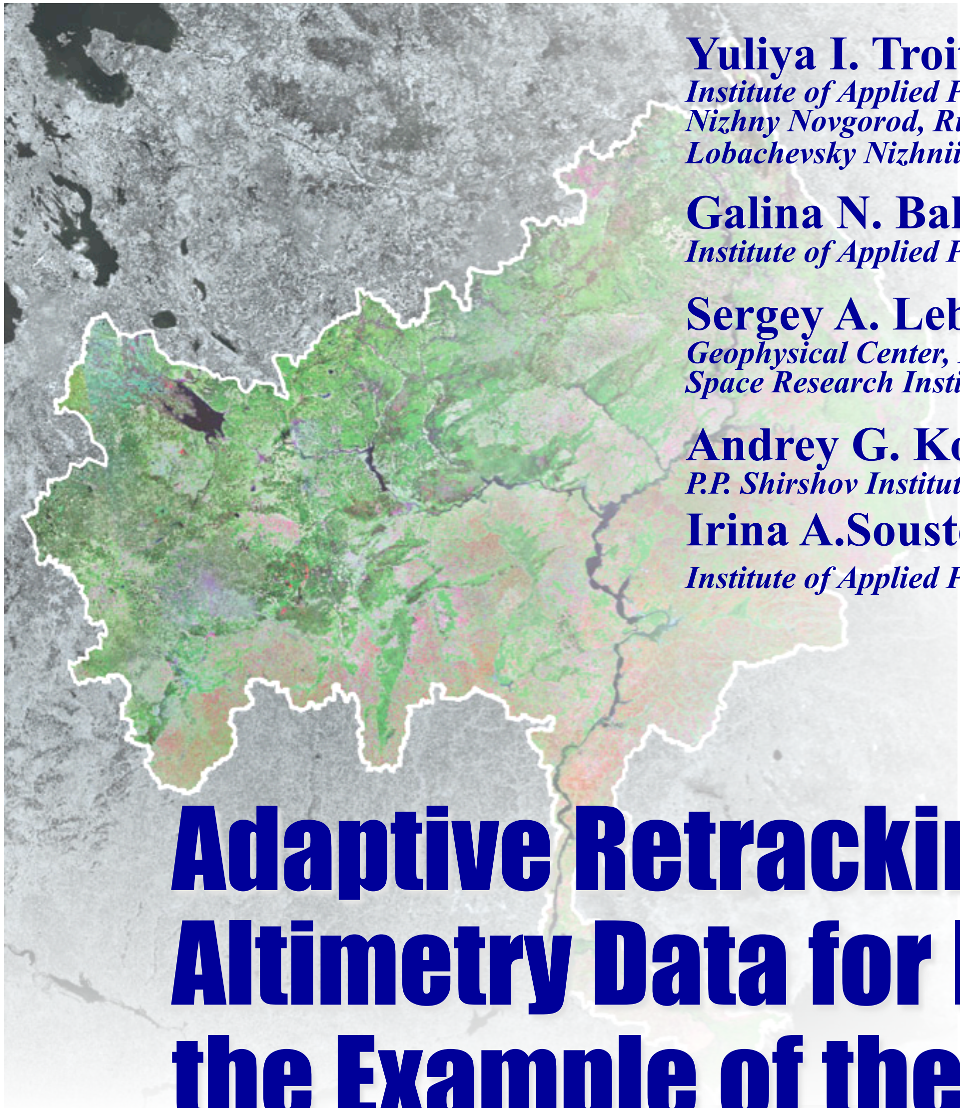

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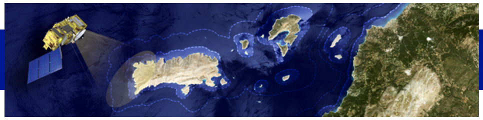
Adaptive Retracking of Jason-1 Altimetry Data for Inland Waters on the Example of the Volga Reservoirs



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Introduction

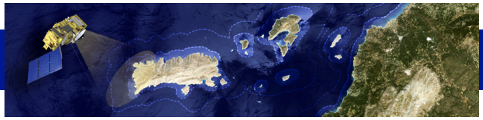
The aim is developing a method of monitoring of the water level in the Volga river reservoirs by methods of satellite remote sensing.

Altimetry data processing developed for the open ocean can be inapplicable for the case of inland waters. The problems of data processing are very similar to those arising in the coastal zone of the ocean from contamination of the received signal by reflection from the land.

This effect is very strong for most of the Volga river reservoirs (or example the Gorky reservoir have maximal width of 14 km with steep 10-20 m banks and two hydrological regime – river and river-lake). Under these conditions few telemetric impulses fit the validity criteria, which causes a severe loss of data.

In a result the Gorky and some reservoir is not included in the data bases by GOHS/ LEGOS project "Hydrology from Space" (http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/) and USDA Foreign Agricultural Service project "Satellite Radar Altimetry: Global Reservoir and Lake Elevation Database" (http://www.pecad.fas.usda.gov/ cropexplorer/global_reservoir/)

This talk is about experience of retrieval water level in some of the Volga river reservoirs (which have very bad conditions) by a kind of adaptive re-tracking algorithm, which dramatically increases the number of data involved in monitoring. General principles of local re-tracking algorithm can be useful for Gorky reservoir and the coastal altimetry.



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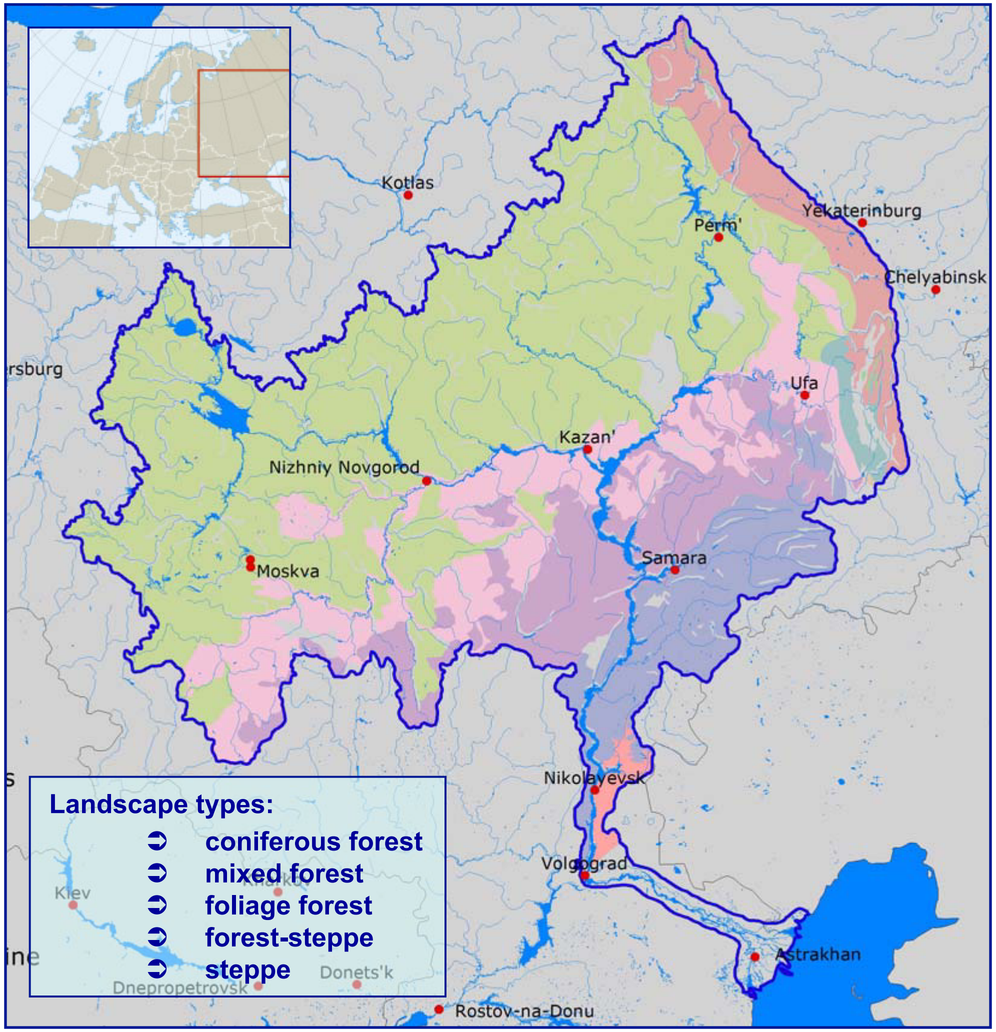
The Volga River Basin

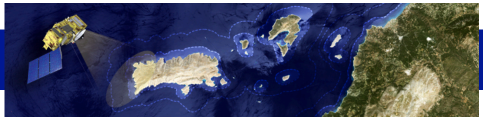
The Volga is the largest river in Europe in terms of length, discharge, and watershed. It flows through the western part of Russia, Volga rises in the Valdai Hills 228 meters above sea level north-west of Moscow and discharges into the Caspian Sea near Astrakhan' at 28 meters below sea level.

The Volga River belongs to the closed basin of the Caspian Sea, which is 28 meters below sea level.

The course of the Volga is divided into three parts: the upper Volga, the middle Volga and the lower Volga.



Length:	**3 530 km**
Area:	**1 380 000 km^2**
Annual runoff:	**260 km^3·yr^{-1}**
Annual discharge:	**8 060 m^3·s^{-1}**



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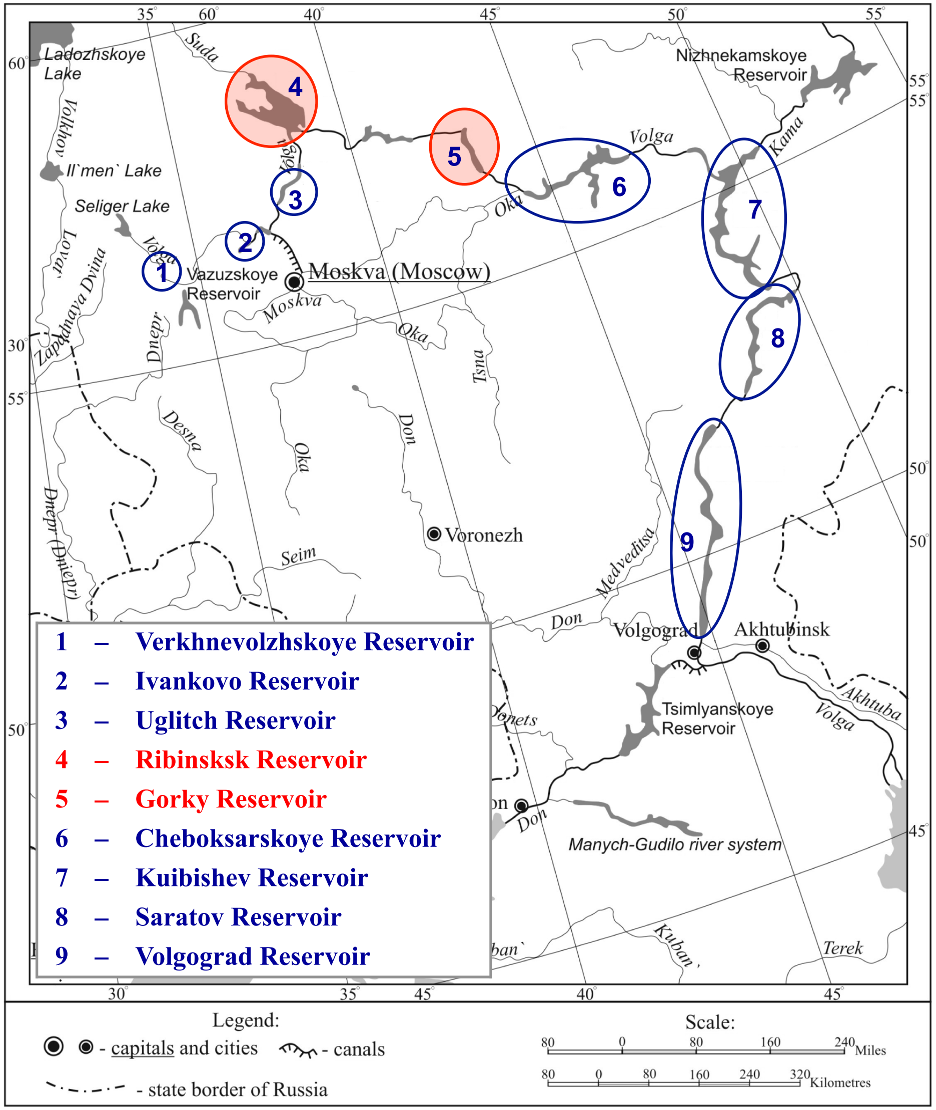
The Volga Water Reservoirs System



Nine of large hydroelectric reservoirs were constructed on the Volga during the Soviet rule.

