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remote sensing

Article

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Abstract: Calibration/Validation (C/V) studies using sites in the oceans have a long history and protocols are well established. Over lakes, C/V allows addressing problems such as the performance of the various retracking algorithms and evaluating the accuracy of the geophysical corrections for continental waters. This is achievable when measurements of specific and numerous field campaigns and a ground permanent network of level gauges and weather stations are processed. C/V consists of installation of permanent sites (weather stations, limnigraphs, and GPS reference points) and the organization of regular field campaigns. The lake Issykkul serves as permanent site of C/V, for a multi-mission purpose. The objective of this paper is to calculate the altimeter biases of Jason-3 and Sentinel-3A, both belonging to an operational satellite system which is used for the long-term monitoring of lake level variations. We have also determined the accuracy of the altimeters of these two satellites, through a comparison analysis with in situ data. In 2016 and 2017, three campaigns have been organized over this lake in order to estimate the absolute bias of the nadir altimeter onboard the Jason-3 and Sentinel-3A. The fieldwork consisted of measuring water height using a GPS system, carried on a boat, along the track of the altimeter satellite across the lake. It was performed at the time of the pass of the altimeter. Absolute altimeter biases were calculated by averaging the water height differences along the pass of the satellite (GPS from the boat system versus altimetry). Jason-3 operates in a Low Resolution Mode (LRM), while the Sentinel-3A operates in Synthetic Aperture Radar (SAR) mode. In this study we found that the absolute biases measured for Jason-3 were −28 ± 40 mm with the *Ocean* retracker and 206 ± 30 mm with the *Ice-1* retracker. The biases for Sentinel-3A were −14 ± 20 mm with the *Samosa* (*Ocean* like) retracker and 285 ± 20 mm with the *OCOG* (*Ice-1*-like) retracker. We have also evaluated the accuracy of these two altimeters over Lake Issykkul which reached to 3 cm, for both the instruments, using the *Ocean* retracker.

Keywords: calibration; validation; lake; Issykkul; SAR; radar altimetry; Jason-3; Sentinel-3A

1. Introduction

The determination of global and regional mean sea-level variations using satellite altimetry, with an accuracy higher than 1 mm/year, is an important challenge. It is central in the current debate on climate change and its impact on the environment [1,2]. Highly accurate time series from both satellite altimetry and tide gauges are needed to address this issue. However, the desired accuracy represents a significant challenge for the geodetic community. From the perspective of a space-borne altimetry, systematic errors from the altimeter systems are limiting factors and must be minimized in order to derive data products of the greatest geophysical value. Indeed, the objective for the overall accuracy of future altimeter systems is 1 cm, along with a stability below 1 mm/year. From the terrestrial perspective, estimating the vertical velocity of tide gauge sites with sufficient accuracy is also one of the most important and challenging problems in modern geodesy. To reach these goals, ultra-precise validation and calibration techniques, including in situ absolute calibration experiments, are needed. Most of the present calibration experiments are on or near the seacoast, reinforcing the need for developing such techniques to unify the altimetry error budget, for both open-ocean and local (coastal) conditions. The number and variety of C/V sites over the continent allows performing more robust assessment of the radar altimetry, over different types of water surface, from oceans to lakes and rivers [3,4]. It also allows verifying whether estimation of the absolute bias is dependent on the specific water conditions.

Within the framework of the Ocean Surface Topography Science Team (OSTST), a C/V project, named FOAM (From Ocean to inland wAters Monitoring [5]), including continental waters (rivers and lakes) has been setup in 2007. In collaboration with the CNES and NASA oceanographic missions—Topex/Poseidon (T/P) and Jason—the OCA (Observatoire de la Cote d'Azur) has developed a verification site in Corsica, since 1996; LEGOS has installed sites in Kerguelen in 1993 and at Vanuatu in 1999, for oceanic validation, and at lake Issykul and along the Amazon River, for continental waters [6]. Recently, new coastal sites in France (île d'Aix and Pertuis Charentais, Arcachon Bay, and Gironde Estuary) have been developed to deal with the littoral context. Within the FOAM project we have investigated different approaches for C/V activities, including the development of dedicated instruments. This last point, which ensures consistent procedures and equipment among all different calibration sites, is crucial for a multi-mission C/V approach.

C/V embraces a wide variety of activities:

- Interpretation of information from internal-calibration modes of the sensors;
- Selection of the best algorithm in picking up the range in the radar echoes in various contexts;
- Selection of the best measurement or model to account for the delay in travelling through the atmosphere;
- Validation of the fully corrected estimates of the heights, whether it is sea-level or inland water-level.

The inland sites are unique in the scientific community. They provide the only estimates of altimeter range bias and assessment of geophysical corrections for non-oceanic retracking algorithms used for continental waters or for ranges determined from ocean-like waveforms, in a context of very low Sea State Bias (SSB), as is frequently encountered over lakes.

In-situ calibration of altimetric height is usually performed at the nadir of a dedicated C/V site, by direct comparison of the altimetric data with in-situ data. This configuration leads to better handling of the differences observed in the altimetric measurements system at the global scale—the geographically correlated errors at regional (orbit, SSB, atmospheric corrections, etc.) and local scales (geodetic systematic errors, land contamination for the instruments (e.g., the radiometer), land contamination for the radar echoes (e.g., tracking/retracking concerns), and geophysical corrections).

In addition, we enter a new era of altimetry with SAR and wide swath altimetry and our group is taking a particular focus on the new measurement systems and their reliability with the past ones (LRM). Although not being specifically designed for hydrology, the SAR mode is expected to have substantial benefits for continental waters monitoring. In SAR mode, the large circular footprint is sliced into bands in a cross-track direction, allowing an optimal selection of the water body. Compared to the LRM measurements, the contamination of the echo from the surrounding terrain is also reduced. In the case of Lake Issykkul, the coastline is closely oriented, in a direction perpendicular to the along-track direction of Sentinel-3A.

In this context of using satellite altimetry over continental waters, the C/V over lakes and rivers took a central place over the last decade. Since the mid-nineties, more and more scientific studies have used satellite altimetry to monitor inland waters [7,8]. However, as for ocean studies, linking time series from different missions requires accurate monitoring of the biases and drifts of each parameter, contributing to the final estimate of the surface water height. Moreover, the calibration of satellite altimetry over ocean does not apply directly to inland seas (e.g., corrections, retracking, and geographical effects).

Comparisons using results over Lake Ontario and Lake Issykkul have shown that lakes' sites allow performing C/V of radar altimeter with a quality similar to the ones obtained using sites over the oceans [3,4,9–11].

Fifteen campaigns with GPS receivers have been conducted on Lake Issykkul from 2004 until 2017, with receivers installed on a boat, and receivers on the shore. Cruise with GPS data were conducted along the ground track of each satellite. They allowed estimating absolute bias of each altimeter, and relative bias between them. They also allowed assessing if C/V over continental surface leads to different results than those obtained over the historical C/V on the ocean.

Moreover, C/V over lake surfaces has interesting characteristics—tides are low, inverse barometric effect is fully negligible, and dynamic variability is much smaller. SSB is also very low and not accounted for over the inland waters.

