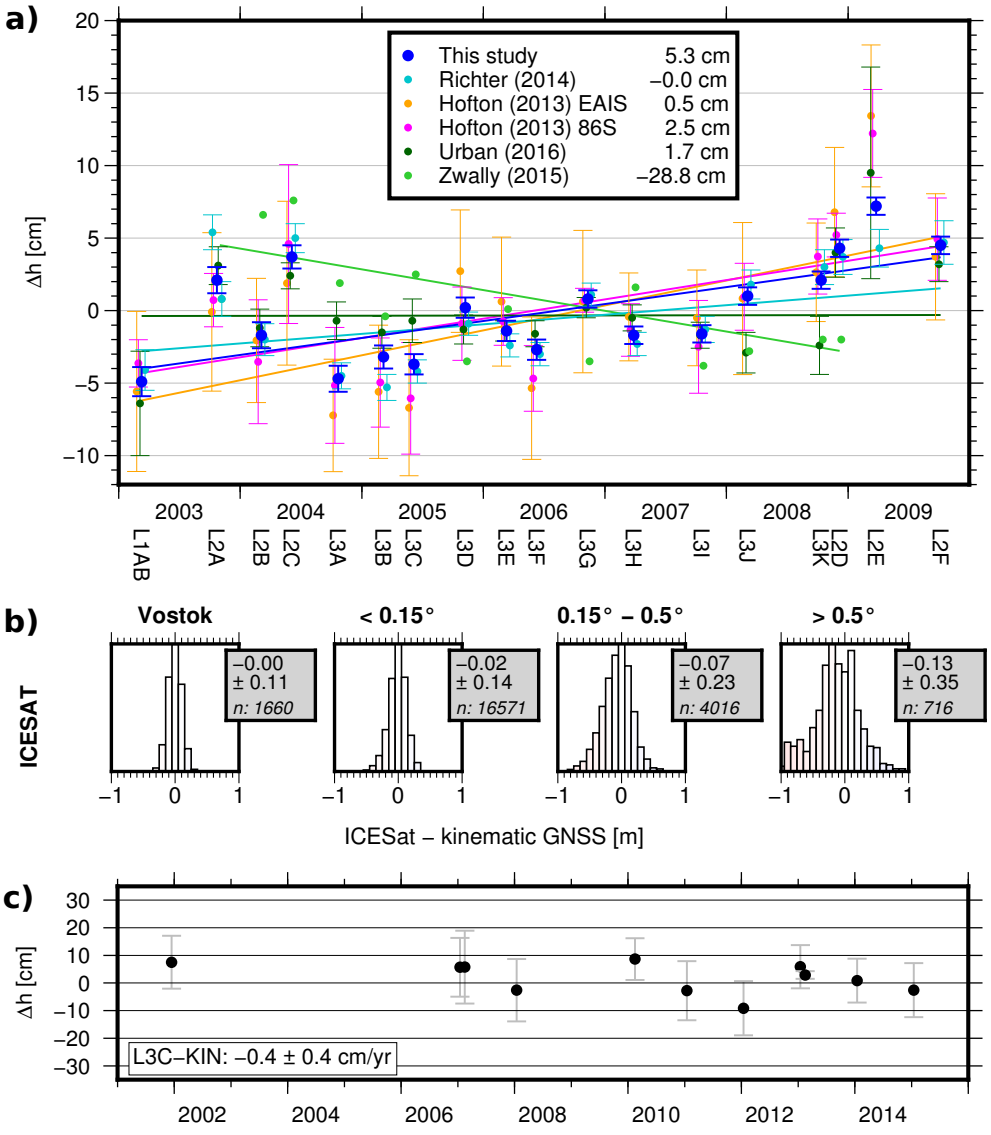

Figure 7. a) ICESat laser campaign biases (release 34) determined in the present study ~~over~~ in the Lake Vostok region (100–108.5 °E, 76–79 °S) from inter-campaign crossovers and from crossovers with kinematic GNSS profiles (in dark blue) compared to other recently published ~~bias~~ sets of biases and their trends. Error bars represent the standard deviation (if given) for the respective dataset. All bias sets have been reduced by their mean value, given in the legend. **b)** Histograms, means and standard deviations of crossover differences between ICESat and the kinematic GNSS profiles for four zones of characteristic surface slope. The range of the histograms is kept fixed to ±1 m. The displayed crossover differences contain uncertainties in the kinematic GNSS profiles (4 ~~–~~ 9 cm) and possible elevation changes between the observation epochs of both techniques in addition to the uncertainty in the ICESat data. **c)** Monthly averages of crossover differences between ICESat campaign L3C and the kinematic GNSS profiles in the region used for the bias determination.

