The Problem of the Internal Waters Monitoring by the Dual-Frequency Precipitation Radar: the First View

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The permanent monitoring of the internal waters in the cold regions with long time snow and ice covers is very important for population safety. Modern spaceborne radars may significantly extend the capabilities of the terrestrial hydrological network, since they enable one to perform measurements over large areas. In 2014 the Japan Aerospace Exploration Agency (JAXA) launched spaceborne Dual-frequency Precipitation Radar (DPR). The main objective of mission is the measurements of the precipitation. However, the radar cross section (RCS) measured at the maximal range contains the information about the scattering surface. For the first time the DPR measurements over the Russian territory were processed. The sources of in-situ data were hydrological stations. Gorky reservoir and the Volga River were selected as an example for sensing of the small inland water. Data processing confirmed the possibility to detect the inland water which is significantly less than radar footprint. Introduction of the ground-to-water ratio may be used for estimation of the square of the open water inside footprint. Processing the DPR data obtained for Baykal Lake permitted to calculate the dependence of RCS from incidence angle and the original algorithm for separation of the open water and ice cover was suggested. Moksha river basin was selected as wetland with many small rivers. Data processing is shown that spring changing of the inland waters and soil can be observed in DPR image. Further researches will be done.

***Index Terms* — Dual-frequency precipitation radar, backscatter radar cross section, a spring flood, hydrological monitoring of internal waters, ice cover, open water**

This paragraph of the first footnote will contain the date on which you submitted your paper for review.

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I. Introduction

Monitoring of inland water bodies is important for solving hydrological tasks and ensuring the safety of the population, in particular, the spring floods are a threat. Modern remote sensing techniques are extensively used for flood monitoring, but they are not always capable of solving this problem in full scale, e.g., during heavy rains, the investigated area is covered with a dense layer of clouds, thus optical methods are inefficient. The task is also complicated by the presence of vegetation that can impede the water surface detection. Scatterometers and radiometers have low spatial resolution, which makes it difficult to use them in such applications. The most effective tool is the synthetic aperture radar (SAR). However, SAR does not make a continuous mapping of the Earth, thus a preliminary order is needed to get an image of the area of interest at the right time.

May be in the future will be possible to use the aircraft performing regular passenger flights as a source of information about a scattering surface with a high spatial resolution, for example, [1]. However, they fly on a fixed route, which makes it impossible to carry out measurements outside of it.

In 1997, a joint American-Japanese project (Tropical Rainfall Measurement Mission) was launched. Its purpose is to determine the spatial distribution of precipitation and its vertical profile, and measure the precipitation intensity in the tropical and subtropical zones of the World Ocean [2-4]. To solve this problem, a complex of measuring equipments was installed on the satellite, and it included a microwave radar for measuring the vertical profile of precipitation (Precipitation Radar - PR).

PR was successfully used to measure precipitation intensity, but its potential for recovery of additional information from PR data attracted attention and several attempts were made to use PR data to measure the variance of sea wave slopes and the wind speed, for example [5-9]. In addition, PR data were used to classify the land surface [10] and the land surface to measure the soil moisture [11, 12].

Further development of the remote sensing at the small incidence angles was started after the launch of a Dual-frequency Precipitation Radar (DPR).

GPM (Global Precipitation Mission) satellite with on-board DPR of wavelengths of 2.2 cm and 0.8 cm [13] has been in orbit since 2014. The Earth surface were sensed by orbital radars (PR and DPR) at small incidence angles (<18.5°). Other radar systems are not capable of measuring at such incidence angles, thus it is necessary to estimate the prospects of DPR data for monitor of the internal waters and flood detection. In this paper, we first study this effect in the DPR image by the example of the 2015-2016 time interval.

A feature of backscattering at small incidence angles is that the backscattered RCS of the water surface can be much larger than that of the soil (ground). As a result, water bodies will be seen in the radar image as areas with an increased RCS. Data processing has shown that the major rivers are clearly visible in the radar image in summer. In winter, when water bodies are covered with ice and snow, the radar ground-water contrast almost disappears and the river bed becomes scarcely noticeable in the radar image. Spring floods increase the water surface area in the footprint (vary the ground-to-water ratio in the scattering area), which results in a larger RCS of this footprint in the radar image, while severe flooding results in an increased size of inland water with a large RCS.

