Advanced Technology for Assessment of Soil Hydrological Regimes Using Multichannel Passive (Radiometric) and Active (SAR) Microwave Measurements.

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Abstract: Advanced technology for assessment of soil hydrological regimes using multichannel passive (radiometric) and active (SAR) microwave measurements is presented. Physical backgrounds of the technology, the equipment used, examples of experimental data, and prospects of the technology application are discussed.
Keywords: microwave radiometry, radar (SAR), soil moisture, depth to a shallow water table, water seepage, ground water resources

1. Introduction

The problem of Earth's environment monitoring and land use control has been growing in importance over the last 20 to 30 years. The successful solution of this problem required the research, development and application of different remote sensing technologies. Among these technologies there are radio-physical remote sensing methods and instruments that play an important role in the Earth's surface investigation. These methods and instruments are based either on the measurements of the parameters of natural radio-thermal electromagnetic radiation from the Earth's surface or on the measurements of the parameters of artificially radiated electromagnetic signals scattered by the Earth's terrain. In the first case, the remote sensing tools are called either Microwave Radiometers (MR) or Passive Microwave Radar (PMR); in the second case, the tools are called either Side-Looking Airborne Radar (SLAR) or Synthetic Aperture Radar (SAR), or Nadir Viewing Radar (NVR) with hyper-short (nanoseconds) length of pulses, etc. The instruments mentioned above are being installed on board of aircraft and satellites and orbital stations and tested in many scientific campaigns.
Research team of Institute of Radioengineering & Electronics, RAS and Radioengineering Corporation "Vega", Russia has developed an advanced technology for the assessment of soil hydrological regimes using multispectral passive (radiometric) and active (SAR) microwave measurements.
This technology is aimed to measure:

- surface soil moisture;
- underground moistening at different depths (profiling);
- depth to a shallow water table (down to 2 meters in humid areas and down to 3-5 meters in arid/dry areas, (to 10 m for active system),
- groundwater resources presence;
- contours and amount of water seepage through hydro technical constructions (levees),
- biomass of vegetation above a water surface or wet ground
- etc.

Passive system includes airborne scanning multichannel radiometer "Radius" (2.25, 5.5, 21, 43 cm) and a set of nonscanning radiometers (2.25, 6, 18, 21, 27 cm).
Active system includes airborne multichannel SAR system (3.9, 23, 68, 254 cm).
Successful tests of this equipment have been conducted in Russia, Ukraine, Uzbekistan, Turkmenia, Moldova, Bulgaria, Cuba, USA.

Paper discusses physical backgrounds of above technology, the equipment, examples of experimental data and perspective ways of the technology development and it's practical application.

2. Physical background

1) <u>Microwave Radiometry (MR) or Passive Microwave Remote Sensing</u>
is based on measurements of the natural electromagnetic radiation of objects and Earth covers in the millimeter to decimeter wavelength range. Inside this band, <u>the land surface radiation</u> <u>is primarily a function of free water content</u>

in soil and also influenced by other parameters of the "soil-canopy" system, such as above ground vegetation biomass, soil density, water salinity and temperature of the system. Free water content in soil is dependent on rainfall rate, artificial watering, shallow groundwater and processes of soil drying of at interface soil-atmosphere, etc.
Hence Microwave Radiometry is an important tool for the assessment of soil hydrological regimes, namely:

- surface soil moisture;
- underground moistening at different depths (profiling);
- depth to a shallow water table;
- contours of water seepage through hydrotechnical constructions;
- biomass of vegetation above a water surface or wet ground;
- etc. [5].

The measure of the intensity of radiation in the microwave band is referred to as a brightness temperature Tb , which is a product of emissivity κ , and thermodynamic temperature Te, within the effectively emitting layer of the object.

$$T_b = \kappa T_e.$$

The emissivity is a function of dielectric permittivity/permeability of the object/surface of observation. For a land surface, the dielectric permittivity is first of all a function of soil moisture. The higher a soil moisture content, the higher the permittivity of soil, the lower the emissivity/intensity of radiation/brightness temperature of this piece of land.
For a water surface, the dielectric permittivity is first of all a function of electric conductivity of a water solution that is dependent on a concentration of salts, acids, on a presence of oil films and many other chemical substances. For example, the higher salinity of water, the higher the dielectric permittivity of water solution, the lower the emissivity/intensity of radiation/brightness temperature of this water body.