Five reservoirs (Verkhnevolzhskoye, Ivankovo, Uglitch, Ribinsk and Gorky Reservoirs) are located in the upper part of the Volga, two reservoirs (Cheboksary and Kuibishev Reservoirs) – in the middle part, and two (Saratov and Volgograd Reservoirs) – in the lower Volga.

The Volga water reservoir System have total volume – 143.35 km^3 and effective volume – 66.56 km^3.

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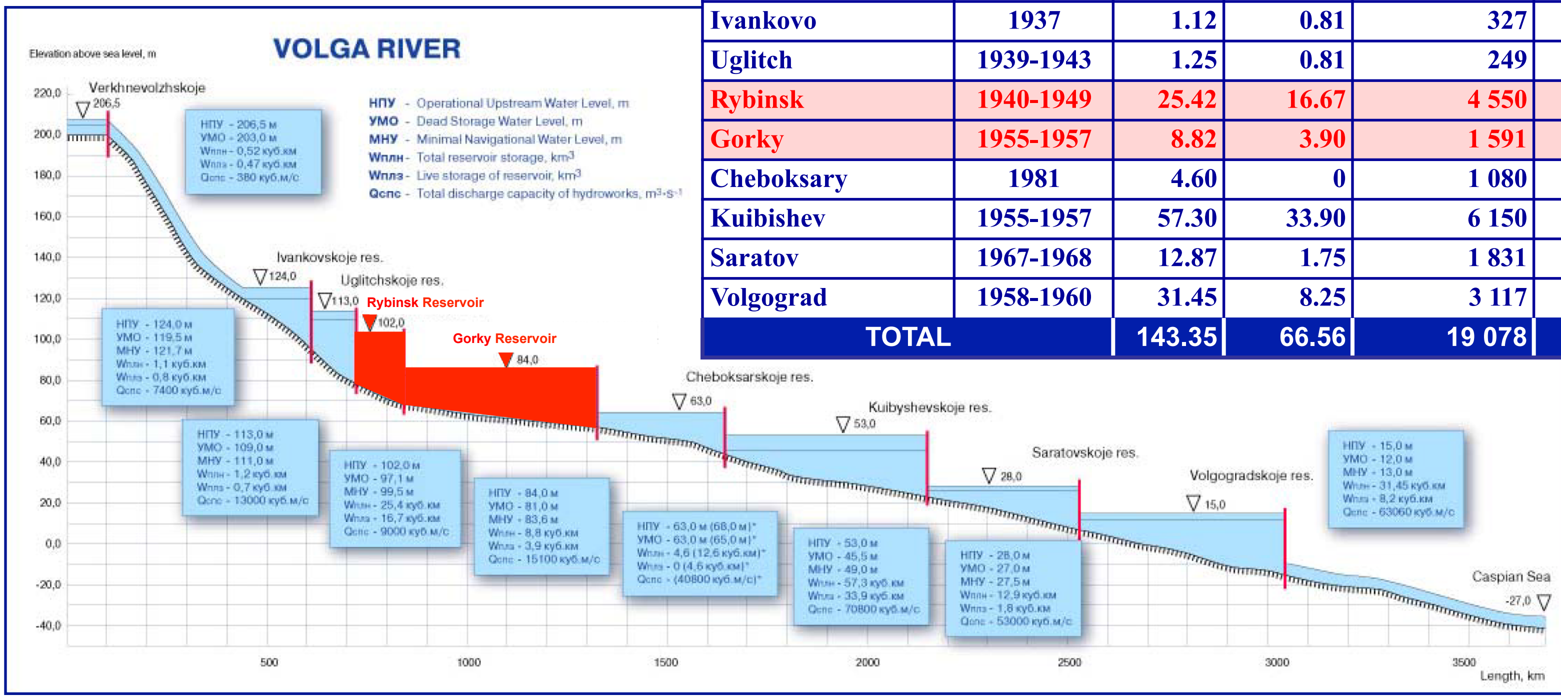
The Volga Water Reservoirs System

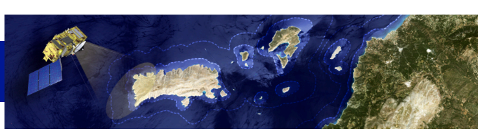
Difference of heights between the Volga River source and the river outlet makes 256 m.

Table: The general parameters of the Volga water reservoirs system

Reservoir	Year	Volume, km³		Water surface area, km²	Surface elevation, m	Discharge max, m³/s
		total	effective			
Verkhnevolzhskoye	1843,1944	0.52	0.47	183	206.5	47
Ivankovo	1937	1.12	0.81	327	124.0	7 400
Uglitch	1939-1943	1.25	0.81	249	113.0	13 000
Rybinsk	1940-1949	25.42	16.67	4 550	102.4	9 000
Gorky	1955-1957	8.82	3.90	1 591	84.0	15 100
Cheboksary	1981	4.60	0	1 080	63.0	40 800
Kuibishev	1955-1957	57.30	33.90	6 150	53.0	70 800
Saratov	1967-1968	12.87	1.75	1 831	28.0	53 000
Volgograd	1958-1960	31.45	8.25	3 117	15.0	63 060
TOTAL		**143.35**	**66.56**	**19 078**		



The Volga River length is 3 530 km and only 940 km (320 km in the Upper part and 620 km in the Lower Volga) have unregulated or natural hydrological regime.



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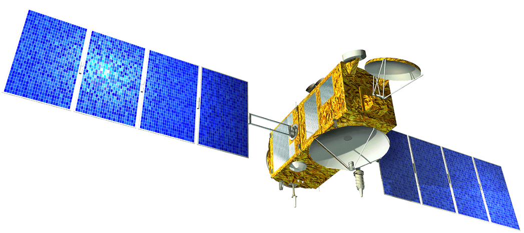
Using Satellite Altimetry Data

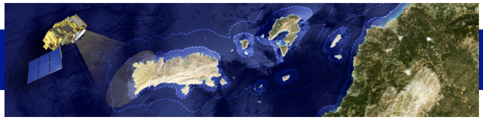
TOPEX/Poseidon



Jason-1/2

For the investigation of water level reservoir the measurements of TOPEX/Poseidon (T/P) and Jason-1/2 (J1/2) satellites were used because:

- **The orbital repeat period (~9.916 days) is close to characteristic temporal scale of the basic hydrological and hydrodynamic phenomena.**
- **The altimetry data coverage for the Volga water reservoirs system allows to take into account all hydrological and hydrodynamic features.**
- **The T/P data represent the most long time series of altimetry measurements (September 1992 - August 2002) with a capability of its extension by the J1 data (January 2002 - present time) and Jason-2 (August 2008 - present time).**



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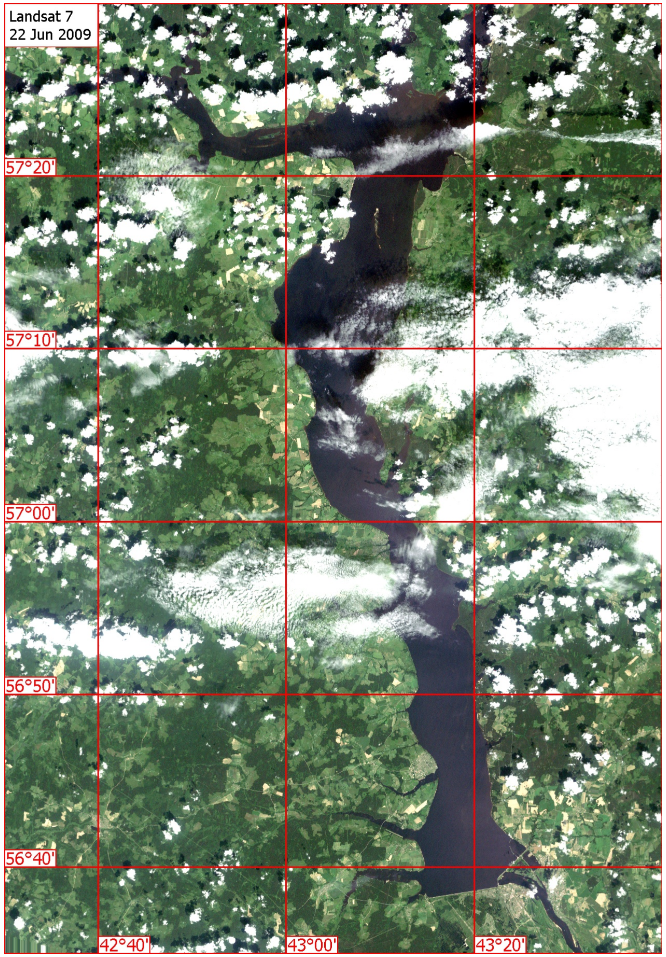
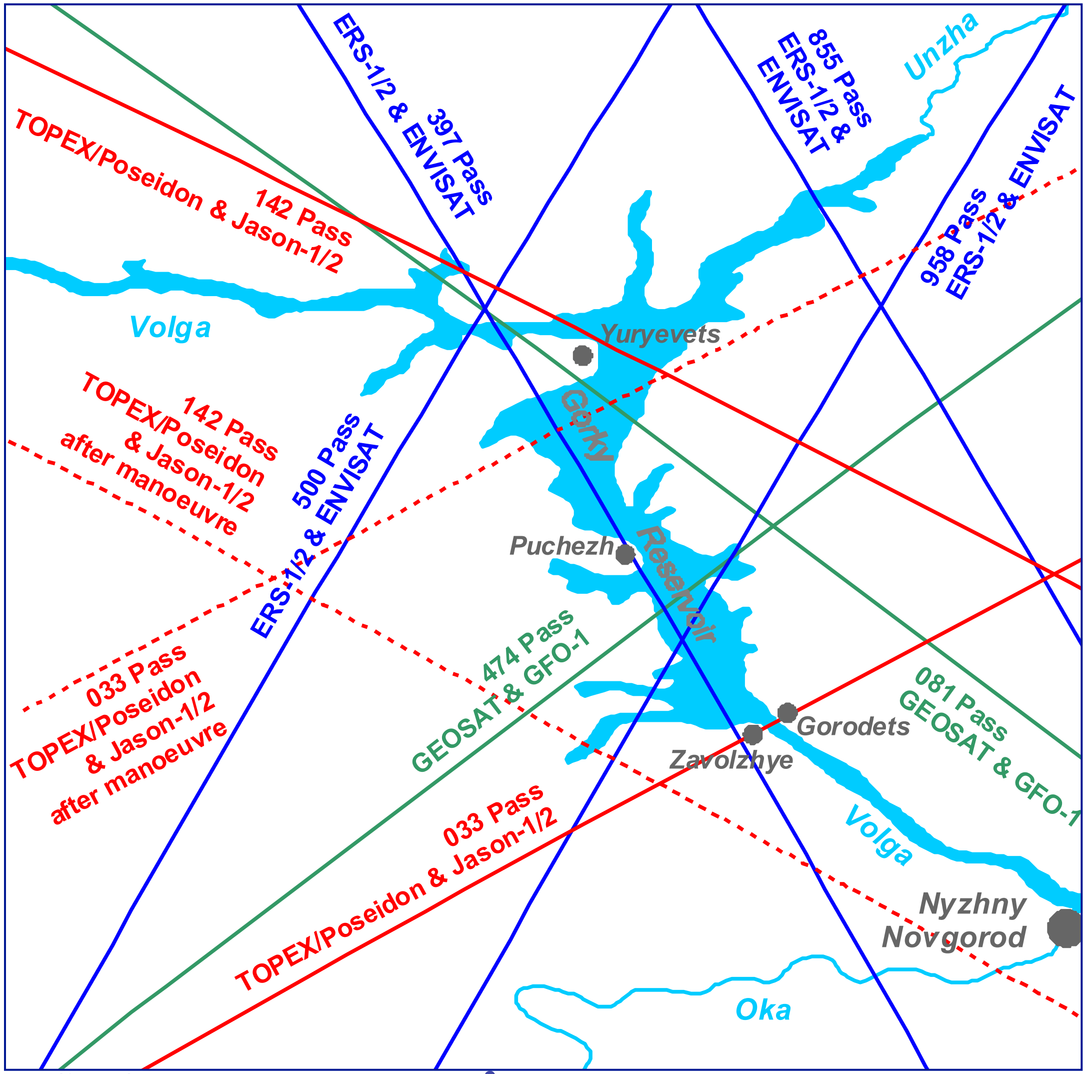
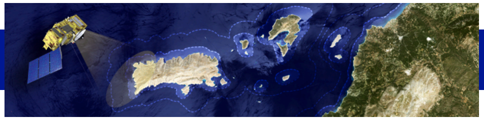
The Gorky Reservoir



