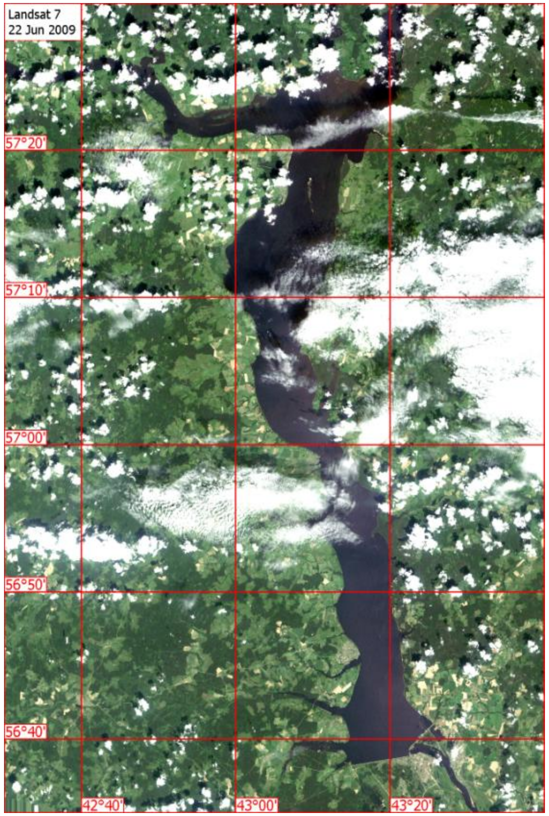


*Троицкая Ю.И.(1),*
*Рыбушкина Г.В.(1),*
*БаландинаГ.Н.(1),*
*Соустова И.А.(1),*
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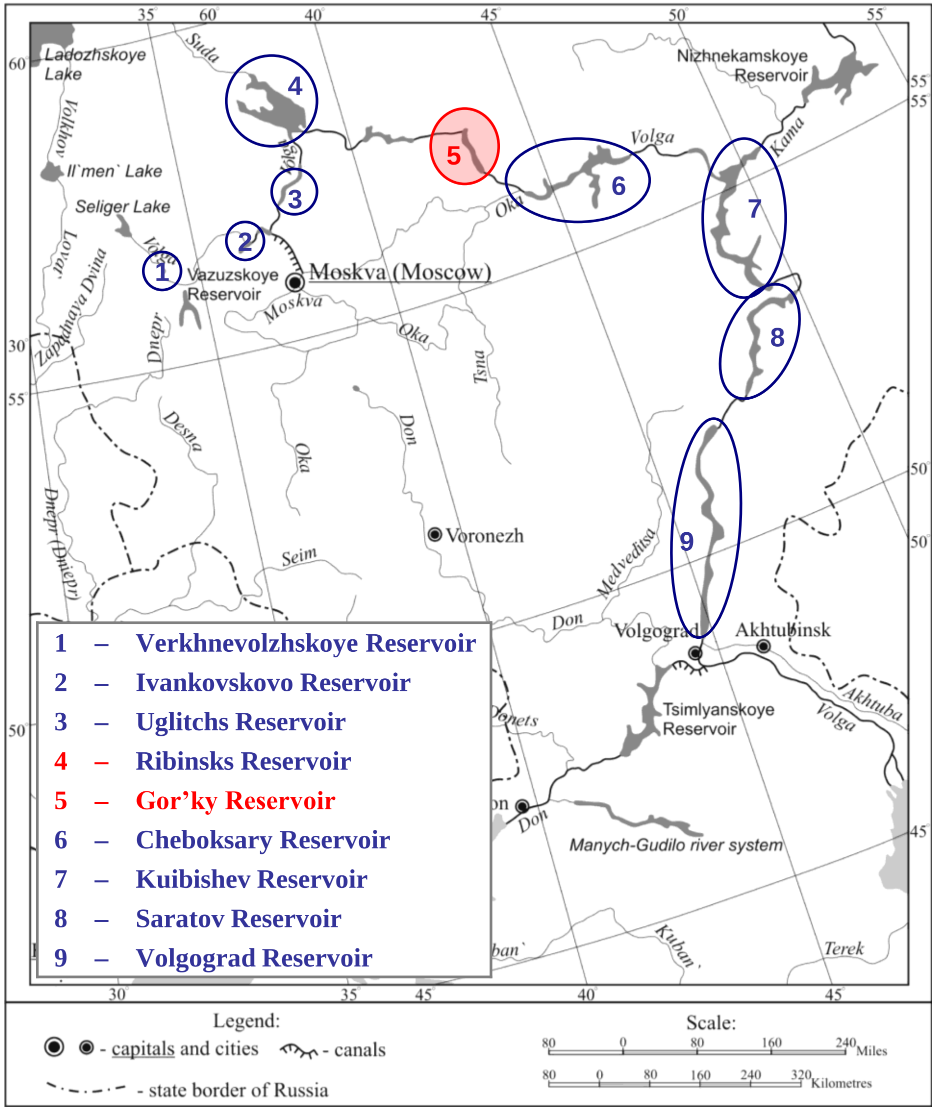
# Satellite altimetry of inland water bodies. II. Experimental Coastal and Hydrology products and results of analysis

# The Volga Water Reservoirs System




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

**Five reservoirs (Verkhnevolzhskoye, Ivankovo, Uglitch, Ribinsk and Gor'ky 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.**

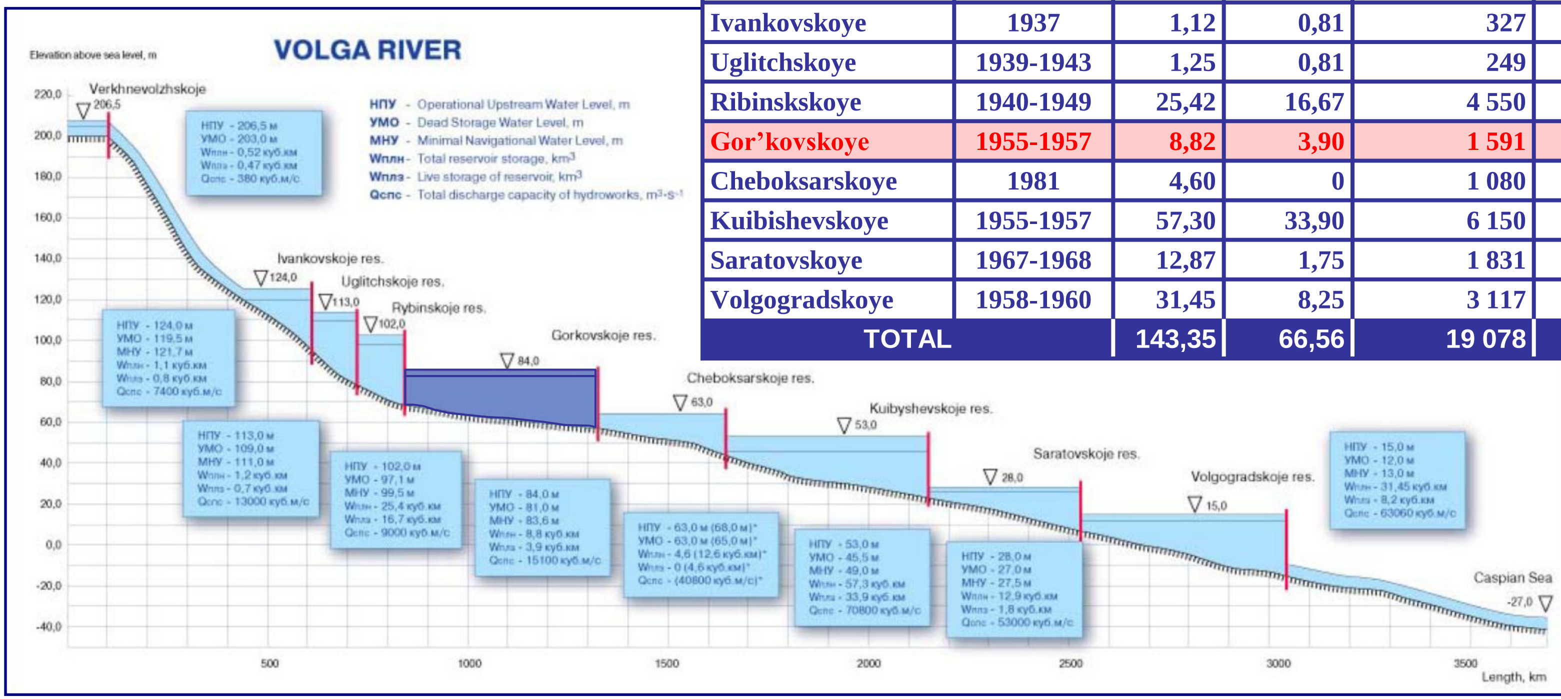
**The Volga Water Reservoir System have total volume – 143.35 $km^3$ and effective volume – 66.56 $km^3$.**

# The Volga Water Reservoirs System

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

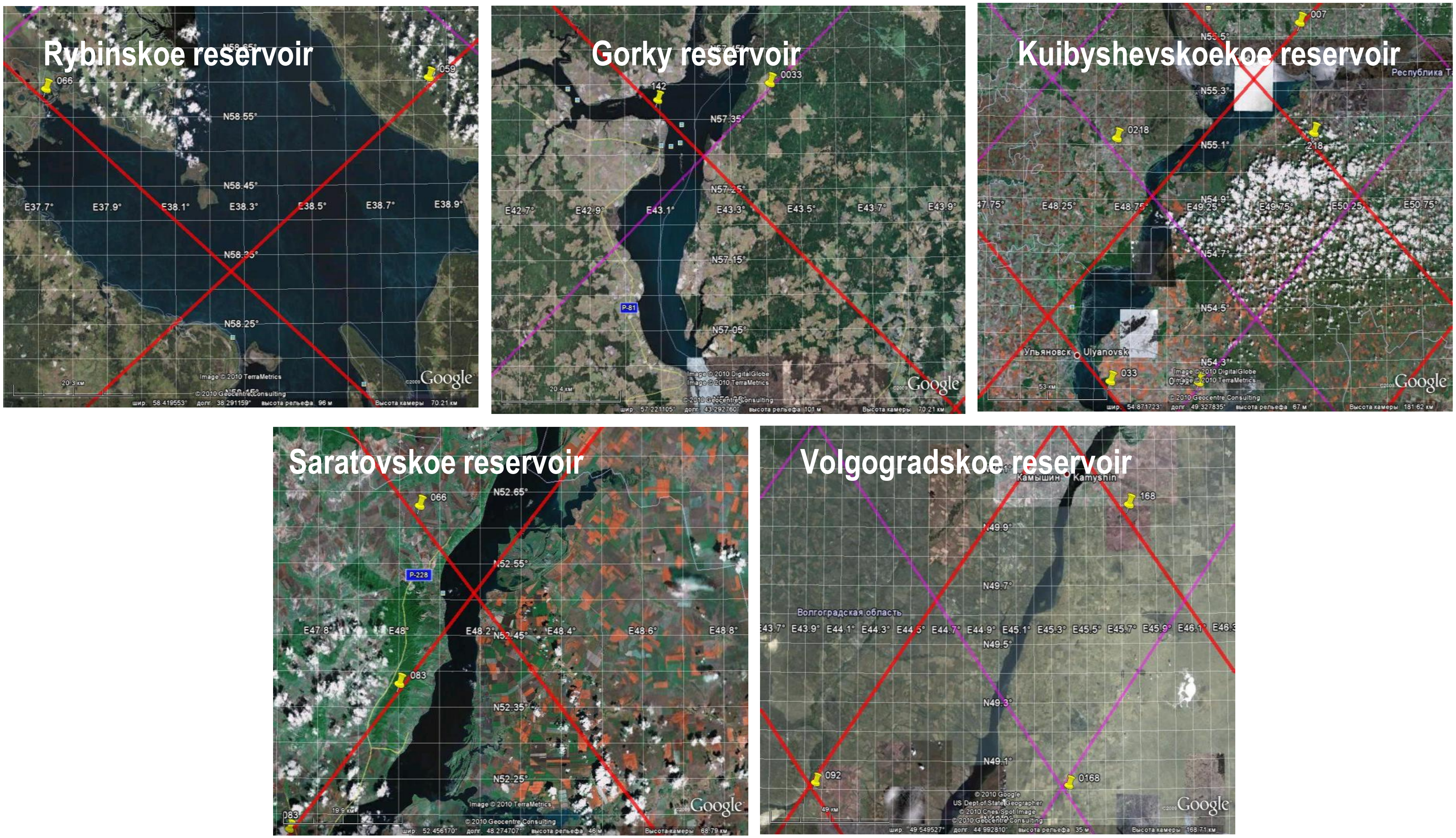
<u>Table:</u> The general parameters of the Volga water reservoirs system

| Reservoir | Year | Volume, km$^3$ | | Water surface area, km$^2$ | Surface elevation, m | Discharge max, m$^3$/s |
|---|---|---|---|---|---|---|
| | | total | effective | | | |
| Verkhnevolzhskoye | 1843,1944 | 0,52 | 0,47 | 183 | 206,5 | 47 |
| Ivankovskoye | 1937 | 1,12 | 0,81 | 327 | 124,0 | 7 400 |
| Uglitchskoye | 1939-1943 | 1,25 | 0,81 | 249 | 113,0 | 13 000 |
| Ribinskskoye | 1940-1949 | 25,42 | 16,67 | 4 550 | 102,4 | 9 000 |
| Gor'kovskoye | 1955-1957 | 8,82 | 3,90 | 1 591 | 84,0 | 15 100 |
| Cheboksarskoye | 1981 | 4,60 | 0 | 1 080 | 63,0 | 40 800 |
| Kuibishevskoye | 1955-1957 | 57,30 | 33,90 | 6 150 | 53,0 | 70 800 |
| Saratovskoye | 1967-1968 | 12,87 | 1,75 | 1 831 | 28,0 | 53 000 |
| Volgogradskoye | 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.**

