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Interactive comment on "Observation of a local gravity isosurface by airborne LIDAR of Lake Balaton, Hungary" *by* A. Zlinszky et al.

A. Zlinszky et al.

azlinszky@gmail.com

Received and published: 1 April 2014

Final Author Comments on the manuscript "Observation of a local gravity isosurface by airborne LIDAR of Lake Balaton, Hungary"

A. Zlinszky, G. Timár, R. Weber, B. Székely, C. Briese, C. Ressl and N. Pfeifer

Referee 1:

-1)"The paper reports an interesting link between LIDAR measurements and the gravity field over lakes. We do not find many papers on this topic. From the theoretical point of view, the findings are not surprising, but worth to be published, as the paper gives a lot of information on computational strategies which allow for extracting the desired information (ellipsoidal surface height) from LIDAR data sets."

Mapping the Earth's gravity field in ever increasing detail is a challenge that has been addressed by high-resolution measurement campaigns (Diehl et al., 2013). In some rare cases, lakes as level surfaces are exploited either for satellite calibration or to provide orthometric and ellipsoidal heights as shown by the literature overview of the manuscript. Before our study, to our best knowledge, the reliability of a lake as a level surface has not been investigated in high resolution. In the cases where lakes as level surfaces were studied, the spatial resolution was not higher than previously applied for comparable marine studies: satellite altimetry and GPS buoys were used. We propose to adapt LIDAR, a common terrain surveying method to this problem, and we carry out (again to our best knowledge) the first investigation of such data for this purpose.

-2)"However, the paper would get more importance by showing how and to which extent the proposed technique indeed yields a more accurate quasi-geoid solution when added to the classical approach. From the current figures, it is hard to see where the existing quasi-geoid map is improved (spatial pattern) and how large the improvement would be."

The full process of creating a new local quasi-geoid model and the evaluation of this quasi-geoid map would be outside the scope of the current paper. The LIDAR-derived lake surface data can be used in a way similar to GPS-levelling data: LIDAR provides an ellipsoidal height while local water gauges provide (in the Hungarian case) the normal height of the same object, the water surface. In practice, the following steps (beyond those already described in the methods section) are recommended: Any data points where elevation can be considered uncertain from visual inspection should be excluded (surface glint, strip edges); LIDAR data points should be aggregated to larger raster cells (eg. 100×100 m, 10 000 points) which also further reduces error; the levelling of the water gauges should be checked and any biases corrected; and for each LIDAR-derived raster cell, the local water stage interpolated based on timed water level records and proximity to gauges. After these steps, the quasi-geoid height of each raster cell can be calculated from the difference between ellipsoidal (LIDAR)

and normal (gauge) water surface height and can be loaded to the least-squares collocation for the geoid model together with other data types. Without creating a new geoid model, Figs 2 and 3 show where and to what extent the current model would be changed by including the LIDAR-derived data: In the Eastern corner of the lake, the ellipsoidal heights of the water surface are slightly lower than the corresponding isosurface model (Fig. 2a) and the LIDAR-derived water surface height corrected by the model-derived geoid undulation is also lower than elsewhere, in several overlapping consecutive strips (Fig 2 b). Fig. 3 also shows that in this corner, where the model-derived geoid undulation is the lowest (below 44.7 m), the LIDAR-derived water surface is consequently even lower, by up to 15 cm. Since the water gauge of Balatonaliga which we included in correction is exactly in this area of the lake, any dynamic lake topography effects can be excluded. This phenomenon would be well explained by the fact that the Eastern corner of the lake is the furthest from the Balaton uplands ridge that is causing the geoid high, but the interpolation process involved in creating the geoid model involves some over-smoothing, reducing the slope of the isosurface in the model compared to reality. While this would be a logical explanation, and the results show a consistent difference here, we are aware that this is not sufficient to prove the LIDAR-derived model better beyond any doubt. Other candidate areas would be the SW corner of the lake, where the lake level is consistently higher in several strips than would be expected from the HGTUB2007 model, and the bay to the N of the Tihany peninsula, where the water level is slightly higher. In these cases Fig.3 does not provide a clear indication, and the differences between the isosurface model and the lake height are only in the range of 5 cm.

-3)"Also, Figs 2a,b exhibit clear stripe pattern at some locations. Tackling this problem when converting the LIDAR data to height anomalies should be deeper discussed."