II. Dual-Frequency Precipitation Radar

DPR substituted the single-frequency precipitation radar (PR) of a wavelength of 2.2 cm mounted on the TRMM satellite. The observation area of the new satellite significantly increased in latitude (+/- 65 degrees in relation to the equator), therefore, one more frequency was added to measure average- and low-intensity precipitation typical of mid-latitudes, as well as snowfall.

Its main objective is to measure the vertical precipitation profile from a height of 10 km to the Earth surface with a vertical resolution of 250 m in swaths of 245 km in the Ku-band and 125 km in the Ka-band. The final range measuring refers to the Earth surface reflection and the reflected signal contains information on the scattering surface.

DPR operates in the scanning mode in the direction normal to that of the satellite motion. The beam width is about 0.7 degree. The satellite travels less than 5 km along the track in one scan and thus forms a continuous observation area with a footprint size of about 5 km.

RCS measured at the maximum distance corresponds to the backscatter from surface and therefore can be used to determine the scattering surface parameters. However, the JAXA standard information product does not contain information about the parameters of sea waves, snow and ice cover.

Our team has the experience in the processing of the PR data over the sea surface and has developed algorithms for retrieving the variance of large-scale sea wave slopes and surface wind speed, for example, [8, 9, 14, 15]. We begun to use the DPR data for the study the scattering from inland waters and soil [16-18].

III. Statement of the Problem

For further consideration, let us select two basic states for the water surface: open water and ice cover.

In spring, the ground changes from the "winter" state to the "summer" one and this process at mid-latitudes is accompanied by spring flood, which can be seen in DPR data. The problem of inland waters monitoring by remote sensing methods is not new but, in this case, radar measurements at low incidence angles (<18.5°) are employed for the first time.

The advantages of DPR data are:
1) continuous monitoring (~ one time for 1-2 days);
2) rather high spatial resolution (5 km);
3) measurement at the two frequencies at small incidence angles.

Their disadvantages are:
1) insufficiently high resolution to detect floods that are not accompanied by a significant increase of the water surface area;
2) dependence of the RCS on the surface relief, which makes it difficult to compare data obtained in different sensing directions.

Three sites with hydrological stations were chosen for the analysis:
1) Nizhegorodsky region (Gorky reservoir and Volga river);
2) Baykal lake;
3) Ryazan region (Moksha river basin).

As an example, we use the data collected for the period from February to June 2016 for Volga river, from November 2015 to May 2016 for Baykal lake and from March to June, 2015 for Ryazan region.

IV. Volra River Basin

Let consider the observation by the DPR the internal waters which have size significantly less than radar footprint.

A map of the first considered area is shown on Fig. 1.

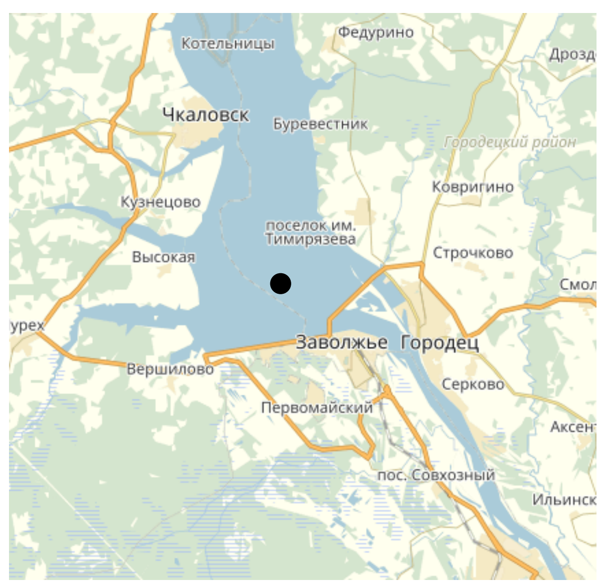

Fig. 1. Map of the Gorky water storage and Volga river. Black circle: 56.68° N and 43.32° E.