Within the 2 to 30 cm band, for t=10-30°C, the radiation characteristics of several surface types are shown in Table 1.

Table 1. Microwave Radiation Characteristics of Some Typical Surface Types

Surface	T_b (K)	κ
Metal	0	0
Water surface	90 – 110	0.3 – 0.4
Very wet soil	160 – 180	0.55 – 0.65
Very dry soil	250 – 270	0.85 – 0.93

Table 2 shows the sensitivity of radiation in the X-band (2-3 cm) and L-band (18-30 cm) to the changes in free water content in bare soil, soil density, salinity and temperature of the soil surface [1, 2]. These data show that the main parameter affecting the intensity of a bare soil radiation, practically independent of spectral band, is the soil moisture. Based on this sensitivity it is feasible to estimate the value of soil moisture without *a priori* data on the soil parameters. It has also been seen that even for rather high values of biomass, up to 2 to 3 kg/m^2, the plant canopy is still transparent in the decimeter wavelength range.

Table 2. Sensitivity of a Bare Soil Microwave Radiation to Variations in Soil Moisture (W), Soil Density (D), Salinity (S), and Surface Temperature (T)

Wavelength (cm)	Spectral Band	$\Delta T_b / \Delta W$ (K/g/cm^3)	$\Delta T_b / \Delta D$ (K/g/cm^3)	$\Delta T_b / \Delta S$ (K/ppt)	$\Delta T_b / \Delta T$ (K/^{o}C)
2 – 3	X	- 200	- 15	0.05	0.5
18 – 30	L	-(200 to 300)	- 10	- 0.5	0.1

There are different sources of natural microwave radiation in microwaves, which can influence on accuracy of measurements: Galaxy, ionosphere, atmosphere (clouds), land. The minimum influenced by different sources of "radio-noise" is 2-cm to 21-cm wavelength band, which is window of transparency" at microwaves.

The centimeter and decimeter wavelength microwave radiometers are not influenced by the conditions of illumination, by presence of fog, smoke, clouds, and are very useful for measurements in different meteorological conditions. [1-5]

The examples of operating range and errors for the three main parameters that can be established with the system are listed below [1-5]:

Soil Moisture Content

- operating range 0.02 - 0.5 g/cc
- maximum absolute error:
  - if vegetation biomass is less than 2 kg/m² 0.05 g/cc
  - if vegetation biomass is greater than 2 kg/m² 0.07 g/cc

Depth to a Shallow Water Table

- operating range:
  - humid, swampy areas 0.2 – 2 m
  - dry arid areas, deserts 0.2 – 5 m
- maximum absolute error 0.3 - 0.6 m

Plant Biomass (Above Wet Soil or Water Surface)

- operating range 0 – 3 kg/m²
- maximum absolute error 0.2 kg/m²

2) <u>Radar (SAR) Survey or Active Microwave Remote Sensing.</u>

Radar (SAR) Survey or Active Microwave Remote Sensing is based on measurements of the parameters of artificially radiated electromagnetic signals scattered by the Earth's covers and objects. Due to high spatial resolution radar systems are very important instruments of remote sensing from space. Previously studies of scattered signal from soil and vegetation were conducted using on-ground and airborne scatterometers and radars. The results of these studies are the dependences of scattered signal on soil moisture, soil surface roughness, vegetation parameters, etc. [6, 7]

Theoretical models for electromagnetic waves scattering by bare soil are based at Kirchgoff approximation. Different expressions were obtained for the backscattering coefficient σ_s^0 but most of them may be written as

$$\sigma_s^0 = he^{-h} F(klSin\vartheta) R_s Cos^2\vartheta + \sigma(h^2)$$

$$h = 4k^2\sigma^2 Cos^2\vartheta,$$

where σ is the standard deviation of rughness height, *l* is the roughness correlation length, k is the wave number in free space (2π/λ), ϑ is the nadir viewing angle, R is the soil reflectivity [6].