In order to show the potential and also the limitations of the technology, areas with sensor or target artefacts were not excluded from Fig. 2. Most of the stripe artefacts are a consequence of water as a target surface. If the target surface is water, part of

the incoming laser light energy passes through the surface, enters the water column and is absorbed, since water is a weak reflector at the near-infrared wavelength used (1064 nm). Part of the pulse energy can nevertheless be scattered back to the sensor from below the water surface. The rest of the light is reflected from the surface, part of it with near-Lambertian characteristics, part of it specularly. In case of specular reflection, at nadir very high amounts of radiation are reflected back into the sensor, while off-nadir, the energy is reflected away from the sensor and none of it is received. In case of waves, every crest may have a surface inclined to produce a specular reflection towards the sensor. However, given a constant wave amplitude chances for a reflection towards the sensor will decrease with increasing look angle. The proportions of light absorbed, volume scattered, specularly reflected and scattered from the water surface depend on sensor wavelength, the optical characteristics of the water, the roughness and inclination of the water surface and the look angle of the outgoing pulse, discussed in detail in Guenther et al. (2000). Our general observation is that over completely flat water, in our case in the wind shadow of terrain (W of the Tihanyrév gauge and area around the Badacsony gauge), specular reflection dominated. This means that for most of the strip, the pulse energy is reflected away from the sensor, with an insufficient return for triggering the detector and therefore no recorded point. At nadir and again over calm water, the pulse energy reflected specularly arrives back in the sensor, producing a point and also often a glint effect with very high echo intensity. This is known to result in slightly shorter range measurements (10–50 cm), as the high amount of incoming energy causes the system to detect a peak too early (range-walk effect). Obvious glint range-walk effects were encountered in less than 1% of the data (see histogram in fig 2b), since for most of the areas where the water surface was completely flat, no points were registered as described above. For most of the flight campaign, moderate waves were encountered. These were sufficient to produce non-specular reflection over most of the covered strip surface, but no data points were produced closer to the edges of the strips due to a combination of water absorbing the pulse energy and semi-specular reflection away from the sensor. The width of this "blank" strip varies again depending

on local water surface characteristics. Closer to the strip centreline, but still nearer to the edge of the strip, slight decrease of the heights from the strip centre to the strip border by about 5 cm (Fig. 2a) can be observed in some cases. This small systematic "smile" error may have two causes: (i) The most likely reason for this observed "smile" error may lie in the interaction of the laser signal with the water surface as explained above. That is, perhaps in this part of the affected strips the pulse energy entered the water, and volume scattering of water contributed to the reflected energy besides surface reflection, and thus produced a measurement of erroneously long range, i.e. low water surface. The width of this "too low" part of the strip is usually not more than 100 m. (ii) Small internal errors of the laser sensor might also have contributed to the smile error, which during the adjustment could not be fully corrected by the applied sensor correction parameters including a constant range offset (which can cause such type of "smile" error over land as well). One reason for this could be that the features used for that adjustment where obtained from the laser data over dry land. Therefore the correction was adapted to the error situation over dry land and not to that over the water areas. Having systematically inspected each flown strip for the "empty edge", smile, specular centre and wave effect, the following conclusions were made:

-The width of the strip edges where no LIDAR echo from water was observed is typically 200 m on either side of the strip, and practically all LIDAR strips collected were affected by this. This varied by about 50 m depending on surface conditions, with narrower empty strips where waves were encountered, and exceptionally very broad empty strips where water was completely flat and specular reflection dominated. This suggests that the "empty edge" effect is caused by the dominance of specular reflection and absorbance above a certain angle of incidence between the pulse and the water surface.

-Up to 15-20 cm overestimations of water surface height due to specular effects were observed in small parts of 20 of the 58 strips we used. All of these were in very calm water conditions. In some extreme cases (5 strips) the strip area would be completely

empty except for the very narrow (5-20 m) centreline where points would have erroneous heights due to specular effects; implying that specular reflection dominated in these cases and data were only collected at nadir.

-The artefact of erroneously low strip edges ("smile") was encountered in 19 of the 58 strips, all of these in the eastern basins of the lake where the water is less turbid than in the west. Most strips are completely free from this artefact, suggesting no systematic internal errors of the scanning system were encountered. The affected strips were all on the Northern shore in deep water and local wind shadow, again implying low turbidity. The smile effect typically happened at scan angles near 20°, which follows our expectation that the entry of the laser pulse into the water column is limited to a certain angle of incidence (a fact well known in the bathymetric LIDAR domain).

