

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

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Received and published: 20 January 2014

General Comments

This manuscript estimates water levels, water areas, water volume changes and water volumes of Lake la Bure. It is a small lake of maximum 52 hectare in size, and this makes it interesting to pursue the publication of this paper. By gradually moving from larger to smaller lakes, the scientific community becomes closer to the estimation of water volumes in small reservoirs and ultimately water depths in rivers. This will have great potential for manifold applications. Radar altimetry (ENVISAT-RA2) and high resolution images from one optical and two SAR satellites are all combined, being a good example of fusion of multi-source satellite data. This study is valuable for the hydrologic community to understand the potential of satellite observations to monitor water stocks in ungauged basins. It fits the scope of HESS. The manuscript is technically sound and the work can be published by HESS, if more attention to small lakes and the dependency of in situ data is provided. Also more emphasis should be given to the systematic mapping of lake levels (possible but not very regularly), lake area (easy and accurate), volume changes (difficult, unless in situ data is used) or volumes (impossible, unless in situ data is used). If these major critique is addressed in a next version of the manuscript, then I recommend this paper to be published.

We want to thank W.G.M. Bastiaanssen for his constructive comments that will help us in improving the quality and the clarity of our manuscript and the overall good opinion he has about this study. In the followings, we will answer the best we can his general and specific comments.

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

1. The study objectives should be more clearly described. Many other research groups have published methodologies related to satellite measurements for estimating volume changes in larger lakes and reservoirs. In that sense, the level of innovation of this paper is limited. The core objective should be described more precisely: detect limitations of the remote sensing technology for small lakes ? To use radar measurements for the detection of the size of water bodies, instead of optical imagery ? Is it new because volumes are estimated, instead of volume changes ?

Objectives have been clarified in the text in the abstract and in the introduction parts:

In the abstract : *“In spite of the strong interest for monitoring surface water resources at small-scale using radar altimetry and satellite imagery, no information is available about the limits of the remote sensing technologies for small lakes, mainly use for irrigation purposes.”*

In the introduction, we replaced the two first sentences of the last paragraph (“In this study, we developed a method to estimate the water volume of small lakes (<100 ha) by combining satellite altimetry and high-resolution imagery. The method was used to determine the variation 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.”) with *“This study proposes three different methods to estimate water volume and water volumes changes 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)”*.

2. The manuscript refers to volume changes by using altimetry and water body sizes. The manuscript refers to volumes if bathymetry information is used. The difference and integration of these different approaches need to be spelled out more clearly. What kind of information is used

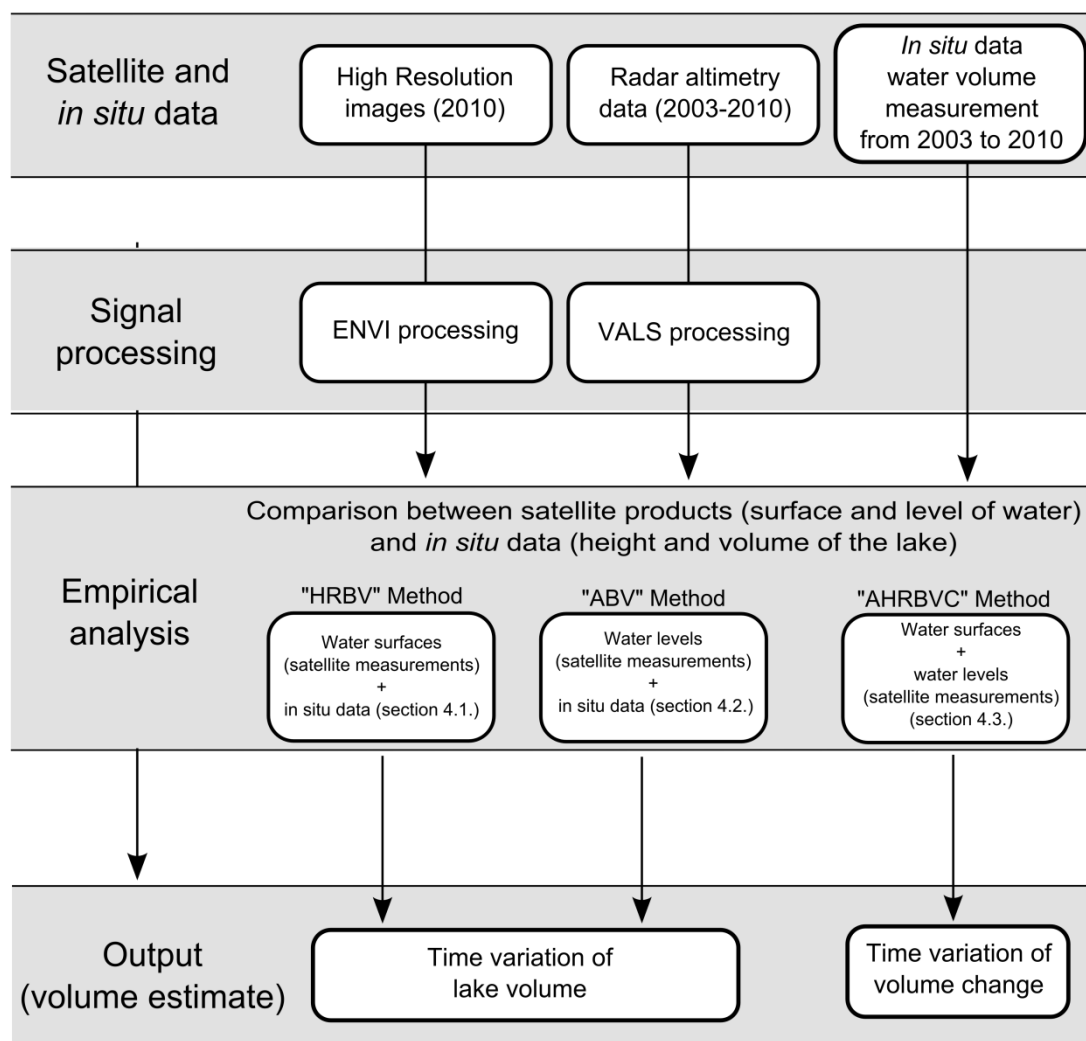
when ? Figure 5 is a good start, but needs to be made more complete, with explicit descriptions of levels, areas, volume changes and volumes.

The different types of information used to infer water volumes and water volume changes appear now clearly in the abstract. To help the reader to keep in mind which kind of information is used for each method, we named them:

- *HRBV (High Resolution images Based Volumes),*
- *ABV (Altimetry Based Volumes),*
- *AHRBVC (Altimetry and High Resolution Based Volumes Changes),*

and we added the following sentence in the introduction: "The two firsts consist in relating either lake area derived from satellite images or altimetry-based water levels in combination with in situ estimates of water levels and volumes to determine the water volume of the lake. They are respectively called HRBV (High Resolution images Based Volumes) and ABV (Altimetry Based Volumes). The third one, called AHRBVC (Altimetry and High Resolution Based 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)".