Analysis of formulas showed that

a) the sensitivity of electromagnetic wave scattering by bare soils to reflectivity variations of bare soil surface doesn't depend on roughness parameters, wavelengths and observation angle; dynamic range of scattering by bare soils is no more 9 dB, when reflectivity varies from 0,05 (very dry soil) to 0,4 (very high soil moisture); 6-8 gradations of reflectivity may be obtained with an accuracy of soil backscatter mesurements of 1,5 dB
b) Maximal dynamic range of backscatter by bare soils is equal to about 18 dB, when standart deviation of roughness height σ varies from 0,5 to 4 cm.
c) There are two independent parameters: the standard deviation of roughness and the reflectivity. It is obvious to separate and to estimate the reflectivity (soil moisture) and roughness parameters, it is necessary to use measurements at minimum 2 frequencies. The best separation of these parameters is observed for observations at wavelengths satisfying the condition: h (λ_1) ≈ 1, h (λ_1) << 1; that produces wavelengths 10 cm and 24 cm. These optimal wavelengths were used for radar in the "Priroda" project.

These conclusons were verified by experimental data.

Quantitative and qualitative analysis showed that radar data may be good tool for soil moisture measurements. It is possible to obtain 6-8 gradations of soi moisture for bare soil and 3-4 for soil covered by vegetation [6].

2. Comparative analysis of passive and active microwave remote sensing systems using

It has theoretically been shown and experimentally proven in investigations [8-9] and in the studies conducted by other teams that active and passive systems are sensitive to soil moisture changes and to changes in surface roughness, peculiarities of relief, vegetation biomass and structure, and angles of observation. In general, the terrain features, surface roughness, changes in relief, and vegetation characteristics influence the radar return more than natural emitted radiation, other conditions being equal.

The approximate ranges of radar return changes are as follows: 6-8 db for whole range of soil moisture changes; 10-18 db for whole possible scale of roughness changes; 8-10 db for vegetation characteristics changes; 6-8 db for changes in angle of observation, 30°< Θ<60° off nadir. Now, let the changes in radar returns caused by soil moisture changes be referred to as "signal", and the changes in radar returns caused by the changes in other than moisture parameters referred to as "noise". Then, the "signal-to-noise" ratio calculations will result in a s/n=0.33-0.8 for roughness, a s/n=0.6-1.0 for vegetation, and a s/n=0.75-1.33 for changes in angle.

Similarly, calculations of the "signal-to-noise" ratio for the naturally emitting radiation are higher: s/n=2-5 for roughness, s/n=1-3 for vegetation, s/n=2-3 for changes in angle. This shows the benefits of using passive systems, in spite of a more coarse spatial resolution and a smaller swath, in combination with active systems.

3. Microwave Remote Sensing Equipment

1) Microwave Radiometer Systems:

Microwave Radiometer (Non-Scanning) System (designed by Ablazov V.S., Khaldin A.A. – IRE RAS)

IRE RAS Single-Beam Multi-Wavelength Microwave Radiometer (Non-Scanning) System (Fig. 1) consists of three single-beam radiometer channels operating at the wavelengths of (0.8 cm as an option) 2 cm, 6 cm and 18 or/and 21 cm. The basic wavelength related technical parameters of the radiometer are given in Table 3.

Table 3. Instrumentation Characteristics Wavelength Dependent (H is height above ground)

Frequency	Wavelength	Band	Beam-width, deg	Ground Resolution	Mode
13.3 GHz	2.25 cm	X	30	0.65 * H	Single-beam
5 GHz	6 cm	C	30	0.65 * H	Single-beam
1.4 GHz	18/21 cm	L	30	0.65 * H	Single-beam

