Interactive comment on "Combining high-resolution satellite images and altimetry to estimate the volume of small lakes" by F. Baup et al.

Anonymous Referee #1

Received and published: 8 January 2014

OVERALL: An interesting paper outlining techniques for the determination of lake volume or volume changes - a much needed hydrological parameter, and a research area that is currently being addressed by the community in the light of improvements in satellite radar altimetry and imagery.

The authors want to thank Referee 1 to its overall good evaluation of the paper.

All the modifications appear in red in the revised paper, and are highlighted in green in this document.

GENERAL COMMENTS: Is radar altimetry marginally better than imagery for the lake La Bure case because a) it's more accurate, or b) the level variation is greater? In such a shallow lake, I would expect the areal extent to vary greatly, and the altimeter to have the greater error due to little variation and few data points across the ground track. If the imagery has greater error – is this due to lake size, or failure to detect water in the coastline "edge" pixels, perhaps due to vegetation? How applicable are these techniques to global lake studies? In the light of little in situ data and/or unknown bathymetry for example, or, for those lakes with some in situ data, will radar altimetry be expected to be the best method? What could cause the methods to be temporally unstable? Can the authors outline what types of research will benefit from having direct lake volume estimates, and those that will benefit from having only changes in volume? Are your derived error estimates acceptable? Where some in situ data is available, what advantage is there to combining the in situ/area and in situ/elevation results to remove their individual disadvantages?

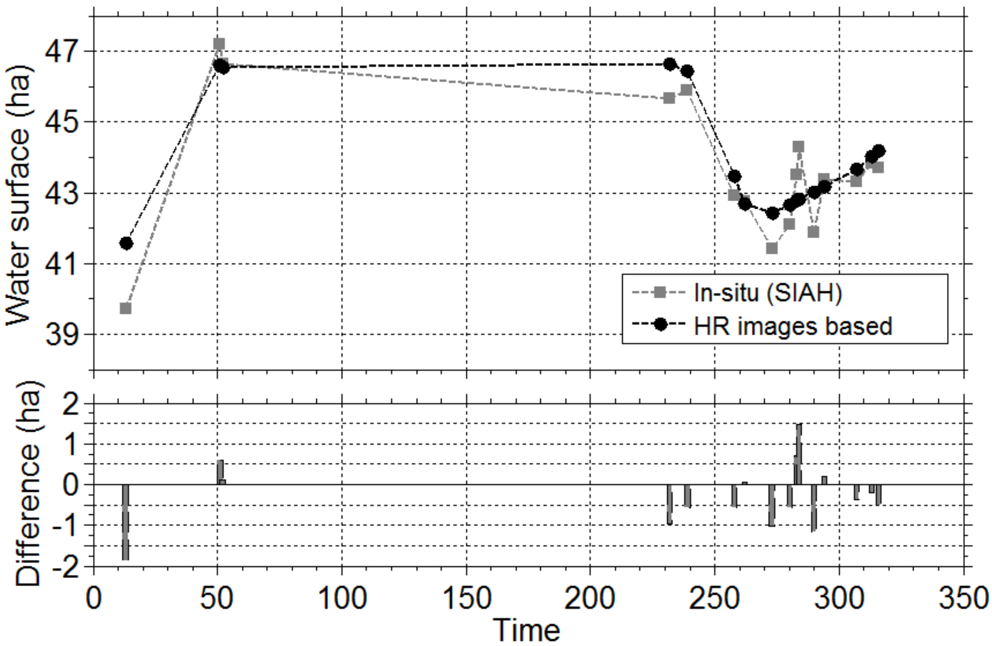
As mentioned by Referee 1, the different methods provide good estimates either of water volume of the lake or water volume changes.
The area of the lake is first control by shore limiting its extent: water volume is mostly controlled by changes in elevation. Once reached a maximum elevation, the lake is spilling on the land around, and water volume changes are dominated by the variations of the lake area. The surface of the lake varies greatly along the hydrological cycle from 42 to 52 ha, that is to say of around 20% of its maximum extent.

On lake La Bure, the accurate determination of the lake surface is still challenging as the shores are covered with vegetation (grass and/or trees). Some uncertainty can also come from the mixels effect (pixels superposed on both water and land), and the shadow effects occurring at high incidence angle on SAR images. In accordance with your remark, we added a new paragraph and a new figure in order to estimate the accuracy of surface estimation in the revised paper (section 4.1: Estimating the lake volume using *HR* images – Method HRBV) :

"The satellite water surfaces derived from HR images were validated by using in situ surface estimated by bathymetric measurements in 2010 (for which the surface have been estimated for each satellite overpass in the domain of validity of the bathymetry data, from 0 to 47ha). Results, presentedin figure 7, show that the water surface estimated from satellites and from bathymetry is strongly correlated (R^2=0.83). Differences never exceed 1.8 ha, which represent a maximum relative root mean square error of 4.3% (RRMSE)."

Results, presented in sections 4.1 and 4.2, show that both errors from altimetry and imagery are acceptable with high value of the coefficients of determination (0.98 and 0.83) and low rrmse (5.0% and 4.3%). Concretely, the good accuracy of the results helped the manager of the lake to re-calibrate his pressure sensor inside the lake for the period 2011 to now.