Figure 5 was modified as follows (the data used for each section is now clearly mentioned in the "Empirical Analysis" part):



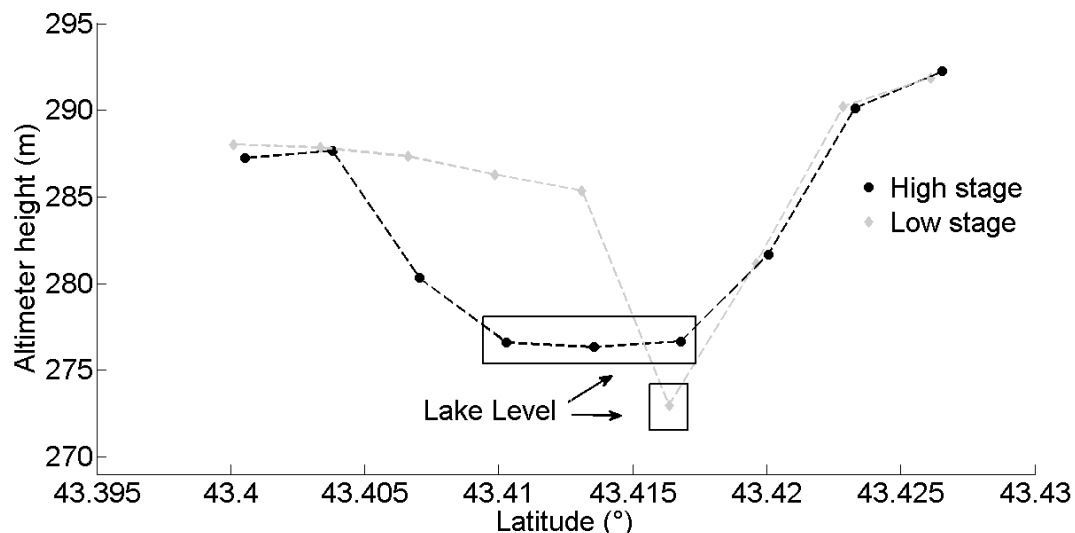
3. The Radar Altimeter onboard Envisat had a footprint of 2 to 10 km, depending on the geographical area. This footprint is approximately 10 times larger than the size of the water body, hence elevation effects of the surround terrain are incorporated into the altimeter signal. How is this potential mismatch of scale solved? By ascribing all differences in elevation to water, assuming that the elevation differences on land can be ignored? What is the effect of a growing crop on the RA-2 signal?

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 Fig. 7".

New figure 7: *"Along-track evolution of the altimeter height over the lake of "la Bure". Two cases are presented; corresponding to high and low stage of lake."*



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

Michailowsky, 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

4. This study only tested one lake (42-52 ha) but the title was generalized to small lakes. A plural term could be justified if more discussion on the challenge of measuring small lakes is included. It is for instance interesting to quantify the limit of small lakes to which the method can be applied.

Our goal was to test these methods on three small lakes under the same Envisat groundtrack, in the area continuously monitored by CESBIO in the framework of the “Sud-Ouest” project. We obtained temporal variations of the elevation that could be consistent with water level changes for these three small lakes. Unfortunately, no in situ data (gauge records or bathymetry) were available to validate our results for two of the three lakes. Nevertheless, as previous studies on small rivers in tropical areas (i.e., where the vegetation cover is denser) showed promising results, we are optimistic that this kind of study is likely to be generalized to small irrigation lakes on plains. The major drawback is the poor density of altimetry track at low and mid latitudes and their low temporal frequencies. But this could be overcome in the next years with the launch of SAR and SAR-interferometry altimeters that will provide elevation measurements in a swath with better spatial and temporal (the same lake will be in the field of view of different altimeter tracks) resolutions. In our opinion, with the current sensors, this kind of study is likely to be done for lakes presenting a cross-section with the altimeter track larger than 200 to 300 m, variations of the water levels greater than the accuracy of the current altimeter (i.e., an annual amplitude greater than several tenths of centimeters), a minimum surface of ~ 0.04 km² to be able to be detected by both sensors.

We added a new section:

4.4 Discussion

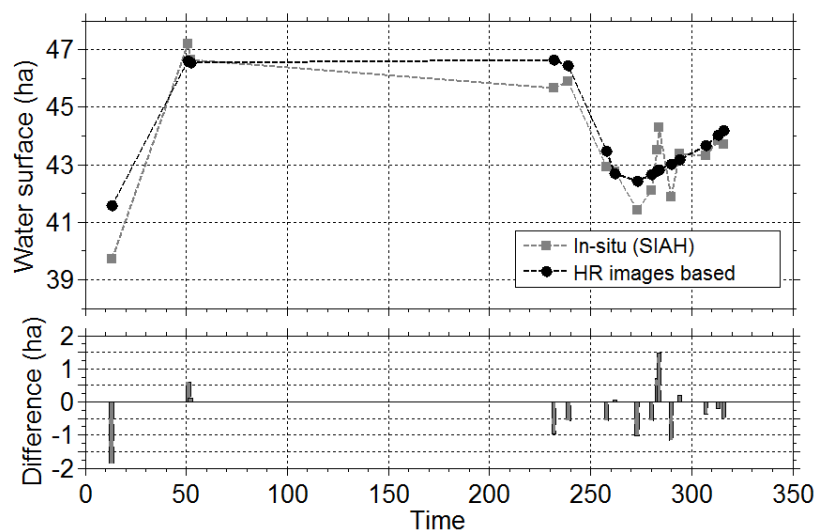
“In view of improving the management of water resources, monitoring the available water volume of small lakes at regional, national or global scale is crucial stake, but still challenging using remote sensing technologies. The results presented in the previous sections demonstrate the potential of three 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.”

5. What is the accuracy of the estimated lake area from images? The estimated level and volume have been validated and presented in this manuscript, but a discussion on the accuracy of

estimates lake area is absent. The lake area is an important input to the investigated first and third methods, thus it is also relevant to validate the estimated lake area. As a matter of fact, I like to see also the views from the authors on using optical vs. radar imagers for lake area detection. A small discussion on accuracy vs. time intervals, complexity of processing and costs would increase the value of this paper.

This important point has been improved in the paper. One figure has been added to increase the value of the paper, showing the relationship between the estimated water surface from satellite images and those estimated by using bathymetry measurements (for which, surfaces have been calculated for each satellite overpass). Results show that the surface estimated by satellite is quite accurate with a mean rmse of 0.68 ha and a coefficient of determination of 0.83 (figure shown below). This relationship has been obtained for surfaces ranging from 0 and 47 ha, because the lake was not completely full during bathymetric measurements in 2010.



