This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Adaptive Retracking of Jason-1, 2 Satellite Altimetry Data for the Volga River Reservoirs

Yu. Troitskaya, G. Rybushkina, I. Soustova, and S. Lebedev

***Abstract*—The problem of minimization of errors in water level retrieval for the Volga reservoirs from altimetry measurements can be resolved by retracking Jason-1, 2 satellite altimetry data. For justification of the optimal retracking algorithm average impulse response of a statistically inhomogeneous surface was calculated theoretically for a model of the terrain in the neighbourhood of the reservoirs. The modeled waveforms are in good agreement with Jason-1, 2 waveforms for the same area. Comparison of the data with *in situ* measurements shows that retracking significantly improves measurement of the water level. General principles of the retracking algorithms for complex areas (land, coastal zone, inland waters, etc.) based on calculations of the waveforms taking into account statistical inhomogeneity of the reflecting surface adapted to a certain geographic region, are discussed.**

***Index Terms*—Inland waters, retracking, satellite altimetry.**

I. Introduction

ONE of the recent applications of satellite altimetry originally designed for measurements of the sea level [1] is associated with remote investigation of the water level of inland waters: lakes, rivers, reservoirs. A possibility of using altimetry data for determining hydrological characteristics of inland basins is actively studied aimed at determining the hydrological regime of large rivers in South America, Africa and Siberia [2]–[5], as well as for assessing water level in the lower reaches of the Volga river [6] and other inland basins [7]. Numerous applications of satellite altimetry to monitoring of inland waters are reviewed in [8]. Standard altimetry data processing developed for open ocean conditions [1] cannot be used in the case of inland waters, where reflection from the land dramatically alters the altimeter waveforms and leads to significant errors in estimation of the water level. Appreciable scatter of satellite data may evidently be explained by the shortcomings of direct extension of the algorithms of water level calculation developed for large water basins (seas and oceans) to medium area basins when the radar return is significantly contaminated by reflection from the land. This effect is very strong in the Volga reservoirs with the width of 10–15 km (except for the Rybinsk reservoir). Under these conditions very few telemetric impulses fit the validity criteria which cause a severe loss of data. The problem of minimization of errors in the water level retrieval for inland waters from altimetry measurements can be resolved by retracking satellite altimetry data. Recently, special retracking algorithms have been actively developed for re-processing altimetry data in the coastal zone when reflection from land strongly affects echo shapes: threshold retracking, β-retracking [9], [10], three new retrackers improved the accuracy altimetry observations were proposed in [11]. The latest development in this field is PISTACH product [12], in which retracking bases on the classification of typical forms of telemetric waveforms in the coastal zones and inland water bodies (see also references in [13], [14]). A new method of regional adaptive retracking based on constructing a theoretical model describing the formation of telemetric waveforms by reflection from the piecewise constant model surface corresponding to the geography of the region was proposed in [13], [14], where the algorithm for assessing water level in inland water basins and in the coastal zone of the ocean with an error of about 10–15 cm was constructed. This algorithm was tested for the 142 pass of satellite Jason-1 at the Gorky Reservoir with complex topography, where the standard Ocean-1 algorithm is not applicable. In [14] a model of an average waveform reflected from a statistically inhomogeneous piecewise constant surface (topographic model) was used for theoretical calculation of the reflected power on the basis of the works [3], [15]. The model allowed substantiating criteria of data selection for the Gorky Reservoir. The water level was calculated by means of regional adaptive retracking of the SGDR database for the Gorky Reservoir, and it was shown that application of this algorithm greatly increases the number of included data and accuracy of determining water level. General principles of the proposed algorithm for complicated areas (coastal zones, inland waters, and so on) based on calculations of the signal with allowance for inhomogeneity of a reflecting surface may be used in different geographical regions.

In our work this algorithm is used for reprocessing data of pass 33 of Jason-1 satellite after maneuver in the Gorky reservoir and for several passes of Jason-2 satellite in the Rybinsk, Gorky, Kuibyshev, Saratov, and Volgograd reservoirs, the general parameters of which are presented in Table I. The coastal topography of the reservoirs is significantly different. Shores of Rybinsk Reservoir are primarily low grasslands, forests, wetlands. The right shore of Gorky, Kuibyshev, Saratov, and Volgograd reservoirs are high and sometimes steep, the left shore are low.