# Jason-1 and Jason-2 altimetry satellites' tracks intersecting the Volga River Reservoirs

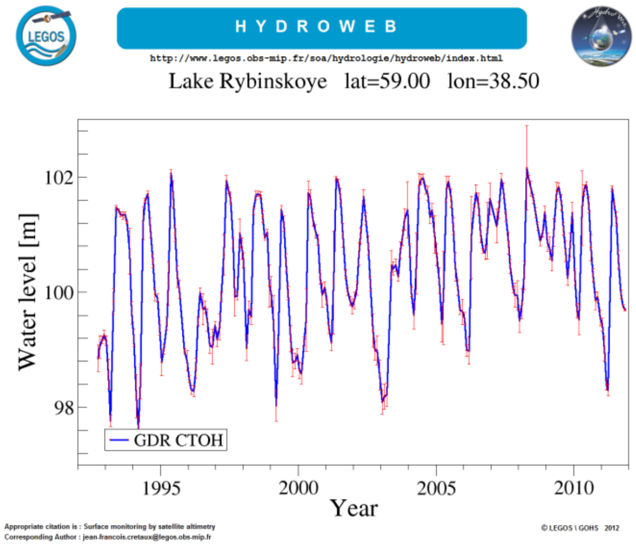


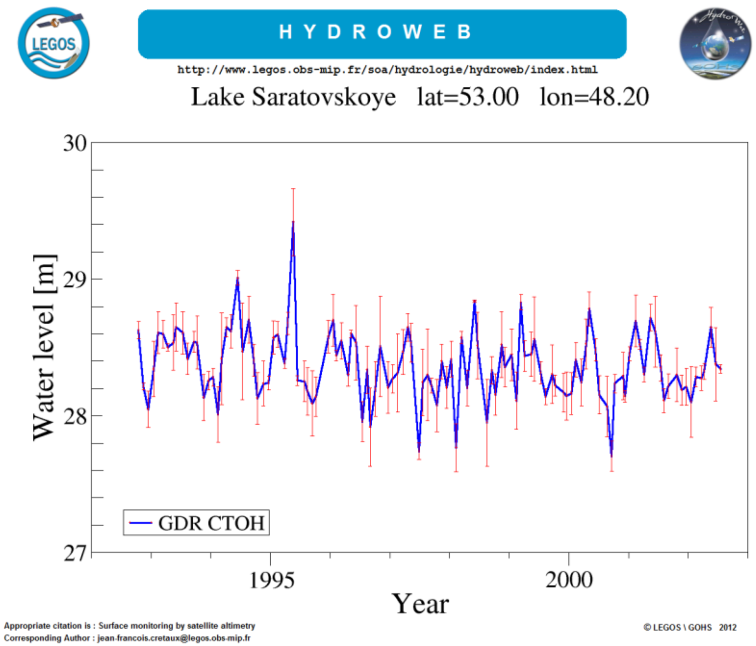

**Main Volga River reservoirs with appropriate ground tracks of altimetry satellites Jason-1 and Jason-2: (a) Rybinsk Reservoir – 059 and 066 passes; (b) Gorky Reservoir – 142 and 0033 passes; (d) Kuibyshev Reservoir – 007, 142, 218 and 0218 passes; (e) Saratov Reservoir – 083 and 066 passes; (f) Volgograd Reservoir – 168 and 0168 passes**

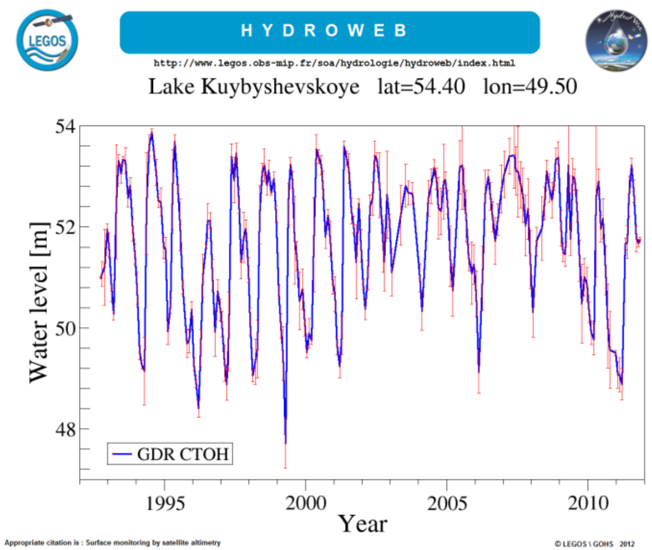
# H Y D R O W E B
## Water level of rivers and lakes by satellite altimetry

http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb

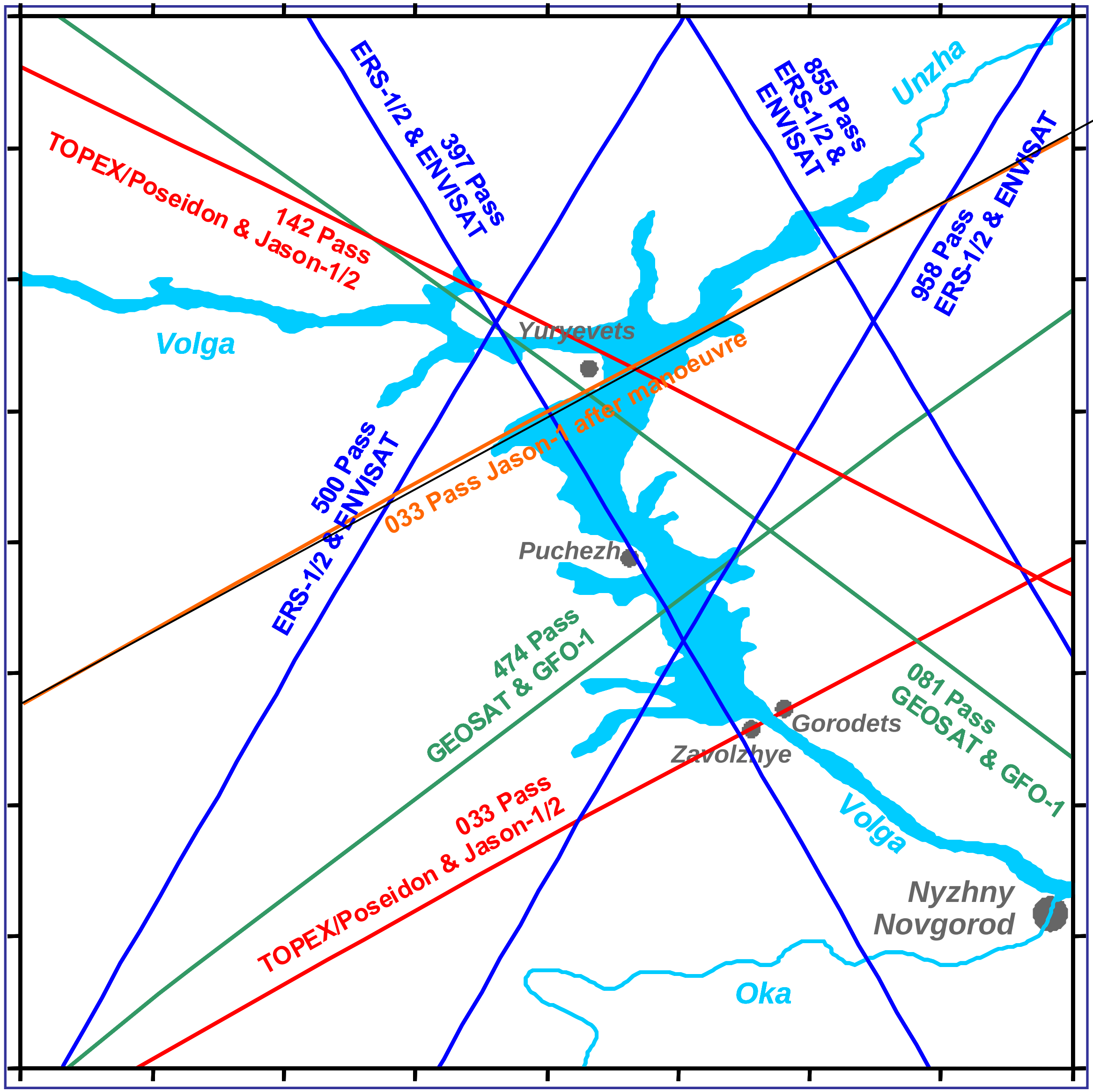
Volga reservoirs



# The Gorky Reservoir and ground tracks of satellites




| | |
|---|---|
| Total surface | 1 591 km$^2$ |
| Water volume | 12.9 km$^3$ |
| Total length | 429 km |
| Max. width | 14 km |
| Max. depth | 22 m |
| Average surface level with respect to Baltic system | 84 m |

Envisat, ERS-1,2

TOPEX/ Poseidon Jason-1,2 (before manoeuvre)

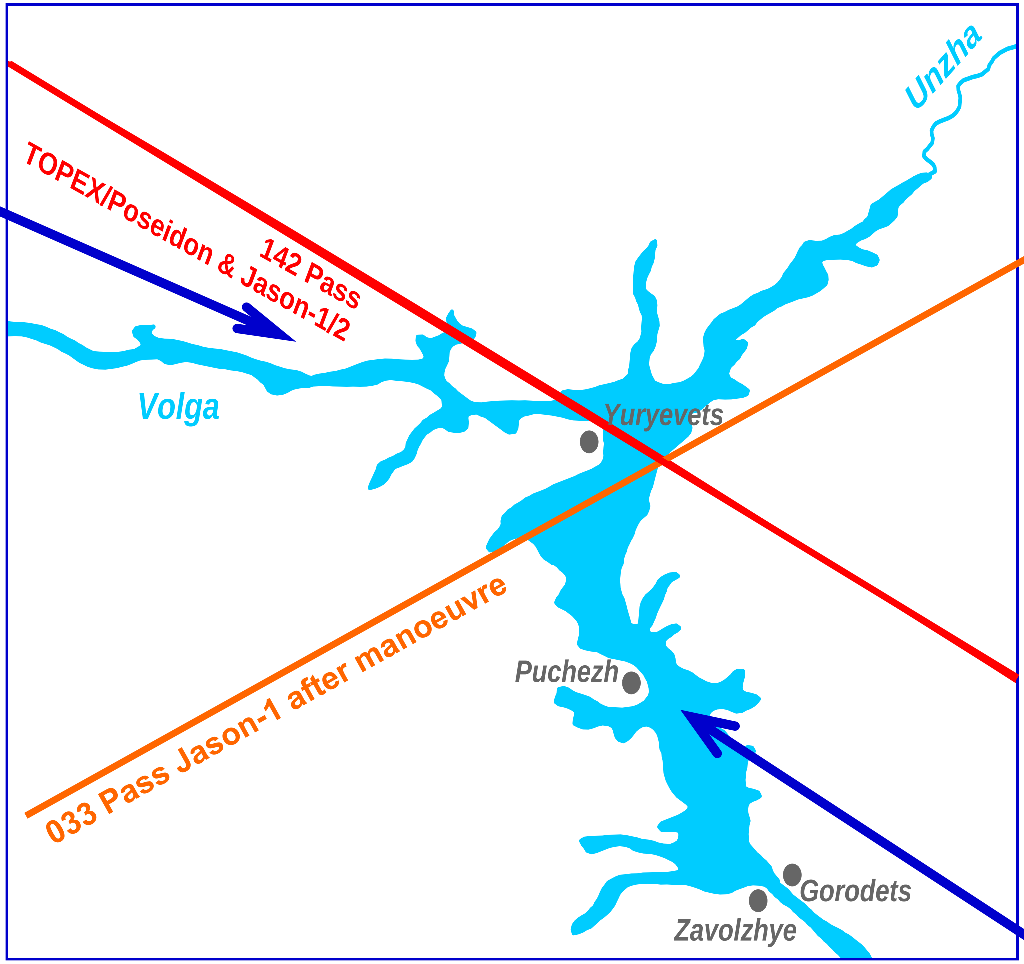
Jason-1 (after manoeuvre)

GEOSAT GFO-4

# Map and groundtrack of GDR Data Jason-1

River and river-lake parts of the Gorky reservoir

| | |
|---|---|
| Total length | 332 km |
| Width | 0.6-3.5 km |




Lake part of the Gorky reservoir

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

These satellites were selected because:

