Combining high-resolution satellite images and altimetry to estimate the volume of small lakes

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ABSTRACT

This study presents an approach to determine the volume of water in small lakes (<100 hectares) by combining satellite altimetry data and high-resolution (HR) images. 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.The lake being studied is located in the south-west of France and is only used for agricultural irrigation purposes. The altimetry satellite data are provided by RA-2 sensor on board Envisat, and the high-resolution images (<10 m) are obtained from optical (Formosat-2) and synthetic aperture radar (SAR) antenna (Terrasar-X and Radarsat-2) satellites. The altimetry data (data are obtained every 35 days) and the HR images (77) have been available since 2003 and 2010, respectively. *In situ* data (for the water levels and volumes) going back to 2003 have been provided by the manager of the lake. Three independent approaches are developed to estimate the lake volume and its temporal variability. The first two approaches (HRBV and ABV) are empirical and use synchronous ground measurements of the water volume and the satellite data. The results demonstrate that altimetry and imagery can be effectively and accurately used to monitor the temporal variations of the lake (R^2_{ABV}=0.98, $RMSE_{ABV}$=5%, R^2_{HRBV}=0.90, and $RMSE_{HRBV}$=7.4%), 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). The third method (AHRBVC) combines altimetry (to measure the lake level) and satellite images (of the lake surface) to estimate the volume changes of the lake and produces the best results (R^2_{AHRBVC} =0.98) of the three methods, demonstrating the potential of future Sentinel and SWOT missions to monitor small lakes and reservoirs for agricultural and irrigation applications.

Keywords: altimetry radar, high-resolution image, Envisat, Formosat-2, Radarsat-2, TerraSAR-X, SAR, volume, water reserve, small lake

1. INTRODUCTION

Water supply issues are creating unprecedented pressures because of increasing population and economic demands. As irrigated agriculture represents 70% of global water consumption, managing water resources is a major concern in maintaining sustainable agricultural practices. Water management will become even more relevant in the future as urbanisation, industrialisation, and climate change exert greater pressures on water use (OECD, 2012). Water resources can be monitored at a global scale using three approaches: *in situ* measurements, modelling, and remote sensing observations (Jorgensen et al., 2005; Harding and Warnaars, 2011; Hall et al., 2011; Duan and Bastiaanssen, 2013). Given the dramatic decrease in the number of *in situ* gauges used in recent years and the difficulty of modelling water resources at a global scale (because of complex mixing between inflows and outflows), measuring water stages by remote sensing and especially by satellite has become a major goal in hydrology for the coming decades (The Ad Hoc Group on Global Water Datasets, 2001; Alsdorf et al., 2007; Duan and Bastiaanssen, 2013).

Satellite radar altimetry was originally developed to accurately measure ocean surface topography and has been successfully used to obtain valuable information for land hydrology by estimating the variation in lake water levels (Birkett, 1995; Cazenave et al., 1997; Crétaux et al., 2011), rivers (Birkett, 1998; Birkett et al., 2002; Frappart et al., 2006a; Santos da Silva et al., 2010), and floodplains (Frappart et al., 2006b, 2008; Santos da Silva et al., 2012). The accuracy of altimetry-based water levels can vary from 5 to 80 cm depending on the altimetry data used (i.e., from Topex/Poseidon and ERS-2 to Envisat and Jason-2), the size of the water bodies being flown over, the configuration of the terrain, and the presence of vegetation (Frappart et al., 2005, 2006a, 2006b; Santos da Silva et al., 2010; Crétaux et al., 2011; Ricko et al., 2012).

However, comprehensive monitoring of surface resources also requires knowledge of the extent of the surface water and the water volume. Earth observation missions have been developed to provide images of the Earth's surface at various spatial, temporal, and spectral resolutions, which have been used to map land use and land cover dynamics over the last few decades (Kümmerle et al., 2013; Klein et al., 2014). 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 offer high spatial resolution, frequent revisit times, and a unique opportunity to monitor the extent of global water resources, even small-sized resources. Among other applications, high-resolution images were recently used to inventory tank irrigation systems in India (Abdul Hakeem and Raju, 2009), detect lakes and river courses in various environments (Strozzi et al., 2012; Karbouche and Clavet, 2013), and monitor the spatial distribution and temporal dynamics of wetlands (Zhou et al., 2010; White and Lewis, 2011).

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

Recent studies have demonstrated the potential of combining satellite imagery and radar altimetry to estimate the volume of water stored in lakes, rivers, and floodplains and how these volumes change in response to climate variability and/or anthropogenic effects using SAR images, multispectral images, or multi-satellite observations (Frappart et al., 2005; Frappart et al., 2006b; Frappart et al., 2008; Yesou et al., 2007; Ding and Li., 2011; Haibo et al., 2011; Frappart et al., 2012; Duan and Bastiaanssen, 2013). 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 (Sentinel-1/2, Jason CS, Radarsat constellation, Swot…). The lake “la Bure” offers a unique opportunity to apply these techniques over a well-monitored small lake.

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). 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. The paper is structured as follows: the primary characteristics of the study site, satellite data, and *in situ* data are presented in section II. In section III, the three different methods are presented for estimating the water volume of the lake. 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 named HRBV (High Resolution images Based Volumes) and ABV (Altimetry Based Volumes). The third one, named 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).The results are analysed and discussed in section IV, in which the *HR* images, altimetry, and a combination of the two techniques is used to accurately estimate seasonal changes in the water volume. Concluding remarks and future work are presented in section V.

2. STUDY AREA AND DATASETS

2.1 Study area

Lake “la Bure” (43°24’54’’ N; 1°09’07’’ E) is located in the south-west of France, close to the city of Rieumes (which is 40 km south-west of the city of Toulouse), in a study area monitored by CESBIO in the framework of the "Sud-Ouest" Project (Dejoux et al., 2012; Baup et al., 2012, Fieuzal et al., 2012; Fieuzal et al., 2013) (Figure 1). The area has a temperate climate with a mean annual rainfall of approximately 600 mm. Rainfalls are regularly distributed (with a monthly mean of 50 mm), with a maximum of 80 mm in the spring and a minimum of 32 mm in the summer according to the records from meteorological station number 3145400 of Météo-France, the French Meteorological agency (http://www.meteofrance.fr). Inside the watershed (2070 ha) of the lake, the relief is not clearly delineated (min=0%, max=16.9%, and mean slope=2.8%), and the land use is composed of crops (40.90%), forest (24.02%), grassland (33.4%), and water bodies (1.68%). Lake “la Bure” is an artificial reservoir that was constructed in 1987 for crop irrigation purposes. Since its construction, the barrage has been managed by the SIAH (Syndicat Intercommunal d'Aménagement Hydraulique de la vallée du Touch et de ses affluents) company. The extent of the lake can reach 52 hectares for a maximum water volume of 4.1 hm^3. The charge and discharge of the lake only occur via rainfall events (throughout the year) and irrigation pumping (primarily in the summer). The lake is located under Envisat RA-2 altimetry track 773 and is inside the footprint of three high-resolution images that are acquired by the Formosat-2, TerraSAR-X, and Radarsat-2 satellites.

[Please insert Figure 1 here]

2.2 Satellite data

The satellite data used in this study were composed of *HR* images and altimetry data. Forty-five *HR* images were acquired in 2010, between January and November, by sensors on board three different low-orbiting satellites (Radarsat-2, TerraSAR-X, and Formosat-2) (Figure 2). Thirty-three of these images were acquired in the microwave domain using SAR instruments (Radarsat-2 and TerraSAR-X), and 12 were acquired using the multispectral mode of the Formosat-2 satellite. The altimetry data were acquired by the Envisat RA-2 sensor between February 2002 and October 2010.

[Please insert Figure 2 here]

2.2.1 SAR images

The SAR images were acquired at X- and C-bands by TERRASAR-X and RADARSAT-2, respectively (Table 1).

[Please insert Table 1 here]

TerraSAR-X is a German Earth observation satellite that was launched in June 2007 (Fritz et al., 2008; Breit et al., 2010). The SAR instrument on board the satellite operates in the X-band (f=9.65 GHz and λ=3.1 cm). All of the images (which numbered 18 in 2010) were provided by the German Aerospace Centre (DLR) and were acquired with the same polarisation state (HH) for incidence angles ranging from 27.3° to 53.3° to increase the repetitiveness of observations from an initial 11-day orbital cycle. Two acquisition modes were combined: StripMap (SM) and SpotLight (SL), which were characterised by pixel spacings of approximately 3 and 1.5 m, respectively. The backscattering coefficients were calculated using Equation 1 (Lavalle, 2009):

$$\sigma_{pq}^{O} = 20\log\left(DN_{pq}\right) + 10\log\left(CF_{pq}\right) + 10\log\left(\sin(\theta)\right) \qquad \textbf{(1)}$$

where DN denotes the digital number of pixels, CF denotes the calibration factor, and θ denotes the incidence angle. The indexes p and q denote the linear polarisation states of the electromagnetic wave (H or V), respectively.

The Canadian satellite Radarsat-2 was launched in December 2007 (Morena et al., 2004). Its payload encompasses a SAR instrument operating in the C-band (f=5.405 GHz and λ=5.5 cm). The orbital cycle of the satellite is 24 days, but different orbit and incidence angles can be combined to increase the numbers of possible acquisitions per cycle. The images (which numbered 15 in 2010) were provided by the Canadian Space Agency through the SOAR (Science and Operational Application Research) program and were all acquired in quad-polarisation mode (Fine Quad-Pol: HH, VV, HV, and VH). The incidence angles ranged from 23° (FQ5) to 41° (FQ21) with a pixel spacing of 5 m. The images were calibrated using NEST software (NEST, 2013) and Equation 2 (Skriver et al., 1999):

$$\sigma_{i}^{O} = 20\log_{10}\left(DN_{i} / A2_{i}\right) + 10\log_{10}\left(\sin(\theta_{i})\right) \qquad \textbf{(2)}$$

where DN_i denotes the digital number of the pixel "i", θ denotes the incidence angle, and A2 denotes the gain (which is provided by the image product data table).