-Waves affected 23 of our 58 strips, nearly all collected during day 3, some during day 4. As expected, strips affected by waves were always free of smile and major specular effects. Wave amplitude was between 5 and 30 cm, wave length typically around 6 m between crests. Surface waves showed areas both above and below average water surface height.

-A further, final cause of strip patterns may lie in remaining errors of the strip adjustment process. During surveying, a sensor problem was discovered to affect the data: the centre position of the scanning mirror was determined with some uncertainty, resulting in a slight "twist" of the affected data strips along their longitudinal axis, with erroneously low cells on one edge and erroneously high on the other (+/- 5 cm). Strip adjustment corrected this effect as described in the text, but in some rare cases (definitely not more than 7 of our 58 strips), the low overlap with other strips means that some such error may have remained.

All in all, these stripe artefacts seem to have a limited effect on the inferred LIDAR heights. As shown by the histogram of Fig. 2 b, the distribution of the difference between ellipsoidal water heights and local quasi-geoid height remains rather narrow

despite these. We believe a major cause for the local deviation from the mean is the effect of waves. The smile effect may be responsible for the slight skew of the distribution, with more low points than high, while specular effects fall mainly into the highest shown histogram bin (105.05m) and have a very low proportion (0.2%). Twist effects also cause some broadening of the distribution, but their overall contribution is low since they were corrected successfully in the overwhelming majority of the strips. Since the smile and specular errors are quite systematic, linked to scan angle (which is an attribute of every LIDAR point) and water surface characteristics (which is well represented by the registered LIDAR echo amplitude), they could relatively easily be filtered automatically in case the water surface heights are to be input in a geoid model. The effect of waves would be easily corrected when averaging over areas substantially larger than the wave length. Manually detecting and removing LIDAR strips affected by the twist error is a routine step of quality control, therefore these would not introduce error in a real geoid modelling case either. All these effects have not been removed in case of our manuscript in order to provide a detailed understanding of the characteristics of the sensor and the target.

-4)"In the paper, water level gauges are used only for correction purposes. The link between water level gauges and their normal height which directly yields the height anomaly at the gauge sites (provided there is no "lake topography" similarly to the well-known SST on oceans) is missing. One could directly see how the LIDAR derived height anomalies match the data the interpolated quasi-geoid grid relies on."

In this study, we did not have access to the "data the interpolated quasi-geoid grid relies on"; therefore it would not have been possible to compare these with the quasi-geoid heights inferred from the LIDAR ellipsoidal heights and the water gauge normal heights. Comparing these and creating a new quasi-geoid model would have been outside the scope of this manuscript, but in a geoid modelling study the ellipsoidal heights of the water gauges would of course have been used as local normal heights for the water surface. In our case (as discussed in the Appendix) we used the water gauges to study

whether the surface of the lake was in hydrostatic equilibrium. For this purpose, the deviations from Local Mean Lake Level were sufficient.

-"Technical aspects: Figure caption 2 is wrong (same as that of Fig. 3). Explain in more detail, what we really see in Figs 2a and 2b. What do we see in the inset of Fig. 2b (supplement)? It is not only a zoom; colors (especially on N-S stripes) differ clearly from that of the entire map."

The caption of Fig. 2 is truly a mistake. Please find the intended captions below: -Fig. 2a: Map of LIDAR-measured ellipsoidal water surface heights (inside flight strip outlines) and gravity isosurface height (background raster) with the same elevation colour scheme. Inset shows detailed height distribution of water surface measurements, histogram refers to LIDAR measurements (not to quasi-geoid height). -Fig. 2b: Map of LIDAR-derived normal water surface heights, obtained by correction with local quasi-geoid height. Histogram refers to water surface normal heights. The slightly varying colours are a technical issue of pyramid generation for low-resolution viewing of high-res data and shrinking .pdf data sizes to the journal technical limit. The intention was to have exactly the same colours in the large map and the inset, this will be corrected for the final version.

Referee 2:

-1)"Technically, I find the paper well-written and containing a lot of information. The authors describe an experiment – they had funding for airborne surveys, they collected a lot of data, and they compute a lake topography that they believe is close to hydrostatic equilibrium, which then does not really come as a surprise."

