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Estimation of Lake Nasser Water Level: Comparison between Two Satellite Radar Altimetry Datasets

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ملخص عربي
مقياس الرادار الساتلي هو تقنية للاستشعار عن بعد ، وهي في الأصل مخصصة لدراسات المحيطات المفتوحة. منتج الهيدرولوجيا Jason-2 PISTACH هو منتج تجريبي ، تم تصميمه خصيصًا لتحسين منتجات مقياس الرادار الساتلي فوق المسطحات المائية الداخلية. تهدف هذه الدراسة إلى اختبار دقة مستويات المياه المشتقة باستخدام منتج الهيدرولوجيا PISTACH بالمقارنة مع منتجات Jason-2 SGDR القياسية. تعتمد المقارنة على المتوسط الشهري لمستويات المياه في بحيرة ناصر ، ويتم قياسها خلال الفترة 2008-2012. تم استخدام برنامج BRAT و تم تطويرنص Python لتحليل البيانات. التعدادات الاحصائية معامل التحديد R^2 والجذر المتوسط للخطأ المربع RMSE تستخدم لتقييم دقة مستويات المياه المستمدة من كلا المنتجين. أظهر كلاهما اتفاقًا كبيرًا مع القياسات الأرضية ، حيث R^2 تساوي 0.97. RMSE لمستويات المياه المستمدة من PISTACH (0.4 م) لا يختلف اختلافًا كبيرًا عن المستويات المستمدة من SGDR (0.38 م). وخلص إلى أن منتجات PISTACH لا تظهر زيادة في دقة حساب مستويات المسطحات المائية الداخلية.

ABSTRACT
Satellite Radar Altimetry (SRA) is a remote sensing technique, originally meant for open ocean studies. Jason-2 PISTACH hydrology product is an experimental product for improvement of SRA over inland water bodies. This study aims to test the accuracy of derived water levels using PISTACH in comparison with the standard Jason-2 SGDR products. Comparison is based on Lake Nasser monthly mean water levels, measured during the period 2008-2012. Analysis is performed using BRAT software and a developed Python Script. Coefficient of determination R^2 and root mean square error *RMSE* statistics are used to evaluate the accuracy of altimetry-derived water levels from both products. Both showed significant agreement with ground measurements (R^2 =0.97). *RMSE* of water levels derived from PISTACH (0.4 m) is insignificantly different from that of SGDR products (0.38 m). It is concluded that the PISTACH products don’t show an increase the accuracy of calculating inland water bodies’ levels.

KEYWORDS: Altimetry, SGDR, PISTACH, Lake Nasser, Water Level.

1. INTRODUCTION
Regular and accurate monitoring of water storage variations in lakes and reservoirs is rather crucial for equitable water allocation to water use sectors, ecosystem services. Water level in most lakes and reservoirs is measured by means of gaging stations. However, measured water levels is not often disclosed to water and environmental professionals because it is sensitive national and international information that affects the lives of large populations. Satellite data are found to be very useful in natural resource monitoring and management, since it is, freely available and not constrained by geopolitical boundaries. It also provides a wide spatial extent and temporal coverage. While satellite data are up to date, historical data archives are also available.

Satellite altimetry is a remote-sensing technique which has been successfully used to derive water-level data for approximately two decades [1]. Several satellite radar altimetry datasets are available from past and current missions. The most commonly used are datasets from T/P, Jason-1, Jason-2, GFO and ENVISAT past missions. In addition, few databases are developed, combining data from multiple missions, to provide water level variations for target water bodies.
Global Reservoir and Lake Monitor (GRLM) database utilizes data from T/P, Jason-1, Jason-2 and GFO and recent additional ENVISAT satellites to monitor time-series of water level variations for world's largest lakes and reservoirs in a near-real time manner. River Lake Hydrology product (RLH) is based on altimetry data mainly from ERS, ENVISAT and additionally from Jason-2 to provide water levels for lakes, reservoirs and rivers. Hydroweb provides time-series of water levels of large rivers, lakes/reservoirs, and wetlands around the world using the merged T/P, Jason-1, Jason-2, ENVISAT and GFO data.

