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Present State of Lake Studies from Satellite Altimetry – a Case Study in Poland

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Abstract. Satellite radar altimetry is a successful technique for monitoring elevations of continental surface water. The surface water level is measured within a terrestrial reference frame with a repeatability varying from 10 to 35 days depending on the orbit cycle of the satellite. With several decades of technique refinement; current data processing can be fairly simple or complex depending on the mission and the tracking methods. Data acquisition is not affected by weather conditions; but the technique can have a number of limitations. However; the technique is sufficiently advanced to have allowed a number of inland water case studies. Focusing on the large lakes; the links between lake evolution and the local climate cycle on seasonal to interannual timescales can be explored; and water storage balance for water management also can be brought into focus. This article reviews present day lake level monitoring and the case study of the Łebsko lake in Poland. First the basic principle of satellite altimetry, current altimetry missions, hydrology application and lake and reservoir altimetry measurements in web sites are shortly describe. Next the investigation of the surface of the Łebsko lake in Poland was carried out. From our study reveals that altimetry could provide a promising future for true global lake studies with height and width observation of all targets with centimeter accuracy.

Keywords: satellite altimetry, water surface altitude, hydrology altimetry product, inland water body.

Conference topic: Technologies of geodesy and cadaster.

Introduction

The principle of radar altimetry measurements was envisaged in the sixties, and recognized as a high priority measurement. The first objective of the measurement was to measure the shape of the Earth, which can be considered today as a very limited ambition, but the error in the first space-borne measurement was of the order of 100 m. It was clear that a lot was to be gained with this technique, if the error could be beaten down below the level of the ocean dynamic topography. The development of altimeter technology was a constant effort, which gave birth to a series of early missions: Skylab (1973), GEOS-3 (9 April 1975–December 1978) and Seasat (June 1978–October 1978). With the advent of more precise instruments flying on a much better known trajectory, radar altimetry began to supply invaluable information in geodesy, oceanography, geophysics, glaciology and continental hydrology e.g. (Benveniste 2011). The next-generation of radar altimeters is already flying and providing more accurate data for monitoring the variation in elevation of continental surface water, such as inland seas, lakes, rivers and wetland zones. The future SWOT (Surface Water Ocean Topography) mission will serve both land hydrology and oceanography communities. The one of the science goal, while providing sea surface heights and terrestrial water heights over a 120 km wide swath with a ±10 km gap at the nadir track, is to produce a water mask able to resolve 100-m wide rivers and lakes, wetlands, or reservoirs of surface greater than 1-km^2. Associated with this mask will be water level elevations with an accuracy of 10 cm and a slope accuracy of 1 cm/1 km (Benveniste 2011).

Basic principle

Radar altimeters on board the satellite transmit signals at high frequencies, over 1700 pulses per second, to Earth and receive the echo from the surface e.g. (Fu, Cazenave 2001). This is analysed to derive a precise measurement of the time taken to make the round trip between the satellite and the surface. This time measurement, multiply by the speed of electromagnetic waves yields a range R measurement (Fig.1).

The altitude of a satellite h is the satellite's distance with respect to an arbitrary reference e.g. the reference ellipsoid, a rough approximation of the Earth's surface. It depends upon a number of constraints e.g. inclination, atmospheric drag, gravity forces acting on the satellite, area of the world to be mapped, etc. The satellite can be tracked in a number of ways so as to measure its altitude with the greatest possible accuracy and thus determine its precise orbit, accurate to within 1 or 2 cm. Combining satellite altitude with the range data allows the elevation above the ellipsoid of the lakes water surface to be calculated with respect to the ellipsoid.