Calculating multi-mission absolute altimeter bias allows for the continuity with further missions on the same orbit (the Sentinel-3 and Jason-series). For hydrology, in particular, it is essential to calculate long-term (multi-decadal) water-level time-series. Continuity can be obtained if during a certain period of time (few months) the satellites are in the same orbit as the so-called tandem phase. It has been done for T/P with Jason-1 (9 months in 2002), then Jason-1 with Jason-2 (8 months in 2008), and Jason-2 with Jason-3 (8 months in 2016). In other cases, like with the Envisat and the Saral/AltiKa missions, the continuity, unfortunately, has not been possible, and at least a one and half years separated the last repeat cycle of the Envisat, with the first one of the Saral/AltiKa. C/V operations were performed over Lake Issykkul with these two satellites allowing the absolute bias of each satellite to be calculated, therefore, estimating the relative bias between them [11,12].

The main objective of this work is to determine the absolute bias of the two altimeters onboard Jason-3 and Sentinel-3A, using the two retracking algorithms (*Ocean* and *Ice-1*). We also quantify the final accuracy of these two altimeters in the specific context of the lake's water-level measure.

In order to determine the altimeter's absolute bias, the ellipsoidal altitude of the lake along the altimeter track is measured by two means—using the altimeter and using the GPS survey from a boat cruising, along the satellite tracks. The absolute bias is simply the averaged difference between both sets of measurements.

In Section 2, altimetry data processing for lake level calculation and the new experimental design for C/V over Lake Issykkul are described. The main results on the atmospheric correction, first, then on the biases of the respective Sentinel-3A and Jason-3, from the last two field works, are given in Section 3. Conclusion and future perspectives are then proposed in Section 4.

2. Methodology for C/V of Radar Altimeters

2.1. Lake Issykkul C/V Site Description

Lake Issykkul (42°10′–42°40′ North, 76–78° East, Republic of Kyrgyzstan, Figure 1), is the 7th deepest lake in the world. It is situated in Central Asia in the Tien-Shan Mountains at a height of, approximately, 1607 m above sea-level. It is the second largest mountain lake in the world, after Lake Titicaca in South America. In the north and south, it is surrounded by Kungei-Alatoo and Terskei-Alatoo ranges, elevating up to 2000–4500 m above the lake [13]. The length of the lake is 178 km, width is 58 km, maximum depth is 668 m, and its area is 6247 km^2.

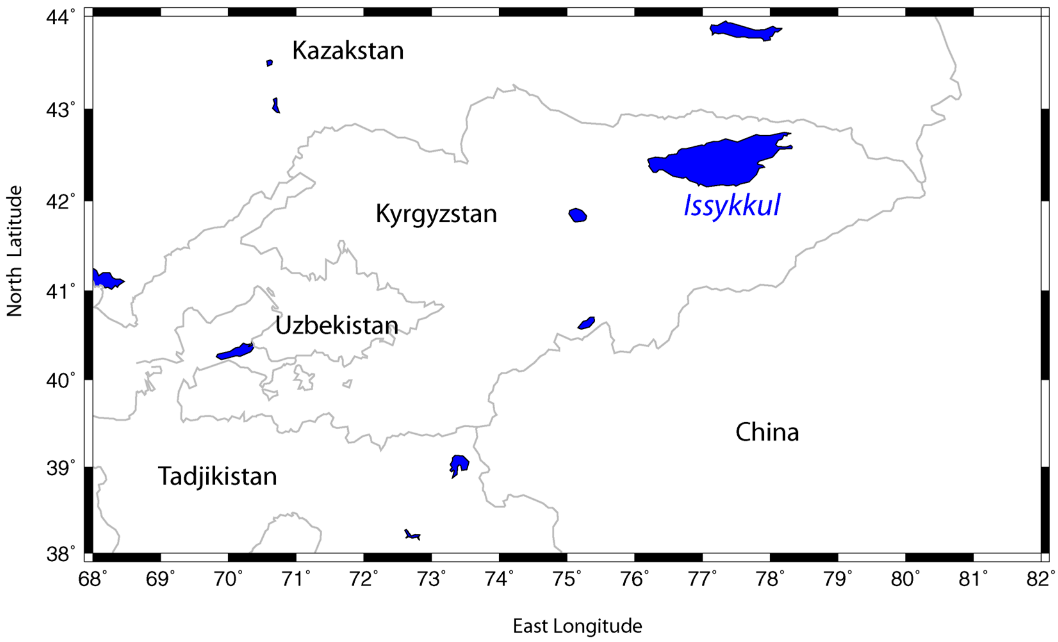

Figure 1. Map of the central Asia region around Lake Issykkul.

Since the launch of T/P in 1992, Lake Issykkul, has been overpassed by all of the satellites, carrying an altimeter onboard: GFO (Geosat Follow On), T/P, Jason-1,2,3, Envisat, ERS-1,2, Cryosat-2, Saral/AltiKa, HY2A, Icesat-1, and Sentinel-3A/B. In the near future, the Sentinel-3B, Jason-CS/Sentinel-6, and IceSat-2 will also measure Lake Issykkul's water-level. In 2021, the SWOT (Surface Water Ocean Topography [14]) mission will be launched, for which Lake Issykkul has been already chosen by NASA and CNES, as a dedicated C/V site for hydrology.

Lake Issykkul is moreover a good C/V site because in situ measurements are available and some instruments have been installed along the coast, over the last 15 years. We used, for example, the data from a weather station located in Cholpon Ata (see map on Figure 2), to calculate the Dry Tropospheric Correction (DTC). The cooperation with the Institute of Water Problem and Hydropower (IWPH) of Kyrgyzstan, since 2003, also allows for having facilities during the fieldwork, including a long vessel (named Multur) which is capable of navigating for many consecutive days on the lake and performing the C/V measurements. It is also under the framework of this cooperation that we have been authorized to perform in situ measurements and install permanent instruments—two permanent GPS receivers near the lake, two weather stations, and radar on the southeast bank of the lake, providing atmospheric pressure, air temperature, and humidity, and water-level every 5 min, since September 2010.

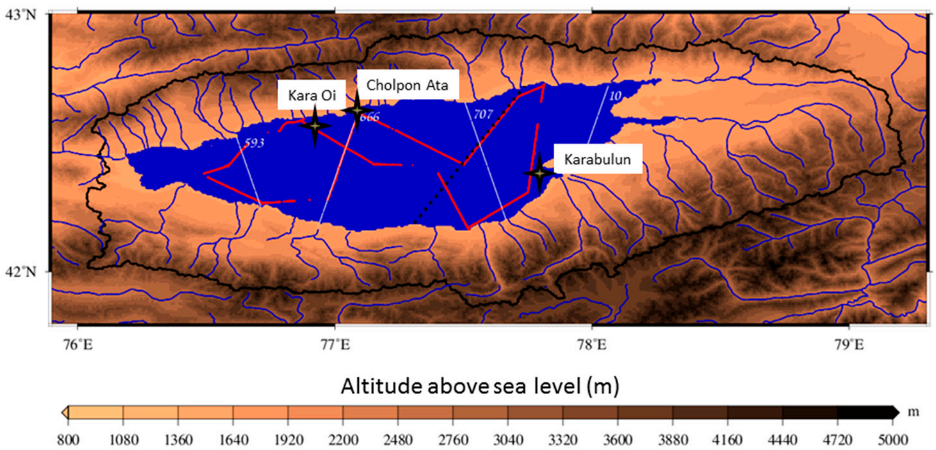

Figure 2. Last campaign done in July 2017 over Lake Issykkul—in red are the cruise tracks, in white are the Sentinel-3A tracks, and in black (dots) the Jason-3 track, over the lake. Numbers indicate the pass number of Sentinel-3A orbit ground track. The blue dots represent the Jason-3 track over the lake. The color scale represents the altitude of the land around the lake. The brown/black stars represent the weather stations.