In the presence of additional peaks generated by reflection from land, a smooth coastal water surface and highly reflective

Manuscript received September 28, 2012; revised January 23, 2013; accepted May 09, 2013. This work was supported by RFBR (project codes 13-05-01125, 13-05-97068, 13-05-41476).

Yu. Troitskaya is with the Institute of Applied Physics RAS, Nizhny Novgorod, Russia, and is also with the Obukhov Institute of Atmospheric Physics RAS, Moscow, Russia.

G. Rybushkina and I. Soustova are with the Institute of Applied Physics RAS, Nizhny Novgorod, Russia.

S. Lebedev is with the Geophysical Center of RAS, Moscow, Russia, and is also with the P. P. Shirshov Institute of Oceanology RAS, Moscow, Russia.

Digital Object Identifier 10.1109/JSTARS.2013.2267092

1939-1404 © 2013 IEEE

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE I
GENERAL PARAMETERS OF THE MAIN VOLGA RESERVOIRS

Reservoir	Area, km^2	Length, km	Maximal width, km
Rybunsk	4550	112	56
Gorky	1590	427	14
Cheboksary	2190	341	16
Kuibyshev	6450	580	30
Saratov	1830	357	25
Volgograd	3117	540	17

coastal objects (buildings, slicks, etc.), the reflected waveforms are poorly approximated by Brown's formula [15], which leads to errors in determining the position of the leading edge and, hence, to wrong determination of satellite altitude and water level. In this case, other quantities, such as wind speed and significant wave height (SWH) are also determined incorrectly. The adaptive algorithm described in [13], [14] permits determining the area of satellite pass over the water basin where reflection from the water determines formation of the leading edge of the telemetric pulse and the influence of land is insignificant. The algorithm includes four consecutive steps:

— constructing a local piecewise model of a reflecting surface in the neighbourhood of the reservoir;
— solving a direct problem by calculating the reflected waveforms within the framework of the model;
— imposing restrictions and validity criteria for the algorithm based on waveform modelling;
— solving the inverse problem by retrieving a tracking point by the improved threshold algorithm.

The adaptive algorithm was tested for reprocessing of the SGDR data of Jason-1 in the Gorky and Rybinsk Reservoirs of the Volga River and showed good accuracy of the water level determination. Study of the possibility of applying this algorithm to the data of Jason-1 satellite after maneuver for Gorky reservoir and of Jason-2 satellite for five Volga reservoirs is of considerable interest, also because the standard on-board tracking logic of Jason-2 differs from that used previously in Jason-1 so as to make it more useful for inland water basins.

II. ADAPTIVE RETRACKING FOR PASS 33 OF JASON-1 SATELLITE AFTER MANEUVER IN THE GORKY RESERVOIR AREA

In this section we use the method of adaptive retracking for studying the variability of the hydrological regime of the Gorky Reservoir for the period from 2010 to 2012 on the basis of track 33 of Jason-1 satellite after maneuver. For modeling the formation of telemetric waveforms in accordance with the procedure of regional adaptive retracking [13] first we construct a piecewise constant model surface (Fig. 1) corresponding to the geography of the region. The model assumed three types of reflected surface: water (the area inside white lines in Fig. 1), land (the area outside white lines in Fig. 1), and coastal slicks which are long strips of smoothed water extended along coastlines (white lines in Fig. 1). Such smoothed regions 20–30 m wide are regularly observed near the coastline (which are usually caused by high concentrations of surface active substances) and are known to give rise to peaks in telemetric pulses [16]. The coastal slicks that were revealed in the Gorky Reservoir water area by field studies can significantly influence the reflected waveforms [14].