New Figure 8: Comparison of satellite-estimated and bathymetry time series of the water surface of lake "la Bure" in 2010. Bathymetry data are only available for water surface ranged between 0 and 47ha. No satellite data (HR images based) outside of this range is therefore presented.



Altimetry data have an overall good quality because of the signature of the lakes that dominates the radar echo (see our detailed answer below). Due to the problem of availability of in situ data, the third method, named AHRBV, will be the most interesting in the years to come. With the future launches of new SAR (Sentinel-2, Jason-3, Radarsat constellation) and InSAR (SWOT) altimetry and HR imagery (Sentinel-2, Spot 7…) missions, these approaches are likely to generalized to provide a more complete survey of the surface water reservoir. When in situ data are available, the two other techniques (HRBV and ABV) present the advantage to give the estimates of the water volume and not only of its variations. It is worth noticing that in the case of the time-sampling of HR images is denser, HR images can combined with in situ measurements of water levels to estimate water volumes and their changes, similarly to what is done with radar altimetry.

These methods could be temporarily unstable (decrease of the accuracy) in the cases of important variations in the orbit variations of the altimeter (causing hooking effects), of dense cloud cover (for multispectral images), and of dense vegetation cover (for multi-spectral images, SAR images, and also radar altimetry).

These comments were added to a new section in the revised paper.

"4.4 Discussion

"In view of improving the management of water resources, monitoring the available water volume of small lakes at regional, national or global scale is crucial stake, but still challenging using remote sensing technologies. The results presented in the previous sections demonstrate the potential of three approaches to provide an accurate monitoring of the volume water of small reservoir. The methods HRBV and ABV could be applied when they are located under an altimetry track or in the field of view of HR images, and when in situ data are available (which is rare worldwide). It is worth noting that the time-sampling of HR images is generally denser, allowing a more frequent survey of lakes, unlike altimeter.

Due to the lack of in situ data, the method AHRBVC will present the major interest in the coming years, even if it only provides water volume variations. Nowadays, the major drawback is the poor density of altimetry track at low and mid latitudes and their low temporal frequencies, as illustrated in the results of the methods ABV and AHRBVC. With the future launches of new SAR (Sentinel-3, Jason-CS) and InSAR (SWOT) altimetry and HR *imagery (Sentinel-1 and 2, Spot 7, Radarsat constellation) missions, these approaches are likely to be generalized to provide a more complete survey of the surface water reservoir. The interest of these new sensors is double. The first interesting point concerns the wide-swath capabilities of high resolution imagers (<20m), which allow monitoring a wider continental surface (more lakes can be consequently detected during one orbit).The second point concerns the satellite altimeters. Indeed, the new generations of SAR and InSAR altimeters will provide elevation measurements in a medium or a wide swath with better spatial and temporal resolutions (i.e., the same lake will be under several altimeter swaths). Lakes having a crossing with an altimeter track larger than 200 to 300 m, and presenting variations of the water levels greater than the accuracy of the current altimeter (i.e., an annual amplitude greater than several tenths of centimeters), with a minimum surface of ~ 0.04 km² should be detected by both sensors. In this context, the method AHRBVC could be the easier mean to collect water volume change information at large scale. The three methods are weather independent thanks to the use of microwave data (except for multi-spectral HR images). The main factor that could restrict the use of this method is the presence of dense vegetation over the free water, which present the use of multi-spectral images and some SAR at high acquisition frequencies (at C and X bands), and degrade the radar altimetry estimates except during the high water period if the vegetation is covered with water. For most of the irrigation lakes located at mid-latitudes, meteorological conditions and density of the vegetation cover will be similar to the case of lake La Bure. It seems very realistic to think that the three methods presented above will be transferable to other similar lakes located throughout the world."*

SPECIFIC COMMENTS:

Abstract: The abstract should state what bathymetry (lake shape) is being assumed for the 3rd remote sensing only method. State the % error in derived lake volume.

In the new version of the paper, bathymetry is firstly used in the method HRBV. Details about the form of the lake has been added in the abstract when the HRBV is mentioned: *"…assuming a time-varying triangular shape for the shores slope of the lake (this form is well adapted since, it implies a difference inferior to 2% between the theoretical volume of the lake and the one estimated from bathymetry)."*

Introduction:

The space agencies which operated each altimetry/imagery mission should be stated.

The space agencies operating the different remote sensing missions used in this study are mentioned in the data description part 2: "Study area and datasets".

Previously published research estimating lake volume determination should be cited with their error estimates.

Previous works on the determination of lake volumes were added in the introduction.

"Previous studies combined satellite observations of either water levels or extent with bathymetry or in situ measurements of water storage to determine the water volume variations of lakes and inland seas. Water volumes were estimated using bathymetry and Topex/Poseidon water levels for the Big Aral sea (Crétaux et al., 2005), using in situ measurements of water storage and Topex/Poseidon water levels for Lake Dongting, China (Zhang et al., 2006). Water volume variations were determined using in situ water levels and MODIS-derived inundated areas for nine lakes in the Athabasca delta, Canada (Smith and Pavelsky, 2009), in situ water levels and ENVISAT-ASAR images for Lake Izabal, Guatemala (Medina et al., 2010)".