From a certain perspective it is clearly not a surprise that the water surface is close to hydrostatic equilibrium. Nevertheless our reviewers themselves (including Referee 2) draw our attention to a number of effects they believe influences this, suggesting that in fact they do not expect the lake to be in equilibrium. Therefore we allocated some effort to proving that this is the case, especially since LIDAR provides a snapshot in time and

does not allow averaging over a longer time similar to GPS buoys. -2)"Scientifically, the manuscript appears mediocre as a clear hypothesis is missing. In particular, this reviewer can neither discover an open scientific question to be addressed, nor a result which is supported by thorough validation. With a background in physical geodesy, it appears hard for me to grasp how the results can be used for improving an actual geoid model. In fact, it appears the authors had all the information required in hand but did not make proper use of them. More details follow below" We acknowledge the hypothesis and the objectives might not have been formulated clearly enough. This will be corrected by inserting a dedicated "objectives and hypotheses" section into the next version of the manuscript.

We investigated two questions and hypotheses through this case study: Q1: To what extent does a lake resemble a level surface? Our hypothesis is that while many effects known to physical limnology influence the local height of a lake surface, observations can be timed to minimise these, the remaining effects can be corrected from gauge data, or are negligible. Lake Balaton is a suitable setting to investigate this due to the known variation in geoid undulation across its area, the shallow depth and relatively well studied water movements, and a dense network of water level gauges. The hypothesis can be considered proven if the deviations of the measured ellipsoidal lake heights from the best available quasi-geoid model are small, and if their pattern corresponds to known uncertainties of the geoid model and the sensor process, also if the height range of dynamic lake level processes is much smaller than the quasi-geoid height range; or disproved if the deviations are large compared to the range of quasi-geoid heights encountered, if they show a random pattern or can be explained based on physical limnological processes, or if variations of local water level measured by gauges are comparable to the quasi-geoid height range.

Q2: Can LIDAR measure water surface elevation accurately enough for inferring variations in geoid undulation? Our hypothesis is that through strip adjustment based on terrestrial target surfaces, the accuracy of georeferencing the point cloud can be in-

creased sufficiently to deliver data comparable with a geoid model and suitable for inclusion in the geoid modelling process. This hypothesis can be considered proven if the errors of the sensor process after applying the possible corrections are significantly smaller than the ellipsoidal height range of the lake, if a realistic way for including LIDAR-derived water surface heights into quasi-geoid modelling is proposed, if the feasibility of LIDAR campaigns or the availability of such data is shown to compare favourably with other methods of measuring gravity pattern. The hypothesis could be considered disproved if the cumulative error budget is comparable to the range of the pattern to be observed, or if it appears to be unfeasible to use existing LIDAR data or carry out specialized airborne surveys for this purpose.

-3)"In fact my view might have been somewhat biased from the onset, since already the title of the manuscript is incorrect or at least misleading. The authors write about observing a "gravity isosurface" being observed; later this is equated with geoid determination but this is not correct. A gravity isosurface implies that a surface of constant gravity is observed, such as an isobaric surface implies a surface of constant pressure and so on, however, a geoid is not a surface of constant gravity but of gravity potential. This should be corrected."

We were aware of the difference between a gravity isosurface and a gravity potential isosurface (the latter is used consequently in the body text), however, we used the former in the title for brevity. As requested by the reviewer, this will be corrected in the next version of the manuscript also in the title.

-4)"Lidar, as radar altimetry, provides the current sea surface which equals to an equipotential surface (not necessarily the local geoid) plus waves plus atmospheric (wind and pressure response), Earth, pole and lake tides plus non-tidal surface variability due to density change, currents, up-and downwelling, river plumes and many other effects – all of this has been observed in large lakes. In order to correct from sea surface to the geoid, all these need to be corrected, and I am missing a sound error budget for this procedure here. Was surface pressure change accounted for at

all? Tides? There is a number of foggy statements "low current intensity at the time of flight", "the turnaround time for water is more than two years, so the flow is very weak", which appear unsupported by evidence (I cannot even see turnaround time, commonly a measure how long a water parcel stays in the lake, related to geostrophic current intensity)"

Presentation of the error budget in the current version of the paper is by no means complete and will be improved as requested by several reviewers, providing a table of typical and worst-case errors and their propagation. Meanwhile, no error budget can take into account all possible effects that may influence water surface height. Many such factors deliver major or at least measurable effects on oceans or deep lakes, and are therefore familiar to the physical geodesist. Several of these can however be expected to have very limited influence on such a shallow and small lake. However long the list of such factors, new ones can always be added that truly do have a small effect on water height. We chose to study those where experience and literature suggested that the change in lake height they cause would be significant in proportion to quasi-geoid height variation. The distribution of water surface elevations corrected with quasi-geoid heights has a ?MAD of 5.6 cm. This implies that the uncorrected errors that remain in the dataset have a characteristic range around 5-10 cm. In the following, we briefly discuss the effects suggested by the reviewer:

-Waves: waves truly affect local water level height, at scales smaller than the wave-length. At observation scales larger than the wavelength, the waves themselves do not change the average water level. The wave lengths we observed are around 6 meters or less, the total wave height range 30 cm from trough to crest. We believe this to be the most important source of height dispersion, however, the pattern is well understood and does not contribute to the lake-scale pattern of ellipsoidal height that we derive our conclusions from.