Duan and Bastiaanssen [2] estimated water volume changes in lakes and reservoirs from four different satellite altimetry databases (GRLM, RLH, Hydroweb and ICESat-GLAS level 2 Global Land Surface Altimetry data) in combination with satellite imagery data. Three lakes/reservoirs with different characteristics were studied; Lake Mead (U.S.A.), Lake Tana (Ethiopia) and Lake IJssel (The Netherlands). Compared to measured water levels, satellite altimetry products provided accurate water level variations for Lake Mead and Lake Tana but not for Lake Ijssel. Muala et al [3] studied the feasibility of estimating discharges from Roseires Reservoir (Sudan) and Aswan High Dam/Lake Nasser (Egypt) using satellite altimetry (GRLM and Hydroweb) and satellite imagery. Results for water levels and estimated water volumes significant match with data for both lakes (R^2 from 0.81 to 0.96).

Standard distributed altimetry datasets, mostly meant for open ocean studies, contain missing or degraded data due to observations perturbed by emerged land. However, the instruments do give measurements which contain useful information. This is why the CNES funded the PISTACH project (Prototype Innovant de Système deTraitement pour les Applications Côtières et l'Hydrologie) as a part of the Jason-2 Project, it aimed to improve satellite radar altimetry products over coastal areas and continental waters. J2 PISTACH products are an experimental evolution of the Jason-2 Level-2 products. Those products were conceived in the frame of the PISTACH project. The PISTACH product input is Jason-2 Level 2 S-IGDR products. They include new re-tracking solutions, several geophysical corrections (wet and dry tropospheric corrections), as well as higher resolution global/local models, in addition to the content of standard Jason2 IGDRs. Two products are available: one for coastal applications, the other for hydrology applications.
For the purpose of this study, accuracy PISTACH hydrology product is compared to Jason-2/OSTM SGDR using the daily Lake Nasser water level ground measurements. The hypothesis that PISTACH satellite altimetry datasets have higher accuracy than standard SGDR distributed datasets is examined statistically. Basic Radar Altimetry Toolbox (BRAT) followed by a developed Python script are used in this process

2. BASIC PRINCIPLES OF RADAR ALTIMETRY

Satellite radar altimeters transmit signals (in two frequencies k_u and c bands) towards the Earth's surface and receive the echo reflected by the surface. Time taken from the pulse transmission to the reception of its echo back by the altimeter, coupled with the speed at which the pulse travels (light speed), is used to calculate the distance between satellite and the reflecting surface (Range). When the Range is subtracted from the satellite altitude, it gives level of the reflecting surface. (Fig.1)

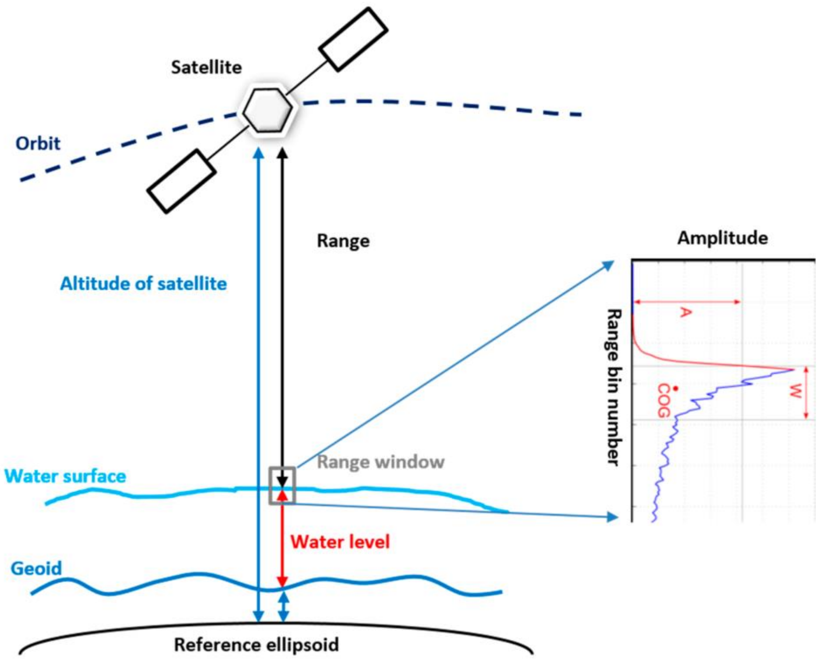

Figure. 1.Altimetry Principle of Water Level Measurement (photo credit[4])