No error estimates are provided in these studies.

The following references have been also added:

Crétaux, J. F., Kouraev, A. V., Papa, F., Berge-Nguyen, M., Cazenave, A., Aladin, N., and S.Plotnikov, I.: Evolution of sea level of the big Aral Sea from satellite altimetry and its implications for water balance. Journal of Great Lakes Research, 31, 520–534, 2005.

Medina, C., Gomez-Enri, J., Alonso, J. J., and Villares, P.: Water volume variations in Lake Izabal (Guatemala) from in situ measurements and ENVISAT Radar Altimeter (RA-2) and Advanced Synthetic Aperture Radar (ASAR) data products. Journal of Hydrology, 382, 34–48, 2010.

Smith, L. C., and Pavelsky, T. M.: Remote sensing of volumetric storage changes in lakes. Earth Surface Processes and Landforms, 34, 1353–1358, 2009

Zhang, J. Q., Xu, K. Q., Yang, Y. H., Qi, L. H., Hayashi, S., and Watanabe, M.: Measuring water storage fluctuations in Lake Dongting, China, by Topex/Poseidon satellite altimetry. Environmental Monitoring and Assessment, 115, 23–37, 2006.

Why have historical studies not included very small lakes?

Historical studies based on radar altimetry did not include small lakes because of the limited coverage of current radar altimetry missions. They mostly studied level changes of great lakes and reservoirs to relate them to climate variations and/or anthropogenic changes. Our goal in this study was to demonstrate the potentialities of radar altimetry (combined or not with satellite images) for the monitoring of water resources for agricultural purpose (i.e., over smaller lakes). This makes sense with the future launches of new altimetry missions (Sentinel-2, Jason-3, SWOT). We added the following sentences in the introduction:

"Despite the relevance of these results, these techniques have not been applied to the study of small lakes due to the difficulty to collect synchronously radar altimeter data, high resolution images and consistent ground data. No information is thus available about the limits of the remote sensing technologies for small lakes, contrary to great lakes (Birkett, 1995; Cazenave et al., 1997; Crétaux et al., 2005; 2011; Zhang et al., 2006; Medina et al., 2010), which is a strong limitation for further take full advantage of the future satellite missions (Sentinel-1/2, Jason CS, Radarsat constellation, Swot…).

This study proposes three different methods to estimate the water volume of lakes using high-resolution imagery, satellite altimetry and/or in situ measurements. Our goal is to demonstrate the feasibility of these techniques over small lakes (<100 ha). The method are used to determine the variations in the volume of Lake "La Bure", a small reservoir (with an average area of 52 ha) located in an irrigated agricultural area in the south-west of France). Although this study is limited to a single example because of the sparse cover of current altimetry tracks and the lack of in situ observations on other lakes to validate the approaches presented below, it shows that can be achieved with current altimetry missions."

Study Area: Are there any other (e.g., 10-day) altimeter ground tracks across Lake La Bure? Would the ICESat-1 data set been of (sporadic) use in the 2003-2009 period for such a small lake?

Unfortunately, lake La Bure is under neither any other altimeter track from Topex/Poseidon – Jason-1 – Jason-2 or at the crossings with other Envisat track, nor any ICESat-1 one.

SAR images: Provide/define the backscatter symbol. For absolute novices why are equations 1) and 2) relevant to the determination of areal extent?

The backscatter symbol has been defined. Equation 1 and 2) and the following information how were processed the images to obtain the final product on which were performed the classifications. They are useful for anyone who wants to know what was really done in this study.

What is the difference between "full quad" and "Fine Quad"?

Two quad-pol modes are available with radarsat-2: standard and fine. they are differentiable by their pixel spacing, resolution. In our work, we only use the finer quad-pol mode, for which specification are given in table 1. To avoid confusion, the term "full" has been removed.

SAR+Optical Images: What are the theoretical estimates on a real estimation? Is there a method of determining this? Optical (cloud detection, atmospheric correction, resolution), SAR (backscatter, geo-referencing, speckle filtering, resolution).

We did not understand the Referee comment. We will be pleased to answer if the referee reformulates this question.

Altimetry Data: State the along-track resolution of the ENVISAT GDR data. How many valid elevation data points were acquire with each pass? With the lake being only a maximum of 52ha (_0.52km2), and the reference ground track looking as though it passes to the East of the lake (Fig.6), and an along track sampling of _300m it is surprising that any elevation measurements could be acquired. Could Fig.6 be redrawn to show the actual pass locations and their spatial variation?