All of the SAR images were geo-referenced using aerial IGN ortho-photos (with a spatial resolution of 50 cm). The ortho-photos were first resized to the resolution of the image and then 70 reference points were taken between the base (IGN ortho-photos) and wrap images (satellite data). The geo-location accuracy was under 2 pixels (i.e., 3 to 6 m) on average for the different products. Finally, all of the radar images were filtered to reduce speckle effects using a Gamma filter with a filtering window of 6 by 6 pixels.

2.2.2 Optical images

The optical images (12) were provided by the Taiwanese Formosat-2 satellite (which was launched in 2004) for four narrow wavelengths between 0.45 and 0.90 µm corresponding to the blue, green, red, and near-infrared ranges (Liu, 2006; Chern et al., 2008, Table 1). All of the images used in this study were acquired in multispectral mode (*MS*) with a theoretical daily orbital cycle (sun-synchronous orbit) at the same viewing angle (±45°). This mode was characterised by a spatial resolution of 8 m for a scene coverage of 24 km×24 km. All of the images were processed by the French company: "CS Systèmes d'Information" in the framework of Kalideos projet (http://kalideos.cnes.fr). They were ortho-rectified using CNES ortho-rectification tools. Cloud detection and atmospheric correction were also applied (Sand et al., 2006; Hagolle et al., 2010).

2.2.3 Altimetry data

RA-2 (Advanced Radar Altimeter) is a nadir-looking pulse-limited radar altimeter on board ENVISAT that operates at two frequencies: the Ku-band (13.575 GHz / wavelength of 2.3 cm) and the S-band (3.2 GHz / 9.3 cm) (Zelli, 1999). The Geophysical Data Records (GDRs) distributed by ESA (ESA, 2002) include accurate satellite positions (i.e., the longitude, latitude, and altitude of the satellite in its orbit) and timing; altimeter ranges; instrumental, propagation, and geophysical corrections applied to the range; and several other parameters used to build altimetry-based water levels. The along track resolution of Envisat RA-2 is around 350 m in hi-frequency mode.

For the ENVISAT mission, four different retracking algorithms are operationally applied to RA-2 raw data to provide range estimates and backscattering coefficients. Each retracking algorithm, namely Ocean, Ice-1, Ice-2, and Sea-Ice, has been developed for a specific type of surface, but none of these algorithms has been specifically designed for processing altimeter echoes over land (Brown, 1977; Wingham et al., 1986; Laxon, 1994; Legrésy and Rémy, 1997). Previous studies have shown that the Ice-1 algorithm measures the water levels of small lakes and reservoirs, rivers, and floodplains most accurately (Frappart et al., 2006a; Santos da Silva et al., 2010; Ricko et al., 2012). In this study, the altimetry measurements contained in the ENVISAT RA-2 GDRs were made available by the Centre de Topographie des Océans et de l'Hydrosphère (CTOH — http://ctoh.legos.obs-mip.fr/) for February 2002 to October 2010 (cycles 8 to 93), corresponding to the reference repetitive orbit of the satellite.

2.3 *In situ* data

The monthly rainfall data came from the records of weather station number 3145400, which is located less than five kilometres from the centre of the lake and is operated by the French meteorology Agency (Météo France). The relationship between the water levels and the volume of water stored in the lake was established in 1987 when the lake was dug (Figure 3). More recent information on the storage capacity of the lake is available from bathymetric surveys that were performed in 2010 by AEAD ("Agence de l'Eau Adour-Garonne", which depends of the Ministry of Ecology, Sustainable Development, and Energy). The water levels were recorded at two different time steps, pressure probes were used to obtain automatic weekly measurements, and monthly data were provided by gauge readings. Figure 4 shows the temporal variation in the volume of water stored in Lake "la Bure" over the study period. 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. The difference between the volume obtained from the *in situ* water levels and the volume obtained from the bathymetric survey performed in 2010 was less than 2%. This difference was attributed both to the accuracy of the bathymetric measurements and to possible siltation. Various characteristics of the available ground data are summarised in Table 2.

[Please insert Table 2 here]

[Please insert Figure 3 here]

[Please insert Figure 4 here]

3. METHODOLOGY

Figure 5 summarises the methods used to monitor the water volume of Lake "la Bure". The satellite data acquired within the optical and microwave regimes were processed to estimate the water surfaces (using HR images) and levels (using altimetry) throughout the hydrological cycle. The temporal variation in the volume of the lake (HRBV and ABV methods), or in the volume change (AHRBVC method), was finally estimated by combining one type of satellite data (HR images or radar altimetry) with ground measurements or using two types of complementary satellite data.

[Please insert Figure 5 here]

3.1. Determination of the extent of the lake area from satellite imagery

An automatic parallelepiped classification was performed using ENVI software on each HR image to determine which pixels could be associated with open water (Richards, 1999; ENVI, 2004; Lillesand et al., 2008). This supervised classification method relied on a simple logical rule to classify a given pixel based on its radiometry (4 channels are considered: blue, green, red, and near infra-red). The decision boundaries formed a 4-dimensional parallelepiped in the image data space. Each class was defined in terms of a threshold for the standard deviation from the mean of each training site (i.e., the region of interest). Four classes were identified as being representative of the landscape: forests, open water, bare soils, and crops. Once the classification process was completed, all of the surface elements that were identified as open water were vectorised and exported to an ArcGIS shape file format in which the boundary represented the lake shoreline (artefacts in the polygon that represented open water were suppressed using the FillHoles toolbox of the software). Figure 6 shows the temporal variations in the lake shoreline for four different dates in 2010 that were acquired by the Radarsat-2 satellite.

[Please insert Figure 6 here]

3.2. Altimetry-based water levels

The principle behind radar altimetry is as follows: the altimeter emits a radar pulse and measures the two-way travel-time from the satellite to the surface. The distance between the satellite and the Earth surface – the altimeter range (R) – is thus derived with a precision of a few centimetres. The satellite altitude (H) with reference to an ellipsoid is also accurately known from orbitography modelling. Taking into account propagation delays from the interactions of electromagnetic waves in the atmosphere and geophysical corrections, the height of the reflecting surface (h) with reference to an ellipsoid or a geoid can be estimated as follows:

$$\boldsymbol{h = H - R - C_{ionosphere} - C_{dry\ troposphere} - C_{wet\ troposphere} - C_{solid\ Earth\ tide} - C_{pole\ tide}} \qquad \textbf{(3)}$$

where $C_{ionosphere}$ is the correction for delayed propagation through the ionosphere, $C_{dry\ troposphere}$ and $C_{wet\ troposphere}$ are corrections for delayed propagation in the troposphere from pressure and humidity variations, respectively, and $C_{solid\ Earth\ tide}$ and $C_{polar\ tide}$ are corrections that account for crustal vertical motions from the solid and polar tides, respectively.

An altimetry station, which is the equivalent of an *in situ* water level gauge, can be defined at each intersection between a lake, a river, or a floodplain and the satellite ground-track. For each altimeter pass or cycle, the altimetry measurements are processed using the three following primary steps to obtain a water level: a 2-D selection is made from the data contained in the window corresponding to the altimetry station using satellite imagery; the altimetry heights from Equation 3 are filtered (at varying degrees of complexity depending on the approach chosen) using a statistical and/or hydrological criterion; and the altimetry-based water level is computed using estimates of either the median or the mean of the selected altimetry heights, which may or may not have been corrected for hooking effects (Frappart et al., 2006a; Santos da Silva et al., 2010). This process is repeated for each cycle to construct a water level time-series at the altimetry station. In this study, Virtual ALtimetry Station (VALS) software was used to derive the time-series of water levels for Lake "la Bure" from ENVISAT RA-2 data from February 2002 to October 2010. The processing of altimetry data using VALS consisted of four primary steps:

(i) a coarse selection of the altimetry data over the water body contained in a polyline using Google Earth was obtained,

(ii) the VALS visualisation tool was used to obtain a refined selection of the valid altimetry-derived water levels in which outliers were removed and the hooking effects were likely to be corrected for,

(iii) 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 may 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,

(iv) the time-series of water levels was computed using the median value of all of the valid altimetry-based water levels for each cycle.

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. Further details on processing the altimetry data using VALS software can be found in Santos da Silva et al., 2010. 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. All water levels are given with reference to WGS84 ellipsoid, and presented as relative value of water level.

[Please insert Figure 7 here]

3.3. Lake volume estimates

Three independent approaches were developed to estimate the lake volume and its temporal variability. In the first two methods (HRBV and ABV), an empirical relationship between either the lake surface derived from the HR images or altimetry-based water levels and quasi-synchronous estimates of the lake volume was determined from the *in situ* water level measurements. In the third method (AHRBVC), the lake surface from the HR images was combined with altimetry-based water levels that were acquired quasi-synchronously. A combination of satellite products was used to estimate the change in the lake volume from both the variation in the water level and the surface. To this end, the lake of interest was modelled as a simple geometric shape, for which the variation in the water volume (ΔV) between two dates (t_1 and $t_{2,\ respectively}$) was computed using equation 4, similarly to the second method proposed by Taube, 2000:

$$\Delta V = S(t1) * |\Delta H| + sgn(\Delta H) * (|\Delta S| * |\Delta H|)/2 \quad (4)$$

where $\Delta H = H(t2)-H(t1)$ and $\Delta V = V(t2)-V(t1)$ denote the difference in the water levels (*H*) and the volume between two dates, *t1* and *t2*, respectively. $\Delta S = S(t2)-S(t1)$ denotes the variation in the surface between the two dates.

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 t1 and t2. 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.

4. RESULTS AND DISCUSSION

4.1. Estimating the lake volume using *HR* images – HRBV Method

The satellite water surfaces derived from HR images were validated 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 8, 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).

[Please insert Figure 8 here]

Figure 9 shows the temporal evolution of the water surface of Lake "la Bure" for the complete series of 45 HR images that were acquired in 2010. The lake surface was estimated by applying the method presented in section 3.1 to the Formosat-2, Radarsat-2, and TerraSAR-X images that were acquired in 2010. The measurement of the temporal behaviour of the lake surface from the three sensors was highly consistent and ranged between 42 and 52 ha. The difference between the three estimates never exceeded 3.94 ha (RRMSE=8.5%) and equalled 0.51 ha (which was 1.1% of the mean water surface) when averaged over the complete period of observation for the quasi-synchronous satellite acquisitions (i.e., time-lags below 5 days).