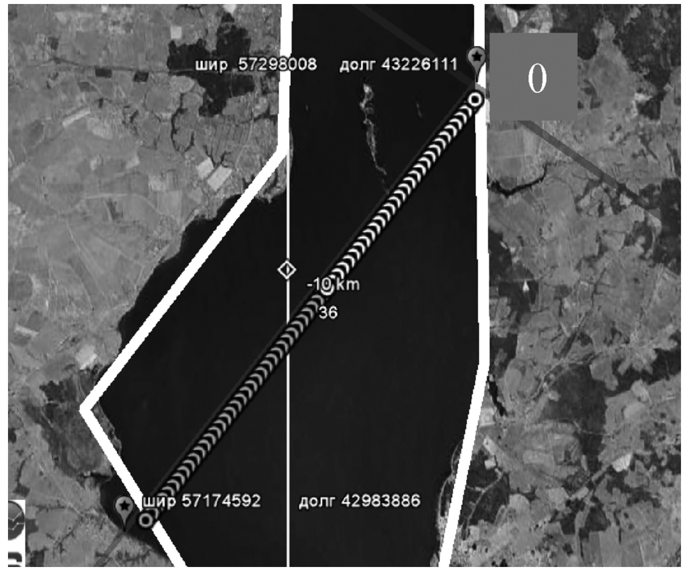

Fig. 1. A simplified model of the water area of the Gorky Reservoir and nadir points of Jason-1 20 Hz pulses.

In the case of inland water bodies, when the altimeter footprint is a combination of several different (in heights and reflecting properties) parts, the total reflected power is a sum of contributions from all piecewise-constant areas [14]:

$$P(\tau) = P_{water}(\tau) + P_{land}(\tau) + P_{coast}(\tau). \tag{1}$$

If the altimeter antenna axis is directed strictly at nadir, the contribution of each part of water and land to the reflection is described by the analogue of Brown's formula:

$$P_k(\tau) = \frac{P_0 \sigma_k^{(0)}}{4\pi h^4} e^{-((4/\gamma)+\alpha_k)((c\tau - 2H_k)/h)} \times \left(1 + \operatorname{erf}\left(\frac{(c\tau - 2H_k)}{\sqrt{2}\sqrt{(2s_k)^2 + c^2\tau_i^2}}\right)\right) \times \Delta\varphi_k \tag{2}$$

where h is the mean distance from the satellite to the underlying surface. The parameters with index k: H_k, α_k, s_k correspond to the level, scattering properties and roughness for a given (kth) part of the underlying surface (H_k is the deviation of the surface level from the mean value, it is positive when the distance from the surface to the satellite is greater than the mean value and the surface level is lower than the mean value) [14]. In(2) we take into account the fact that at time $\tau = t - 2h/c$ the main contribution to the reflection from the kth illuminated area is given by an arc $\Delta\varphi_k$ centered at the nadir point with coordinates x_N, y_N and determined by the condition of equality of the distance from the antenna to the kth piece of surface (see [14]). The radius of the arc is equal to $\sqrt{h(c\tau - 2H_k)}$ and depends on the deviation of the surface level of this area from the average value. For coastal slicks the reflected power is

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

$$P_{sl}(\tau) = \frac{P_0\sigma_{sl}^{(0)} d_{sl}}{\sqrt{2\pi} h^4 c\tau_i} e^{-((4/\gamma)+\alpha_{sl})\ (c\tau - 2H_{water})/h} \bullet \int_C e^{\left\{-\left(c\tau - 2H_{water} - \frac{(x(l)-x_N)^2+(y(l)-y_N)^2}{h}\right)^2 \Big/ 2c^2\tau^2{}_i\right\}} dl, \qquad (3)$$

where $y = y(l)$, $x = x(l)$ is the equation of the coastal line C, and d_{sl} is the width of the slick [13].

Using (1)–(3) one can calculate the reflected waveforms and their change when the satellite moves along the track. Parameters in formulas (2), (3) are determined by the properties of the reflecting surface. For the water surface: elevation H is water level, s is a significant wave height and σ is determined by the wind speed. For the land surface, H is determined by topography (it was supposed to be constant and equal to 20 m – an average height of the land area according to the data on the topography of the land surface in the neighbourhood of the Gorky Reservoir from Global Land One-km Base Elevation Project [GLOBE] [17]), s is surface roughness, and σ is determined by the reflecting properties of the land. The model was constructed assuming that parameters of land are fixed, and the characteristics of surface water (water level, wave height and roughness) are variable and must be determined using the retracking algorithm.

Based on formulas (1)–(3) the reflected waveforms for track 33 of Jason-1 satellite after maneuver were calculated.