We added the along-track resolution of the Envisat RA-2 data in paragraph 2.2.3 Altimetry data:
“The along track resolution of Envisat RA-2 is around 350 m in hi-frequency mode”

When a water body is encompassed in the footprint, the signal received by the altimeter is dominated by the presence of water (Michailowsky et al., 2012). The corresponding radar echo or waveform has a specular shape. The signature of vegetation could be eventually identified by the presence of secondary maxima in the trailing edge (Calmant et al., 2008). This allows retrieving reliable water levels even for rivers of width less than 300 m under a forest cover (Frappart et al., 2005; 2006b; Santos da Silva et al., 2010; 2012; Michailowsky et al., 2012). Due to the small dimensions of the lake, we used a tool that allows us to eliminate manually the non-valid measurements. In the figure below, you can see that, for each altimeter cycle, we are able to clearly discriminating the lake level from the elevation of the land. To make this clear in the manuscript, we added the following paragraphs in the end of part 3.2 Altimetry-based water levels:

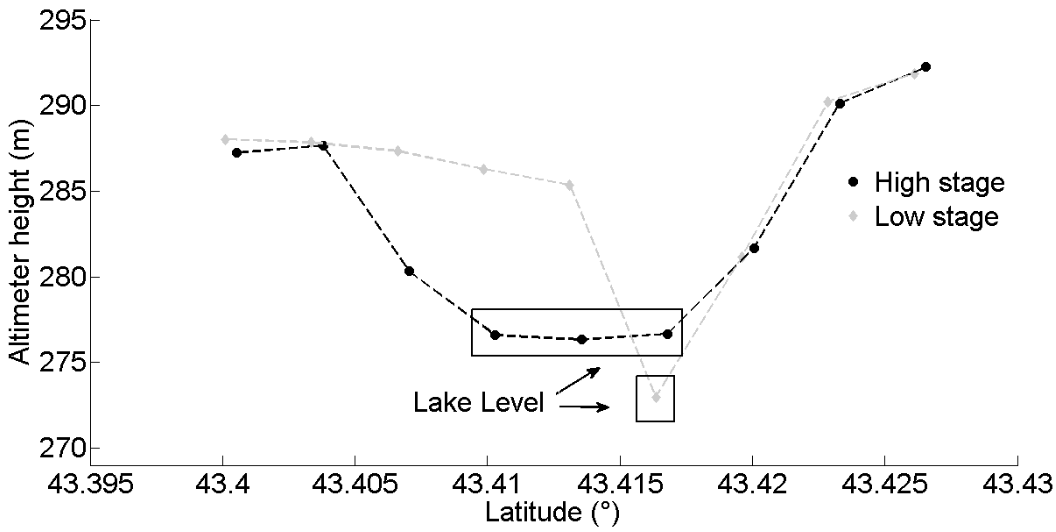
“Valid water levels were identified as they exhibit low levels variations (typically of a few centimeters) between the shores of the lake (Figure 7). During Low water periods, only one valid water level is likely to be found. Due to the few valid points present each cycle, from one to five, no specific processing to remove hooking effects was applied”.

“When a water body is encompassed in the footprint, the signal received by the altimeter is dominated by the presence of water (Michailowsky et al., 2012). The corresponding radar echo or waveform has a specular shape. The signature of vegetation could be eventually identified by the presence of secondary maxima in the trailing edge (Calmant et al., 2008). This allows retrieving reliable water levels even for rivers of width less than 300 m under a forest cover (Frappart et al., 2005; 2006b; Santos da Silva et al., 2010; 2012; Michailowsky et al., 2012). Due to the small dimensions of the lake, VALS allowed us to pick up manually the valid measurements using its selection tool as presented in Figure 7”.

The number of valid for each altimeter cycle elevation points varies from 1 to 5 along the hydrological cycle.

The associate new figure 7 of the revised paper is presented below:

New figure 7: “*Along-track evolution of the altimeter height over lake “la Bure” and its surroundings, before, during and after the lake of “la Bure”. Two cases are presented corresponding to high and low stage of the lake.*”



Calmant S., F. Seyler, et Crétaux J-F. (2008). Monitoring continental surface waters by satellite altimetry. Surveys Geophys., 29, 247-269. doi:10.1007/s10712-008-9051-1.

Michailovsky, C. I. B., McEnnis, S., Berry, P. A. M., Smith, R., & Bauer-Gottwein, P. (2012). River monitoring from satellite radar altimetry in the Zambezi River basin. Hydrology and Earth System Sciences, 16(7), 2181-2192. 10.5194/hess-16-2181-2012

In Situ Data: How was the 1987 volume estimated? What are the estimated errors on the in situ volumes?

The abacus of the lake has been established in 1987 by engineers, from the studying of the digital elevation model of the valley (derived from detailed maps provided by the French Geographic Institute (IGN)). No error is provided by the manager of the lake about this abacus.

Moreover, as shown in the revised paper, bathymetry data are in accordance with the abacus (less than 2% of relative errors).

