Use of SARAL/AltiKa over Mountainous Lakes, Intercomparison with Envisat Mission

Article in Marine Geodesy · January 2015
DOI: 10.1080/01490419.2014.1002590

CITATIONS
14

READS
150

3 authors:

Adalbert Arsen
FPRO
8 PUBLICATIONS 525 CITATIONS
SEE PROFILE

J. Cretaux
Paul Sabatier University - Toulouse III
153 PUBLICATIONS 5,771 CITATIONS
SEE PROFILE

Rodrigo Abarca-del-Rio
University of Concepción
63 PUBLICATIONS 1,621 CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Solar activity and climate variability View project

New Earth Observations tools for Water resource and quality monitoring in Yangtze wetlands and lakes (EOWAQYWET) View project
Use of SARAL/AltiKa over Mountainous Lakes, Intercomparison with Envisat Mission

Adalbert Arsen, Jean-François Crétaux & Rodrigo Abarca del Rio

To cite this article: Adalbert Arsen, Jean-François Crétaux & Rodrigo Abarca del Rio (2015) Use of SARAL/AltiKa over Mountainous Lakes, Intercomparison with Envisat Mission, Marine Geodesy, 38:sup1, 534-548, DOI: 10.1080/01490419.2014.1002590

To link to this article: http://dx.doi.org/10.1080/01490419.2014.1002590

Accepted author version posted online: 22 Jan 2015.

Submit your article to this journal

Article views: 93

View related articles

View Crossmark data

Citing articles: 2 View citing articles
Use of SARAL/AltiKa over Mountainous Lakes, Intercomparison with Envisat Mission

ADALBERT ARSEN,1 JEAN-FRANÇOIS CRÉTAUX,1 AND RODRIGO ABARCA DEL RIO2

1Centre national d’études spatiales (CNES), Laboratoire d’Etudes en Géophysique et Océanographie Spatiales (LEGOS), Toulouse, France
2Departamento de Geofísica (D GEO), Universidad de Concepción (UDEC), Concepción, Chile

The SARAL/AltiKa project is based on a single Ka band altimeter (35.75 GHz), which is the first oceanography altimeter to operate at such a high frequency. Ka band offers reduced radar footprint in comparison to traditional Ku band altimeters and negligible ionospheric effects. In this paper we present and evaluate benefits of AltiKa altimeter applied in the study of lakes in Andean chain in South America. Water levels time series obtained with Envisat/RA-2 and SARAL/AltiKa altimeters over 17 lakes of various sizes are calculated and compared to in situ observations. SARAL/AltiKa measurements tend to be extremely well correlated with in situ measurements and offer significant improvements compared to the Envisat mission.

Keywords AltiKa, altimetry, Envisat, lakes, SARAL

Introduction

Since the launch of Topex/Poseidon in 1992, many studies have shown the potential of radar altimetry for the monitoring of lake height variations (Birkett 1995; Mercier et al. 2002; Coe and Birkett 2004; Aladin et al. 2005; Crétaux et al. 2005; Hwang et al. 2005; Crétaux and Birkett 2006; Crétaux et al. 2009; Crétaux et al. 2011; Hwang et al. 2011; Lee et al. 2011; Gao et al. 2012; Yi et al. 2013; Duan and Bastiaanssen 2013). Despite some limitations (e.g., rapidly varying topography, loss and complex shape of the echoes, limited spatial coverage of worldwide lakes), altimetry is the only source of information for most lakes in remote areas. The existing gauge networks on a regional and a global scale tend to decline and observations are often nonexistent, particularly in developing countries (Crétaux and Birkett 2006). Remote sensing hence offers an opportunity to improve this situation. The accurate and continuous monitoring of lakes and inland seas is available since 1993 thanks to the satellite altimetry missions such as Topex/Poseidon (1992–2005), GFO (2000–2008), ERS-2 (1995–2003), Jason-1 (2001–2013), Jason-2 (2008–), and Envisat (2002–2011). Recent scientific missions such as Cryosat-2 (Labroue
et al. 2012) and SARAL/AltiKa provide new opportunities to study lakes water balance. In addition to improved data availability and coverage, these missions are also the “test ground” for new techniques. Until now altimeters have been operating at dual frequencies, including 13.6 GHz “Ku” band and 5.3 GHz “C” or 3.2 GHz “S” bands.

