Response to Anonymous Referee #2:

We thank this anonymous reviewer for their constructive comments. Edits based on your input (and that of the first reviewer) have substantially improved this manuscript.

Here are our responses (in red) to your specific comments (in black):

This is a short and concise paper on the quality of airborne laser altimetry data over a flat ice sheet surface. The authors calculate error statistics from comparisons with near-coincident surface GPS profiling near the Greenland Summit Station. Considering how often these data are used in ice-sheet change assessments, and how accurate they need to be to detect cm-level elevation changes, I think it is a timely and highly appreciated contribution to the community. It also paves the way for using designated airborne surveys to validate satellite altimetry data, in particular the upcoming ICESat-2 mission.

I have only some smaller comments and questions as given in chronological order below. They all refer to line numbers in the discussion paper, but some are of more general character and could warrant changes also elsewhere in the manuscript.

P1, L21: I think it's worth to mention that you get equally good correspondence with DGPS and PPP techniques. The latter could simplify fieldwork for many applications.
We were pleasantly surprised by that result, with respect to this application. We have added text to the abstract ("*Ground-based GPS positions determined both with and without differential post-processing techniques provided consistent solutions.*").

P2, L7: I would also cite Borsa et al. (2014, The Cryosphere) here since the other papers are prior to that do not all account for the Gaussian-Centroid bias.
Excellent point; we have added this to the manuscript.

P2, L18: I don't think airplanes can really bridge the gap between satellite missions at the scale of ice sheets, so I would add "…in areas of special interest" or something like that.
Agreed. We have modified the text to capture your comment, while still acknowledging the OIB mission: '*… 1) "bridging the data gap" between the satellite missions, with a focus on areas of significant change and interest.*'

P2, L31: Write out GEDI.
Thanks for catching this; we have added the full name.

P4, L20: I don't see the need for this abbreviation since it is only used a few times.
This acronym does show up 2 other times in the text and multiple times in Table 1. So we are inclined to keep it. Further, other publications associated with NASA altimetry (especially when the altimeter is integrated with the ER-2) use ASL, and thus our explicit use of AGL in this manuscript is for clarity.

P5, L1: The software incorporates GLONASS, but does any of the actual observations include that? It would be a strength if they did, and in that case you should use the general term GNSS in cases where you do not mean solely the GPS system.
The reviewer makes a good point here about non-GPS constellations. The Summit Base Station and the roving receiver associated with the traverse only logged data from the GPS constellation. We have added text to clarify this ("*Both the base station and the rover logged data solely from the GPS constellation.*").

P5, L21: Is GLONASS or GALILEO included in any of this processing? If so, it should be mentioned.
ATM has used GLONASS since 2011; we have added that detail to the text. LVIS (which is what this comment was addressing) uses GPS only; we have added text to clarify this ("*Position information for the 2007 and 2010 LVIS campaigns incorporated data from the GPS constellation only.*").

P5, L22: I don't think the term PPP has been introduced yet.
Excellent catch; it had not been defined. Further, we moved the succinct definitions of both 'DGPS' and 'PPP' methods up to their first usage (originally they were defined at the start of section 3).

P5, L23: Since MABEL is included for reference, I think it's also worth to describe ICESat-2 in a similar fashion as a part of the same section or a brief separate one. In perspective of future ICESat-2 validation, it would be useful to know roughly how many comparison points one would get with the present GPS survey lines.
This is a good point, although we don't feel that this is the place for this comment. We note that the pertinent aspects of ICESat-2/ATLAS (e.g., along-track sample spacing of 70 cm) are described in the Introduction. We now recall this information at the end of the Discussion and add the text: ("*The ICESat-2 ice-sheet elevations released on the data product will be validated to 0.025 m. Given this requirement, and the ~0.7 m along-track sampling interval of ICESat-2, long length-scales (1000's of km) of airborne data over the ice sheets will be required for satellite data validation in order to increase the number of realizations of the satellite to airborne comparisons in order to significantly improve precision estimates based purely on an increased sample size (Boas, 1983).*").

P6, L23: Since this PPP software is commercial and many people these days use freely available services like the Canadian CSRS-PPP, it would be nice to see how one of these automatic processors would compare in the validation exercise.
The reviewer makes a great point. We experimented with an online service (specifically JPL's GIPSY) and had mixed results. We attribute much of this to the handling of the atmospheric corrections. These black-box resources are fantastic, especially for static applications. However, for cm-level accuracy associated with kinematic surveys, and for direct comparison to the aircraft data (i.e., specifying ITRF00, 05, or 08), we had more success with software that we could customize/control for this application.