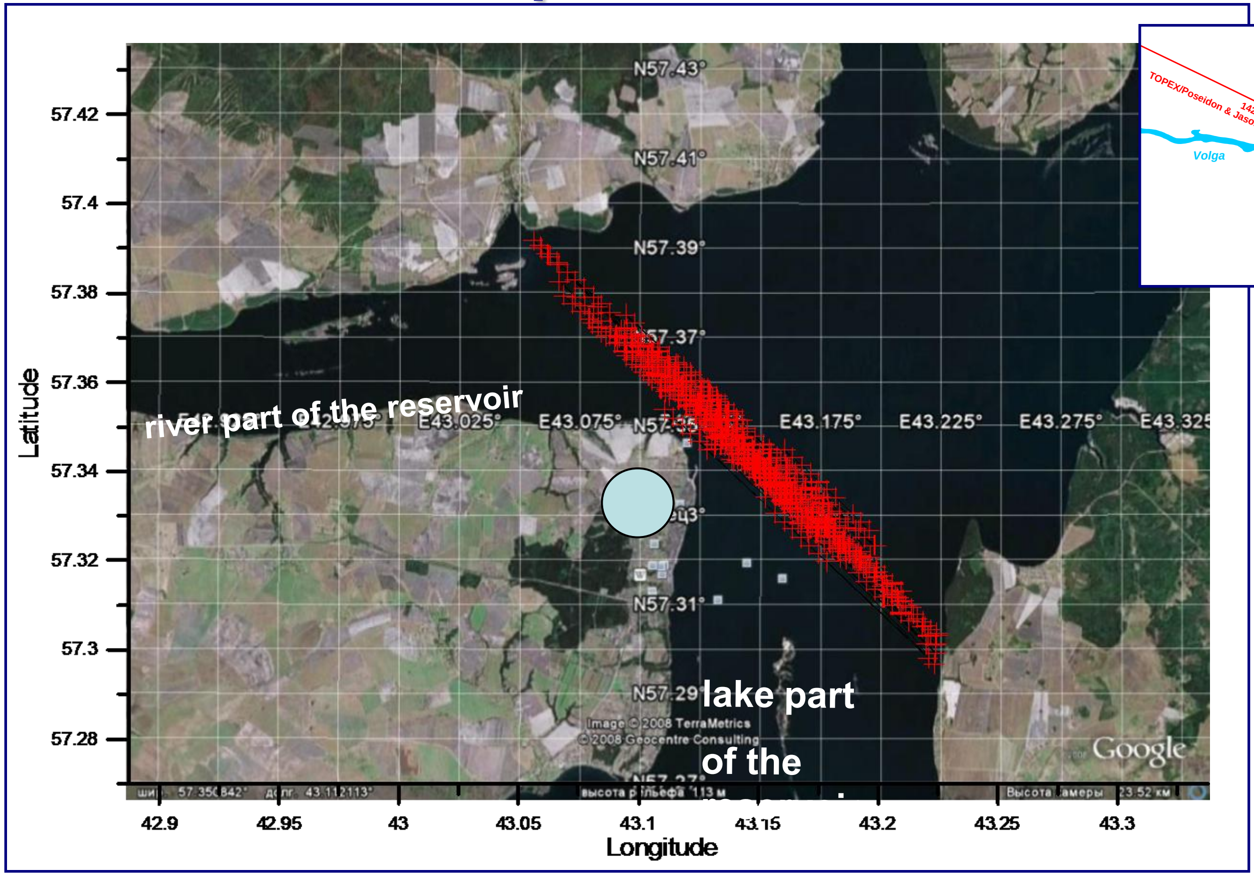
- The orbital repeat period (~9.916 days) is close to characteristic temporal scale of the basic hydrological phenomena.
- The T/P and J1 data represent the longest time series of altimetry measurements.

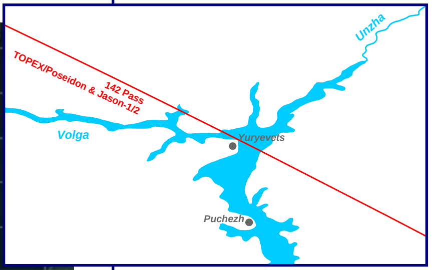
# First stage of Processing of Satellite Altimetry Data

- In the first stage Geophysical Data Records (GDR) of TOPEX/Poseidon (T/P) and Jason-1 (J1) satellites were processed. All available along track 10Hz TOPEX / Poseidon and 20Hz Jason-1 altimetry data were used.

- 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.

# Groundtrack of 142 pass of GDR Data Jason-1



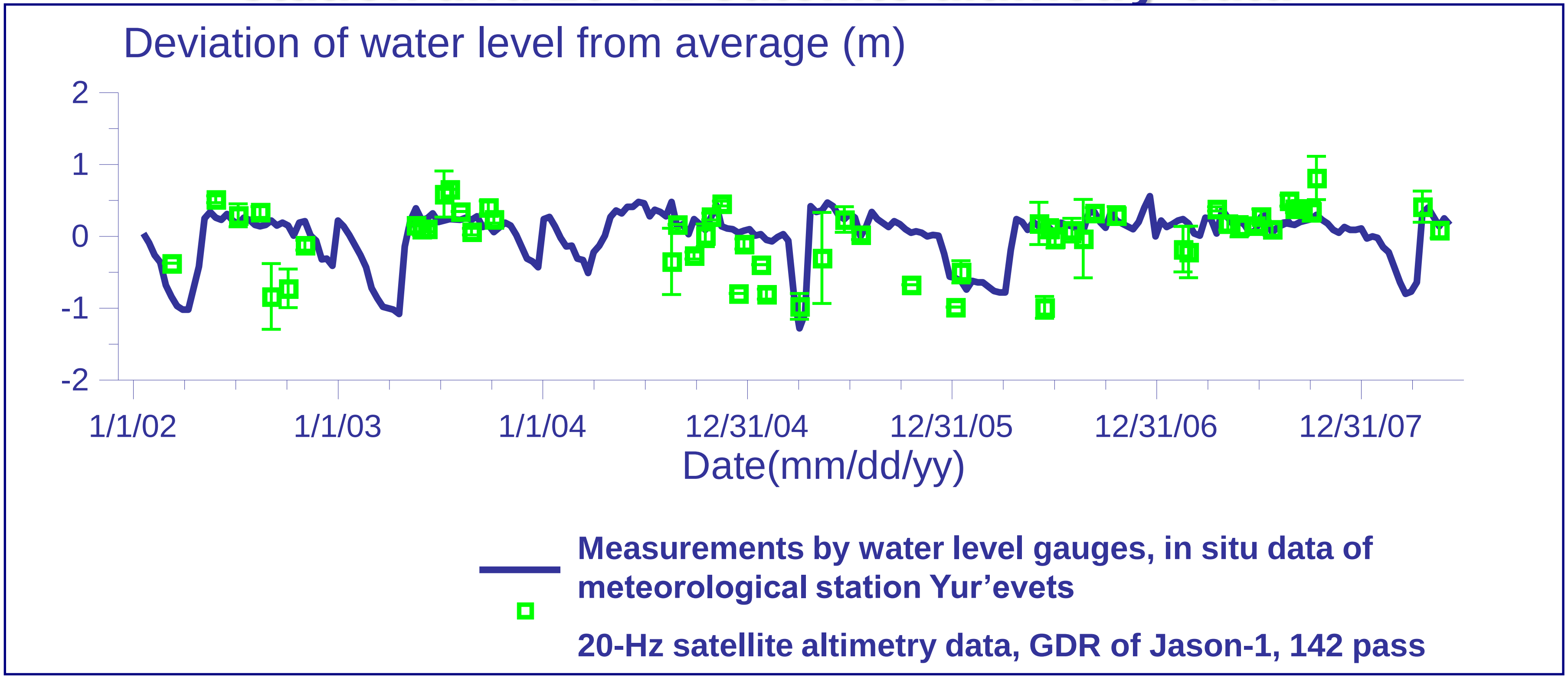




Nadir points for 20Hz GDR data for 142 pass Jason-1
(2002-2009 years)

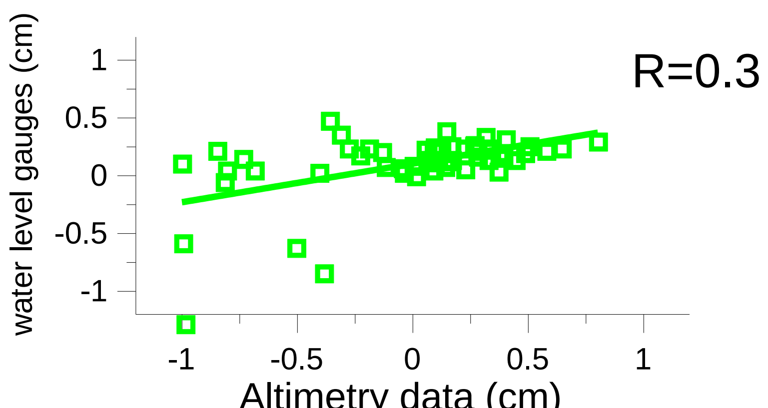
The number of points is essential

Altimetry data were compared with measurements from the ground station

# Comparison of water level variations measured by ground station and 20 Hz satellite altimetry data



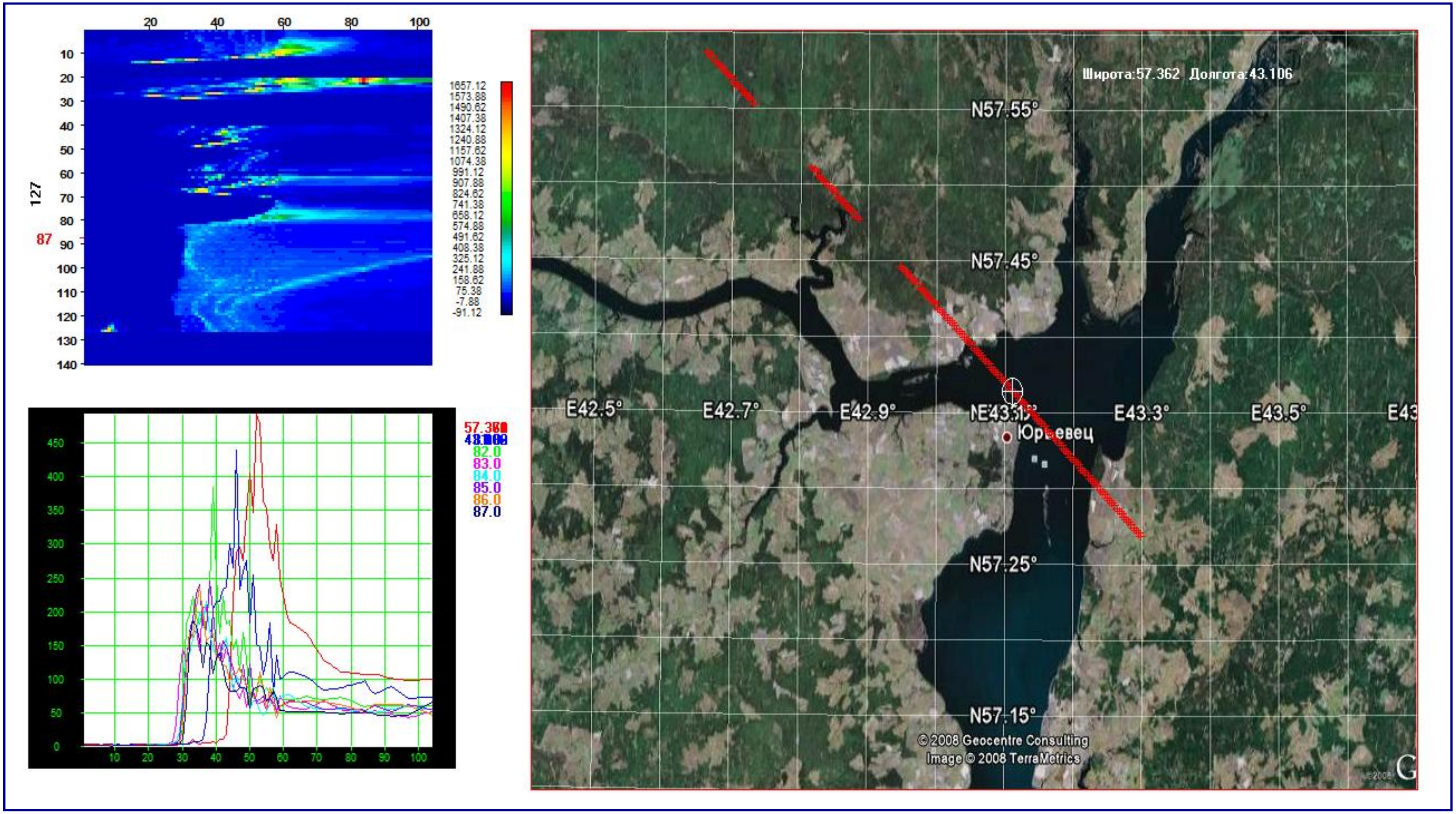

**Water level**
**(correlation of altimetry data and in situ measurements)**




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

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

# The cause of large errors of the ocean re-tracking algorithm is complicated waveforms of Jason-1




**Land topography and hydrometeorological regime of the Gorky reservoir should be taken into account when constructing the local re-tracking algorithm**

# The hydrometeorological regime of the Gorky reservoir has strong seasonal variability

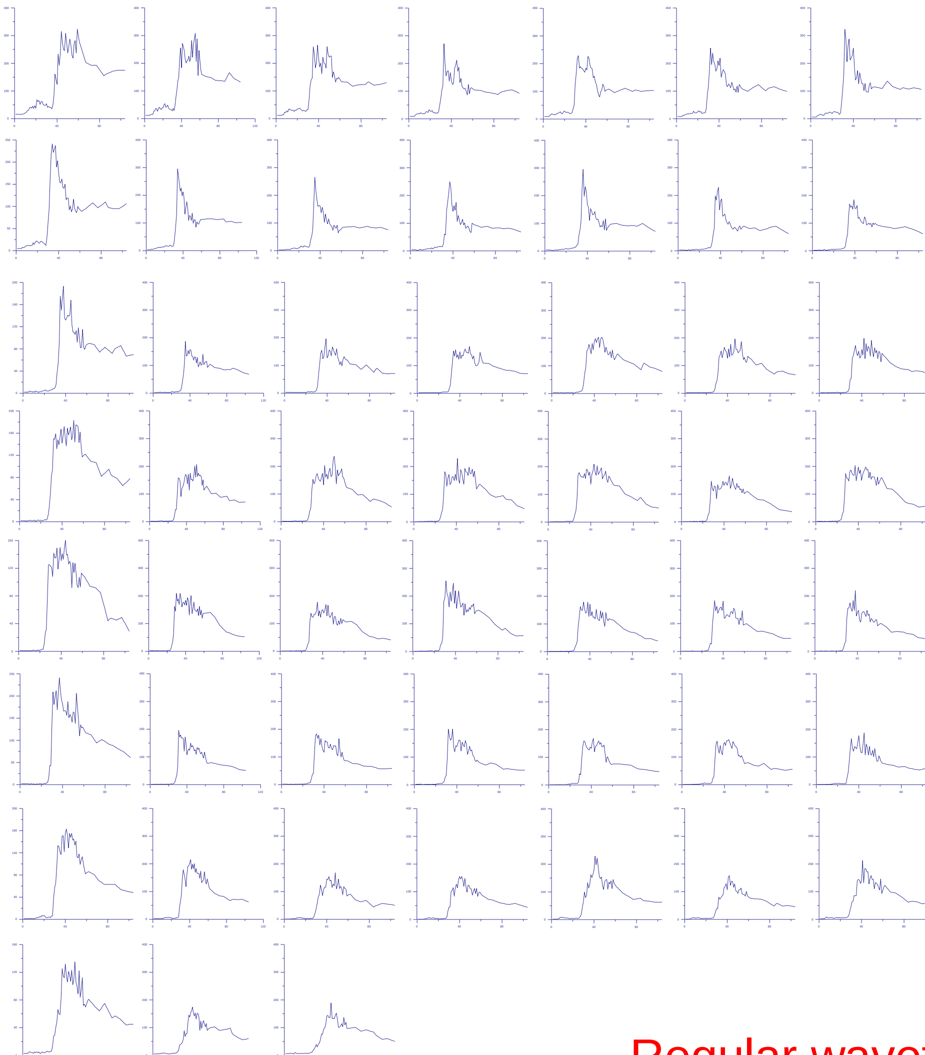
**Winter (ice over the total water area covered by a show layer) (November – April)**