-Wind response: The main results of wind response are seiche (a periodic standing wave along or across the lake) or setup (a disequilibrium of the lake surface stable

as long as the wind is constant). We believe these two effects have been adequately described and studied in the current version of the manuscript. They have been quantitatively investigated based on the deviation of the water level from the local mean at each gauge.

-Air pressure response: The rule of thumb for air pressure response is 1 cm decrease in water level for 1 mbar increase in air pressure (Ponte and Gaspar, 1999). However, this only applies to the open ocean and after a period of 1-2 weeks. In our case since the flights took place within 10 days and since the lake was very shallow, most of the air pressure is directly forwarded to the lake bottom. Therefore we assume that air pressure changes could not have influenced the local lake level by more than a few millimetres during the measurement.

-Lake tides are known to have amplitudes of up to 10 cm in larger lakes (Trebitz, 2006). In case of Lake Balaton, the shallow depth and the relatively low water volume of the lake suggest this effect would be even smaller. During long-term investigation of water movements conducted in the 1970's, no evidence of lake tides was observed (Muszkalay, 1973), therefore we do not expect these to have influenced lake level more than 1-2 cm.

-Solid Earth tides: Solid Earth tides can introduce height variations of up to 30 cm within 12 hours. However, as mentioned in the "Methods" section, GNSS positioning of the aircraft platform involved differential corrections from a base station. In differential GNSS, the solid Earth tide effects are not accounted for (as long as the base is close enough), since the reference station itself also moves due to solid Earth tides.

-Pole tides: These displacements are due to the centrifugal potential that arises as the rotational axis of the Earth circulates around the mean pole. The major constituent is the Chandler wobble with an amplitude of about 0.8 arcsec and a period of 14 months. This could cause a radial displacement of 25 mm. While this would certainly have to be taken into account for longer surveys (typically beyond 2 months), for our 10 days

flight window the effect is believed to be negligible (Petit and Luzum, 2010).

-Density change: Due to its fresh water, shallow depth (3.3 m avg!), limited inflow and small water volume (2 km3) compared to its surface (600 km2), Lake Balaton experiences very limited variations in water density. There is no thermocline, warming and cooling can only create maximum vertical temperature gradients of up to 1.1 °C/m, and horizontal differences in surface temperature between basins have been documented to remain below 3 °C (Virág, 1998). The height effect of local warming or cooling can dissipate relatively quickly on this scale, therefore only a very limited contribution of density change to lake topography can be expected. The salinity of the water is also quite constant over its area and over time, so no major changes in density are expected.

-Currents: On Lake Balaton, currents are driven by wind forcing and by seiche while thermal convection remains hardly observable (Muszkalay, 1973). Current flow can locally reach 1 m/s in cases of storms or strong seiche. While no direct current measurements have been carried out during our survey, the wind speeds were low (<5 m/s) as documented by the METAR reports, and seiche displacements were within a few centimeters as detailed in the appendix. Therefore we have a reason to believe currents have been negligible.

-Up-and downwelling: The Ekman force, which is one of the main reasons for oceanic upwelling, has not been confirmed on Lake Balaton due to shallow depths and low shore slopes. Nevertheless, up-and downwelling can happen even on calm days, and Langmuir-cells can form. Nevertheless, these probably don't affect the kilometre-scale height pattern of the lake surface.

-River plumes: Visual inspection of all LIDAR strips colour coded in 5-cm bins identified no river plumes. These are also unlikely to have any major effect as 6 of the 10 largest tributaries have mean discharges below 0.5 m3/s, 3 more below 1.5 m3/s and even the largest tributary has a mean discharge of only 7.5 m3/s. All these effects, had

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they produced changes over the scale of whole lake basins and variable in time during the flight window, would have been included in the assessment of dynamic water level changes based on the nine gauge stations, and were also subject to the corrections we carried out with respect to Local Mean Lake Level. Therefore, we expect that they were accounted for by the water gauge-based correction.