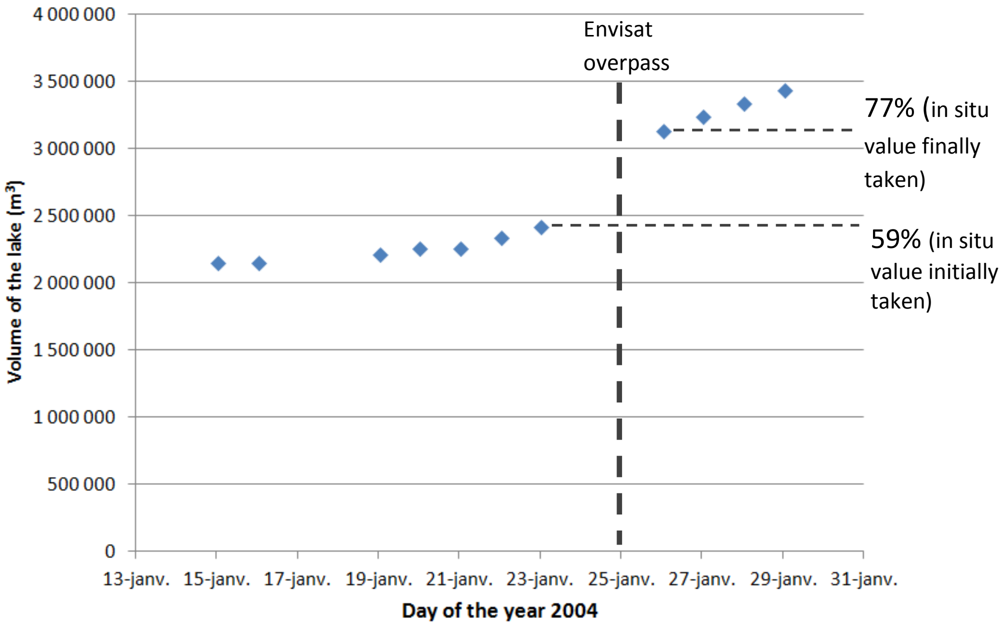
What frequency are the in situ volume estimates cf altimetry or imagery?

In situ data of volume are estimated from weekly measurements of in situ water level (see Table 2 of the revised paper).

Altimetry-based water levels: The altimeter range precision can vary from cm to tens of cm over lakes/reservoirs. “Hooking effects” is really the more technical term of “offranging”. Were all hooked elevations rejected, and what is the difference in elevation accuracy between direct and off-ranging elevations? How were the “hooked” measurements corrected for? Could these hooked measurements been responsible for the >1m differences between instrument and in situ measurements?

To clarify this point, the following sentence has been added in the section 3.2: *“Valid water levels were identified as they exhibit low levels variations (typically of a few centimeters) between the shores of the lake (Figure7). During Low water periods, only one valid water level is likely to be found. Due to the few valid points present each cycle, from one to five, no specific processing to remove hooking effects was applied”.*

The unique difference greater than 1 m was in fact due to a mistake in the reading of the in situ water levels. As you can see on Fig. 11 of the submitted manuscript, there is a huge change in volume in the end of January 2004 caused by a large rainfall event (a zoom on volume change is presented on figure below). The volume of lake is rising from 59% to 77% of the maximum from the 23 to 26 January 2004. This represents a change in water level around 1.47m (following equation given in Figure 3 of the revised paper. Envisat flew over the lake on January 25, after the rainfall. Mistakenly, we use the water level of 23 January instead the one from the 26. We corrected this mistake and recomputed the relationship between altimetry-based water levels and volumes, and changed the figures from 9 to 11 and the corresponding statistics.

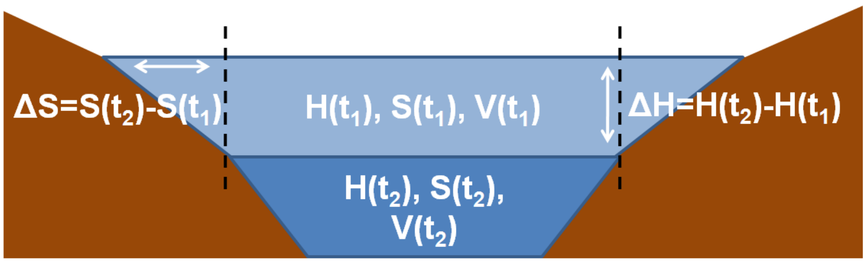


Lake Volume Estimates: What simple geometric shape was the lake modeled as? Provide references for equations 4+5 (e.g., based on C.M. Taube, chapter 12 "Three Methods for Computing the Volume of a Lake". Annual of Fisheries Survey Methods II, 2000 ??)

Referee 1 is right. We implicitly choose a shape for the lake shores which slope depends on the ratio between the variation of surface and the variation of height between t1 and t2.
We simplified equations 4 and 5 into one (in the revised paper) and added a figure (in this document only to not overload the revised paper) that makes clearer what was done, and referred to Taube (2000): "similarly to the second method proposed by Taube (2000). We added the reference Taube (2000), and the following paragraph in the end of part 3.3, Lake volume estimates:

"A triangular geometric shape was chosen to reflect the volume changes as a function of the variations of both surface (ΔS) and height (Δh) between t_1 and t_2. The ratio between ΔS and Δh characterizes the slope of the lake shores and permits to reproduce the changes of regime that occurs during the lake's filling and the emptying phases." (See figure below for details).

The figure below is not included in the revised paper, in order to not overload the number of figures. Nevertheless, we propose to add it if the referee thinks that it is necessary to do it to improve the clarity of the paper.