DPR image is shown in Fig. 2. It is clear seen the Gorky reservoir. The maximal width of Gorky reservoir is approximately 11 km, therefore one footprint completely inside water surface. Width of Volga river equals approximately 1 km however the river is clear seen on the radar image. It is explained by the big difference between RCS of water surface and RCS of soil.

On the fig. 2 the large fluctuations of RCS (narrow area) at zero incidence angle is observed. This deals with the peculiarities of backscattering at normal incidence.

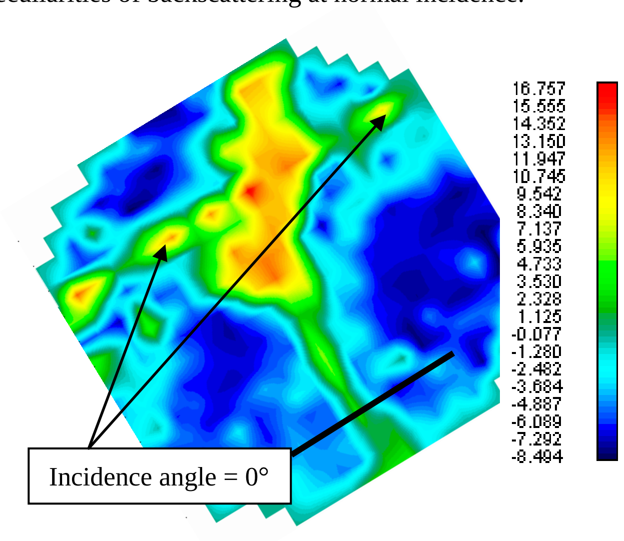

Fig. 2. Radar image of the Gorky reservoir and Volga river (Ku-band). Black line is the section of radar image.

RCS of the open water is significantly larger than that of the soil; therefore, DPR can detect water body which significantly less than footprint. In some cases there is possibility to roughly estimate the square of the open water surface inside footprint.

The example of the radar image section (along black line) is shown in fig. 3.

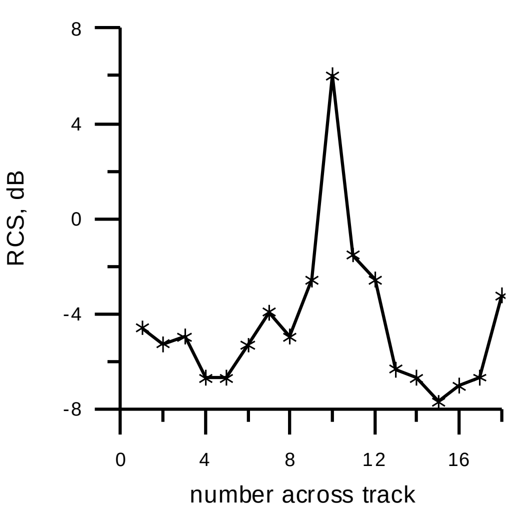

Fig. 3. Section of the radar image in the Ku-band (along the black line – fig. 2).

To illustrate this effect, we use the simplest model and introduce the ground-to-water ratio, i.e. the ratio of the ground area S_{ground} to the total area $S_0 = S_{ground} + S_{water}$:

$$R_{GW} = \frac{S_{ground}}{S_0} .$$

Assume that the water surface and the ground participate in the reflected signal generation and the RCS of the water surface is much larger than that of the soil. It is possible to roughly estimate the RCS of footprint by the formula:

$$\sigma_0 = \sigma_{water} \frac{S_{water}}{S_0} + \sigma_{ground} \frac{(S_0 - S_{water})}{S_0} .$$

This is a radically new radar effect, since in the SAR image and scatterometry, the inverse effect is observed, i.e., the ground RCS is usually larger than the RCS of the water surface.

