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Derivation and validation of the high resolution satellite soil moisture products: a case study of the Biebrza Sentinel-1 validation sites

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Abstract: Soil moisture content is a key variable for numerous disciplines hence the need for its constant monitoring at a global scale. Satellite imagery is the only mean to fulfil this objective. New generations of satellite sensors such as the Sentinel-1 SAR (Synthetic Aperture Radar) system provide measurements at fine spatial and temporal scales. In order to validate such estimates dense in-situ networks measuring soil moisture are required. The scarcity of such networks was the main motivation to establish two validation sites over the Biebrza wetlands within the project funded by the ESA (European Space Agency). The sites are covered by grassland and marshland and are internally homogeneous as far as the soil type and vegetation cover are concerned. Each site is equipped with 9 soil moisture monitoring stations installed every 130 m which allows the derivation of reliable mean soil moisture estimates across the site featuring small standard deviation (0.035 m^3/m^3 for the grassland site and 0.074 m^3/m^3 for the marshland site). The main objective of the presented study is to review the soil moisture derivation and validation methodologies suitable for the Sentinel-1 SAR satellite data and to describe physiographical settings of the Biebrza validation sites together with the installed instrumentation. Furthermore, the relationship between the time series of soil moisture measurements and Sentinel-1 sigma nought backscatter coefficient (σ^0) is examined. Ultimately, the validation results of the low resolution SM-DAS-2 soil moisture product are presented due to the unavailability of the high resolution product.

Keywords: soil moisture, Sentinel-1, Biebrza wetlands, satellite remote sensing, soil moisture validation

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1. Introduction

The retrieval of accurate global soil moisture estimates by means of the spaceborne systems is of interest for a wide range of disciplines such as agronomy, hydrology, meteorology, pedology, civil engineering and transportation (Western et al., 2004; Xu et al., 2004; Rodríguez-Iturbe and Porporato, 2007). New generations of satellite sensors featuring high spatial and temporal resolutions offer unprecedented capabilities for accurate soil moisture retrieval. One example of the new generation is the Sentinel-1 (S-1), a constellation of two radar satellites (status February 2017) designed and operated by the European Space Agency (ESA). The soil moisture products derived from the S-1 data require a specific validation strategy to account for small-scale soil moisture variability. In this regard, a dense soil moisture measuring network has been established over the Biebrza wetlands by the Remote Sensing Centre (RSC) of the Institute of Geodesy and Cartography (IGiK), within the ESA funded project. The main objective of this study is to present validation results of the determination of soil moisture content for two sites established over the Biebrza wetlands together with an extensive instrumentation suited for the measurement of water, carbon and energy fluxes.

2. Characteristics of satellite sensors and validation sites suited for soil moisture products

In principle soil moisture retrieval is based on microwave satellite measurements acquired by active SAR (Synthetic Aperture Radar) systems and passive radiometers. The active systems emit radiation at a certain wavelength and polarization and measure the radiation reflected by the Earth's surface. This allows high-spatial resolution measurements (of the order of metres) to be retrieved as the reflected signal is sufficiently strong to achieve the appropriate level of the signal to noise ratio. In contrast, the passive sensors measure weak microwave radiation emerging from the Earth's surface, therefore the spatial resolution of such data is low (of the order of kilometres). Apart from the sensor type, an important factor that influences satellite soil moisture retrieval is the wavelength at which the measurements are performed. The most commonly used wavelengths for these applications are C-band for the active sensors and L-band for the passive sensors. The C-band features a frequency range from 8 to 4 GHz (3.75 to 7.5 cm wavelength) and it is capable of penetrating through clouds and rain showers regardless of the time of day but not through dense vegetation. The L-band operates at a frequency range from 1 to 2 GHz (30 to 15 cm wavelength) that allows deeper penetration through the vegetation canopy at the price of reduced spatial resolution. Some attempts have been made to merge both radar and radiometer systems operating in the L-band on one satellite that would enhance the spatial resolution. Such a concept was introduced by NASA (National Aeronautics and Space Administration) with the SMAP (Soil Moisture Active Passive) mission. Unfortunately, due to a malfunction of the SMAP radar system encountered on 7 July 2015 such a fusion has not yet been established.

Concerning the passive radiometers, such as the MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) operating aboard the SMOS (Soil Moisture and Ocean Salinity) satellite, the acquired brightness temperatures and the soil moisture product are of low spatial resolution (35–50 km) but of relatively high temporal sampling (3 days). Likewise, some of the active systems such as the ASCAT (Advanced SCATterometer) instrument record low resolution data simultaneously from two SAR systems. This sensor is mounted aboard two MetOp (Meteorological Operation) satellites, which allow near global coverage in a period of less than five days. Other instruments such as the decommissioned SAR aboard ERS (European Remote Sensing) satellites and ASAR (Advanced Synthetic Aperture Radar) aboard the ENVISAT (Environmental Satellite) satellite allow high resolution data (120 m) at low temporal resolution (35 days). These characteristics affect fields of application of soil moisture data. In general, if a high temporal sampling is needed (e.g. weather forecasting) the radiometers are more suitable as opposed to SAR systems, which are used where high spatial resolution is required (e.g. hydrological modelling, precision farming). This issue is solved by the constellation of two S-1satellites described in the next Section.

2.1. Sentinel-1 characteristics

The S-1 satellite constellation sharing the same sun-synchronous, near-polar orbital plane consists of two platforms equipped with the C-band (5.4 GHz) SAR systems. The S-1 acquires measurements with the radiometric accuracy of 1 dB at the following polarization modes: VV+VH, HH+HV, HH, VV, and at the incidence angles ranging from 20º – 46º. Sentinel-1A was launched on 3 April 2014 and Sentinel-1B on 25 April 2016. The revisit time at the same acquisition geometry is 6 days for both platforms. There are 4 observing modes of the SAR system:

- Interferometric wideswath mode at 250 km and 5 × 20 m resolution;
- Wavemode images of 20 × 20 km and 5 × 5 m resolution (at 100 km intervals);
- Strip map mode at 80 km swath and 5 × 5 m resolution;
- Extra wideswath mode of 400 km and 20 × 40 m resolution.