-5)"Even if this may be difficult, the resulting corrected lake surface would have to be compared to a physical reference surface, the local geoid. While a lengthy description is provided on how the Hungarian national geoid has been computed in general, the essential information is missing: how good is the national geoid model around Lake Balaton? An overall predicted accuracy of 2 cm is meaningless in this context. What kind of data did they use over the lake and in the vicinity, and how accurate is the geoid? Were aerogravity data over the lake used?"

We cite Tóth (2009), who give a detailed overview of the measurements they used and interpolated and the location of their data points in their fig. 1. The reviewer is right to request more information on the data source, since Tóth et al do not describe the exact locations or methods of the "300000+" gravimetric measurements they use. The raw measurement data originate from terrestrial gravimetric measurements (Csapó and Völgyesi, 2001), and no ship- or airborne gravimetry was carried out over the surface of Lake Balaton. Nevertheless, free-air gravity anomalies were interpolated to a regular grid of 2'×3', also over the lake, and this might have introduced smoothing errors compared to the isosurface determined by the lake. However, since our flight strips mostly remain in the immediate vicinity of the shore, the nominal accuracy of the dataset over land would apply. One more issue has to be addressed: while the eastern part of Hungary is well covered with gradiometric measurements and these were used in modeling the quasi-geoid and the calculation of its overall accuracy, the western part of Hungary where the lake is located has less dense coverage in gradiometry and the model relies on astrogeodesy, GPS levelling and gravimetry. The difference between a geoid model relying on all four data sources and one based on only the latter three available

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near Balaton has been checked by Tóth et al. (2009) and is displayed in fig. 8 of their publication. This shows that in the areas where gradiometric data was available, the difference compared to a model excluding these data remained zero, except for the immediate vicinity of the measurement points. This implies that even though gradiometric data is sparse around Lake Balaton, the nominal accuracy of 2 cm applies for the dataset in this area (and close to the shore!) as well.

-6)"With the geoid, and with the levelling stations connected to the national datum, it is not clear why the authors chose to disregard this information – ok, they want to do it independent – but compute a "reference surface" LMLL from 4 days of observation, of which they then complain it is "less accurate" as a reference surface."

Using the zero point of the levelled water gauges as a reference surface for dynamic water topography calculations might have compromised the independence of the LIDAR-measured data from any a priori geoid model. There were some differences between the LMLL of the individual stations (<5,5 cm, see table), which are probably a result of levelling errors of the water gauges. Alternatively, the long-term disequilibrium of water over several days could be suspected, but we believe this is not realistic at the wind speeds encountered during the flight window based on. The relative accuracy of single water level measurements is within a centimetre as specified by the instrument vendor, however, the daily local means have standard deviations (from 4 days) up to 1,7 cm. While this is "less accurate" than the single measurements as we wrote, it is still accurate enough for assessing the hydrostatic equilibrium of the lake from this baseline.

-7)"Consequently, many of the authors' claims in the Discussion and Conclusions chapter are totally unsupported. While I have no doubts that Lidar is a valuable technique which should be studied to support physical geodesy, I don't think the authors provide a convincing proof that "ellipsoidal heights measured by Lidar might be used in the future to refine local gravity models"."

While we agree to the referee's comments as indicated above, and will deliver a more thorough error budget and discussion, it is not clear to the authors which of our claims are "totally unsupported". Our main claims in the Discussion and Conclusions chapter are:

-i)"Variations in the ellipsoidal height of the lake water surface are mainly a product of the variations in local gravity potential represented by the geoid undulation; the slight water level changes induced by movement of water during the flight period were corrected for." The proof for this is the close observed correlation between the water surface height and the quasi-geoid heights, together with the water gauge-based observation and correction of the effect of potential processes that may alternatively result in such a lake-scale surface height pattern (seiche, setup) and artefacts shown in the error budget (which will be improved as stated above).