Equations 4 and 5 have been simplified following this development:

Eq 4: $\Delta H > 0$: $\Delta V = S(t_1) * \Delta H + ½ * (\Delta S + \Delta H) = S(t_1) * |\Delta H| + ½ * (|\Delta S| * |\Delta H|)$

Eq 5: $\Delta H < 0$: $\Delta V = -(S(t_1)-|\Delta S|) * \Delta H + ½ * (\Delta S * \Delta H)$

$\Delta V = S(t_1) * |\Delta H| + |\Delta S| * \Delta H - ½ * (|\Delta S| * \Delta H)$

$\Delta V = S(t_1) * |\Delta H| - ½ * (|\Delta S| * |\Delta H|)$

So the new Eq. 4 is: $\Delta V = S(t1) * |\Delta H| + sgn(\Delta H) * (|\Delta S| * |\Delta H|)/2$

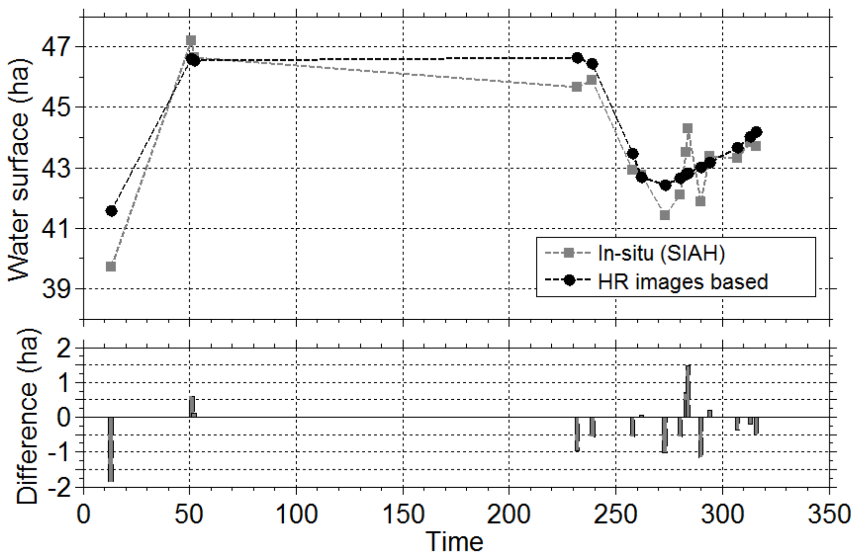
What can the readers deduce from the horizontal spread of data points in Figure 13?

The horizontal spread of data is both attributed to the time lag between RA-2 and images acquisitions, and to the capability of estimating the water surface from HR images. This last point has been developed in the paper at the beginning of the section 4.1:

"The satellite water surfaces derived from HR images were validated by using in situ surface estimated by bathymetric measurements in 2010 (for which the surface have been estimated for each satellite overpass in the domain of validity of the bathymetry data, from 0 to 47ha). Results, presentedin figure 7, show that the water surface estimated from satellites and from bathymetry is strongly correlated (R^2=0.83). Differences never exceed 1.8 ha, which represent a maximum relative root mean square error of 4.3% (RRMSE)."

One figure has been added in the revised paper to help the reader:

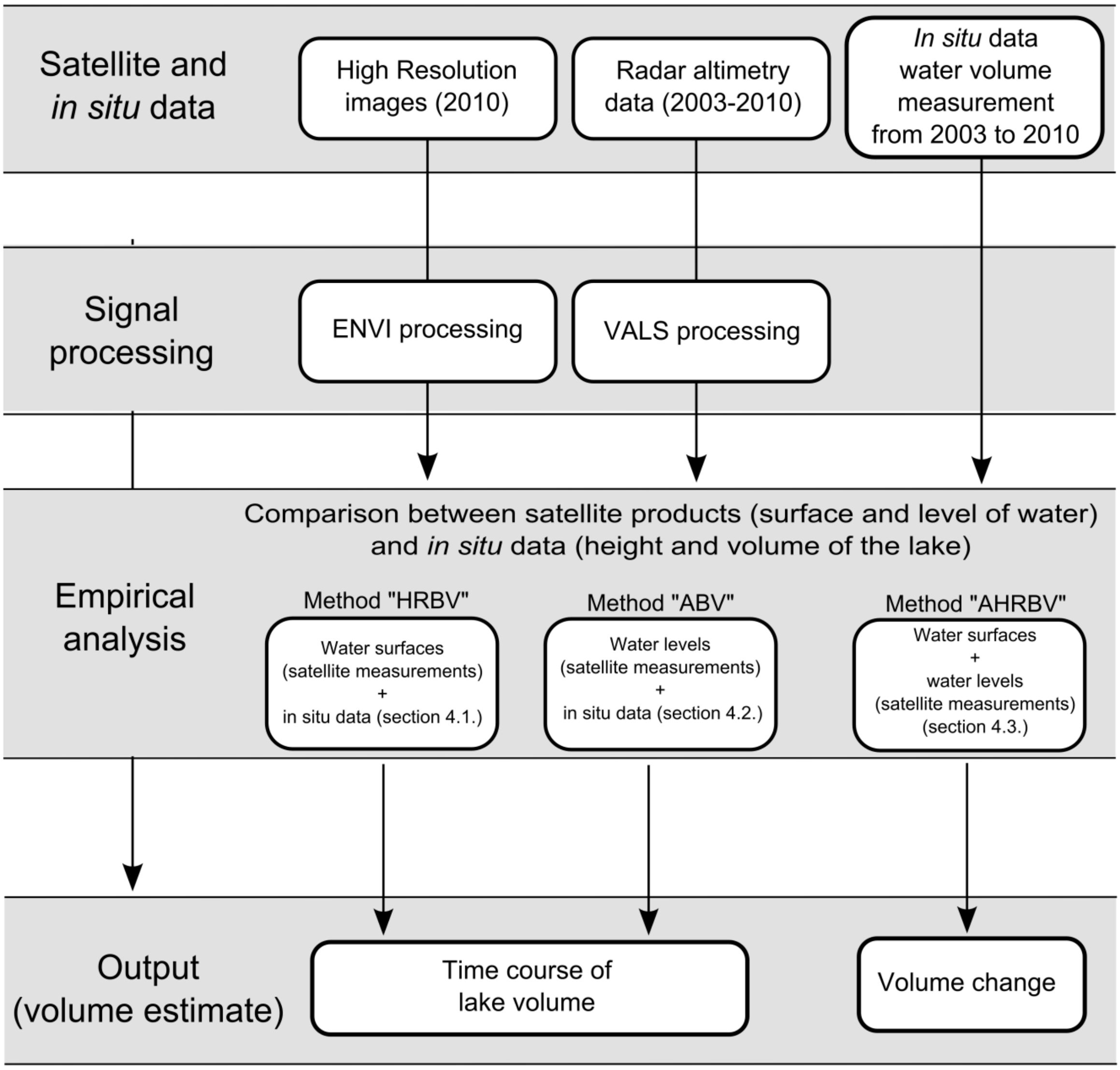
New Figure 8: Comparison of satellite-estimated and bathymetry time series of the water surface of lake "la Bure" in 2010. Bathymetry data are only available for water surface ranged between 0 and 47ha. No satellite data (HR images based) outside of this range is therefore presented.