To estimate the square of the open water in the footprint it is necessary to know a few parameters: 1) the RCS of the open water, 2) the RCS of soil, and 3) the RCS of analyzed footprint. All RCS are in the natural value.

In result the final formula for square of the open water is the following:

$$S_{water} = S_0 \cdot \left(\frac{\sigma_0 - \sigma_{ground}}{\sigma_{water} - \sigma_{ground}} \right) .$$

In the Table 1 we give the example (see Fig. 2 and Fig. 3) which illustrates the potential of using of the DPR data. Width of Volga river in the place of section is approximately 1.05 km and result of calculation is 0.93 km and R_{GW} = 0.76.

TABLE 1.
Example of data processing

	RCS, dB	RCS, no dB	square, km^2	width, km
water	12	15.85		
soil	-5	0.32	15	
river	6	3.98	4.63	0.93

If we want to obtain the numerical estimation the square of the open water, it is necessary to remember, that exist many limitations. First of all, it is necessary to measure the RCS of water surface (footprint must be less than size of water body). RCS depends on wind speed, therefore it is necessary to measure water's RCS close to the investigated object. During calculation is used the assumption about the same wind speed in both places. RCS depends from incidence angle, therefore it is necessary to use approximately the same incidence angles.

Data processing shown, that it is possible to easy find the small water body using DPR data. It is necessary the additional information to estimate his size.

Development of this investigation will probably allow in future introducing a new term in hydrology to describe the relationship between the ground and the open water surface in the footprint. We tentatively call it the “ground-to-water ratio”. The new term may be useful for description of the scattering surface using radar data.

V. Baykal Lake

In the cold period lakes are covered by ice. Transition from the open water to ice cover and back may be detected by radar images. Let consider this process on the example of the Baykal lake.

The red line in the Fig. 4 shows the coastline. This mask will be used for radar image. Dots on the map illustrate the position of the radar footprint (diameter 5 km).

Radar images of Baykal lake are shown on the Fig. 5 (open water) and Fig. 6 (ice cover). Black dots are the mask of the lake.

It is clear seen the big difference between radar images of the open water and ice cover: RCS of the open water is bigger than RCS of the ice cover.

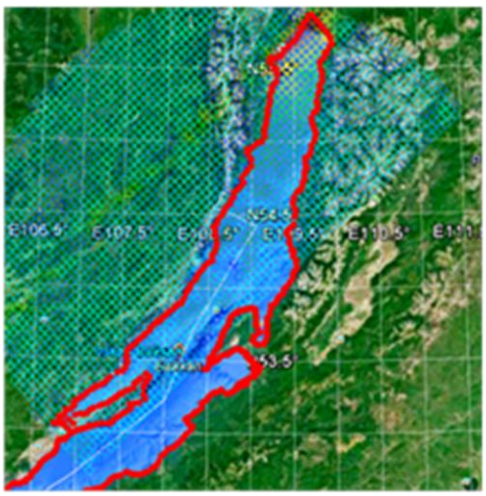

Fig. 4. Map of north part of Baykal Lake. The red curve shows the coastlina. Dots illustrate the positions of the radar footprint (diameter 5 km) on the map.

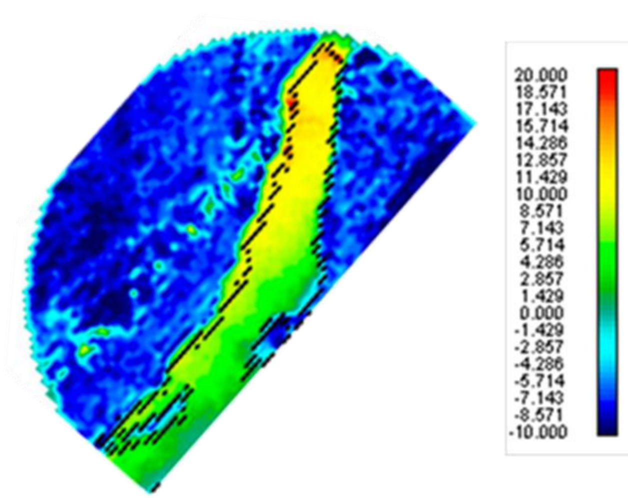

Fig.5 Radar image of the north part of the Baykal lake (3.12.2015).