The AltiKa project is based on a single “Ka” band altimeter (35.75 GHz), which is the first oceanography altimeter to operate at such a high frequency. The main advantage of AltiKa is a reduced antenna beam width, reduced radar footprint (approximately by a factor 2 to 3), increased Pulse Repetition Frequency (PRF), and better range resolution (0.47 m Envisat/RA-2, 0.3 m SARAL/AltiKa). In Ka band the ionospheric effects are negligible allowing altimeter to operate with single frequency and the instrument itself to be more compact and lightweight. Nevertheless, this frequency is more sensitive to rainy and cloudy conditions. The main purpose of this article is to present and evaluate benefits of Ka band altimeter applied to the study of mountains lakes.

Few studies have been dedicated up to now for checking the quality of the altimetry data over the continental waters. For big lakes, the altimetry clearly provides accurate level data in a continuous manner with accuracy of $\pm 3$ to 5 cm (Shum et al. 2003; Crétaux et al. 2011; Ričko et al. 2012; Duan and Bastiaanssen 2013). Few studies devoted to an in-depth assessment of radar altimetry over rivers have proved 12–40 cm accuracy for the Amazonian rivers (Da Silva et al. 2010). Lakes in mountains are reputed to be difficult targets. Quick changes in topography and strong noise from multiple lands returns recurrently affect radar measurements. Thus, it is very interesting to compare the effects of a reduced Ka footprint and traditional Ku band measurements. The Andean chain in South America is covered by hundreds of lakes with various sizes. In the present study, we will compare water level time series obtained with Envisat/RA2 and SARAL/AltiKa altimeters over 17 lakes in Chile and Argentina (Figure 1). In our study, the size of the lake is not defined by its surface but rather by the length of available satellite over-passes. For lakes with multiple tracks, every track has different orientation and length relative to local topography. A large section offers more consecutive measurements to be processed, allowing the mean surface height to be better estimated. Therefore, the radar altimetry is much less accurate for smaller lakes, but the derived level variations are generally an order of magnitude higher than the total error budget (Crétaux and Birkett 2006; Ričko et al. 2012). In this study the result comparison is made by calculating the Pearson correlation and root mean square error (RMS) between Envisat/RA2 and SARAL/AltiKa time series and in situ water levels. The reasons for data loss are identified and discussed. Based on these conclusions, perspectives for future missions using Ka band are drawn. For better understanding, sources of errors in radar altimetry are briefly presented.

**Sources of Errors in Radar Altimetry**

Satellite altimeters are active microwave instruments designed to measure the two-way travel time of short radar pulses reflected from the Earth’s surface. The shape of the reflected signal, known as the waveform or echo, represents the time evolution of the reflected power as the radar pulse hits the surface. By noting the two-way time delay between pulse emission and echo reception, the surface height is determined by the difference of the satellite orbit and the altimeter range measurement (Fu and Cazenave 2001). The position of the listening window is adjusted thanks to an on-board system called a tracker (Chelton et al. 1989). During flight, the on-board tracker predicts the likely position (range) of next waveforms based on information derived from the echoes recorded previously to ensure quick and fine adjusting of the signal reception window. On-board
trackers are usually tuned up for oceanic surfaces. Over continents, especially in rapidly changing topography trackers can be misled. Apart from flight operations and maintenance the data losses can be explained with following tracking anomalies:

- During the data acquisition, irregularly shaped waveforms processed by the onboard tracker will cause signal gain attenuation problems or erroneous reposition orders (Chelton et al. 1989), and the signal source will be lost. The satellite then switches from data acquisition mode to target research mode. Target research last no more than 0.5–3 s, but during this time the satellite overfly dozens of kilometers. For a small lake, an entire cycle can be lost.
- The satellite measures the slant range of a random topographic feature. Slant range measurements are caused by the tracker’s ability to lock on a target which is not directly situated at their nadir position. In some cases, echoes from lakes or rivers can be foreseen several or even ten of kilometers before the satellite pass their real position. This phenomena is exploited in data processing over rivers (Da Silva et al. 2010). However, if the altimeter stays locked on a random feature in the mountains
(e.g., volcano cone or hills), the scientifically important target even situated at nadir can never enter in the field of view of the altimeter as shown on Figures 2a and 2b. The difference between radar estimated elevation and true elevation is then greater than 45–60 m (up to several hundreds of meters).