The annual cycle of the open water surface consists of two phases: the filling of the lake (from the end of September to mid-June) and the emptying of the lake (during the summer). The filling of the lake only occurs through rainfall events (primarily from runoff inside the watershed). The lake surface significantly increases over this period. No additional pumping is needed to fill the lake more rapidly, unlike some of the other lakes in the region studied. The lake empties during the irrigation period, which occurs between July and October (Figure 9). In the summertime, the low amount of rainfall is not sufficient to compensate for losses from irrigation and evaporation.

[Please insert Figure 9 here]

Figure 10 shows an empirical relationship between the estimates of the lake surface from the *HR* images and *in situ* volume measurements (daily-interpolated). The relationship is clearly non-linear (*i.e.*, a 2nd-order polynomial function) with a coefficient of determination of 0.90 and a mean error of 0.200 hm^3 for the volume estimates (*i.e.*, 7.4% of the average water volume in 2010). In agreement with the bathymetric measurements, the surface changed dramatically (from 40 to 44 ha) for small volume changes between 2.2 and 2.5 hm^3 when the filling began (sensitivity of 0.080 hm^3.ha^{-1}). The relationship is fairly linear for volume changes from 2.5 hm^3 to greater than 4 hm^3, with a higher sensitivity compared to the beginning of the filling phase (0.237 hm^3.ha^{-1}).

[Please insert Figure 10 here]

4.2. Estimating the lake volume from altimetry – ABV Method

4.2.1. Validation of altimetry-based water levels

The altimetry data (RA-2) were validated by directly comparing the altimetry-based water levels with the *in situ* water levels from gauge measurements made by the Lake Management Institute (SIAH) over the 2003-2010 period (Figure 11). Similar temporal variations were observed for both datasets, in which the *in situ* water levels exhibited annual (peak to peak) amplitudes between 2.65 m (2007/2008) and 5.36 m (2003/2004). Both the seasonal variations (*i.e.*, the maxima from May to June and the minima from September to October) and the inter-annual variations (*i.e.*, the minimum during the drought of 2003) were also successfully detected. Although the difference between the *in situ* and altimetry-derived water levels reached 0.75 m one time, it did not exceed 0.3 m in 77% of the cases studied. 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. The results obtained in this study were comparable to results for large lakes (Crétaux and Brikett, 2006; Ricko et al., 2012; Duan and Bastiaanssen, 2013) and large rivers (Frappart et al., 2006a; Santos da Silva et al., 2010) and were better than those obtained for various small rivers (Santos da Silva et al., 2010).

[Please insert Figure 11 here]

4.2.2. Pluri-annual water volume estimates

Figure 12 shows the empirical relationship that was obtained between the ground-measured volumes and the altimetry-derived water levels. Sixty-five measurements were used from the period between 2003 and 2010 to obtain a 2nd-order polynomial that related the altimetry-based water levels to the water volume stored in the lake. The statistical parameters highlighted the quality of the regression (R^2=0.98, RMSE=0.12 hm^3, and RRMSE=5%). No yearly dependence was observed, confirming the temporal stability of the method. 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.

[Please insert Figure 12 here]

For subsequent comparison with the HR images, a specific empirical relationship relating altimetry-based water levels to water volumes was determined for 2010 (Section 4.3). Figure 13 compares the water volumes that were estimated using these two relationships. The results were very similar, although the results obtained using the empirical function that was determined using over 8 years of altimetry data were slightly more accurate than those obtained using the empirical function for 2010 (Table 3). The lake RMSE never exceeded 0.17 hm^3 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%).

[Please insert Figure 13 here]

[Please insert Table 3 here]

4.3 Combined use of *HR* images and altimeter data – AHRBVC Method

In this section, we show how variations in the lake volume were obtained by combining the *HR* images (section 2.2.1 and 2.2.2.) with the altimetry-derived water levels (section 2.2.3). This approach was validated for 2010, for which satellite images and altimetry data were simultaneously available to compare with *in situ* measurements of the lake volume. Figure 14 shows the temporal variations in the lake volume that were estimated using three different methods: ground measurements (*SIAH*), *HR* images (section 3.1.), and altimetry-based water levels (Section 3.2.). In 2010, the emptying and refilling phases of the lake were accurately detected and reproduced by both the satellite estimates. The errors were equal to 0.20 and 0.14 hm^3 using the *HR* images and the *RA-2* data, respectively. All of the altimeter-derived volumes had an error below 5% of the measured volume; whereas only half of the *HR*-image-based volume estimates reached this level of accuracy. The precision for the estimated lake volume obtained using all of the satellite products was always below 19%. Figure 15 shows the relationship that was estimated between the water level obtained using the satellite products (from *RA-2*) and the water surface (from the *HR* images). Only the satellite acquisitions that were performed quasi-synchronously (for a time-lag below 5 days) were retained to reduce the signal scatter because of the potential variation in the lake properties (i.e., the surface, level, and volume) between the images and the altimeter acquisitions. The two satellite products were strongly linearly correlated with a high coefficient of determination (R^2=0.94).

[Please insert Figure 14 here]

[Please insert Figure 15 here]

Figure 16 shows the relationship that was obtained between the variations in the volume estimated using the ground measurements and the satellite products. Five dates were retained in accordance with the two following constraints:

- the satellite acquisitions were performed in 2010,
- the altimetry data and *HR* images were acquired for a time lag below 5 days (so implying that ΔV was less than 0.7% of the average volume during this period using the relationship between the water levels and the water volumes stored in Lake "la Bure", as shown in Figure 3).

[Please insert Figure 16 here]

The ground-based estimates of the variations in the water volume shown in Figure 16 were in very good agreement with the results from this approach (i.e., $R^2=0.98$, RMSE=0.06 hm^3, and the linear regression slope was close to 1). The major drawbacks of this method are its low temporal resolution, which depends on the availability of data obtained around the same time period from both satellites, and the fact that only variations in the volume and not the volumes themselves can be determined. Figure 14 also shows the estimates of the variations in the water volume from the *RA-2* altimetry-based water levels and the *in situ* data, and the *HR* images and the *in situ* data for the same dates. The two estimates were in very good agreement with the volume derived from the *in situ* data ($R^2=0.95$ and RMSE=0.17 hm^3 for altimetry-based volume variations and $R^2=0.90$ and RMSE=0.25 hm^3 for the HR-image-based volume variations); however, more accurate results were obtained by estimating the water volumes using altimetry and imagery. These results should be confirmed for longer time-series. The results confirmed the efficacy of these products to estimate the temporal volume changes of the lake ($R^2 \geq 0.90$). A strong limitation of the last two relationships is that they require *in situ* data.

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, Alos-2) 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. CONCLUSION AND PERSPECTIVES

This study demonstrated the high potential of remotely sensed observations (HR images and radar altimetry) for accurately monitoring the surface volume of small lakes and reservoirs (*i.e.*, with areas<100 ha). Three different approaches were developed that combined quasi-synchronous multi-satellite data and/or *in situ* measurements to monitor the temporal variations in water resources. All of these methods provided reliable estimates of the variations in the water volume with an average accuracy greater than 7.4% of the average volume.

In the first method, named HRBV (section 4.1.), the water surface estimates were converted from multispectral *HR* images into water volumes using *in situ* measurements. For our study site, this method enabled the volumes of water stored in the lake on a weekly basis to be monitored continuously. The high correlation (R^2=0.90) was associated with a good average accuracy of 0.20 hm^3 (*i.e.*, 7.4% of the average volume of Lake "la Bure") of the results, thereby confirming the applicability of this method.

In the second method, named ABV (section 4.2.), altimetry-based (from ENVISAT RA-2) water levels were similarly combined with ground measurements to estimate the water volumes stored in the lake. This method produced more accurate estimates of the water volumes than the previous method with an average accuracy of 0.12 hm^3 (*i.e.*, 5.0% of the mean lake volume) and a coefficient of determination of 0.97. The major drawback of this approach was the low temporal resolution (below one month) of the satellite data. These two methods cannot be generalised because they require *in situ* data.

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. However, the third method is currently limited by the poor availability of quasi-synchronous remotely sensed observations. In addition, the third method can only be used to calculate changes in the volume and cannot be used to estimate the volume itself. This latter drawback could be overcome by using lake bathymetry.

These results can be used to monitor and manage water resources, especially for agricultural purposes and even for small lakes and reservoirs. A higher spatial resolution and temporal repetitiveness allowing higher quasi-synchronous acquisitions could be achieved by using additional data from current and future satellite missions. Future launches of Sentinel-1, 2, and 3 will provide access to multispectral and SAR *HR* images combined with a dense temporal sampling (Le Roy et al., 2007; Berger et al., 2012). For radar altimetry, higher accuracy can be expected from the Saral-AltiKa mission over small water bodies because the footprint of the Ka band is smaller than that of the Ku band from current missions. The development of SAR-altimeter (Cryosat-2, Sentinel-3, Jason CS) and SAR-interferometry (SWOT) techniques for altimetry will densify the spatial coverage of radar altimetry over land and ocean, offering high spatial and temporal resolution (ESA Communications 2012a, ESA Communications 2012b).

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Figure 1: 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 (orange dashed line) (b). The weather station (black star) and the lake (in white) are presented inside the watershed, superimposed to the digital elevation model (c).