For the calculation of waveforms, we choose the model surface parameters from physical considerations: for land $\sigma^{(0)} = 20$, $\alpha = 10$, $\sigma_s^{land} = 3\text{m}$, for water $\sigma^{(0)} = 50$, $\alpha = 10$, $\sigma_s^{water} = 0.3\text{m}$, for coast slicks $\sigma^{(0)} d_{sl} = 0.5$, $\alpha = 1000$. The parameters specific to the radar altimeter were set equal to $\gamma = 0.0005$, $\tau_i = 0.425\,T$ [13] ($T = 3.125 \cdot 10^{-9}$ s – the point target response 3 dB width).

Results of the calculations of model waveforms are presented in Figs. 2, 3. Fig. 2 shows an example of the partially modeled waveforms reflected from the areas of the water, land, and slick, and the total power (scattered by all three areas) for the piecewise model of the Gorky Reservoir, presented in Fig. 1. The isolines of the calculated model waveforms reflected from the surface close to the Gorky Reservoir are shown in Fig. 3 in the following coordinates: time – distance along the track. Time is measured in units of telemetry gate (3.25 ns), and distance in kilometers. Like in [15] one can note complex images, which reflects complexity of the calculated model waveforms. Similarly to track 142 of Jason-1 in the Gorky reservoir area [13] there exist parabolic singularities corresponding to the reflection from the coast and scattered on the slicks near the coast and the waveforms have an extremely narrow leading edge (corresponding to less than 1 telemetry gate) due to the small value of the average SWH (about 30 cm).

Analysis of the waveforms and their comparison with the waveforms from the SGDR database of Jason-1 enabled us to formulate the first criterion for selecting telemetry impulses: to determine the water level of the Gorky Reservoir the waveforms should be taken from the range 42.12° – 43.18°E along the track

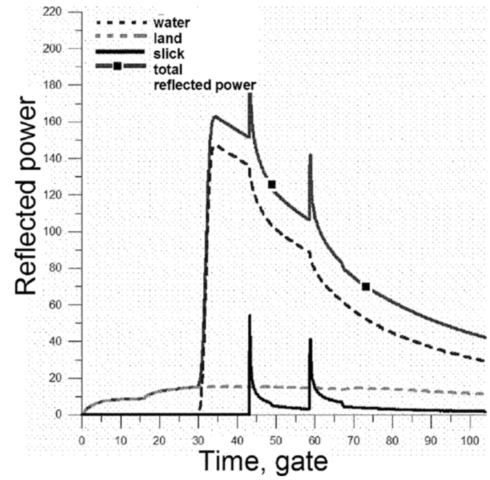

Fig. 2. An example of modeled waveform reflected from the areas of water, land, and slick, and the total reflected power of all three areas for the piecewise model of the water area in the Gorky Reservoir shown in Fig. 1.

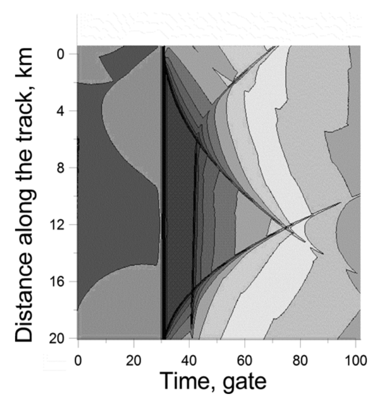

Fig. 3. Isolines of model telemetric waveforms in the Gorky Reservoir area along the trajectory of Jason-1 satellite.

33. In this region the model waveforms are in good agreement with the measured ones, and the leading edge of the waveforms is determined by the reflection from the water surface. In addition to the first criterion, in accordance with the long-term observations at gauging station Yuryevets, the deviation of the water level from an average value by more than 2 m should be considered erroneous. For the valid waveforms we used regional retracking algorithms appropriate for the Gorky Reservoir for track 142 [14], including 2 steps. At the first step we estimate a tracking point determined by a definite threshold. The second step is refinement of the estimates: the alleged weak leading edge – 4 points in the neighborhood of the threshold (see [14, fig.12]) are fitted by the error function (taking into account the analytical results):

$$A\left(1 + \operatorname{erf}\left(\frac{(\tau - \tau_R)}{S}\right)\right). \qquad (4)$$

The parameters in (4) are retrieved by minimization of root-mean-square deviations. The minimization procedure was slightly modified in comparison with [14]. To improve the algorithm convergence the initial value of the parameter S, which characterizes SWH on the water surface, was estimated from the mean slope of the leading edge of the waveform. The