Waveforms can be, and mostly are, reprocessed second time on the ground with more advance algorithms (retracking). Altimetry for continental water bodies has specific requirements, different from those for the oceanic domains (Birkett and Beckley 2010). This includes range estimates by retracking echoes different from the ocean paradigm (Frappart et al. 2006), altitude-dependent dry tropospheric corrections (Crétiaux et al. 2009), wet tropospheric corrections from global meteorological models to replace the radiometer deficiency in the land environment (Crétiaux et al. 2009), and use of high frequency (10 Hz, 18 Hz, 20 Hz or 40 Hz depending on the mission) sample values and coordinates instead of 1 Hz averages. Nowadays, the routine processing of altimetry data uses four retracking algorithms, namely Ocean (Brown 1977), Ice-1 (Bamber 1994; Wingham et al. 1986), Ice-2 (LeGrésy 1995), and Sea-ice (Laxon 1994). Over the continents, big variety of waveforms exists (Gommenginger et al. 2011; Kuo and Kao 2011). Many of them are strongly contaminated by noise from multiple lands returns, and the retracking often fails to retrieve the correct elevation. Therefore, the major part of uncertainties can be explained with small retracking anomalies.

Retracking fails to retrieve the correct elevation. The retracking errors can be often seen as “spikes” in time series. All existing retracking algorithms calculate the range in a purely mathematical way. The complexity of waveforms over the continents hampers the calculation of the range between the satellite and the reflecting surface. A big lake gives the possibility of filtering and averaging a large number of measurements. This explains why the best accuracy is usually achieved for the biggest lakes. At some occasions, retracking can also fail due to boundary limitations imposed in its code (e.g., some parts of the waveform may be excluded from signal processing). Retracking errors can vary from a centimeter to a few dozen meters.

**Data and Methodology**

For this study, data from gauge stations are available in two countries. In Argentina, daily gage heights are available from Argentina’s Subsecretaría de Recursos Hídricos.
(www.hidricosargentina.gov.ar) through Base de Datos Hidrológica Integrada (BDHI). In Chile, daily gage heights are available from Dirección General de Aguas (DGA) through a system of public request (www.dga.cl). Lakes shared between Chile and Argentina can have different names. Data availability and lakes names for each country are listed in Table 1.

The water height variations for lakes in Table 1 were calculated from the radar altimetry data of Envisat from October 2002 to October 2010 and SARAL from February 2012 to April 2014. The time period of Envisat data availability is much longer than that of SARAL/AltiKa; however, accuracy tends to be constant for each location. Thus, this does not affect the evaluation of results. General informations about radar altimetry data processing performed for this comparison can be found in Crétaux and Birkett (2006) and Crétaux et al. (2011). In the present study, the water height variations are calculated separately for each satellite track covering the lake and all points are kept regardless elevation standard deviation error. Altimetry data gaps and points with elevation 45 m above the mean will be considered as lost due to tracking problems. The datum of SARAL and Envisat are based on two different ellipsoids: a specific ellipsoid defined for the Topex/Poseidon mission in the case of SARAL/AltiKa and WGS84 for Envisat which differs from the other one by about 70 cm in the radial component. Geoid corrections are applied on both time series for each track, based on the EGM08 models with additional second order corrections inferred from the satellite altimetry data themselves (Crétaux et al. 2011). As the in situ data are given in their own reference frame, time series obtained with radar altimetry are adjusted to in situ water levels by removing the bias. The bias is simply calculated differencing between the mean of two time series. Exceptionally for visual presentation’s purpose the Lake Cochrane in situ data from DGA (ends in 2008) and BDHI (starts in 2010) are supposed to be at the same mean level. For each radar altimeter track, the Pearson correlation coefficient and RMS error are calculated. Overall number of missing cycles is given.