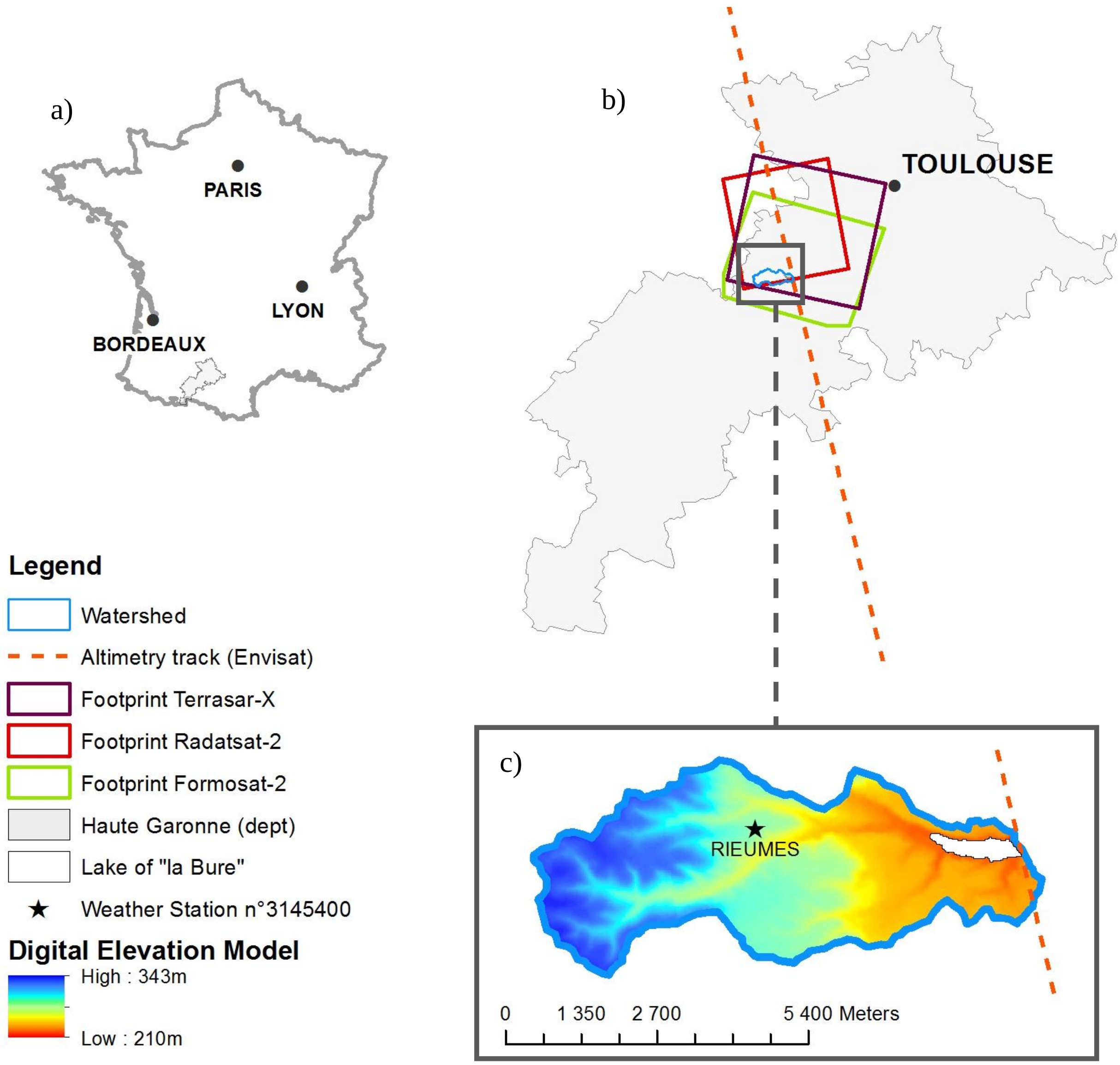

Figure 2: Timeline for acquisition of high spatial resolution satellite images in 2010 (Formosat-2, Radarsat-2, Terrasar-X).

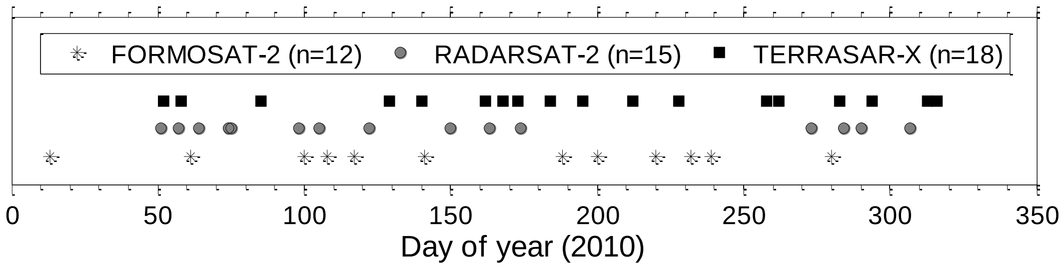

Figure 3: Relationship between in situ water levels and the volumes of lake "la Bure" established in 1987 (abacus of the lake).

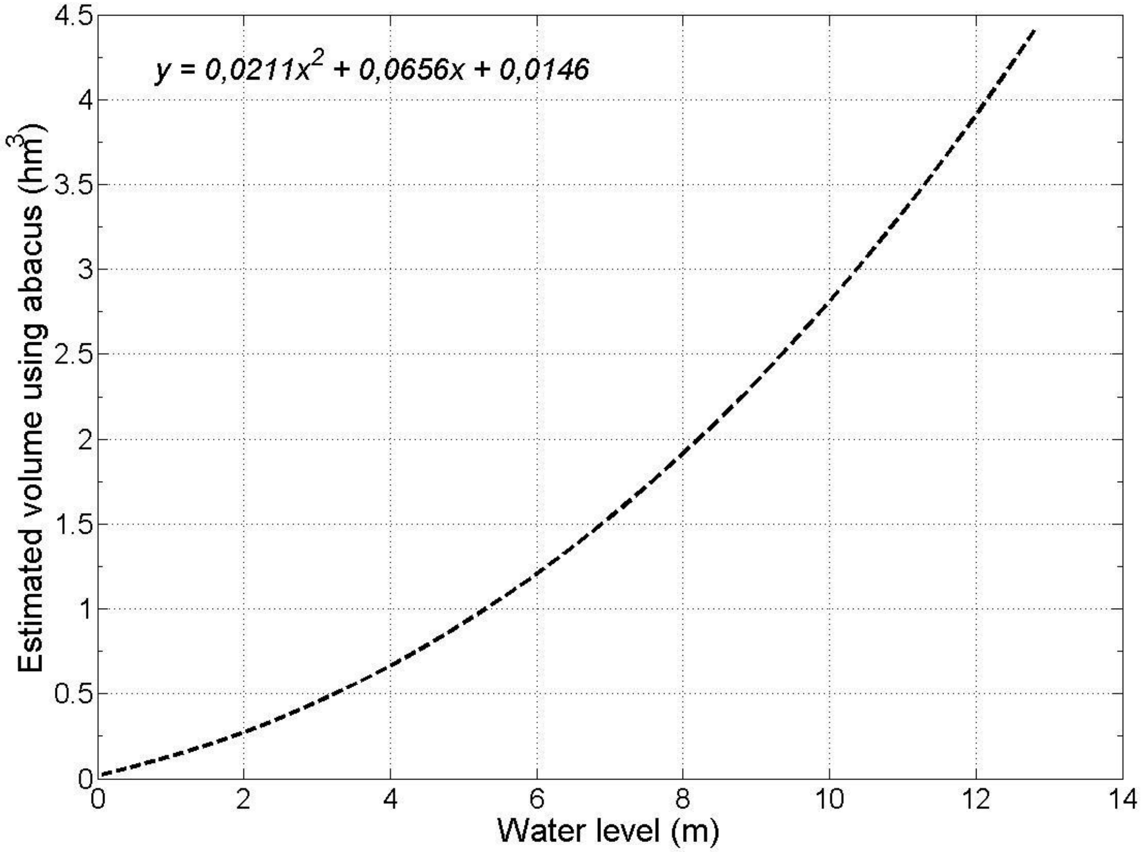

Figure 4: Temporal variations of the local rainfall (vertical gray bars) and measured water volume of Lake "la Bure" (black dots) from 2003 to 2011.

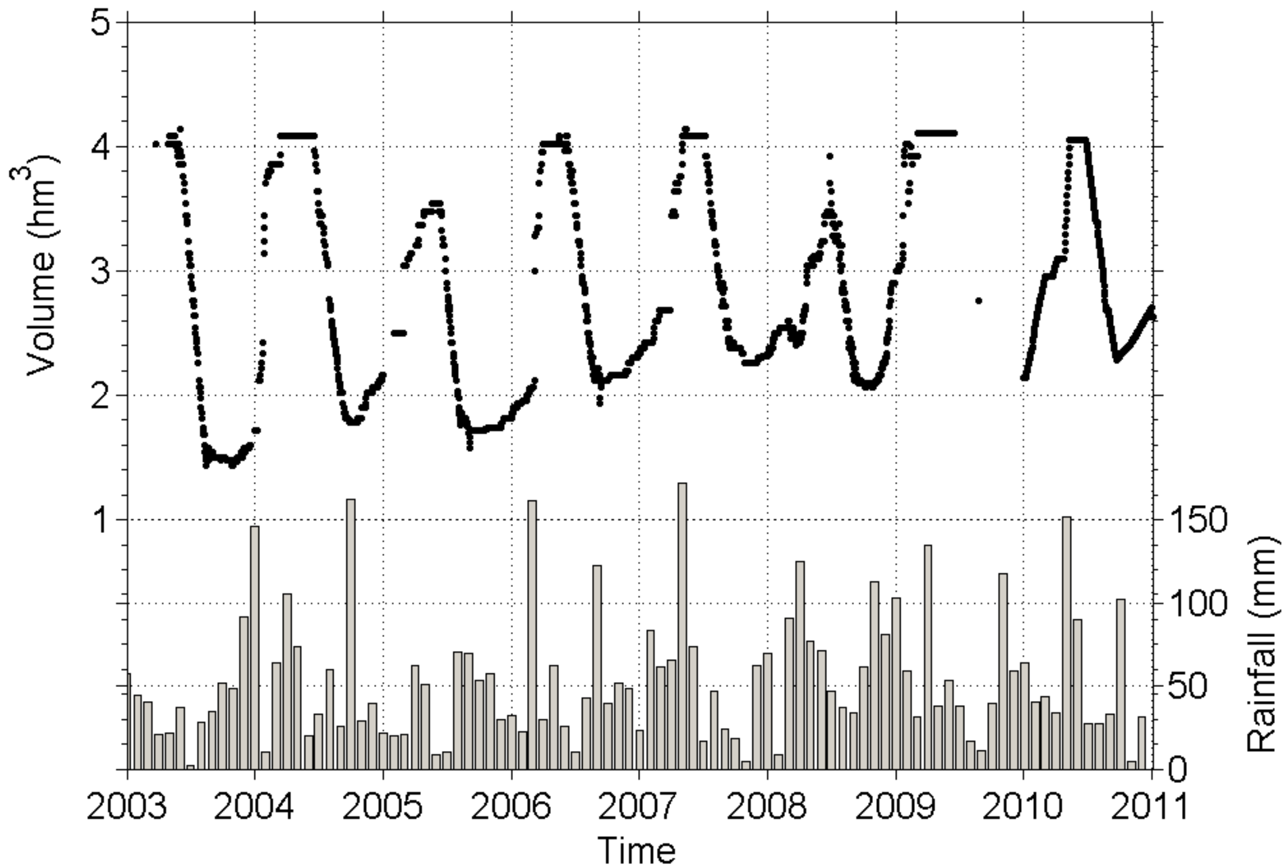

Figure 5: Flowchart showing the processing steps used to estimate the volume of Lake "la Bure" using high-resolution images (HR), radar altimetry (RA-2), and ground data for each of the three methods (HRBV, ABV and AHRBVC).