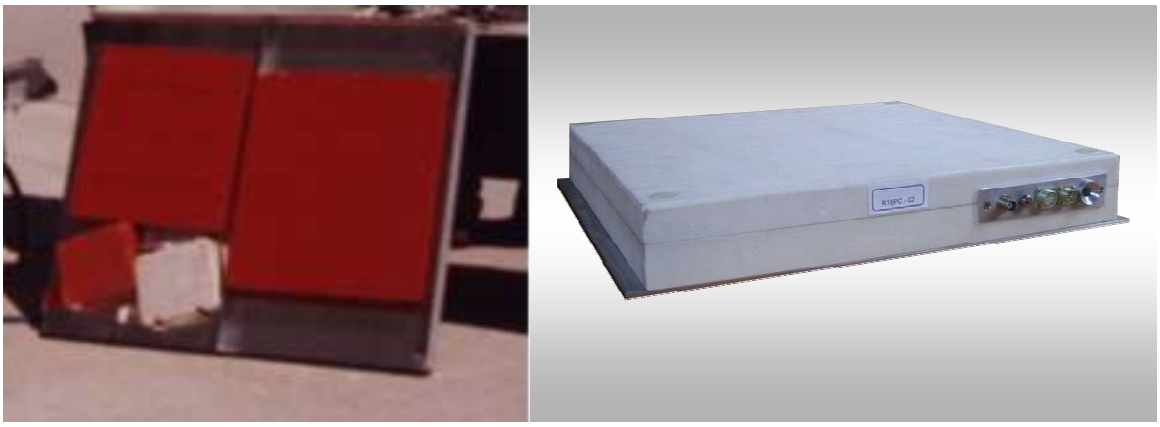


Fig. 1 . Nonscanning Microwave Radiometer and antennas for different wavelengths

Mechanically/conically scanning microwave Radiometer System RADIUS.

(designed by Manakov V. Ju., Pljushchev V.A., Sidorov I.A. - Radioengineering Corporation "Vega"**)**

Mechanically/conically scanning microwave Radiometer System RADIUS (Fig. 2) operates at the wavelengths of 0.8 cm, 2 cm, 5,5 cm, 21 cm and 43 cm. The basic wavelength related technical parameters of the radiometer are given in Table 4. New version of scanning radiometer is electronically scanning.

Fig. 2. RADIUS – Multi-Band Scanning Microwave Radiometer System

Table 4. Scanning Microwave Radiometer System (RADIUS) parameters

Frequency GHz	Pixels / scan	Resolution	Mode
37.5	48	0.02 * H	Scanning
15	16	0.06 * H	Scanning
5.5	6	0.16 * H	Scanning
1.4	2	0.5 * H	Scanning
0.7	1	H	Non Scanning

Power consumption:	200W
Power supply:	27 VDC
Aircraft mounting hole:	50 cm
Weight:	100 kg
Platform:	small aircraft

Microwave RADAR systems

Airborne SAR system IMARC

(designed by Manakov V. Ju., Pljushchev V.A., Sidorov I.A. - Radioengineering Corporation "Vega")

The IMARK [8,10] is a four-wavelength polarimetric airborne SAR system designed at MNIIP/VEGA Corporation. The basic technical characteristics of this radar are given in Table 5. Radar system operates at wavelengths: X (3.9 cm), L (23 cm), P (68 cm), and VHF (2.54 m); polarizations in all bands: VV, HH, VH, and HV; spatial resolution is around 12+/-8 m; maximum swath: 24 km. The carrier of this system was a twin-turbine jet airplane TU-134A (Fig. 3) and other planes. Allocation of the IMARK antennas on the airplane is presented at Fig. 4. The main IMARK SAR mission goals were to map the characteristics of Earth covers (including soil hydrological regimes), to map the ground terrain in a presence of vegetation with eliminating of the influence of vegetation and, to produce elevation models, to detect areas with on-ground and underground irregularities, etc. [8, 9].

Fig. 3. Airborne SAR system IMARC

IMARC SAR Complex parameters are given in Table 5.