The following sentence has been added in the revised paper in 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, presented in 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)."

6. The captions are all rather short in general. The graphs and tables will be better understood if more technical information is provided. Like "in situ measurements of water level" or "Formosat satellite data".

Figure and table captions have been more detailed.

Two figures have been also added in the revised paper, in accordance with all your comments (new figure 7 and 8).

Specific comments

P2 L17: It should be $R^2 = 0.98$? as the same in the text and conclusions

You are right. This value has been modified in the abstract.

P3 L30: Envisat and Alos are no longer current systems (both died)

In accordance with your remark, the phrase has been modified as follow: "Past (ALOS, ENVISAT), current (Formosat-2, Radarsat-2, Spot 4-5, TerraSAR-X...), and future (Radarsat Constellation, Sentinel 1-2, TerraSAR-L...) Earth observation missions..."

P4 L 13: Describe why earlier solutions are not applied to small lakes, and mention more explicitly how you envisage a solution that tackles this problem

The small size of radar altimeter swath combined to the scarcity of *in situ* data acquired over small lake, and to the few synchronous HR images make very difficult to study the potential of radar altimetry and imagery for monitoring small lakes. The paper aim to evaluate the potentiality of multi-sensors approaches in view of using the next generation of wide swath satellites sensors (Sentinel-1-2-3, Jason-3, Radarsat Constellation, Swot...).

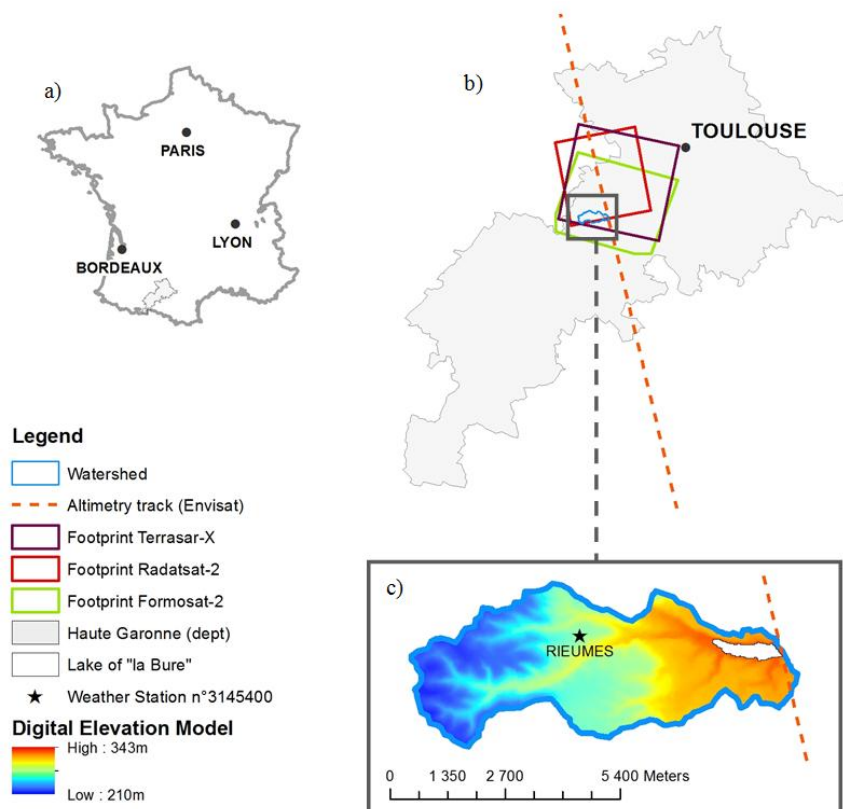
The sentence has been modified as follow: *"Despite the relevance of these results, these techniques have not been applied yet to study small lakes due to the difficulty to collect synchronously radar altimeter data, high resolution images and consistent ground data. No information is thus available 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 taking full advantage of the future satellite missions. The lake "la Bure" study site offers a unique opportunity to apply these techniques over a well-monitored small lake."*

References have been added in the revised paper.

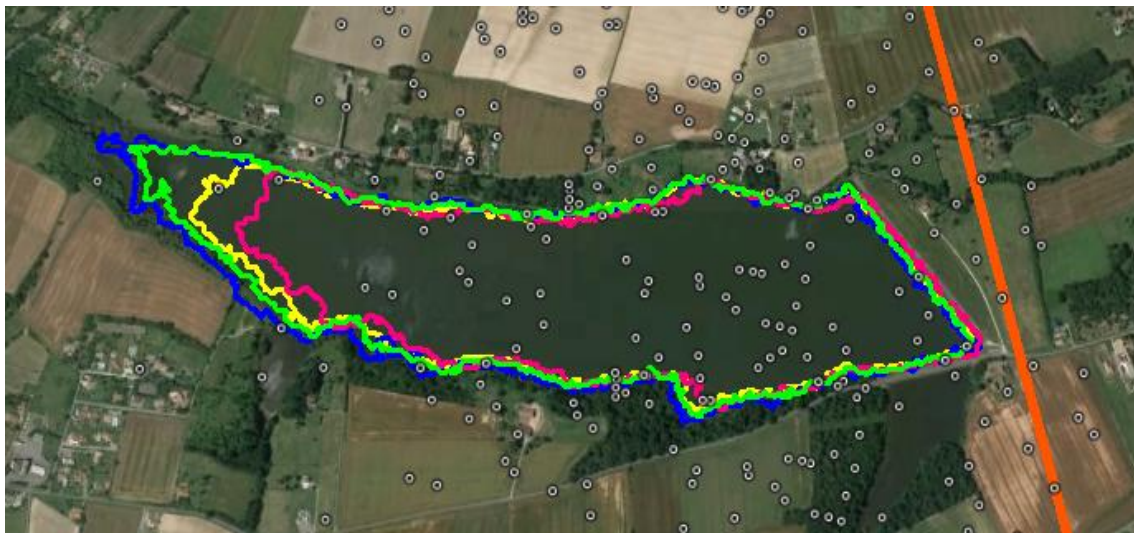
P5 Figure 1: A messy figure, and difficult to interpret. What does the cloud of points in the lower figure represent ? Are this all individual radar pulses ?

Each point represents each altimetry radar pulse over the lake. For best clarity, Figure 1 has been simplified, and the cloud of point has been moved to figure 6, as illustrated below:

New figure 1, for which the figure caption has been completed as follow: *"Lake "la Bure" is located in the south-west of France 40 km south-west of Toulouse, in the department of Haute Garonne (a), within the footprint of TERRASAR-X (purple empty rectangle), RADARSAT-2 (red empty rectangle), and FORMOSAT-2 (green empty rectangle) and under ENVISAT RA-2 altimetry track 773 (b). The weather station and the lake are presented inside the watershed, superimposed to the digital elevation model (c)."*



New figure 6, for which the legend has been slightly modified as follow: *“Examples of temporal... The black and white dots represent 20 Hz altimetry measurements over the lake.”*



Explain in the main text how many original RA-2 data points you have, and how is this processed further into one single final value of the water level

This point has been explained in the response of your comment number 3.