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

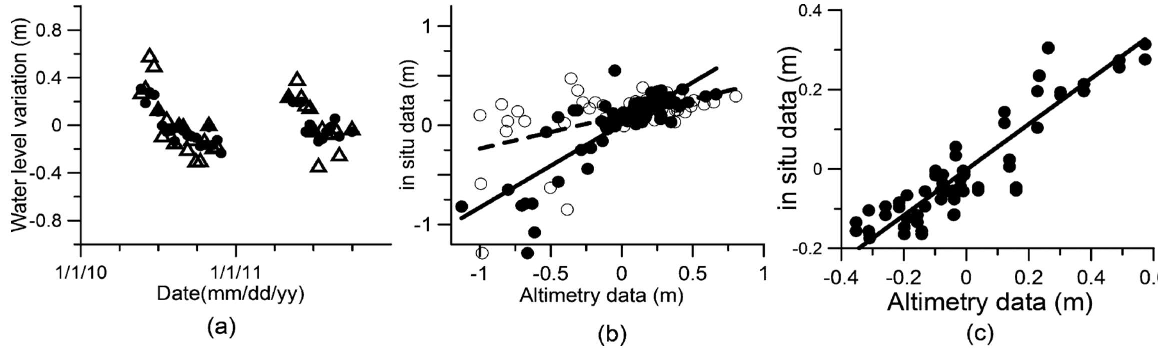

Fig. 4. (a) Retrieved from retracking 33 track Jason-1 SGDR data water level variations in the Gorky Reservoir (triangles) and in situ measurements (circles), (b) water level via in situ measurements for 142 track of Jason-1 before the maneuver, the Yurevets water level gauge station, Gorky reservoir, (c) for 33 track of Jason-1 after the maneuver, the Sokolskoe water level gauge station, Gorky reservoir.

signal amplitude A is found by averaging the values of the power over several points, following the leading edge. Then the parameter τ_R characterizing the arrival time of the reflected signal is determined by the one-parameter optimization. The modified optimization algorithm provides a more accurate value for the tracking point τ_R.

III. Water Level and SWH Variations in the Gorky Reservoir on the Base of SGDR Data of Jason-1 Pass 33

The results of calculating the water level (SSH) variations in the Gorky reservoir and their comparison with measurements gauging station Yuryevets are presented in Fig. 4(a). The re-tracking algorithm was tested by comparison with in situ measurements. In Fig. 4(b),(c) the results of retrieving the water level (SSH) variations in the Gorky reservoir via measurements at gauging stations are presented. Comparing with the data from GDR Jason-1 ploted in the same figures showed an increase in the number of valid points, as well as a significant improvement in the correlation from 0.5 to 0.85 for 142 track of Jason-1(Fig. 4(b)), and to 0.92 for 33 track of Jason-1 (Fig. 4(c)).

The parameter S in (4) is related to the magnitude of surface roughness and pulse duration: $S = \sqrt{2} \times \sqrt{(2\sigma_s/c)^2 + \sigma_p^2}$. For a normal distribution of wave heights with variance σ_s, significant wave height SWH $= 4\sigma_s$. Taking into consideration that for Jason-1, 2 satellites $\sigma_p = 0.513$, we find $SWH = 2 \times 93.75 \times \sqrt{S^2/2 - 0.513^2}$.

Calculation of the parameter SWH for the Gorky Reservoir from May 2010 to March 2012 showed that the majority of SWH values are within the 40–110 cm interval, which is much higher than a typical wave height in sufficiently small inland basins. Anomalously high values of SWH suggest that the calibration of the waveform leading edge width, which in ocean altimetry was held on the marine buoys, located in the open ocean, is not applicable to inland waters characterized by other parameters of the surface waves. Therefore, one needs to calibrate the obtained SWH values.

To this end, in August-October 2011, four scientific expeditions to the Gorky reservoir were organized (22. 08, 01. 09, 11. 09 and 01. 10 during Jason-1 satellite flights). During the expeditions the values of wave height, wind speed and air temperature were measured by the equipment placed on the Froude pole.