It is necessary to emphasize that RCS of the water surface depends on wind speed and RCS of ice depends from air temperature. Therefore not always the difference in RCS will be such evident.

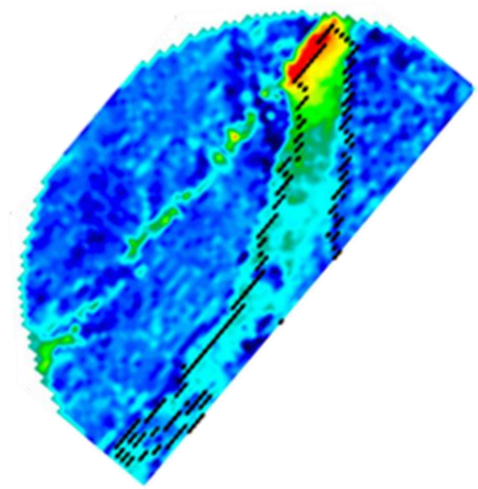

Fig.6 Radar image of the north part of the Baykal lake (15.01.2016).

We can divide the types of the scattering surface not only using the absolute values of the RCS, but also from the angular dependence of RCS. DPR made it possible to obtain for the first time the angular dependences of the RCS for ice cover at the small incidence angles (0-18 degrees).

On Fig. 7 is shown the dependence of the RCS on the incidence angle for open water (Ku-band, November-December 2015) and on Fig. 8 for the ice cover at a negative air temperature (dry ice) for the Ku-band (February-March 2016). In the figures, data relating to different days is marked with different symbols.

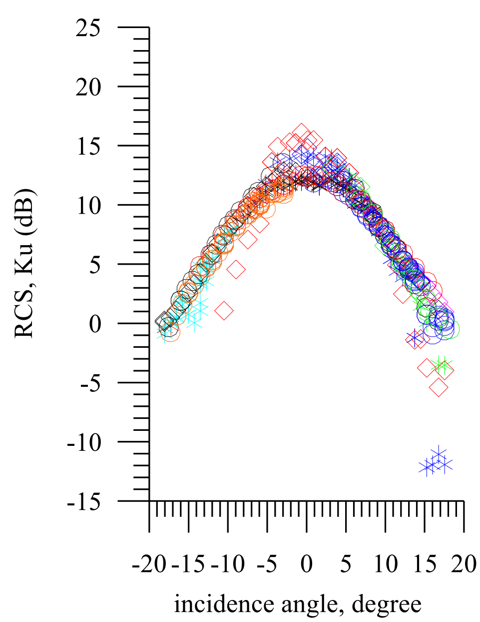

Fig. 7. Dependence of the RCS on the incidence angle in the Ku-band for open water (November-December 2015).

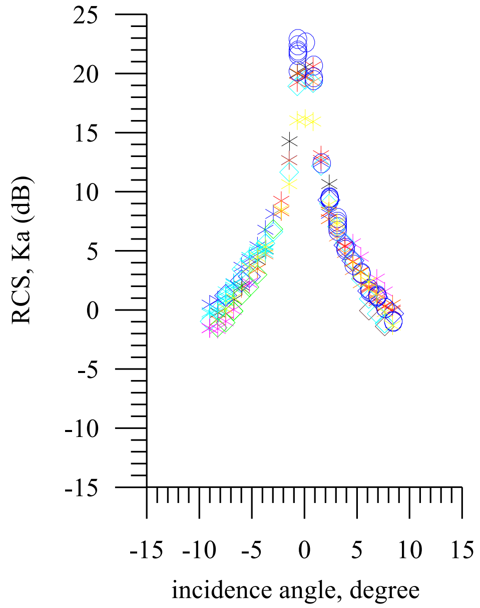

Fig. 8. Dependence of the RCS on the incidence angle in the Ku-band for the ice cover at a negative air temperature (February-March 2016).