P5 Figure 2: No need to present this time table. The intervals and frequency is clear when you present the results

The timeline acquisition of HR images is very important here. Indeed, the temporal sampling is not regular, contrary to altimetry data and we think that it is judicious to present this figure for best readability.

P6 L4. Better to provide spatial and temporal resolutions for the three sensors in Table

For best clarity, these two information have been added in the table 1 (orbit cycle and spatial sampling).

Satellite	Frequency/ wavelength	Mode	Polarisation states	Range of incidence angle	Orbit cycle	Spatial sampling
Radarsat-2	C-band ($f=5.405$ GHz)	FQ	HH,VV,VH,HV	23° to 41°	24 days	5 m
Terrasar-X	X-band ($f=9.65$ GHz)	SL/SM	HH	27° to 53°	11 days	1.5 m (SL) 3 m (SM)
Formosat-2	λ : 0.44-0.90 μm	Multi-spectral	-	$\pm 45^\circ$	1 day	8 m

P7 L13. Provide the links for each data source throughout the text.

This information has been added in the revised paper: *"Formosat-2 images were processed by the French company: "CS Systèmes d'Information" in the framework of Kalideos projet (<http://kalideos.cnes.fr>)."*

The source of Terrasar-X, radarsat-2 and Envisat data are already mentioned in the text (respectively SOAR projet of the Canadian Space Agency, DLR and ESA).

P8 L24. Table 2, Better to specify the dates, e.g. for water levels, 2003-2010; please check the date for the rainfall, shouldn't be 2003-2010? As in Figure 4, the rainfall data last from 2003 to 2010.

You are right; water levels and rainfalls are available since 2003. The dates and the title of the second colon have been modified in Table 2 as follow:

Ground data	Available period	Sampling frequency
Lake calibration function (abacus)	In 1987	-
Bathymetric draw	In 2010	-
Water level	2003-2010	Weekly
Rainfall	2003-2010	Daily

P8 Figure 4: Explain the plateau for maximum volume. Is that a spillway effect because the water level cannot rise further ?

This plateau effect is effectively due to spillway effect. The water level can't rise further. This point has been clarified in the revised paper : *"The volume ranged between 1.5 and 4.1 hm³ and describes an annual cycle with alternation of filling and emptying phases. The water level can not rise further than 4.1 hm³ due to spillway effect."*

Figure 4 could be improved by showing P – ET₀, because lake evaporation will largely affect the volumes. Actual lake evaporation is rather complex to compute, but I suggest to take a simple reference evaporation for this sake. That is at least better than ignoring the effects of evaporation on lake volumes.

Figure 4 represents the measured water volume of the lake. *In situ* measurements include the effects of rainfall and evapotranspiration (P-ET₀). It is thus unnecessary to mention and to display these terms on Figure 4.

P9 Figure 6: This confirms that RA-2 is not having a central overpass over the lake. How did you derive the lake level fluctuations (see comments before) ? More details on the footprint size, the intervals between two footprints and number of valid footprints within lake should be given.

The explanations on the derivation of lake level variations are given in response to your previous comment. (comment number 3)

P10 L23. More details are needed here. How to determine a footprint as an outlier? What was the procedure to correct for hooking effects ?

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".*

P10 L25. No geoid was used? What datum/reference the water level is with respect to? The error bar for the estimated water levels should be provided.

In this study, it is not necessary to use a geoid as reference for the water level time series because only one time-series has been built. It would have been different in the case of a great lake or for a river basin. In these cases, the referencing to a geoid would have been mandatory to monitor the flow from upstream to downstream for instance. For only one time series, the major interest would have been to have a common reference with the gauge to estimate the bias in the altimetry measurement. Unfortunately, the *in situ* gauge is not leveled yet. The water levels of the lake are calculated with reference to WGS84 ellipsoid, and expressed as relative value of water level (in the new version of the paper). It has been added to the manuscript at the end of the section 3.2. *"All water levels are given with reference to WGS84 ellipsoid, and presented as relative value of water level."*

The error bar is provided on the lower panel of figure 11 as the difference between the altimetry-based and in situ water levels.

P10 L28. On average, how many valid footprints were finally captured for each cycle ? Better to provide the minimum and maximum value for a certain cycle. How many water levels were finally obtained during the studied period?

The number of valid for each altimeter cycle elevation points varies from 1 to 5 along the hydrological cycle. This was added in the text. We also added:

"At the end of the end of the process, 67 valid water levels were estimated that corresponds to 77 % of all the available altimetry cycles"

P11 L24. Specify the RRMSE when it was used at the first time.

At the first use of this acronym, the phrase has been modified as follow: *"(Differences never exceed 1.8 ha, which represent a maximum relative root mean square error of 4.3% (RRMSE)."*

P12 L7. The satellite images were acquired on certain days, while as described in Table 2 the in-situ levels and volumes were at weekly intervals, specify how you did match them for regression and validation. Similar comment applies to matching altimetry level and weekly in-situ data later.

As you mentioned, ground measures are weekly performed. Then, they are daily-interpolated to match satellite surface estimates and altimetry data. The phrase has been modified as follow for more precision: *"Figure 10 shows an empirical relationship between the estimates of the lake surface from the HR images and the volume measurements (daily-interpolated)".*

P12 L9-13. Different units have been used such as ha, hm³, m³, km² through the text. It is better to keep consistency and use only one type of unit.

The unit km² has been replaced by hectare (ha), and the unit m³ by hm³, to be consistent with all the figures.