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)–

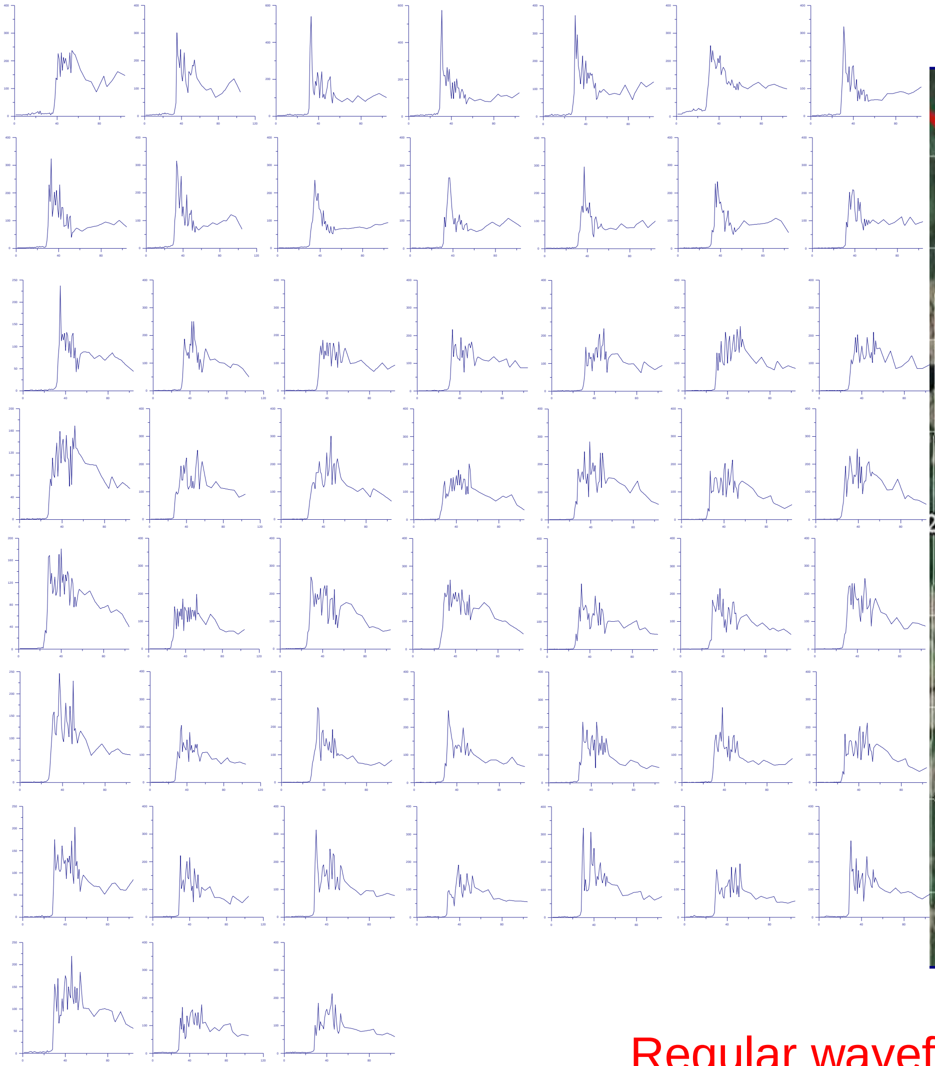
**Summer (the water area is free of ice ) (May-October)**

# Jason-1, Cycle 118, Pass 142, Ku band
# Winter (25.03.2005)



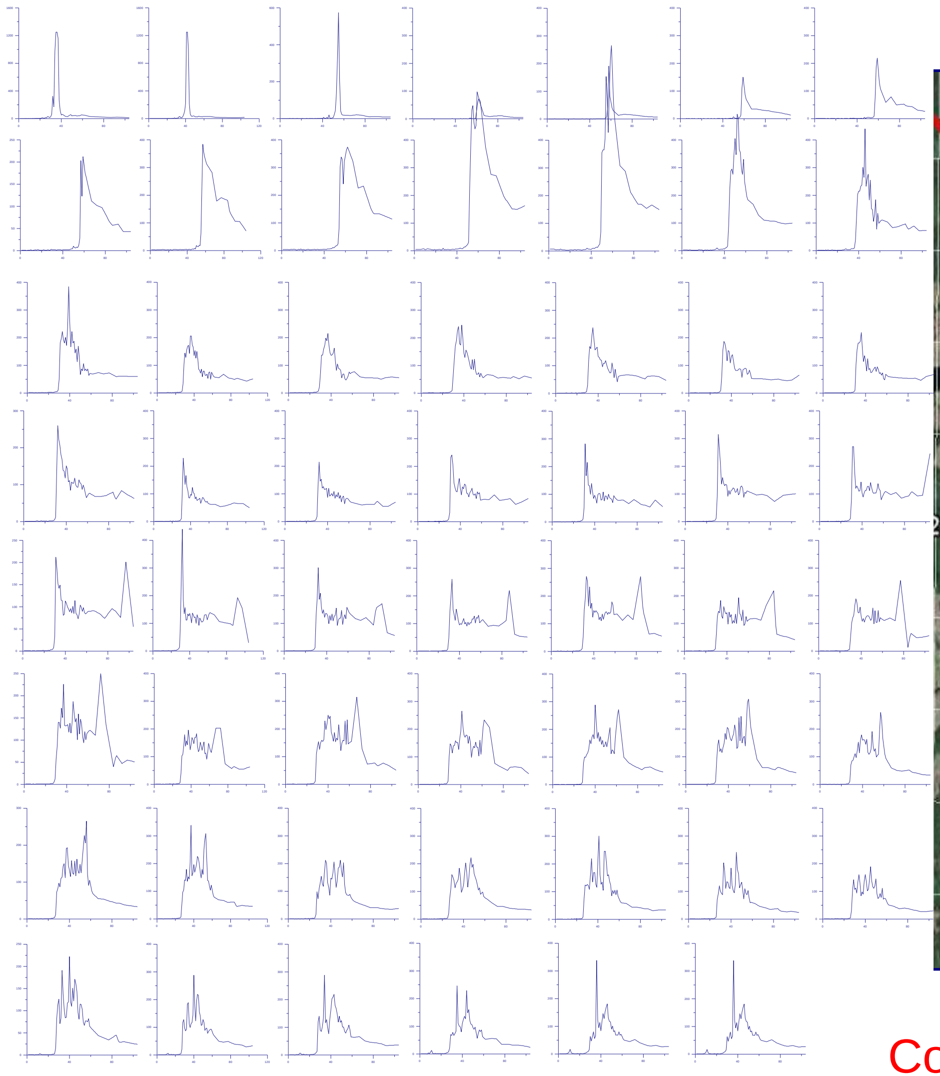

Regular waveforms valid for ice-retracking

# Jason-1, Cycle 118, Pass 142, C band
# Winter (25.03.2005)



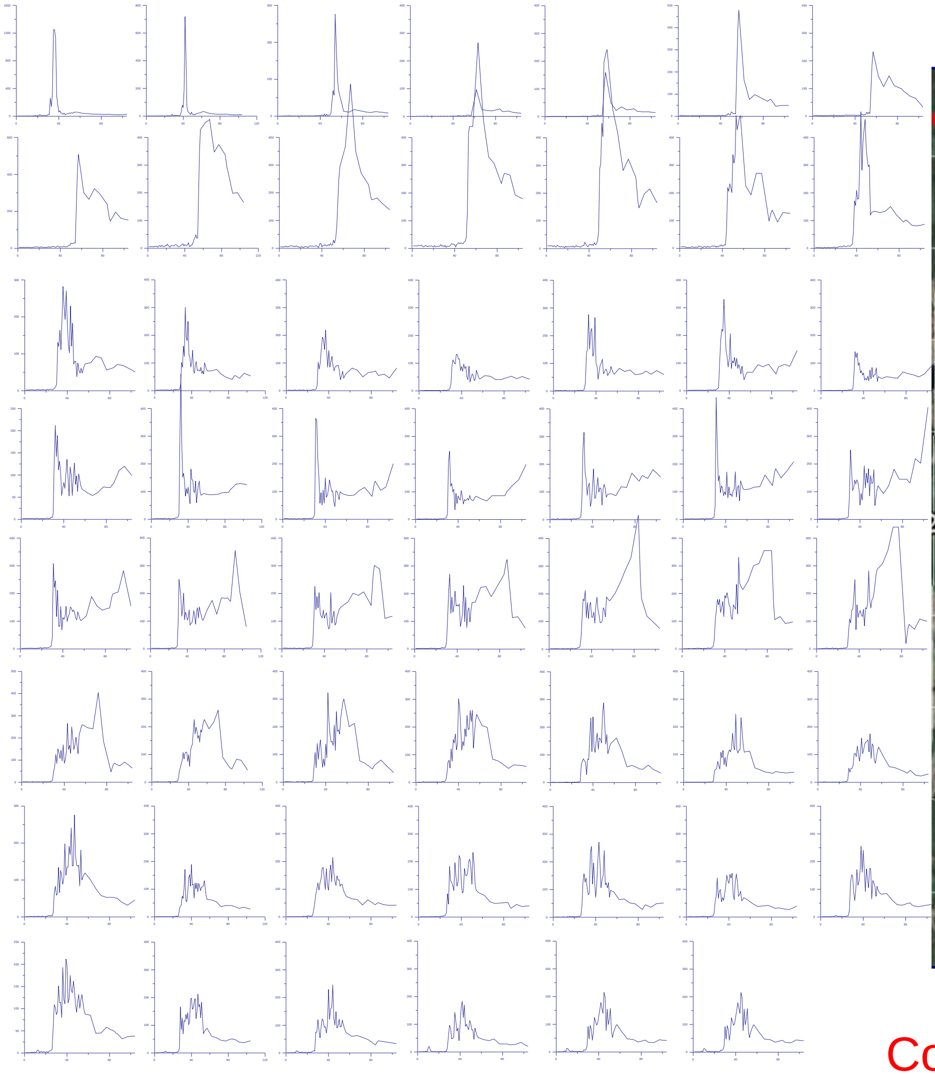

Regular waveforms valid for ice-retracking

# Jason-1, Cycle 162, Pass 142, Ku band
# Summer (05.06.2006)




Compex waveforms

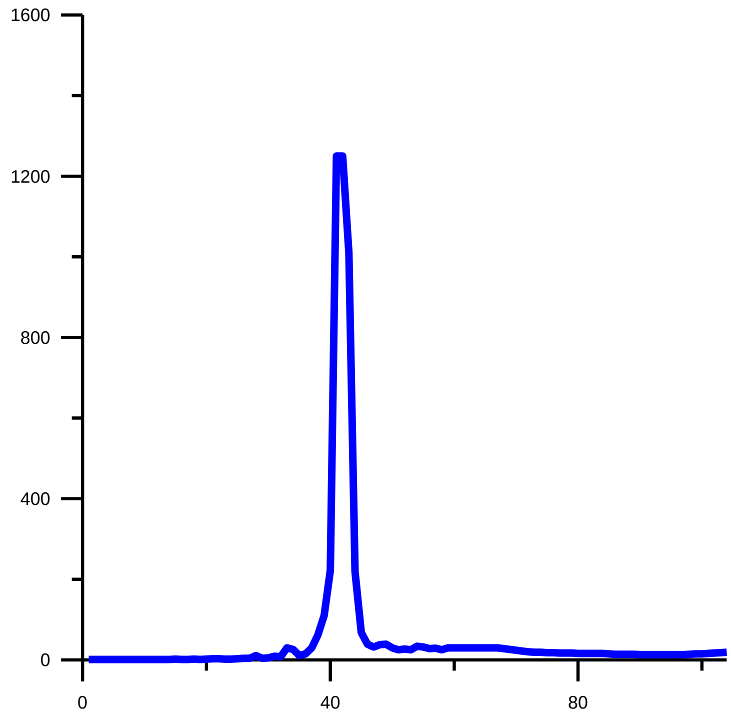
# Jason-1, Cycle 162, Pass 142 C band
# Summer (05.06.2006)



