Testing the method for increasing the spatial resolution of satellite radiometric images in the L-band

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Abstract. The results of testing a method for increasing the spatial resolution of satellite radiometric data in the L-band are presented. Data obtained by satellite-borne radiometer is characterized by low spatial resolution. The use of satellite radar data can increase the spatial resolution of radiometric images in the L-band to hundreds of meters. At the moment, the L-band radiometric data processing is possible with the use of radar data C-band. For this reason the method gives satisfactory results in the absence of cloudiness on the radar image.

1. State of the satellite remote monitoring system of soil moisture
Soil moisture, as a fundamental parameter for the formation of land water resources, plays an important role in climate change. Microwave radiometry technologies allow the construction of maps of the volumetric moisture content of soils on a global scale with a short repeat determination time for the area of interest. However, the spatial resolution of such geoinformation products is very low and amounts to tens of kilometers on the ground. Remote mapping of soil moisture on a global scale is carried out using data from the SMOS satellites [1], SMAP [2], GCOM-W1 [3] and Haiyang 2 spacecrafts [4]. The SMOS spacecraft was launched by the European Space Agency (ESA) in 2009. It carries a novel L-band interferometric radiometer MIRAS that operates in the L-band (1.4 GHz). A distinctive feature of MIRAS is the ability to measure at multiple sensing angles in the “full” polarization mode. The SMAP spacecraft carries radiometer and a radar at frequencies of 1.4 GHz and 1.2 GHz, respectively; it employs a conical-scanning geometry at two polarizations at a fixed sounding angle of 40°. However, the SMAP satellite radar unit has not been operational since July 2015. The GCOM-W1 radiometer AMSR2 measures at seven frequencies in the range of 6.9-89 GHz in a conical scanning mode at two polarizations for a fixed angle of incidence of 55 °. The design and specifications of the Hai Yang 2 satellite microwave radiometer are very similar to AMSR2. For a number of reasons, L-band radiometric data is most suitable for global remote monitoring of soil moisture with acceptable accuracy.

According to the plan of the deployment of the satellite constellation within the framework of the Copernicus program [5], the first spacecraft of the series (Sentinel 1A) was successfully launched in 2014. A synthetic aperture radar (SAR) mounted on the Sentinel 1 board operating at a frequency of 5.4 GHz (C-band). Currently, two satellites of this type are operating in orbit - Sentinel 1A / B [6]. The best spatial resolution of Sentinel SAR images is 5 m. With a spatial resolution comparable to optical sensors, radars allow you to obtain surface images in the presence of cloud at any time of the day.

The value of backscatter, measured by SAR, is largely depended by the geometry of the probed surface. For this reason, SAR satellite data are widely used in problems of thematic mapping of the Earth's surface. The products created using thematic maps are used in the field of cadastral services, supervisory monitoring of vegetation, creation and technical support of geoinformatic system. Also, the value of backscatter is correlated with the complex dielectric permittivity (CDP) of the surface layer of...
the sensing object. This allows the use of X-ray diffraction data to assess the moisture content of the surface layer of soils.

The method of increasing the spatial resolution of radiometric images is based on the correlation between the values of the brightness temperature ($T_B$) measured by the radiometer and the SRCS measured by the SAR. As a result of complex processing of radiometric and radar data, SMAP was able to obtain moisture maps of the surface layer of soils with a spatial resolution of 3 km. However, after the failure of the SMAP radar unit, humidity maps were built only according to the radiometer with the best spatial resolution of 9 km. In this regard, the curators of the program decided to use Sentinel 1 radar data to increase the spatial resolution of SMAP radiometric data.

2. Sentinel 1 and SMAP Data Features

In the study process, the data obtained for the territory of the south of Omsk region and Northern Kazakhstan were analyzed. The Sentinel 1 data archive is publicly available at [7]. The Sentinel 1 revisit time, i.e. the minimum time between observations of the same area with the same geometric characteristics of the survey is 12 days. During revisit time, the spacecraft is able to provide coverage with images of the entire Earth's surface. With increasing latitude, overlapping survey footprints in the ascending and descending portions of the spacecraft orbit are observed, which leads to a decrease in revisit time to the first time in 5–7 days (for middle latitudes). For two Sentinel 1 satellites, the revisit time for middle latitudes can be one time in 3 days. However, the Sentinel 1 spacecraft carry out a selective survey of the Earth’s surface according to the Sentinel 1 Observation Scenario. The curators of the Sentinel 1 mission draw up a surface survey program for a time equal to revisit time, i.e. for 12 days. Within the Sentinel 1 Observation Scenario, between the satellites (Sentinel 1A and Sentinel 1B) the surface areas for which the survey will be carried out are distributed, the mode and polarization are determined. After 12-day period the Sentinel 1 Observation Scenario is update, however, the changes made are local in nature and relate to the highest resolution mode of 5 m (SM mode).

For the territory of the south of the Omsk Region and Northern Kazakhstan, images obtained by one Sentinel 1 satellite in the Interferometric Wide Swath mode (interferometric wide-angle mode or IW) at polarizations VV and VH were available. This mode combines a relatively high spatial resolution (5 × 20 m) and a wide capture footprint (about 250 km). The range of angles of incidence of radiation within the image does not remain constant and varies from 29° to 46°. The Sentinel 1 data were processed in SNAP; free ESA software (http://step.esa.int/main/toolboxes/snap/). Pre-processing of the images consisted of:

- data calibration,
- removal of thermal noise,
- speckle filtering,
- geometric correction.