ICESat release versions used, their mean offsets are not comparable to our results. Siegfried et al. (2011) use measurements on snowmobiles near Greenland summit for a similar validation. Their spread of ICESat - GPS differences is significantly lower than in our study. However, their assessment is limited to a single ICEsat repeat pass section of 6km length. In contrast to those studies, our profiles cover a much longer temporal range. This allows us to pinpoint the maximum range of elevation changes $\dot{h}$ in this area to very tight limits. Hence, we do not correct for ~~any~~ elevation changes in this comparison~~, these crossover differences also include any $\dot{h}$~~. Especially in the coastal zone, this could explain the increased offset as well as the larger noise of the crossovers. The obtained ~~small~~ offset and standard deviation, in turn, ~~constrains~~ constrain the magnitude of possible elevation changes in these zones ~~.~~ in addition th the results of Sect. 2.5.

A deeper view into the temporal variability of the crossover differences in the Lake Vostok region is given in Fig. 7c. To show the variability during the different GNSS seasons, we selected a single ICESat campaign (L3C, which has the highest precision RMS_X, see Tab. 3) as reference and analysed the spread of the crossovers over time. The monthly averages vary by less than 10 cm and within their standard deviations, nearly all of them can be considered to be zero. The spread of the values is very likely a result of the remaining uncertainties of the antenna height reduction in the GNSS profiles. Inter-annual variations in accumulation (Ekaykin et al., 2004, $\sigma < 5$ mm/yr) or a water discharge from Lake Vostok (Richter et al., 2014b) can be ruled out as possible causes. Due to the long temporal base, those datasets nevertheless allow to derive a precise trend $\dot{h}$. Being very close to zero (-0.4 $\pm$ 0.4 cm/yr), this again confirms the result of Sect. 2.5 and $\dot{h}$ during the bias estimation.

4 Validation of Digital Elevation Models

4.1 Data

Our kinematic GNSS profiles allow us to validate not only altimetric surface elevations but also derived products such as gridded digital elevation models (DEMs). These products are used in a wide range of applications in polar sciences. In some cases, as the topographic correction in repeat track analysis (Moholdt et al., 2010) or the estimation of drainage basins (Zwally et al., 2012), only the ~~accuracy~~ precision of elevation differences between ~~neighboring~~ neighbouring cells is important. Other applications, such as the derivation of ice thickness at the grounding line (Rignot et al., 2008) depend on the absolute accuracy.

We validate four DEMs of Antarctica derived from satellite altimetry. The 500 m resolution DEM from data of the ICESat mission by DiMarzio et al. (2007) (further called ICESat-DEM) was a milestone for many applications. Compared to previous, SRA-based DEMs, it provided a "greater latitudinal extent and fewer slope-related effects". Nevertheless, a weak spot was the coarse cross track spacing, especially for applications in coastal regions. The DEM provided by Bamber et al. (2009) (Bamber-DEM) overcame this problem by combining the high accuracy of ICESat with the high spatial resolution of ERS-1. The DEM produced by the ~~Bedmap 2~~ Bedmap2 project (Bedmap2-DEM) combined the Bamber-DEM with regional models in the margins, the ice shelves and the Antarctic Peninsula (Fretwell et al., 2013). To make the Bedmap2-DEM comparable, we converted the elevations from the GL04C geoid to ~~WGS84~~ the WGS-84 ellipsoid reference surface. Even though it should be identical to the Bamber-DEM for the major part of the region, we included this model to show the loss of accuracy by rounding ~~towards integer meters~~ the elevations towards integer metres as it has been done for Bedmap2.

