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Hydrology and Earth System Sciences Discussions
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Interactive comment on "Bathymetry observations of inland water bodies using a tethered single-beam sonar controlled by an Unmanned Aerial Vehicle" *by* Filippo Bandini et al.

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Response to the review of Anonymous Referee 1. We have copied the comments of the referee hereunder with our comments appearing after the referee's comments.

This manuscript describes an innovative approach to measuring bathymetry: using an Unmanned Aerial Vehicle (UAV) with a tether to deploy a compact sonar system. This idea is a simple one but has not, to my knowledge, been explored previously and is worth investigating. The authors effectively summarize the advantages of this new approach relative to conventional methods of surveying water bodies, such as depth retrieval from passive optical image data, boat-based sonar measurements, and wading surveys. The UAV-sonar combination allows for data collection in inaccessible and/or non-navigable waterways and does not suffer from the same turbidity-related constraints as other remote sensing methods and thus can obtain bathymetric data from far greater depths. The description of the new system is thorough but not too detailed and the methods used to obtain the sonar position from the drone's GNSS receiver and an offset calculation are explained reasonably well. Two case studies are used to quantify the accuracy of this approach, with encouraging results. The tables comparing various ground-based and remote sensing methods and their costs are useful additions to the manuscript. Overall, I believe this paper makes a nice methodological contribution and can be published with only a few minor revisions. I have made a number of comments and (mostly minor) edits on a PDF document uploaded separately and refer the authors to that document for detailed line-by-line corrections, but a few more substantive comments are highlighted here. We thank the referee for the feedback and the comments on the article. We have incorporated the line-by-line corrections into the revised manuscript. We hereunder discuss the review comments.

1. In several cases, obscure and unnecessary references are included while in other places relevant citations are omitted, or used inappropriately – please see detailed comments in the PDF.

In our revision plan, we will follow the reviewer's suggestions to remove unnecessary references. However, the reviewer suggests to remove the reference to (Heritage and Hetherington, 2007); and (Charlton et al., 2003) in Table 4. These are the two references:

Charlton, M. E., Large, A. R. G. and Fuller, I. C.: Application of airborne lidar in river environments: 5 The River Coquet, Northumberland, UK, Earth Surf. Process. Landforms, 28(3), 299–306, doi:10.1002/esp.482, 2003.

Heritage, G. L. and Hetherington, D.: Towards a protocol for laser scanning in fluvial geomorphology, Earth Surf. Process. Landforms, 32(1), 66–74, doi:10.1002/esp.1375, 2007.

These references appear relevant to us because they deal with bathymetric observations from Lidar and TLS, respectively. We would like to keep these references in the manuscript. Furthermore, on page 2 (L3), the reviewer suggests citing Legleiter et al. (2016, ESPL), instead of Legleiter (2012). The authors did not find a paper published in that year/journal regarding LIDAR observations with Legleiter as first author. Could the referee kindly provide the title of the paper? Does the referee refer to "Removing sun glint from optical remote sensing images of shallow rivers (Brandon T. Overstreet, Carl J. Legleiter, 2016)"? This paper is focused on hyper-spectral observations of bathymetry, not LIDAR, thus it will be included in the paragraph in which we report about these spectral methods to retrieve water depth. Please clarify.

2. Page 2, line 3: need to clarify that you are talking about bathymetric lidar sensors with green laser wavelengths. Near-infrared lasers are absorbed by water.

We will clarify this.

3. Page 3, line 10 (and throughout): I think the large beam angle of the Deeper sonar is an important limitation you need to acknowledge more explicitly. Even at 1 m depth, the footprint is 26 cm, so at greater depths this system will have very poor spatial resolution and you will not be able to detect small-scale differences in depth. I think the beam angle might be the most important source of the bias you discuss later in the paper as well.

We acknowledge these limitations. In the Materials and Methods section we will specify that the Deeper footprint is not suitable for resolving small-scale features at large water depths, and again discuss this limitation in the Conclusions. The spatial resolution of the observations was already explicitly defined and the limitations of a large measuring angle were also considered when comparing between the Deeper sensor (15°) and the reference sonar SS510 Smart Sensor (9°). Please note that, as we will describe in the discussion, most single beam sonars have a beam width angle between 8 and

30 degrees (smaller angles are generally associated with higher sonar frequency). Thus, these single beam sonar systems always tend to have large footprint and interact with a bottom areas of significant diameter. When a detailed survey of small features is required, different instruments need to be used, e.g. side-scan sonars (imaging sonar) or multi-beam swath sonars (sonars collecting data in a swath by forming a series of transmit and receive beams which measure the depth to the sea floor in discrete angular increments or sectors across the swath). These sonar systems are considerably heavier and more expensive than single beam sonars.