<table>
<thead>
<tr>
<th>BDHI Argentina</th>
<th>DGA Chile</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARGENTINO</td>
<td>CALAFQUEN</td>
</tr>
<tr>
<td>BRAZO RICO</td>
<td>COCHRANE</td>
</tr>
<tr>
<td>BUENOS AIRES</td>
<td>GEN. CARRERA</td>
</tr>
<tr>
<td>(GEN. CARRERA)</td>
<td>(Buenos Aires)</td>
</tr>
<tr>
<td>GEN. VINTTER</td>
<td>LLANQUIHUÉ</td>
</tr>
<tr>
<td>(PALENA)</td>
<td></td>
</tr>
<tr>
<td>MUSTERS</td>
<td>PANGUIPUlli</td>
</tr>
<tr>
<td>PUELO</td>
<td>PUYEHUE</td>
</tr>
<tr>
<td>PUEYRREDON</td>
<td>RANCO</td>
</tr>
<tr>
<td>(COCHRANE)</td>
<td></td>
</tr>
<tr>
<td>ROSARIO</td>
<td>RINHUE</td>
</tr>
<tr>
<td>SAN MARTIN (O’HIGGINS)</td>
<td>RUPANCO</td>
</tr>
<tr>
<td>VIEDMA</td>
<td>VILLARICA</td>
</tr>
</tbody>
</table>

Table 1

List of lakes with available in situ data that have been compared to satellite altimetry derived water heights

---

538  A. Arsen et al.
In the present study we investigate separately lakes with: a) large sections with more than 18 km of consecutive measurements (e.g., Lakes General Carrera, Ranco, Llanquihue, Viedma, Muster); b) average size sections with 6–14 km (e.g., Lakes Argentino, Viedma, General Carrera, Villarica, Calafquen, Cochrane, San Martin); c) small size lakes 3–6 km (e.g., Lakes Cochrane, Villarica, General Vinter, Brazo Rico, Rinhue, Rupempo, Pangupulli, General Carrera, San Martin, Argentino); and d) very small lakes with sections lower than 3 km (e.g., Lakes Brazo Rico, Rinhue, Musters, Puelo, Rupanco, General Vinter). The last category includes very small cross (e.g., Rosario track 437) sections that can be analyzed as punctual signal sources (Da Silva et al. 2010).

Results

For each individual track, the time series of Envisat (2003–2010) and SARAL/Altika (2013–2014) are stacked over the in situ water levels. For visibility purposes we do not present individual error bars for individual points. Pearson correlation coefficient and RMS are resumed in Table 2. The following results are obtained.

**Large Size Cross Section (>18 km)**

Figure 3 shows results for large cross sections. Eight time series of five different lakes enter in this category. For the Lake Llanquihue, the Envisat results (Figures 3a and 3b) are “decent” in terms of accuracy (43–82 cm RMS). SARAL results are both well correlated (95–98%) within 5–6 cm RMS. The same situation can be seen for the Lake General Carrera/Buenos Aires (Figures 3c and 3d). In this case in situ data show some issues. Apart being rounded to 5 cm for both Chilean and Argentinian sides, they do not correlate entirely, which may explain low accuracy for SARAL track 106 (Figure 3c). Lake Musters (Figure 3e) do not present any tracking or retracking problems. The accuracy and correlation are excellent for both satellites. The tracks of the Lake Ranco (Figures 3f and 3g) are separated only with 5 km in terms of ground distance. The Envisat track 736 (Figure 3f) have average correlation of 75% and with 65 cm RMS cannot be qualified as exploitable. The Envisat track 437 is also not exploitable (33% correlation) although it presents 18.8 km cross section over the lake. Results obtained with SARAL for Lake Ranco have a high correlation of 98% and 96% with RMS 11–16 cm. For Lake Viedma, the Envisat results can be assessed only during 2010. Results obtained with track 151 (Figure 3g) are affected by important retracking anomalies and are not exploitable. In the case of SARAL, the results are correlated at 99% with 11 cm RMS.