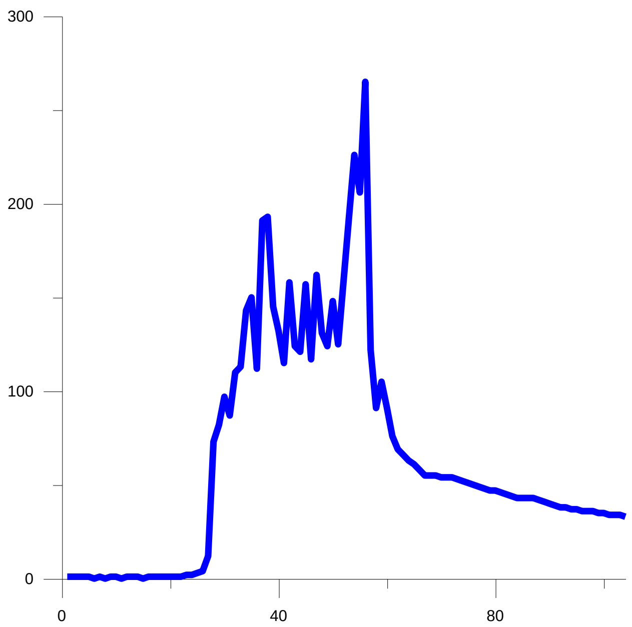

Complex waveforms

# Compex waveforms

## Quasi Specular components




## Multiple Quasi-Specular components



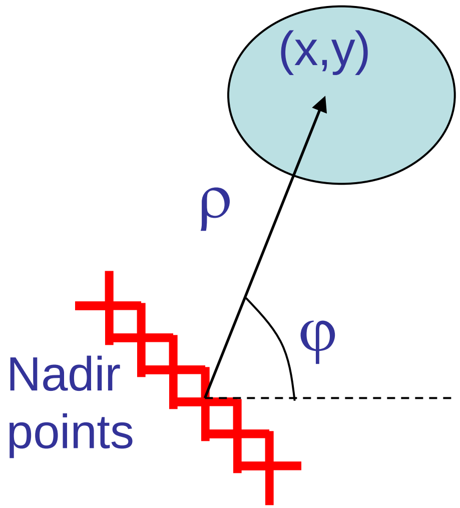

**The Brown's formula are not typically valid for approximation of the wave forms, an adaptive retracking algorithm is required.**

# Model of waveforms for Gor’ky Reservoir

# The average impulse response of the rough inhomogeneous surface

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

$$\times \exp\left\{ -\frac{\left(c\tau - 2H(\rho,\varphi) - \rho^2/h\right)^2}{8\left(s^2(\rho,\varphi) + c^2\tau_i^2\right)} \right\} \rho d\rho d\varphi$$




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

**For water surface**

Elevation *H* is the water level

*s* is significant wave height

σ is determined by the wind speed

**For land surface**

Elevation *H* is determined by topography

*s* is surface roughness

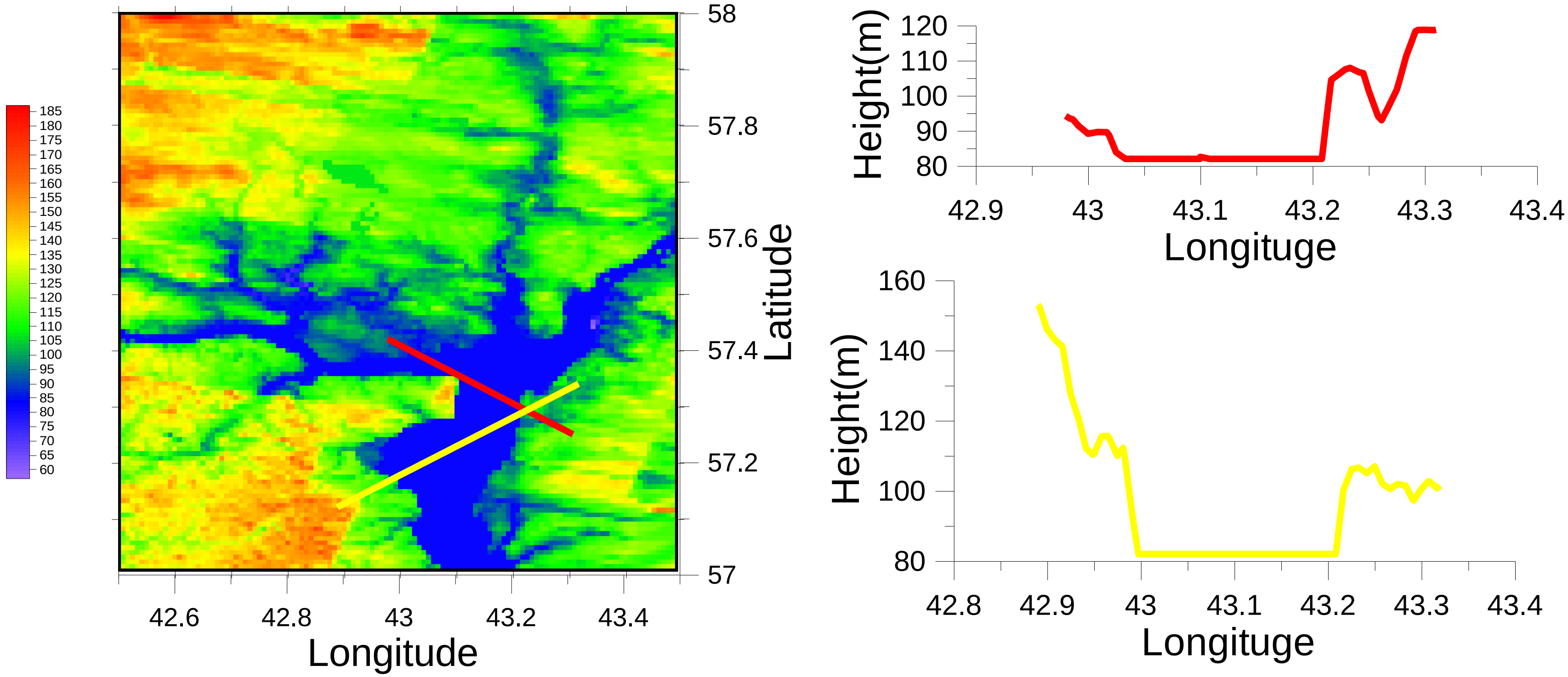
σ is determined by the reflecting properties of the surface

*s* and σ depend on ρ and φ

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

# Topography and along-track cross section for 142 pass of Jason-1

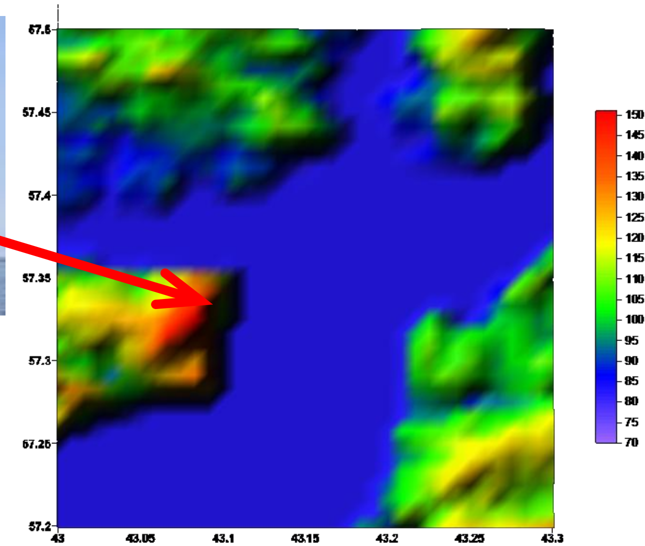
***Global Land One-km Base Elevation Project (GLOBE). Digital data base on the World Wide Web (URL: http://www.ngdc.noaa.gov/mgg/topo/globe.html***

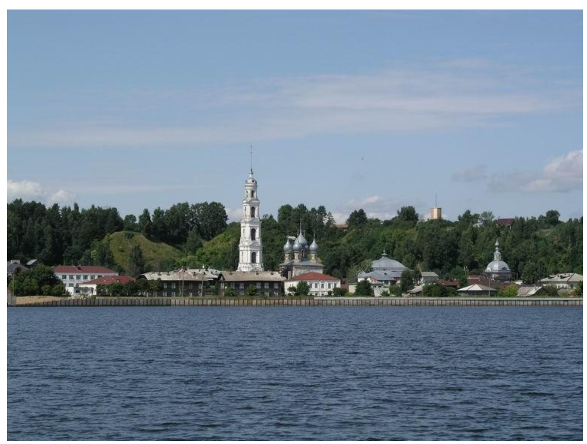



**A 30-arc-second (1-km) gridded, quality-controlled global Digital Elevation Model (DEM) gives right bank height – 30 m, left bank height – 20 m).**

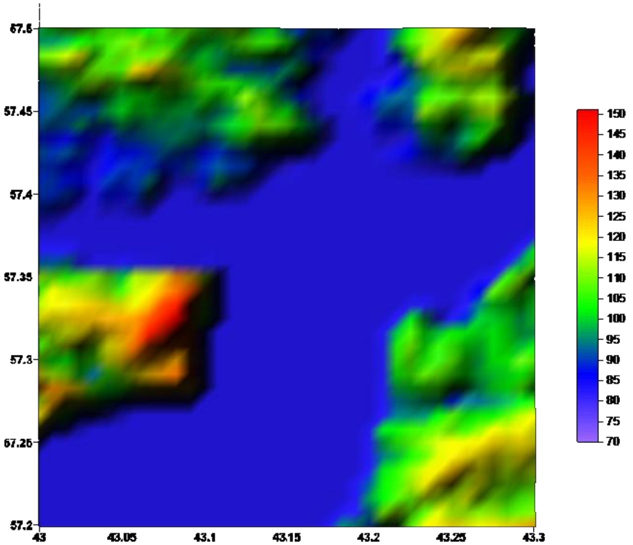
**The backscattering coefficient at the land is an order below than at the water surface**

# Landscapes and water area of the Gorky reservoir near the ground track of Jason-1,2 (right bank, 20-30 m height) (field studies, July 2009)



