Use of altimetry data to determine the height of inland water surface – the case study

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Key words: satellite altimetry, hydrology applications, lake level monitoring

SUMMARY

The first satellite missions were intended to measure the open ocean globally and partially to study the presence of ice. Along with the progress, altimetry began to provide the necessary information in the field of geodesy, oceanography, and continental hydrology. The advantage of this technique is the possibility of systematic data acquisition with the simultaneous lack of disturbances resulting from the presence of vegetation in the study area or the time of day. The aim of this work is an attempt to determine the height of the surface of inland waters in Poland on the example of our largest lake Śniardwy. The work was done using PISTACH products, adapted to the specifics of coastal altimetry and surface water testing. The calculations were conducted with a package of BRAT programs.

The results of the calculations showed annual and seasonal changes in the level of the tested object. To compare the possibilities of the results with other sources of information, the mean level of Lake Śniardwy was calculated relative to the global geoid model. The average heights calculated in the period from 2008 to 2016 are in the range of 115.57 m to 115.9 m. The regression line indicates an increase in the surface of the lake of 3.4 cm/year.

1 INTRODUCTION

Satellite altimetry determines the distance from the satellite to a target surface by measuring the satellite-to-surface round-trip time of a radar pulse. However, this is not the only measurement made in the process, and a lot of other information can be extracted from altimetry e.g. (Calmant et al., 1997), (Escudier and Couhert, 2017) and (Rummel, 2008).

The earliest altimeters were intended to demonstrate proof of concept. With Seasat (1978), the first scientific results were shown. The 1970s saw the development of accurate satellite altimeter systems, with Skylab (which produced the first measurements of undulations in the marine geoid to seafloor features), GEOS-3, and Seasat, whose data were widely and freely distributed to scientists throughout the world, laying the foundations for a new generation of ocean satellites. In the 1980s, only Geosat was launched, whose data was at first classified (Exertier et al., 2001), (Vignudelli et al. 2011), (Benveniste, 2010).

In the 1990s, with ERS-1 and Topex/Poseidon, altimetry began providing vital information to a growing international user community. In the 2000s begin a revolution in ocean observation. Jason-1 and Envisat opened a new pathway for radar altimetry, and they have helped to build up a 20-year time series of continuous sea surface measurements.

There are four altimetry satellites currently in service. Satellite Jason-2 with a relatively short repeat cycle (10 days), can observe the same spot on the ocean frequently but with relatively widely spaced ground tracks (315 kilometers at the equator). Jason-2 is in the same orbit as their predecessors, Topex/Poseidon (1992-2005) and Jason-1 (2001-2013). Satellite – Saral – with a longer repeat cycle (35 days) but tighter ground track spacing (90 - 120 kilometers at the equator), complementary to the Jason-2 orbit. Satellite – 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) and satellite. For more information see e.g. (Cazenave and Nerem, 2004),

Hydrology and land applications. Altimetry has the advantage of taking being able to take global, homogeneous, repeated 151 measurements (thus enabling systematic monitoring to be carried out over several years), unhindered by clouds, night, or even vegetation (Cazenave and Creataux, 2009). The measured surface heights are referenced to the same frame. However, this technique is mainly optimized for the ocean (but although specific land re-tracking can be applied) and takes measurements only at the nadir (i.e., just under below the satellite), with a rather narrow footprint — and averaging everything in that footprint. Over non-ocean surfaces (wet or dry), the accuracy of the altimetry measurements can be degraded by several centimeters or tens of centimeters, mainly because of the heterogeneity of the reflecting surface (a mix of water and emerged lands land surfaces) (Vignudelli et al., 2011). Another important source of error lies in the signal's propagation of the signal through the atmosphere. The satellites' repeat-orbits are rather long (10 to 35 days), which do not fit with suit real-time monitoring of river or lake level variations (e.g. flood alerts), but agree to work well with seasonal or inter-annual monitoring.

Lake level monitoring. 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 (Benveniste, 2004). 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 that are difficult to access e.g. (Sulistioadi et al. 2015). Studying altimetry over lakes was first undertaken to validate altimeter measurements. Lakes have few dynamics compared to the ocean, and many of them are being monitored. Today, a great number of lakes of all sizes are monitored by altimetry (Crétaux and Birket, 2006). However, in situ data (river runoff, temperature, or precipitation) are still critically needed for studying the evolution of each lake's water mass balance. Currently, 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 km^2 (Birkett,1998).