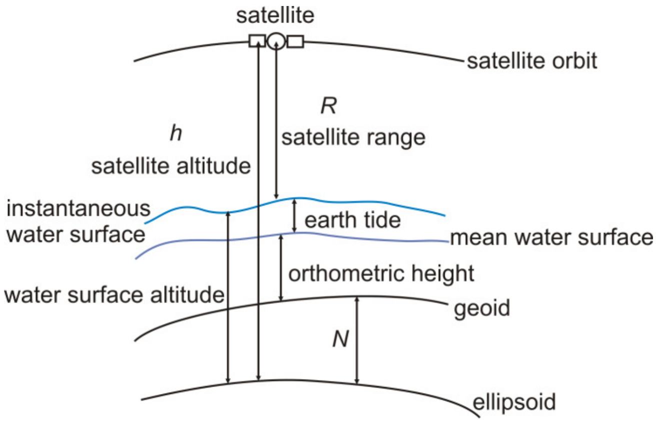

Fig. 1. Principle of satellite altimetry

The water surface altitude (*WSA*), is the range at a given instant from the sea surface to a reference ellipsoid. This is simply the difference between the satellite height *h* and the satellite range *R*:

$$WSA = h - R. \quad (1)$$

In order to obtain heights of inland water, several processing functions have to be performed. The first is data ingestion and pre-processing. The second, crucial step is the re-analysis of each individual echo over inland water to optimise the range to surface by characterising the echo shape and selecting one of several "retracking" algorithms. This function is performed automatically by the system.

In the same way as for altimeter data obtained over the ocean, in order to transform the range estimates into orthometric heights, these ranges must first be combined with orbit data, and corrections applied for the radar pulse propagation through the atmosphere. Instrument and surface related corrections along with a tidal model are then applied, and finally a global geoid model is used to model mean sea level under the continental surfaces, and thus transform the ellipsoidal heights to orthometric heights.

However, as electromagnetic waves travel through the atmosphere, they can be slowed by water vapour or ionization. Once these phenomena have been corrected for, the final range *R* can be estimated with a great accuracy. The final aim is to measure surface height relative to a terrestrial reference frame. This requires independent measurements of the satellite's orbital trajectory, i.e. exact Cartesian coordinates *X*, *Y*, *Z* or geodetic coordinates φ, λ, h. Precise satellite altimetry missions have transformed the way we view Earth and its oceans. Highly accurate altimetry measurements give us the ability to observe sea surface height systematically.

The earliest altimeters were intended to demonstrate proof of concept. With Seasat (1978), the first scientific results were shown. Since 1986 (Geosat), these missions have been providing vital information for an international user community. Besides international programs dedicated to studying global oceans and climate, such as WOCE, WCRP, Clivar and GOOS, and others working on the El Niño phenomenon (TOGA), ocean forecasting projects such as GODAE are now getting underway. All these programs call for high-quality altimetry measurements, which are merged with other data to obtain the broadest picture possible of the underlying mechanisms at work, and assimilated into ocean and climate prediction models.

Current altimetry missions

There are six altimetry satellites currently in service. Jason-2 with a relatively short repeat cycle (10 days), able to observe the same spot on the ocean frequently but with relatively widely-spaced ground tracks (315 kilometres at the equator). Jason-2 is on the same orbit as their predecessors, Topex/Poseidon (1992–2005) and Jason-1 (2001–2013).

Saral which orbit is similar to the orbit of ENVISAT allowing continuation of the ERS/ENVISAT time series. The repeat cycle is 35 days and the ground track spacing is 90 kilometres at the equator, complementary to the Jason-2 orbit. CryoSat-2 with an altimeter (Siral) ables to work with an interferometric mode, with a high orbit inclination of 92° to satisfy the scientific requirements for observing the poles and the ice sheets, and with an orbit non-sun-synchronous (commonly used for remote-sensing satellites). HY-2 with a 14-day orbit and Jason-3 to ensure continuity of the global sea level record. Jason-3 is flying in the same 9.9 day repeat track orbit as all previous Jason missions, meaning the satellite is making observations over the same ocean point once every 9.9 days. The orbital parameters are: 66.05 degree inclination, 1380 km apogee, 1328 km perigee, 112 minutes per revolution around the earth. The Sentinel-3 mission is based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for Copernicus Services. Sentinel-3 is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean and land colour with high-end accuracy and reliability. The orbit is a near-polar, sun-synchronous orbit with a descending node equatorial crossing at 10:00 h Mean Local Solar time. In a sun-synchronous orbit, the surface is always illuminated at the same sun angle. The orbital repeat cycle is 27 days (14+7/27 orbits per day, 385 orbits per cycle). Summary of six present missions is given in Table 1.

