

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

W.G.M. Bastiaanssen (Referee)
wim.bastiaanssen@gmail.com

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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

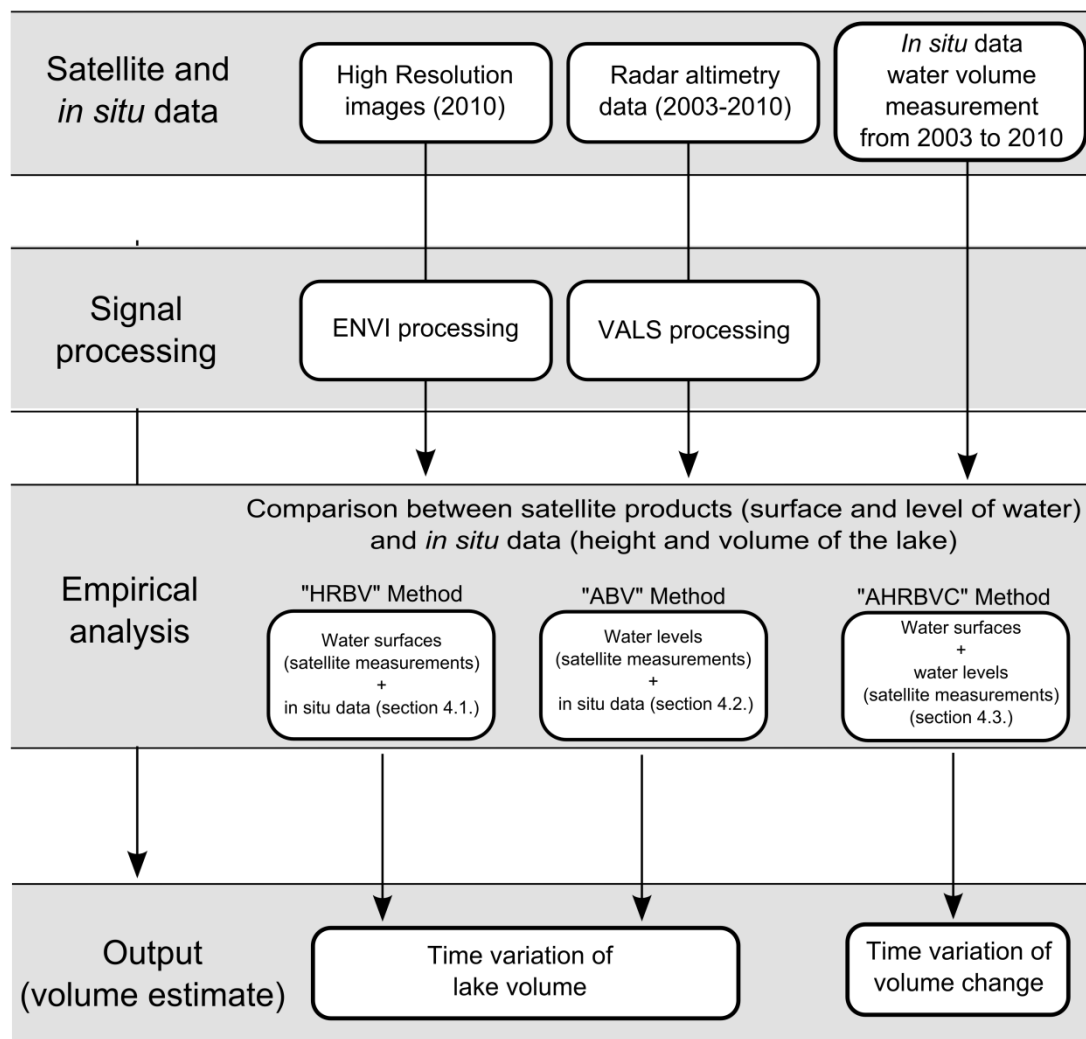
when ? Figure 5 is a good start, but needs to be made more complete, with explicit descriptions of levels, areas, volume changes and volumes.

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):