Combined use: The research also needs an assumed lake bathymetry which the authors are not highlighting sufficiently.

The third method, now identified as the method "AHRBVC", do not require bathymetry to be apply. Bathymetry data is only used for validation. This point has been clarified by adding a sentence in the introduction part ("*The third one, named AHRBVC (Altimetry and High resolution Base Volumes Changes), is based on the combination of information on the lake area derived from satellite images and altimetry-based water levels to estimate water volume changes. No ground data are used in the third method (except for validation)",* and by modifying the figure 5 as shown below. The use of ground data is clarified for the three methods.

New Figure 5: Flowchart showing the processing steps used to estimate the volume of Lake "la Bure" using high-resolution images (HR), radar altimetry (RA-2), and ground data for each of the three methods *(HRBV, ABV and AHRBVC).*



What variations in estimated volume arise by assuming various lake bed geometries?

We check the pertinence of the choice of the form of the lake bed by comparing the measured volume and those given by the bathymetry. There is a difference lower than 2%. Studying the impact of various lake bed geometries appears thus not necessary.

Conclusions: The 3rd method still requires bathymetry – how can this be achieved?

As discussed in our previous response, bathymetry is not required to apply the third method. This fact is clear in the conclusion:" Finally, in the third method, named AHRBVC (section 4.3.), almost-synchronous satellite estimates of water surfaces and levels were used to estimate the variations in the water volume. This approach did not require any *in situ* measurements and produced promising results (R^2=0.98), which were better than those obtained using the first two approaches."

The bathymetry is achieved by using a triangular form of the lake as explained in a previous response.

TECHNICAL CORRECTIONS:

References:

Frappart et al., 2012 or 2013?, Wang et al., 2011 missing, Baup et al in the reference list has the date as "201" and not "2012" , Frappart et al., 2008 reference not used in the main text.

The technical corrections were taken into account in the revised version of the manuscript.

Figures:

Figure 3 could indicate typical errors on the curve

This curve represents the abacus of the lake, established by engineer in 1987 from the real relief of the valley. We consider this curve as a true reference, with no error.

Figure 6 could indicate the real track locations and their variation across this small lake

As you proposed, real track locations of the altimeter have been added on figure 6 and removed from figure 1c for best clarity.

New Figure 6: Examples of temporal evolution of the lake shorelines resulting of the supervised classification of Radarsat-2 image: the green, blue, yellow, and pink lines represent the lake shoreline *on 31 July, 23 June, 11 October, and 30 September 2010, respectively; the orange line to the east of the lake represents the theoretical groundtrack of the Envisat altimeter. The black and white dots represent 20 Hz altimetry measurements over the lake.*