Based on a literature review, it can be concluded that currently, the technique of altimeter measurements makes it possible to observe the change in the level of oceans and inland waters. Therefore, the main aim of this work is an attempt to determine the height of the surface of inland waters in Poland on the example of our largest lake Śniardwy and assessment its usefulness. It is planned to use PISTACH products, adapted to the specifics of coastal altimetry and surface water testing, and to perform calculations using of BRAT package.

2 DESCRIPTION OF THE STUDY AREA

The object of research in this work is the largest lake in Poland – Śniardwy. The lake is located in the north-eastern part of Poland, within the Masurian Landscape Park. Lake Śniardwy is connected through the strait with lakes Mikołajskie and Bełdany and a short channel with Lake Łuknajno. Together with the lakes Białawki, Roś, Tuchlin, and Tyrkło, the reservoir is part of the Great Masurian Lakes (see Figure 1).

The area of the lake covers an area of 1148 km^2 and the estimated dimensions of the lake are 22.1 km by 13.4 km. The lake is quite shallow, the maximum depth does not exceed 23 m, while the average depth reaches about 6 m. The circumference of the lake exceeds 80 km, and the height of the water surface is about 116.1 m above the sea (Kowalski, 1954).

An additional factor influencing the choice of an object for studying the height of the water surface is the range of the Jason-2 orbit. Although altimetry missions are optimized to monitor open oceans, the range of measurement from the satellite is several kilometers. The repeatability of the measurement cycle, which is 10 days, also plays an important role. For some rivers and wetlands, obtaining hydrological information may be difficult due to the inaccessibility of the region. Satellite radar altimetry potentially makes it possible to monitor changes in the altitude of inland waters (Birkett, 1998).

Figure 1. Jason-2 orbital path (red line) passing through a fragment of Lake Śniardwy (Zawierowska, 2020).

3 DATA USED

Near coasts and lands, the use of satellite altimetry is limited due to increased measurement errors. To recover this data near the coast, which contains useful information for coastal research, the French Spatial Agency (CNES) funded the development of a PISTACH project dedicated to processing altimeter measurements of the Jason-2 satellite in the coastal ocean zone. Therefore, the data from this project have been used in this paper.

To obtain the relevant data first, it was checked whether the Janson-2 satellite was ever over a studied object. For this purpose, .kml files for orbit from the Avisto website (https://www.aviso.altimetry.fr/en/data/tools/pass-locator.html) were used. The downloaded files contain sets of numbered Jason-2 orbital paths for the entire globe. To find the appropriate track number passing through the area of Lake Śniardwy, .kml files can be loaded in Google Earth Pro. Satellite Jason-2's orbital path from June 2008 to October 2016 is shown in red on Figure Figure 1. The fragment of the orbital path passing through the north-western part of the lake has the order number 085. This is important information in the further part of the work because the number is required to find PISTACH products.

PISTACH "hydro" products for land areas are available on the Aviso FTP server. To determine the height of the area of Lake Śniardwy, 300 PISTACH files were used in this work, covering the measurement period from July 15, 2008, to September 26, 2016, with a 10-day repetition cycle.

4 METHOD

Radar altimeters onboard the satellite transmit signals at high frequencies, over 1700 pulses per second, to Earth and receive the echo from the surface e.g. (Fu and Cazenave, 2000). This is analyzed 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 Figure 2.

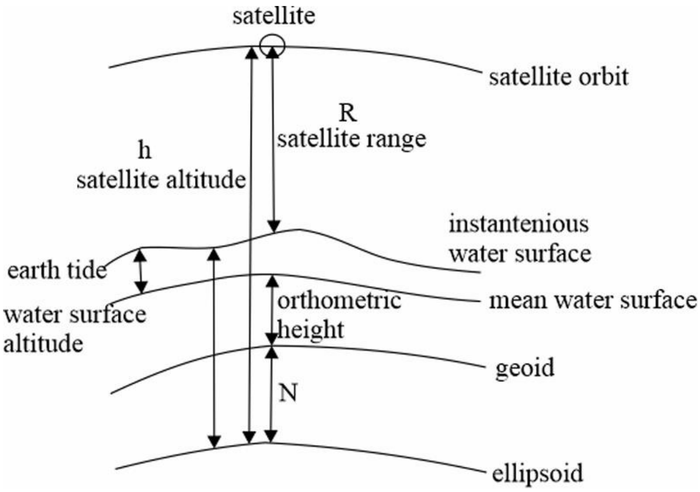

Figure 2. Principle of satellite altimetry.