Satellite Landsat 7 image of the Gorkv Reservoir.
22 June 2009



Surface area	1 591 km^2	Average depth	3.65 m
Water volume	12.9 km^3	Surface elevation	84 m
Max. length	430 km	Max. width	16 km
Max. depth	22 m		



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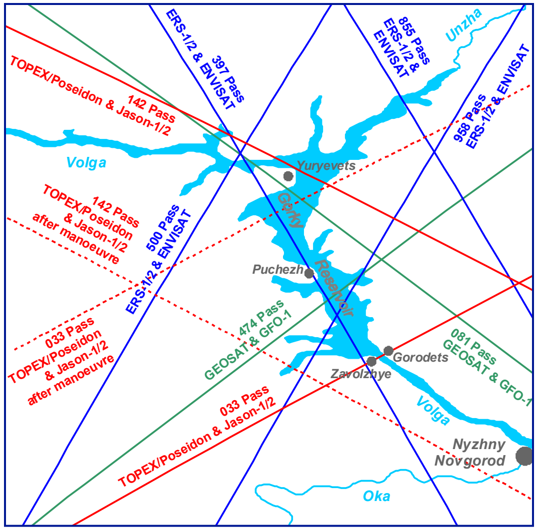
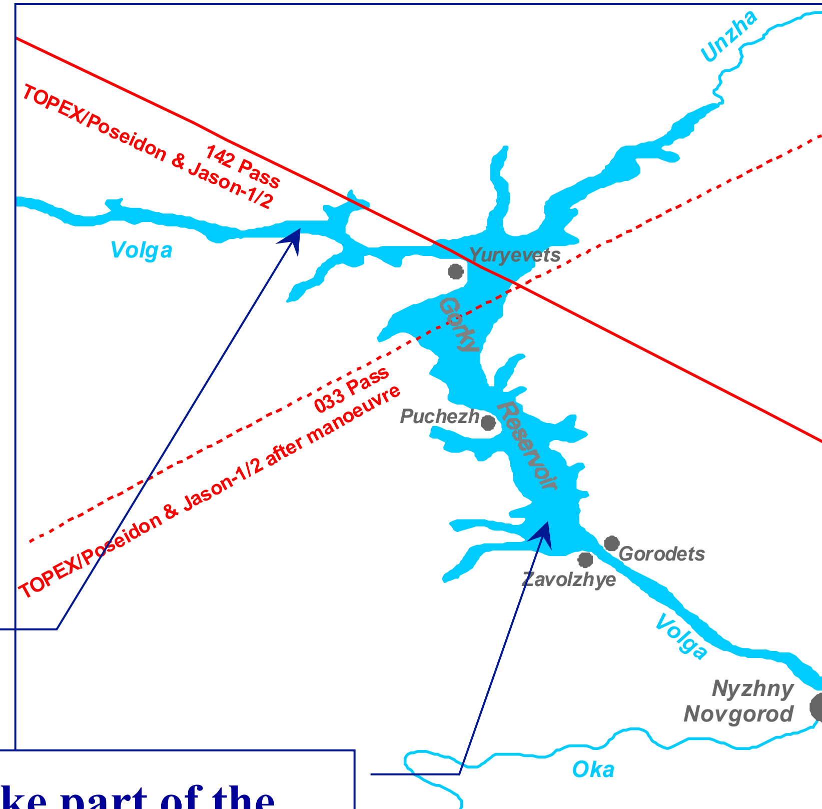
The Gorky Reservoir Groundtraks Map



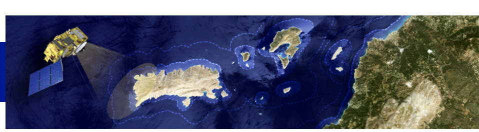


River and river-lake parts of the Gorky reservoir

Total length	332 km
Width	0.6-3.5 km
Max. depth	5 m

Lake part of the Gorky reservoir

Total length	97 km
Width	3-14 km
Max. depth	22 m



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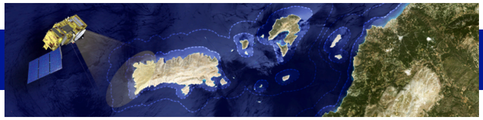
The Hydrometeorological Regime of the Gorky Reservoir Has Strong Seasonal Variability

- Winter (ice over the total water area covered by a snow layer) (November – April)
- Average date of freezing-over is November 22 (between November 7 – December 7)
- Average date of clearing from ice of the lake part of the reservoir is May 3 (between April 18 – May 18)
- Summer (the water area is free of ice) (May-October)



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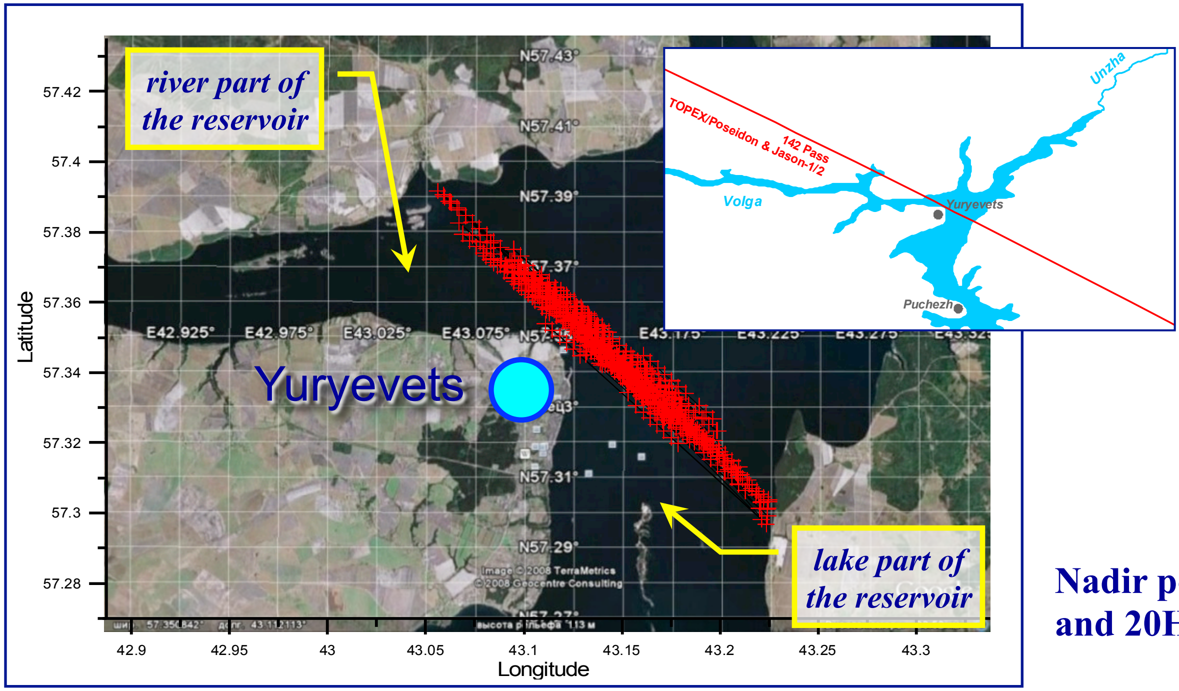
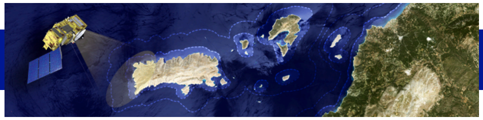
First Stage of Processing of Satellite Altimetry Data

All available high frequency altimetry data from GDR of satellites T/P (10 Hz averaging) and J1/2 (20Hz averaging) were processed



Nadir points for 10Hz GDR T/P data and 20Hz GDR J1/2 data for 142 pass

- **The wet and "dry" troposphere correction was calculated by meteorological data (atmospheric pressure and air humidity) from nearest weather station.**
- **DORIS ionosphere correction was used for correction altimetry measurements of reservoir surface height.**



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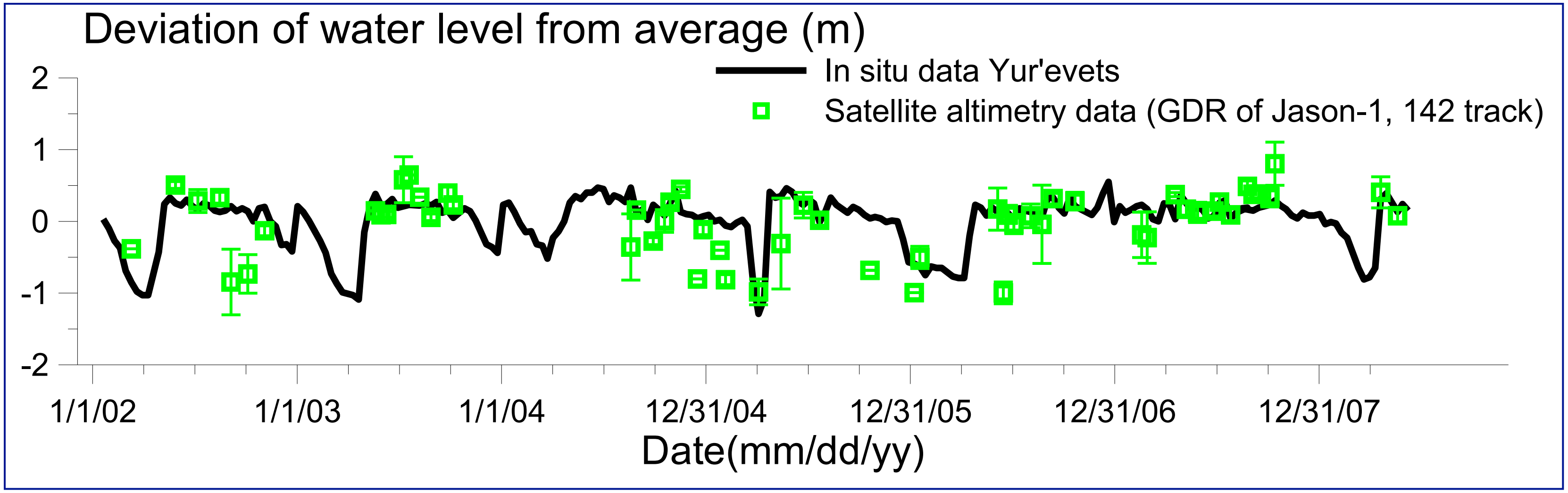
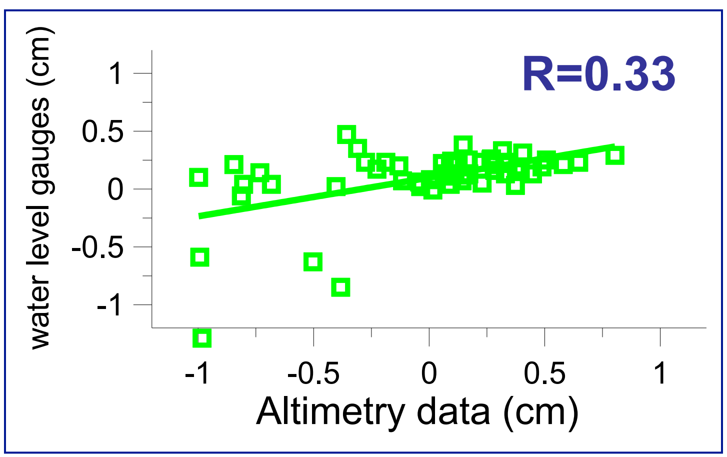
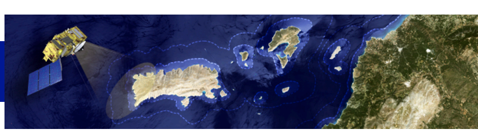
Comparison of Water Level Variability Measured by Level Gauge and 20 Hz GDR J1 Altimetry Data





Shortcomings of the ocean re-tracking algorithm in application to the Gorky reservoir, namely

- a severe loss of data
- substantial errors, correlation coefficient of altimetry data and *in situ* measurements is about 0.33.