The return echoes represent the power of the returned pulse as a function of time and is called a waveform. The shape of waveforms differs according to the reflecting surface off the earth. The waveform is then further analyzed using waveform re-tracking algorithms to estimate the exact time corresponding to the reception of its echo back by the altimeter resulting in the Retracked Range. Different re-tracking methods could cause several tens of centimeters difference [5] or sometimes up to several meters [6] in the final estimated range. Detailed discussion on the waveform re-tracking methods can be found in [6]and [7].

As the signal propagates through the atmosphere, a path delay in radar return signal occurs due to the atmospheric electron content, cloud liquid water and water vapor, and dry gases. These require for application of ionosphere correction, wet troposphere correction and the dry troposphere correction (propagation corrections) respectively to the retracked range. Moreover, geophysical corrections are added to account for solid earth height variations due to forces of attraction between the sun and moon (solid earth tide), and water surface height variation due to the rotation of the earth about its axis (pole tide). Eq. (1) expresses surface level as the mean value within the altimeter footprint converted into surface level above geoid, by subtracting the geoid height above the reference ellipsoid.

$$L = Alt - (RR + C_p + C_g) - G \qquad \text{Eq. (1)}$$

Where L is the surface level, Alt is the satellite altitude, RR is the retracked range, C_p is the sum of propagation corrections, C_g is the sum of geophysical corrections, and G is the geoid height.

Satellite altimeters rotate in an almost fixed orbit. The measurements are provided at intervals of several kilometers or tens of meters depending on satellite altitude and speed. The vertical resolution reaches a few centimeters. Satellites pass a given area with a constant revisit period, allowing for the acquisition of temporal surface height variations for this area along the satellite ground track [2]. Several past and current altimetry missions are available. Missions differ in orbits, speed, altitude leading to different vertical resolution and effective illuminated altimeter footprint size.

Satellite radar altimetry datasets is organized into tracks representing the satellite orbit path during the revolution of the earth. Different cycles' files corresponding to satellite revisit times fall under each track. Files contain the following parameters**:** time tag, altimeter footprint geolocation, range measurements, output from different retracking algorithms (range, wind speed, significant wave height, etc.) at 1 Hz, as well as some 20 Hz parameters: range, and precise orbit information and altitude. Also included are multiple solutions for atmospheric, geophysical, and instrumental corrections suitable for different reflecting surfaces. Moreover, Flags parameters which consist of three parts: instrument flags (provide information about the state of instruments on the satellite, and data quality flags (geophysical processing flags) that are set if gaps in the data are detected, or residuals have exceeded predetermined thresholds, or if the gradients of the data exceed predetermined thresholds. It should be noted that ranges, retracked ranges and ionosphere corrections are separately reported for each of the k_u and c band ranges. The k_u band parameters are recommended for use for most applications [8, 9].

3. METHODOLOGY

Jason-2 (July2008 – Oct. 2016) is a follow-on mission to Jason-1(Sept. 2002- Jan. 2009), which followed the TOPEX/POSEIDON (T/P) mission. These successive missions fly on the same exact orbit. Jason missions have revisit time of 9.9 days. The details of the missions are listed in Table. 1 [8].