Table 1. Present satellite altimetry missions

Satellite	Mission	Launch	Altitude	Repeat cycle	Inclination
Jason-2	Measure sea surface height	2008	1336 km	10 days	66°
Cryosat	Polar observation	2008	720 km	369 days	92°
HY-2	China, observe the ocean dynamics	2010	963 km	14 days and 168 days	99.3°
Saral	Measure sea surface height	2013	800 km	35 days	92°
Sentinel 3	To provide operational oceanography data for GMES	2016	814 km	27 days	98.5°
Jason-3	Measure sea surface height	2016	1336 km	9.9 days	66°

Hydrology application

The earliest altimetry missions were dedicated to studying the open ocean and some ice measurements. However, every stretch of water (enclosed seas, lakes, rivers, flooding areas...) or even flat surfaces over lands can give valid data – as long as the satellite fly over them.

Studying altimetry over lakes was first undertaken to validate altimeter measurements, lakes having few dynamics compared to the ocean, and many of them being monitored. Today, a great number of lakes of all sizes are monitored by altimetry. However, in situ data (river runoff, temperature, or precipitation) are still critically needed for studying the evolution of each lake's water mass balance. 43 lake systems can be observed by Topex/Poseidon or Jason-1, and 215 by ERS-2 or Envisat, out of a total global population of 842 lake systems of more than 100 km².

The level of lakes (such as the American and African Great Lakes, etc) varies through the seasons according to inputs (rain rates, snow melting, etc) and outputs (evaporation, withdrawal, etc), and is thus a very sensitive indicator of regional climate variations (Alsdorf *et al.* 2001). Moreover, the level of enclosed seas (Aral Sea, Caspian Sea, etc) is a major indicator of their good (or bad) health. Altimetry enables us to continually monitor these levels, even in areas which are difficult to access.

For certain major rivers and wetlands, hydrological information can often be difficult to obtain due to a region's inaccessibility, the sparse distribution of gauge stations, or the slow dissemination of data. Satellite radar altimeters can potentially monitor height variations of inland waters (Birkett 1995, 1998). Hydrological products from satellites are unaffected by political and logistical considerations and can provide accurate height measurements not only for lakes but also for large rivers such as the Amazon, which has been a primary target of study over the last ten years.

Lake and reservoir altimetry measurements in web sites

Hydrology from Space is database developed at the Legos laboratory in Toulouse. This web database contains time series over water levels of large rivers, lakes and wetlands at the global scale. The lake levels are based on merged T/P, Jason-1, Envisat, ERS-2 and GFO data freely available through the NASA and the CNES data services (PODAAC and AVISO). The monthly level variations deduced from multi-satellite altimetry measurements for almost 150 lakes and reservoirs are freely provided. Potentially, the number of lakes monitored could be significantly increased. These lake and reservoir level time series are available at: http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/ (Legos 2017). This data base has no information concerning lakes and rivers in Poland.

United States Department of Agriculture Foreign Agricultural Service (USDA) has developed, among others, a database of water level variations on a 10-day basis for almost 100 lakes monitored in a near real time from the satellite missions T/P and Jason-1. The data are freely available directly on the web site: http://www.pecad.fas.usda.gov/ (USDA 2017).

The data base contains height variations from TOPEX/POSEIDON/Jason-1 and Jason-2/OSTM Altimetry only for one Polish lake Śniardwy for profile 4.6 km long.

The attached graph (Fig. 2) shows that periodic (annual) changes in the level of the lake Śniardwy over the past 10 years which are the order of 0.6 meter, which multiply by the lake area of about 11400 ha indicates a important seasonal change in water balance near 6.84×10^7 m^3. In addition, the regression curve for this data set (Fig. 2) indicates the systematic reduction of the level of the lake about 8.5 mm/year which gives loss of water almost 9.69×10^5 m^3 per year. Presented here the study level changes at the Śniardwy lake means that satellite altimetry can be successfully used to test the other lakes and rivers in the area of Polish.