**Average Length Cross Section (6–14 km)**

Figure 4 shows results for average length cross sections. Ten time series of seven different lakes enter this category. For the Lake Viedma the Envisat results can be assessed only during the year 2010 (Figure 4a). A hydrological cycle can be seen, which let us consider this time series for exploitation in terms of annual tendencies. For the same track, the SARAL result is better correlated (98%) and precise (13 cm RMS). Results obtained with Envisat for Lake Argentino (Figures 4b and 4c) are poor, with 40–57% correlation and RMS > 1 m. The SARAL time series shows excellent correlation > 99% and a precision 6–8 cm RMS. For Lake General Carrera/Buenos Aires (Figures 4d and 4e), 20 Envisat cycles are missing. Seasonal water level variations of Lake General Carrera do not exceed 2 m. Thus it is clearly visible that none of the eight available cycles is
Table 2  
Summary of results for each individual track. Legend: 1p = only one point, ‘-’ data missing

<table>
<thead>
<tr>
<th>Lake</th>
<th>Track</th>
<th>Length</th>
<th>Correlation Envisat</th>
<th>Correlation SARAL</th>
<th>RMS [m] Envisat</th>
<th>RMS [m] SARAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLANQUIHUE</td>
<td>981</td>
<td>28.7</td>
<td>0.38 0.98</td>
<td>0.82 0.06</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>LLANQUIHUE</td>
<td>736</td>
<td>27.0</td>
<td>0.60 0.95</td>
<td>0.43 0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>106</td>
<td>22.8</td>
<td>0.49 0.36</td>
<td>0.95 0.31</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>523</td>
<td>21.8</td>
<td>0.78 0.68</td>
<td>0.39 0.14</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>MUSTERS</td>
<td>351</td>
<td>21.8</td>
<td>0.99 1.00</td>
<td>0.09 0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>RANCO</td>
<td>736</td>
<td>20.2</td>
<td>0.75 0.96</td>
<td>0.65 0.16</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>437</td>
<td>18.8</td>
<td>0.33 0.98</td>
<td>1.64 0.11</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>VIEDMA</td>
<td>151</td>
<td>18.4</td>
<td>0.90 0.99</td>
<td>1.28 0.11</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>VIEDMA</td>
<td>20</td>
<td>13.8</td>
<td>0.65 0.98</td>
<td>0.60 0.13</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>564</td>
<td>11.0</td>
<td>0.28 0.83</td>
<td>1.72 0.17</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>609</td>
<td>8.8</td>
<td>0.14 1p</td>
<td>3.34 1p</td>
<td>1p</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>736</td>
<td>8.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>VILLARICA</td>
<td>736</td>
<td>7.1</td>
<td>0.70 0.90</td>
<td>0.32 0.09</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>CALAFQUEN</td>
<td>65</td>
<td>6.9</td>
<td>0.19 0.90</td>
<td>1.77 0.08</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>COCHRANE</td>
<td>695</td>
<td>5.8</td>
<td>0.98 0.99</td>
<td>0.21 0.13</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>VILLARICA</td>
<td>151</td>
<td>6.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>SAN MARTIN (O’HIGGINS)</td>
<td>695</td>
<td>5.8</td>
<td>0.98 0.99</td>
<td>0.21 0.13</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>ARGENTINO</td>
<td>106</td>
<td>5.0</td>
<td>—0.37 —</td>
<td>2.38 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>COCHRANE (PUEYREDON)</td>
<td>564</td>
<td>4.3</td>
<td>0.00 —</td>
<td>1.53 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>BRAZO RICO</td>
<td>20</td>
<td>4.0</td>
<td>0.88 1p</td>
<td>1.15 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>RUPANCO</td>
<td>736</td>
<td>4.0</td>
<td>0.34 —</td>
<td>1.83 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>PANGUIPULLI</td>
<td>736</td>
<td>3.8</td>
<td>0.60 —</td>
<td>1.10 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>RINIHUE</td>
<td>736</td>
<td>3.3</td>
<td>0.58 0.99</td>
<td>0.99 0.12</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>65</td>
<td>3.2</td>
<td>0.06 —</td>
<td>3.59 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>GEN. CARRERA</td>
<td>564</td>
<td>3.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>GEN. VINTTER (PALENA)</td>
<td>564</td>
<td>3.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>BRAZO RICO</td>
<td>695</td>
<td>2.6</td>
<td>0.25 —</td>
<td>4.54 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>MUSTERS</td>
<td>936</td>
<td>2.5</td>
<td>0.67 —0.02</td>
<td>0.83 1.18</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>ROSARIO</td>
<td>106</td>
<td>1.9</td>
<td>0.06 —</td>
<td>5.40 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>PUELO</td>
<td>650</td>
<td>1.8</td>
<td>—0.70 —</td>
<td>1.79 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>RUPANCO</td>
<td>437</td>
<td>1.2</td>
<td>0.10 —</td>
<td>2.92 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>ROSARIO</td>
<td>437</td>
<td>0.8</td>
<td>—</td>
<td>1.98 —</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>GEN. VINTTER (PALENA)</td>
<td>981</td>
<td>0.7</td>
<td>0.38 —</td>
<td>4.88 —</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>
retracked correctly. Results obtained with Envisat are poorly correlated for the track 564 (28%) and decorrelated (−0.14%) for the 609 track. Those times series are unexploitable and retracking is the major issue. With SARAL, the water heights calculated from the track 564 are correlated at 83% with 17 cm RMS. Similarly to Envisat the SARAL track 609 is affected by tracking anomalies. Envisat and SARAL tracks of Lake Villarica are affected by considerable tracking problems. Figure 2b shows a scatter plot of elevations