The altitude of a satellite *h* is the satellite's distance to an arbitrary reference e.g., the reference ellipsoid, a rough approximation of the Earth's surface. It depends upon several 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 several ways 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 lake's water surface to be calculated concerning the ellipsoid.

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*:

$$WSA = h - R_{corr} - N_{GM} \cdot \tag{1}$$

where:

- *h* is the height of the satellite above the ellipsoid,
- R_{corr} is the measured distance considering ionospheric, tropospheric corrections, and corrections due to the earth tides,
- N_{GM} is the height difference between an ellipsoid and a geoid, calculated e.g. from the GM geopotential model.

5 CALCULATIONS

To calculate the height of Lake Śniardwy, free software BRAT (Broadview Radar Altimetry Toolbox) was used. BRAT is a set of tools designed to process radar altimeter data. The program was created based on an agreement between ESA and CNES in the years 2006-2011 under the name "Basic Radar Altimetry Toolbox". Since 2015, together with the consortium of Deimos Engenharia S.A., isardSAT UK, and TU Delft (niderl. Technische Universiteit Delft), the BRAT application is extended with new features while updating the content of the tutorial "Radar Altimetry Tutorial".

The software supports most altimeter data formats, including editing, counting statistics, visualizing, and exporting results. BRAT as a set of tools consists of several modules. One of them, the most user-friendly, is the graphical interface (GUI). More advanced modules offered by BRAT are command-line tools, an API for cooperation with programming languages such as Python or Fortran, and ready-made overlays for existing applications, for example, MATLAB and IDL (BRAT, 2018).

5.1 Choice of individual parameters

Before calculating the final height of the surface of Lake Śniardwy, an important part of the research is the verification and selection of individual parameters. One of the elements of the practical part of this work was also a comparison of propagation corrections, geophysical corrections, and selected retracker algorithms.

Therefore, first, it was checked whether the quality of PISTACH data is acceptable for the area of the selected test object. It means the selection of appropriate retracker algorithms *Ice1, Ice3,* or *Range* algorithms.

First, the extent of algorithms for the lake area was verified. The commands that determine the range of algorithms in the BRAT software look like this:

• *alt – ice_range_ku* for *Ice1,*
• *alt – range_*ice3*_ku* for *Ice3,*
• *alt – range_ku* for the standard *Range* algorithm,
where *alt* is satellite altitude.

The comparison of the *Ice1* and *Ice3* algorithms together with the standard *Range* algorithm used mainly in the oceans is shown in Figure 3.

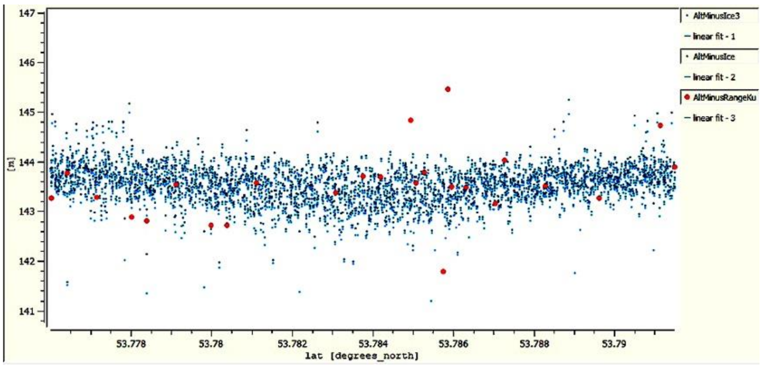

Figure 3. Comparison of *Ice1*, *Ice3,* and *Range* algorithms for Lake Śniardwy (Zawierowska,2020).

From the illustration above, it can be concluded that the *Range* trace reproduction algorithm is not adapted to land areas. Due to the insufficient number of determined values, this algorithm was not used to study the lake heights. In the case of *Ice1*, there is a large discrepancy, as the values range from 34 m to 145.2 m. Less discrepancy occurs when using the *Ice3* algorithm, values range from 134 m to 145 m.

Therefore, the most reasonable choice was to choose the *Ice3* algorithm due to the smallest discrepancies in limit values. Another argument suggesting the choice of *Ice3* is its use for larger areas of inland waters (Mercier et al. 2010). The calculated range of the *Ice3* algorithm is shown in Figure 4.