ii)"However, the high resolution of the LIDAR-derived water surface model shows even shorter wavelength patterns in height, and therefore potentially in geoid undulation, which are beyond the scale of the geoid model. This implies that water surface ellipsoidal heights measured by LIDAR might be used in the future to refine local gravity variation models." The quasi-geoid model we currently use has a resolution of about 1,5 km, while LIDAR allows deriving lake level at a resolution of 100m if sensor artefacts such as glint and smile are appropriately removed, and dynamic lake topography effects at this scale can be excluded. Such a dataset would be informative about the within-cell variability of the quasi-geoid models we routinely use, and perhaps also about lithology (Borsa et al., 2008) including the formation of lakes (Dietrich et al., 2013), or more specifically the response of the gravity field to topographical density variations (Kingdon et al., 2008). We believe LIDAR collection of lake surface heights is at least as efficient as e.g. aerogravimetry, especially since the existing data coverage is so widespread, but only the future will show if this method really gains ground. Perhaps this latter claim is truly somewhat far-fetched based on the data we have. We will modify this in the next version of the manuscript, to be closer to what the reviewer

also suggests: instead of "water surface ellipsoidal heights measured by LIDAR might be used in the future to refine local gravity variation models." in the current version of the text, we will state in the conclusions the following: This implies "Lidar is a valuable technique which should be studied to support physical geodesy".

iii)"We conclude that LIDAR mapping of lake surface elevations can deliver information on the ellipsoidal height patterns of the water surface, and thus on the local gravity anomalies"

We show that 90.1% of the ellipsoidal height variation of the lake level as measured by LIDAR is explained by variation in the quasi-geoid height model. We interpret this as a proof that the lake surface elevation mapped by LIDAR is mainly a product of local gravity anomalies. While the relatively short error budget in the current version of the paper may have fuelled doubt on this claim as also indicated by the reviewers, we believe a more detailed error discussion will be sufficient to support this main conclusion of our study.

-8)"The Discussion chapter also contains a misleading discussion on how altimetry is closer to GRACE that airborne gravity – all these three techniques work on totally different spectral domains, which means they complement each other but do not compete."

The "misleading discussion" is a short summary of the conclusions of the study by Kingdon et al. (2008) as cited in the manuscript. The following statement is in the "Results" section of Kingdon et al (2008): "Also, in general the altimetry results agree better with the EIGEN-GL04C model than with the shipborne and airborne results. This implies that there is little bias in the altimetry results (no more than 16 mgal in magnitude, for these profiles), while there is certainly a larger bias in some of the airborne/shipborne results (as much as 48 mgal)."

And in the "Conclusions" section: "Satellite altimetry data provides a higher frequency gravity field over lake areas than satellite-derived geopotential models, and is sometimes better than publicly available shipborne gravity data in the same areas. Altimetry

results are mostly unbiased with respect to satellite-derived global geopotential fields such as EIGEN-GL04C." (...) "Furthermore, the altimetry results agree often with airborne and sometimes with shipborne gravity results, showing that they are able to accurately model the high frequency component of the gravity field."

Thus, we implied from this paper that the satellite altimetry technique they used works on a similar spectral domain as ship- and airborne gravimetry, but altimetry is truly found to generally have a smaller bias with respect to EIGEN-GL04C (which is based on GRACE data) than gravimetry. We will try to reformulate in order to avoid the impression that the three methods would compete.

-9)"Comparing sea surface measurements to a geoid is complicated by the fact that the geoid itself is derived by integration over terrestrial gravity measurements which are usually sparse over water surfaces. A path that altimeter people went for validation, and that might be useful for assessing Lidar capabilities, would be to numerically derive marine gravity anomalies over the lake. These could be compared with ship-borne gravity measurements, should they exist over Lake Balaton."

No ship-borne gravity measurements were carried out over Lake Balaton, the only available data source would be the gradiometry measurements carried out by Loránd Eötvös in 1901 on the ice of the lake (Eötvös, 1908). Creating a quasi-geoid model incorporating our water surface height measurements and comparing these with the historic measurements would be an interesting study, but reaches outside the scope of the current paper.

Referee 3:

-"The paper deals with a topic which has been discussed recently but only a few publications yet exist. Using Lidar for measuring the lake surface for a local geoid (or a lake equipotential surface) determination is an interesting idea to improve geoid determination accuracy. The research was made from the data which originally was taken for a totally different purpose, and therefore the observing procedure was not optimal.

Some of the comments below may raise from this fact. There are some topics which I would like to mention here, and hope that the authors are able to comment them and take into account where appropriate:"

The data we based our study on was truly collected for a different purpose. However, we believe our study implies that other existing LIDAR datasets, mainly regional LIDAR scan campaigns, may also be successfully used for this purpose.

-1)"The paper itself is well written and on technical point of view there are no comments."

The technical comments of reviewer 1 have been addressed above.