In the past, this lake has already been used to determine the absolute bias of T/P, GFO, Jason-1,2, and Envisat altimeters and results were published and detailed by Cretaux et al. [9–11]. Results have been compared to other studies performed with ocean C/V sites: Harvest platform in California [15]; Corsica site [16]; Gavdos Island [17]; and Bass Strait in Australia [18].

2.2. Instrumental Design of the Field Campaigns

The instrumental design of the field campaigns was aimed at computing the height of the water surface, independent of that provided by the altimetry. It was based on a kinematic GPS survey of the lake height, along the different satellites tracks. A boat (28 m long, hence very stable) carried a GPS receiver at the bow, coupled with a microwave radar (named RLS in the following), and continuously measured the height of the GPS antenna, above the lake surface (Figure 3). The boat cruised along the altimeter tracks (Sentinel-3A and Jason-3 in the present study), when the satellite passed over the lake. The GNSS-based navigation system of the boat insured that we followed the theoretical track of the satellites, with a decameter precision. The RLS and the GPS systems were synchronized and they both provided their measurements every 30 s. Practically speaking, the 30 s measurements were obtained by averaging individual measurements at a much higher frequency (one measurement, every 0.5 s for the RLS and the GPS). This also allowed averaging the potential attitude pitch and the roll of the boat. However, due to the very calm weather conditions during all three of our campaigns, the noise in these measurements that could be provoked by wind and waves on the lake, was insignificant.

We also installed a permanent GNSS station in the vicinity of the lake which enabled complementary estimates of the zenithal tropospheric corrections. Combined with the atmospheric pressure measured by a permanent weather station located on the shoreline of the lake, these allowed for separate determination of the wet and dry tropospheric delays that could be compared to the tropospheric corrections, distributed with the altimetry data, or used as the tropospheric corrections themselves.

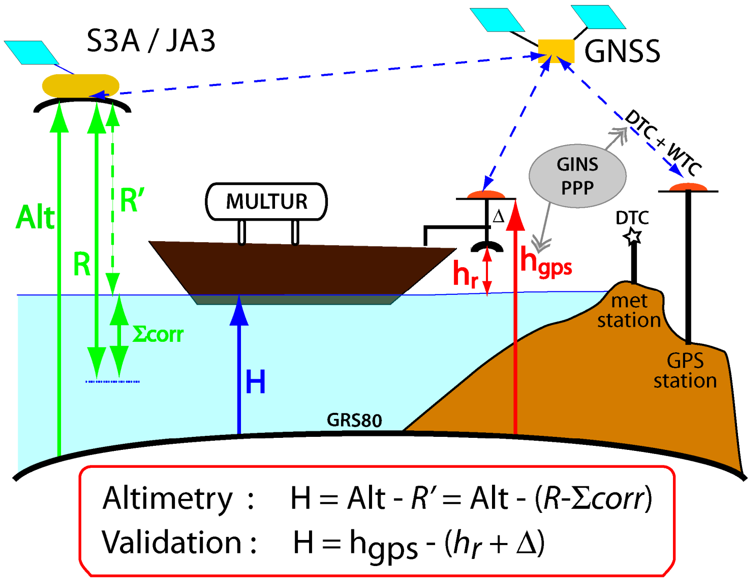

Figure 3. Experimental design set-up over Lake Issykkul for the validation of altimeter measurements.

We identified that the three main sources of uncertainty in the C/V, over Lake Issykkul were coming from:

- The weather conditions, including wind driven waves and Seiche effects.
- The computation of the height of the GPS antenna, embarked on the boat.
- The estimate of the distance between this antenna and the water surface during the cruise.

The instrumental design is, thus, a source of uncertainty. From the first campaign in 2004 to the last six ones since 2014, we have tested different settings and performed different types of fieldwork and data processing.

Cretaux et al. [15] showed that Seiche-induced errors could be avoided by cruising exactly at the same time as the pass of the altimeter and by using the GINS (Géodésie par Intégrations Numériques Simultanées) software in the Precise Point Positioning (PPP) mode [19] (see Section 2.3). Moreover, we scheduled the cruise in order to be in the middle of the lake at the very time the satellite overpassed the lake. This allowed us to eliminate any shoreline effect on the altimeter range.

Instantaneous GPS antenna height above the lake surface was another question, which has been solved, since the campaign was done in July 2014, for the calculation of absolute bias of Saral/AltiKa [20]. In contrast to a former work and to avoid errors introduced by time-dependent variations of GPS antenna height, we now used an additional instrument. This instrument was a radar measuring the distance between its antenna and the lake surface, linked physically to the GPS antenna, in order to estimate instantaneous GPS height above the lake surface, when the boat is moving, from a slow to a high speed (see Section 2.3). Radar correction also took into account the shifts in antenna height, due to fuel consumption, after four days of cruising with the boat, which might have reached a few centimetres per day [11]. It has allowed eliminating one of the main sources of uncertainty in the previous studies. This was the major improvement of the experimental design, as compared to previous works.

Figure 4 shows the impact of the velocity of the boat on the GPS antenna height. These values are directly removed from the individual vertical position of the GPS antenna, since both instruments, the GPS, and the RLS, were synchronized. We also have quantified the stability of the RLS measurements at a constant velocity, for each day. When the boat was moving at the velocity between 10 and 12 km/h, which was the nominal condition chosen for the calculation of the absolute bias of altimeters, the standard deviations (StD) of the distance between the RLS and the water surface was 1 cm. We have also checked that small movements of the equipment (GPS and RLS are fixed together) were followed well, by the RLS. In summary, the precision of in situ measurements of the water-level from the boat was ~2 cm StD (cumulating radar precision and GPS data processing in PPP mode).