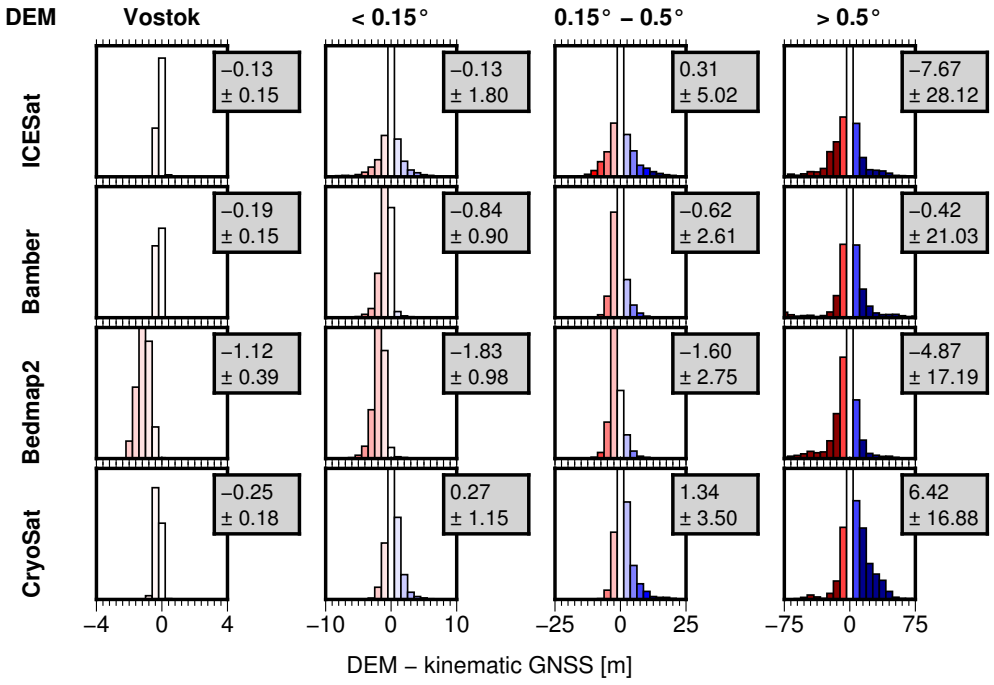

Figure 8. Histograms, means and standard deviations of differences between four different DEMs and kinematic GNSS profiles for four zones of characteristic surface slope.

In addition to these ICESat-dominated DEMs, Helm et al. (2014) compiled the first 3 years of the CryoSat-2 mission to a new DEM (CryoSat-DEM). With its improved design, the radar altimeter ~~aboard~~ of CryoSat-2 is capable to provide very precise ~~data~~ elevations in the margins. Furthermore, the high data density due to the orbit configuration allows to produce a very homogeneous dataset. There is almost no need to fill data gaps due to the very small across-track spacing.

4.2 Methods

By interpolating the DEM grid to the positions of the individual GNSS measurements using bicubic interpolation, we obtain an elevation difference for every single GNSS data location. Hence, the DEM validation relies on much more elevation differences than the validation of the altimetry profiles themselves, where the heights could only be compared at crossover locations.

To facilitate the comparison with the results from Sect. 3, we subdivide these elevation differences into the same zones as described in 3.2.1. In the validation of DEMs, special attention has to be paid to interpolation errors. The high resolution of 500 m of the ICESat-DEM seems reasonable when working with cells which contain measurements. However, no data exist within the almost 20 km gaps between the altimeter tracks. Thus, for a closer look into these interpolation errors, we examine the dependence of the elevation differences from the distance to the nearest track.

4.3 Results

The results of the validation (Fig. 8) of the ICESat-DEM shows that over Lake Vostok the accuracy is close to that of the original ICESat elevations. This indicates that in this case of exceptionally smooth topography the interpolation error is negligible. However, with increasing slope the standard deviation of this DEM grows fast due to the scarce across-track spacing of the altimetric profiles. In the Bamber-DEM, the inclusion of the additional ERS-1 data reduces this interpolation error between the ICESat tracks by 50% in terms of standard deviation. In the coastal zone, the gain in accuracy is minor as the precision of the radar altimetry data deteriorates.

The comparison of the Bedmap2-DEM with the Bamber-DEM reveals remarkable differences. Firstly, the rounding to integer elevations in Bedmap2 increases the standard deviation by several ~~decimeters~~decimetres. Secondly, a constant offset of -1 m becomes evident in the Bedmap2 dataset. This seems to be an issue in the compilation procedure as the original Bamber-DEM shows a good agreement in terms of mean difference with our GNSS profiles in all regions. Finally, in the coastal zone the two models behave differently. In Bedmap2 regional elevation models have been included here, but the sparse sampling of these areas by our profiles (see Fig. 3) does not allow a ~~reliable~~ representative evaluation.

The comparison of the CryoSat-DEM with the ICESat-based models proves that SRA with the advanced instrument design is able to provide accurate elevation information even in steep topography too. As for the CryoSat-2 altimetry data, a slope dependent offset is observed which presumably results from the systematic under-representation of local depressions.

In order to shed light on the relation of the DEM accuracy with the surface slope, the median absolute deviations (DEM vs. kinematic GNSS) are binned in 0.1 ° slope intervals (Fig. 9). The medians of the entire set of deviations (thick black lines) reveal a significant increase with the slope. Splitting the deviations into subsets according to the distance to the nearest ICESat track the impact of the interpolation error on a particular DEM becomes evident (panels a, b). It demonstrates the much greater dependence of the ICESat-DEM on the across-track distance compared to the Bamber-DEM. While the ICESat-DEM yields superior accuracy close to the tracks (i.e. distances < 1 km) due to its small grid interval (500 m), its median deviations exceed 10 m at large slopes (> 0.5°) and distances (> 6 km).