2.2. Soil moisture measuring network suited for satellite data

The soil moisture field retrieved from the satellite data features a significant variability induced by a number of environmental conditions such as soil characteristics, land cover/land use, topography, vegetation cover, and surface roughness. Therefore, to objectively assess the accuracy of the soil moisture product the reference in-situ measurements across a particular validation site should characterize a homogeneous area in respect to the aforementioned aspects. The spatial extent of the validation site and the density of a measuring network should correspond to the characteristics of a satellite soil moisture product and its accuracy requirements. The anticipated nominal spatial resolution of the S-1 soil moisture products should range from 100×100 m to 1 × 1 km, which defines the minimum spatial extent of the site. Regarding the required S-1 soil moisture product accuracy, which should stay within the 5% Volumetric Water Content (VWC) range, the density of a measurement network should not be less than one measurement per 250 m^2. Nevertheless, this value may vary with the soil type and sensor installation depth. Based on the literature review by Crow et al. (2012), it could be estimated that in order to estimate the soil moisture field with an accuracy of 0.02 m^3/m^3, the average maximum measurement density should be lower than 1/155 m^2. Concerning the temporal sampling of measurements from the automatic stations, it is usually set to 30–60 min. This ensures stable soil moisture conditions as compared to the satellite overpass time.

2.3. Overview on soil moisture measuring networks

The need for operational soil moisture monitoring and retrieval has been raised by a number of studies and emphasized by the Global Climate Observing System (GCOS) by endorsing soil moisture as an Essential Climate Variable (ECV). In this respect many soil moisture measuring networks and field campaigns have been initiated with dedication to various applications such as hydrology, meteorology, agronomy, or satellite data validation. As a result an extensive set of measurements has been acquired in different types of soil, climatic conditions, and land covers by a variety of sensors at different temporal and spatial scales. In order to harmonize this extensive data set, evaluate its quality and disseminate it within the large scientific community, the International Soil Moisture Network (ISMN) was set up (Dorigo et al., 2011) to serve as a centralized data hosting facility. It contains data of 55 networks and more than 500 stations located in North America, Europe, Asia, and Australia (status on February 2017). The following description will summarize the characteristic of the networks from the perspective of satellite soil moisture validation.

2.3.1. Spatial extent and sampling of soil moisture measuring networks

The main field of application of the soil moisture measuring networks alters their spatial extent, which can be divided into 3 categories (Crow et al., 2012):

- macro-scale networks, which span the continental scale, have a permanent character, and consist of dozens of sites with a mean density lower than one station per 100 km^2. The soil moisture variability across such a vast area originates from the meteorological forcing, land cover patterns and topography. Such net-

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works contribute as inputs to weather/climate models and are utilized for validation of global satellite products;

– meso-scale networks, which span large watersheds, have a permanent character, and consist of dozens of sites with a mean density higher than one station per 100 km^2. The soil moisture variability across this scale originates from the land cover patterns, topography, and soil characteristics. Such networks contribute as inputs to hydrological models and are utilized for validation of low resolution satellite products;
– micro-scale networks, which spans from a single field to small watersheds, consist of only a few stations with a mean density higher than one station per 1 km^2. The measurements contributing to such networks usually come from temporal stations and/or field campaigns. Few micro-scale networks have operated over an extensive timespan. The soil moisture variability across this scale originates mainly from the soil characteristics. Such networks contribute as inputs to agronomic analyses, fine-scale hydrological models, civil engineering calculations, and are utilized for the validation of high resolution satellite products.

3. Description of soil moisture retrieval algorithms suited for the satellite SAR data

Retrieval of soil moisture from SAR imagery is affected by a wide range of variables such as biomass, vegetation water content, atmospheric state, surface roughness, acquisition incidence angle, signal polarization, and radiometric accuracy of a sensor. At low incidence angles the attenuation of the SAR signal from the soil component prevails, whereas at higher incidence angles canopy scattering dominates. It was found that the VV polarization is better suited for soil moisture retrieval over bare or sparsely vegetated soils, whereas the HH polarization is more useful for retrieving soil moisture over areas covered by moderately dense vegetation characterized by a biomass lower than 2 kg m^{-2} (Mattia et al., 2011). For biomass above this level the vegetation volume scattering dominates in the SAR signal and the feasibility of soil moisture retrieval is limited. Another important variable affecting the SAR signal is the surface roughness, which could be expressed as the root mean square error of the surface height (Hrms). Generally, the C-band SAR signal increases significantly for Hrms values lower than 1 cm, whereas above this threshold this increment is small. The instantaneous state of the aforementioned variables is mostly unknown during a satellite overpass or could be approximated with limited accuracy. This turns soil moisture retrieval into an ill-posed problem, where several combinations of the input variables lead to the same radar signal acquired by a sensor. To overcome this issue a number of approaches have been proposed, which could be divided into 3 categories:

– statistical fitting of the SAR backscatter and in-situ soil moisture measurements. The applicability of this method to different environmental conditions from the ones from a training dataset is questionable;
– radiative transfer model inversion. Such methods are computationally demanding, therefore some approaches based on the Bayesian theory, Nelder Mead minimization or neural networks were proposed. Furthermore, these algorithms utilize a number of a priori data sets which may not be available on a global scale;
– time series analysis of the radar backscatter incorporating elements of change detection. This approach requires an extensive temporal set of the SAR backscatter coefficients to investigate high frequency changes which are attributed to soil moisture content variations. In contrast, low frequency fluctuations of the backscatter coefficient over a range of weeks or months are related to vegetation dynamics or changes in surface roughness.

3.1. ACS algorithm

The soil moisture retrieval algorithm proposed by the Advanced Computer Systems (ACS) operates in mono-temporal and multi-temporal modes (SMAD_S-1_Team, 2011). The mono-temporal algorithm utilizes the artificial neural network (ANN) methodology in order to invert the radiative transfer simulations generated by the ensemble of Integral Equation Model (IEM) and Oh models (Fung et al., 1992) coupled with the water cloud model (Attema and Ulaby, 1978) (which accounts for the vegetation contribution to the SAR signal). Mandatory input variables consist of the co-polarized SAR image and associated incidence angles. However, superior results in terms of the accuracy can be obtained by incorporating optional inputs such as the following: additional cross-polarized image; SAR layover data, land use, shadowing masks (where retrieval is not possible); and NDVI (Normalized Difference Vegetation Index) or other indices characterizing vegetation and its biomass. The algorithm output consists of the volumetric soil moisture, which can be aggregated to variable spatial resolutions (nominal product resolution is assumed to be equal to the sensor resolution). The main limitation of this method is the fact that it requires an extensive training data set covering all of the environmental conditions which can later be encountered during the operational use of the algorithm. This is not possible by means of the in-situ measurements only; therefore synthetic data produced by the IEM and Oh model are used. Nevertheless, this introduces another source of uncertainty into the soil moisture product related to the accuracy of the utilized models, number of model runs, and boundary conditions of the input variables.