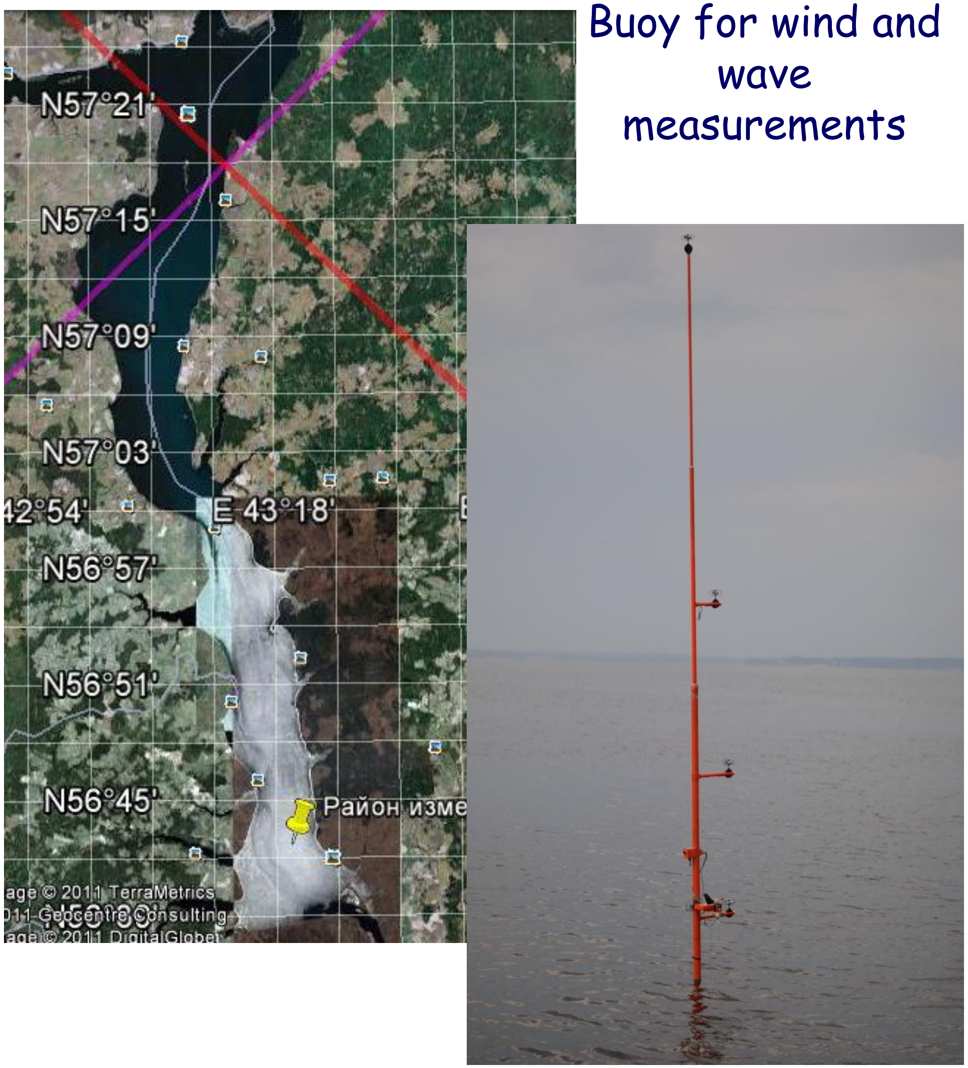



# Landscapes and water area of the Gorky reservoir near the ground track of Jason-1,2 (left bank, up to 10 m height)

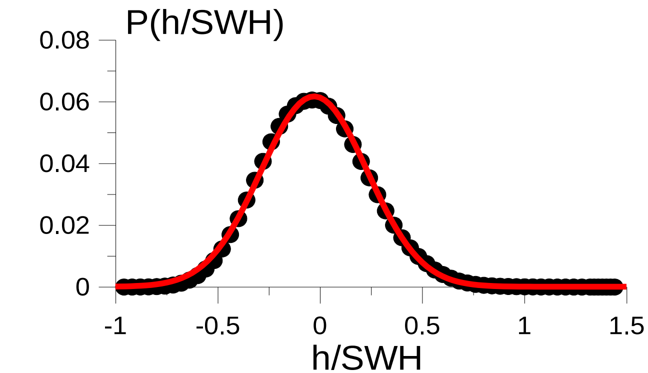


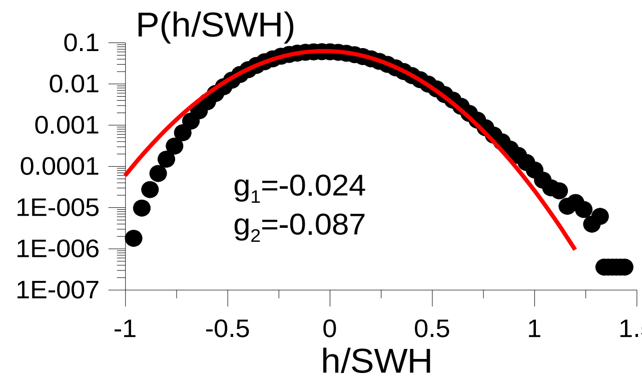

## Probability density of specular points and significant wave height

Buoy for wind and wave measurements

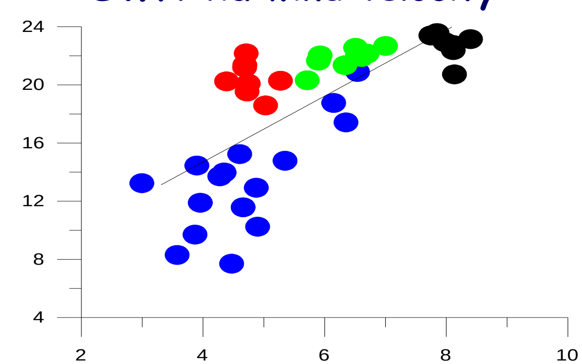



## Probability density of water surface elevation

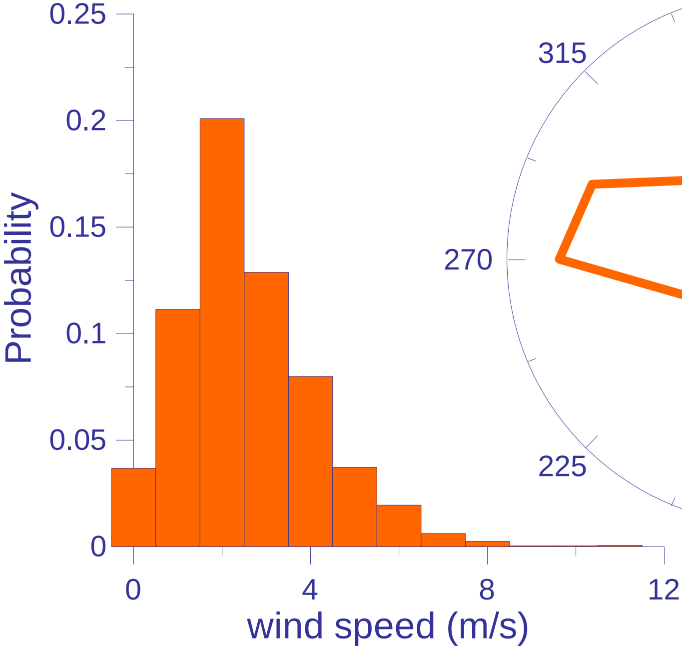


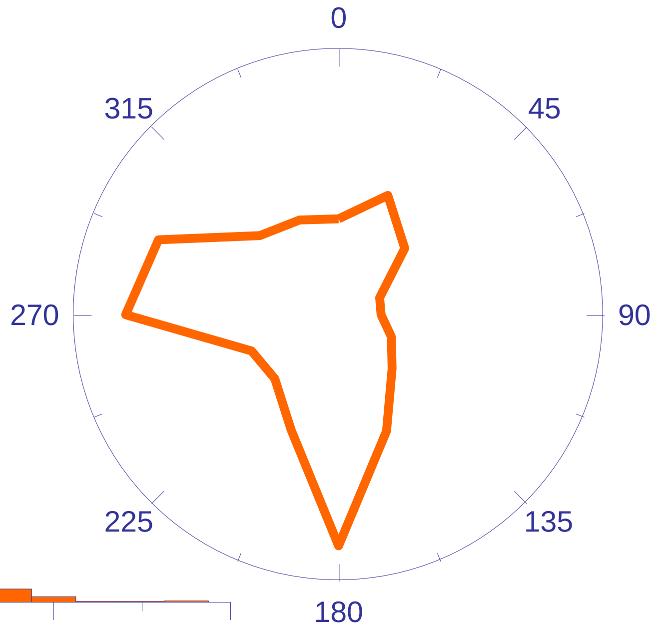




## SWH via wind velocity

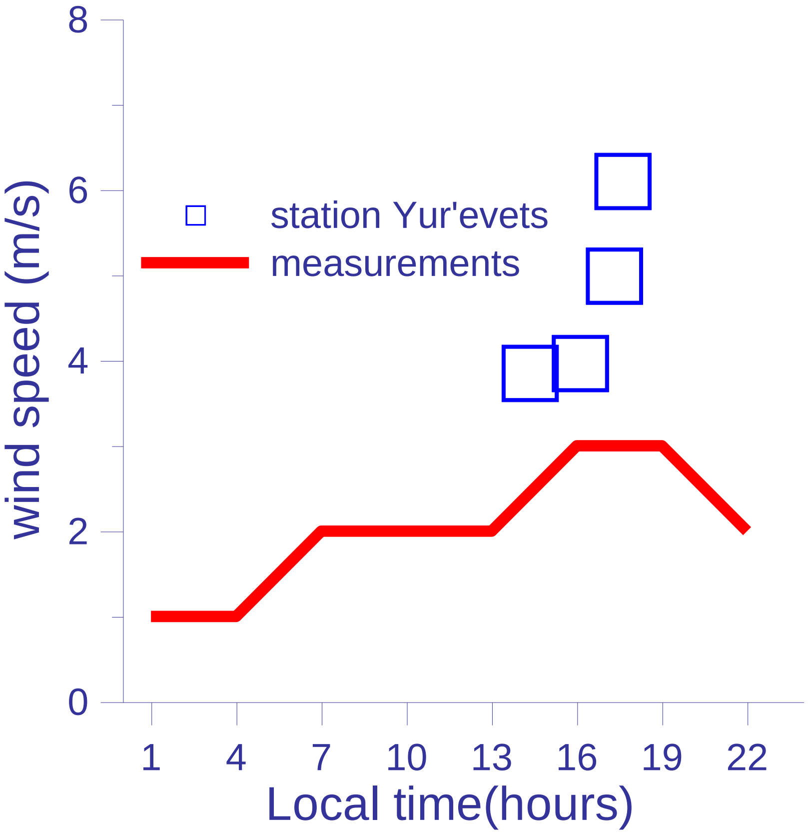


# Wind speed and wind direction, summer 2008-2009 (meteorological station Yur'evets, 57°20'N 43°07'E )




# Comparison of the wind speed data of the station Yur’evets and field measurements 29.07.2009

# Statistics of wind waves

**JONSWAP, 1985**

**Significant wave height for wind speed $U_{10}$ and fetch $x$**

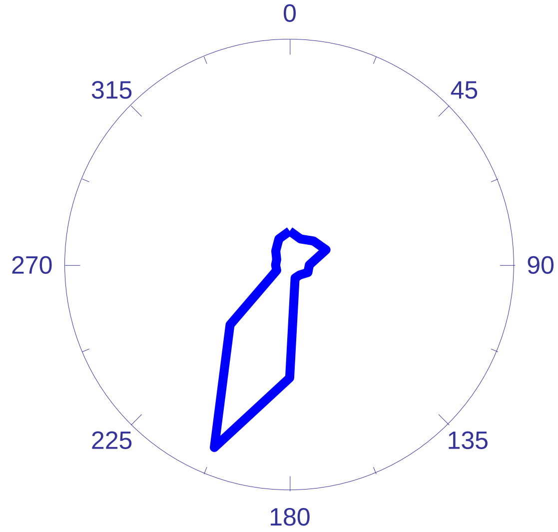
$$SWH = 0.2074 \frac{U_{10}^2}{g} \Omega^{-1.55}$$

**Wave age parameter**

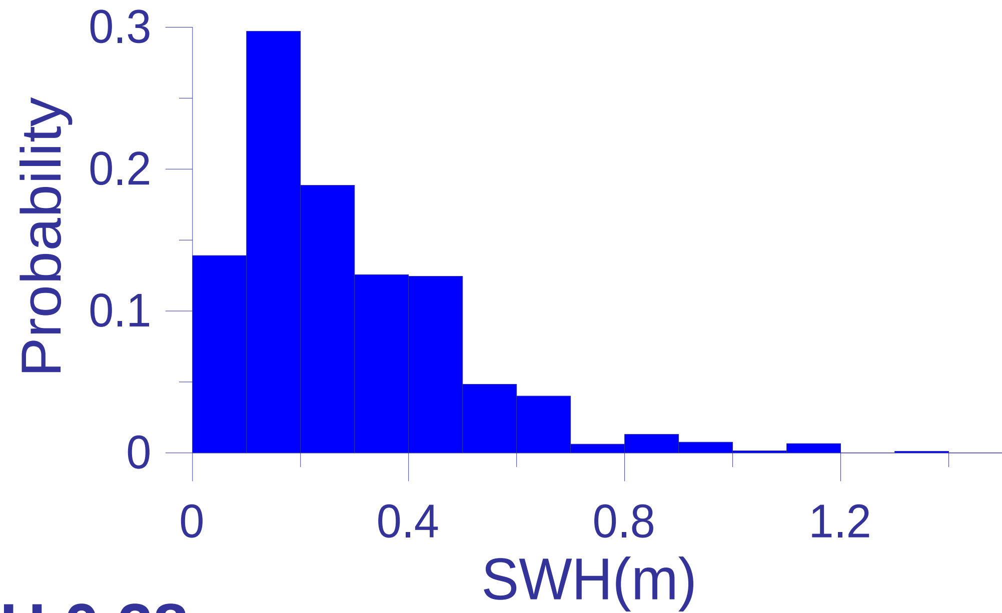
$$\Omega = 11.6 \left( \frac{gx}{U_{10}^2} \right)^{-0.23}$$

**For the middle point of the ground track of the 142 pass of Jason-1**

Angle distribution of fetches for the corresponding wind directions




Statistics of SWH




**Average SWH 0.28 m**

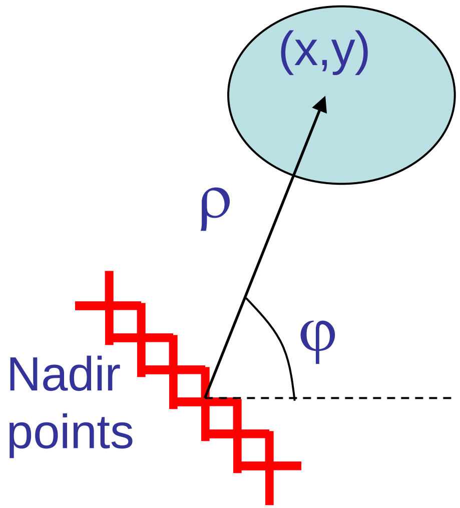
# Algae bloom 29.07.2009

# Special features – slicks the shore (10-30 m width)

# The average impulse response of the rough inhomogeneous surface

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

$$\times\exp\left\{-\frac{\left(c\tau-2H(\rho,\varphi)-\rho^2/h\right)^2}{8\left(s^2(\rho,\varphi)+c^2\tau_i^2\right)}\right\}\rho d\rho d\varphi$$