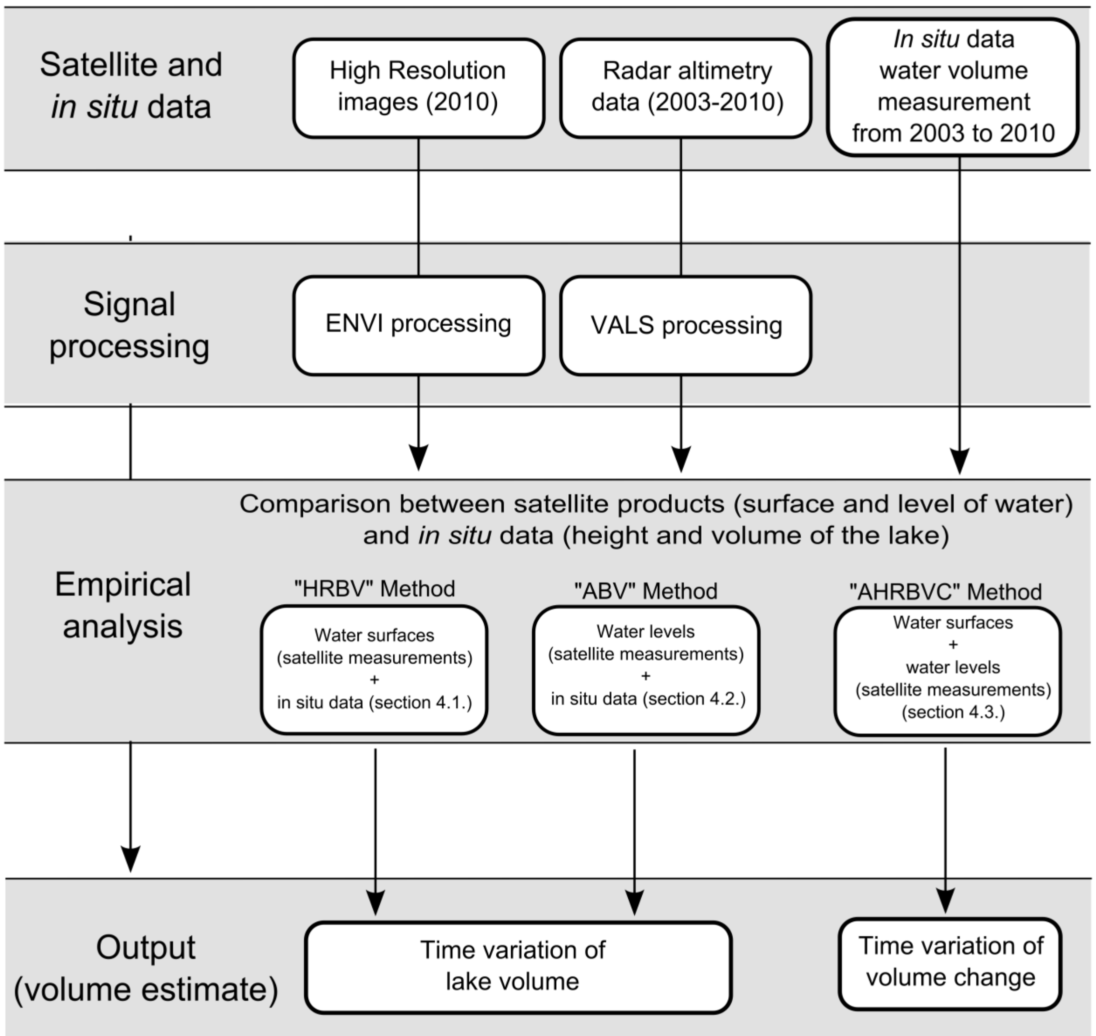

Figure 6: Examples of temporal evolution of the lake shorelines resulting of the supervised classification of Radarsat-2 image: the green, blue, yellow, and pink lines represent the lake shoreline on 31 July, 23 June, 11 October, and 30 September 2010, respectively; the orange line to the east of the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

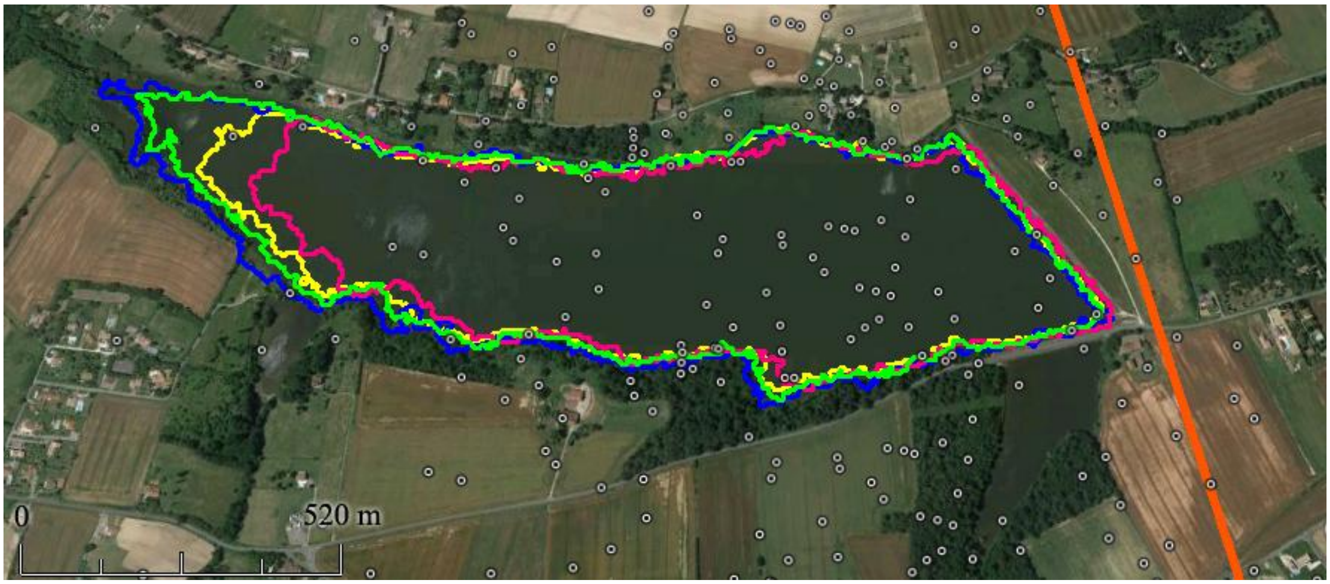

Figure 7: Along-track evolution of the altimeter height over lake "la Bure" and its surroundings. Two cases are presented, corresponding to high and low stage of the lake.

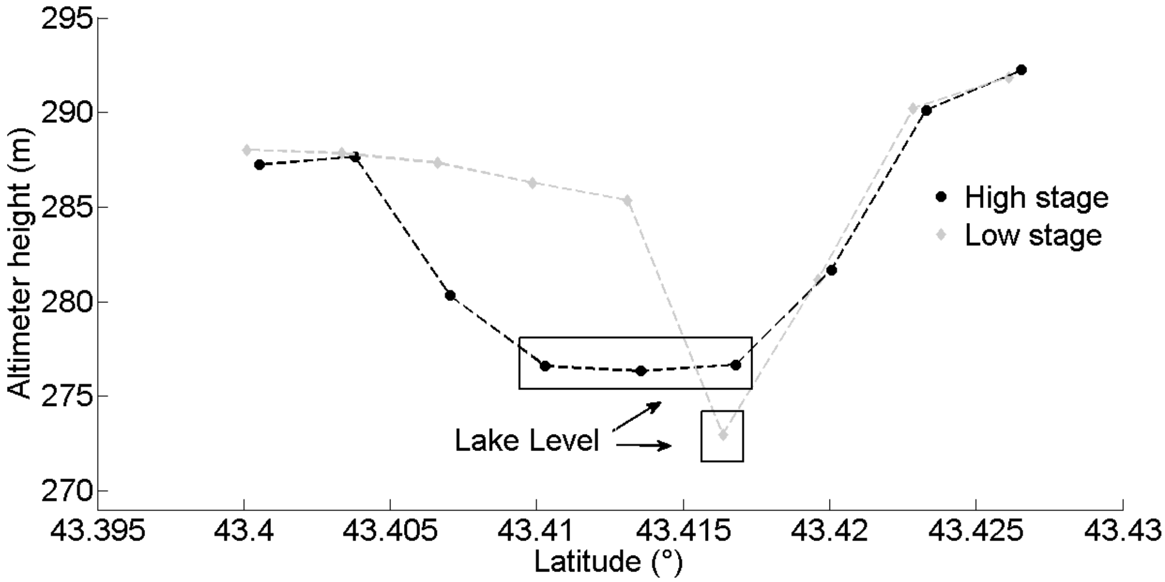

Figure 8: Comparison between satellite-estimated and bathymetry time series of the water surface of lake "la Bure" in 2010. Bathymetry data are only available for water surface ranged between 0 and 47ha. No satellite data (HR images based) outside of this range is therefore presented.