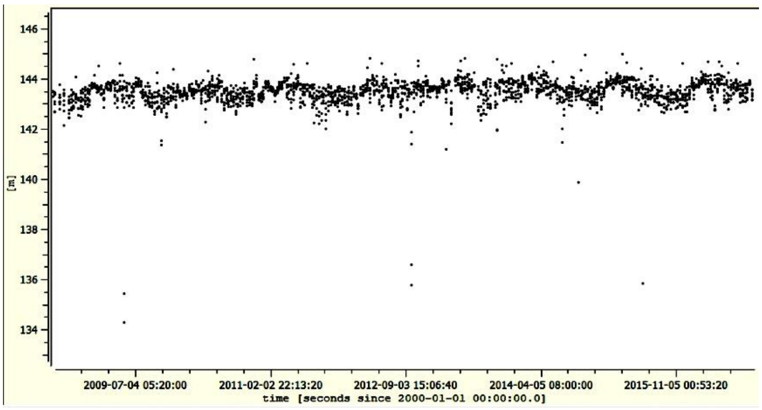

Figure 4. Computation of *alt – range_ice3_ku* as a function of time (Zawierowska, 2020).

5.2 Propagation corrections

The atmosphere and ionosphere slow down the speed of radio pulses in proportion to the total mass of the atmosphere, the mass of water vapor in the atmosphere, and the number of free electrons in the ionosphere. In addition, radio pulses do not reflect from the mean sea level, but from the level, which depends on the height of the wave and the speed of the wind. The errors caused by these processes are significant and must be removed.

The propagation velocity of a radio pulse is slowed down by the "dry" gases and the quantity of water vapor in the Earth's troposphere. In PISTACH products, propagation corrections were defined as the correction of the "*dry*" troposphere part (*model_dry_tropo_corr*), and correction of the "*wet*" troposphere part (*model_wet_tropo_corr*) and ionospheric correction (*iono_corr_gim_ku*). Tropospheric corrections are calculated based on differential pressure and radiometer, while an ionospheric correction is calculated using the GIM (Global Ionosphere Maps) model (Mercier et al. 2010). The calculated corrections are shown in Figure 5 - Figure 7.

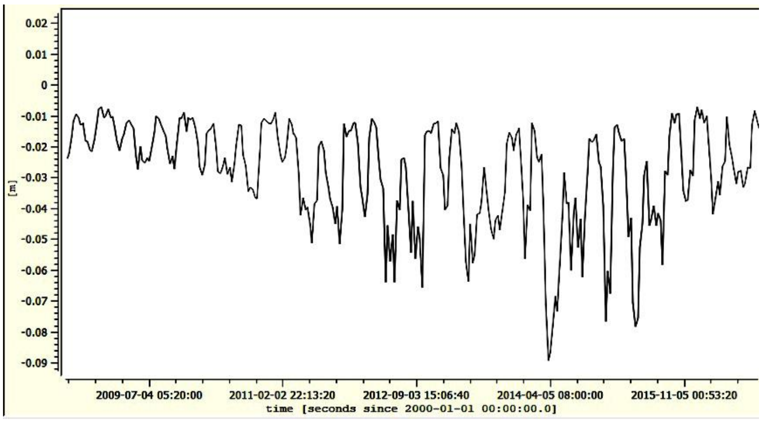

Figure 5. Corrections *iono_corr* is computed from the model GIM (Zawierowska, 2020).

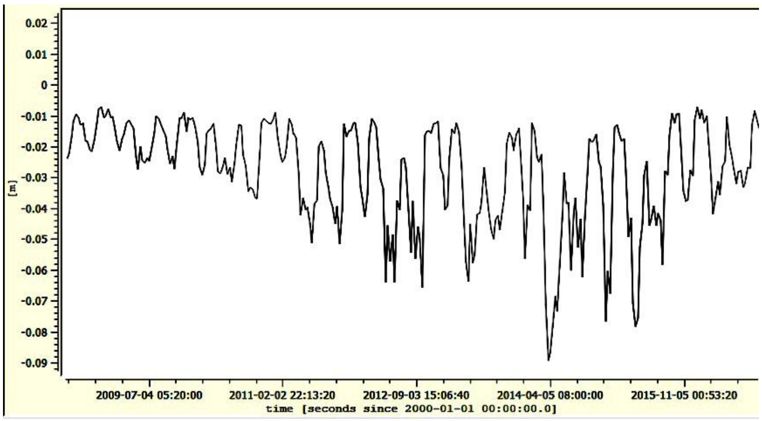

Figure 6. Correction for *wet_tropo_corr* (Zawierowska D. 2020)