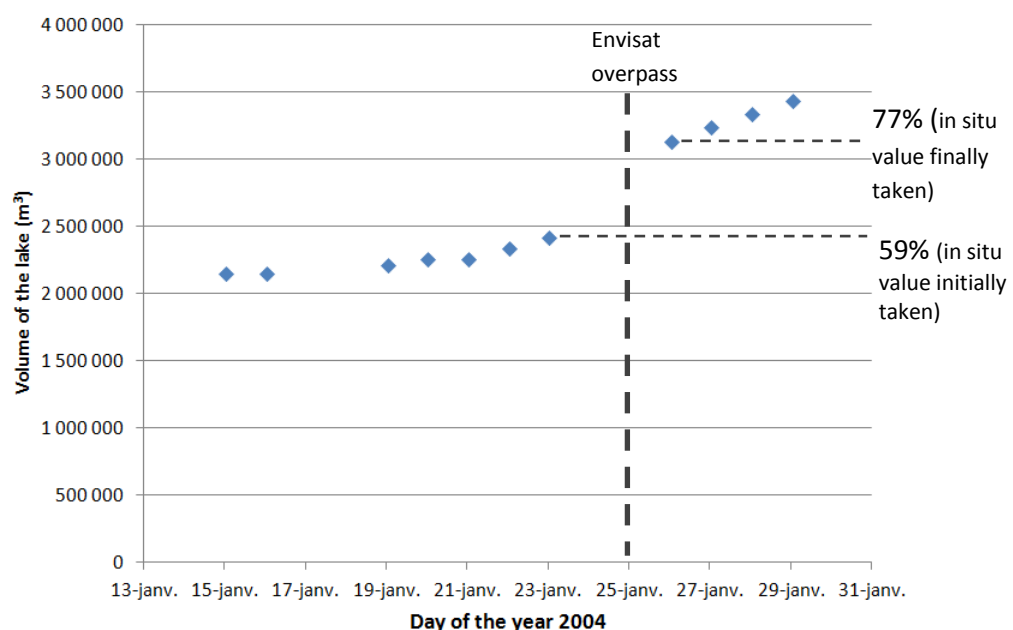
P12 L20. As commented above about the datum of the estimated water level, are in-situ level and estimated water level at the same reference datum? In addition, the in-situ level was at weekly interval, while altimetry measures at a specific date. How did you match altimetry-level and validate them to compute the RMSE? Here it is relevant to give more details.

As said above, the gauge is not leveled. That is the reason why we only gave RMSE and R^2 between in situ and altimetry based water levels, and not the bias. The mean bias has been calculated during the period 2003-2011 between satellite water level and in situ water level, and then removed from the satellite data.

RMSE are calculated by using daily interpolated measurements of volume.

P12 L27. Is there any possible explanation for such high difference ~1.3 m?

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 old figures from 9 to 11, and the corresponding statistics.



P13 section 4.3: this section is very important, but it does not come out easily. You need to describe the analysis and finding more systematically, and probably make this section a bit longer. To compensate for the length of the paper, the general description of the radar signals is not relevant for this type of analysis, and can be left out in the next version of the manuscript. Section 4.3 pertains to various combinations of in situ and satellite data, and finally the dots in Figure 14 tell me what the result of a full remote sensing method is: 5 dots for the season, a fluctuation between -0.75 to + 0.75 hm3 and $R^2=0.98$ with a average slope of 0.76 (or a bias of 24%). Is this accurate enough for the managers of lake La Bure?

We think it is important for the reader to know how were processed the SAR data used in this study.

As you mentioned, the combination of altimeter and HR images do not allow using more than five points, due to the difficulty to get synchronously altimeter data and HR images. The objective of this section is to test the “full-satellite” method to further manage the lake when more frequently data will be available. Despite the number of available point is not sufficient to manage the lake of “la Bure”, the good reproduction of the

volume fluctuations between -0.75 to + 0.75 hm³ ($r^2=0.98$) provides a glimpse of the potential of the method AHRBV (now only limited by the temporal revisit of satellites).

We choose to add a discussion part (section 4.4) in the revised paper to improve the comparison the three methods: HRBV, ABV and AHRBVC.

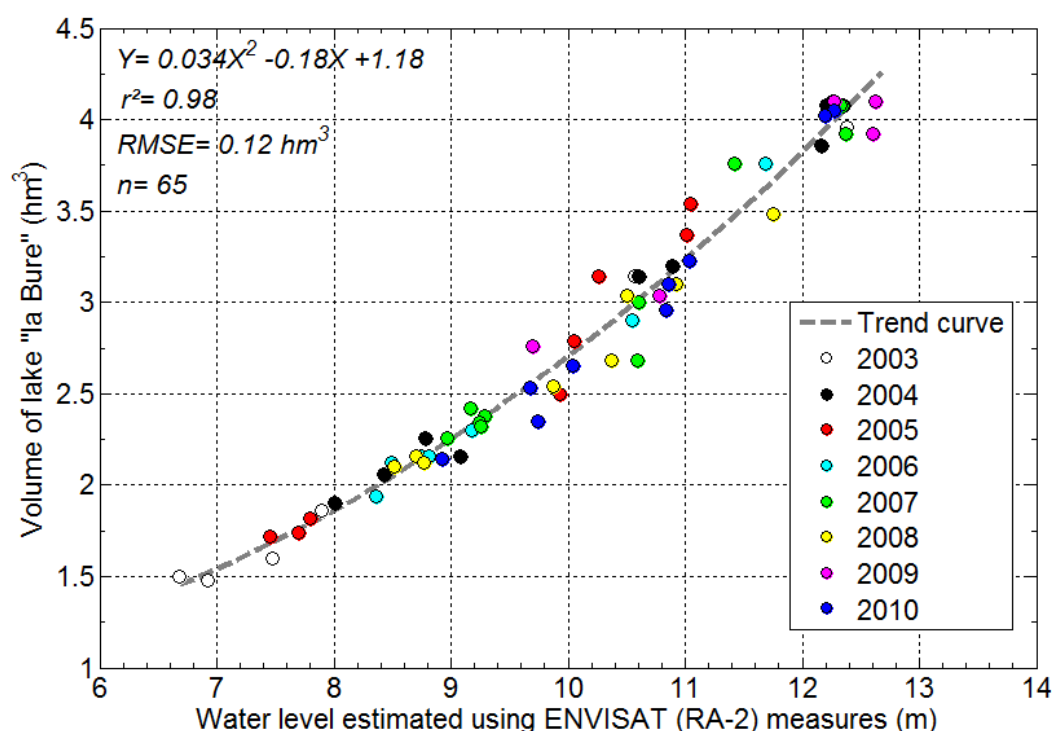
We decided to keep the general description of the radar signals, since all the readers are not familiar with this kind of data (in accordance with the comments of the referee #1).

P13. L21. It should be “the RMSE never exceeded. . .”

You are right. The sentence has been modified as follow: “The lake RMSE never exceeded 0.17 hm³ and corresponded to a high coefficient of determination ($R^2 \geq 0.96$) and a low relative error (i.e., the mean lake volume had an RRMSE of 6.4%)”

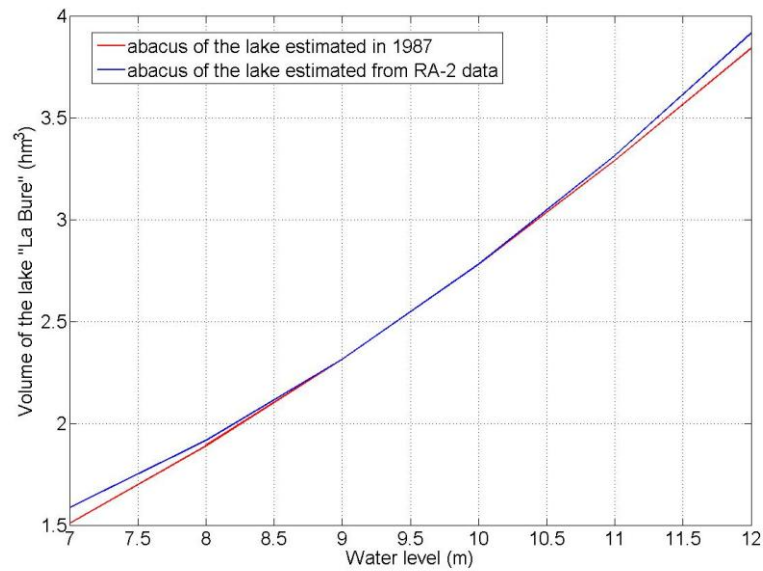
P13 figures 9 and 10: Different values for RA-2 are used, probably because of an offset calibration involved. This makes it difficult to compare figures 9 and 10. Please prepare one range of values.