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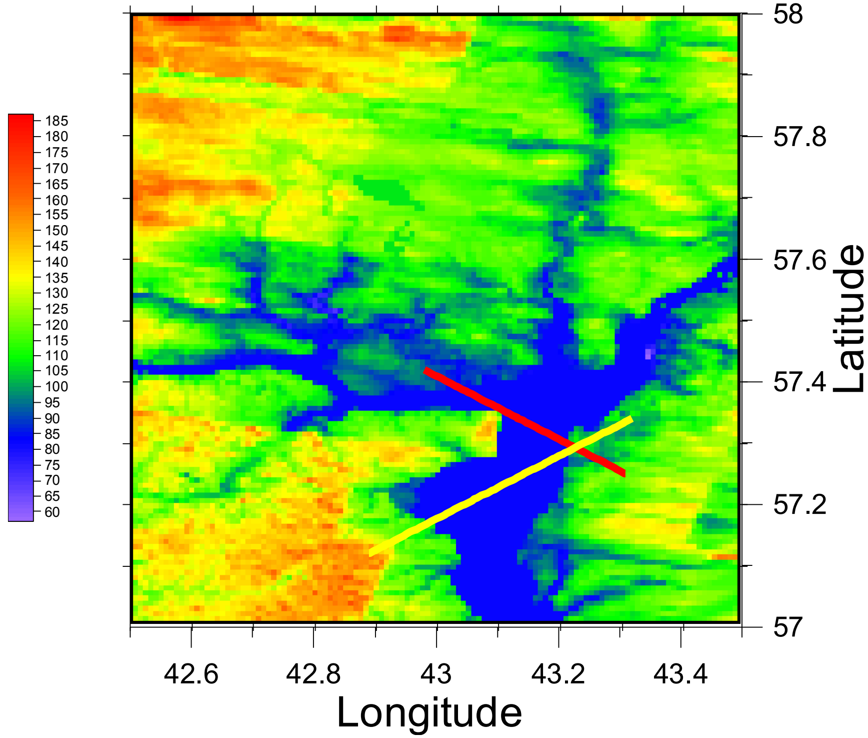
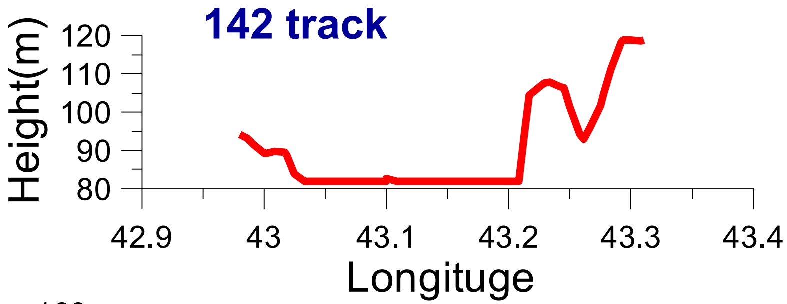
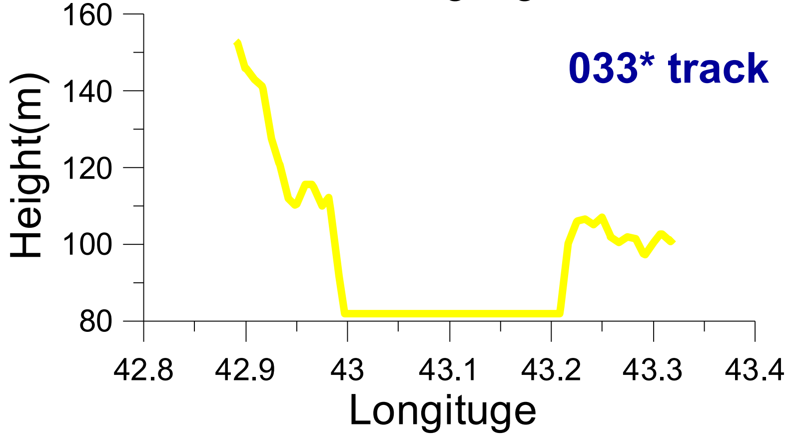
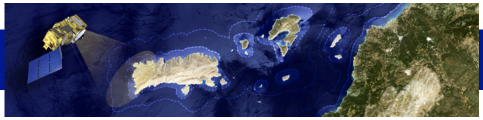
Elevation Along 142 and 033 Track







A 3-arc-second (90 m) gridded, quality-controlled global Digital Elevation Model (DEM) along-cross of 033* and 142 track



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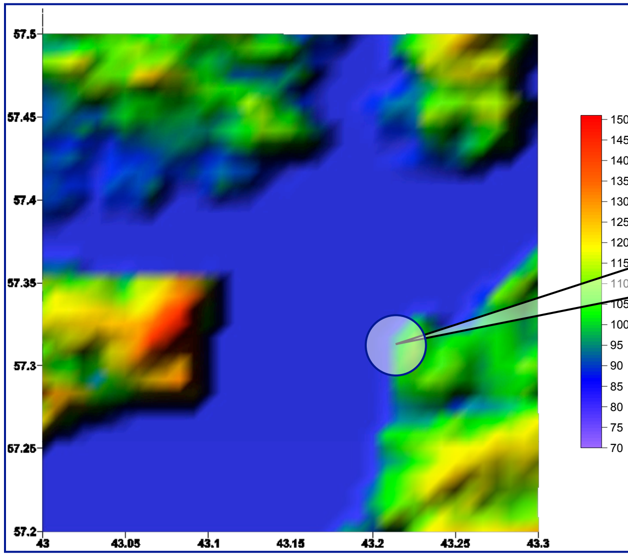
Landscapes and Water Area of the Gorky Reservoir



Landscapes and water area of the Gorky reservoir near the T/P and J1/2 142 and 033* Pass (left bank, up to 10 m height)

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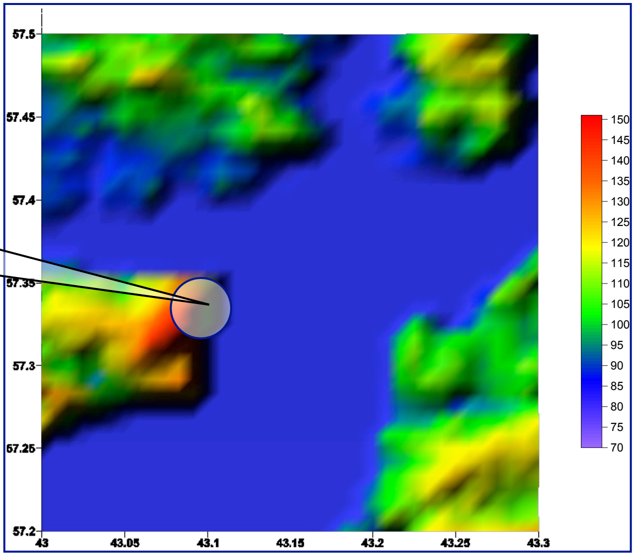
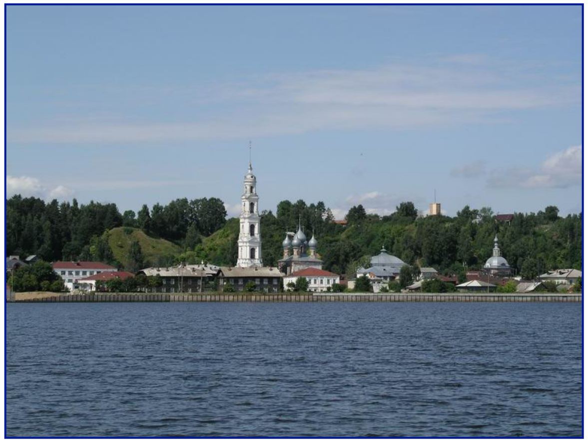
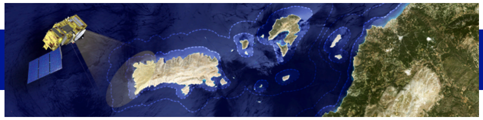
Landscapes and Water Area of the Gorky Reservoir





Landscapes and water area of the Gorky reservoir near the T/P and J1/2 142 and 033* Pass (right bank, 20-30 m height)



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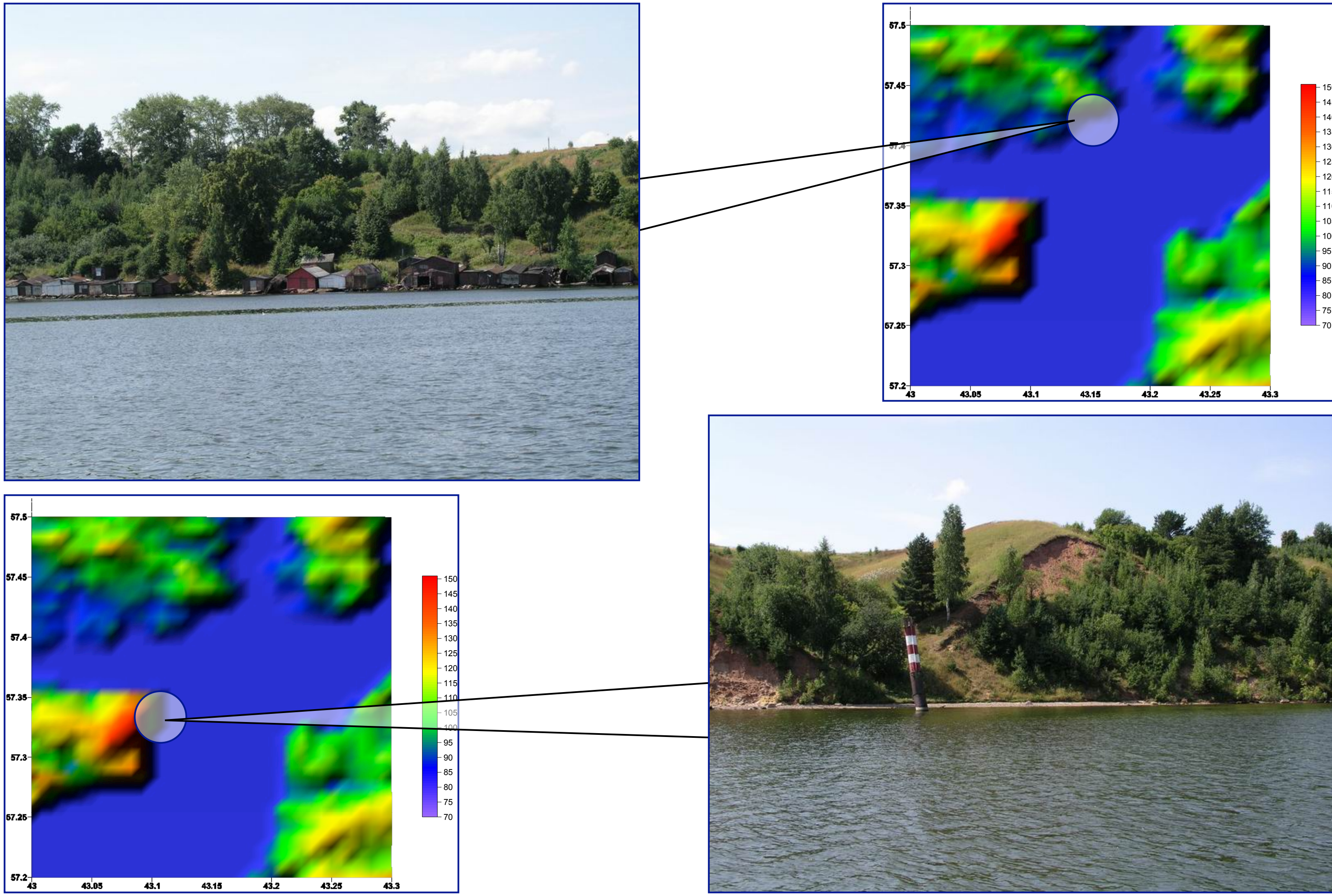
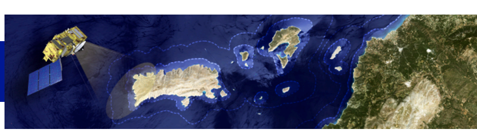
Coastal Slicks on Water Area of the Gorky Reservoir