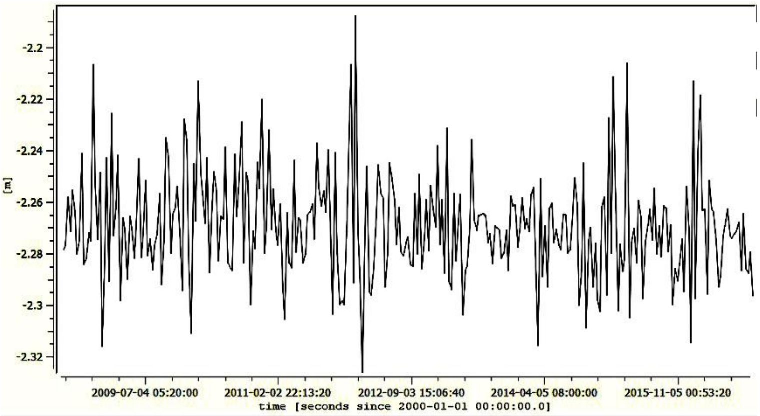

Figure 7. Correction model *dry_tropo_corr* (Zawierowska, 2020)

The above results show a significant impact of the presence of the troposphere on measurement errors. The correction *dry_tropo* is almost constant and changes from -2.33 m to -2.10 m. In the case of correction, the *wet_tropo* values range from -0.02 m to -0.25 m. The ionospheric correction has the least impact on the measurement, the values of which range from -0.01 m to -0.09 m.

5.3 Geophysical corrections

Tides are a significant contributor to the observed sea surface height (Ekman 1993). While they are of interest in themselves, they have more variation than all other time-varying ocean signals. Since they are highly predictable, they are removed from the data to study ocean circulation. The T/P orbit was specifically selected (inclination and altitude) so that diurnal and semidiurnal tides would not be aliased to too low frequencies.

The next step of the practical part of the work was to examine geophysical corrections which should be added to the height measurement. Computed geophysical corrections are shown in Figure 8 and Figure 9.

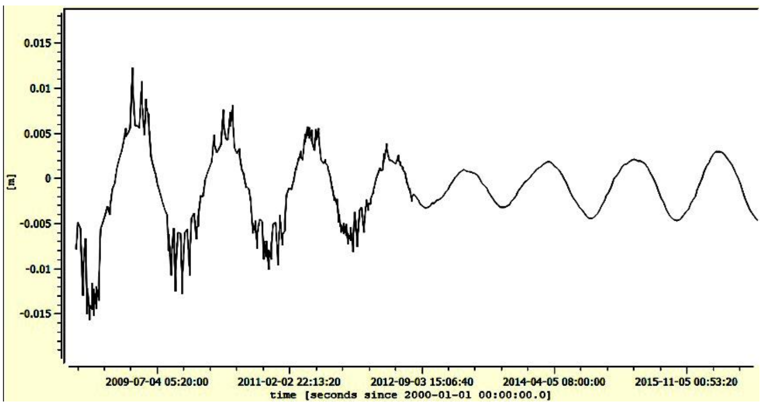

Figure 8. Computed *pole_tide* corrections (Zawierowska, 2020).

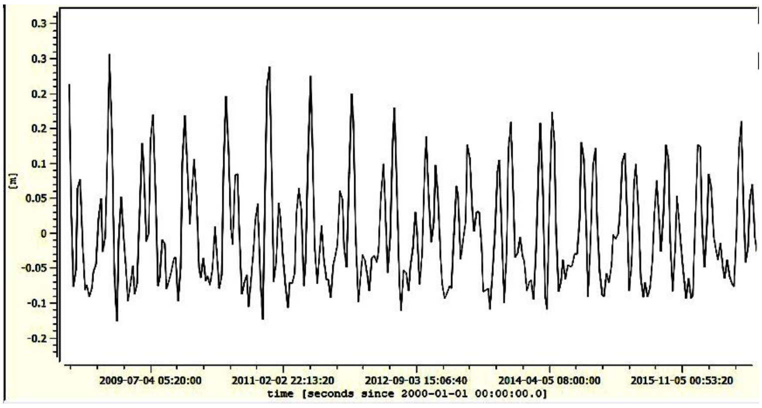

Figure 9. Computed *solid_earth_tide* corrections (Zawierowska, 2020)

The results show higher values for corrections due to the presence of terrestrial tides, which range from -0.13 m to 0.31 m. The correction due to the polar tides does not exceed 0.02 m.