In the Ku-band for open water (Fig. 7), at the "large" incidence angles, a low RCS (about -12 dB) is observed, which seems to drop out of the general series of observations. In fact, there is nothing unusual. As was shown in [14], in the case of a weak wind and/or when there are slick areas on the surface, low values of the RCS are observed at the edge of the DPR swath. Decreasing can reach –15-20 dB.

It can be seen from the figures that the behavior of the dependence of the RCS on the incidence angle depends on the type of the scattering surface. For an open water surface, the dependence of RCS on the angle of incidence when probing along the X axis is described by a distribution close to Gaussian (in the transition from dB to natural units) [19-21]:

$$\sigma_0(\theta) = \frac{\sigma_0}{\cos^4\theta} \cdot \exp\left[-\frac{tg^2\theta}{2S_{xx}^2}\right]$$

where σ_0 is the RCS at nadir probing, S_{xx}^2 is the variance of large-scale slopes along *X* axis.

In the case of the ice cover, the angular dependence at small incidence angles in the first approximation can be described by a fractional-rational function of the form:

$$\sigma_0(\theta) = \frac{\sigma_0}{1 + a \cdot \theta^2}$$

where coefficient a can be calculated from experimental data.

The change of the angular dependence of the RCS is a reliable criterion for the separation of the water surface and the ice cover and no depends from absolute value of RCS. For quantitative comparison of angular dependences and selection of the most suitable one, different criteria can be applied [22], for example, the Fisher criterion.

VI. Moksha River Basin

The Moksha River basin was chosen as the example of the wetland area. In summer, river width in the hydrological station area is not more than 50 m, while in spring, it is more than 300 m. Besides, many small ponds also grow in size during spring flood and increase the square of the open water.

The brown line on Fig. 9 show us the section that pass through the hydrological station. The hydrological station in the Kadom village (54.56° N and 42.47° E). It is the red circle. Incidence angle is constant along section.

To gain a better insight into the flood processes, a set of successive radar images made from April to June is shown in Fig. 10.

Snow melted until April 13 and lot of small ponds filled with water therefore the radar image is light, which indicates a large RCS. However, the early flood has not affected the major rivers, in particular, the Oka River is not visible in the radar image (Fig. 10a).

The Oka River is clearly visible in the radar image of May 7 (black curve, Fig. 10b) but in all, the RCS in the image has become smaller (the darker image).

The longer time passes after snow melting, the smaller the number and the area of small rivers/ponds. For a spatial resolution of 5 km, we cannot see small water bodies that affect the ground-to-water ratio as separate objects. However, their presence affects the signal level.

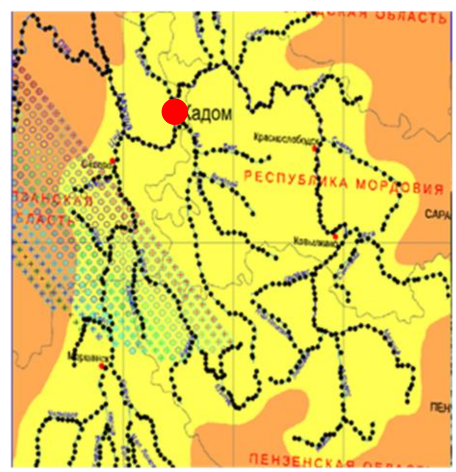

Fig. 9. Map of the Moksha River basin. Hydrological station – Kadom village (54.56° N and 42.47° E). Position of the hydrological station is marked by the red circle.

The second factor which influence of the RCS and which necessary to take into is the account the dependence of the dielectric properties of soil on the moisture. The fulfilled investigations confirmed that reducing of the moisture lead to the decreasing of RCS [10, 11]. The further researches is required to separate two effects.

After spring flood we see in the radar image of June 13, 2015 (Fig. 10c) that even the Oka River became invisible and the signal level became even lower, which can be interpreted as a reduction in the ground-to-water ratio and reduction of soil moisture. Further researches permits to separate the different effects.