The dense spatial sampling of the CryoSat-2 altimetry data usually yields observed elevations for each cell of the CryoSat-DEM. According to the histograms obtained for the four zones, the slightly larger deviations of this DEM compared to the other models are mainly due to the slope dependent offset. ~~The authors of this DEM~~ Helm et al. (2014) provide an error map based on a validation with ICESat and airborne elevation data. These uncertainties are shown in Fig. 9c as a function of slope. Their good agreement with our results confirms them as realistic.

~~Median of absolute differences between various DEMs and the kinematic GNSS profiles binned by surface slope (thick black line). **a+b)** Additionally for DEMs based on ICESat - colored lines show the differences for several ranges of distances to the laser altimeter tracks (color coded). **c)** For the CryoSat-DEM the turquoise line shows the estimated error given by the uncertainty map which comes with the DEM.~~

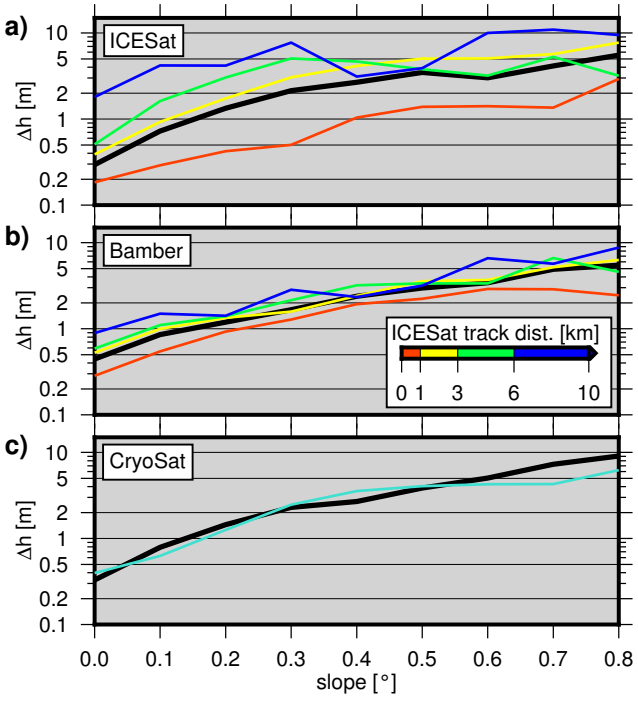

Figure 9. Median of absolute differences between various DEMs and the kinematic GNSS profiles binned by surface slope (thick black line). **a+b)** Additionally for DEMs based on ICESat - coloured lines show the differences for several ranges of distances to the laser altimeter tracks (colour coded). **c)** For the CryoSat-DEM the turquoise line shows the estimated error given by the uncertainty map which comes with the DEM.

5 Conclusions

Between 2001 and 2015 we logged kinematic GNSS data along nine scientific ~~traverses~~ convoys and derived more than 30 000 km of surface-elevation profiles. We resolved the challenges of the GNSS processing, such as the very long baselines and peculiar vehicle dynamics in soft snow. Our elevation profiles have accuracies between 4 and 9 cm for a single data point. Over Lake Vostok crossover differences yield a mean elevation change rate of 0.3 ± 0.5 cm/yr. This confirms the results of Richter et al. (2014a) and qualifies this area as a calibration site for satellite altimetry.

A crossover analysis with three different Envisat elevation datasets reveals the impact of different processing strategies in satellite radar altimetry. Concerning the slope correction the relocation method is clearly superior to the direct method reducing elevation errors by about 66% in terms of standard deviation. Threshold retrackers (ICE1/OCOG) outperform functional fit retrackers by up to 50% in standard deviation. A similar analysis with CryoSat-2 LRM mode data confirms this finding. Hence, we recommend threshold retrackers for the determination of elevation time series because of its significant suppression of the snowpack related pseudo elevation variations.

ICESat elevation data and our kinematic GNSS profiles are comparable in their accuracy, even close to the coast. This comparison ~~constrains also~~ also constrains the magnitude of temporal elevation changes. A combined crossover adjustment above Lake Vostok yields a new set of ICESat laser campaign biases that no longer depends on an a-priori assumption of a stable surface elevation. The here obtained surface-elevation change rate of ~~0.1~~ 0.0 ± ~~0.1~~ 0.2 cm/yr proves nevertheless that this assumption is correct to a very high level of certainty. The correction of ICESat elevation data for the laser campaign biases is crucial for estimates of surface elevation change rates and the according mass balance. These biases are the main cause for the discrepancies between the ICESat-derived mass balances of Zwally et al. (2015) and those of other recent studies (see also Scambos and Shuman, 2016).

The validation of four digital elevation models demonstrates the reduction of interpolation errors achieved by Bamber et al. (2009) by complementing ICESat elevations with radar altimetry data. The advanced instrument design and high spatial resolution of CryoSat-2 ~~permits now also~~ now permits radar altimetry to provide DEMs (Helm et al., 2014) of similar accuracy avoiding extensive interpolation.