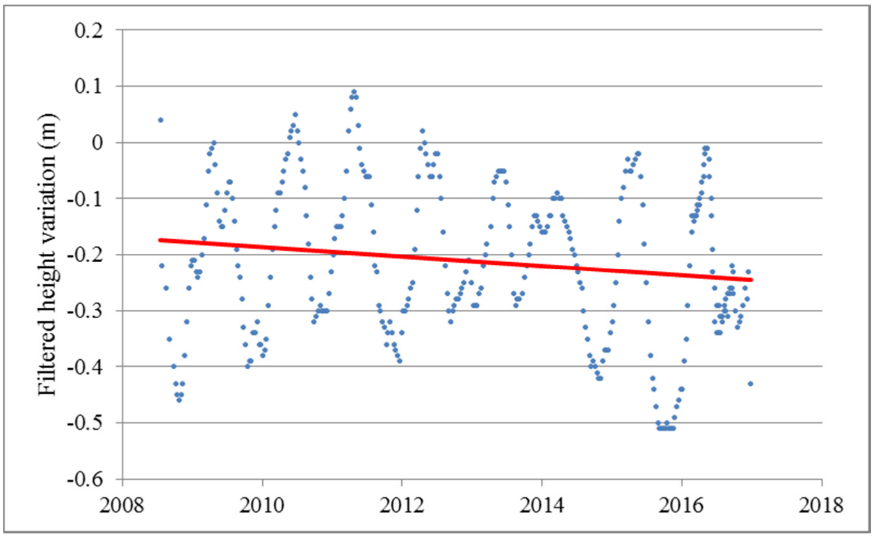

Fig. 2. Filtered lake height variation with respect to Jason-2 reference pass level (meters)[1]

The European Space Agency, in cooperation with the De Montfort University in UK has developed an algorithm for altimetry waveform retracking, which is now operating automatically. They have set up a River&Lakes database: which provides instantaneous water level products on a near real time basis, over the whole Earth. This database does not provide historical altimetry data that can, however, be obtained on demand from ESA. The web site is at the following address: http://earth.esa.int/riverandlake/ (Crétaux *et al.* 2011). This data base has no information concerning lakes and rivers in Poland.

Investigations

The data used in this study include the data from the Jason-2 altimetry mission, which is a follow on mission to Jason1 (OSTM/Jason-2 Products Handbook 2016). The Level-2 products from this mission comprise nine different types of Geophysical Data Records (GDRs). So there are three families of GDRs, divided by increasing latency and accuracy, going from the Operational GDR (OGDR), the Interim GDR (IGDR), to the final GDR. In this paper IGDR Geophysical Data Records containing 20 Hz waveforms have been used. The pass locator on Aviso website gives quick and easy access to the precise ground track coverage of the various altimetry missions on Google Earth. In our case, we have decided to look for a lake or reservoir in Poland.

The detailed analysis show that there is an ability to study changes in water levels of large lakes like Śniardwy, Wigry, Łebsko, Jeziorak, Drawsko, Ros lake and a number of smaller lakes by using satellite observations from Jason-3 and Sentinel- 3.

In our case, we have decided to investigate Łebsko lake. This lake, located in the north Poland, is large coastal lake and is the third largest body of water (after Śniardwy and Mamry lakes) in our country. It extends from 54°40'N to 54°45'N and from 17°17'E to 17°32'E. Satellite track over the lake is almost 7 km long, what gives a huge amount of data to study. Further characteristics of Łebsko lake is presented in Table 2.

Due to instruments on the satellite give measurements containing useful information over continental water bodies and over emerged land, the CNES (Centre National d'Etudes Spatiales) funded the PISTACH project (Innovative Processing System Prototype for Coastal and Hydrology Applications) to improve satellite radar altimetry products over coastal areas and continental waters. One of the two PISTACH products, includes among others new retracking solutions and several state-of-the-art geophysical corrections, is available for hydrology, with all emerged lands plus a 25-km fringe over oceans. In order to study inland water bodies with the PISTACH products one has to download at least one file per track and per cycle. The beginning of interesting files used in this paper is defined as JA2_IPH_2PTP(…) = Jason-2 Hydro product.