Table 5. The IMARC SAR Complex parameters

Parameter	Value			
Frequency	X	L	P	VHF
Wavelength, cm	3.9	23	68	254
Polarization	VV, HH, VH, HV			
Resolution, m	4-6	8-10	10-15	15-20
Antennas: gain, dB	30	14-17	14-17	9-11
Width in azimuth, deg	18	24	24	40
Width in elevation, deg	24	24	24	60

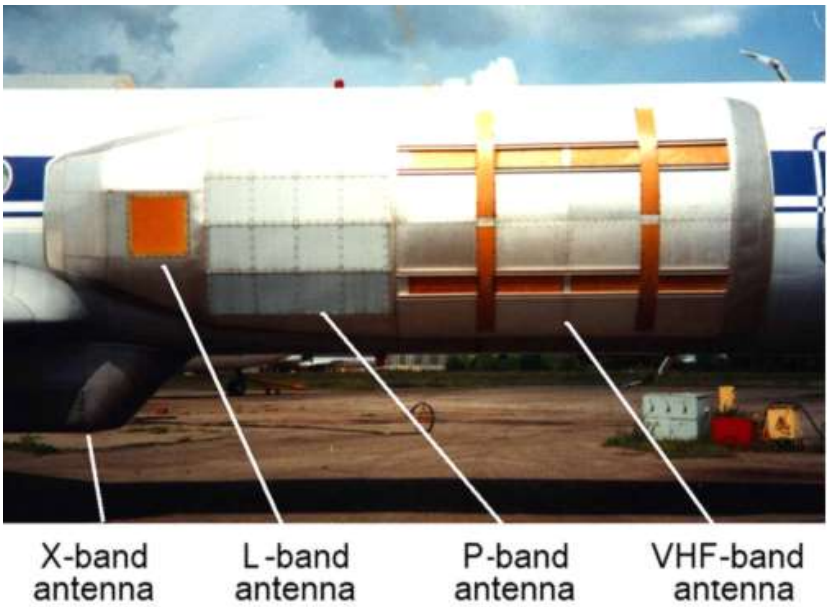


Fig. 4. Allocation of the IMARK Antennas on the Airplane

Materials & Data

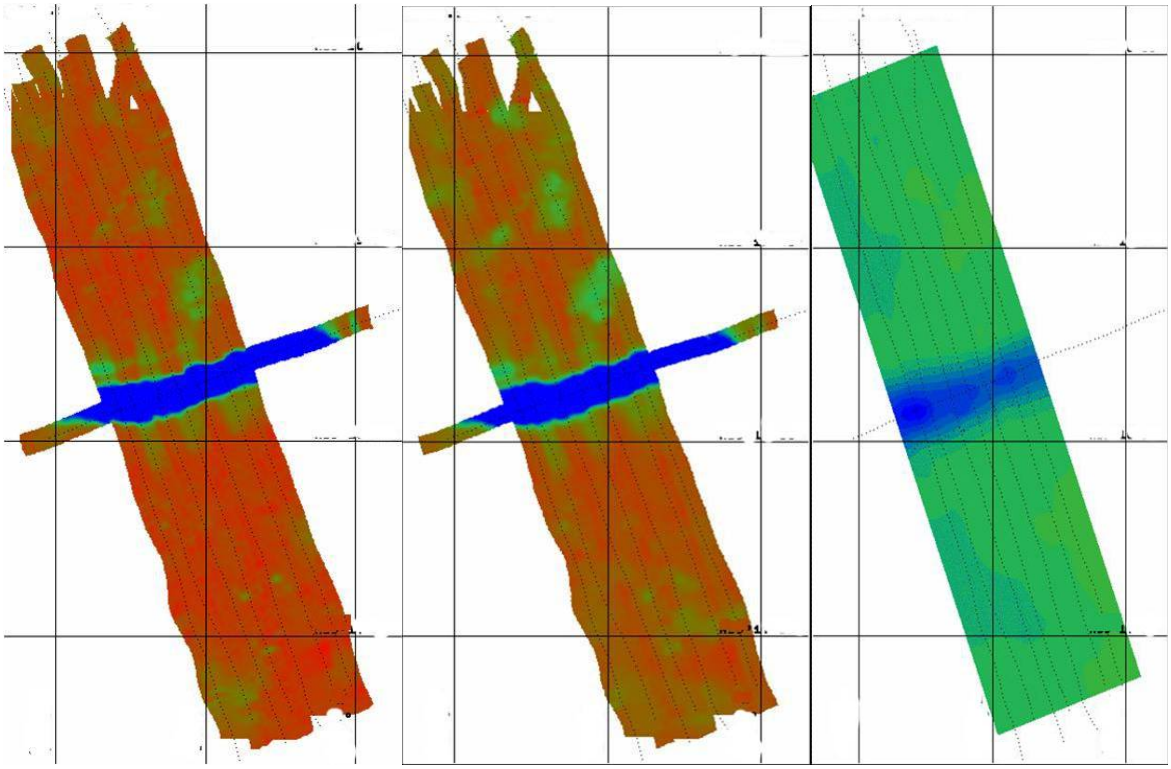


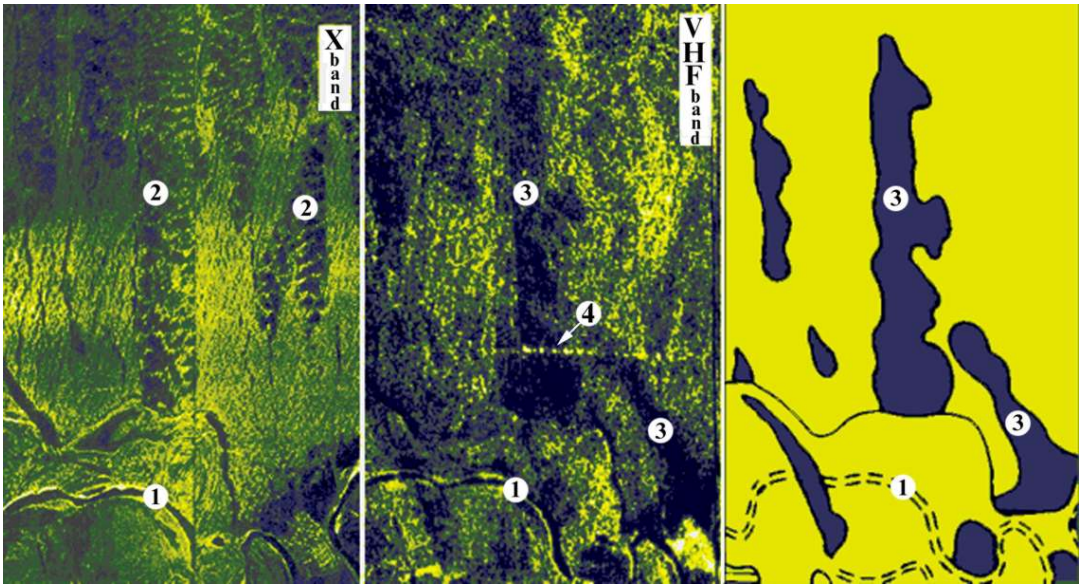
Fig. 5. Maps of 2 cm, 5.5 cm, and 21 cm Microwave Radiometry Data

Examples of MCW/RM estimates for a soil moisture, vegetation index, and depth to a shallow water table retrieving from the 6-cm, 18-cm and 21-cm wavelength data collected by IRE RAS team in the St. Marks National Wildlife Refuge are presented at Fig. 5 (Florida, USA). (The longer the wavelength the more sensitive are the sensors to a subsurface moisture for a bare and vegetation covered soil).

It is well-known that the larger the wavelength is, the higher is the influence of deeper soil layers. This fact allows the development of methods of thick layer deep sensing using multi-frequency radar systems. For subsurface sensing the use of long waves of P and VHF bands is required.