The multi-temporal implementation of the algorithm utilizes a series of 25 images that are used in two independent processing steps: an incremental model to account for the vegetation effect based on the empirical approach, and the multitemporal inversion of a forward model to retrieve the soil parameters. The main assumption is that the temporal variations of the radar measurements with respect to the reference image are proportional to the temporal variations of the biomass and of the soil parameters. The correction of vegetation effects in the SAR signal is performed by extracting the contributing soil component from the canopy backscattering coefficient. The soil component is approximated by means of a backscatter coefficient of a bare soil combined with a temporal linear relationship between differences of VWC and measured backscatter, derived from a particular acquisition and a reference image. The VWC is estimated from the NDWI (Normalized Difference Water Index) retrieved from the optical satellite imagery. Once the soil component of the SAR signal is known, it is subsequently used in conjunction with the electromagnetic forward model to search for the Bayesian maximum posterior probability of soil moisture estimate by minimizing a cost function using the multi-temporal set of images. The input variables to the multi-temporal algorithm consists of a SAR backscatter coefficient at one or two polarizations and associated incidence angles, NDVI, land use, look-up table of electromagnetic forward model simulations expressing the backscattering coefficient as a function of different polarizations and soil state vectors. The output will consist of volumetric soil moisture estimates at nominal sensor resolution together with an associated quality index. The limitation of this method is the fact that it requires a backscatter coefficient of a bare soil to correct for vegetation effects.

3.2. TUW algorithm

The TUW (Technische Universität Wien) method (Hornacek et al., 2011) falls in the category of algorithms which utilize an extensive time series (at least 2 years) of SAR observation. It is a change detection technique that expresses soil moisture in terms of the empirical relationship between the measured SAR backscatter and the two historical backscatter coefficients associated with the wilting and saturation soil moisture levels. On this basis the soil moisture index in the 0–1 range is derived, which corresponds to its saturation level. Consequently, it can be further multiplied by the soil porosity value to retrieve a VWC estimate. The backscatter coefficients associated with the wilting and saturation soil moisture levels are derived as minimum and maximum values encountered in a long time series. Such statistics are stored and updated on a per pixel basis as a function of incidence angle. The input variables consist of SAR imagery and associated incidence angle information, soil wilting and saturation statistics data base, land use, and porosity estimates. The output products at the spatial resolution of 1 km^2 consist of the soil moisture index, soil VWC (if a porosity map is available), and retrieval quality indicators.

3.3. ISSIA algorithm

The SMOSAR algorithm "Soil MOisture retrieval from multi-temporal SAR data" (Mattia et al., 2011) proposed by the ISSIA (Istituto di Studi sui

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Sistemi Intelligenti per l'Automazione) exploits multi-temporal series of radar backscatter differences computed over a short period. It operates in two modes: fast delivery providing rough soil moisture estimates to be used in near real-time applications, and precision delivery, where temporal averaging is applied to increase product accuracy and compute error estimates. Due to the characteristics of the S-1 C-band (5.4 GHz) radar systems that penetrate dense vegetation only to a small extent, the SMOSAR algorithm incorporates a masking module where the soil moisture retrieval is not possible. This discrimination is based on an adaptive thresholding scheme applied to cross-polarized SAR data that indicates if the volume scattering occurs due to the dense vegetation cover characterized by a biomass greater than 2 kg/m^2. The premise of the SMOSAR retrieval assumes that high frequency variations of the backscatter can be used to decouple the influence of soil moisture on the SAR signal from the contributions of vegetation and soil roughness (which usually change over a longer period). This allows the so-called alpha approximation to be implemented that simplifies the backscatter ratio between subsequent observations into a quantity that depends on the dielectric constant and incidence angle only. The alpha coefficient can be estimated by solving an under-determined linear system composed of the co-polarized backscatter ratios between subsequent acquisitions by means of the least squares method. Once the alpha coefficient is known, the dielectric constant can be derived and then the VWC can be estimated by inverting the empirical expression proposed by Hallikainen et al. 1985. The acquired soil moisture product corresponds to the fast delivery mode and to improve its accuracy the process described above is repeated for different temporal stacks of input SAR backscatters. This allows the generation of multiple soil moisture products for a single acquisition, which are averaged producing the precision delivery product. Further, their standard deviations are computed, which can be regarded as retrieval error estimates. The SMOSAR input variables consist of time series of SAR imagery and associated incidence angle information, a land use map (for masking purposes), NDVI data, and a soil texture map. The output products at the spatial resolution of 0.5-1.0 km^2 consist of a fast delivery SM product, and a precision delivery product with error estimates.

3.4. IGiK algorithm

The IGiK soil moisture retrieval algorithm is based on the water cloud model (Attema and Ulaby, 1978) modified by Prevot et al. (1993) and Dabrowska-Zielinska et al. (2007). The water cloud model expresses the total SAR backscatter from a canopy as a sum of contributions from the vegetation and underlying soil. Since the backscatter is affected by the dielectric and geometrical properties of the canopy, it is possible to expand the water cloud model by incorporating robust vegetation descriptors such as leaf area index (LAI), leaf water area index (LWAI), and vegetation water mass (VWM). The LWAI is defined as LWAI = LAI×W, where W is the amount of water (unitless) expressed as a ratio of the wet and dry biomass to the wet biomass. This is equivalent to the amount of water present in the leaves. The VWM is defined as the difference between wet and dry biomass. The modified cloud model was successfully applied to co-polarized ENVISAT ASAR data (Dabrowska-Zielinska et al., 2009). On the basis of the acquired results it was concluded that the soil moisture contribution to the C-band backscatter is greater than the one from vegetation. However, for dry conditions and dense vegetation the sensitivity of the C-band signal to the soil moisture is low. Across the three utilized vegetation descriptors, the LWAI proved to be the most correlated with the radar backscatter, as it accounts for the area and dielectric properties of leaves at the same time. Furthermore, it was shown that for the dense vegetation characterized by the LAI > 4, a moderately saturated soil (<40%) has no impact on the SAR signal. Nevertheless, for moist soils (≥40%) the soil contribution in the C-band SAR signal with the VV polarization is still significant even for the LAI values greater than 4.5.