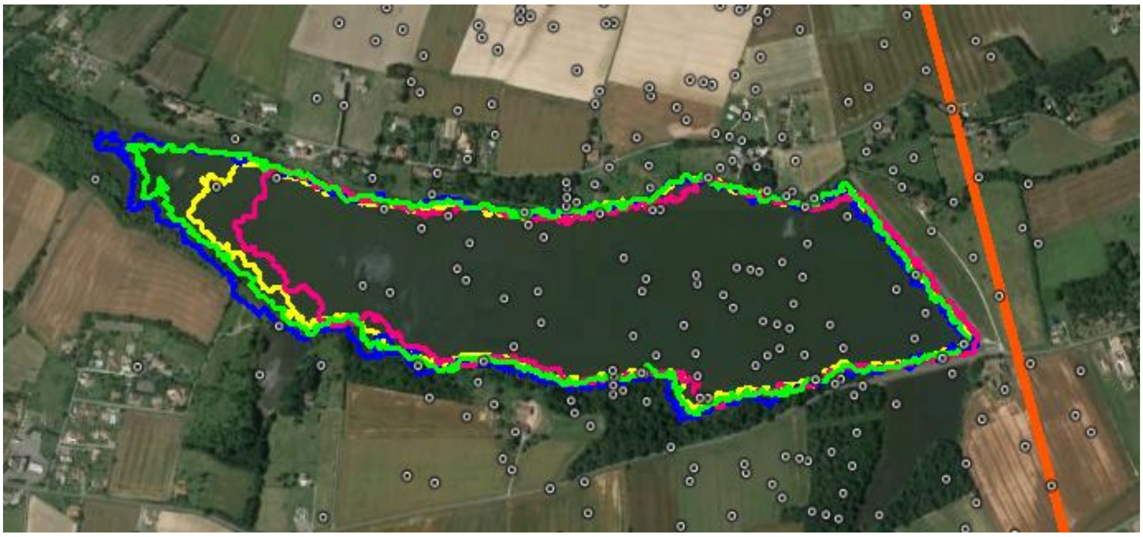


Figure 12, ground measurements are displayed as "a solid grey line"?

Now Figure 14, this point has been clarified in the figure caption as follow: "*Comparison between volume estimates from altimeter (gray square), HR images (black dots), and ground measurements (grey diamond). Differences of volume estimates with in situ measurements are presented on the lower panel for both HRBV and ABV methods.*

Figure 13, define symbols

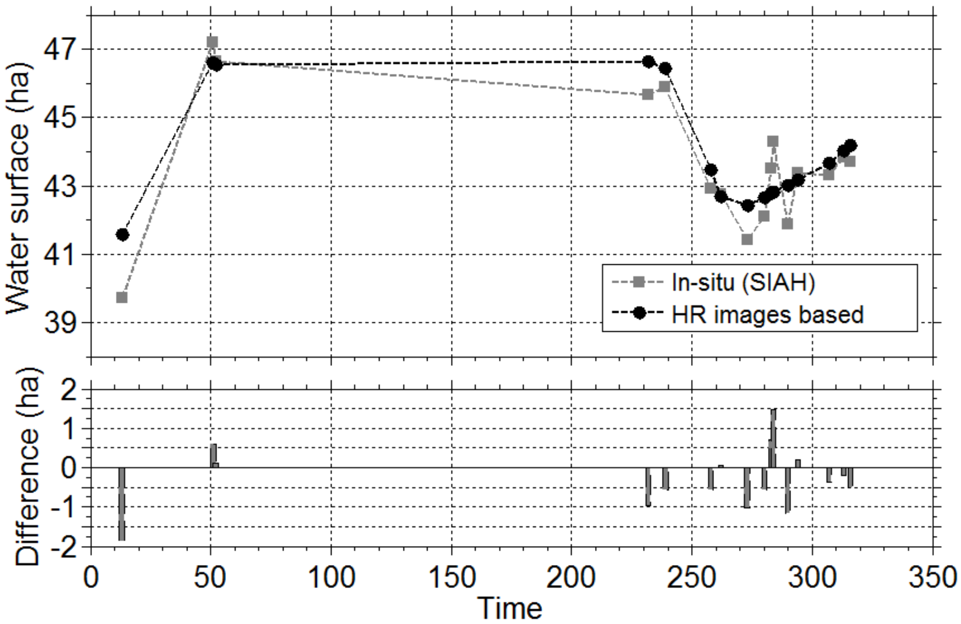
Now Figure 15, symbols are now defined in the figure caption, as follow:

“Relationship between satellite water surface (HR images) and water level products (Altimetry) acquired with a time lag of less than 5 days. *The gray-scale color of each dot is used to represent the time lag observed between altimetry and imagery data.”*

All figures showing altimetry levels or imagery extents should have error bars.

To avoid overloading the figures, we choose to well specific the errors associated to altimetry and imagery in the text of the revised paper. To this end, we added a paragraph and a figure at the beginning of the section 4.1, which focuses on the error of HR imagery for the estimation of the water surface: *“The satellite water surfaces derived from HR images were validated by using in situ surface estimated by bathymetric measurements in 2010 (for which the surface have been estimated for each satellite overpass in the domain of validity of the bathymetry data, from 0 to 47ha). Results, presentedin figure 7, show that the water surface estimated from satellites and from bathymetry is strongly correlated (R^2=0.83). Differences never exceed 1.8 ha, which represent a maximum relative root mean square error of 4.3% (RRMSE).”*

New Figure 8: Comparison of satellite-estimated and bathymetry time series of the water surface of lake "la Bure" in 2010. Bathymetry data are only available for water surface ranged between 0 and 47ha. No satellite data (HR images based) outside of this range is therefore presented.



The errors associated to the use of altimetry data are mentioned in the section 4.2.1: The RMSE and R^2 were equal to 0.27 m and 0.99, respectively, showing that the two sources of data were in very good agreement.