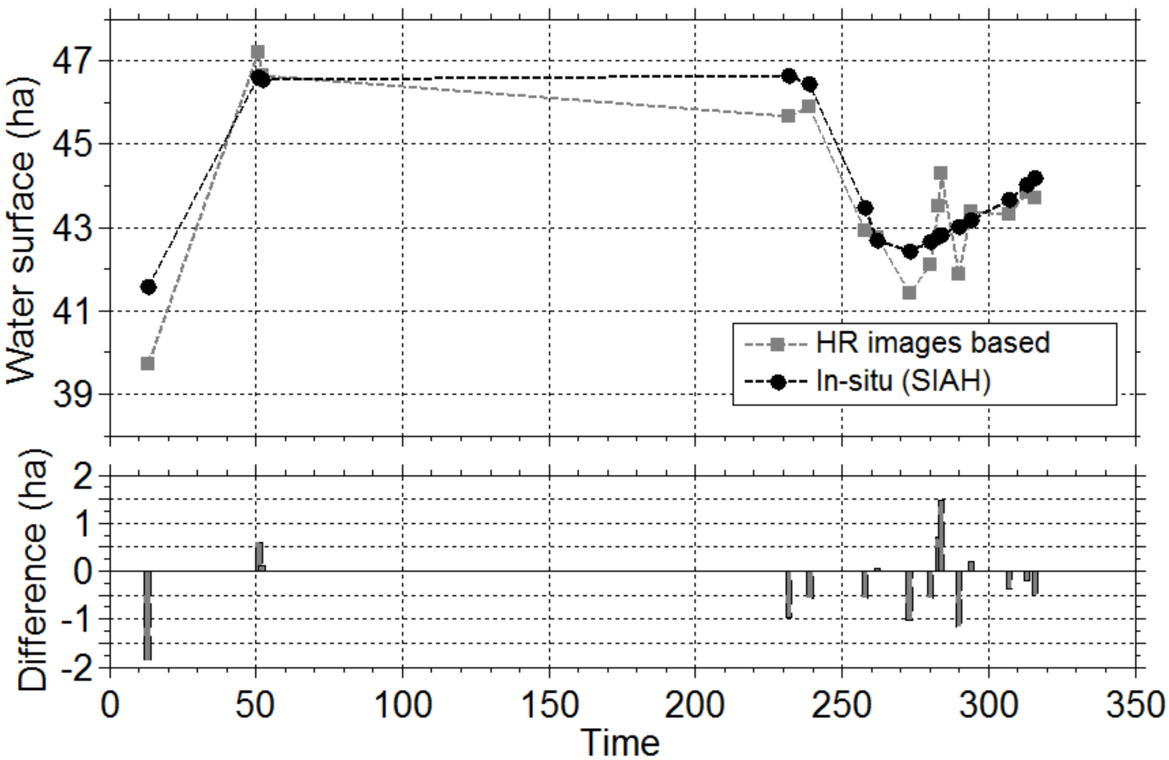

Figure 9: Temporal evolution of water surface of lake « la Bure », as estimated by HR satellite images in 2010, superimposed with daily rainfall events (TerraSAR-X data are shown as black squares, Radarsat-2 as gray circle, Formosat-2 as black stars and irrigation period as gray rectangle).

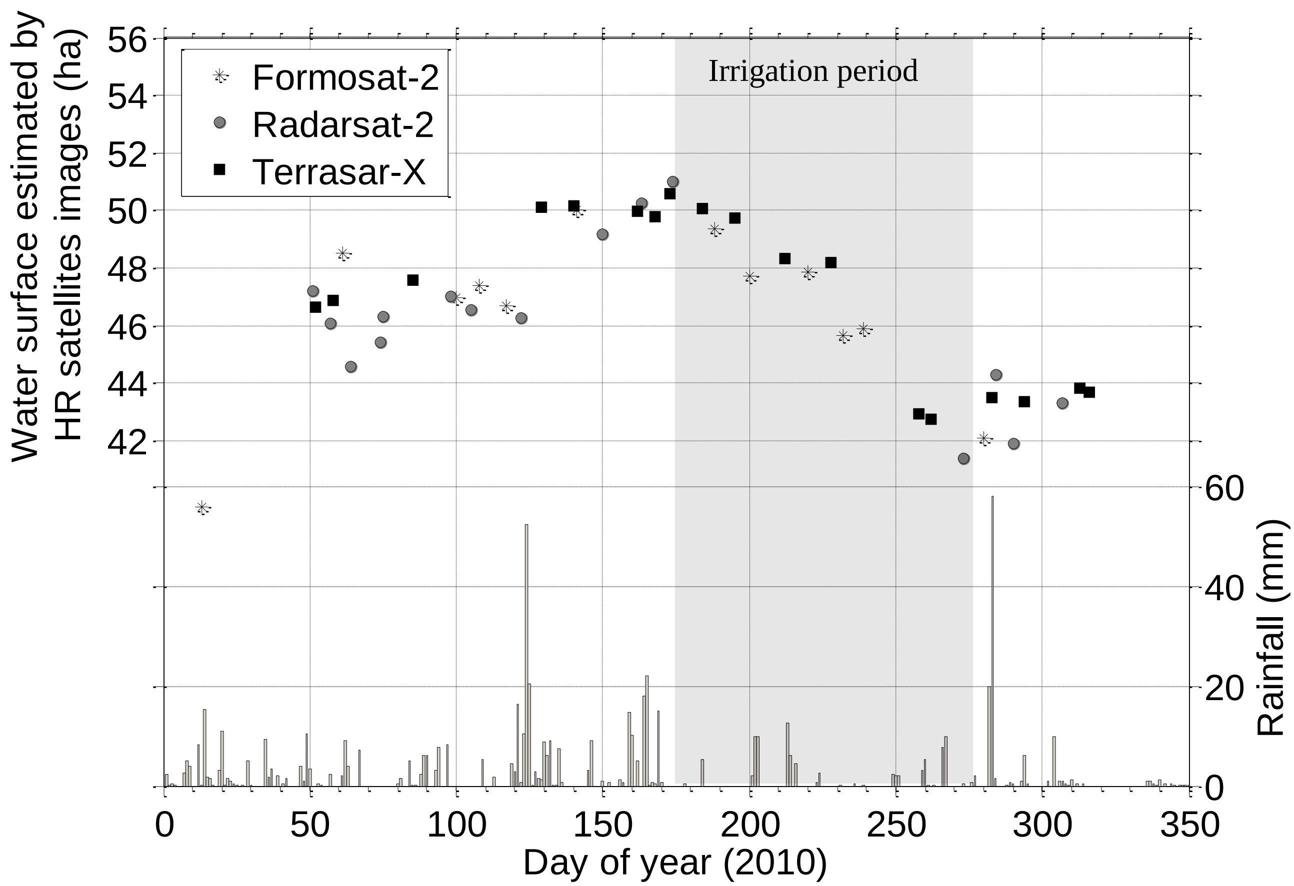

Figure 10: Empirical relationship between surface products (from HR satellite images) and measured volume (SIAH). Volumes are daily-interpolated from weakly measurements.

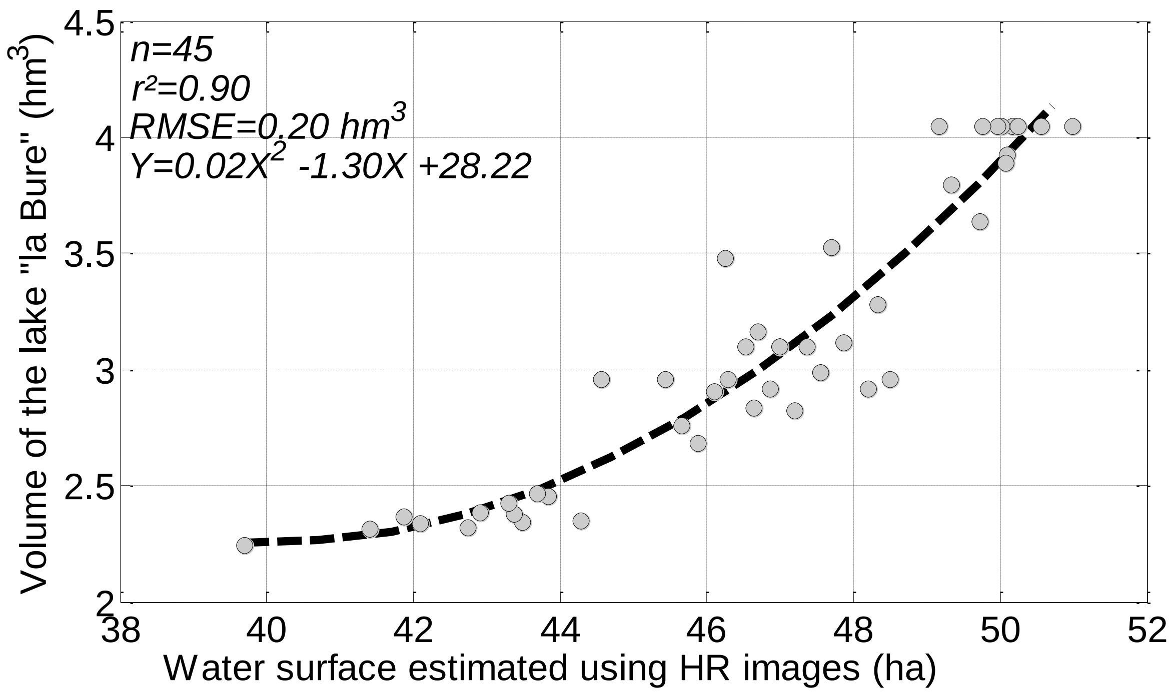

Figure 11: Comparison of satellite-estimated (RA-2) and ground-measured (SIAH) time series of the water level of lake "la Bure" from 2003 to 2010. Differences between altimetry-based and in situ water levels are given in the lower panel.