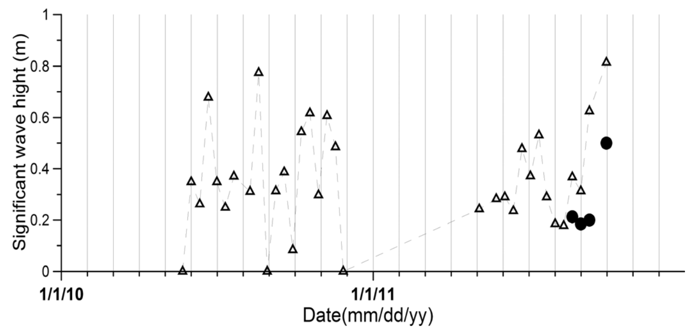

Fig. 5. Significant wave height (SWH) variations in the Gorky Reservoir: results of retracking SGDR base for pass 33 of Jason-1 satellite. Triangles – calibrated value retrieved from altimetry with the calibration by field data, circles – the field data.

The calibrated values of SWH data obtained during the expeditions are shown in Fig. 5.

IV. Jason-2 Water Level Monitoring in the Volga Reservoirs on the Base of Adaptive Retracking

According to NASA/CNES data (see Fig. 6) the water areas of the 5 main Volga River reservoirs are intersected by ground tracks of Jason-2 altimetry satellite (except for the Cheboksary reservoir). Only in the case of the Rybinsk reservoir the water area is sufficiently large and the reflection conditions are similar to the oceanic ones. In other reservoirs the ground tracks pass near the shore lines, which may lead to pronounced influence of land reflection on the waveform of the received telemetric pulse and appropriate errors in GDR data of water level. The standard on-board tracking logic of Jason-2 differs from that used previously in Jason-1 so as to make it more useful for inland water basins. It is therefore interesting to calculate the water level on the base of the standard algorithm and the algorithm of regional retracking to compare their efficiencies.

At the first stage, Geophysical Data Records (GDR) of Jason-2 satellite were processed. All 20 Hz Jason-2 altimetry data available along passes 066, 083, 142, 168, 185, 218 were used and all corrections available in the original altimetry data bases were calculated. The results for water level variations on the base of standard GDR data processing are shown in Fig. 7 by squares. One can see significant scatter of results although they were clipped by the axis. At the second stage,