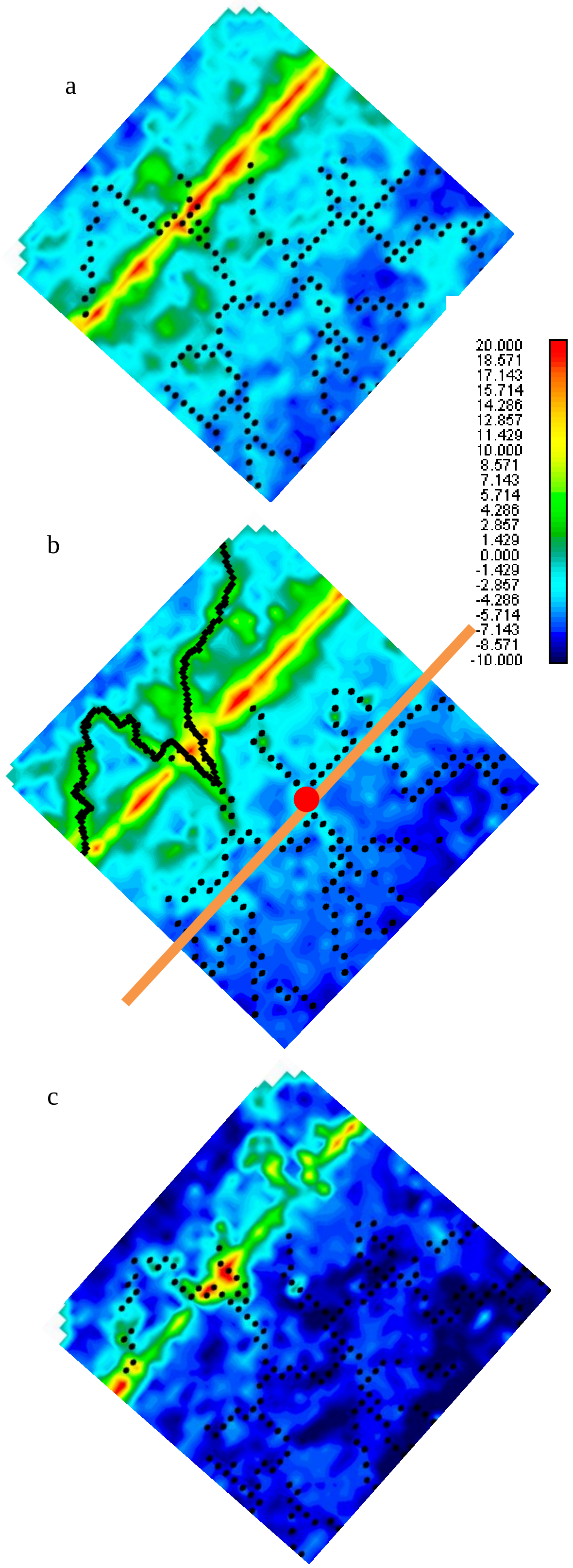

Fig. 10. Radar images of the Moksha River basin obtained on April 13 (a), May 7 (b), and June 13 (c) 2015 (from top to bottom). Black curve is the Oka River (May 7). Black dots show the river beds (small rivers). Brown line is the section, the red circle is hydrological station.

Sections of the radar images passing through the hydrological station are shown on Fig.11.