Figure 3. Comparison of Envisat/RA-2 and SARAL/ALtiKa time series for large cross sections. Envisat (dark gray) and SARAL (black) data are plotted on in situ data (light gray).
for the Envisat track 736 realized with first 80 cycles. Due to tracking problems, Lake Villarica situated approximately at 220 m above sea level was seen only twice in 80 cycles. The same problem occurs for Lake San Martin (not shown). *In situ* data are discontinued for Lake Calafquen at several occasions during 2006–2010 (Figure 4f), and a large portion of *in situ* data is missing. For the available points, the Envisat water level’s correlation seems to be average (70%). Envisat data are not complete. With only 29 cycles

![Figure 4. Comparison of Envisat/RA-2 and SARAL/ALtiKa time series for average cross sections. Envisat (dark gray) and SARAL (black) data are plotted on in situ data (light gray).](image-url)
available, this time series presents only limited interest. SARAL shows there 90% correlation and 9 cm RMS. In situ measurements are also discontinued between 2008 and 2010 for the Lake Cochrane/Pueyrredon (Figure 4g). Envisat results for track 65 are poorly correlated (19%) with RMS > 1.7 m. Water levels obtained with SARAL are correlated at 90% with 8 cm RMS.

Figure 5. Comparison of Envisat/RA-2 and SARAL/ALtiKa time series for small cross sections. Envisat (dark gray) and SARAL (black) data are plotted on in situ data (light gray).
Small Size Cross Section (3–6 km)

Figure 5 shows results for small cross sections. Nine time series of nine different lakes enter in this category. Results obtained with Envisat and SARAL for Lake Argentino (Figure 5a) are well correlated (98% and 99%). The accuracy improve from 21 cm RMS for Envisat to 13 cm RMS for AltiKa. All SARAL data are lost for the lakes: Vintter/

Figure 6. Comparison of Envisat/RA-2 and SARAL/ALtiKa time series for very small cross sections. Envisat (dark gray) and SARAL (black) data are plotted on in situ data (light gray).
Palena (Figure 5b), Cochrane (Figure 5c), Brazo Rico (Figure 5d), Rupanco (Figure 5e), Panguipulli (Figure 5f), and General Carrera (Figure 5h). For all mentioned lakes, data are available in case of Envisat; however, except for Brazo Rico (Figure 5d), these time series are not exploitable due to poor correlation and high RMS (1.0–3.6 m). For Lake Rinihue (Figure 5g), SARAL shows improved correlation (99%) and accuracy (12 cm RMS). The Envisat results are affected by retracking problems at low levels in winter period.

**Very Small Cross Section (<3 km)**

Figure 6 shows results for very small or punctual cross sections. Seven time series of six lakes enter in this category. As in previous section, almost all SARAL data are lost. Envisat data are available; except for Lake Musters (Figure 6b), none of Envisat time series is qualified as exploitable due to poor correlation and high RMS (1.8–5.4 m).