4. Soil moisture validation methodology

Large satellite footprints of the passive radiometers or the L-band radars cover a heterogeneous area composed of various land covers and soil types. This implies that a single in-situ soil moisture measurement may not correspond well with the areal average over a vast terrain. This problem is significantly resolved by the S-1 SAR systems that allow the retrieval of soil VWC at high spatial and temporal resolutions. In order to compare satellite soil moisture data with the in-situ measurements they have to be unified in terms of spatial scale and observation time. Regarding the temporal matching, usually the observations closest to the satellite overpass are selected or linear interpolation between the two measurement times is performed. The spatial matching can be obtained by means of the following approaches:

- nearest neighbour technique, where the closest measurement to the centre of a pixel is selected (Imbo and Baghdad, 2012). This technique works best for the high resolution satellite data where there is a small within-pixel variability of the land cover and topography. In the case of a large satellite footprint, this method may fail, because the most central soil moisture measurement may not be representative for a vast area;
- correlation analysis, where a station with the highest temporal soil moisture correlation with a SAR signal is selected. This method is mainly applicable to validation of low resolution soil moisture products;
- spatial averaging, where several measurements within a SAR pixel are averaged to produce a single estimate. A more sophisticated approach introduces land-cover dependent weights which are computed as a spatial contribution of a certain class within a pixel. Then the measurements taken over a specific land cover class are alternated by weights and then averaged to increase the spatial representativeness of the acquired estimate;
- spatial interpolation by means of statistical methods, which is applied to map a sparse observational network to a higher resolution grid. This could be achieved by various operators: bilinear/bicubic interpolation, splines, inverse distance weighting, or kriging. The choice of the most suitable method depends on the network density and its characteristics combined with the geophysical dynamics of the soil moisture field;
- spatial interpolation by means of the hydrological modeliing, which is applied with the same purpose as the statistical averaging (Mattia et al., 2011). However, it incorporates a physical model which requires additional ancillary information about soil characteristics, topography, land cover, and meteorological variables. Nevertheless, the acquired soil moisture estimates are of higher accuracy as compared to the statistical methods.

5. Description of Biebrza validation sites

5.1. Physiogeographical description of the Biebrza Wetlands

The Biebrza Wetlands, located in Northeastern Poland, are one of the largest areas in Europe covered with marshes, swamps, and wet meadows. The unique flora and fauna of this region, including numerous endangered bird species, have led to the establishment of protected areas such as Biebrza National Park (BNP) established in 1993, Ramsar site established in 1995, and Natura2000 site established in 2004. The Biebrza Wetlands are flat with the average altitude about 105 m above sea level (a.s.l.). The main river is the Biebrza whose valley is naturally divided into three basins: the Upper Basin, the Middle Basin and the Lower basin. In the Upper Biebrza Basin the peat deposit is 3 to 6 m thick and covers an area of 14 000 ha. The Middle Basin has peat up to 3 m depth on an area of about 45 000 ha. The peat in the Lower Biebrza Basin covers an area exceeding 23 000 ha with an average depth equal to 1.5 m. The spongy structure of the peat, which holds and stores liquids, makes the valley a huge reservoir of fresh water (Sienko and Grygoruk, 2003).

The climate of the Biebrza Wetlands is one of the coldest in Poland with a mean annual air temperature of 6.5˚C. The coldest month is January with a mean air temperature of –4.2˚C and the warmest is July with a mean air temperature of 17.5˚C. The annual precipitation sum is one of the lowest in Poland and it ranges from 550 to 650 mm. Wetlands are flooded annually in the Spring, and this is the main water supply for the peat soil. The peats are mostly fens types, which receive nutrients from sources other than precipitation such as upslope sources, drainage from surrounding mineral soils, ground water movement, or surface waters. These natural conditions are disturbed by a decreasing water table induced by drainage systems and scrub encroachment that triggers the moorshing/mineralization process (Okruszko, 1994). Protection of the peat soils against this process requires sustainable water management enabling the optimal moisture content to be maintained in the root zone of plant communities. Therefore, continuous monitoring of the soil moisture dynamic of the Biebrza wetlands by means of remote sensing techniques is of great environmental importance.

5.2. Description of Biebrza soil moisture validation sites

Within the scope of the ESA funded project (No. 4000112578/14/NL/MP) two soil moisture validation sites covering grassland and marshland environments have been operating in the Biebrza Wetlands since May 2015. They are located within 7 km distance (Fig. 1) and therefore weather conditions are the same but the soil type and soil moisture regimes differ. This diversity allows the evaluation of the S-1 soil moisture products under a wide range of conditions. Both sites are homogeneous as far as the soil type and the vegetation cover are concerned and they spread across a flat terrain.

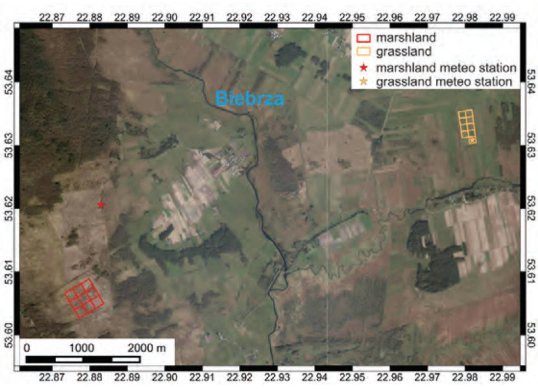

Fig.1. Location of the Biebrza validation sites. Soil stations are located within the centroids of the square polygons; numbers denote the soil profile numbers collected for the laboratory analyses

The marshland site (Fig. 2) has a regular 500 × 500 m measuring grid composed of the 9 SM stations equipped with 5 probes each, measuring at depths of 5 (2 probes), 10, 20, and 50 cm. The grassland site (Fig. 3) has analogous instrumentation with the stations arranged in two rows (230 × 580 m), one with 4 SM stations and the second with 5 SM stations. Each site was equipped with a weather station to monitor the air temperature, precipitation, wind speed and direction, solar radiation, and leaf wetness. Over the marshland site additionally heat fluxes in the soil are measured together with the net PAR (Photosynthetically Active Radiation) radiation and the water and CO_2 fluxes. Due to the inhomogeneous management of the marshland site encountered in September 2015, its location was moved 1 km southwards.

5.3. Instrumentation installed at the validation sites

The equipment installed over each validation site has common instruments for the soil moisture monitoring and separate weather stations. For the soil moisture monitoring the Decagon GS3 probes are used to measure soil moisture, temperature and electrical conductivity. The Decagon weather station installed at the grassland site is equipped with the following instruments:

- ECRN-100 Decagon High Resolution Rain Gauge with the 0.2 mm resolution;
- Decagon VP-3 air humidity, temperature, and vapour pressure sensor ;
- Decagon LWS leaf wetness sensor;
- Decagon Davis Cup anemometer;
- Decagon pyranometer.