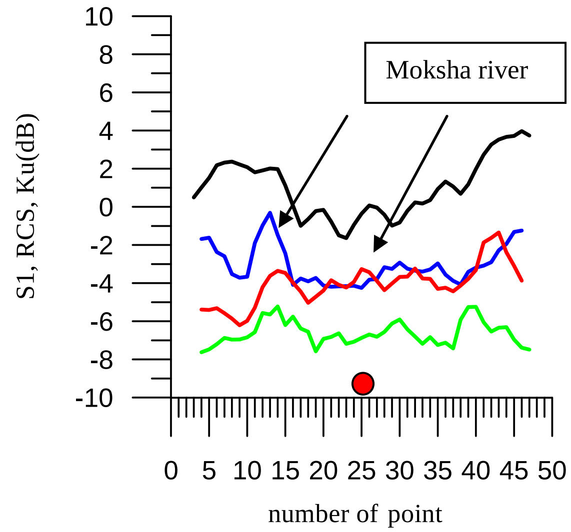

Fig. 11. Sections of radar images in Ku-band. Black curve – 11.02.2015, snow, negative temperature, ice cover of small rivers, and the water level is 150 cm (Kadom); Blue curve – April 13, 2015, no snow, no ice, the water level is 326 cm (Kadom); Red curve – May 7, 2015, the level is 310 cm (Kadom); Green curve – May 26, 2015 the level is 161 cm (Kadom).

The black curve refers to February 11, 2015. There is snow cover, the air temperature is negative, small rivers are covered with ice. The water level at the hydrological station (Kadom) is 150 cm. The blue curve corresponds to the beginning of the water level rise at the Kadom – water level is 326 cm (April 13, 2015). The hydrological station is located in the vicinity of the 25th point (red circle).

The longer time passes from the time of snow melting, the less open water remains and soil moisture decreases; the average signal level reduces, which is shown by the red curve, water level is 310 cm (May 7, 2015).

The tendency to reduction of the relationship between ground and open water leads to a decrease of the RCS, which is shown by green curve obtained on May 26. Water level is 161 cm. Peak dealing with Moksha river is very small.

An additional information parameter in the analysis can be the difference in the RCS behavior in Ku- and Ka-bands. Taking into account that they are close for water surface reflection, the observed difference can be due to scattering by soil. This case requires further study.

VII. Conclusions

The effect of the processes that occur on the ground in spring on the DPR image was analyzed for the first time. The data processing has shown that in the DPR image, one can observe the variation of the ground surface state: the transition from snow to soil, ice cover formation and destruction, and a change in the level of inland waters during spring flood, a detection of small inland waters.

First of all, the possibility of DPR to detect the small inland water was investigated. Due to big difference between RCS of water surface and RCS of soil at small incidence angles, it is possible to find the small inland waters (open water) which have size significantly less than DRP's footprint.

To describe this effect was suggested to introduce the ground-to-water ratio which determines the relationship between the ground and open water surface in the footprint of radar. In-situ measurements are made at a point, thus the proposed ratio is different from those used now in hydrology.

Using the example of the Gorky Reservoir and the Volga River, it was shown that it is possible to determine this coefficient and estimate the area of open waters in the footprint under a few conditions, in particular, obtaining information on the RCS of the open water. RCS is sensitive to wind speed, so the measurement should be carried out synchronously with measurement over a large water body located not far away. This allows to remove of the influence of the wind speed on the result.

Dependence RCS on the incidence angles was investigated for open water and ice cover. The test site was the north part of the Baykal lake. Obtained results permitted to suggest a new algorithm which can separate water surface and ice cover. Advantage of the suggested algorithm deals with the analysis of type of angular dependences of RCS but not absolute value of the reflected signal.

The process of the transition from snow cover in winter to soil (spring) on the example of the Moksha river basin was considered. In spring, the water level in rivers and lakes increases and observed the intensive floods in this area. This area is marshy, so the area of open water is additionally increasing due to wetland.

Comparison of successive radar images shows that the snow cover at a negative temperature has a higher RCS than the soil (Fig. 10a).

During the spring flood, the water level in the rivers increases and the area of open water increases. As a result, some rivers, in particular the Oka River, become visible on the radar image (see Fig. 10b).

In general, due to the increase in the size of smaller rivers and lakes, the level of the RCS in the radar image remains quite high (Fig. 10b). During the drying process, the area of open water decreases (see water level from the hydrological station), which leads to a decrease of RCS and it is seen on Fig. 10c.

It should be noted that soil moisture affects the RCS. The drying of the soil will change the dielectric properties and this effect will also lead to a decrease of RCS. In order to surely separates these effects, additional researches are needed.

The obtained results show good prospects of DPR data application for estimating the ground surface state. The study has just started and there are still many problems to be considered in the future researches.

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