Table 1: Details of Jason 2 Altimetry Mission

Satellite	satellite Altitude (km)	Revisit Period (days)	Measurements Interval (m)	Foot print Circular Area (km)	Accuracy (cm)
TP/J1/J2	1336	9.9	295	2*	2.5

*information form Chelton [10]

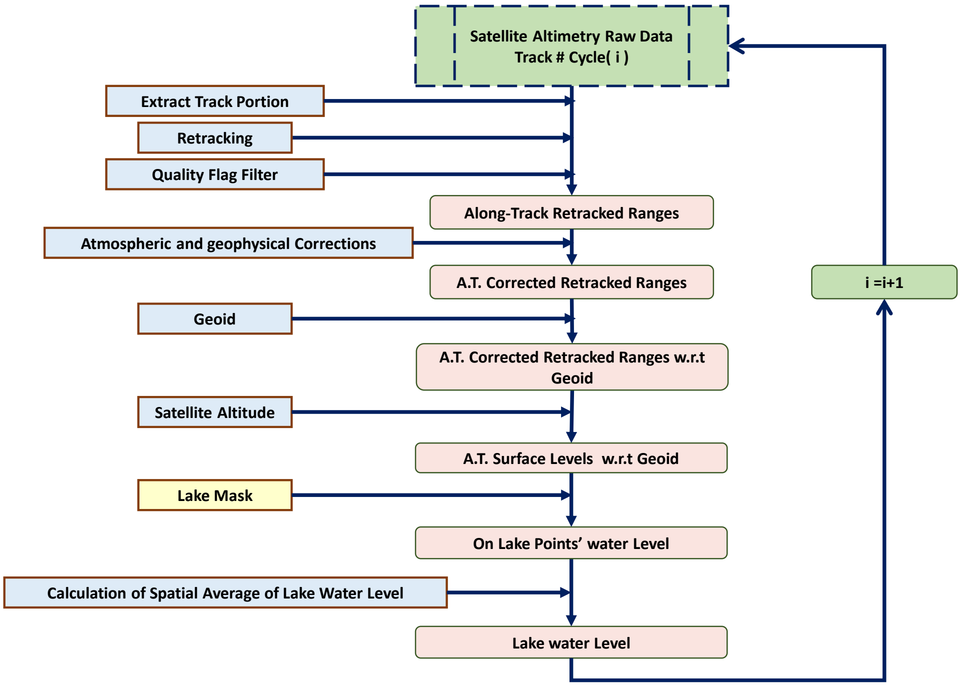

Figure 2. Schematic of Methodology

Sensor Geophysical Data Record family products (SGDR) supplied Jason 2 mission are employed in this study. Data set contains 1 Hz subset of the full dataset as well as 20 Hz high-rate values, in addition to the full radar-echo waveforms in NetCDF format. The SGDR data is organized into tracks numbered from 1 to 254 representing a full repeat cycle of the Jason ground track. Tracks covering the study area are determined, and files corresponding to cycles within the study period are downloaded. PISTACH hydrology product and Jason-2/OSTM SGDR datasets have similar structure except for minor variations; therefore, they are subjected to the same processing method unless otherwise mentioned.

The Basic Radar Altimetry Toolbox (BRAT) is used to extract portion of the track that crosses the study area. Data with re-tracking quality flag set to 'bad quality' were excluded from the data. For outliers removal, abnormal high/low values were removed by a simple visual inspection. Ice1 retracking algorithm was selected to calculate retracked range in Eq. (1) for SGDR datasets while Ice3 is employed in case of PISTACH datasets. Instrumental corrections are included in the retracked range. For other correction terms in Eq. (1) suitable solution for inland applications is selected (Table. 2). The k_u band parameters are used in this study. BRAT outputs are footprints with latitude, longitude, time tag, and surface elevation with respect to Geoid

Table. 2. Corrections Applied for SGDR and PISTACH datasets

Variable	Jason2 SGDR	Jason2 PISTACH
Retracking algorithm	Ice1	Ice3
Dry Troposphere	ECMWF	ECMWF
Wet Troposphere	ECMWF	ECMWF
Ionosphere Correction	Global Ionosphere TEC maps	Global Ionosphere TEC maps
Solid Earth Tide	Catrwright and Taylor[1971]	Catrwright and Taylor[1971]
Pole tide	Equilibrium model	Wahr 1985
Geoid	EGM96	EGM2008

Finally, footprints are converted into an ArcGIS shapefiles to show the geolocation of the calculated elevation points. Altimetry-derived water levels are values along the ground tracks overflying the target lake. Spatial analysis is carried out to extract water level points within the boundaries of the lake, and an average water level is computed for each cycle. The time-series of average water levels (with respect to geoid) within the specified study area are generated. ArcGIS Spatial Analyst extension libraries are incorporated into a Python script that is particularly developed to automate the entire procedures (Fig.2).