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References

Arthern, R., Wingham, D., and Ridout, A.: Controls on ERS altimeter measurements over ice sheets: Footprint-scale topography, backscatter fluctuations, and the dependence of microwave penetration depth on satellite orientation, Journal of Geophysical Research – Atmospheres, 106, 33 471–33 484, 2001.

Bamber, J.: Ice Sheet Altimeter Processing Scheme, Int. J. Remote Sensing, 14, 925–938, 1994.

Bamber, J., Gomez-Dans, J., and Griggs, J.: A new 1 km digital elevation model of the Antarctic derived from combined satellite radar and laser data – Part 1: Data and methods, The Cryosphere, 3, 101–111, doi:10.5194/tc-3-101-2009, 2009.

Bouffard, J.: Level 2 product evolutions and quality improvements in Baseline C, Tech. rep., 2015.

Brenner, A., Bindschadler, R., Zwally, H., and Thomas, R.: Slope-induced errors in radar altimetry over continental ice sheets, J. Geophys. Res., 88, 1617–1623, doi:10.1029/JC088iC03p01617, 1983.

Brenner, A., DiMarzio, J., and Zwally, H.: Precision and Accuracy of Satellite Radar and Laser Altimeter Data Over the Continental Ice Sheets, IEEE Trans. Geosci. Remote Sens., 45, 321–331, doi:10.1109/TGRS.2006.887172, 2007.

Brown, G.: The average impulse response of a rough surface and its applications, IEEE Transactions on Antennas and Propagation, 25, 67–74, doi:10.1109/TAP.1977.1141536, 1977.

Brunt, K., Hawley, R., Lutz, E., Studinger, M., Sonntag, J., Hofton, M., Andrews, L., and Neumann, T.: Assessment of NASA airborne laser altimetry data using ground-based GPS data near Summit Station, Greenland, The Cryosphere, 11, 681–692, doi:10.5194/tc-11-681-2017, 2017.

Cerri, L., Couhert, A., Houry, S., and Mercier, F.: Improving the long-term stability of the GDR orbit solutions , OSTST Meeting 19-21 Oct. 2011, San Diego (CA) , http://earth.eo.esa.int/pcs/envisat/ra2/articles/Ollivier_OSTST2011_GDR-D_presentation.pdf, 2011.

Dach, R., Lutz, S., Walser, P., and Fridez, P., eds.: Bernese GNSS Software Version 5.2, Astronomical Institute, University of Bern, Bern Open Publishing, Bern, doi:10.7892/boris.72297, 2015.

Davis, C.: A robust threshold retracking algorithm for measuring ice-sheet surface elevation change from satellite radar altimeters, Geoscience and Remote Sensing, IEEE Transactions on, 35, 974–979, doi:10.1109/36.602540, 1997.

Davis, C. and Ferguson, A.: Elevation change of the Antarctic ice sheet, 1995-2000, from ERS-2 satellite radar altimetry, IEEE Trans. Geosci. Remote Sens., 42, 2437–2445, doi:10.1109/TGRS.2004.836789, 2004.

DiMarzio, J., Brenner, A., Schutz, B., Shuman, C., and Zwally, H.: GLAS/ICESat 500 m Laser Altimetry Digital Elevation Model of Antarctica, Version 1, National Snow and Ice Data Center, Boulder, Colorado USA, doi:http://dx.doi.org/10.5067/K2IMI0L24BRJ, 2007.

Ekaykin, A., Lipenkov, V., Kuzmina, I., Petit, J., Masson-Delmotte, V., and Johnsen, S.: The changes in isotope composition and accumulation of snow at Vostok station, East Antarctica, over the past 200 years, Ann. Glac., 39, 569–575, 2004.

Ekaykin, A., Vladimirova, D., Lipenkov, V., and Masson-Delmotte, V.: Climatic variability in Princess Elizabeth Land (East Antarctica) over the last 350 years, Climate of the Past, 13, 61–71, doi:10.5194/cp-13-61-2017, 2017.

ESA: ENVISAT RA2/MWR Product Handbook, 2007.

Ewert, H., Popov, S., Richter, A., Schwabe, J., Scheinert, M., and Dietrich, R.: Precise analysis of ICESat altimetry data and assessment of the hydrostatic equilibrium for subglacial Lake Vostok, East Antarctica, Geophys. J. Int., 191, 557–568, doi:10.1111/j.1365-246X.2012.05649.x, 2012.

Flament, T. and Rémy, F.: Antarctica volume change from 10 years of Envisat altimetry, in: Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International, pp. 1848–1851, doi:10.1109/IGARSS.2012.6351149, 2012.