5.4 The first approach to water surface altitude calculation

The corrections obtained in this way can be used for the first approach of determining the height of the lake surface to the geoid computed from the EGM2008 geopotential model. In addition, for further verification of the data, the height of the WSA was compared with a topographic model calculated based on the SRTM_CGIAR (Shuttle Radar Topographic Mission) terrain model. In the BRAT application, the function determining the level of Lake Śniardwy relative to the geoid looks like this:

WSA = alt - range_ice3_ku - model_dry_tropo_corr - model_wet_tropo_corr - iono_corr_gim_ku - pole_tide - solid_earth_tide – geoid_EGM2008. (2)

The height of the area of Lake Śniardwy calculated in the above manner is shown in Figure Figure 10 - Figure 13.

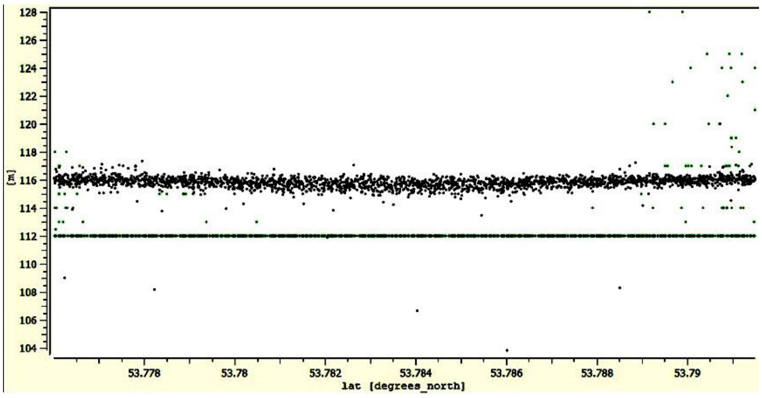

Figure 10. The height of the surface of Lake Śniardwy was determined for the years 2008-2016 (black), and together with the topography model (green) (Zawierowska, 2020)

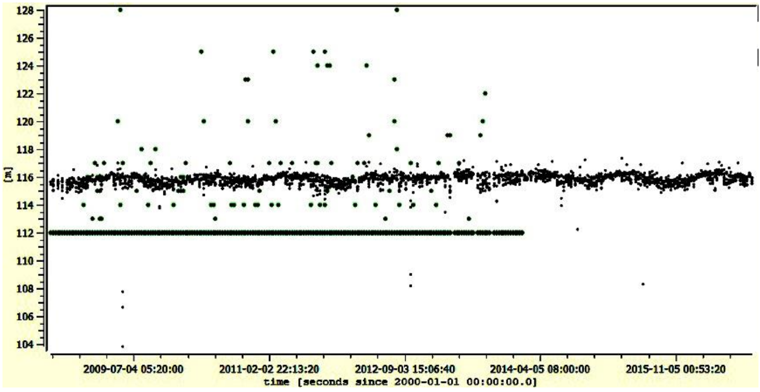

Figure 11. The height of the surface of Lake Śniardwy was determined for the years 2008-2016 (black) together with the topography model (green) as a function of time (Zawierowska,2020)

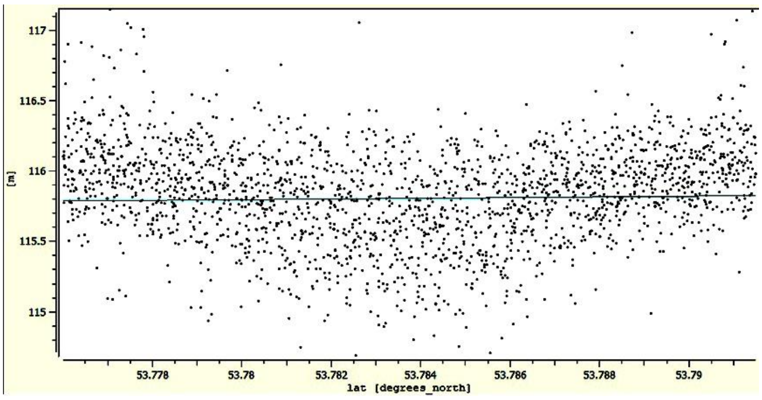

Figure 12. The mean height of the area of Lake Śniardwy (WSA) was determined from observations in the years 2008-2016 (Zawierowska, 2020)