Because altimetry tracks don't coincide with the gaging stations, which have their own reference datum, direct comparison between the water level absolute values of satellite altimeter products with gauge measurements cannot be held. Moreover, water levels obtained from different satellite altimeter products are based on different geoids or references. Therefore, only the water level variations can be derived from the operational databases. The validation method by Birkett and Beckley (2010)[5] is commonly used, and thus adopted in this study. In this method, the Bias between altimetry-derived water levels and measured water levels is calculated. Then a shift constant is added to the altimetry-derived water levels that corrects for the calculated Bias. The *RMSE* (root mean square error) of the water level differences is computed to signify error. The coefficient of determination R^2 was also used to evaluate the agreement between measured and altimetry-derived water levels patterns.

4. APPLICATION AND RESULTS

High Aswan Dam (HAD) construction started in Egypt in 1964, and was completed in 1970. The dam height is 111 m. The water accumulation behind the Aswan high dam created one of the largest manmade lakes: Lake Nasser (Fig. 3). It is located between 20.45° and 23.97° N and 30.12° and 33.25° E. Lake Nasser extends over 500 km to the south with an average width of 12 km, and 6500 km^2 surface area when water level reach 182 m above the mean sea level in case of full storage. It can store up to 130 km^3 of water. Apart from this amount, 31 km^3 is reserved as dead storage, leaving about 90 km^3 as a live storage to satisfy Egypt's agricultural and domestic needs from water [11]. Egypt as it is classified as a dry arid area, thus, the loss of surface water by high evaporation rate. Average annual evaporation amounts to 10 km^3 as estimated by the 1959 agreement between Egypt and Sudan.

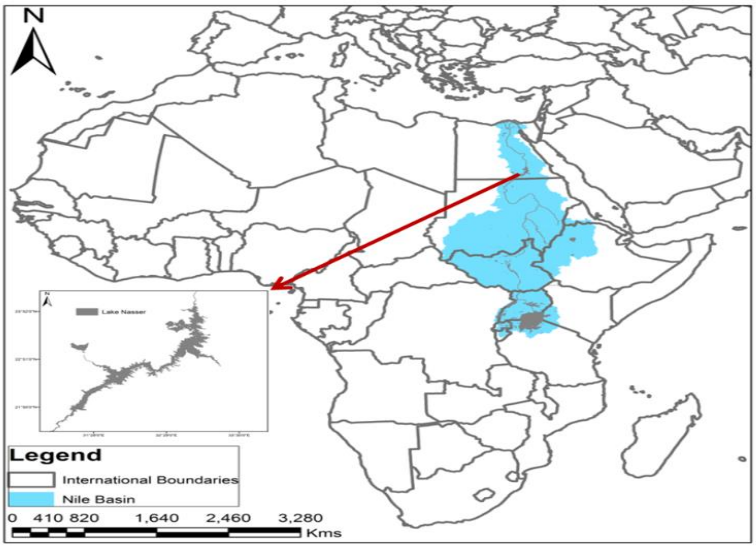

Figure 3. Geographic Location of Lake Nasser

The staff gauge is erected just upstream HAD (Fig. 4.), on the west bank of the lake. It is part of the abutment wall at the upstream entrance of the diversion channel. As for Jason2 mission, ground tracks 235 and 094 intersect with Lake Nasser, but the latter is closer to the gauging station. Monthly mean staff gauge records are obtained from the Ministry of Water Resources and Irrigation, for the period 1964-2012. However, only records from 2008 to 2012, coincide with Jason 2 mission operation time. Finally, track 094 cycles 1 to 165 are downloaded from J2 SGDR and PISTACH datasets.