Fretwell, P., Pritchard, H., Vaughan, D., Bamber, J., Barrand, N., Bell, R., Bianchi, C., Bingham, R., Blankenship, D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A., Corr, H., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J., Hindmarsh, R., Holmlund, P., Holt, J., Jacobel, R., Jenkins, A., Jokat, W., Jordan, T., King, E., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K., Leitchenkov, G., Leuschen, C., Luyendyk, B., Matsuoka, K., Mouginot, J., Nitsche, F., Nogi, Y., Nost, O., Popov, S., Rignot, E., Rippin, D., Rivera, A., Roberts, J., Ross, N., Siegert, M., Smith, A., Steinhage, D., Studinger, M., Sun, B., Tinto, B., Welch, B., Wilson, D., Young, D., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7, 375–393, doi:10.5194/tc-7-375-2013, 2013.

Fricker, H., Borsa, A., Minster, B., Carabajal, C., Quinn, K., and Bills, B.: Assessment of ICESat performance at the salar de Uyuni, Bolivia, Geophys. Res. Lett., 32, L21S06, doi:10.1029/2005GL023423, 2005.

Fritsche, M., Sośnica, K., Rodríguez-Solano, C., Steigenberger, P., Wang, K., Dietrich, R., Dach, R., Hugentobler, U., and Rothacher, M.: Homogeneous reprocessing of GPS, GLONASS and SLR observations, J. Geod., 88, 625–642, doi:10.1007/s00190-014-0710-3, 2014.

Geng, J., Teferle, F., Meng, X., and Dodson, A.: Kinematic precise point positioning at remote marine platforms, GPS Solut., 14, 343–350, doi:10.1007/s10291-009-0157-9, 2010.

Groh, A., Ewert, H., Rosenau, R., Fagiolini, E., Gruber, C., Floricioiu, D., Abdel Jaber, W., Linow, S., Flechtner, F., Eineder, M., Dierking, W., and Dietrich, R.: Mass, volume and velocity of the Antarctic Ice Sheet: present-day changes and error effects, Surv. Geophys., 35, 1481–1505, doi:10.1007/s10712-014-9286-y, 2014.

Gunter, B., Urban, T., Riva, R., Helsen, M., Harpold, R., Poole, S., Nagel, P., Schutz, B., and Tapley, B.: A comparison of coincident GRACE and ICESat data over Antarctica, J. Geod., 83, 1051–1060, doi:10.1007/s00190-009-0323-4, 2009.

Gunter, B., Didova, O., Riva, R., Ligtenberg, S., Lenaerts, J., King, M., van den Broeke, M., and Urban, T.: Empirical estimation of present-day Antarctic glacial isostatic adjustment and ice mass change, The Cryosphere, 8, 743–760, doi:10.5194/tc-8-743-2014, 2014.

Helm, V., Humbert, A., and Miller, H.: Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2, The Cryosphere, 8, 1539–1559, doi:10.5194/tc-8-1539-2014, 2014.

Hofton, M., Luthcke, S., and Blair, J.: Estimation of ICESat intercampaign elevation biases from comparison of lidar data in East Antarctica: Estimating ICESat elevation biases, Geophys. Res. Lett., 40, 5698–5703, doi:10.1002/2013GL057652, 2013.

King, M., Coleman, R., Freemantle, A.-J., Fricker, H., Hurd, R., Legrésy, B., Padman, L., and Warner, R.: A 4-decade record of elevation change of the Amery Ice Shelf, East Antarctica, J. Geophys. Res., 114, F01 010, doi:10.1029/2008JF001094, 2009.

Kohler, J., Neumann, T., Robbins, J., Tronstad, S., and Melland, G.: ICESat Elevations in Antarctica Along the 2007–09 Norway-USA Traverse: Validation With Ground-Based GPS, IEEE Trans. Geosci. Remote Sens., 51, 1578–1587, doi:10.1109/TGRS.2012.2207963, 2013.

Lacroix, P., Legrésy, B., Rémy, F., Blarel, F., Picard, G., and Brucker, L.: Rapid change of snow surface properties at Vostok, East Antarctica, revealed by altimetry and radiometry, Remote Sens. Environ., 113, 2633–2641, doi:10.1016/j.rse.2009.07.019, 2009.

Legrésy, B., Papa, F., Rémy, F., Vinay, G., van den Bosch, M., and Zanife, O.-Z.: ENVISAT radar altimeter measurements over continental surfaces and ice caps using the ICE-2 retracking algorithm, Remote Sens. Environ., 85, 150–163, doi:10.1016/j.rse.2004.11.018, 2005.

Luthcke, S., Rowlands, D., Williams, T., and Sirota, M.: Reduction of ICESat systematic geolocation errors and the impact on ice sheet elevation change detection, Geophys. Res. Lett., 32, L21S05, doi:10.1029/2005GL023689, 2005.