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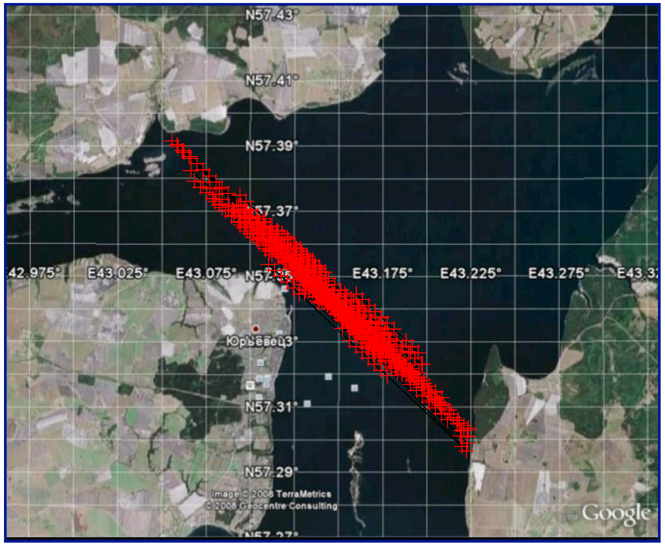
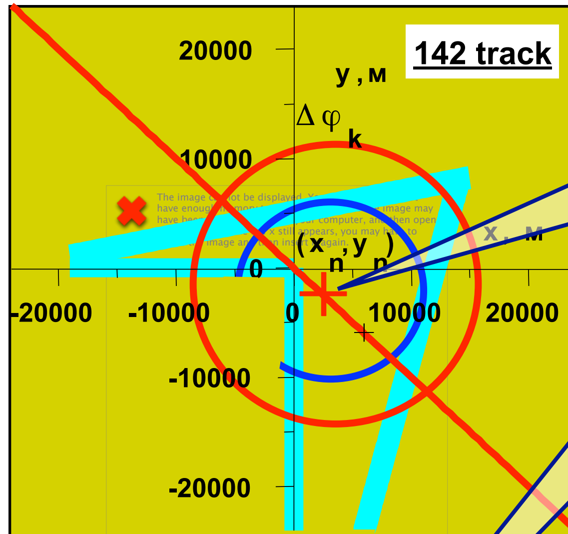
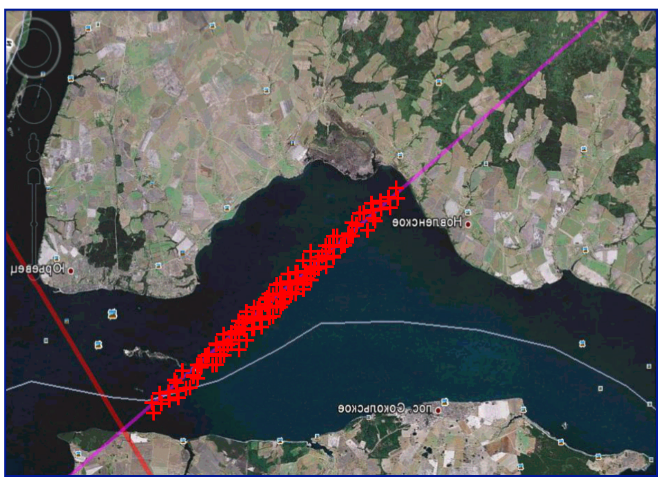
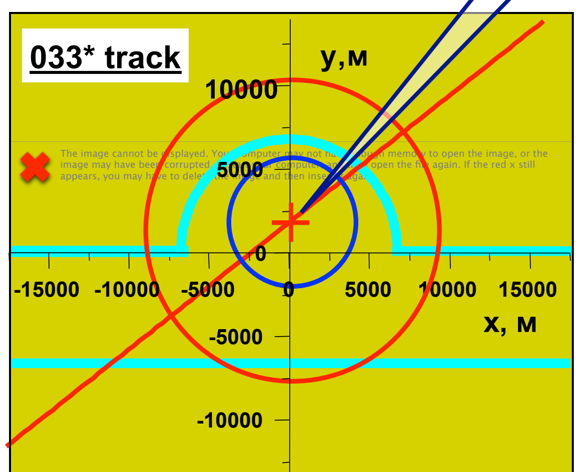
A Piecewise Constant Geographical Model of Reflecting Surface for Gorky Reservoir





Nadir points of J1/2 SGDR data for 033* or 142 pass accordingly

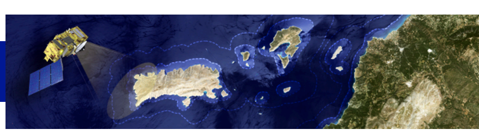




The model of the reflecting surface

land – gold gray,
water – dot shading blue,
coastal slicks – light blue,

small blue circles – positions of the footprint, the big red circle – an area illuminated by the gain of the radar antenna



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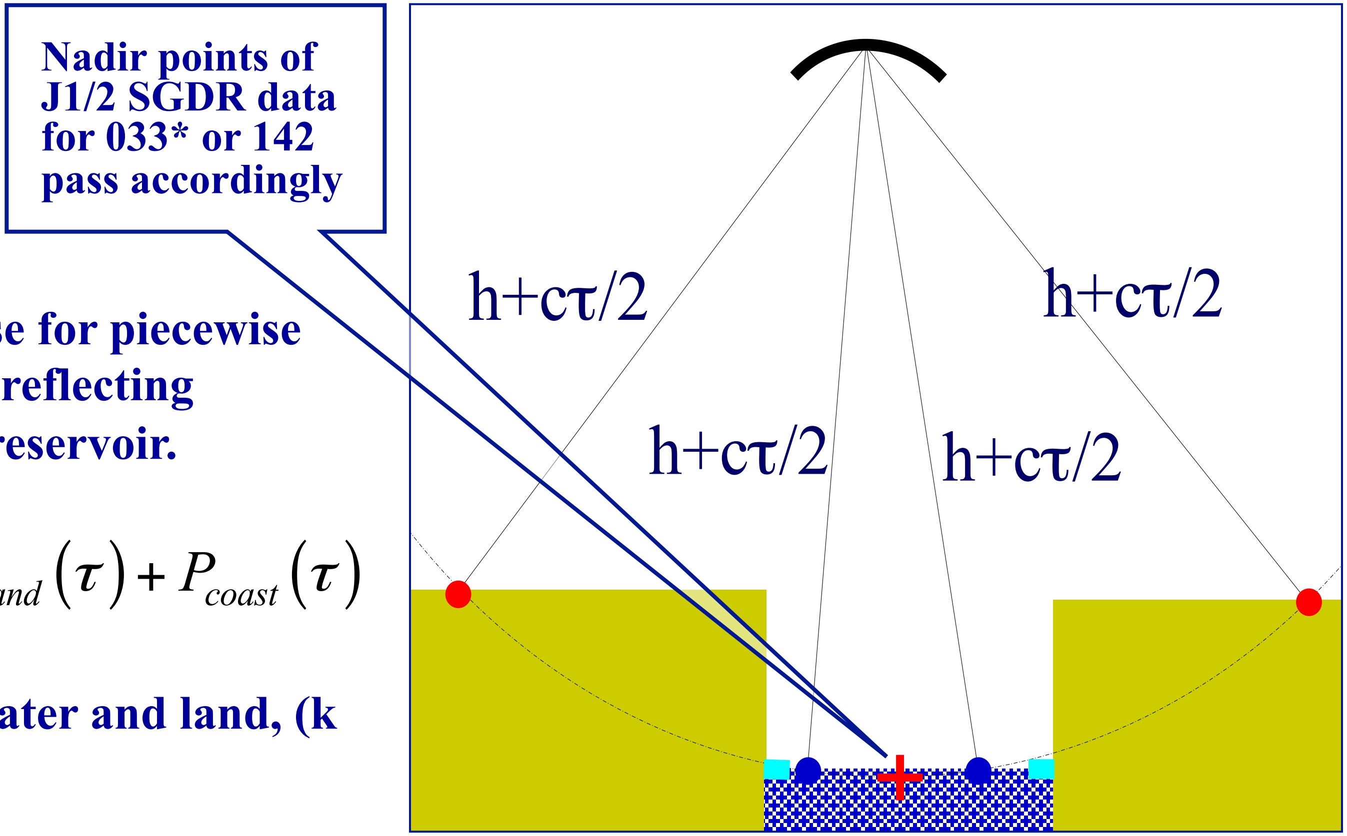
A Piecewise Constant Geographical Model of Reflecting Surface for Gorky Reservoir

Average reflected pulse for piecewise constant model of the reflecting surface in the Gorky reservoir.

$$P_i(\tau) = P_{water}(\tau) + P_{land}(\tau) + P_{coast}(\tau)$$

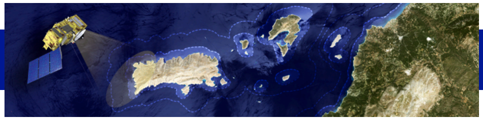
The contribution of water and land, (k = water, land)

$$P_k(\tau) : \left(1 + \mathrm{erf}\left(\frac{(c\tau - 2H_k)}{\sqrt{2}\sqrt{s_k^2 + c^2\tau_i^2}}\right)\right)$$



The model of the reflecting surface

land – gold gray (H = 10 m),
water – dot shading blue (H = 0 m),
coastal slicks – light blue,
blue point – positions of the footprint, the red point – an area illuminated by the gain of the radar antenna



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A Piecewise Constant Geographical Model of Reflecting Surface for Gorky Reservoir

Nadir points of J1/2 SGDR data for 033* or 142 pass accordingly

Average reflected pulse for piecewise constant model of the reflecting surface in the Gorky reservoir.

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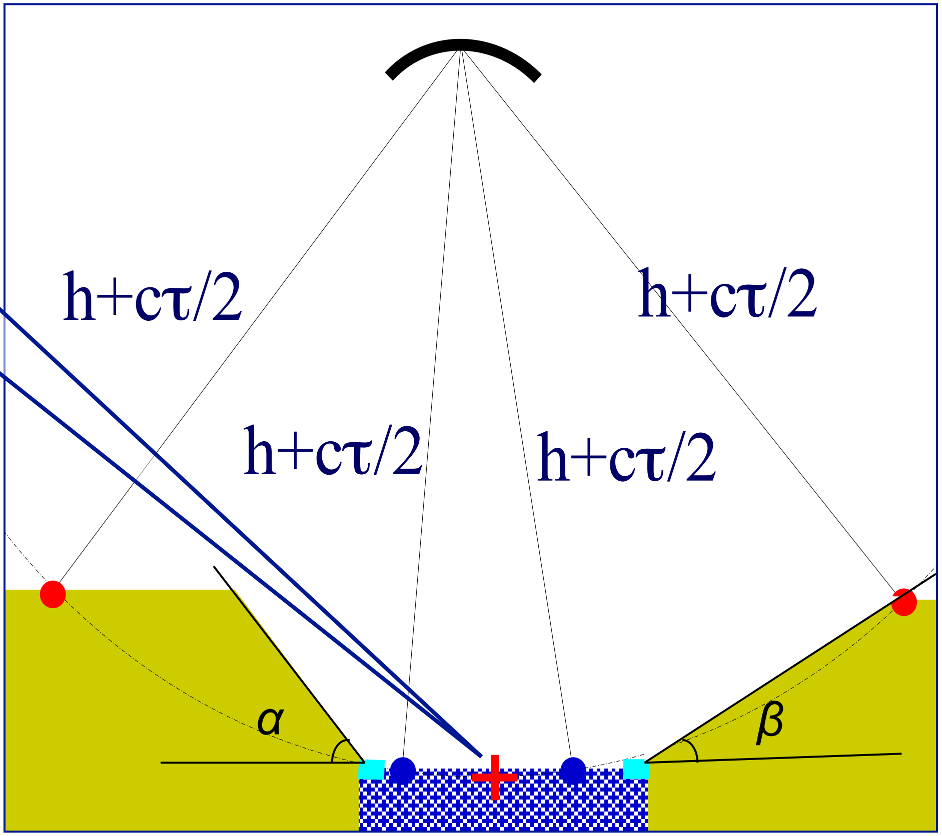
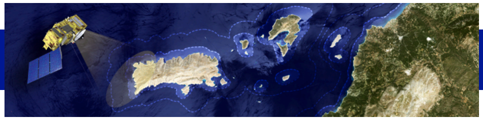


The model of the reflecting surface
land – gold gray, *α* – slope of the left bank, *β* – slope of the right bank, water – dot shading blue (H = 0 m), coastal slicks – light blue, blue point –positions of the footprint boundary, the red point – an area illuminated by the gain boundary of the radar antenna