To examine this Łebsko lake, we downloaded track #187, as it is shown in the Fig. 3, for cycle from 276 to 303 which gives 26 files. They are corresponding to an acquisition date between 29th of December 2015 and 29th September 2016.

To visualize the results of the Łebsko lake the Broadview Radar Altimetry Toolbox (BRAT 2016) has been used. This application is a collection of tools designed to facilitate the processing of radar altimetry data and is able to read currently most distributed radar altimetry data. The BRAT is a joint project between ESA and CNES to develop an open source tool available to all the altimetry community for free. It is accessible in 32-bit and 64-bit versions for

[1] Data used in diagram are from https://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/

Windows, Mac OS X and Linux. In order to minimise the data volume, usually the BRAT Graphical User Interface (GUI) which is a windowed interface to the BRAT tools is used.

Table 2. Characteristics of examined Łebsko lake

Characteristics of the Łebsko lake	
Surface area [km^2]	71,42
Volume [km^3]	0,118
Maximum depth [m]	6,3
Mean depth [m]	1,6
Surface elevation [m]	0,3

Fig. 3. Track#187 for Jason-2 satellite over Łebsko lake in the northern Poland

The most popular operation to check the data is to visualize the difference between altitude and range along the track of satellite. The dual frequency altimeter on Jason-2 performs range measurements at the Ku and C band frequencies but the Ku band has much higher accuracy than the C band measurement. The Ku band is the 12–18 GHz portion of the electromagnetic spectrum in the microwave range of frequencies. The range at this band in GDRs is corrected for all instrumental effects i.e. distance antenna-COG, USO drift correction, internal path correction, Doppler correction, modelled instrumental errors corrections and system bias.

Using BRAT we computed differences between altitude and range on each data point of each cycle for chosen track #187 concerning area of Łebsko lake (see Fig. 3). The selected track has been cut off to the section between latitude 54º40'N and 54º45'N over examined lake by using appropriate BRAT function. First look on computed differences is gives on Fig. 4 in red. In this case the typical oceanic retracking solution was used.

The PISTACH Project has developed two new retracking algorithms: Ice1, Ice3. The authors of the project recommend that it is the responsibility of the user to determine which retracker output is appropriate to his specific data set. They also advise to use the Ice1 standard altimeter range solution or Ice3 range to small water bodies which do not present ocean-like waveforms. In this paper we used the Ice1 and Ice3 retrackers output to compare them to the ocean retracking solution used in this study. The results of this computations are plotted on the Fig. 4 (left).

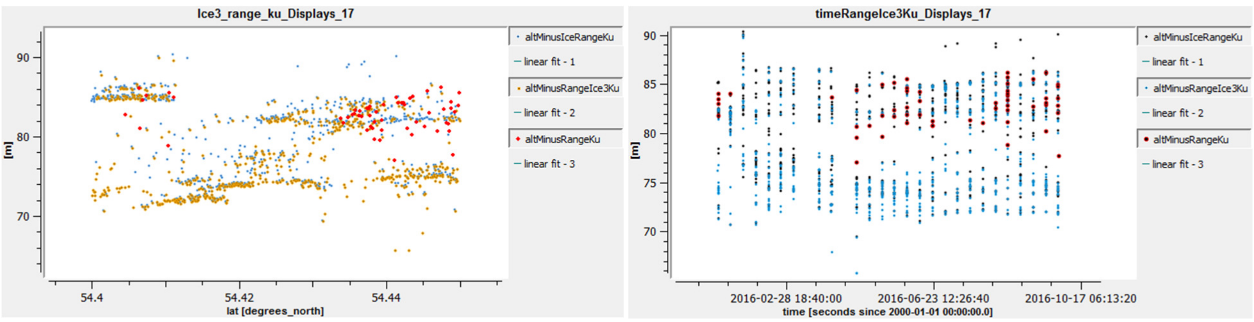

Fig. 4. Computation of the difference between orbit and range with the Ice1 in blue and with the Ice3 in yellow retracking and compare to a standard ocean retracking in red (left) and the differences between orbit and range for Ice1, Ice3 and oceanic "range" expressed as a function of time for Łebsko lake