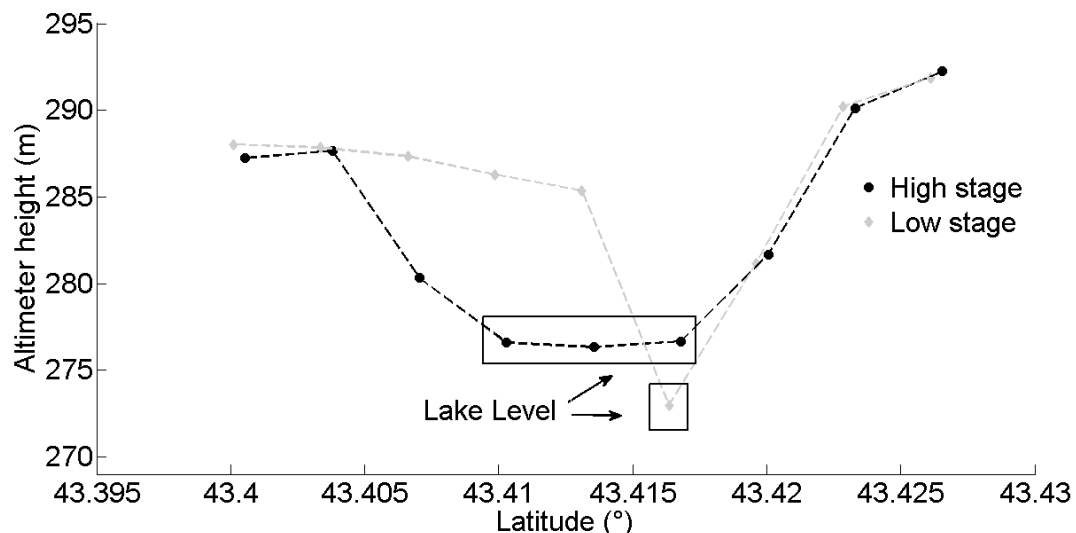
3. The Radar Altimeter onboard Envisat had a footprint of 2 to 10 km, depending on the geographical area. This footprint is approximately 10 times larger than the size of the water body, hence elevation effects of the surround terrain are incorporated into the altimeter signal. How is this potential 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

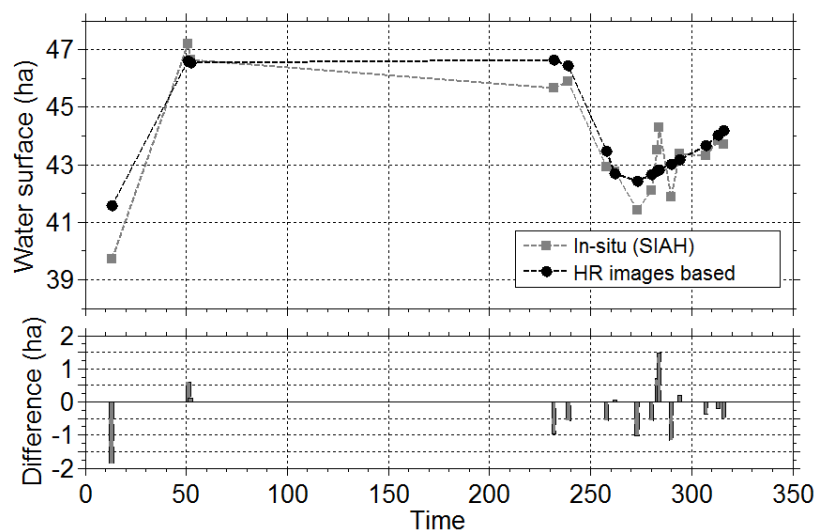
“In view of improving the management of water resources, monitoring the available water volume of small lakes at regional, national or global scale is crucial stake, but still challenging using remote sensing technologies. The results presented in the previous sections demonstrate the potential of three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

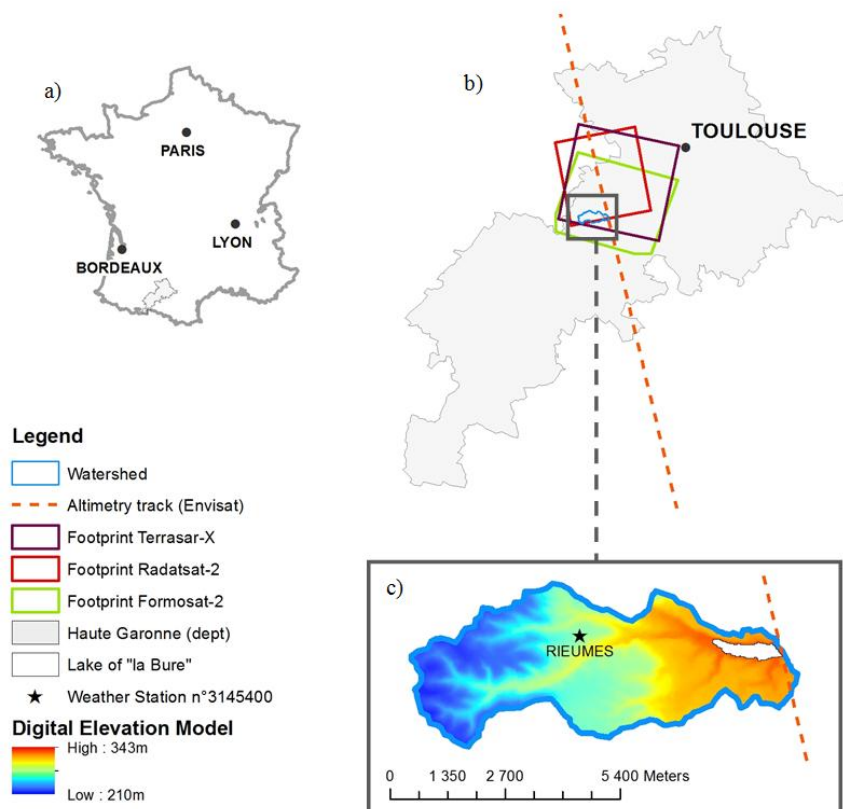
The sentence has been modified as follow: *"Despite the relevance of these results, these techniques have not been applied yet to study small lakes due to the difficulty to collect synchronously radar altimeter data, high resolution images and consistent ground data. No information is thus available 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.