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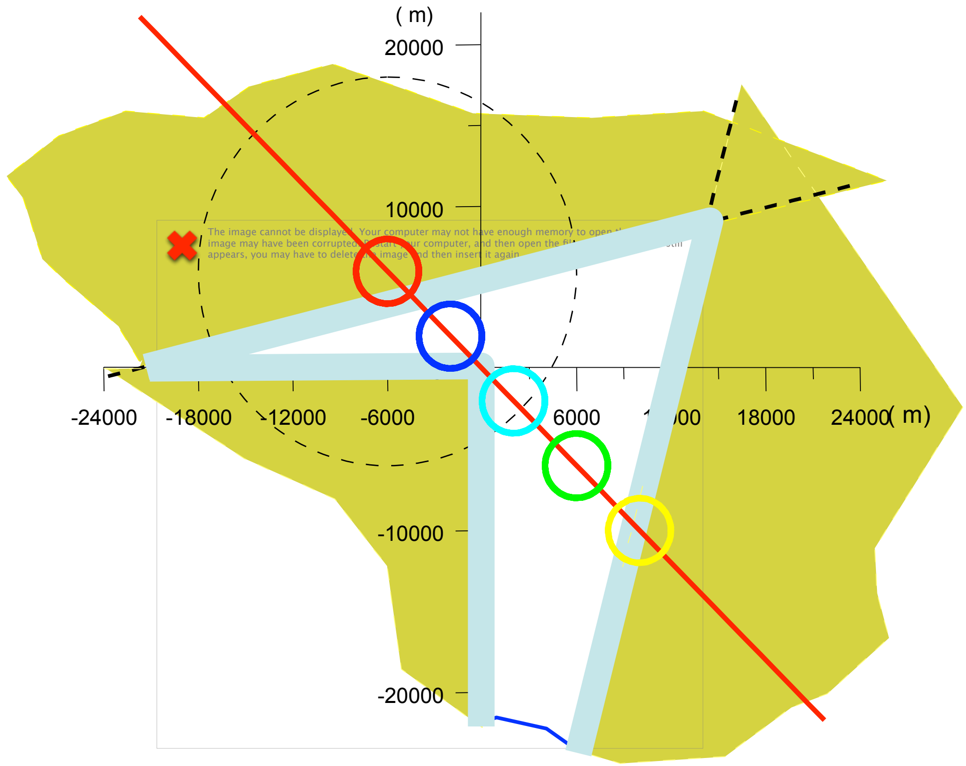
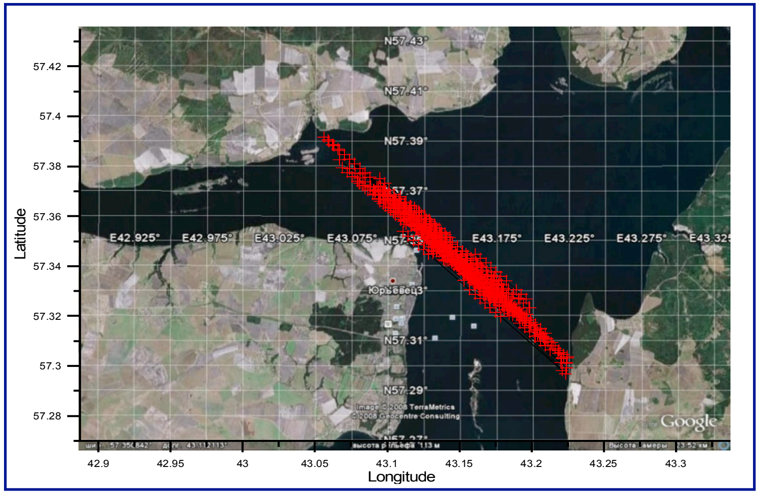
A Piecewise Constant Geographical Model of Reflecting Surface for Gorky Reservoir

The model of the reflecting surface

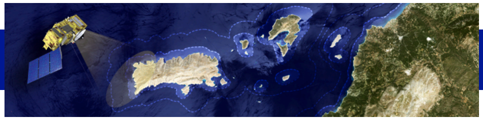
land – gold gray,
water – dot shading blue,
coastal slicks – light blue,

small circles – positions of the footprint,
the big dotted circle – an area illuminated by the gain of the radar antenna





Nadir points of 20Hz J1/2 SGDR data for 142 pass



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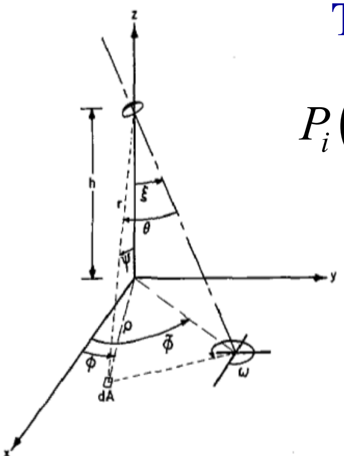
Theoretical Model of Waveforms

Based on the theory of non-coherent scattering of microwaves by rough surface

The average impulse response of the rough surface



Geometry (Brown, 1977)

$$P_i(t) = P_0 \iint\limits_{\substack{illu\min ated \\ area}} \frac{G^2(\theta)\sigma(x,y,\theta)}{r^4} dA \int_{-\infty}^{\infty} p\left(t_1 - \frac{2r}{c}\right) q\left(x, y, \frac{c}{2}(t-t_1)\right) dt_1$$

G – gain of the radar antenna

r – range from the radar to the elemental scattering area dA on the surface

h – mean distance from the satellite

σ – backscattering cross section per unit scattering area

$q\ (z)$ – height probability density of specular points

Suppositions:

1. Small-angle approximation valid for satellite altimetry

$$r = \sqrt{\left(h + H(x,y)\right)^2 + x^2 + y^2} \approx \left(h + H(x,y)\right) + \rho^2 / 2h^2; \rho^2 = x^2 + y^2$$

2. Zero off-nadir angle

3. Gaussian probability density of specular points

$$q(z) = \frac{1}{s(x,y)\sqrt{2\pi}} \exp(-z^2 / 2s^2(x,y))$$

4. Model expressions for backscattering cross section per unit scattering area, gain of the radar antenna and initial impulse shape

$$\sigma = \sigma^{(0)}(\rho,\varphi) \cdot e^{-tg^2\theta/\alpha} \qquad \mathrm{G}(\theta) = \exp(-2\sin^2\theta/\gamma) \qquad p(z) = \frac{1}{\tau_i\sqrt{2\pi}} \exp(-z^2/2\tau_i^2) \qquad \theta^2 = \rho^2/h^2$$

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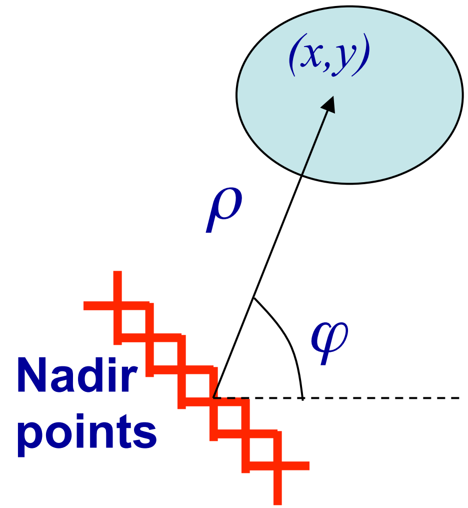
The Average Impulse Response of the Rough Inhomogeneous Surface

$$P_i(\tau) = \frac{P_0}{\sqrt{2\pi} h^4} \int_0^{\infty} \int_0^{2\pi} \frac{\sigma^{(0)}(\rho,\varphi)}{\sqrt{s^2(\rho,\varphi) + c^2\tau_i^2}} e^{-\left(\frac{4}{\gamma} + \alpha(\rho,\varphi)\right)\frac{\rho^2}{h^2}} \times$$

$$\times \exp\left\{ -\frac{\left(c\tau - 2H(\rho,\varphi) - \rho^2/h\right)^2}{2\left(s^2(\rho,\varphi) + c^2\tau_i^2\right)} \right\} \rho d\rho d\varphi$$



Parameters in the formula are the functions of the coordinates of the surface

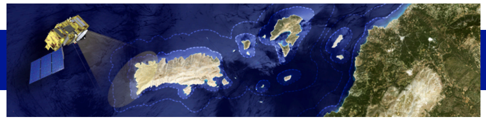
For water surface:

- **Elevation H is constant**
- **s is significant wave height**
- **σ is determined by the wind speed**

For land surface:

- **Elevation H is constant**
- **s is surface roughness**
- **σ is determined by the reflecting properties of the surface**
- **s and σ depend on ρ and ϕ**

Along-track topography and parameters of the surface are required to construct the model



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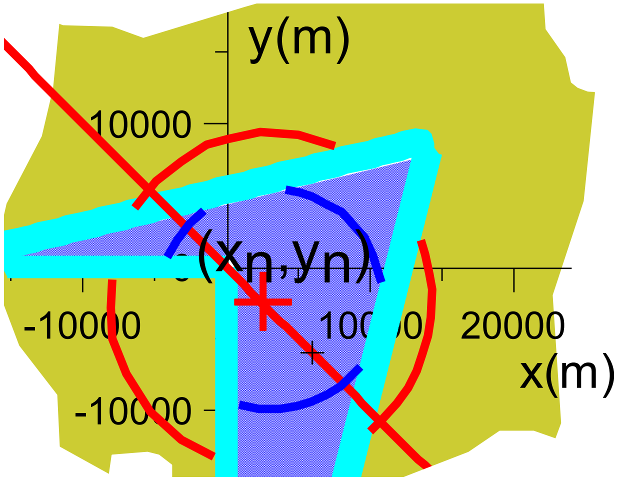
The Average Impulse Response for Piecewise Constant Geographical Model of Reflecting Surface for Gorky Reservoir



$$P_i(\tau) = P_{water}(\tau) + P_{land}(\tau) + P_{coast}(\tau)$$

Contributions of water and land, (k=water, land)

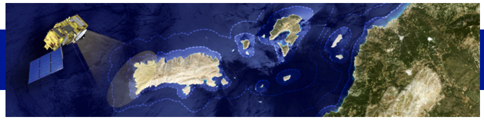
$$P_k(\tau) = \frac{P_0 \sigma_k^{(0)}}{2h^4} e^{-\left(\frac{4}{\gamma}+\alpha_k\right)\frac{(c\tau-2H_k)}{h}} \left(1+\mathrm{erf}\left(\frac{(c\tau-2H_k)}{\sqrt{2}\sqrt{s_k^2+c^2\tau_i^2}}\right)\right) \Delta\varphi_k\left(x_N, y_N, \sqrt{h(c\tau-2H_k)}\right)$$

$\Delta\varphi_k\left(x_N, y_N, \sqrt{h(c\tau-2H_k)}\right)$ **– is the arc corresponding to distance from which the reflected signal from the land (red) or from the water (blue) is received at a certain moment τ, smooth function in comparison with the erf near the leading edge.**

Contribution of slicks

$$P_{coast}(\tau) = \frac{P_0}{\sqrt{2\pi}h^4 s_{coast}} e^{-\left(\frac{4}{\gamma}+\alpha(\rho,\varphi)\right)\frac{c\tau-2H_{water}}{h}} \int_C e^{\left\{-\left(c\tau-2H_{water}-\frac{(x(l)-x_N)^2+(y(l)-y_N)^2}{h}\right)^2 \Big/ 8s_{coast}^2\right\}} dl$$

(x_n, y_n) **–coordinates of nadir points,** $y=y(l)$, $x=x(l)$ **– equation of the coastal line**