The weather station installed at the marshland site is equipped with:

- Campbell 083E-L air Temperature and Relative Humidity Sensor;
- Hukseflux NR01 4-component net radiation sensor to analyse short- and long-wave downwelling and upwelling radiation;
- two Hukseflux HFP01SC-L heat flux plates to analyse energy transfer within the soil;
- Vaisala CS106 Barometric Pressure Sensor;
- Campbell 05103-L wind speed and direction turbine;
- Decagon LWS leaf wetness sensor;

Fig. 2. Marshland site

Fig. 3. Grassland site with the soil stations

– ECRN-100 Decagon High Resolution Rain Gauge with 0.2 mm resolution;
– Licor LI-7500A Eddy Covariance system to analyse CO_2 fluxes;
– Gill WindMaster 3d ultrasonic anemometer to analyse the vertical and horizontal wind components within eddies;
– Decagon PAR sensors.

On a monthly basis a field campaign is conducted over the validation sites to inspect the instrumentation and to perform additional measurements related to LAI, biomass, chlorophyll content, and TDR (Time-Domain Reflectometry) soil moisture measurement. This complementary material expands the soil moisture validation analysis with ancillary information about the variables influencing the SAR signal (biomass, vegetation state) and provides one more reference soil moisture dataset acquired by the TDR technique.

6. Calibration performed

The standard calibration of the GS3 probes is suited mainly to mineral soils, which substantially differ from peat soils as far as the physical properties are concerned. Therefore, the probes were recalibrated in the laboratory using precise gravimetric soil moisture measurements. This was performed to relate the apparent dielectric constant (ka) measured by the probe to the volumetric water content (VWC) of the soil (Topp et al., 1980; Malicki and Skierucha, 1989). As a result of the laboratory measurements the calibration curves (Fig. 4) for the peat soil were determined. The basic equation describing such a calibration curve expresses the linear relationship between the square root of dielectric constant and the VWC (Herkelrath et al. 1991; Schaap et al. 1996; Caron et al., 2002; Oleszczuk et al., 2004).

$$\Theta_v = a + b\, k_a^{½} \tag{1}$$

where:
Θ_v – volumetric soil moisture content (%),
k_a – dielectric constant [-],
a, b – fitting parameters.

Nevertheless, the selection of the calibration curve polynomial degree depends on specific soil characteristics and may alter the VWC measurements by a factor up to 15%. Equations 2 and 3 describe the calibration curves presented in Figure 4 for the grassland and marshland sites respectively.

$$\text{grassland: } \Theta_v = (-0.107\, k_a^3 + 13.184\, k_a^2 + \\ + 615.236\, k_a + 21787.5)\, 10^{-3} \tag{2}$$

$$\text{marshland: } \Theta_v = (6.763\, k_a^3 + 42.2892\, k_a^2 + \\ + 43546.821\, k_a + 3178346.759)\, 10^{-5} \tag{3}$$

During the GS3 probes installation in April 2015 nine soil profiles were dug at each validation site. The undisturbed soil samples (886 cm^3 volume) were collected from the following depths: 5, 10, 20 and 50 cm. Additionally soil samples were also taken from the 0-10 cm layer. In the laboratory the soil samples were saturated for 30 days. Then in each of the soil samples GS3 probes were installed to measure dielectric constant (k_a) and the samples were left to dry at room temperature (~20°C). Changes in the dielectric constant values as well as

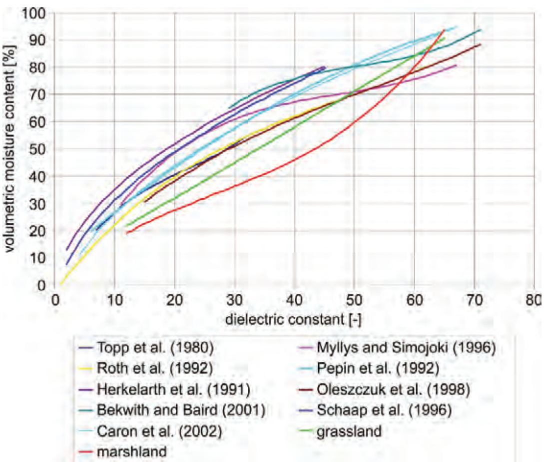

Fig. 4. Comparison of the calibration curves derived for grassland and marshland sites with the calibration curves found in the literature

in the sample weight were measured simultaneously during the drying process. The measurements were conducted until the soil moisture changes were negligible. Then the samples were dried in an oven at a temperature of 105°C in order to determine their final dry weight values, which were used to calculate the volumetric water content and also to determine the bulk density as well as the porosity of each sample (Skawina et al., 1993; Mocek et al., 2000). The results of basic soil properties are presented in Table 1.

7. Preliminary results

7.1. Variations in soil moisture and Sentinel-1 backscatter over the Biebrza validation sites

The suitability of the selected areas for the validation of soil moisture product derived from the high resolution satellite data should be evaluated from the perspectives of temporal soil moisture dynamics and its spatial variability. Regarding the first aspect it can be noticed in Figure 5 that the selected sites feature different soil moisture regimes at the depth of 5 cm. The marshland site is fully saturated with water in the spring and then during the vegetation season soil moisture slowly decreases. In the late cold part of the year (November till April) the water table rises due to precipitation and snow melt. The grassland site is also almost saturated with water in the spring; however, later during the vegetation season soil moisture sharply decreases. In February soil moisture sharply increases analogically to the marshland site. Concerning the soil moisture variability within the site it is represented as the shaded areas in Figure 5. They were computed as mean values +/- the standard deviations of all soil moisture measurements at 5 cm across the particular site. The soil moisture spatial variability over the grassland site is small (0.035 m^3/m^3) and it slightly increases during the periods with heavy precipitation. In this respect the marshland site features lower spatial soil moisture variability (0.074 m^3/m^3) than its former location (0.083 m^3/m^3). Nevertheless, the variability is still small for both sites as compared to the total soil moisture amplitude. Finally it has to be emphasized that the first year (2015) of measurements at the Biebrza S-1 sites was extremely dry in the summer and the following year was significantly more moist.

In anticipation of the high resolution soil moisture product derived from the S-1 data a limited analysis was performed to assess correlation of the sigma nought backscatter (σ^0) estimates with the soil moisture (Figures 5 and 6). In the scope of the study all of the available S-1 GRDH (Ground Range Detected at High resolution) data since October 2014 for both field sites have been downloaded. The nominal acquisition frequency of the S-1 satellite is 12 days for a single track; however, the grassland site is covered by 4 different S-1 tracks (two descending and two ascending orbits) and the marshland site is covered by 3 different S-1 tracks (one descending and two ascending orbits). This significantly increases the S-1 revisit time, which on average equals 4 days. Nevertheless, the SAR data acquired from different viewing geometries and atmospheric conditions cannot be easily compared.