<u>For water surface</u>

Elevation *H* is constant

*S* is significant wave height

σ is determined by the wind speed

<u>For landsurface</u>

Elevation *H* is variable

*S* is surface roughness

σ is determined by the reflecting properties of the surface

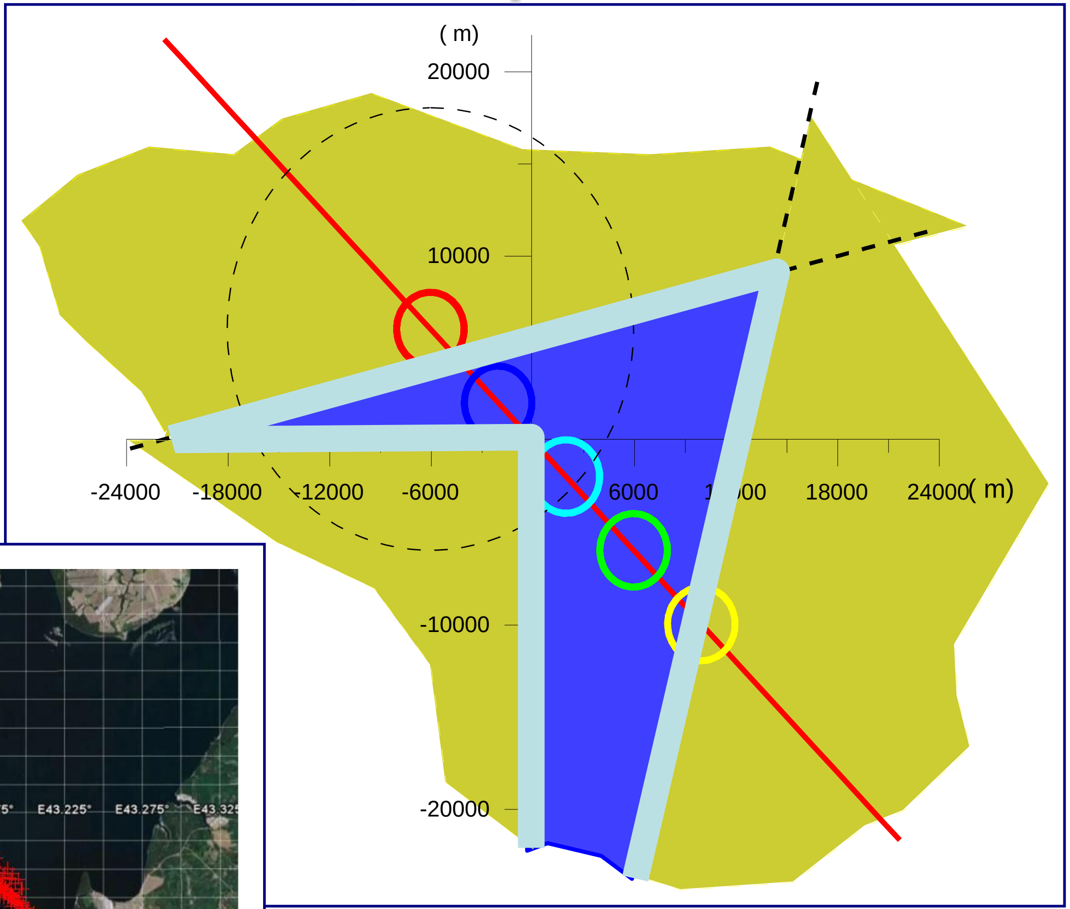
*S* and σ depend on ρ and φ

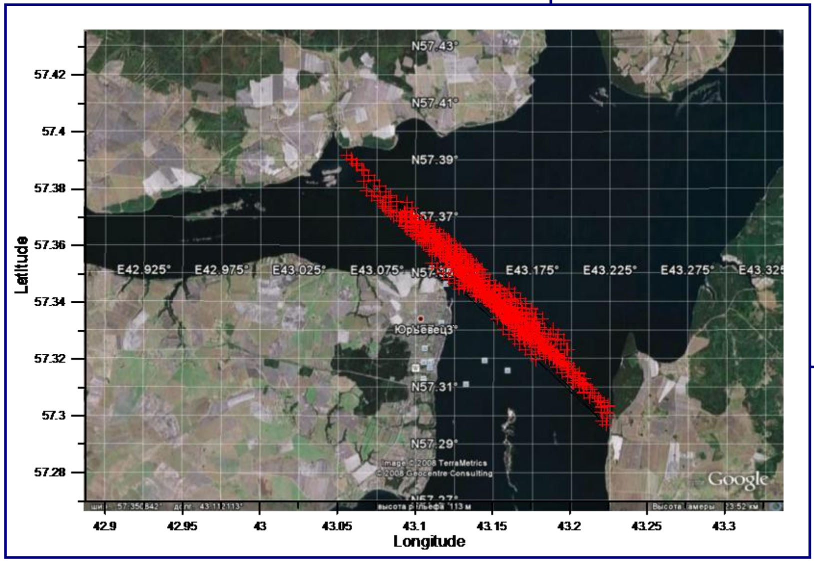
**A simplified piecewise constant model of surface**

# A piecewise constant model of Reflecting Surface for Gor’ky Reservoir , 142 pass

## The model of the reflecting surface

*land – gold grey color,*
*water - dot shading blue color,*
*light blue – coastal slicks,*
*small circles – positions of the footprint,*
*the big dotted circle – an area illuminated by the gain of the radar antenna*



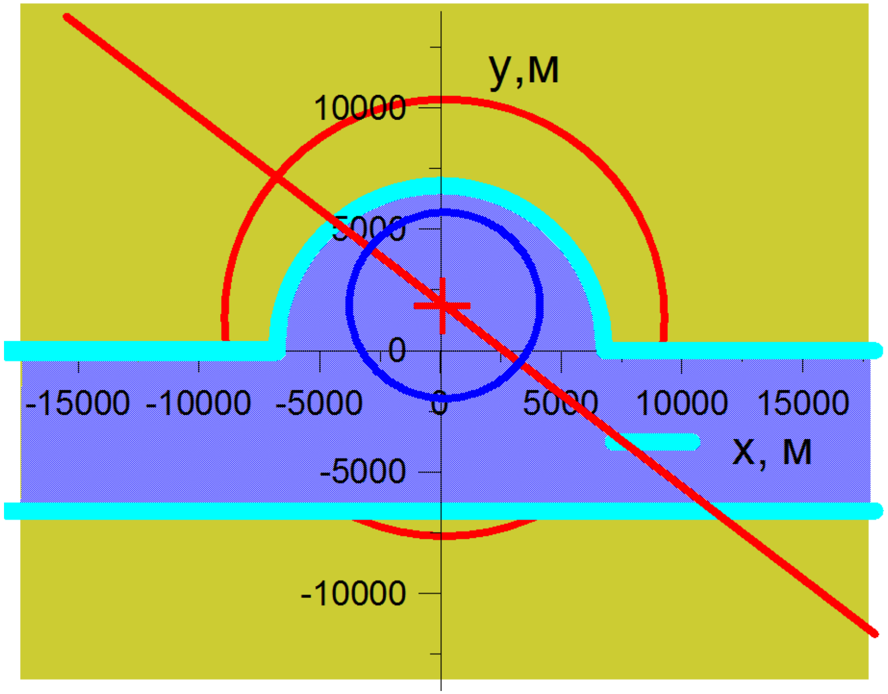



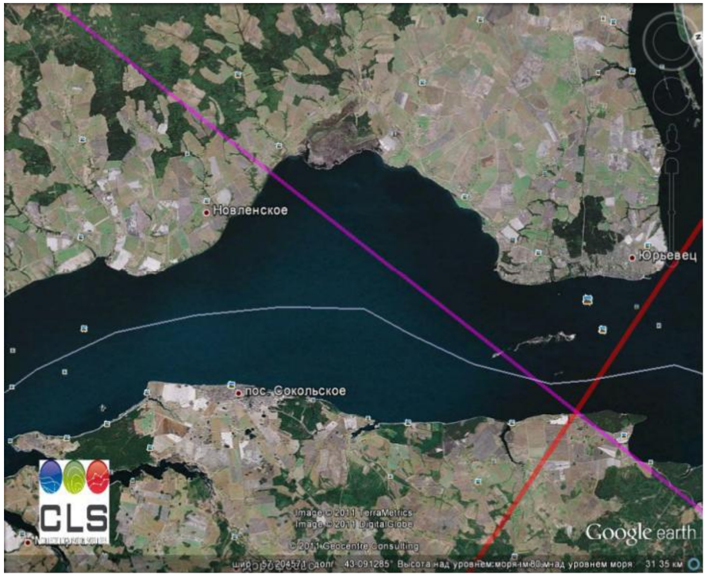

**Nadir points of 20Hz SGDR data for 142 pass Jason-1 (2002-2009 years)**

# A piecewise constant model of Reflecting Surface for Gor'ky Reservoir , 33 pass (after manoeuvre)

**The model of the reflecting surface**

*land – gold grey color,*
*water - dot shading blue color,*
*light blue – coastal slicks,*
*small circles – positions of the footprint,*
*the big dotted circle – an area illuminated by the gain of the radar antenna*




**Ground track for 33 pass Jason-1**

## The average impulse response for piecewise constant model of surface

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

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

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

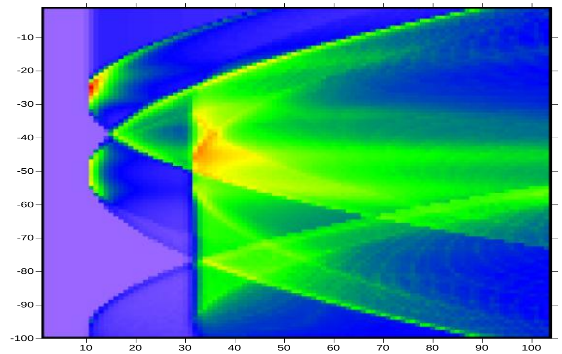
$\Delta\varphi_k(\rho)$ arc corresponding to the land (red) or to the water (blue), smooth function in comparison with the erf near the leading edge.

## Contribution of slicks

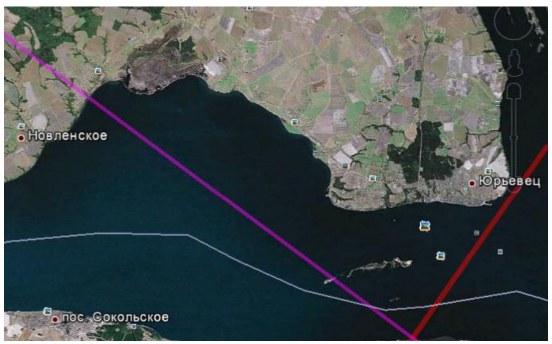
$$P_{coast}(\tau) = \frac{P_0}{\sqrt{2\pi} h^4 s_{coast}} e^{-\left(\frac{4}{\gamma}+\alpha(\rho,\varphi)\right)\frac{c\tau-2H_{water}}{h}} \int_C e^{\left\{-\left(c\tau-2H_{water}-\frac{(x(l)-x_N)^2+(y(l)-y_N)^2}{h}\right)^2 \Big/ 8s_{coast}^2\right\}} dl$$

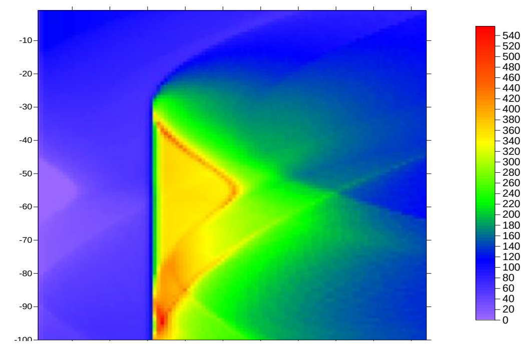
$(x_n, y_n)$ – coordinates of nadir points, $y=y(l)$, $x=x(l)$ – equation of the coastal line

# Модельные формы импульсов для кусочно-постоянной модели поверхности в районе Горьковского водохранилища

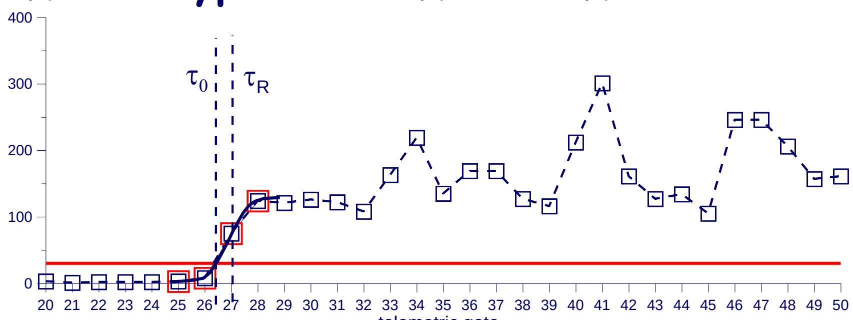
**142 pass**



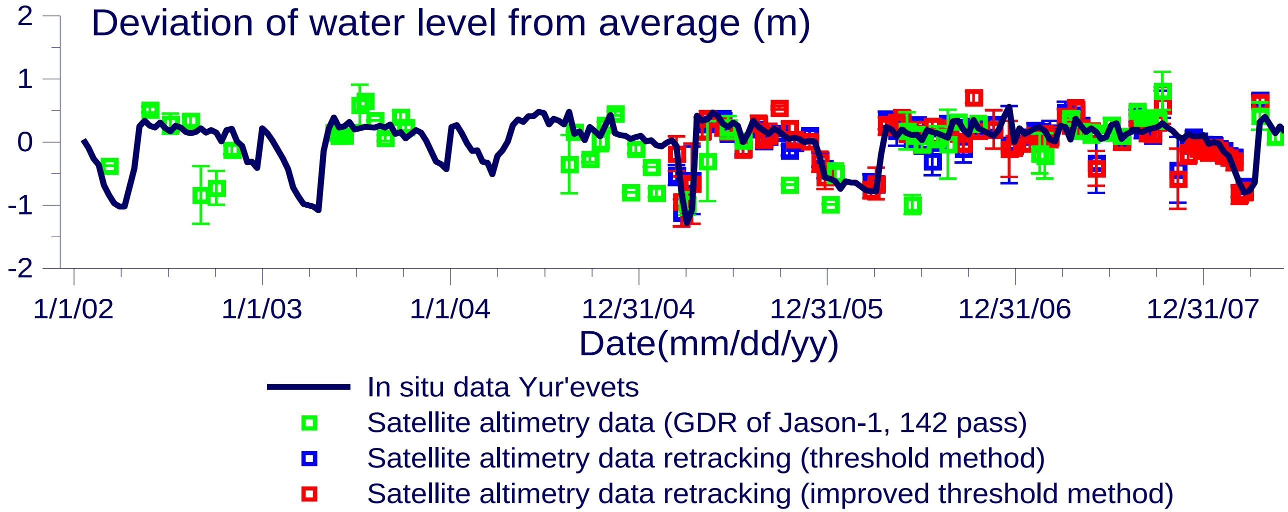
**33 pass (after manoeuvre)**

**Аппроксимация переднего фронта импульса функцией ошибок позволяет определить уровень воды в водоеме и высоту волн**

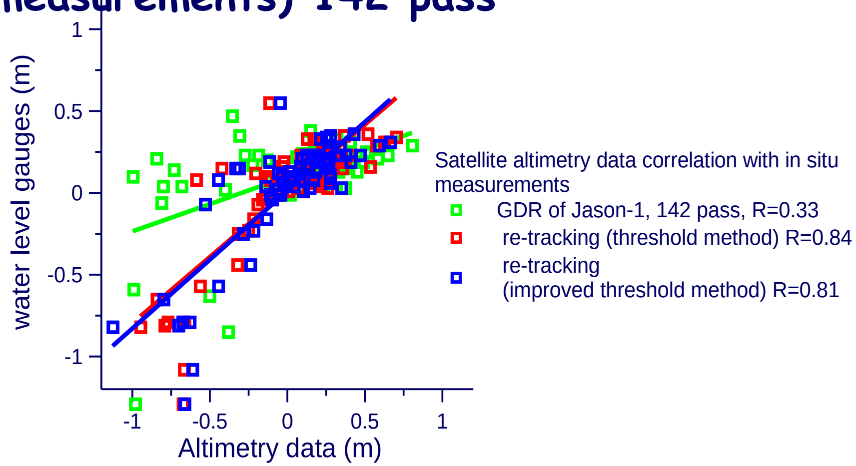



$$P_k(\tau) \propto \left(1+\operatorname{erf}\left(\frac{(c\tau-2H_k)}{\sqrt{2}\sqrt{s_k^2+c^2\tau_i^2}}\right)\right)$$