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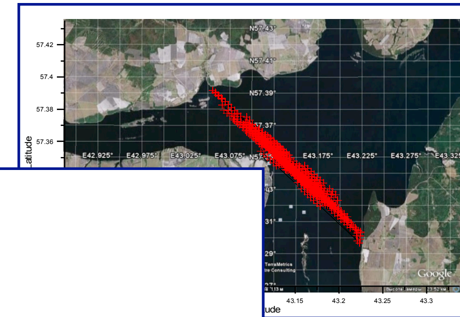
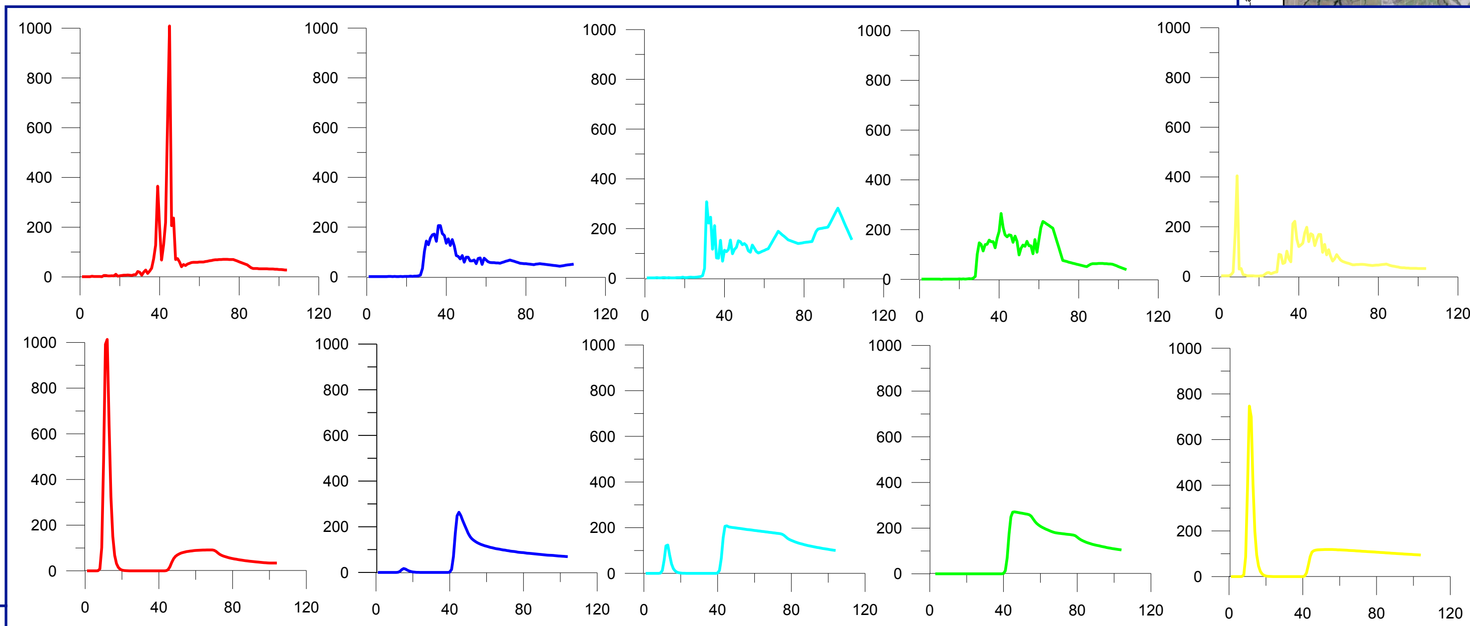
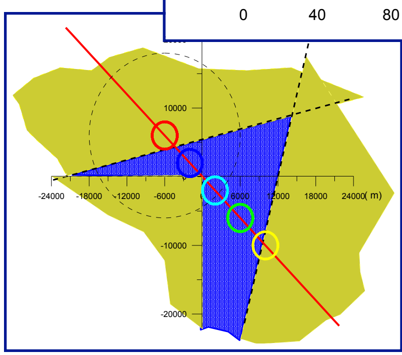
Waveforms from SGDR of Jason-1 and Model calculations







Time dependences of reflected signal capacity for SGDR Jason-1 (162 cycle, 142 pass) data (*top*) and model calculations (*bottom*).

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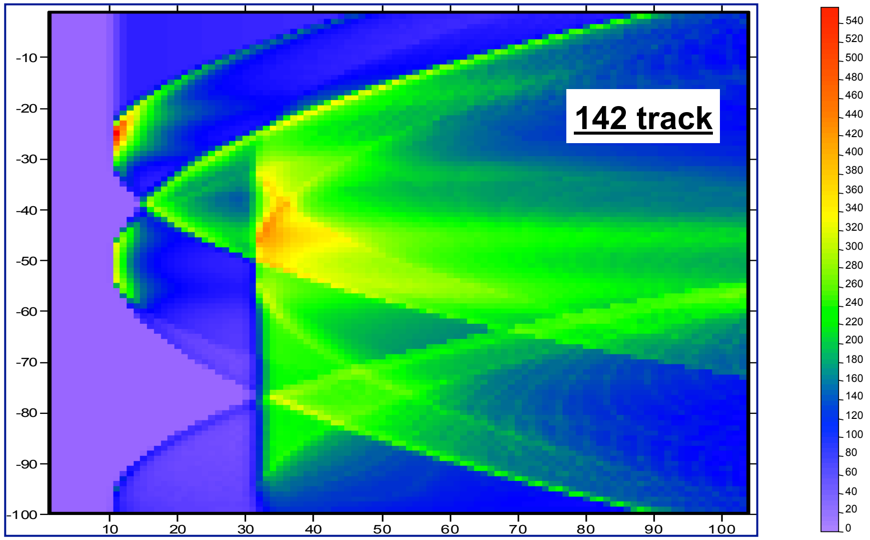
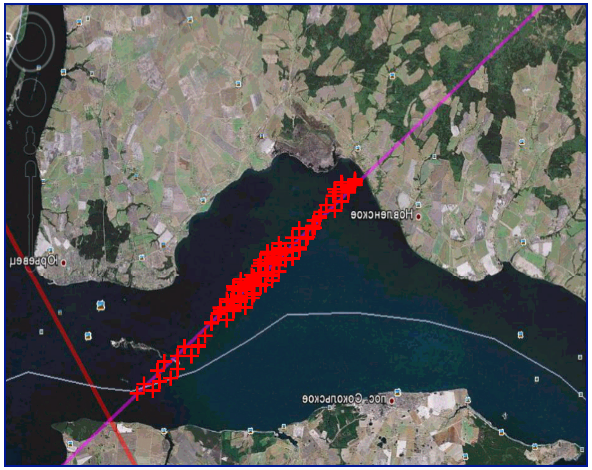
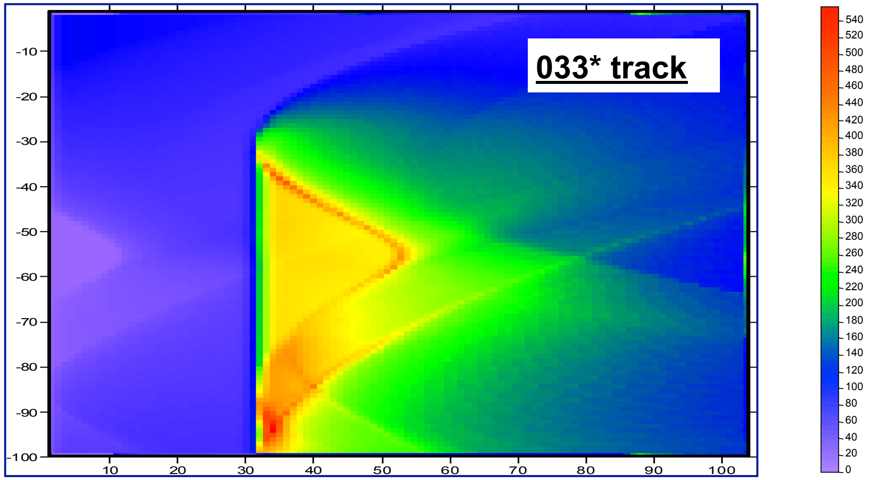
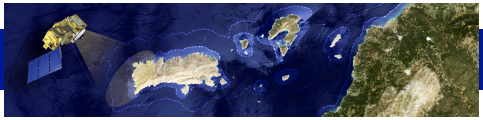
Model waveforms of reflected pulses for the Gorky Reservoir for 033* and 142 Pass









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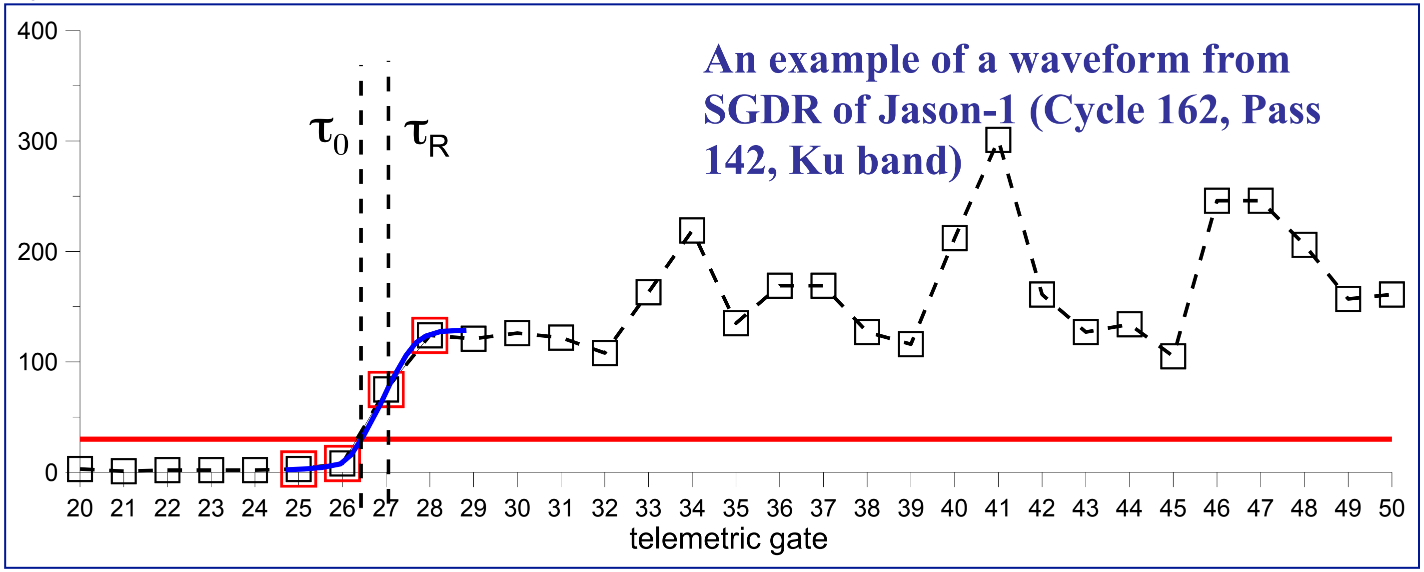
The Local Re-tracking Algorithm Appropriate for the Gorky Reservoir and Surroundings for 033* and 142 Pass

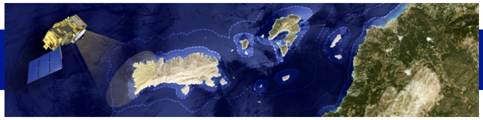
1. Threshold re-tracking algorithm, provides tracking point τ_0, determined by a definite threshold