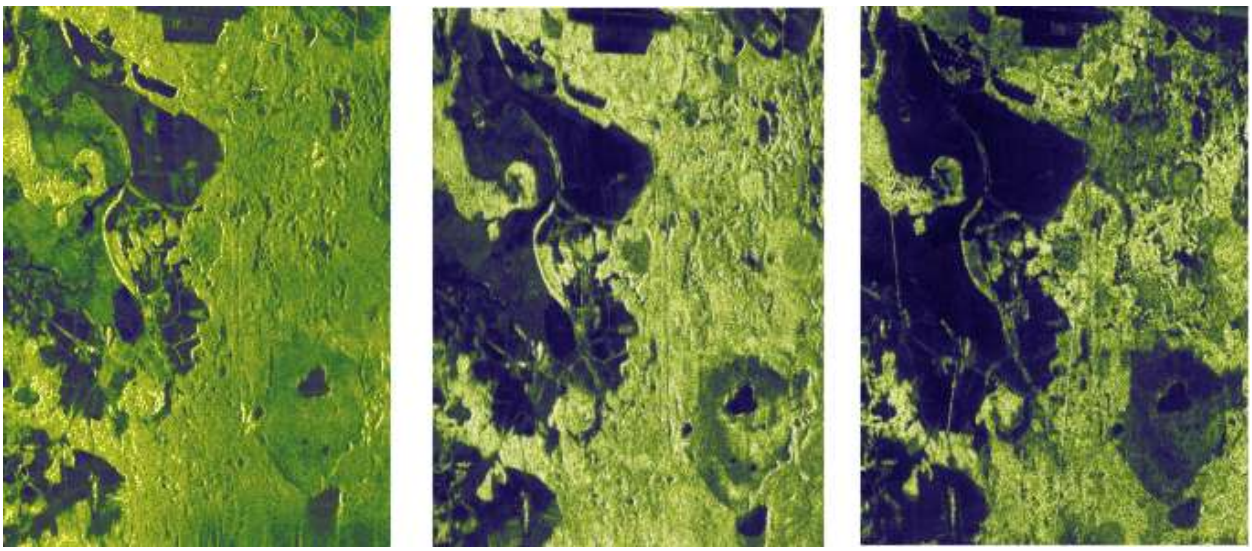
Information about soil properties (soil moisture) profiles can be received from the analysis of measurements of scattering at different wavelengths. The influence of soil moisture profile into backscattering cross section it is necessary to develop the models of reflection from the layers situated at different depth. Solution of the inverse problem can be obtained set at the measurement of backscatter at several wavelengths and at different polarization modes. To have complete information about soil moisture profile it is necessary to solve of the problem by images interpretation in broad band of wavelengths including meter band where attenuation in soil and vegetation is comparably low.

The results of multiband radar survey obtained with the help of 4-bands airborne SAR IMARC (Radioengineering Corporation "Vega") illustrate the possibility of measuring of hydrological soil regimes and water lenses allocation in Kara-Kum desert. Lenses of underground water at the depth of 50-70 m were detected. Results were validated by control well-boring. We can see at radar images: 1) dry river-Uzboy bed; 2) Sand dunes of 6-15 m height; 3) Underground water lenses; 4) Transmission facilities.



(A) **(B)** **(C)**

Fig. 6. Radar images of Kara-Kum desert region in X-band (λ = 4 cm) (A) (near surface layer information); VHF-band (λ = 2,5 m) (B) (thick layer information), and geologic map of distribution of underground waters as a result of radar survey (C) [8-10]



L-band **P-band** **VHF-band**

Fig. 7. Images Obtained by the Improved SAR System IMARC, Spas-Klepiki, Ryazanskaya Region [8]

Comparison is given in Fig. 7 of a different penetrative ability of L-, P-, and VHF-band radars to "see" a ground surface through vegetation cover. In L-wavelength band, the signal is mainly dependent on canopy characteristics. The P- band returns are much less affected by grass vegetation and a back-scattered signal clearly indicates the effect of a soil and water surface along with some effect of vegetation. The VHF-band image clearly demonstrate no effect of canopy on signal returns for grass and bushes.

Conclusions. Perspective ways of the technology development.

The potentiality of radar survey may be sighificantly increased by using of statistical properties of scattered signal and polarization measurements data together with spectral ones [6].

Calculations of the "signal-to-noise" ratio for the naturally emitting radiation are higher than for scattered radar signal: s/n=2-5 for roughness, s/n=1-3 for vegetation, s/n=2-3 for changes in angle. This shows the benefits of using passive systems, in spite of a more coarse spatial resolution and a smaller swath, in combination with active systems [8-9].

Unique system of microwave remote sensing is described. This system can solve problems of soil hydrological regimes assessment in optimal way using advantages of SAR and microwave radiometry depending on requirements specification for specific program of measurements.

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