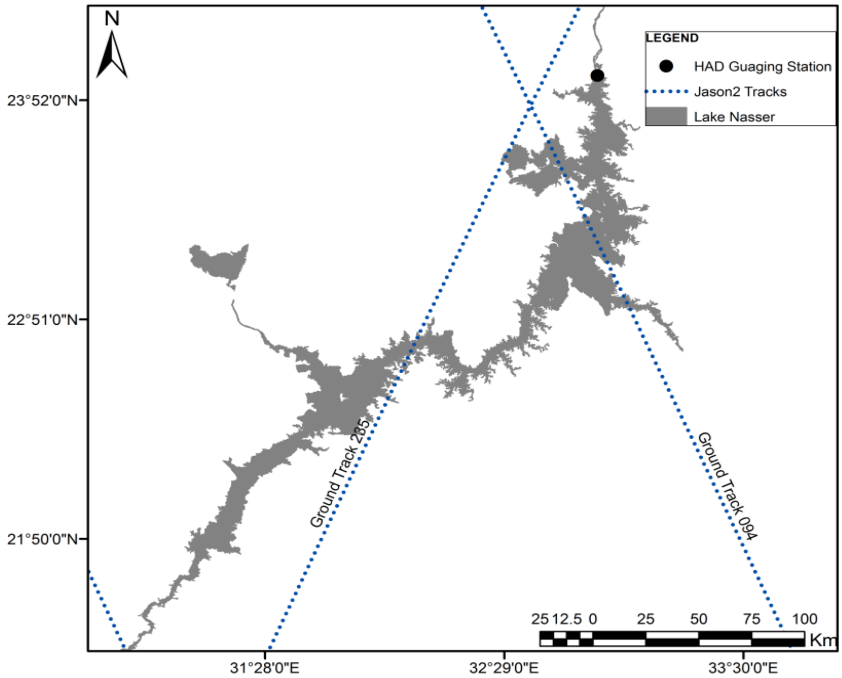

Figure 4. Location of Lake Nasser Gauging Station and Jason 2 Mission Ground Tracks

Using BRAT software, raw data is processed, data with bad quality flags are excluded. Levels points with their geolocation are produced. Points within the boundaries of the lakes (obtained from historical maps and digitized using ArcMap software) are extracted. A spatial mean WL is computed representing Lake Nasser water level at a 10-day time step. They were averaged to get altimetry-derived Lake Nasser mean monthly water levels time series.

Original WL time-series derived from both datasets were in good agreement with in-situ measurements in phase and amplitude (Fig.5.) with coefficient of determination R^2 of 0.97 (Table. 3). It is clear that there is a positive bias in water levels derived from SGDR; while PISTACH obtained levels show negative bias (Fig. 5.). Therefore, a shift constant equal to the bias was applied for each of the time series (Table. 3). On the other hand, the patterns generated from PISTACH water levels and SGDR are identical. Therefore, the root mean square of errors *RMSE* with respect staff gauge measurements is the only differentiating criteria that can be applied to compare the two datasets. *RMSE* of datasets is within the acceptable range (Table. 3). However, *RMSE* for SGDR is insignificantly less than that of PISTACH datasets (Fig. 6, Fig.7).

Table.3. Statistics for satellite altimetry Lake Nasser water levels when compared to in-situ measurements

DataSet	R^2	Shift Constant (m)	*RMSE* (m)	$RMSE/_{Mean\,WL_{measured}}$
SGDR	0.97	-0.95	0.38	0.22%
PISTACH	0.97	1.2	0.4	0.23%