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

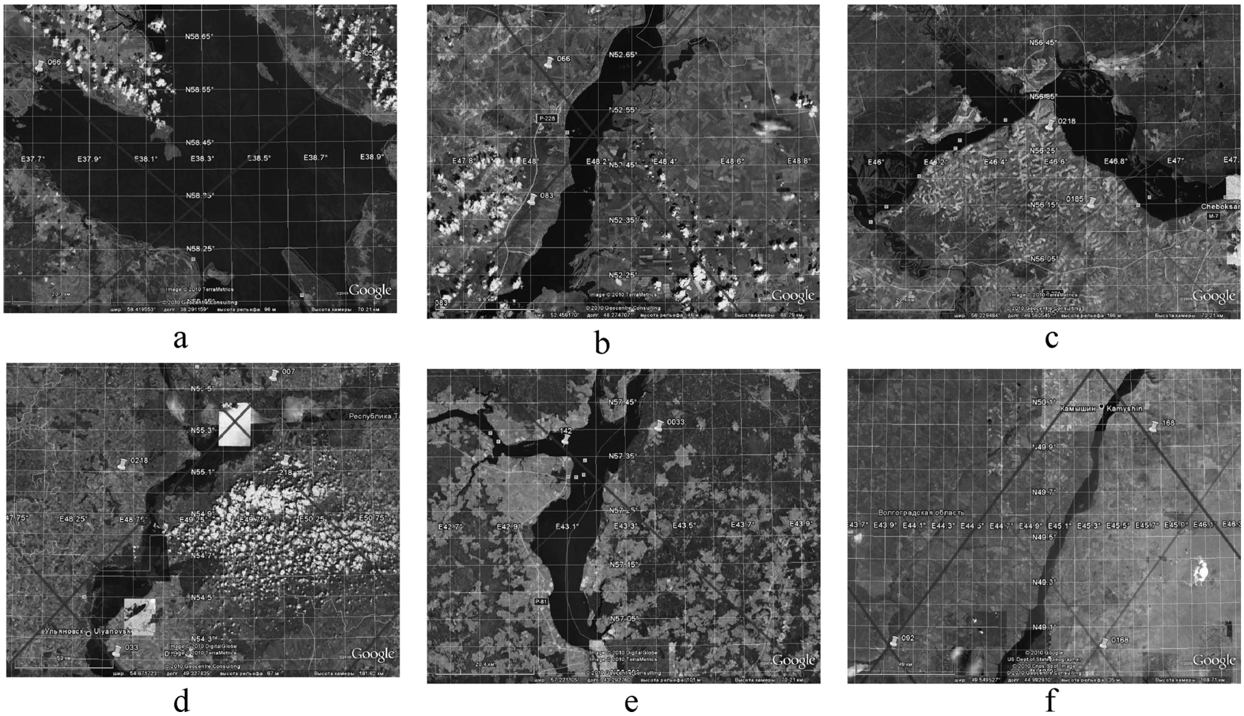

Fig. 6. Google maps of the main Volga River reservoirs with appropriate ground tracks of altimetry satellites Jason-1 and Jason-2: (a) Rybinsk Reservoir – 059 and 066 passes; (b) Gorky Reservoir – 142 and 0033 passes; (c) Cheboksary Reservoir – 0128 and 0185 passes; (d) Kuibyshev Reservoir – 007, 142, 218 and 0218 passes; (e) Saratov Reservoir – 083 and 066 passes; (f) Volgograd Reservoir – 168 and 0168 passes (a,b,c,e – longitudinal scale ∼80 km, d,f ∼200 km).

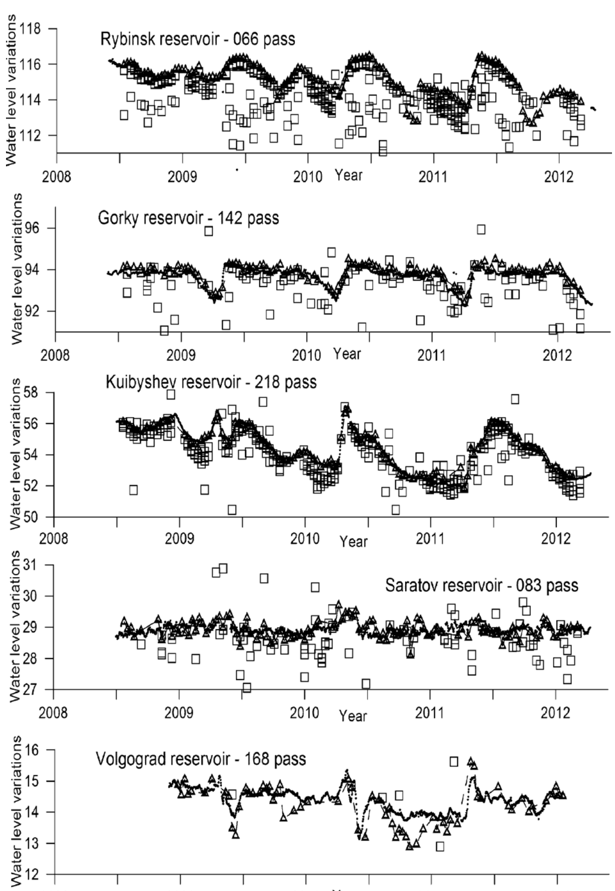

Fig. 7. Water level variations in the Volga River Reservoirs: GDR data for 1 satellite Jason-2 (squares), results of retracking SGDR base from Jason-2 satellite (triangles), in situ data (circles).

TABLE II
STATISTICAL RESULTS OF AVERAGED BY DATE WATER LEVEL VARIATIONS FROM ALTIMETRY COMPARING WITH IN SITU DATA

Reservoir	Coefficient of determination (retracking)	Standard deviation (m)	
		Retracking	GDR data
Rybunsk	0.98	0.09	0.24
Gorky	0.86	0.15	0.56
Kuibyshev	0.97	0.16	0.46
Saratov	0.77	0.26	0.58
Volgograd	0.44	0.22	1.6

we applied the adaptive retracking algorithm, first analyzing validity of waveforms on the base of topological models of the investigated regions [13], [14]. For the valid waveforms we use the retracking algorithm comprising two steps: threshold and improved threshold method for definition of track point (the middle of the leading edge). The percent of valid waveforms depends essentially on the reservoir width and topography and is about 50% for the Gorky reservoir.