The plot Fig. 4 suggests that the data sets are very coherent, irrespective of the used retracking algorithm. The best consistency of the data occurs nearby to latitude 54°44' degrees. Differences (*h*-*R*) are plotted also as a function of time (Fig. 4 right) and they similarly give a clear signal. It means that there are no significant blunders in altimetry data.

In equation (1) *WSA* is referred to the ellipsoid. In order to refer *WSA* to the geoid, from *WSA* the geoid ellipsoid separation *N* has to be subtracted. Moreover range *R* has to be corrected due to several factors. Therefore the precise *WSA* is represent by the formula:

$$WSA = h - R_{corr} - N_{GM}\,, \tag{2}$$

where corrected range R_{corr} is equal measured range *R* plus corrections: ionospheric correction, wet troposphere correction, dry troposphere correction, tidal correction, and N_{GM} geoid ellipsoid separation computed from global geopotential model.

In the (I)GDR products is provided a ionospheric correction which is derived from Global Ionosphere Maps (GIM). The GIM iono correction may be used over continental waters and it is recommended instead of the dual-frequency ionosphere correction. The **Error! Reference source not found.** illustrates this temporal fluctuation for Łebsko lake. From the **Error! Reference source not found.** we can estimate that the ionospheric correction change with time from –0.04 m to –0.01 m and in average is not significant.

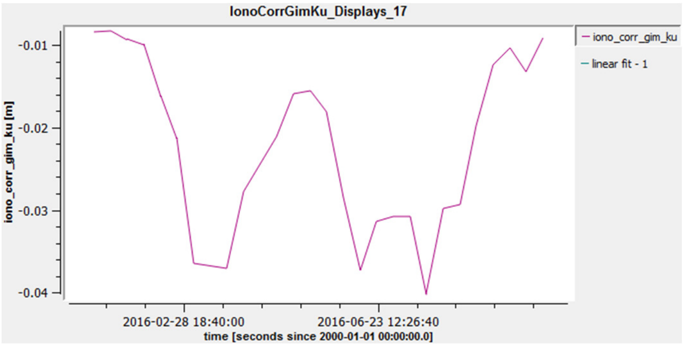

Fig. 5. Amplitudes of the ionospheric correction derived from the GIM model for Łebsko lake

In the troposphere the propagation velocity of a radio pulse from altimeter is restrained by the "dry" gas contribution, it is almost constant and gives height errors of approximately –2,3 m. The water vapour is completely variable and unpredictable and produces in range measurement error of –6 cm to –40 cm. Fortunately, these effects can be measured or modelled. Over inland water bodies the standard model solution i.e. from ECMWF (the European Centre for Medium-Range Weather Forecast) is used although it is not optimal due to a possibly inaccurate knowledge of the atmosphere thickness and the surface pressure above each altimeter data point. In the case of wet tropospheric correction over non ocean areas the radiometer is highly perturbed by emerged lands. Thus a model correction is used. In case of dry tropospheric correction most of its error comes from inexact values of the real surface elevation along the track. The temporal fluctuations of wet and dry tropospheric corrections for Łebsko lake are shown respectively on Fig. 6. From Fig. 6 it is seen that the wet correction is few centimeters up to decimeter while the dry correction is approximately –2.3 meters.