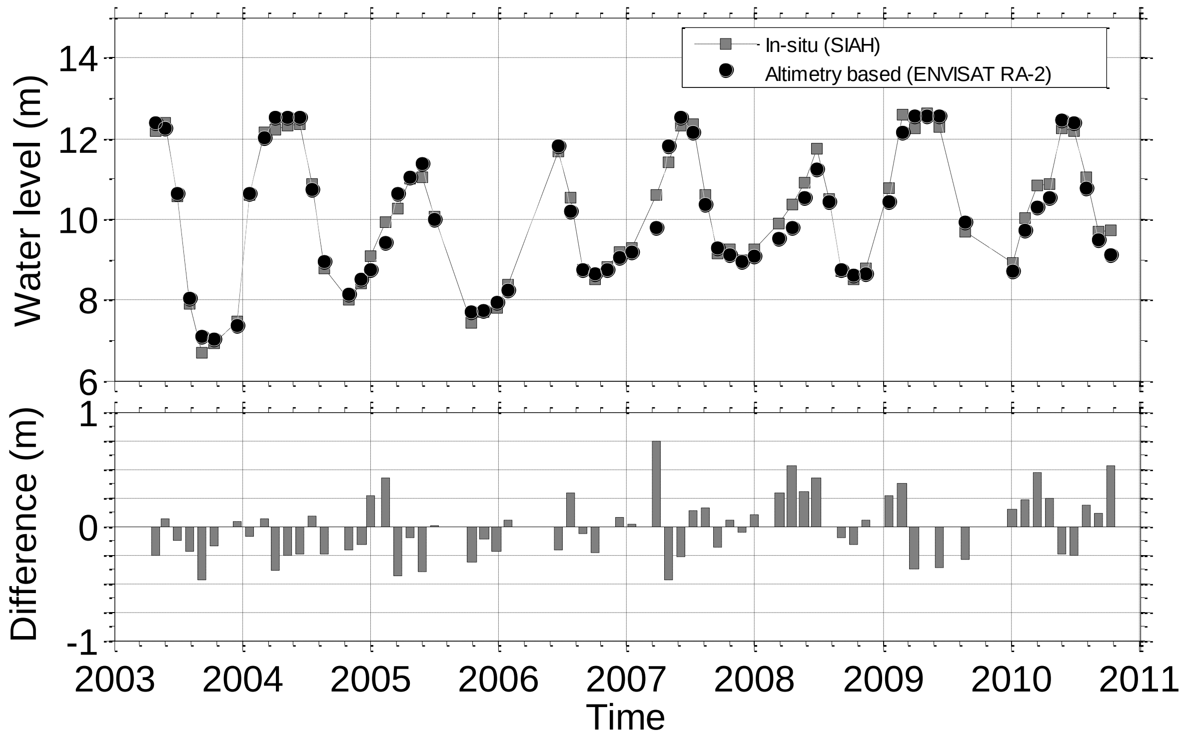

Figure 12: Empirical relationship between the satellite water level (RA-2) and the measured (SIAH) water volume of lake "la Bure" from 2003 to 2010. Each year is colour-separated.

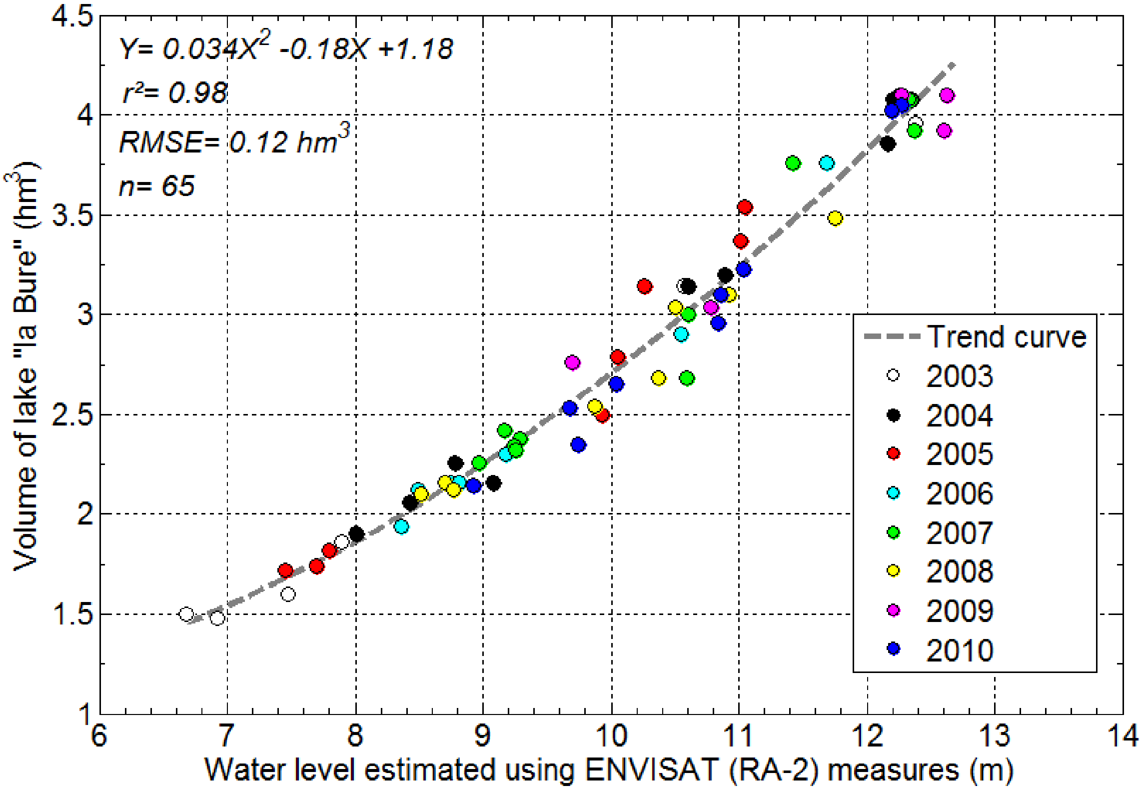

Figure 13: Comparisons between the temporal evolution of water volume of the lake “la Bure”, estimated using two calibration functions: annual for 2010 (gray square) and over the period 2003-2010 (black dots). *In situ* volumes are presented by light gray star. The differences between these results and the *in-situ* measurements are shown in the lower panel.

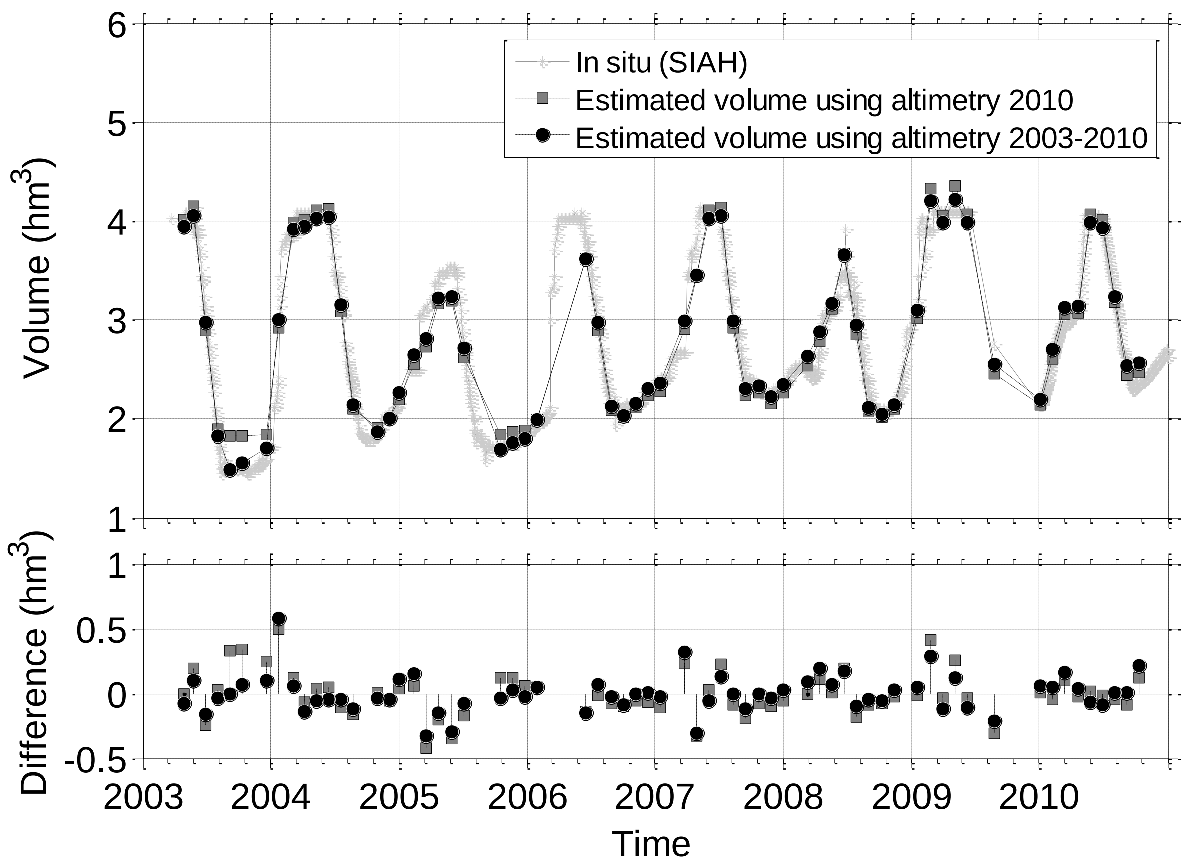

Figure 14: Comparison between volume estimates from altimeter (gray square), HR images (black dots), and ground measurements (gray diamond). Differences of volume estimates with *in situ* measurements are presented on the lower panel for both HRBV and ABV methods.