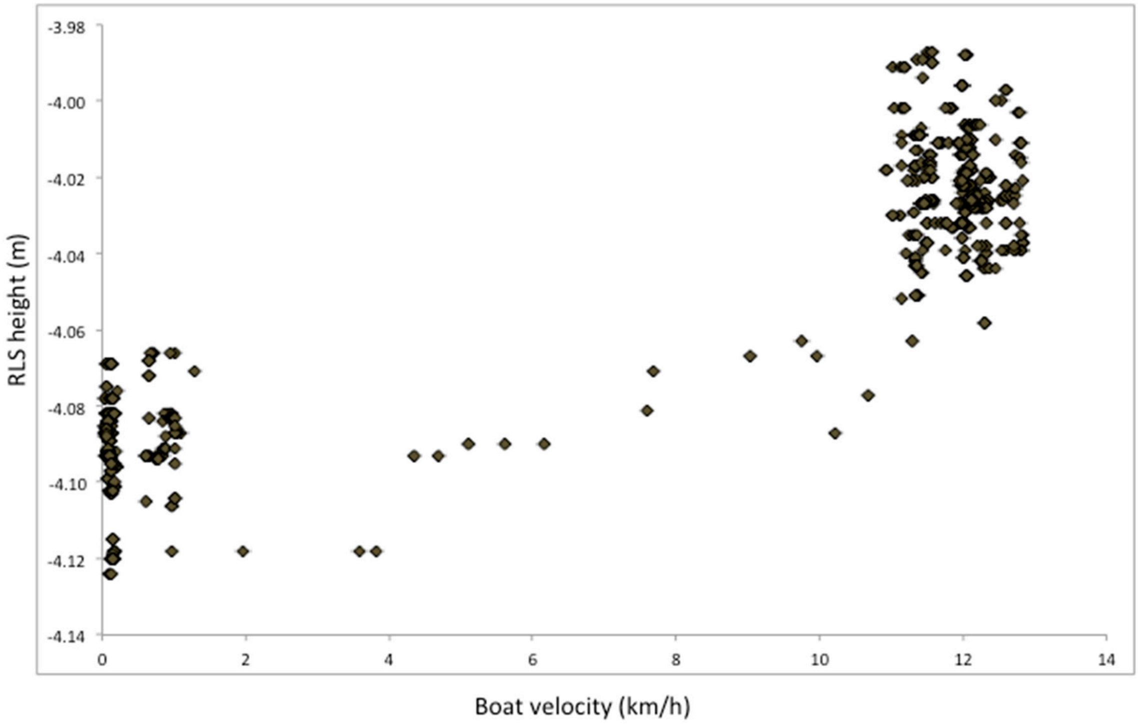

Figure 4. Impact of boat velocity on the GPS antenna height. For a velocity of 12 km/h the bow of the ship was lower by 8 cm in average, with respect to the height, when the boat was not moving.

2.3. Ground Estimate of the Water Height

Ground estimate of the water height was derived by the means of a geodetic grade GNSS system, composed of a dual-frequency receiver and micro-centered antenna, embarked on the ship. To enable projecting the height of the antenna o that of the water surface, the distance between the antenna and the water surface was measured, continuously, by means of an RLS radar unit, sharing a common support. The offset between the phase centers of the two instruments was measured at the beginning of the survey and it was re-checked at the end of the survey (Figure 3). We used the IGS tables to take the internal offset between the phase centers of the GPS antenna and the Antenna Reference Point (ARP), into account.

We used the PPP strategy to process the GNSS data collected by the unit onboard. The result in the antenna position and the ellipsoidal height, was processed every 1s. As much as possible, the boat kept moving at a constant velocity of 11–12 km/h. This constrain enabled the distance between successive points to remain constant and the boat trim to remain unchanged.

The GNSS data were processed using the GINS geodetic software developed by CNES [21]. GINS was run in PPP mode. We selected the PPP mode instead of the traditional Double difference mode for two main reasons. First, several studies have shown that when the baseline between the base station and the moving receiver exceeded 10 km (which was the case, in the middle of the lake), PPP mode performed better than the DD mode, mostly because of changes in the atmospheric delays. Second, in the DD mode, the total error was a combination of the error on the baseline and that on the position of the base station [19].

The PPP mode required precise satellite orbit and clock products. We used the products delivered by the CNES-CLS IGS Analysis Center [19].

As the GINS software provided GPS coordinates that were conventionally tide-free, they could be directly compared to the altimetry observations. In addition to the boat coordinates, a GPS receiver clock offset every epoch, a zenithal wet tropospheric delay every hour (piece-wise linear), and GPS phase ambiguities was estimated. In this configuration, the expected positioning precision was around 2 to 3 cm, in the vertical direction, with no significant bias for the few-hour sessions [22,23]. When comparing the GPS profile along the track of the satellite (Sentinel-3A or Jason-3), the GPS processing errors were averaged.

2.4. Satellite Estimate of the Water Height

Altimetry for estimating the water-level variations over lakes and rivers now has a long history, since the launch of T/P in 1992, and is widely documented [6,7,24,25]. Here, we briefly recall the key equation and the constitutive parameters. The lake water height above the ellipsoid (H) is given by Equation (1):

$$H = Alt - R - DTC - WTC - IC - ET - PT - LT - SSB - IB \quad (1)$$

Alt (Altitude of the satellite) is given by the GDRs downloaded, in our study, from the CTOH (Centre de Topographie des Océans et de l'Hydrosphère). The products used for both Sentinel-3A and Jason-3 were the ones generated by the ground segment of each mission. We used the GDR-D version for Jason-3 and the ESA Land_IPF_06.07_V1.5 version for Sentinel-3A.

For the range R, we have used the 20 Hz LRM (Low Resolution Mode) with Jason-3, and SAR (Synthetic Aperture Radar) with Sentinel-3A.

The DTC is directly proportional to the atmospheric pressure [26] and it is given by the GDRs. At the altitude of Lake Issykkul, DTC was about −1.9 m, with a variation of few centimeters, depending on atmospheric conditions. In previous studies [9–11] we have shown that for C/V purpose, over Lake Issykkul, it is recommended to use in situ data for the calculation of DTC. Since the distribution of atmospheric pressure over the lake Issykkul was very homogeneous, we simply used the atmospheric pressure, at the Cholpon Ata station (Figure 2).

For the WTC (Wet Tropospheric Correction), it has been often pointed out that the correction using radiometer is highly erroneous over continental water or coastal regions, due to land contamination, up to a distance of 20 to 30 km from the coastline ([9–11,16,27]). Therefore, apart from the very large lakes, the WTC used in continental water comes directly from a model based on climate gridded data sets—multi-layer water vapor and temperature fields [26]. It has been estimated that the models used for WTC, in the GDRs of past missions, generated an StD of several centimeters, on the water-level estimation [9–11,27]. However, recent models, based on the ECMWF reanalysis, have significantly reduced the errors in the determination of WTC [27,28], by up to 1 cm. WTC varies spatially and temporally and can reach several decimeters.

WTC cannot be estimated with ground measurements only, as soundings are required. For C/V application where we expected to reduce, as much as possible, the sources of uncertainties in the calculation of the altimeter's absolute biases, we estimated an alternate WTC correction (hereafter $WTC_{\text{in-situ}}$), by the Total Path Delay, using the GINS processing and the GPS data from a permanent receiver installed in 2012, in Kara Oi (Figure 2). WTC was simply given by the difference between the TPD and the DTC, derived from the in-situ met stations.

For IC, bi-frequency and model are provided. The presence of charged particles in the high atmosphere, also named ionosphere, causes refraction of the radio signal emitted by the altimeter that must be taken into account. It is proportional to the Total Electronic Content (TEC), in this layer of the atmosphere and inversely proportional to the square of the frequency. With Jason-3 and Sentinel-3A, it could, therefore, be calculated from the Ku and C bands, using a combination of ranges in both bands, allowing the elimination of the TEC in the expression of the correction. For altimeters in the Ku band, the IC (Ionospheric Correction) ranged from a few millimeters to a few centimeters.