Martín-Español, A., Zammit-Mangion, A., Clarke, P., Flament, T., Helm, V., King, M., Luthcke, S., Petrie, E., Rémy, F., Schön, N., Wouters, B., and Bamber, J.: Spatial and temporal Antarctic Ice Sheet mass trends, glacio-isostatic adjustment and surface processes from a joint inversion of satellite altimeter, gravity and GPS data, J. Geophys. Res. Earth Surf., 121, 182–200, doi:10.1002/2015JF003550, 2016.

Masolov, V., Lukin, V., Sheremetiev, A., and Popov, S.: Geophysical Investigations of the Subglacial Lake Vostok in Eastern Antarctica, Doklady Earth Sciences, 379A, 734–738, 2001.

McCarthy, D. and Petit, G., eds.: IERS Conventions (2003), vol. 32 of *IERS Technical Note*, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, 2004.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A., and Wingham, D.: Increased ice losses from Antarctica detected by CryoSat-2, Geophys. Res. Lett., 41, 3899–3905, doi:10.1002/2014GL060111, 2014.

Moholdt, G., Nuth, C., Hagen, J., and Kohler, J.: Recent elevation changes of Svalbard glaciers derived from ICESat laser altimetry, Remote Sens. Environ., 114, 2756–2767, doi:10.1016/j.rse.2010.06.008, 2010.

Petit, G. and Luzum, B., eds.: IERS Conventions (2010), vol. 36 of *IERS Technical Note*, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany, 2010.

Popov, S.: Recent Russian remote sensing investigations in Antarctica within the framework of scientific traverses, Advances in Polar Sciences, 26, 113–121, 2015.

Popov, S. and Chernoglazov, Y.: Podlednikovoe ozero Vostok, Vostochnaya Antarktida: beregovaya liniya i okruzhayushchie vodoemy [Vostok Subglacial Lake, East Antarctica: lake shoreline and subglacial water caves], Ice and Snow, N1(113), 12–24, 2011.

Rebischung, P., Griffiths, J., Ray, J., Schmid, R., Collilieux, X., and Garayt, B.: IGS08: the IGS realization of ITRF2008, GPS Solut., 16, 483–494, doi:10.1007/s10291-011-0248-2, 2012.

Richter, A., Popov, S., Dietrich, R., Lukin, V., Fritsche, M., Lipenkov, V., Matveev, A., Wendt, J., Yuskevich, A., and Masolov, V.: Observational evidence on the stability of the hydro-glaciological regime of subglacial Lake Vostok, Geophys. Res. Lett., 35, L11 502, doi:10.1029/2008GL033397, 2008.

Richter, A., Fedorov, D., Fritsche, M., Popov, S., Lipenkov, V., Ekaykin, A., Lukin, V., Matveev, A., Grebnev, V., Rosenau, R., and Dietrich, R.: Ice flow velocities over Vostok Subglacial Lake, East Antarctica, determined by 10 years of GNSS observations, J. Glac., 59, 315–326, doi:10.3189/2013JoG12J056, 2013.

Richter, A., Popov, S., Fritsche, M., Lukin, V., Matveev, A., Ekaykin, A., Lipenkov, V., Fedorov, D., Eberlein, L., Schröder, L., Ewert, H., Horwath, M., and Dietrich, R.: Height changes over subglacial Lake Vostok, East Antarctica: Insights from GNSS observations, J. Geophys. Res. Earth Surf., 119, 2460–2480, doi:10.1002/2014JF003228, 2014a.

Richter, A., Popov, S., Schröder, L., Schwabe, J., Ewert, H., Scheinert, M., Horwath, M., and Dietrich, R.: Subglacial Lake Vostok not expected to discharge water, Geophys. Res. Lett., 41, 6772–6778, doi:10.1002/2014GL061433, 2014b.

Richter, A., Horwath, M., and Dietrich, R.: Comment on Zwally and others (2015)-Mass gains of the Antarctic ice sheet exceed losses, J. Glac., pp. 1–3, doi:10.1017/jog.2016.60, 2016.

Ridley, J. and Partington, K.: A model of satellite radar altimeter return from ice sheets, Int. J. Remote Sensing, 9, 601–624, doi:10.1080/01431168808954881, 1988.

Rignot, E., Bamber, J., van den Broeke, M., Davis, C., Li, Y., van de Berg, W., and van Meijgaard, E.: Recent Antarctic ice mass loss from radar interferometry and regional climate modelling, Nature Geosci., 1, 106–110, doi:10.1038/ngeo102, 2008.

Roemer, S., Legrésy, B., Horwath, M., and Dietrich, R.: Refined analysis of radar altimetry data applied to the region of the subglacial Lake Vostok / Antarctica, Remote Sens. Environ., 106, 269–284, doi:10.1016/j.rse.2006.02.026, 2007.