-2)"Connection to the existing geodetic infrastructure and geoid model around the Lake Balaton. Description of existing geoid models is included but to me it remained a bit unclear how the connection to the existing geodetic infrastructure was made. Any GPS-levelling points or such connections? "

In our case, the study is restricted to comparing the LIDAR-derived water surface height and the local geoid model. No attempt was made to refine the existing quasi-geoid model by creating a new quasi-geoid model including the water surface data, we merely prove that this is possible based on the accuracy of the sensor process and the equilibrium of the lake. According to Tóth (2009), the geoid model we used was based (among other data sources) also on 94 GPS levelling points, including 4 in the immediate vicinity of the lake. In the future, as described above, the ellipsoidal lake heights may be used in a way similar to GPS levelling points.

-2b)Also the sentence "In our case the lake itself serves as a leveling instrument providing a vast area where elevations relative to the geoid are shown to be constant." (page l32, line 24) needs more clarification. The lake surface may not follow the geoid due to the lake surface topography (flows, prevailing winds, :::). One needs a more detailed analysis (perhaps a hydrological model) to better understand such deviations.

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Perhaps the authors can a bit open these items."

In this sentence, we refer to an old-school leveling instrument with a spirit level: here the tendency of a fluid in hydrostatic equilibrium to follow the gravity isopotential surface is exploited. In our case, we have proved that the lake surface itself follows the gravity isopotential surface, and thus (within the limits discussed in this study) its surface has the 'same orthometric height'. Measuring the ellipsoidal height in many points of this surface of known orthometric height (based on water gauges) by LIDAR would create observations of geoid undulation, subject to the error arising from the height of the surface above sea level (which also affects GPS leveling) and the conversion between orthometric and normal heights. In the next version of the manuscript, we will refine and extend the error budget, although in its current form it already discusses winds and seiche, which are the prevailing cause of flows on Lake Balaton (Muszkalay, 1973). Applying a full hydrodynamic model to the lake would probably be pointless under such calm wind conditions, but might certainly be needed in case of other surveys carried out under more windy weather.

-3)"Error budget in general. Throughout the text there are error analysis, and especially Ch 4, but all these should be put together (a table?) to better show the full error budget and the total uncertainty of the observations."

We will extend the error budget with a table to produce an output that is more quantitative, discussing both the normal and the worst case, as requested by the reviewer.

-4)"Contribution of this research to the more accurate geoid determination. Please clarify this item because from this text it is difficult to see the improvement (where and how much) of this determination to the geoid model. Can this assumption be justified based on analysis in 3) of the total error budget of the observations? If the Hungarian geoid model accuracy is 2 cm, as mentioned, what is the total error budget of the Lidar determination?"

This is also raised by comment 2 of referee 1, and is mostly answered there. While the

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accuracy of the Hungarian geoid model is 2 cm according to its authors, we show that in part of the lake, there is a discrepancy of up to 15 cm between the lake (which we prove is close to a gravity potential isosurface) and the local quasi-geoid. This implies that even if the total error budget of LIDAR-based surface determination is beyond 5 cm (as described by the ?MAD of 5.6 cm) it is worth using input from these data. In case LIDAR-based surface measurements were used as input, a different error budget would apply, improved by larger interpolation cell sizes (averaging across waves) and removal of smile, specular and twist artefacts, but subject to the error of water gauge levelling.

-5)"The topic itself is actual. There are quite large comments concerning the contents of the paper. I hope the authors will be able to improve the manuscript, after which I can recommend that it can be published."

In summary, the main points we will change in the final submission of the manuscript are the following:

-The objectives and the hypothesis will be described in a dedicated "objectives" section

-The error budget will be re-written to be more systematic, and extended by a table as requested by reviewer 3 comment 3. Waves, lake tides, pressure and density effects will be briefly discussed. The detailed discussion of the sensor-derived artefacts as in the answer to referee 1, comment 3 will be included in the appendix.

-The discussion will be extended by a description of how LIDAR-derived lake surface heights can be integrated into future geoid models, based on the answer to referee 1, comment 3.

-The conclusions will be moved to a separate section, reformulated based on the objectives and our answer to referee 2, comment 7

Technical and minor issues:

-The title will be changed as requested by referee 2 in comment 3)

-Our discussion of the study of Kingdon et al (2008) will be reformulated in line with comment 8 of referee 2.

-The caption of fig.2 will be corrected, and the colour issues identified by the reviewers will be resolved by re-exporting the map from the original GIS.

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