Figure 9 was initially based on relative change of water level, whereas figure 10 was based on absolute value of water level. We decided to change the range of the figure 10 for best clarity, and to improve the comparisons of the results between figure 9, 10 and 3. The values of water level are now consistent between figures, and range between 9 and 13m. The new figure 10 is presented below (figure n°12 in the revised paper):



Discuss the results of Fig. 10 in relation to the results demonstrated as part of Figure 3.

The trend curve obtained on Figure 10 (from satellite data) is similar to the abacus given in Figure 3, as illustrated above:



The following sentence has been added in the middle of the section 4.2.2: *"Moreover, the trend curve obtained from altimetry data over the period 2003-2010 is similar to the relationship given by the abacus of the lake performed in 1987 (Figure 3), confirming the relevance of this satellite approach."*

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.

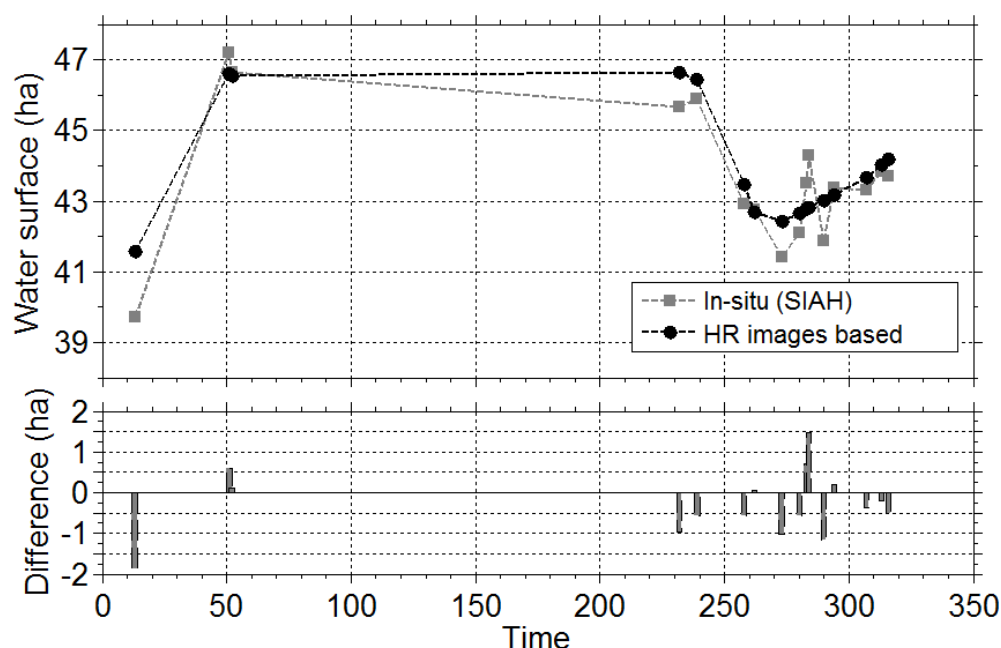
The area of the lake is first control by shore limiting its extent: water volume is mostly controlled by changes in elevation. Once reached a maximum elevation, the lake is spilling on the land around, and water volume changes are dominated by the variations of the lake area. The surface of the lake 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, presented in 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 be 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 be 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 $\sim 0.04 \text{ km}^2$ 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 (Crétau 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:

Crétau, 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; Crétau 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 ($\sim 0.52\text{km}^2$), and the reference ground track looking as though it passes to the East of the lake (Fig.6), and an along track sampling of $\sim 300\text{m}$ 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:

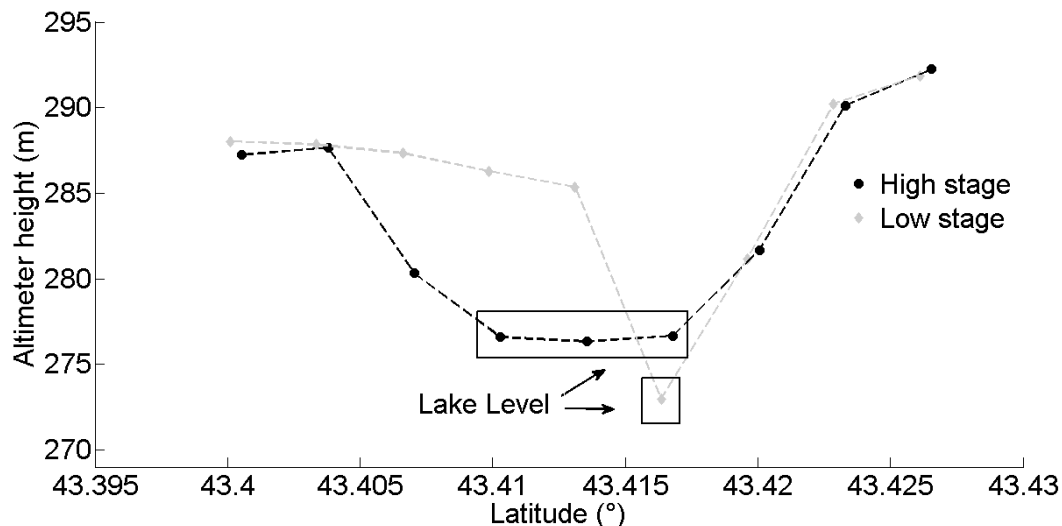
"Valid water levels were identified as they exhibit low levels variations (typically of a few centimeters) between the shores of the lake (Figure 7). During Low water periods, only one valid water level is likely to be found. Due to the few valid points present each cycle, from one to five, no specific 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 of altimetry or imagery?