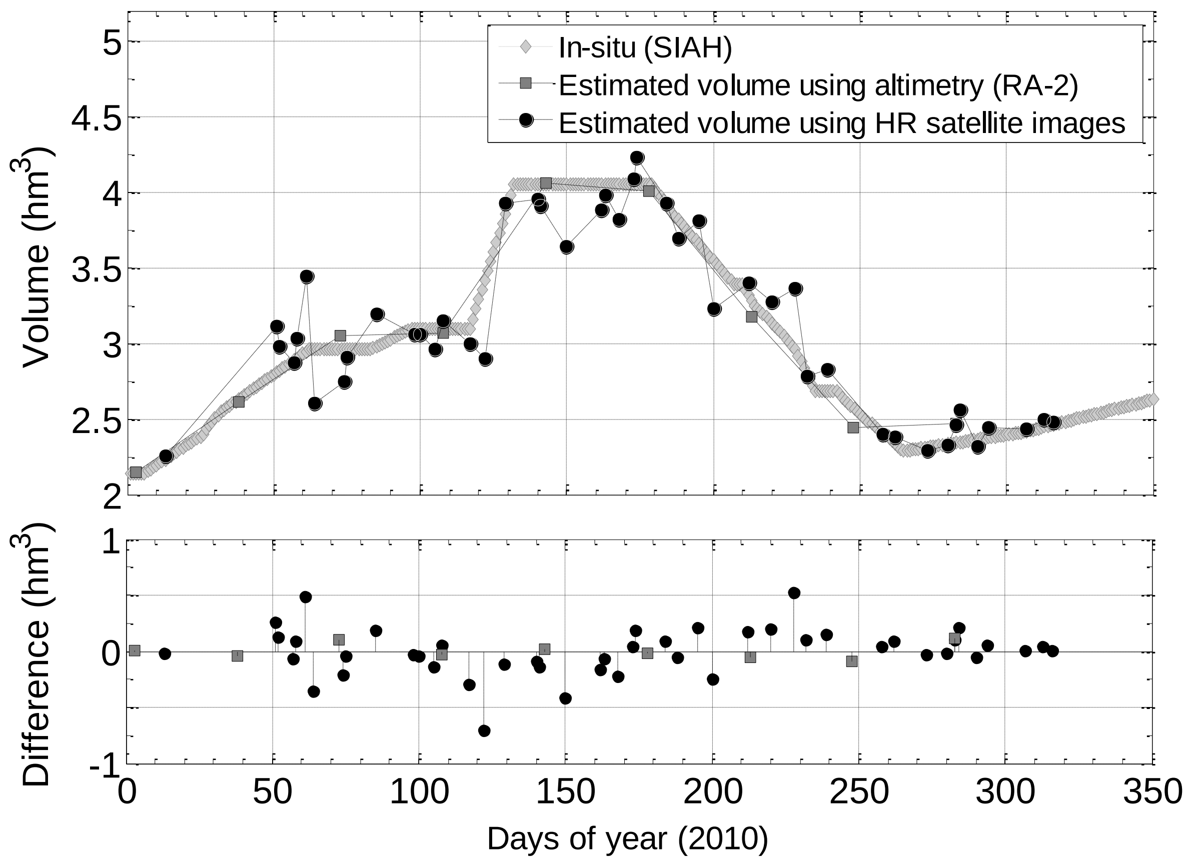

Figure 15: Relationship between satellite water surface (HR images) and water level products (Altimetry) acquired with a time lag of less than 5 days. The gray-scale color of each dot is used to represent the time lag observed between altimetry and imagery data.

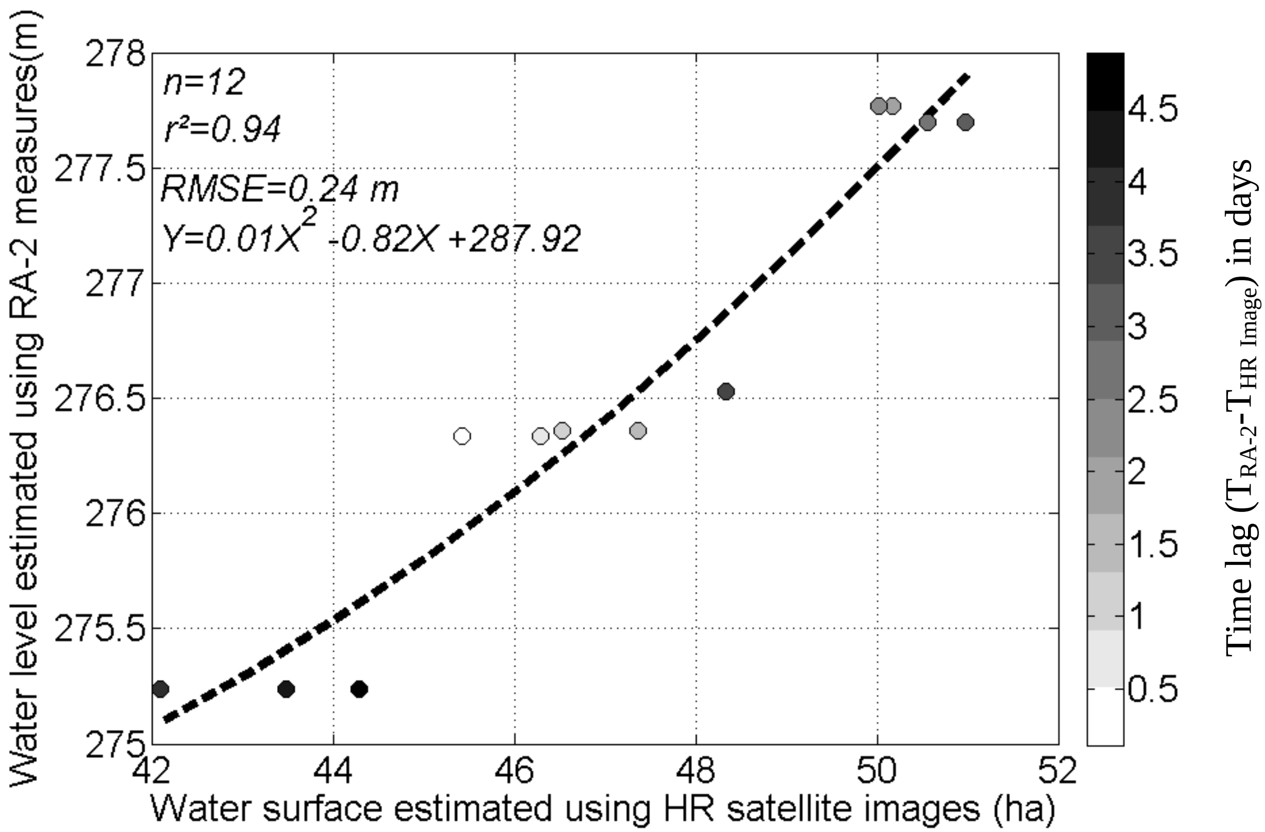

Figure 16: Comparison between the variations in the water volume estimated by satellite data (combining HR imagery and altimetry) and ground-measured (SIAH) data in 2010.

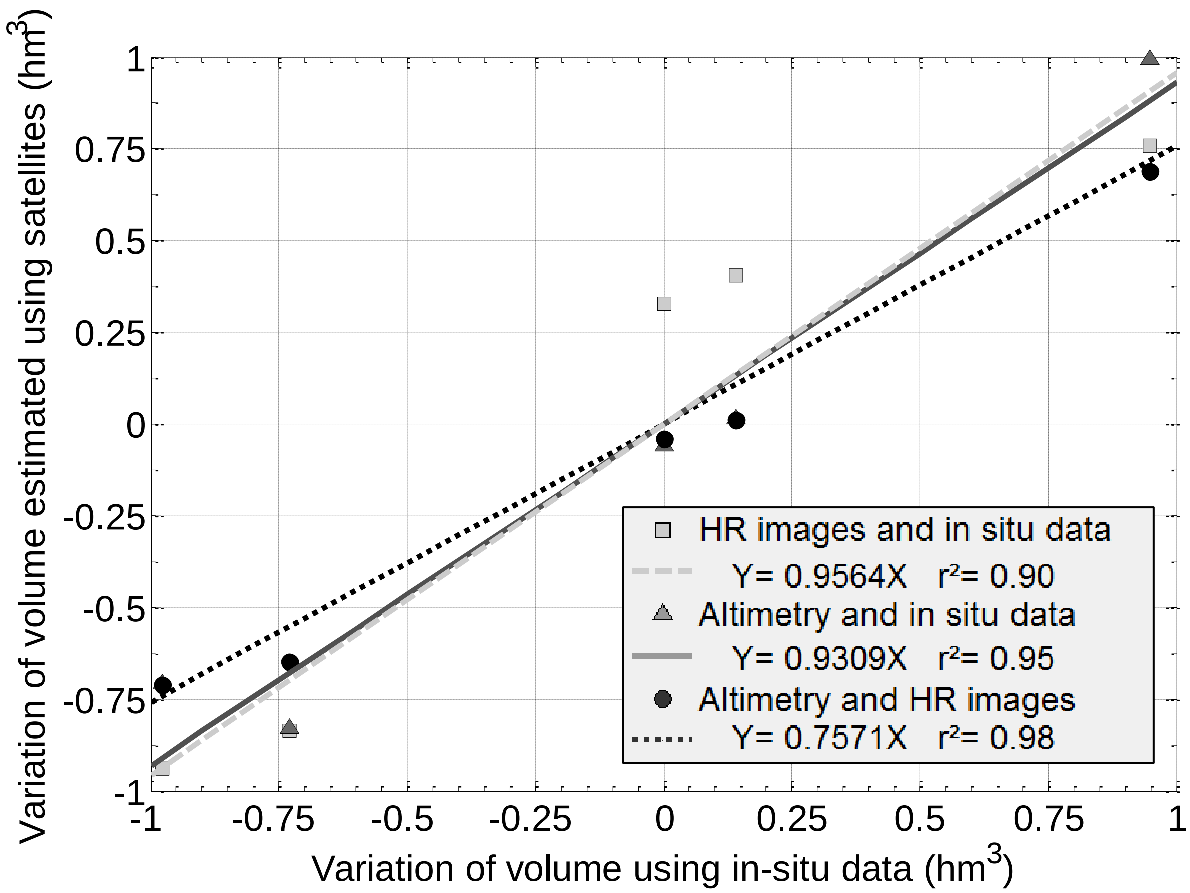

Table 1: Main characteristics of optical and microwave sensors. The given informations are relative to the antenna (Frequency, mode, polarisation states, range of incidence angles) and to the satellite (orbital cycle).

Satellite	Frequency/ wavelength	Mode	Polarisation states	Range of incidence angle	Orbital 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	-	± 45°	1 day	8 m

Table 2: Summary of ground data used (abacus of the lake, bathymetric draw, water level and rainfall). Available periods and sampling frequencies of acquisitions are given.

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

Table 3 : Evaluation of the yearly dependence of the calibration function used to estimate the lake volume from the water level measured by the altimeter (RA-2). Two calibration functions were considered: annual (2010) and pluri-annual (2003-2010).

Period of the estimated calibration function	Number of points	R^2	RMSE (hm^3)	RRMSE (%)
2010	65	0.96	0.17	6.4
2003-2010	65	0.98	0.12	5.0