However, it has been shown that over lakes, this correction could be erroneous, due to land contamination once the measurement was done close to the shoreline [29]. Therefore, it could be preferable to use the IC derived from the Global Ionospheric Maps (GIM), inferred from the GNSS worldwide network [30]. In Cretaux et al. [9], we examined the StD of difference between the bi-frequential IC and the GIM model over Lake Issykkul. It ranged between 4 mm (Jason-2) to 1.1 cm (Jason-1). We obtained similar values with Jason-3 and Sentinel-3A—the RMS (Root Mean Square) of differences from the model or from the combination of the two instrumental frequencies was around 5 mm, once we were 10 km away from the coast. Therefore, we decided to use only the GIM model, in the calculation of the altimeter bias. The GIM model, according to the Birkett and Beckley [29] assessment, has improved performances by 1.5 cm of σ, as compared to the bi-frequential IC (comparison done with in situ levels, from January 2008 to December 2009, over the Lake Ontario). For very big lakes, however, the use of a smoothed bi-frequency IC can provide slightly better performances than the GIM model [26], but in general, over lakes, the model is preferred due to land contamination.

The Earth tide (ET) and Pole tide (PT) are provided by the GDRs. The ET was estimated from the model developed by Cartwright and Tayler [31].

Lake Tide can reach centimetric level over the great lakes of North America [29] but does not exceed a magnitude of 2–3 mm, over Lake Issykkul [10].

The SSB and the IB (Inverse Barometer) corrections applied over oceans are usually not used over lakes. Both effects have very little impact on the lake surface and are, therefore, generally simply ignored when satellite altimetry is used over lakes, except for studies over very big lakes (see Cretaux et al. [9] for more information). For this study, we selected the measurements collected when the lake was in calm weather conditions. This selection eliminated measurements potentially affected by an unknown SSB effect.

Over continental waters, the radar echoes assembled into so-called waveforms in the LRM mode but did not conform to the Brown model, for which the on-board tracking algorithm was adapted. Hence, alternate algorithms that are run during post-processing, and thus, are named retracking algorithms, were used. Among them, for lakes, the *Ice-1* algorithm, based on a OCOG scheme was renowned to outperform the others [8]. In this study, we used the ranges derived from the *Ocean (SAMOSA)* and the *Ice-1 (OCOG)* retracking algorithms. Detailed information on the mathematics of each algorithm can be found in the handbook [32,33].

For the Ocean retracker, it is supposed that the reflecting surface is isotropic. Over continental water the echo can, however, be extremely variable. It depends on the complexity of the topography and the backscatter characteristics of the surrounding terrain for small water bodies. Therefore, the analytical expression given in the *Ocean* retracker is not valid, anymore, or present potential high source of errors, for the range estimation. For a large lake, *Ocean* retracker is valid only when far from the shoreline.

Ice-1 retracker determines the shape of the waveform in terms of its amplitude, width, and center of gravity, allowing calculating the leading-edge position (LEP) of the waveform, which is directly linked to the range. The *Ice-1* has proven to be robust for non-Brownian waveforms, such as those generally registered over lakes and rivers. It is, therefore, often used in the application of satellite altimetry for hydrology studies. *Ocean* is the algorithm dedicated to oceanography and it is the focus of many ongoing C/V studies in coastal and open-sea conditions. Thus, it will allow for comparing our results for the altimetry biases calculation over Lake Issykkul, with the ones published for ocean sites.

2.5. Calculation of the Altimeter Bias

The calculation of the altimeter bias consisted of comparing the ellipsoidal height of the lake surface H, gained by combining the parameters distributed in the altimetry data (in green on Figure 3) with a combination of parameters collected during the cruises (in red on Figure 3), according to the experimental design. Water heights from ship cruise and from satellite were all calculated above the ellipsoid of reference.

The water height above the ellipsoid was measured, instantaneously, both by the GPS and the altimeter in the middle of the track. Then we averaged the data 10 km before and after this point to determine the absolute bias, which was the averaged difference between both set of measurements. Since the geographical sampling of the measurements was different. In average, over the same distance we had two to three times more GPS points of measurements than in the altimetry ones. For each of the altimeter measurement, we selected the closest GPS measurement with a threshold distance of 300 m. Then, for each couple of measurements (altimetry, GPS) we calculated the height difference. In the vicinity of the lake's center, the slope of a geoid is very low, therefore, the induced error in the worst case remained within a few millimeters (see below for the so-called cross-track error). The average of all differences was then calculated, with the associated standard deviation, and it gave the value of the absolute bias and its precision. We chose to perform the calculation near the center of the lake mainly because it avoids the shoreline's effects on the altimeter waveform. It also allowed for diminishing the effect of a geoid slope on the distance between the GPS and the altimetry measurements (within 300 m threshold), and the cross-track shifting of the orbit described below.

The height of the surface of Lake Issykkul varied significantly from the shore to the center of the Lake, and in the East to West direction. In particular, near the coast, the surface slope was steep (it might reach 10–15 cm/km [9]). Such slopes in height were not properly accounted for by any current geoid model and thus could not be cancelled by converting the ellipsoidal heights into orthometric heights. It was then mandatory that the ship collected water heights, exactly, at the nadir of the satellite passes. Yet, due to the cross-track orbital shift of 1 km, approximately, from cycle to cycle, which is inherent to any altimetry mission, it was impossible to predict, in advance, the exact position of the satellite along its theoretical track, at an accuracy greater than 1 km. Consequently, the shipborne measurements could be slightly shifted, with respect to the actual overpass. Yet, the slopes were minimum at the center of the lake, which corresponded to a minimum in the local geoid undulation. We, thus, limited this slope effect in the calculation of the absolute bias, by using only the measurements within $\pm$10 km, on both sides of this local minimum. We expected that the error due to this slope effect did not exceed 1 or 2 cm. By chance, during the last 3 campaigns analyzed here, the surveys were within 200–300 m away from the satellite tracks. The resulting potential error in the area where the biases were calculated, consequently, did not exceed a few millimeters.

3. Results

3.1. Absolute Biases of Sentinel-3A

During the campaign in October 2016, Sentinel-3A passed over the tracks 666 and 707 with a time shift of one day (Figure 2). We had followed these two tracks. Based on the procedure of water height measurements described in Section 2.4, we have studied the surface water along the two satellites tracks, with the *Ocean* and *Ice-1* retrackers, respectively (Figures 5 and 6). Comparisons have been conducted with the water height calculated using GPS data processing, for static and kinematic sessions, which were processed using a PPP method (2.3). The altimeter bias has then been calculated using the methodology presented in Section 2.5. The same procedure has been used for Jason-3, with the track 131.

The two sets of measurements on the two tracks, from the GPS on the boat (and from the altimeter onboard the Sentinel-3A, with *Ocean* and *Ice-1* retrackers, were in a remarkable agreement (Figures 5 and 6). From these data, we have calculated that the absolute bias of Sentinel-3A with *Ocean* retracker was -14 ± 20 mm StD. For *Ice-1*, the offset was 285 ± 20 mm StD. These values represented the mean of both tracks. Owing to the improvement in the instrumental design, and to the very limited dispersion in the Sentinel-3A data, the estimate of the altimeter bias of Sentinel-3A was derived with a small uncertainty, namely 20 mm StD, a result much better than the ones obtained in previous studies (37 mm StD in Cretaux et al. [11] for Saral/AltiKa, and 50 mm StD in Cretaux et al. [9] for Jason-2).