The S-1 processing is performed by means of the Sentinel-1 Toolbox (S1TBX) software distributed by the ESA. The computations consist of the calibration processing chain, which is applied to every S-1 image separately, and the bulk processing chain, which is applied to the entire stack of the S-1 imagery originating from the same satellite relative orbit. The calibration processing chain involves the following steps:

Table 1. The values of saturated volumetric water content (Θ_{sat}) [% vol.], soil bulk density (ρ_b) [g cm^{-3}], and porosity (ϕ) [%] at different peat soil depths derived over the grassland and marshland sites

Variables	Site	Statistics	Layer	Depth			
			0–10 cm	5 cm	10 cm	20 cm	50 cm
Θ_{sat}	grassland	mean	82.31	83.03	81.90	82.96	88.90
		stdev	1.43	1.26	3.18	2.34	1.29
	marshland	mean	88.78	85.88	88.33	88.30	89.00
		stdev	3.47	2.93	2.37	1.17	1.64
ρ_b	grassland	mean	0.30	0.28	0.30	0.25	0.14
		stdev	0.02	0.02	0.01	0.02	0.01
	marshland	mean	0.13	0.12	0.13	0.15	0.13
		stdev	0.01	0.02	0.01	0.01	0.01
ϕ	grassland	mean	81.21	83.53	82.06	-	-
		stdev	1.97	1.84	1.08	-	-
	marshland	mean	88.75	85.78	88.38	-	-
		stdev	2.90	3.03	2.38	-	-

– radiometric calibration, where pixel values can be directly related to the radar backscatter of the scene expressed by σ^0;
– terrain correction, which compensates for topographical variations of a scene and the tilt of the satellite sensor;
– linear to dB conversion, which converts σ^0 values to decibels;
– subset to select region of interest (ROI) that will be further processed.

The bulk processing chain involves the following steps:

– image stack creation, which allows collocation of two spatially overlapping products. Collocating two products implies that the pixel values of one product (the slave) are resampled into the geographical raster of the other (the master);
– Ground Control Points (GCP) selection, where a set of uniformly spaced Ground Control Points (GCPs) in the master image are generated first, and then their corresponding GCPs in the slave image are computed;
– image warp, where GCP pairs are used to construct a WARP distortion function, which establishes a map between pixels in the master and slave images. With the WARP function computed, the co-registered image is generated by mapping the slave image pixels onto the master image;
– subset to obtain imagery with the desired number of rows and columns;
– Multi-Temporal Speckle Filter, to remove salt and pepper noise that degrades the quality of the S-1 image and makes interpretation of features more difficult.

As a result of the described processing chain the GeoTiff images are produced, which are further used to compute zonal statistics over the selected field sites. Zonal statistics summarize the values of a raster within the zones of another dataset. This function utilizes the σ^0 values from the GeoTiff images and polygons describing locations of the sites. The derived statistics consist of mean, median, min, max, standard deviation and count of σ^0 values over a particular site. In Figures 5, 6 it can be noticed that Sentinel-1 σ^0 estimates loosely follow the soil moisture measurements over the validation sites. The correlation coefficients are higher for the natural marshland site – 0.44, 0.46 for the VV and VH polarizations, respectively – than for the managed grassland site: 0.10, 0.15 for the VV and VH polarizations, respectively. This issue can be explained by the lower soil moisture amplitude over the marshland site, which fits better to the rather flat S-1 σ^0 signal. Another factor is related to the SAR signal disturbance caused by the biomass change over the grassland site induced by grass cutting. This correlation analysis indicates that

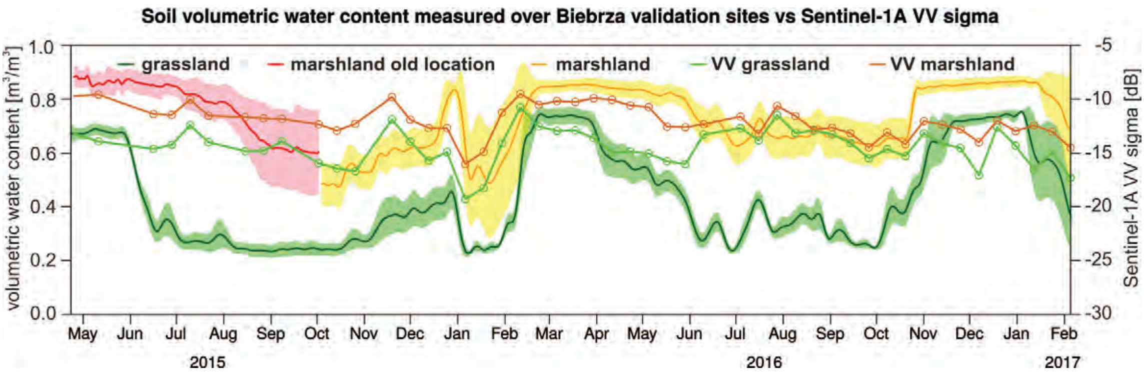

Fig. 5. Time series of soil moisture measurements averaged within the validation sites and Sentinel-1 σ^0 at VV polarization. Shaded areas denote standard deviations of soil moisture measurements across a site

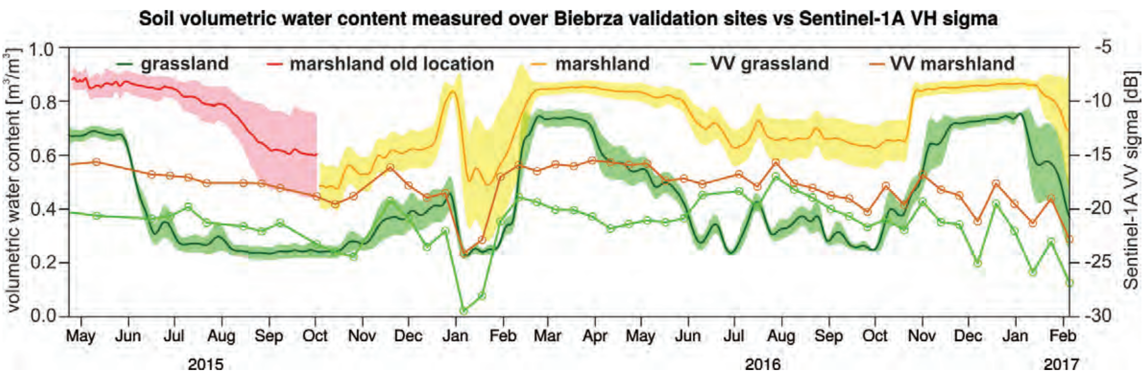

Fig 6. Time series of soil moisture measurements averaged within the validation sites and Sentinel-1 σ^0 at VH polarization. Shaded areas denote standard deviations of soil moisture measurements across a site