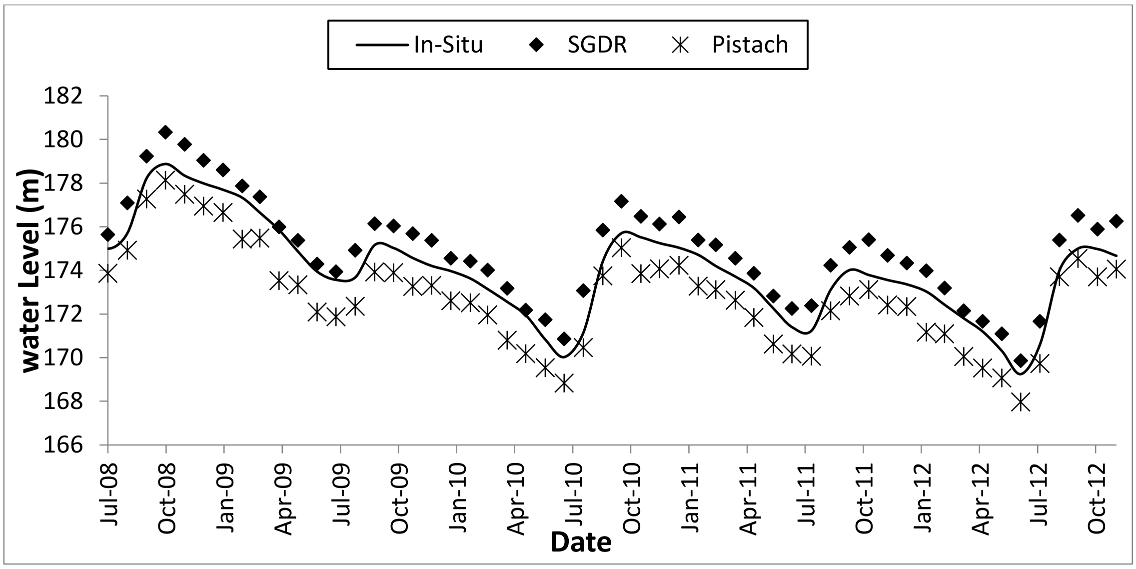

Figure 5. Original Time series of monthly mean in-situ measurements, water levels derived using PISTACH, and SGDR satellite altimetry datasets between 2008 and 2012

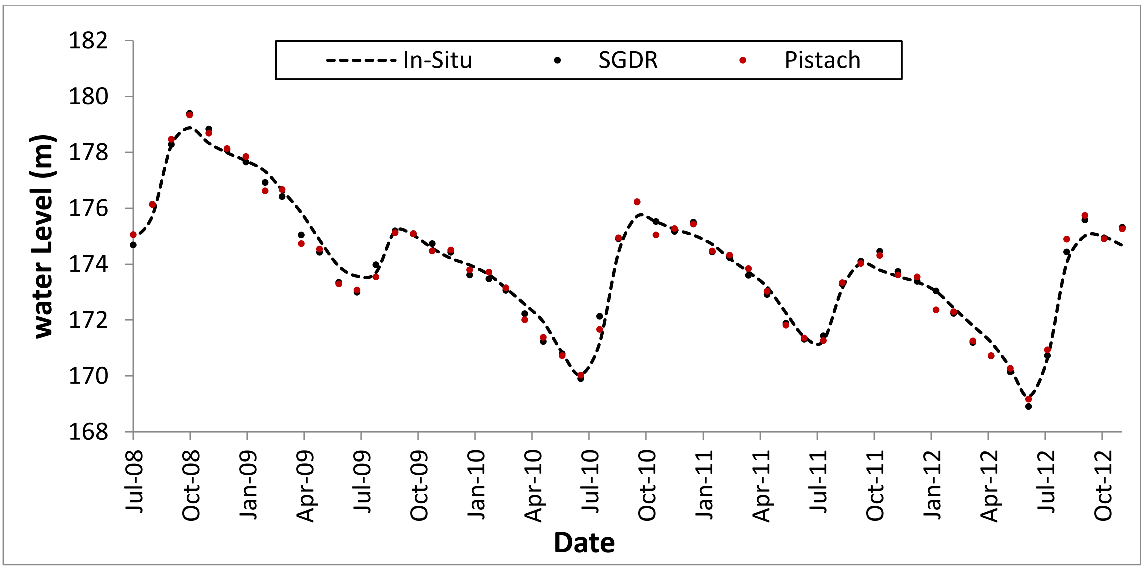

Figure 6. Shifted Time series of monthly mean in-situ measurements, water levels derived using PISTACH, and SGDR satellite altimetry datasets between 2008 and 2012.