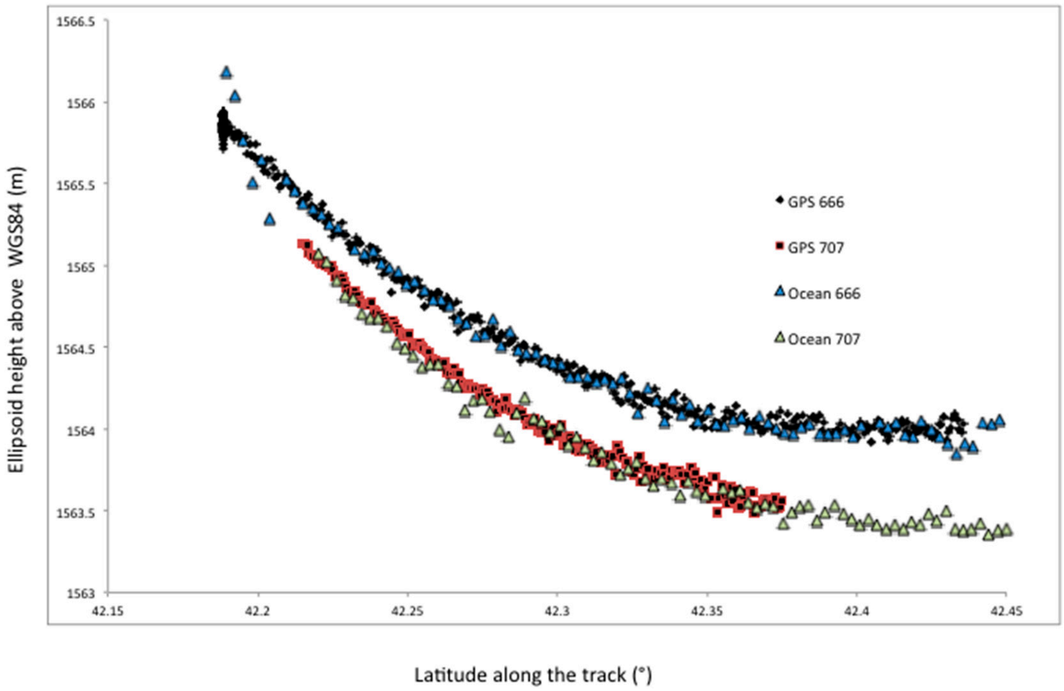

Figure 5. Ellipsoidal height of the lake surface measured by Sentinel-3A with the *Ocean* retracker for cycle 9 (October 2016), for the two tracks (666 and 707) and with the boat instruments.

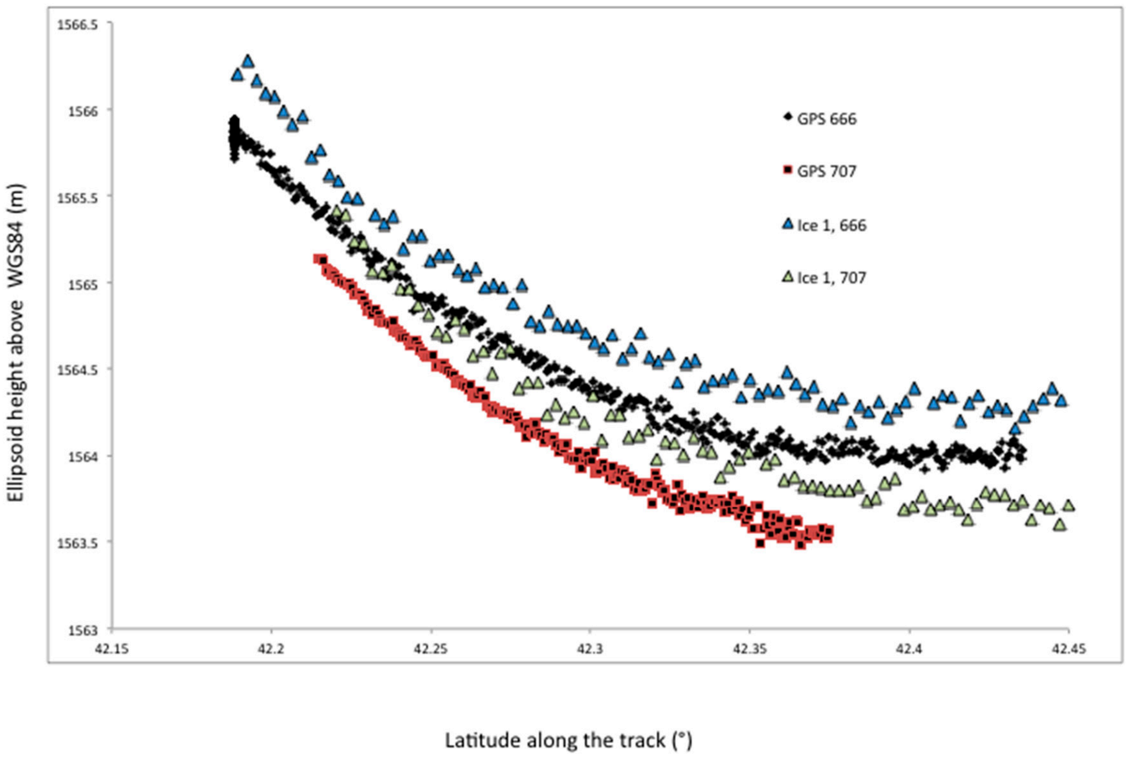

Figure 6. Height above the ellipsoid of the lake measured by Sentinel-3A, with the *Ice-1* retracker for the cycle 9 (October 2016), for the two tracks (666 and 707) and with the shipborne instruments.

3.2. Absolute Biases of Jason-3

In April 2016 and then in July 2017, we measured the vertical profile of the lake along the Jason-3 track, #131 during cycles 5 and 52. The results are shown in Figure 7 for cycle 52, with the along-track vertical's height of the lake, based on the *Ocean* and *Ice-1* retrackers, and compared to the

GPS profile. Absolute bias of Jason-3 (with *Ocean* retracker) measured through the two campaigns was −28 ± 40 mm StD. With *Ice-1* the bias was 206 ± 30 mm StD. This was in very good agreement with other estimation done over the ocean C/V sites [34,35], oral presentations at the last OSTST 2017, in Miami. We could also remark that the along-track stability of the Jason-3 data (characterized by the StD of the comparison with GPS data: 30 mm with *Ice-1* and 40 mm with *Ocean*) was poorer than with the Sentinel-3A (20 mm for both retracking algorithms).