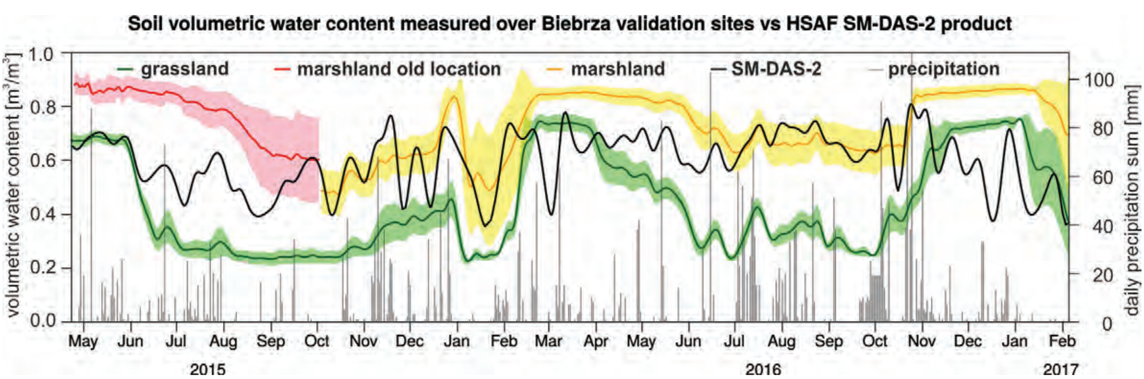

Fig. 7. Time series of soil moisture measurements averaged within the validation sites, precipitation, and SM-DAS-2 product. Shaded areas denote standard deviations of soil moisture measurements across a site

within the soil moisture retrieval algorithm there have to be more variables included to improve correlation (such as optical satellite measurement).

7.2. Validation of the SM-DAS-2 soil moisture product

Due to unavailability of the high-resolution soil moisture product derived from the S-1 data the low resolution SM-DAS-2 product generated by the H-SAF (*EUMETSAT* Satellite Application Facility on Support to Operational Hydrology and Water Management) was used. The SM-DAS-2 product stands for the "Root zone soil moisture index in the root zone by scatterometer data assimilation". It is based on the measurements of the ASCAT instrument mounted onboard two MetOp satellites which consists of two side-looking (left and right) radar antennas with a viewing angle up to 45 degrees. This allows the wide 550 km swathe along each side of the satellite track separated by a 670 km gap in between. The global coverage over Europe is achieved within 1.5 days with a native spatial resolution of 12.5 km. However, the soil moisture products from ASCAT data are generated at a resolution of 25 and 50 km. Later the finer scale product (25 km) is assimilated in the ECMWF (European Centre for Medium-Range Weather Forecast) Land Data Assimilation System (LDAS) to retrieve a root zone soil moisture profile index at the following depths: 0.07, 0.21, 0.72 and 1.89 m. The model run is performed at 24 hour time steps, which is more frequent than the native ASCAT coverage over Europe (36 hours). The root zone soil moisture profile index is limited to the 0-1 range and it relates the current soil moisture to its minimum and maximum potential values for the given pixel. Therefore, to convert the index to the soil VWC expressed in m^3/m^3, its value was multiplied by the mean porosity at 5 cm depth across both Biebrza validation sites (see Table 2).

Within the validation analysis the SM-DAS-2 soil moisture at the topmost 0.07 m layer was selected. The coarse 25 km spatial resolution of the SM-DAS-2 product results in the coverage of both sites by a single pixel. From the time series of the SM-DAS-2 product presented in Figure 7 it can be noticed that it features significant soil moisture variability at higher frequency than the reference in-situ measurements. The validation of the SM-DAS-2 product against the grassland site soil moisture measurements (Fig. 8) reveals weak correlation ($R^2 = 0.19$) and large Mean Bias Error (MBE = 0.21) and standard deviation of differences (SD = 0.15). Slightly better results were obtained for the measure-

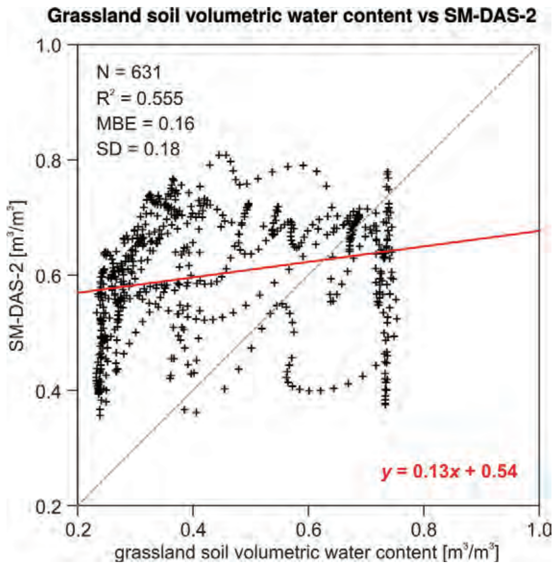

Fig. 8. Validation of the SM-DAS-2 product against the soil moisture measurements collected over the grassland site

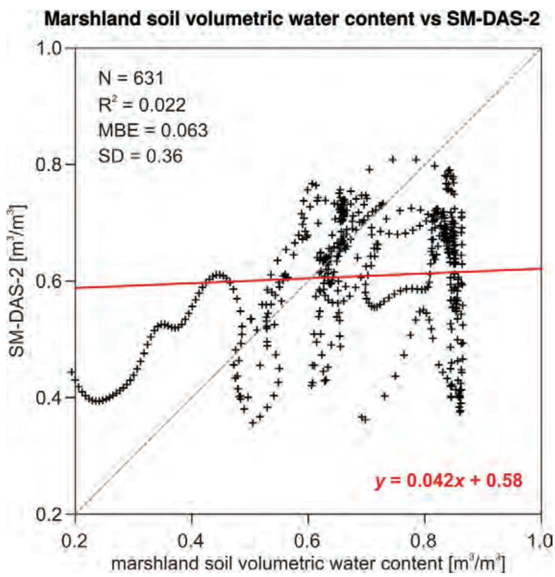

Fig. 9. Validation of the SM-DAS-2 product against the soil moisture measurements collected over the marshland site

ments collected across the marshland site ($R^2 = 0.29$, MBE = -0.06, SD = 0.099), which may indicate that the marshland is more representative for the 25 km ASCAT pixel than the grassland (Fig. 9). Nevertheless, both validation analyses reveal weak accuracy of the SM-DAS-2 soil moisture product over the Biebrza wetlands.