Figure 7 shows the elevation RMS as a function of the cross-section length (Table 2). A strong relationship for Envisat between the length of the cross section and the resulting RMS exists. It indicates that accuracy of Envisat processing over lakes in mountain can reach submetric value only for very long cross sections. In contrast to Envisat, the accuracy of SARAL measurements is independent of the cross-section length.

**Conclusions**

When a time series is calculated for a specific lake, all available tracks are used to increase the time sampling. With result obtained during this study, we are able to identify faulty tracks and remove them definitely from future data processing. This will improve the quality of our lake observation service Hydroweb (http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/). The vertical offsets (bias) calculated with respect to in situ data will allow us to establish the link between SARAL and Envisat observations and ensure the sustainability of altimetry observations.

When available, the SARAL measurements are generally extremely well correlated with in situ measurements and offer high quality improvements compared to
previous Envisat mission. Envisat time series have poor correlation with in situ. Only 2 of the 30 Envisat time series are correlated above 90%. For SARAL 12, a total of 15 time series are correlated above 90%, which is a significant improvement. Envisat time series were previously available for these tracks. From RMS observation and cycle’s availability we can identify retracking as the main problem in case of the Envisat results. It implies that better accuracy of SARAL is achieved due to reduced noise in waveforms. The better accuracy of SARAL/AltiKa is also visible in exploitable cross sections length. Previous studies show that the altimetry provides very accurate level data with accuracy of $\pm 3 - 5$ cm RMS (Shum et al. 2003; Crétaux et al. 2011, 2013; Ríckó et al. 2012; Duan and Bastiaanssen 2013) for big lakes and 12–40 cm RMS accuracy for rivers (Da Silva et al. 2010). In our study, the accuracy oscillates between 9 cm RMS and several meters for Envisat and 5–17 cm for AltiKa. This difference cannot be link to a particular length of the ground segment. Some SARAL results shows better correlation and lower RMS for shorter cross sections (Lake Rinihue, track 736, length 3.3 km) rather than longer segments (Lake Gen. Carrera, track 564, length 11 km). It proves that noise from multiple land returns is likely the factor responsible, which determines accuracy.

An important result from this study is that SARAL/AltiKa mission has the capacity to measure small lakes down to 3.3 km (Lake Rinihue) which in mountain environment which was not possible with Envisat for which the best result was 5.8 km (Lake Argentino). This proves that small water bodies, particularly in mountain environments, can be better observed with SARAL. However, from a global overview we can also point out that only 15 SARAL time series are obtained, where 30 time series were available with Envisat. For mountainous lakes these losses affecting cross sections lower than 7 km. They are partially due to tracking or acquisition issues (not optimal definition when the signal is declared as lost) and occasionally to retracking issues (limitation imposed in retracking algorithms). On one side we cannot qualify the time series availability reduction as a drawback, because previously obtained Envisat time series are often very poorly correlated. On the other side, Envisat data occasionally give unexpected results, for example, capture of the ice damming events of the Brazo Rico (Skvarca and Naruse 2006).

In conclusion, with SARAL/AltiKa better water levels and water balance estimations are expected for lake especially in mountain regions for small lakes where it is usually hard to install dense network of in situ gauges. As lakes can act as proxy of climate a more accurate water height monitoring is necessary to quantify the linkage with their regional environment. Envisat data over lakes in mountain, reaches sub-meteric accuracy only for long cross sections. In contrast to Envisat, the accuracy of SARAL measurements is totally independent of the cross-section length. Also almost all SARAL time series are immediately exploitable. From total 15 time series obtained with SARAL 12 are correlated above 90%, with RMS between 5 and 17 cm. The SARAL/AltiKa accuracy is almost an order of magnitude better than the Envisat/RA2 (95 cm RMS in average over the same cross sections). For small section’s length, SARAL/AltiKa data are generally lost. In the case of Envisat, data were acquired for all small cross sections. Our results shows a rough accuracy of Envisat measurements (several meters of RMS). Thus these data are not exploitable. As the Envisat waveforms seem to be heavily affected by noise, it is unlikely that any future retracking algorithm will improve the retrieval of heights for lakes in the Andean mountains. This proves that single Ka band altimeters are good alternative for traditional bi-frequency altimeters.
References