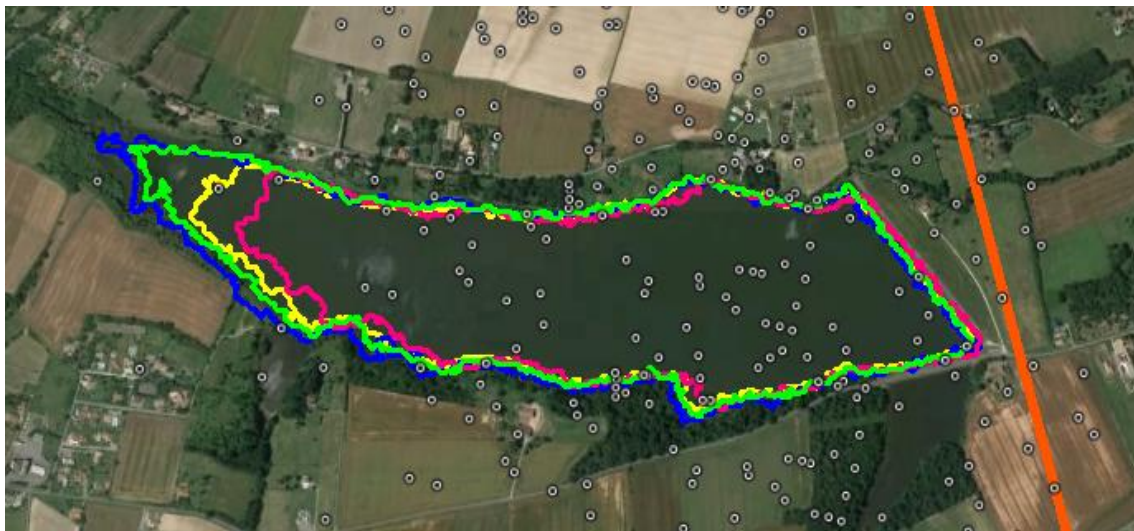
P5 Figure 1: A messy figure, and difficult to interpret. What does the cloud of points in the lower figure represent ? Are this all individual radar pulses ?

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.

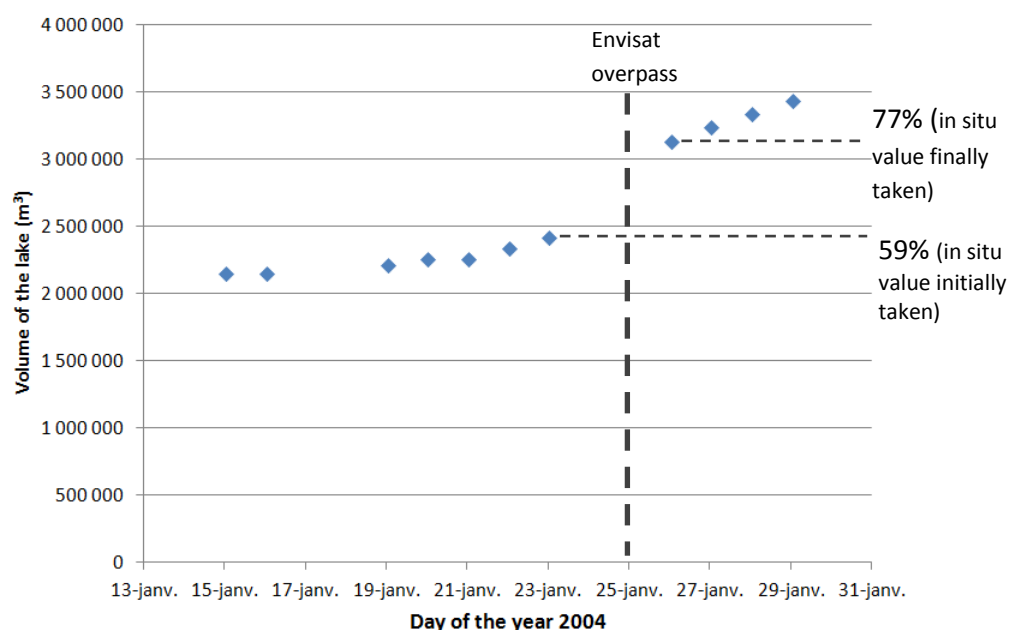
P12 L20. As commented above about the datum of the estimated water level, are in-situ level and estimated water level at the same reference datum? In addition, the in-situ level was at weekly interval, while altimetry measures at a specific date. How did you match altimetry-level and validate them to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