2. Improved threshold re-tracking algorithm – 4 points in the vicinity of the threshold are fitted by the error function

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

The parameters A, τ_R, S are retrieved from an optimization algorithm



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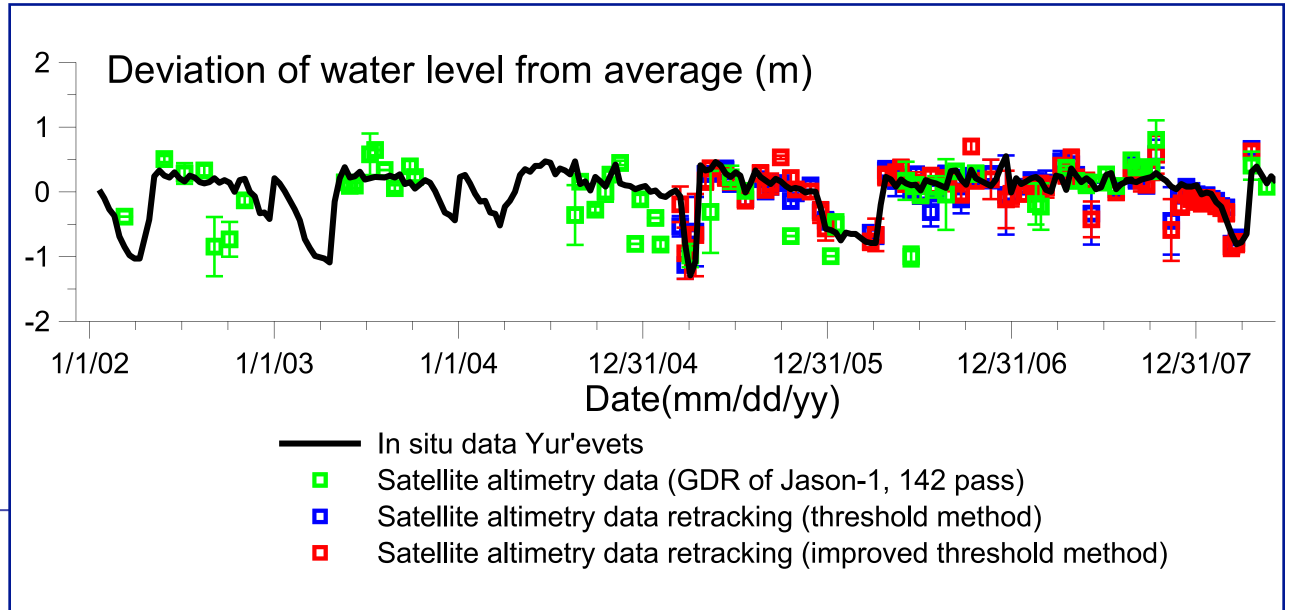
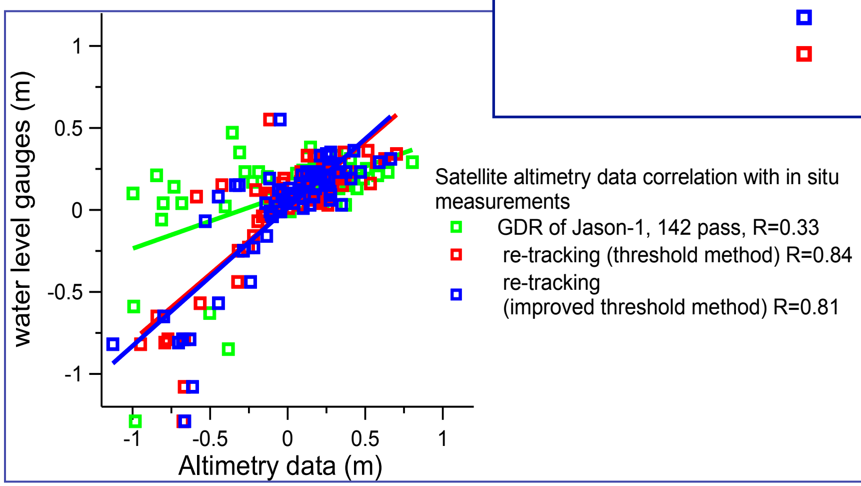
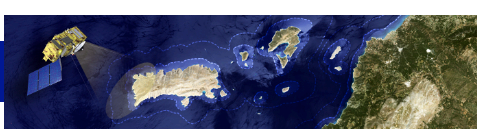
Water Level Variations Based on 142 Pass
(comparing ground measurements, GDR data and results of re-tracking waveforms from SGDR)







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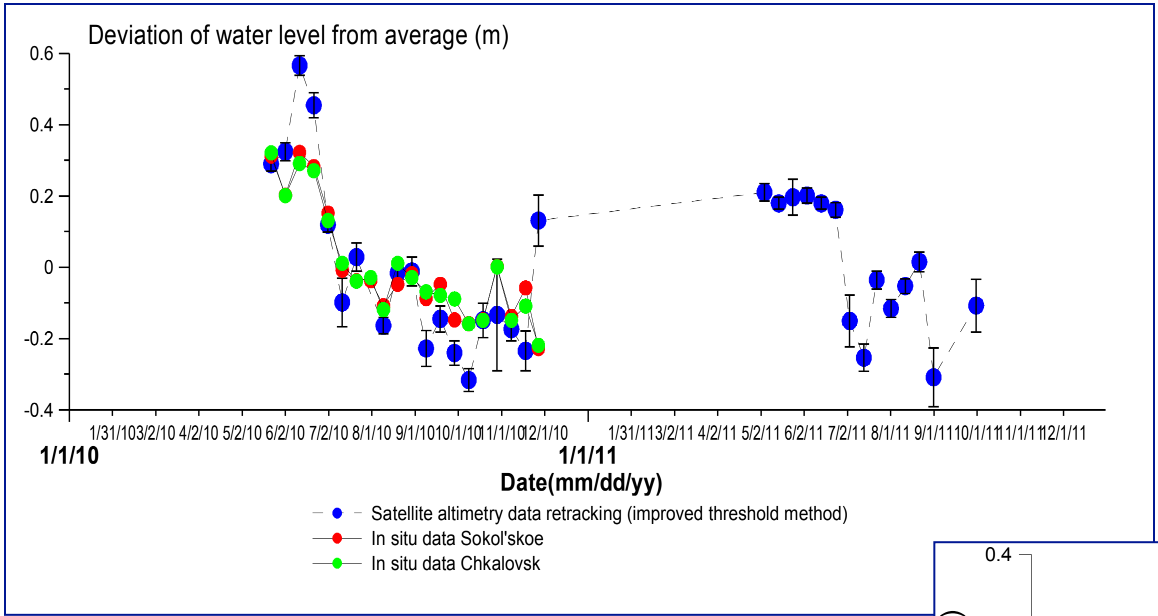
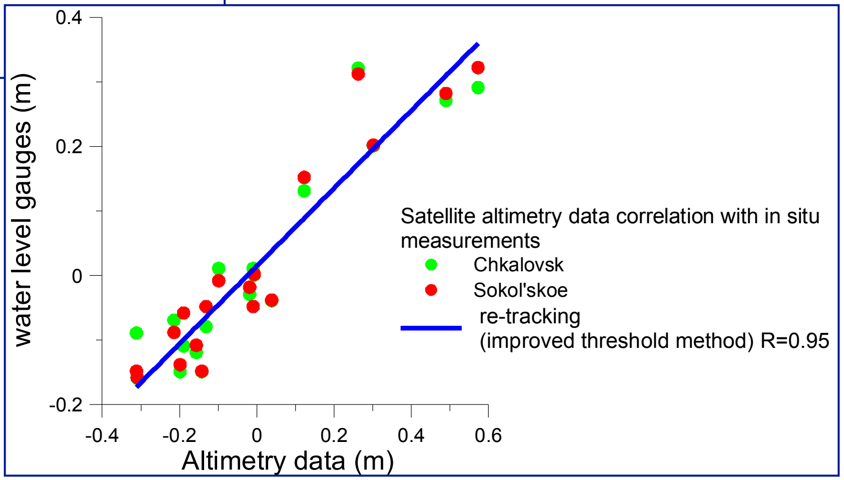
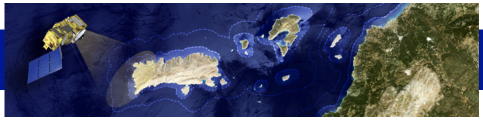
Water Level Variations Based on 033* Pass

(comparing ground measurements, GDR data and results of re-tracking waveforms from SGDR)







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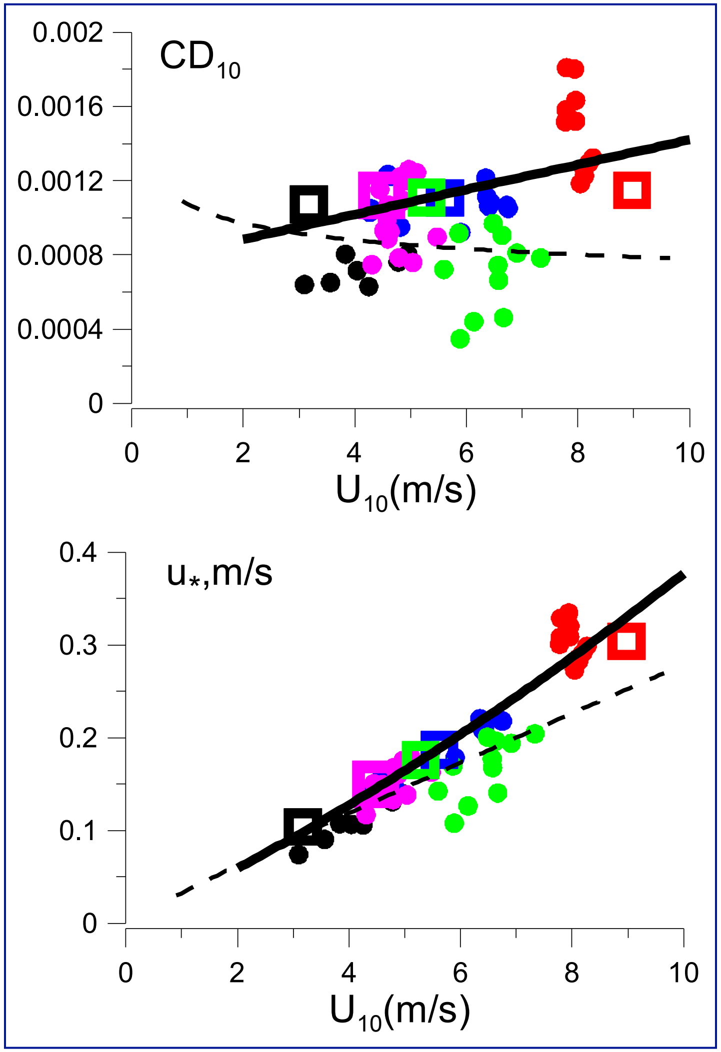
Dependences of Resistance Coefficient and Dynamic Wind Speed



Friction wind speed

$$u_* = \kappa \frac{U(z_2) - U(z_1)}{\ln(z_2 / z_1)}$$

Wind Speed on standard height of 10 m

$$U_{10} = \frac{u_*}{\kappa} \ln\left(\frac{H_{10}}{z_1}\right) + U(z_1)$$

Resistance coefficient

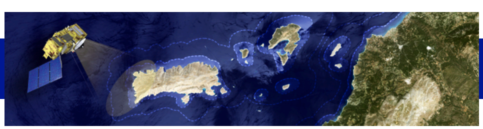
$$C_{D10} = \left(\frac{u_*}{U_{10}}\right)^2$$

Formula Garrett, 1977

$$C_{D10} = 0.001(0.75 + 0.067 U_{10})$$

Aerodynamic smooth surface

Calculation by SGDR-data



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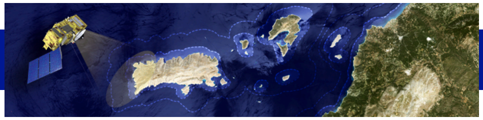
Conclusion

- This work was motivated by a particular problem of retrieving water level in Gorky reservoir. The problem was that for this elongated water body few telemetric impulses meet the validity criteria, which causes a severe loss of data.
- Using of GDR data was not successive (severe loss of data and low correlation with ground measurements).
- The average impulse response of the statistically inhomogeneous piecewise constant surface were calculated theoretically based on the works of Brown, (1977) and Barrick and Lipa (1985). The model was suggested based on the field measurements.
- A local re-tracking algorithm valid for the complex terrain valid for the area of interest. Application of the algorithm increases significantly the number of valid data and improves dramatically the accuracy of the water level retrieving from the altimetry.
- General principals of adaptive re-tracking algorithms for complex area (land, coastal zone, inland waters, etc) bases on calculations of the waveform taking into account statistical inhomogeneity of the reflecting surface adjusted to a certain geographic region are suggested.



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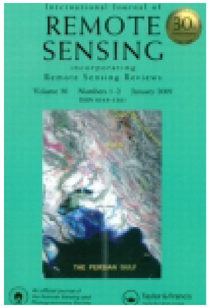
Supplementary Information in Our Publication



- *Yuliya Troitskaya, Galina Rybushkina, Irina Soustova, Galina Balandina, Sergey Lebedev & Andrey Kostianoy* (2012), **Adaptive retracking of Jason-1 altimetry data for inland waters: the example of the Gorky Reservoir,** *International Journal of Remote Sensing,* **33**(23)**,** 7559-7578. doi: 10.1080/01431161.2012.685972.

- *Troitskaya Yu.I., G.V. Rybushkina, I.A. Soustova, G.N. Balandina, S.A. Lebedev, A.G. Kostyanoi, A.A. Panyutin, L.V. Filina* (2012), **Satellite Altimetry of Inland Water Bodies.** *Water Resources*, **39**(2), 184–199. doi: 10.1134/S009780781202008X

  (Original Russian Text published in Vodnye Resursy, 2012, 39(2), 169–185)

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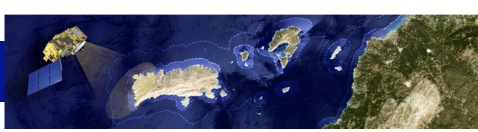
Thank you for your attention



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