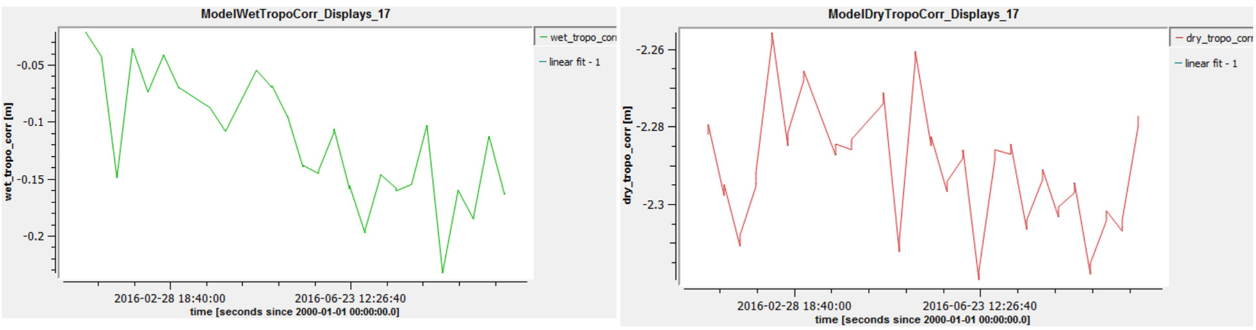

Fig. 6. Amplitudes of the wet tropospheric correction derived from the ECMWF model for Łebsko lake (left) and amplitudes of the dry tropospheric correction derived from the ECMWF model for Łebsko lake (right)

To obtain precise *WSA* the following geophysical corrections should be considered, namely the solid earth tide and pole tide corrections. They cause a vertical deformation of the earth surface and therefore are important in our case.

In the GDR products of Jason-2 the solid earth tide is computed as an entirely radial elastic response of the solid Earth to the tidal potential. This response is modelled using frequency independent Love numbers which are also required, next to a time series of perturbations to the Earth's rotation axis, to modelling the pole tide.

A tide-like motion of the ocean surface which is a reaction of the solid Earth and the oceans to the centrifugal potential is called the pole tide. The Jason-2 mission (O)(I)GDR delivers a single field for the radial geocentric pole tide displacement of the ocean surface and contains the radial pole tide displacement of the solid Earth and the oceans. The IGDR with the pole tide may differ from the GDR because the pole tide on the IGDR is computed with a less accurate time series of the Earth's rotation axis.

The plot on Fig. 7 (left) illustrates amplitude of the solid Earth tide from –0.102 m to 0.185 m for the selected track portion i.e. only over Łebsko lake. The amplitude of the pole tide is shown on Fig. 7 (right) is from –0.005 m to 0.003 m.

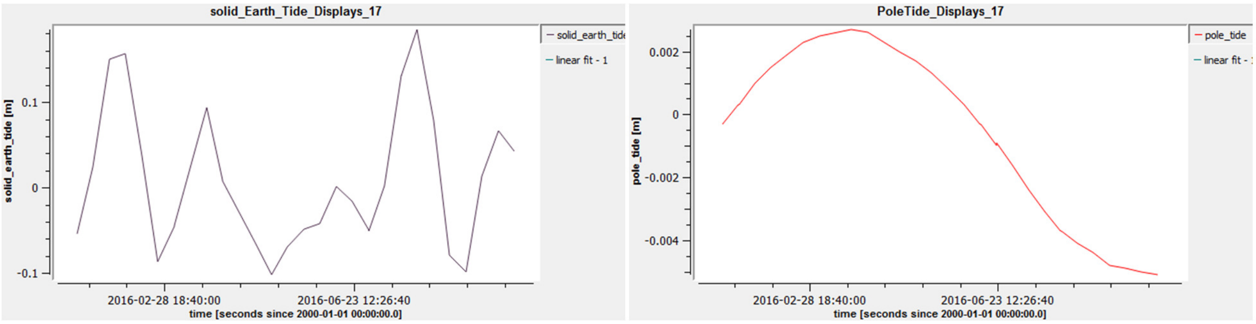

Fig. 7. The amplitude of the solid Earth tide over Łebsko lake (left) and the amplitude of the pole tide over Łebsko lake (right)

The geoid is a equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level. As already mentioned above all Earth's surface heights are referenced to the geoid, therefore should be taken into account when the actual water surface altitude is computed. It is known that over Poland the geoid undulation i.e. the separation between the geoid and the reference ellipsoid ranges from 45 m to 27 m and over Łebsko lake it is about 33m.