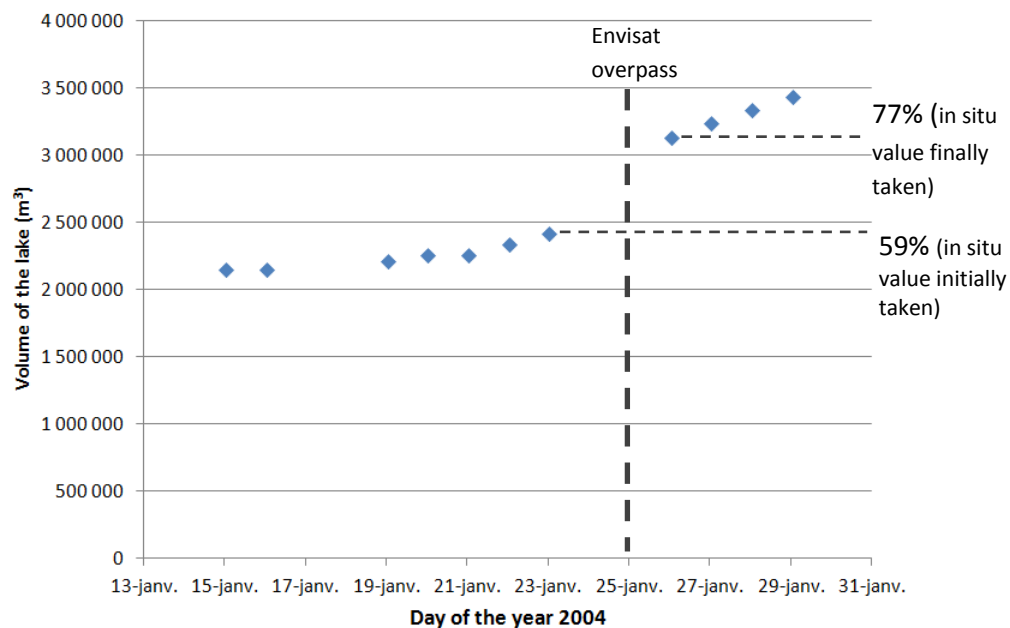
In situ data of volume are estimated from weekly measurements of in situ water level (see Table 2 of the revised paper).

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 “off-ranging”. 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.



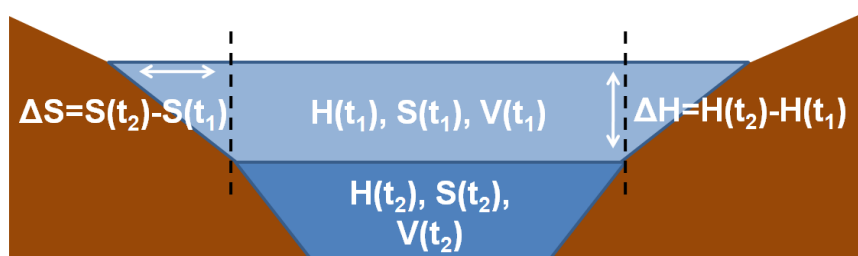
Lake Volume Estimates: What simple geometric shape was the lake modeled as? Provide references for equations 4+5 (e.g., based on C.M. Taube, chapter 12 “Three Methods for Computing the Volume of a Lake”. Annual of Fisheries Survey Methods II, 2000 ??)

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 t_1 and t_2 .

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: $\Delta H > 0$: $\Delta V = S(t_1) * \Delta H + \frac{1}{2} * (\Delta S + \Delta H) = S(t_1) * |\Delta H| + \frac{1}{2} * (|\Delta S| * |\Delta H|)$

Eq 5: $\Delta H < 0$: $\Delta V = -(S(t_1) - |\Delta S|) * \Delta H + \frac{1}{2} * (\Delta S * \Delta H)$
 $\Delta V = S(t_1) * |\Delta H| + |\Delta S| * \Delta H - \frac{1}{2} * (|\Delta S| * \Delta H)$
 $\Delta V = S(t_1) * |\Delta H| - \frac{1}{2} * (|\Delta S| * |\Delta H|)$

So the new Eq. 4 is: $\Delta V = S(t_1) * |\Delta H| + \text{sgn}(\Delta H) * (|\Delta S| * |\Delta H|)/2$

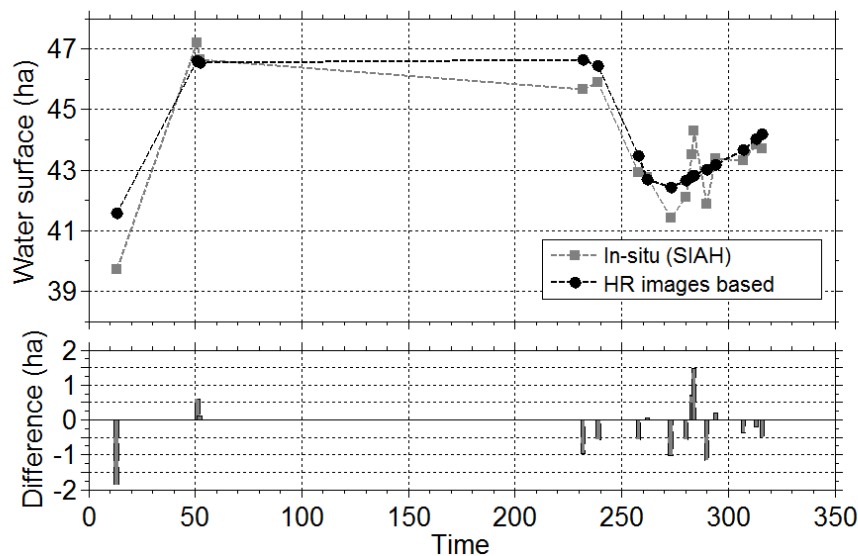
What can the readers deduce from the horizontal spread of data points in Figure 13?

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, presented in 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:

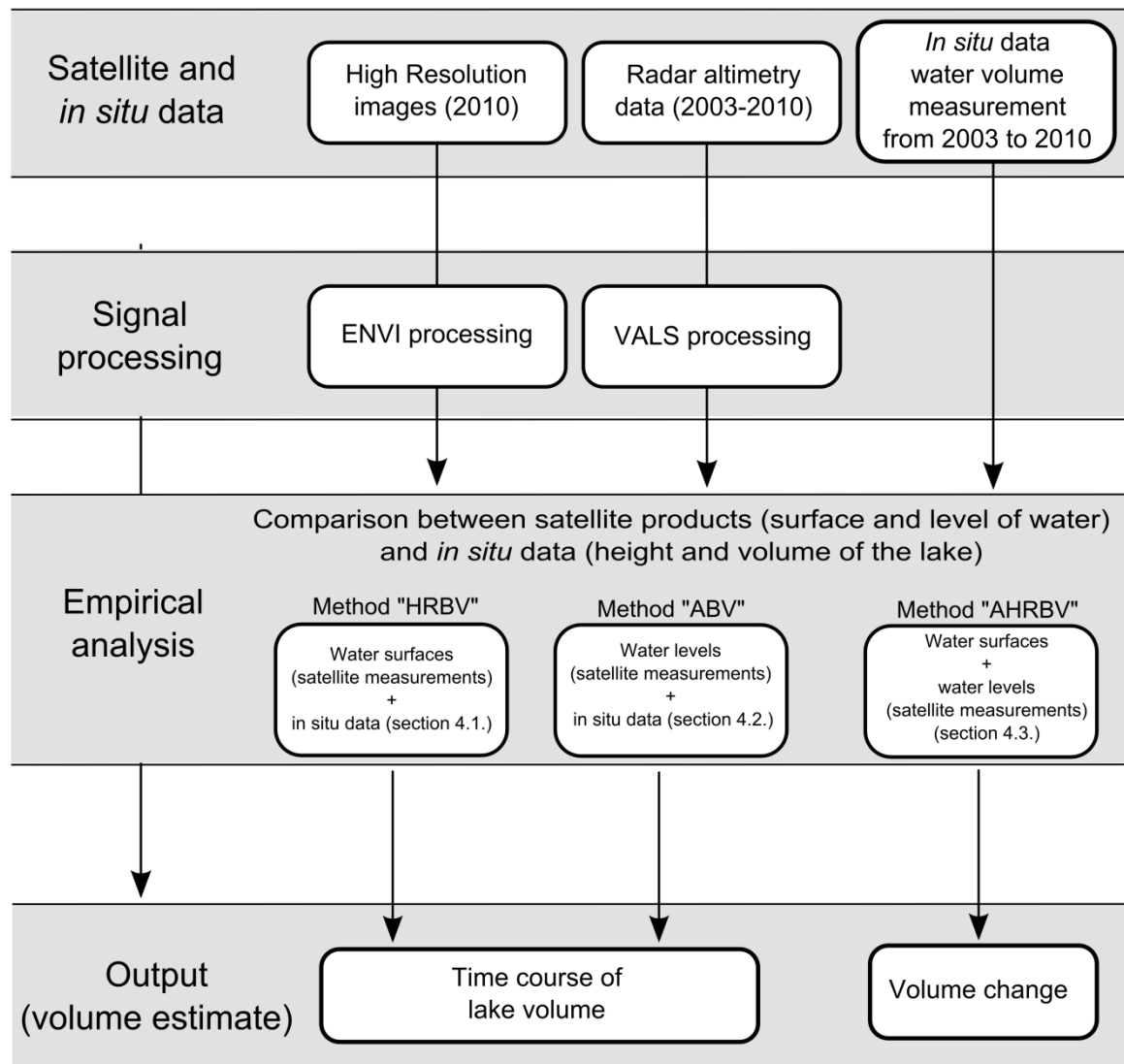
New Figure 8: Comparison of satellite-estimated and bathymetry time series of the water surface of lake "la Bure" in 2010. Bathymetry data are only available for water surface ranged between 0 and 47ha. No satellite data (HR images based) outside of this range is therefore presented.



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.

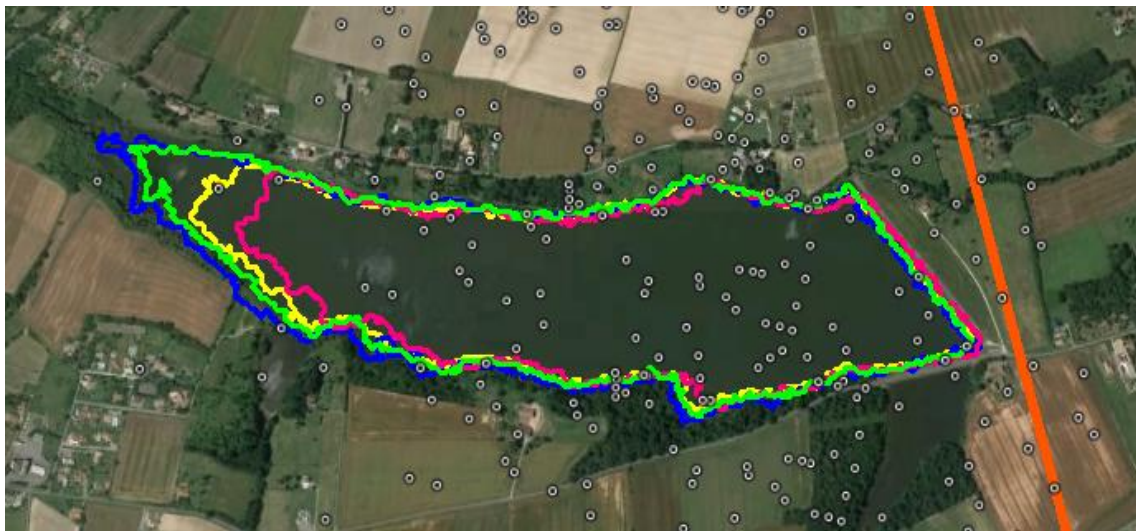


Figure 12, ground measurements are displayed as “a solid grey line”?

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

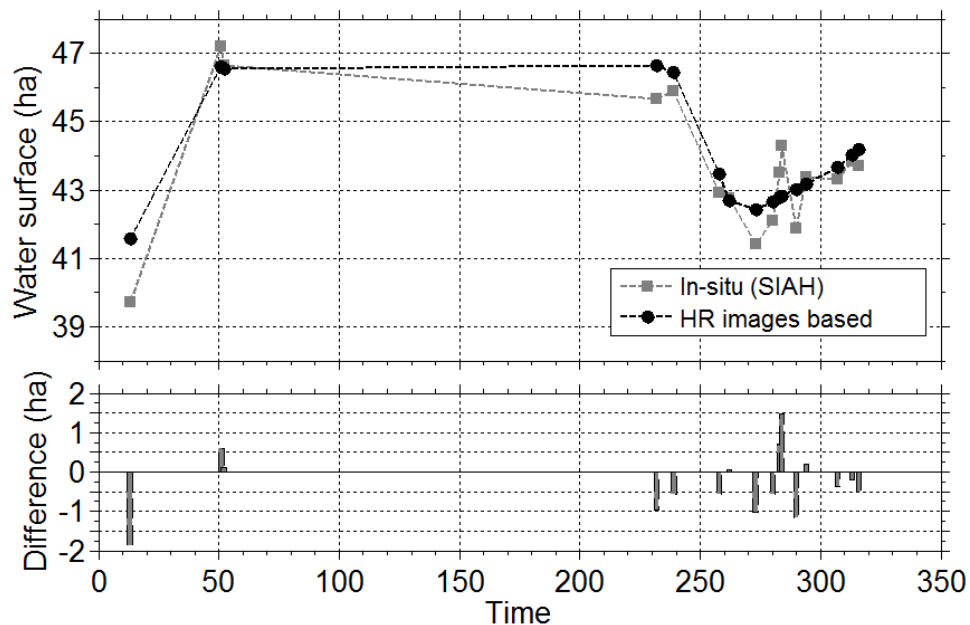
Now Figure 15, symbols are now defined in the figure caption, as follow:

“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, presented in 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.