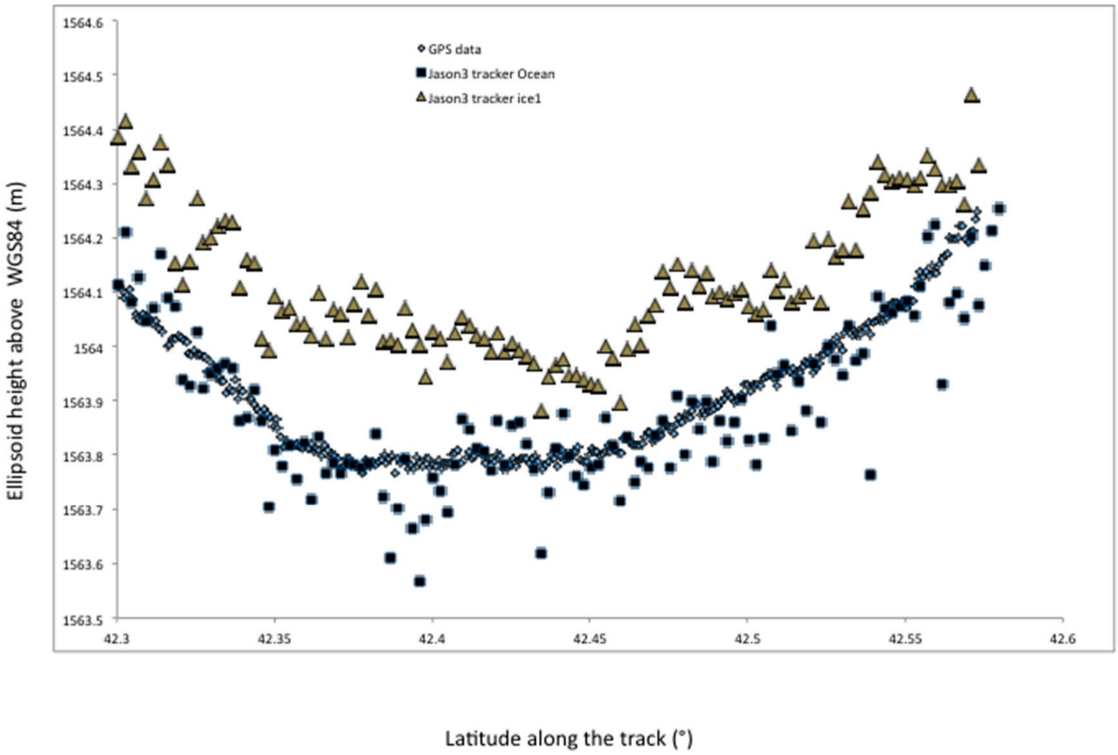

Figure 7. Ellipsoidal height of the lake surface for Jason-3 with the *Ocean* and *Ice-1* retrackers, cycle 52 (July 2017) of track 131, and shipborne measurements.

3.3. Relative Retracking Algorithms Offsets

It has been demonstrated in Cretaux et al. [9] that *Ice-1* gives more accurate results of water-levels of Lake Issykkul than the *Ocean* retracker. An offset of ~24 cm between the two algorithms had been found by Cretaux et al. [10], using the Envisat and Jason-2 satellites data. The offset was due to differences in the algorithms: *Ocean* was directly measuring the travel time of the signal, using the rising front of the footprint. It supposed that the received echo had a theoretical shape defined by Brown et al. [36] who showed that the time needed to calculate the range between the satellite and the reflecting surface was found from halfway up the rising edge of the waveform.

In contrast, the *Ice-1* algorithm was much more robust for non-standard waveforms, such as those usually acquired over small lakes or rivers. It was based on an empirical estimation of the weighted Center of Gravity (CoG) of the waveform.

Since the Envisat mission (launched in 2001), the GDRs of the altimetry missions distributed the range calculated from different algorithms. Here, we have calculated the relative bias between the two retrackers (*Ocean* and *Ice-1*), again, by using the Jason-3 satellite, first, and then the Sentinel-3A. For this, we simply have calculated the lake Issykkul water-level over one and a half year, using altimetry data processed with each retracker [24]. We obtained the usual offset of 230 ± 40 mm StD, using the Jason-3 satellite, which was in very good agreement with the previous results, based on Jason-2 or Envisat. However, the offset calculated using the Sentinel-3A satellite was significantly higher, since the value calculated was 300 mm ± 25 mm StD. This was likely due to the SAR mode of the Sentinel-3A.

3.4. Quality Assessment: Long Term Comparison with In-Situ Measurements

In-situ water-level changes of Lake Issykkul have been observed twice daily at the station of Cholpon Ata, for decades. These data have been used in previous studies to determine the accuracy of altimeters onboard—the T/P, Envisat, Jason-1, Jason-2, GFO, and Saral/AltiKa [9–11,20]. Note that these measurements were referenced to the Baltic Sea geoid. Consequently, a 2.4 m bias had to be applied to the altimetry series to compare them to the latter. In Figure 8, we present the comparison of the water-level changes of Lake Issykkul, from in situ data, over Cholpon Ata with those obtained by the Sentinel-3A (*Ocean* and *Ice-1*), Jason-2 (*Ice-1*), and Jason-3 (*Ice-1*). It highlighted the very high accuracy of each of these satellites for the monitoring of level variations for large lakes, such as Issykkul. The accuracies found in this study, (3 cm rms) was much better than those found for small lakes or reservoirs [22,37]. Noteworthy, the accuracy that we found for Sentinel-3A with *Ice-1* retracker was the best ever found for any altimetry mission. Figure 9 shows the differences of the water-level changes from these three satellites, using the *Ocean* retracker, with in situ data. With this retracker, not known as the most suitable for continental water, the water level still remained at 3 cm of accuracy.

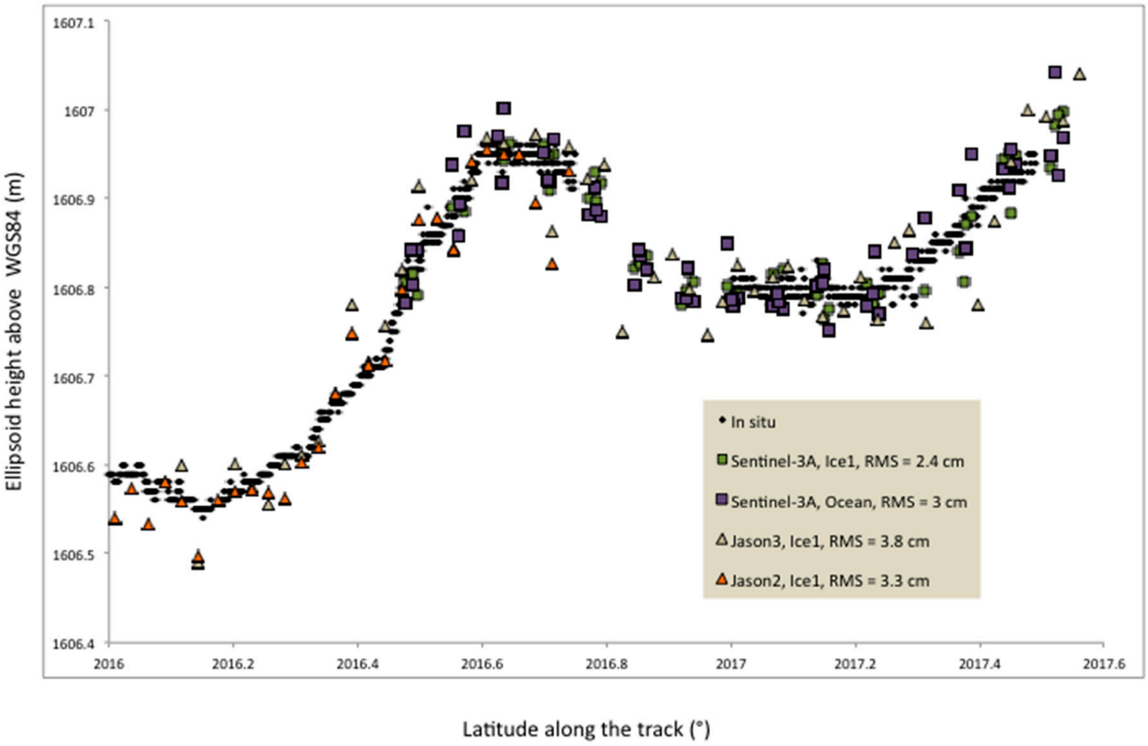

Figure 8. Time series of water height using Jason2, Jason-3, and Sentinel-3A data and in situ measurements of the permanent gauge in Cholpon Ata station over the period from January 2016 to July 2017. A bias of 2.4 m (±the absolute bias of each altimeter) has been applied to the altimeter time series, in order to correct for difference of reference systems, in which both series are given (the Baltic Sea-level for in situ, EGM2008 for altimetry).