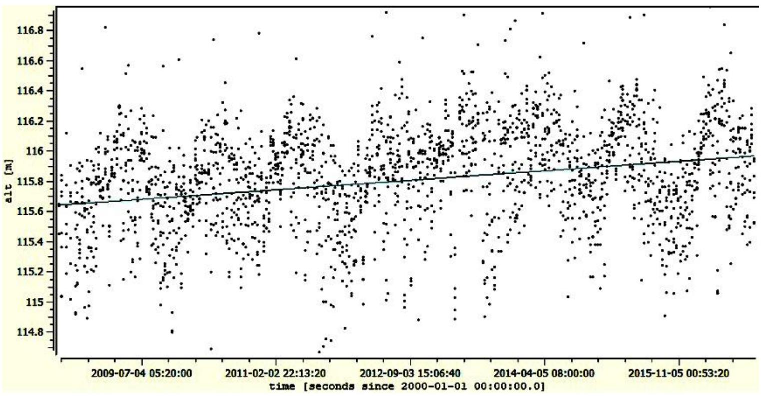

Figure 13. The mean height of the area of Lake Śniardwy (WSA) was determined from observations in the years 2008-2016 as a function of time (Zawierowska, 2020)

The extreme values of the lake level in the first attempt to calculate the WSA change from 104 m to 117 m. The fitted straight line in Figure 13 shows an increase in the water surface of about 30 cm between 2008 and 2016.

PISTACH products can provide a more accurate height analysis by using additional data selection criteria. In the second attempt of calculating the WSA, the shape of the waveforms of the reflected waves and the *sigma0* scattering coefficient was considered and individual classes of waveforms of signals (waveforms) for the area of Lake Śniardwy were examined. The results are shown in Figure 14.

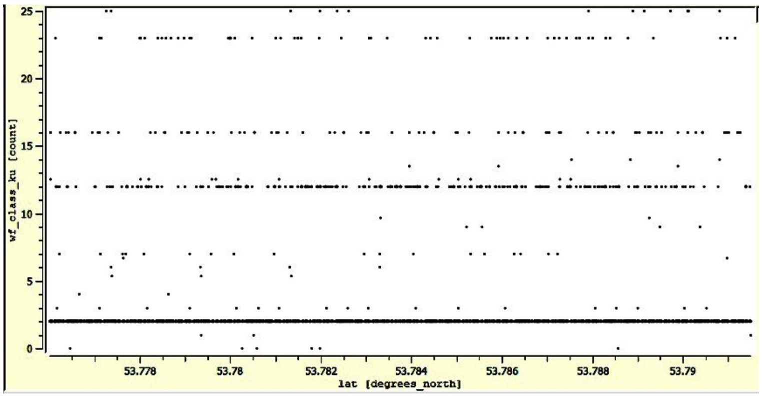

Figure 14. Distribution of waveform classes for the area of Lake Śniardwy (Zawierowska,2020).

The study showed the predominance of the presence of waveforms belonging to class 2. The shape of class 2 waves is characteristic of undisturbed surfaces. This analysis confirmed the acceptance of the choice of the *Ice3* algorithm, which is dedicated to peak waveforms (Rosmorduc et al., 2011).

5.5 The backscatter coefficients

The amplitude of the useful radar altimeter echo signal to the emission amplitude gives the backscatter coefficient, *sigma0*. Subsequently, the determination of the WSA also was examined due to the need for the backscatter coefficient *sigma0*. The results of the analysis are presented in Figure 15.

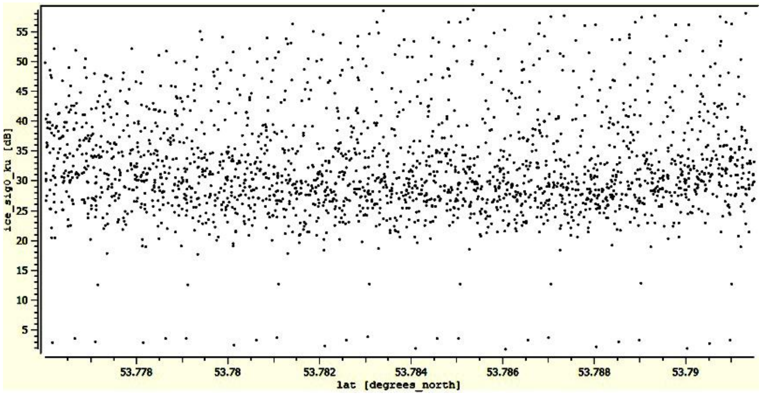

Figure 15. Study of the backscatter coefficient sigma0 between latitudes 53.7°N and 53.8°N (Zawierowska, 2020)

The backscattering coefficient can also bring useful information to the data selection. We observe almost the same *sigma0* values over the water body: it is possible to introduce this specificity in the data selection. However, this criterion is not very discriminating and probably has to be adapted to each water body to its environment.