The appropriate values of geoid undulation along the section of the track #187 were computed using open source tool BRAT from the EGM2008 geopotential model which gives the more precise geoid undulation nowadays and they were used to compute the actual precise *WSA* in this paper. Finally, the precise water surface altitudes (*WSA*) along the Łebsko lake were computed from the formula (2) and the results are displayed on the Fig. 8 (left) as a function of latitude and Fig. 8 (right) as a function of time. Range R_{corr} was computed from the Ice3 retracking algorithm and contains all necessary corrections.

The results from both figures show that it is necessary to make a more accurate selection of the data and using in computation more accurate data as found in the standard Jason-2 GDR because the water surface altitude ranges from 35,13m to 59.20 m.

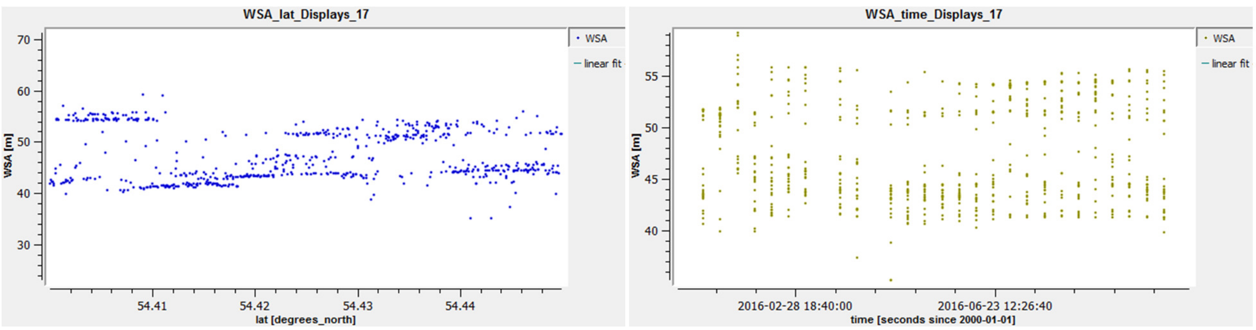

Fig. 8. Water Surface Altitudes (*WSA*) in a function of the latitude over Łebsko lake (left) and Water Surface Altitudes (*WSA)* in function of the time over Łebsko lake (right)

After introducing all necessary corrections to the range R its variability has decreased from 30 m to 15 m (compare Fig. 8 and Fig. 4). The Fig. 8 (left) shows small changes in the level of the lake in the late winter and the beginning of spring.

Conclusions

Both lake elevation and storage volume are important parameters for routine monitoring and for studying water balance variations across the catchment basin. Radar altimetry can contribute to the measurement of lake height variability over the lifetime of the satellite. The measurements can be acquired along the position of the satellite ground track with accuracy of the order of a few centimetres to tens of centimetres rms. Such measurements can be combined with bathymetry and imaging-derived area extent to further deduce changes in storage volume.

This work is the first Polish work for explore the possibility of determining the level changes of the lakes in the area of Poland. Therefore we examined satellite observations of the mission Jason2 for track # 187 passing by Łebsko lake. A total of 26 satellite tracks from the period of 9 months of year 2016 were analyzed. Examination of the altimetry observation was carried out by toolbox BRAT developed by ESA.

Research shows that it is possible to study changes to the surface of the lakes, but it is not simple and requires further study. In order to determine the level of lakes with high precision, it is necessary to use the altimetry observations with at least a couple of years.

There are sampling limitations to the technique, but combining datasets from different altimetry missions provides higher temporal and spatial resolution. Compilation of data from the Jason-1 (10-day repeat), GFO (17-day) and ENVISAT (35-day) missions can provide a repeat measurement at a frequency better than a single mission alone. Could provide a promising future for true global lake studies with height and width observation of all targets with centimeter accuracy.

Contribution

The altimeter products used in this work were produced and distributed by Aviso (http://www.aviso.altimetry.fr/), as part of the Ssalto ground processing segment.

Disclosure statement

Authors of this work have no any competing financial, professional or personal interests from other parties.

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