These operations were performed using the standard features of the Sentinel 1 toolbox, the SNAP extension package. Since the range of angles of incidence of radiation within the Sentinel 1 image varies over wide ranges, the backscatter values were recalculated for the angle of incidence of 40° to facilitate the comparative analysis of the data of the radiometer and radar. The conversion equation has the form:

$$\sigma_{\text{norm}} = \frac{\sigma_0 \cos^n(\theta_{\text{norm}})}{\cos^n(\theta_0)}$$  \hspace{1cm} (1)

$\sigma_{\text{norm}}$ is the backscatter value normalized to the angle $\theta_{\text{norm}}$, $\sigma_0$ is the initial backscatter value for the angle $\theta_0$, $n$ is a number depending on the type of surface (in most cases, 2). To decrease processing time and reduce data volume, Sentinel 1 data was reduced to a spatial resolution of 100 m and converted to the GeoTIFF format. The decrease in spatial resolution also contributed to decrease of residual influence of speckle noise.

The SMAP data is also publicly available [8]. The revisit time for the SMAP spacecraft is 2–3 days for territories located near the equator. For temperate latitudes the revisit time decrease to 1 day. In this study, the SMAP radiobrightness data with a spatial resolution of 9 km were used. This data are presented in the hdf5 format widely used in the field of remote sensing of the Earth. Extraction and
processing of radiometric data was carried out using the free software package Sci-Lab. To find the correlation between the SMAP radiobrightness data and $\sigma_{\text{norm}}$, Sentinel 1 data were averaged over the SMAP pixel.

3. Method of increasing spatial resolution of SMAP radiometric data

The method for increasing the spatial resolution of radiometric data is based on the correlation between radiobrightness and $\sigma_{\text{norm}}$ data [9]. The equation used to create high resolution radiobrightness data maps is:

$$T_{BP}(M) = T_{BP}(C) + \beta(C)[(\sigma_{pp}(M) - \sigma_{pp}(C)) + \frac{\delta \sigma_{pp}(M)}{\delta \sigma_{pq}(M)}(\sigma_{pq}(C) - \sigma_{pq}(M))]$$  (2)

where $T_{BP}$ is radiobrightness temperature on $p$-polarisation (H or V), indexes $C$ and $M$ correspond to low and high spatial resolution, respectively, $\sigma_{pp}$ is the backscatter data on HH or VV polarization, $\sigma_{pq}$ is the backscatter data for HV or VH polarization; $\delta \sigma_{pp}, \delta \sigma_{pq}$ is the standard deviation of the backscatter data, $\beta$ is the angular coefficient of the approximating function of the dependence between $T_{BP}$ and $\sigma$. For Omsk region, the Sentinel 1 data obtained in the VV and VH mode were available. In view of this, the method was tested for radiobrightness data on V-polarization. The state of the soils toplayer can change significantly in an extremely short period of time; in view of this $\beta$ is calculated for values obtained either simultaneously or over a relatively short time interval. For this reason, Sentinel 1 and SMAP data closest to the time of acquisition were selected for joint analysis; the maximum difference in the time of data acquisition did not exceed 12 hours. The values of backscatter data obtained by satellite SAR in the C-wave band is dependence on the state of the cloud cover. So, in the absence of cloudiness, the data on $T_{BP}$ and $\sigma$ demonstrate a correlation relationship with each other (Figure 1a). In the presence of dense cloudiness, such a correlation is not observed (Figure 1b). For this reason, testing the method for increasing the spatial resolution of $T_{BP}$ images was performed using the parameters of the linear regression equation shown in Figure 1a.

![Figure 1](image.png)

**Figure 1.** The dependence between (1) $T_{BV}$ and $\sigma_{VH}$, (2) $T_{BV}(C)$ and $\sigma_{VV}$, (a) in the absence of cloudiness on September 24, 2017 and (b) the presence of cloud on August 31, 2017. A continuous line is a regression line. $R^2$ - approximation confidence value (squared correlation coefficient)

The procedure for increasing the spatial resolution of radiometric images was to apply equation (2) for the Sentinel 1 image. The values of $T_{BP}(C)$ and $\sigma(C)$ did not change when calculating within the territory corresponding to one pixel of the SMAP image. On the $T_{BP}(C)$ map obtained during the calculation by (2) can be identify surface areas that differ in radiophysical characteristics with a characteristic size of several hundred meters: fields, pegs and groves, small lakes (Figure 2a). However, the absolute values of $T_{\delta}(M)$ for areas with similar radiophysical characteristics but relating to adjacent SMAP pixels is different. This is manifested in the “Striped” of high resolution map of $T_{BV}(C)$. The characteristic size of the “strip” and their number coincides with the size and arrangement of the SMAP pixels (Figure 2a, Figure 2b).
Figure 2. The map of (a) $T_B(M)$ calculated according to the Sentinel 1 and SMAP data, (b) the original map of $T_B(C)$

4. Conclusion
Testing of the method showed its functionality at a qualitative level within one SMAP pixel. However, the quantitative values of $T_B$ related to surface areas with similar radiophysical characteristics, but related to different SMAP pixels, may differ. Further improvement of the method should be associated with the elimination of this drawback. Also, this method can be applied to increase the spatial resolution of C-band radiometric data (apparatus GCOM-W1).

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