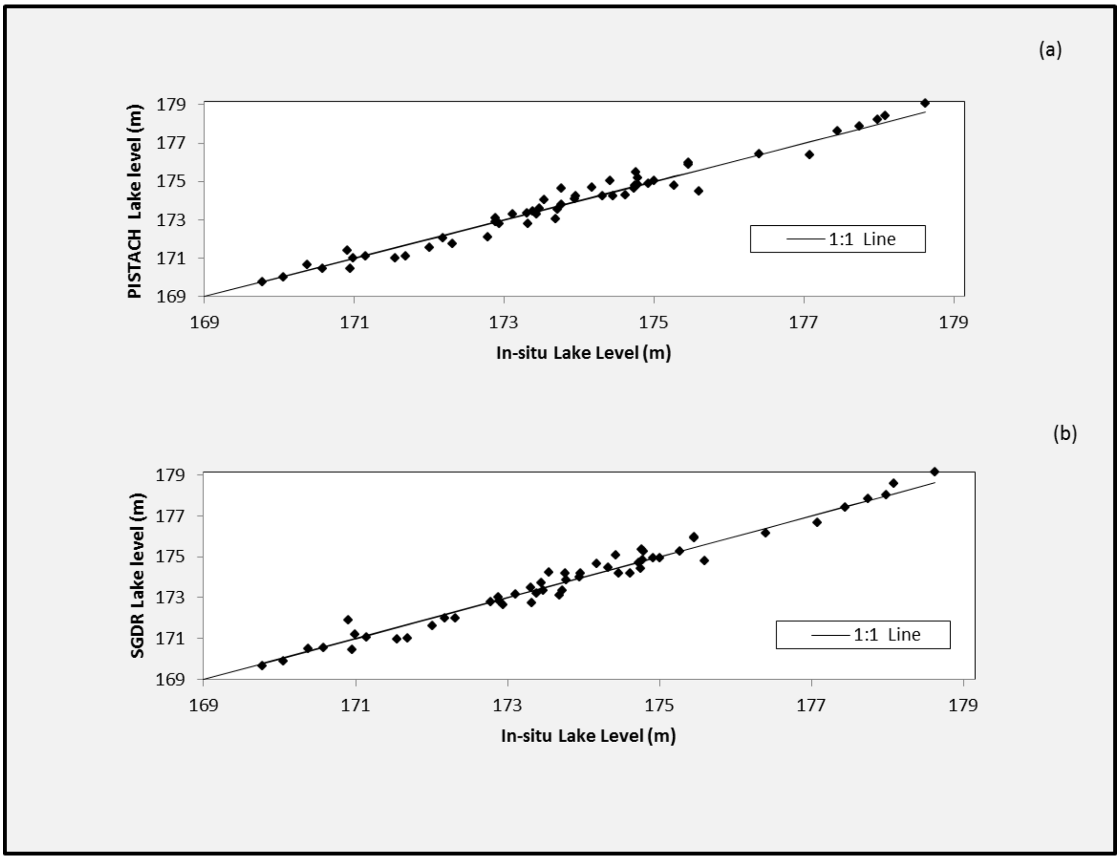

Figure 7. Comparison between monthly mean in-situ measurements and water levels derived using (a) PISTACH and (b) SGDR satellite altimetry datasets

5. CONCLUSIONS

Altimetry-derived water levels from both datasets can replicate the patterns of the measured water levels ($R^2=0.97$). The *RMSE* is minimal (0.38 to 0.4 m) Hence, satellite radar altimetry is a reliable tool for water level monitoring in reservoirs. However, the water levels derived from PISTACH products give the same R^2 as those from the standard SGDR datasets. Moreover, they show more Bias and *RMSE* increased. In Summary, PISTACH datasets and its new retracking algorithm (Ice3) don't demonstrate improvement for water level estimates.

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