5.6 Final computation

After obtaining parameters in the form of the predominance of waveforms class and the range of occurrence of the *sigma0* scatter coefficient, a more accurate determination of the height of the WSA lake surface was done. The range of the lake terrain topography model can also be used for analysis. Figure 11 shows, on the other hand, that the model of topography was not included in the calculation process after 2014. No information was found regarding the reason for the lack of topography for the selected example, therefore, when determining the height of the water surface, the model of the topography of the terrain was not considered. It should be mentioned that PISTACH products are experimental.

To achieve the most optimal results (with the smallest possible WSA discrepancies), the tests were performed by trial-and-error approach. In addition, the coordinates of the area of the Lake Śniardwy surface have been more precisely determined. The expression used in the BRAT software responsible for the classification of data due to the *sigma0* coefficient and the waveform class is as follows:

- (((is_bounded(53.777, lat, 53.789)) && (wf_class_ku == 2)) && (is_bounded(20, ice_sig0_ku, 60))) && (retracking_flag_ice3_ku == 0).

Finally, the calculated height of the surface of Lake Śniardwy is shown in–Figure 16.

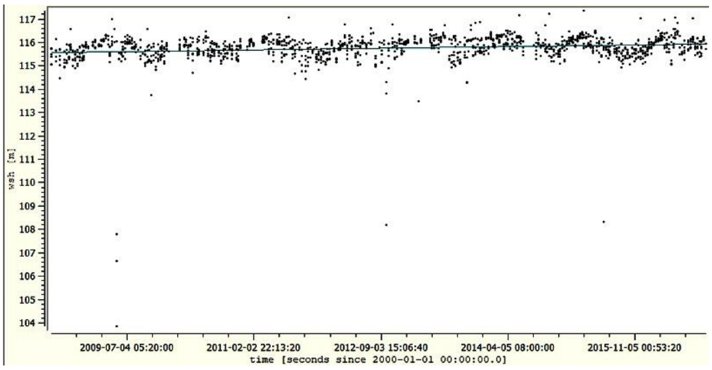

Figure 16. Determination of the WSA of the area of Lake Śniardwy in the years 2008-2016 considering *sigma0* and waveforms of class 2 as a function of time (Zawierowska, 2020).

The figure clearly shows seasonal changes in the height of the lake surface by 10 cm. per year. Consideration of additional parameters in the form of *sigma0* and class waveforms did not significantly change the extreme values of the height of the lake surface.

The limit values of the lake level are in the range from 117 m to 104 m. Outstanding values are single, so they do not have a big impact on the result. The computed regression line (Figure 16) indicates the increase in the average water level from 115.57 m to 115.9 m between 2008 and 2016. The estimated annual increase in the lake level is about +3.4 cm/year.

6 SUMMARY AND 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 with the position of the satellite ground track with an accuracy of the order of a few centimeters to tens of centimeters.

The lake Śniardwy level changes were calculated with 300 altimetric observations repeated every 10 days in the period from 2008 to 2016. The mean level of Lake Śniardwy was calculated relative to the global geoid model EGM2008. The results of the calculations have shown seasonal changes of 10 cm in the level of the tested object. The average heights calculated in the period from 2008 to 2016 are in the range of 115.57 m to 115.9 m. The regression line indicates an increase in the surface of the lake of 3.4 cm/year.

So, altimetry's ability to monitor lakes level has been demonstrated. However, an increased level can mean a very different quantity of water depending on the extent of the stretch of water. Altimetry can not measure now such an extent, since its measurements are "limited" to its beam, directly underneath the satellite. However, other sensors -- imagery sensors -- enable to estimate of the water surface area. Mixing altimetry and water surface area estimates give hydrologists the water volume needed to study lakes and reservoirs variations.

It is estimated that the surface of the lake has been determined with an accuracy of a few centimeters. Unfortunately, there is no independent data from the lake tide gauge, which does not allow a more accurate assessment of the altimetric method.

Since PISTACH products are in the experimental phase, the results can be improved with a different selection of data classification. It is also possible to combine PISTACH products with other altimeter missions to reduce measurement errors.

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