8. Conclusions

The main objective of this study was to discuss the derivation and validation methodologies suitable for the high resolution Sentinel-1 satellite SAR data and to describe the Biebrza soil moisture validation sites. With respect to the soil moisture derivation four algorithms were presented that exploit different numerical techniques and spectral and temporal features to derive soil moisture:

– The Advanced Computer Systems (ACS) algorithm operates in mono-temporal and multi-temporal modes (SMAD_S-1_Team, 2011). The mono-temporal algorithm utilizes the artificial neural network (ANN) methodology in order to invert the radiative transfer simulations generated by the ensemble of Integral Equation Model (IEM) and Oh models (Fung et al., 1992) coupled with the water cloud model (Attema and Ulaby, 1978). The multi-temporal implementation of the algorithm utilizes a series of 25 images that are used in two independent processing steps: incremental model to account for the vegetation effect based on the empirical approach, and the multi-temporal inversion of a forward model to retrieve the soil parameters;

– The TUW (Technische Universität Wien) method (Hornacek et al., 2011) utilizes an extensive time series (at least 2 years) of the SAR observation to derive soil moisture from the relationship between the measured SAR backscatter and two historical backscatter coefficients associated with the wilting and saturation soil moisture levels. On this basis the soil moisture index within the 0–1 range is derived, which corresponds to its saturation level;

– The SMOSAR algorithm “Soil MOisture retrieval from multi-temporal SAR data” (Mattia et al., 2011) proposed by the ISSIA (Istituto di Studi sui Sistemi Intelligenti per l’Automazione) exploits multi-temporal series of radar backscatter differences computed over a short period. It operates in two modes: fast delivery providing rough soil moisture estimates to be used in the near real-time applications, and precision delivery, where temporal averaging is applied to increase product accuracy and compute error estimates. The premise of the SMOSAR retrieval assumes that high frequency variations of the backscatter can be used to decouple the influence of soil moisture on the SAR signal from the contributions of vegetation and soil roughness (which usually change over a longer period);

– The IGiK algorithm is based on the water cloud model (Attema and Ulaby, 1978) modified by Prevot et al. (1993) and Dabrowska-Zielinska et al. (2007). The water cloud model expresses the total SAR backscatter from a canopy as a sum of contributions from the vegetation and underlying soil. Since the backscatter is affected by the dielectric and geometrical properties of the canopy, it is possible to expand the water cloud model by incorporating robust vegetation descriptors such as leaf area index (LAI), leaf water area index (LWAI), and vegetation water mass (VWM).

Concerning the validation methodology of the Sentinel-1 soil moisture products it was concluded that the micro-scale in-situ soil moisture measuring networks consisting of up to several stations, with a mean density greater than one station per 1 km^2, are the most suitable. Scarcity of such networks was the main motivation to establish two Sentinel-1 soil moisture validation sites over the Biebrza Wetlands. The significant differences in the dielectric constant between the peat and mineral soils result in low accuracy of the soil moisture probes with a standard factory calibration. Therefore, probes installed at the Biebrza sites were additionally recalibrated in the laboratory using the soil samples collected in-situ. The sites are covered by managed grassland and natural marshland and are homogeneous as far the land cover and soil type are concerned. Within each site 9 soil moisture stations have been installed forming a 500 × 500 m measuring grid (marshland site) and an irregular 230 × 580 m measuring grid (grassland site). The high density of the measuring stations allows the validation of high resolution soil moisture products derived from spaceborne instruments such as the S-1 SAR system. The time series of averaged soil moisture measurements across a particular site depicted in Figures 5–7 revealed a high temporal variability of soil moisture but a low spatial variability, which confirms the high homogeneity of the sites. Furthermore, the former location of the marshland site featured higher spatial soil moisture variability, which justifies its relocation. The validation of the SM-DAS-2 soil moisture product generated by the EUMETSAT H-SAF revealed weak correlation with the in-situ measurements, which is slightly better for the marshland site (0.29) as compared to the grassland site (0.19). This could be partially attributed to low resolution (25 km) of the SM-DAS-2 product as compared to the dense measuring networks representing only two land cover types.

The future studies conducted over the validation sites will utilize measurements acquired by the meteorological station and the Eddy Covariance system to analyse energy, water, and carbon cycles over wetlands by means of remote sensing. Moreover, it is planned to develop a soil moisture retrieval algorithm suited for the S-1 data.

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Wyznaczanie i weryfikacja wilgotności gleby z wysokorozdzielczych danych satelitarnych na przykładzie zobrazowań satelity Sentinel-1 dla obszaru doliny Biebrzy

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Streszczenie: Stały monitoring wilgotności gleby jest kluczowy dla różnorodnych zastosowań i może być realizowany na globalną skalę jedynie za pomocą teledetekcji satelitarnej. Nowe generacje satelitów środowiskowych np. Sentinel-1 posiadają sensory umożliwiające wysokorozdzielcze pomiary o dużej częstości czasowej. Uzyskane z nich produkty dotyczące wilgotności gleby wymagają gęstej sieci pomiarów naziemnych do celów walidacyjnych. Fakt ten stanowił główną motywację dla założenia dwóch poligonów walidacyjnych wilgotności gleby zlokalizowanych w dolinie Biebrzy w ramach projektu finansowanego przez Europejską Agencję Kosmiczną (ESA). Obiekty te pokrywają łąkę i zbiorowisko turzycowe i są homogenicznie pod względem roślinności i typu gleby. Każdy poligon wyposażony jest w 9 stacji do pomiaru wilgotności gleby oddalonych od siebie o 130 metrów. Pozwala to na rzetelne oszacowanie średniej wilgotności dla całego obiektu odznaczającej się niskim odchyleniem standardowym (0.035 m^3/m^3 dla poligonu łąkowego i 0.074 m^3/m^3 dla poligonu turzycowego). Głównym celem tego opracowania jest opis metodyki wyznaczania i walidacji wilgotności gleby z wysokorozdzielczych radarowych danych satelitarnych oraz charakterystyka obu poligonów badawczych wraz z instrumentami pomiarowymi umożliwiającymi zaawansowany monitoring środowisk bagiennych. Ponad to przeanalizowana została zależność pomiędzy wilgotnością gleby a współczynnikiem rozproszenia wstecznego (σ^0) sygnału radarowego satelity Sentinel-1. Ostatecznie wykorzystano dane z opisywanej sieci pomiarowej do walidacji niskorozdzielczego produktu SM-DAS-2 opisującego wilgotność gleby.

Słowa kluczowe: wilgotność gleby, Sentinel-1, bagna Biebrzańskie, teledetekcja satelitarna, walidacja wilgotności gleby