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



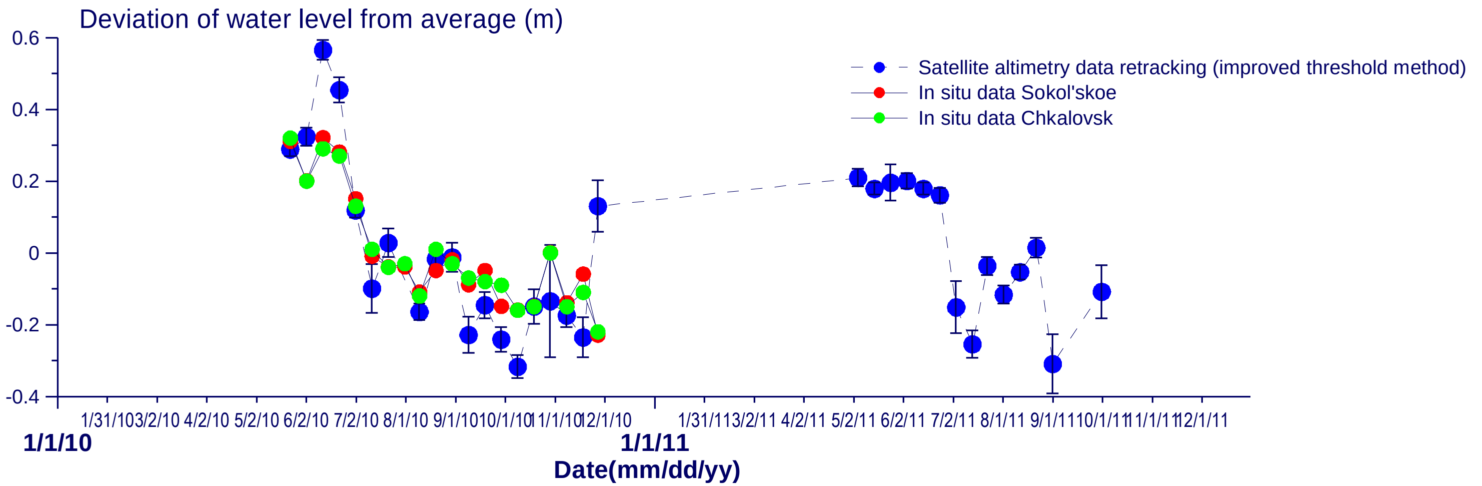

## Water level (correlation of altimetry data and the ground station measurements) 142 pass



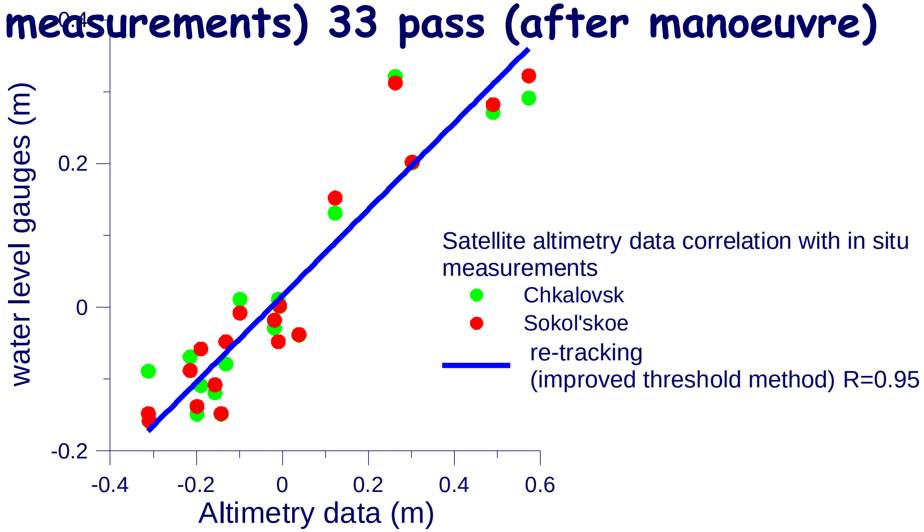

## Errors in retrieving water level and number of valid data points in the Gorky reservoir for various methods of retracking

| Method of retracking | Std of the water revel (m) | Average number of valid points/mont h |
|---|---|---|
| GDR data | 0.16 | 1.2 |
| Retracking by the threshold method | 0.13 | 2.0 |
| Retracking by the improved threshold method | 0.12 | 2.0 |

# Water Level Variations (comparing ground measurements, GDR data and results of re-tracking waveforms from SGDR) 33 pass (after manoeuvre)




## Water level (correlation of altimetry data and the ground station measurements) 33 pass (after manoeuvre)



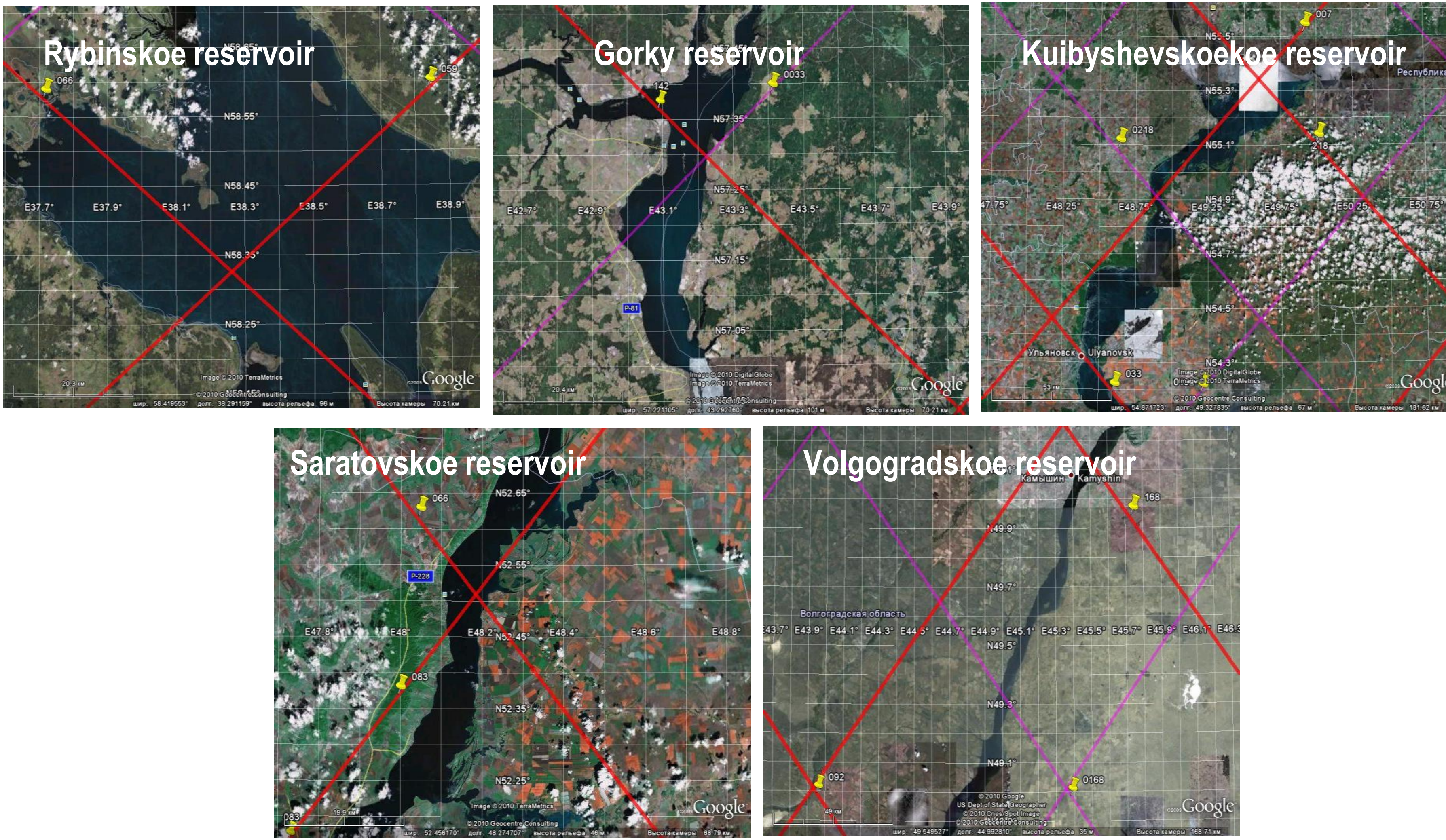

## Errors in retrieving water level and number of valid data points in the Gorky reservoir for various methods of retracking

| Method of retracking | Std of the water revel (m) |
|---|---|
| GDR data | 0.16 |
| Retracking by the improved threshold method | 0.12 |

# Errors in retrieving water level and number of valid data points in the Gorky reservoir in summer and winter seasons for various methods of retracking

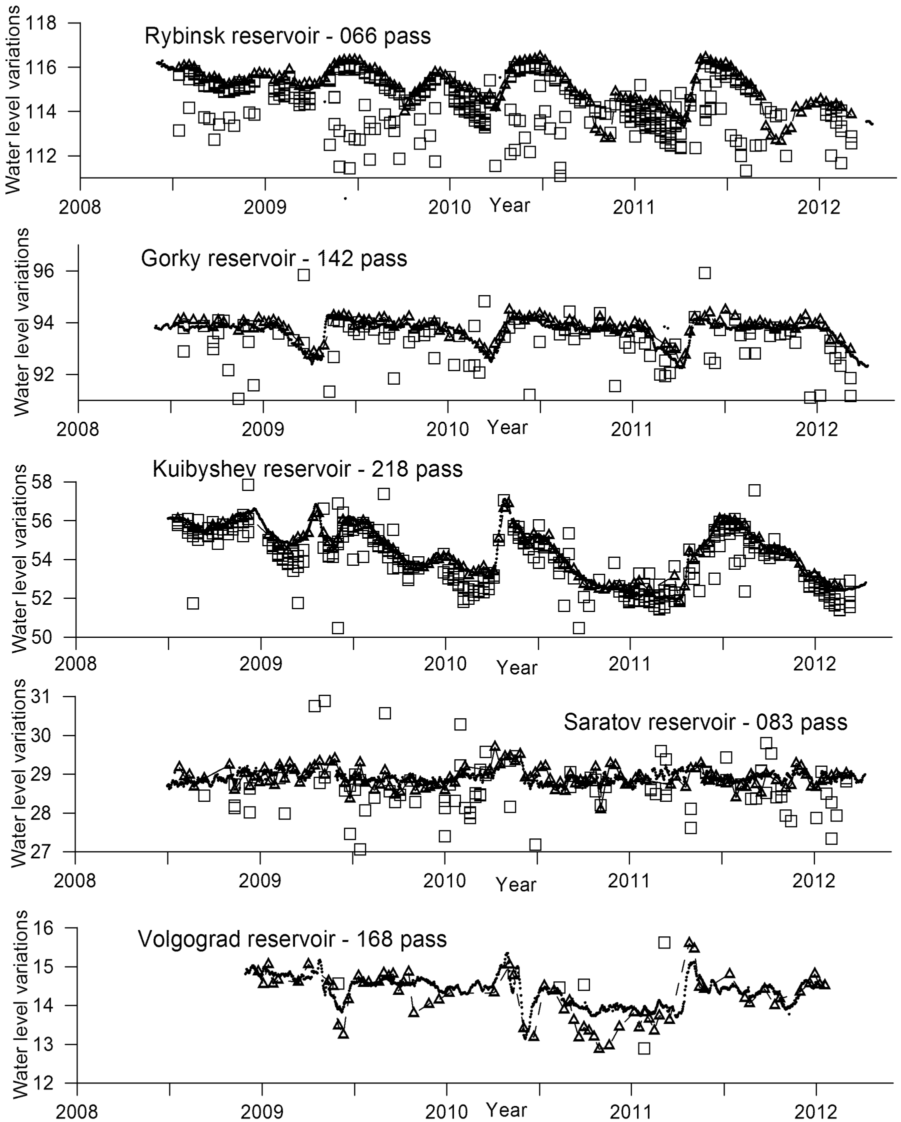
| | Standard deviation of the water revel (m) | | Average number of valid points per month | |
|---|---|---|---|---|
| Method of retracking | Winter (November-April) | Summer (May – October) | Winter (November-April) | Summer (May – October) |
| GDR data | 0.15 | 0.16 | 0.3 | 1.2 |
| Retracking by the threshold method | 0.15 | 0.13 | 1.5 | 2.0 |
| Retracking by the improved threshold method | 0.18 | 0.12 | 1.5 | 2.0 |

# Jason-1 and Jason-2 altimetry satellites' tracks intersecting the Volga River Reservoirs




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; (d) Kuibyshev Reservoir – 007, 142, 218 and 0218 passes; (e) Saratov Reservoir – 083 and 066 passes; (f) Volgograd Reservoir – 168 and 0168 passes

# Water level variations in the Volga River Reservoirs




**GDR of Jason-2 (squares), results of retracking SGDR base from Jason-2 satellite (triangles), in situ data (circles)**

## 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 |

# Conclusions

- **Data of radar satellite altimetry are applicable for determining water level in middle-size inland water bodies.**
- **Special data processing is required taking into account surroundings of the water body.**
- **Application of this kind of 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. The adaptive retracking algorithm adjusted to a certain geographic region can be applied in such areas.**

# Thank you for your attentlon