The results of the improved threshold method for calculation of water level variations in the Volga reservoirs are shown in Fig. 7 by triangles. The data were averaged over the satellite pass. One can see the decrease in the scatter of reprocessed data in comparison with GDR data for all reservoirs and a substantial improvement of the correlation of the data after retracking. Moreover, the improved retracking for the Volgograd reservoir allows determining the water level, while valid GDR data are very rare. Statistical results for averaged by date water level variations from altimetry comparing with in situ data are presented in Table II.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

V. Conclusion

The local adaptive retracking algorithm enables retrieving water level even in the case of sufficiently small water basins with a very complex reflecting surface. It works well for both Jason-1 and Jason-2 SGDR data. Application of the algorithm increases significantly the number of valid data and improves dramatically accuracy of the water level retrieval from the altimetry data. The problems of inland water data processing are very similar to those arising in the coastal zones of the ocean and other complex areas from contamination of the received signal by reflection from the land. Therefore the adaptive retracking algorithm based on calculations of the waveforms taking into account inhomogeneity of the reflecting surface adjusted to a certain geographic region allows constructing a step-by-step strategy for improving estimations of water level and other hydrological parameters in such areas.

References

[1] AVISO/Altimetry. User Handbook. Merged TOPEX/ POSEIDON Products,3.0 ed. AVISO, Toulouse, France, 1996.

[2] C. M. Birkett *et al.*, "Surface water dynamics in the Amazon Basin: Application of satellite radar altimetry," *J. Geophys. Res.*, vol. 107, p. 8059, 2002.

[3] G. Brown, "The average impulse response of a rough surface and its applications," *IEEE Trans. Antennas Propagat.*, vol. 25, pp. 67–74, 1977.

[4] I. O. Campos *et al.*, "Temporal variations of river basin waters from Topex/Poseidon satellite altimetry. Application to the Amazon basin," *Earth and Planetary Sciences*, vol. 333, pp. 633–643, 2001.

[5] A. V. Kouraev *et al.*, "Ob' river discharge from TOPEX/Poseidon satellite altimetry (1992–2002)," *Remote Sens. Environ.*, vol. 93, pp. 238–245, 2004.

[6] S. A. Lebedev and A. G. Kostianoy, *Satellite Altimetry of the Caspian Sea* (in Russian). Moscow, Russia: MORE, 2005.

[7] P. A. M. Berry *et al.*, "Global inland water monitoring from multi-mission altimetry," *Geophys. Res. Lett.*, vol. 32, p. L16401, 2005.

[8] S. Calmant and F. Seyler, "Continental surface waters from satellite altimetry," *Geosciences C.R.*, vol. 338, pp. 1113–1122, 2006.

[9] C. H. Davis, "A robust threshold retracking algorithm for measuring ice sheet surface elevation change from satellite radar altimeters," *IEEE Trans. Geosci. Remote Sens.*, vol. 35, pp. 974–979, 1997.

[10] X. Deng and W. E. Featherstone, "A coastal retracking system for satellite radar altimeter waveforms: Application to ERS-2 around Australia," *J. Geophys. Res.*, vol. 111, p. C06012, 2006.

[11] J. Guo *et al.*, "Lake level variations monitored with satellite altimetry waveform retracking," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 2, no. 2, pp. 80–86, 2009.

[12] F. Mercier, V. Rosmorduc, L. Carrere, and P. Thibaut, Coastal and Hydrology Altimetry Product (PISTACH) Handbook, 1.0 ed., 2010.

[13] Y. Troitskaya *et al.*, "Satellite altimetry of inland water bodies," *Water Resources*, vol. 39, no. 2, pp. 184–199, 2012.

[14] Y. Troitskaya *et al.*, "Adaptive retracking of Jason-1 altimetry data for inland waters: the example of the Gorky Reservoir," *Int. J. Remote Sens.*, vol. 33, pp. 7559–7578, 2012.

[15] D. Barrick and B. Lipa, "Analysis and interpretation of altimeter sea echo," *Adv. Geophys.*, vol. 27, pp. 61–100, 1985.

[16] J. Tournadre *et al.*, "Analysis and interpretation of altimeter sea echo," *J. Geophys. Res.*, vol. 111, p. C04004, 2006.

[17] *GLOBE, Global Land One-km Base Elevation Project*, [Online]. Available: http://www.ngdc.noaa.gov/mgg/topo/globe.html

Author biographies not available at the time of publication.