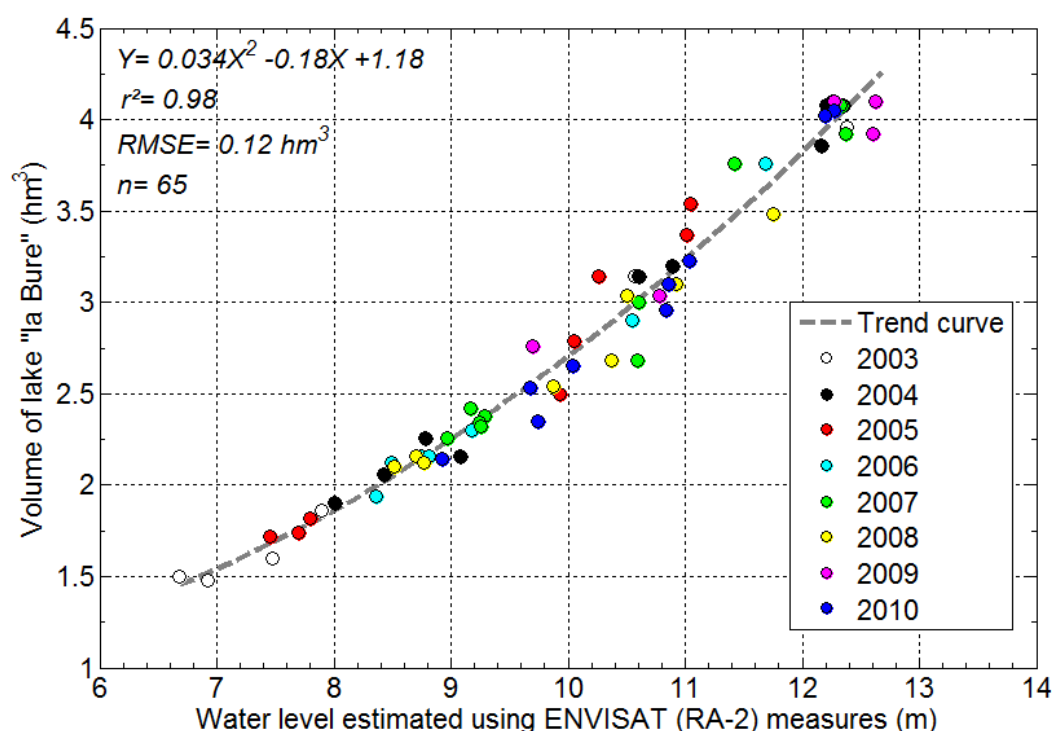
We decided to keep the general description of the radar signals, since all the readers are not familiar with this kind of data (in accordance with the comments of the referee #1).

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%)”

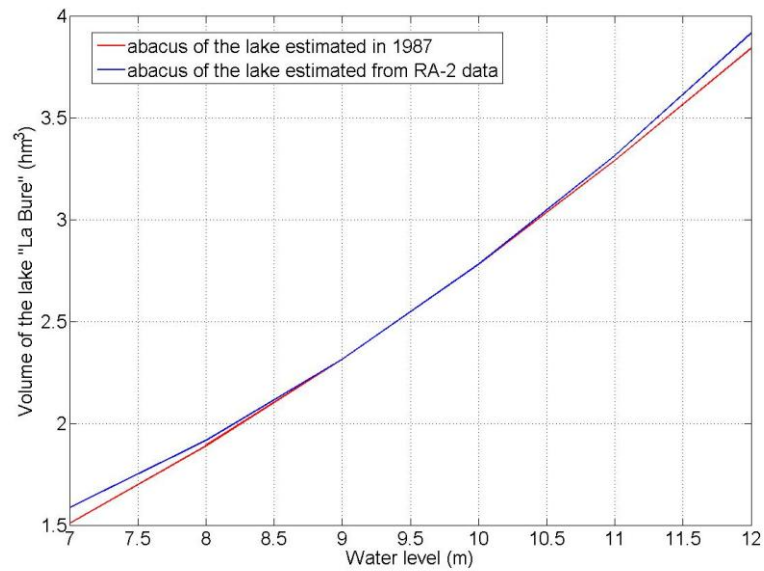
P13 figures 9 and 10: Different values for RA-2 are used, probably because of an offset calibration involved. This makes it difficult to compare figures 9 and 10. Please prepare one range of values.

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."*