P6, L28: I miss some small details on the processing: Were final IGS orbits used in all processing cases? Same for clock corrections? How were tropospheric and ionospheric errors dealt with? Was a cut-off angle used for satellite elevation to mitigate multipath?
P7, L4: How were these solid earth tides estimated?
Reviewer 1 made a similar comment. We have added details about each of the 3 processing methods: "*Independent of post-processing method, all of the ground-based GPS solutions are based on final precise orbit and clock information from the Crustal Dynamics Data Information System, or CDDIS, at GSFC. Processing using TRACK corrected for errors associated with the ionosphere by incorporating an IGS data product. To mitigate the effect of multipath distortion, all processing methods used a cut-off angle (7.5°, 10°, and 12° for Inertial Explorer, TRACK and GITAR, respectively). Inertial Explorer and TRACK used a Saastamoinen model to correct for tropospheric delay, while GITAR used a gridded reanalysis data product from the National Centers for Environmental Prediction (NCEP). And all processing methods corrected for solid Earth tides based on an Earth Rotation and Reference System Services, or IERS, model.*"

P7, L16: I don't understand this logic. From these numbers I only gather a footprint spacing of 5 m, not the actual size.
You are correct. Our error here was associated with radius/diameter confusion. We have changed this text to read: "We note that the GPS data were collected at 1 Hz, with the snowmobile operating at ~5 m s^{-1}, giving the GPS data an effective 5 m diameter footprint."

P8, L5-12: While uncertainty in the ground-based GPS probably influences the inferred lidar precision, it is also worth to mention that the two surface measurement techniques are partly correlated through their common use of GPS (and partly processing techniques) for vehicle positioning. I don't think this will have a large impact, but it is worth to discuss briefly. The problem could be mitigated by additional or isolated use of GLONASS or GALILEO in one of the platforms, but that might not be possible.
This is a great point. We don't have the option of GLONASS or GALILEO for the existing time series of ground-based survey data. This might be something that could be incorporated in future logging during that traverse. LVIS and MABEL only use the GPS constellation. ATM has used both GPS and GLONASS since 2011 (the date is now noted in the text); but we suspect that the solutions would be compromised if we were to use solely GLONASS data. That being said, to acknowledge this comment, we have added a note that we are mindful of the correlation issue: (" *… and 5) observational errors such as variable penetration of the sled into the snow along the course of the survey. Further, we note that the existing ground-based and airborne elevation data are partially correlated, as they are based on similar GPS measurement strategies.*").

P9, L16: In case of outliers it would make most sense to use the median value in each zone. Did you also try that? Worth to mention whether or not it makes a difference.
This is a fantastic point and a great addition to the manuscript. We have edited/added the following text to the manuscript: "*The zone method may mitigate the impact of spurious outliers that could affect the surface measurement precision; this is potentially evident in a comparison of the nearest-neighbor and zone results for the LVIS data, where precisions systematically improve slightly using the zone method. However, we note that results associated with a median method were all within 1 cm, and generally less than 0.1 cm, of results from the mean method. Thus, the effects of outliers in this analysis are generally negligible. Overall, the zone and nearest neighbor methods display similar results, most likely due to the relatively flat surface at Summit Station.*"

P9, L18: How flat is 'relatively flat'? It would be good to provide some kind of information about the summit topography, for example elevation range, mean slope, or average elevation impact of a given geolocation error like 5-10 m.
We assessed the across- and along-track slope based on an ATM Level 2 data product (both either 0° or near 0°) and also included the difference between the maximum and minimum elevations in this region and the impact at 10 m geolocation error (all good additions to the manuscript). We included this text and a new reference: ("*Based on the ATM Level 2 Icessn data product (Krabill, 2010) for all 3 passes associated with the 10 Apr 2014 flight, the slope over the traverse in the along-track direction is 0° and there is a gentle (0.1°) slope in the across-track direction (sloping toward the west); the difference between the maximum and minimum elevations in the vicinity of the traverse, based on the same data product, is only 1.05 m. Given these low slope values, a geolocation error of 10 m is required to achieve a slope-induced elevation error of 0.01 m.*")

P9, L27: This is an interesting finding that I think should also be mentioned in the abstract or conclusions.
We have added this to the abstract (see comment above) and now to the conclusions: "*Results were consistent given various data processing methods (PPP and DGPS) and data analysis methods (nearest-neighbor or zone analysis).*"

We do, however, want to be a little cautious about overstating this result. Our original text does point out that this is the case for 'this application'. We have now also added the following text at the very end of the 'Results' section: "*We attribute some of the success of the PPP method to our ground-survey duration, which is sufficient to minimize errors associated with the convergence period (Bisnath and Gao, 2009), but short enough to minimize errors associated with the tropospheric modeling.*"

P11, L16: Credits to the authors for making all data easily available. Exemplary!
Thank you. But this is probably more of a reflection on new requirement from The Cryosphere.

Fig 3: The TRACK solutions seem to infer a higher lidar bias than GITAR and PPP. Is this random or could there be a viable explanation related to processing?
We attribute this to the fact that the GITAR solutions use a base-station position that is averaged over 4 days, while for TRACK, the base station positions represent an average recorded over the duration of the ground-based survey (~3 to 4 hours). While we originally noted this in the text (in Section 3.1), we have now added similar text to the caption.