Scagliola, M. and Fornari, M.: Main evolutions and expected quality improvements in BaselineC Level1b products, Tech. rep., 2015.

Scambos, T. and Shuman, C.: Comment on 'Mass gains of the Antarctic ice sheet exceed losses' by H. J. Zwally and others, J. Glac., pp. 1–5, doi:10.1017/jog.2016.59, 2016.

Schrama, E., Naeije, M., Yi, Y., Visser, P., and C., S.: CryoSat-2 Precise Orbit Determination and Indirect Calibration of SIRAL – End of Commissioning Phase Report, ESA contract report, TU Delft, http://deos.tudelft.nl/AS/ejo/ejo/text/cs2_cpr_main.pdf, 2010.

Schutz, B. and Urban, T.: The GLAS Algorithm Theoretical Basis Document for Laser Footprint Location (Geolocation) and Surface Profiles, Tech. rep., NASA GSFC, Greenbelt, Maryland, USA, ftp://sidads.colorado.edu/pub/DATASETS/nsidc0587_ICESAT_GLAS_LTA/Section3_Product_Documentation/ICESat_LTA_ATBDs, 2014.

Schutz, B., Zwally, H., Shuman, C., Hancock, D., and DiMarzio, J.: Overview of the ICESat Mission, Geophys. Res. Lett., 32, L21S01, doi:10.1029/2005GL024009, 2005.

Shepherd, A., Ivins, E., A, G., Barletta, V., Bentley, M., Bettadpur, S., Briggs, K., Bromwich, D., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M., Lenaerts, J., Li, J., Ligtenberg, S., Luckman, A., Luthcke, S., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J., Paden, J., Payne, A., Pritchard, H., Rignot, E., Rott, H., Sorensen, L., Scambos, T., Scheuchl, B., Schrama, E., Smith, B., Sundal, A., van Angelen, J., van de Berg, W., van den Broeke, M., Vaughan, D., Velicogna, I., Wahr, J., Whitehouse, P., Wingham, D., Yi, D., Young, D., and Zwally, H.: A Reconciled Estimate of Ice-Sheet Mass Balance, Science, 338, 1183–1189, doi:10.1126/science.1228102, 2012.

Shuman, C., Zwally, H., Schutz, B., Brenner, A., DiMarzio, J., Suchdeo, V., and Fricker, H.: ICESat Antarctic elevation data: Preliminary precision and accuracy assessment, Geophys. Res. Lett., 33, L07 501, doi:10.1029/2005GL025227, 2006.

Siegfried, M., Hawley, R., and Burkhart, J.: High-Resolution Ground-Based GPS Measurements Show Intercampaign Bias in ICESat Elevation Data Near Summit, Greenland, Geoscience and Remote Sensing, IEEE Transactions on, 49, 3393–3400, doi:10.1109/TGRS.2011.2127483, 2011.

Studinger, M.: IceBridge ATM L2 Icessn Elevation, Slope, and Roughness, Version 2. Updated 2016 [2013.11.26]., Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center, doi:10.5067/CPRXXK3F39RV, [date accessed: 2014-06-27], 2014.

Wanninger, L.: Interpolation von GPS-Beobachtungen, Allg. Vermnachr., 107, 360–363, heft 10/2000, 2000.

Wingham, D., Rapley, C., and Griffiths, H.: New techniques in satellite altimeter tracking systems, in: ESA Proceedings of the 1986 International Geoscience and Remote Sensing Symposium(IGARSS'86) on Remote Sensing: Today's Solutions for Tomorrow's Information Needs,, vol. 3, pp. 1339–1344, 1986.

Wingham, D., Ridout, A., Scharroo, R., Arthern, R., and Shum, C.: Antarctic Elevation Change from 1992 to 1996, Science, 282, 1998.

Wingham, D., Francis, C., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., Chateau-Thierry, P. d., Laxon, S., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P., and Wallis, D.: CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields, Adv. Space Res., 37, 841–871, doi:10.1016/j.asr.2005.07.027, 2006a.

Wingham, D., Shepherd, A., Muir, A., and Marshall, G.: Mass balance of the Antarctic ice sheet, Phil. Trans. R. Soc. Lond. A, 364, 1627–1635, doi:10.1098/rsta.2006.1792, 2006b.

Zwally, H., Giovinetto, M., Beckley, M., and Saba, J.: Antarctic and Greenland Drainage Systems, 2012.

Zwally, H., Li, J., Robbins, J., Saba, J., Yi, D., and Brenner, A.: Mass gains of the Antarctic ice sheet exceed losses, J. Glac., 61, 1019–1936, 2015.