4. Page 3, line 16: Does the sonar have a minimum depth?

The minimum depth is variable depending on the substrate type. We will indicate a minimum depth of 0.3-0.5 m.

5. Page 5, line 7 (and throughout): Be careful with the term geographical coordinates, which implies longitude and latitude, whereas a truly Cartesian frame of reference requires a map projection. I recommend using the term spatial or real-world rather than geographical throughout the paper to avoid any confusion on this point.

We fully agree with this comment and we plan to rephrase and correct according to the reviewer's suggestion. 6. Page 6, line 17: I'm confused about the camera alignment – how is it oriented on the UAV? An additional figure could help here. As specified in the paper, the vertical axis of the camera is aligned with the drone nose. We will clarify this also in fig. 5.

7. Page 9, line 17: The supplementary data you mention appear to be missing.

The supplement file is downloadable in the download section of the paper webpage (below the pdf and xml files).

8. Page 10, line 5: I think it would actually be more informative to not use the absolute value so that you know which of the two sonars is reading a greater depth. As long as you clearly define what is being plotted, e.g. SS510 - Deeper, then you'll know whether

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positive or negative corresponds to a deeper reading by one sonar vs. the other. With absolute value, that information is lost.

We will modify the figure showing the error value with its corresponding sign.

9. Table 3: It would be helpful to clearly define how the various statistics included in this table were calculated, just to avoid confusion. Make things explicit when you can.

We will add the definition of these quantities to the manuscript.

10. Page 12, line 13: The bias associated with shallow points in a large footprint is an important issue that will become more problematic as depth increases. The wide beam angle of the Deeper sonar is a major limitation of this sensor.

See answer to comment 3 above.

11. Figure 9: This data set is rather sparse, far less continuous than the boat-based data shown in Figures 6 and 7. Can the UAV-based system provide more continuousk coverage like you'd get from a boat, or are only widely spaced point measurements possible? If you can only obtain a few points, the advantage of the UAV would not be nearly as great. Please comment on this in your revision.

In the original version of the paper, the research goals were to retrieve observations i) in a lake to demonstrate that we can measure deep water several meters from the shore and ii) in a river to obtain river cross sections, which are generally required to inform river hydrodynamic models. In order to show that observations with continuous coverage can be retrieved, we plan to include highly spatially resolved observations of a river stretch. Interpolation of these observations will allow for representation of a bathymetric map of the riverbed.

12. Page 14, line 2: You need to explain how this bias factor is defined and was computed.

We will include the linear regression equation that describes the relationship between the observations of the two sonar sensors (x) and ground truth (y). In this linear regression, the coefficient $\beta 0$ (y-intercept) and $\beta 1$ (slope) and ε (random error term) appear.

y=$\beta_0+\beta_1 x+\varepsilon$

The bias factor between the sonar observations and the ground truth is generally corrected by multiplying for the slope coefficient (assuming $\beta 0 \approx 0$).

13. Page 14, line 2: This bias does not appear to be very pronounced, and Figures 10 and 11 are nearly identical. Don't exaggerate this effect.

The authors suggest that there is a consistent improvement after correction of the bias factor. The improvement is approximately 1

14. Page 16, line 24: I don't see how having a waterproof UAV connects to the operator not being in the area. Is it so the UAV can crash into the water without being destroyed?Please elaborate a bit in your revised manuscript.

We will rephrase with <The new-generation of waterproof rotary wing UAVs equipped with visual navigation sensors and automatic pilot systems will allow retrieving hyper-spatial observations in remote or dangerous locations, without requiring the operator to access the area>.

15. Page 16, line 36: I think the geometry of the bed (i.e., steep side slopes) and the beam angle of the sonar are more important factors contributing to the bias.

In the Conclusions we remark that the beam angle contributes to a low spatial resolution and complicates the recognition of small features.

16. Table B1: Be consistent with number formatting. On the previous line you used , but here you're using '. I think , is more common, so please use that throughout.

The different number format was a typo, which is now corrected with <,>.

Technical corrections: Please see the PDF for detailed line-by-line edits, which are extensive and need to be incorporated into a revised manuscript.

Revision plan: we will correct these changes accordingly.

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