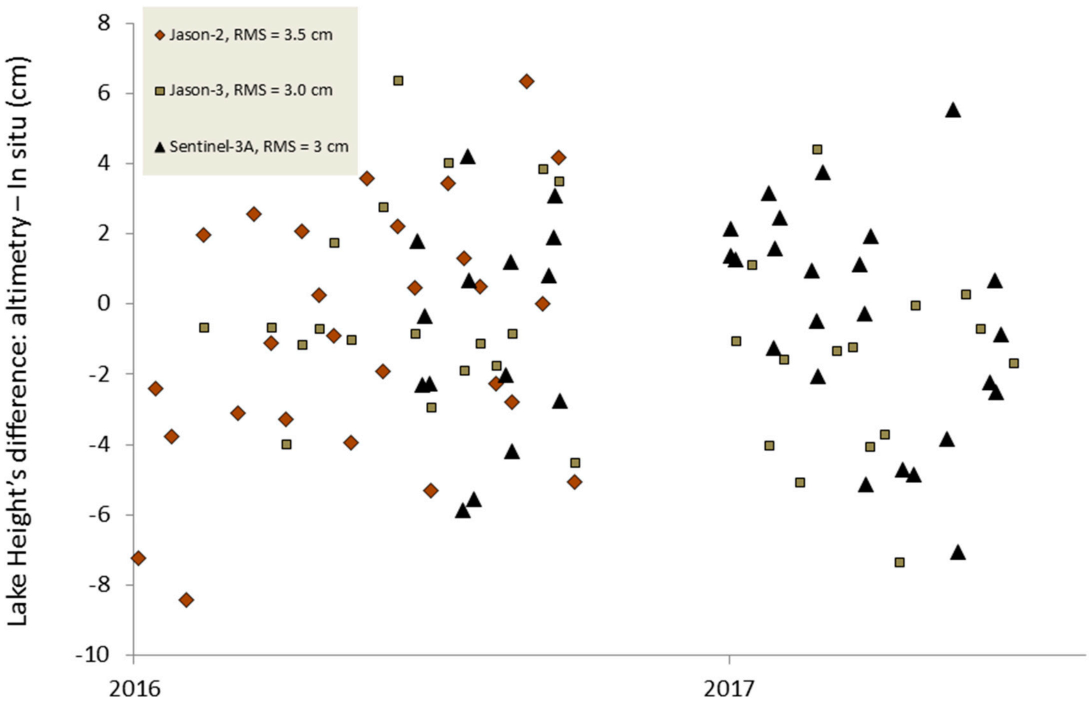

Figure 9. Difference of Jason-2, Jason-3, and Sentinel-3A estimates (with the *Ocean* retracker) with in situ measurements in Cholpon Ata, located in the north coast of the lake.

4. Conclusions

Lake Issykkul has been used as a test area for multi-satellite C/V of radar altimeters, for past missions (T/P, GFO, Envisat, Jason-1, and Jason-2), present ones (Saral/Altika, Jason-3, Sentinel-3A, and Sentinel-3B), and future ones (Jason-CS, and SWOT). It presents the advantages of reducing some the sources of errors in the absolute altimeter bias computation (tides, water dynamic topography, Barometric Pressure, and SSB). Moreover, it allows the performance of a quality assessment of altimetry for the study of continental waters—cross comparing the different retracking algorithms of the waveform and calculating their respective relative biases.

The results of April and October 2016 and July 2017 campaigns were presented in this article for the computation of the altimeter biases of Sentinel-3A and Jason-3, and the estimation of their accuracy. We have determined that the absolute bias of Sentinel-3A and Jason-3 were, respectively, -14 ± 20 mm and -28 ± 40 mm StD, with the *Ocean* retracker. Using *Ice-1* led to different results. For the former, the *Ice-1* offset was 285 ± 20 mm and for Jason-3 it was 206 ± 30 mm StD.

Since the first campaigns over Lake Issykkul, in 2004, a large number of field work have been carried out till July 2017, and we have converged over the last three campaigns to an experimental design for minimizing errors. In particular, for the GPS antenna height, embarked on the vessel, the new procedure allowed us to remove errors due to the velocity of the boat. Performing the GPS levelling of the water surface, along the track, exactly at the same time as the pass of the satellite, eliminated the errors due to Seiche or wave effects. In order to reduce potential errors in the bias calculation, due to the shoreline effect on the waveform, we used only measurements of 10 km before and after the exact pass of the satellite, in the middle of the lake. The choice of using atmospheric corrections directly from the in situ barometric pressure removed the errors on the DTC and the choice to use the fixed GPS station also removed the errors in the calculation of WTC. Therefore, three sources of errors remained—the altimeter range, the orbit, and the GPS positioning. Since orbit calculation and GPS PPP do not depend on the altimetry satellite, the observed differences of C/V errors (20 mm for Sentinel-3A and 40 with Jason-3A, with the *ocean* retracking algorithm) fully reflected the quality of the altimeters, and in particular, reflected the fact that Sentinel-3A uses a SAR mode when Jason-3A still uses an LRM mode.

We also evaluated the accuracy of the Jason-3 and Sentinel-3A, using the ranges derived by the retrackers, through a comparison with in situ data. We obtained a slightly higher accuracy for the Sentinel-3A with the *Ice-1* retracker (2.4 cm), than for Jason-2 and Jason-3 (>3 cm). The results over Lake Issykkul also showed that altimetry is highly capable of detecting small water-level changes at different time scales, ranging from seasonal changes due to local climatology and seasonal water balance of the lake, to long-term changes due to other phenomena, like regional climate changes. Since these two missions belonged to the operational satellite system, it was an essential component for the long-term monitoring of lake-level variations.

We have noticed that the radiometer onboard the Sentinel-3A did not provide any reliable measurement of the WTC. Same as for previous satellite missions, the recommendation for lake studies using Sentinel-3 altimetry was to use the corrections derived from the models for DTC, WTC, and IC.

Our purpose, finally, was to show that Lake Issykkul is an essential C/V site for altimetry, since it presents characteristics not covered by historical oceanic C/V sites, and it can serve for all past, existing, and future altimeters.

Author Contributions: J.-F.C. is the head of the project and has organized all expedition, he wrote the article, and did the main calculation and analysis of altimeter biases. M.B.-N. have run the program for GPS data positioning and is responsible of the data collection during the field campaign, F.P. has developed the GINS software for GPS PPP calculation, N.J. and R.S. have provides all in situ information, P.B. coordinates the FOAM project and supervised the activities of all cal/val sites including Issykkul, S.C., F.P., J.V. and P.B. have also participated to the preparation of the manuscript, and all co-authors have participated to the data collection during the field campaigns.

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Conflicts of Interest: The authors declare any conflict of interest.

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