

## Direct And Inverse Problems Of The Microwave Monitoring Of The Environment

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**Abstract:** Microwave radiometry allows effective observations of the environmental parameters for of soil-water-vegetation system. In the paper are developed methods for the microwave monitoring data processing allowing to reconstruct the environment characteristics. According to algorithms of the multi-channel microwave monitoring, it is possible to promptly measure the wind speed, sea surface roughness and water temperature as the base characteristics to calculate other parameters of the environment. From these measurements, a mutual control of the accuracy of correction of the estimates of the atmosphere-ocean gas exchange is realized. Methods for high precision measurement data obtaining by using of correction of the estimates of the measured parameters are presented.

**Keywords:** microwave monitoring, environment parameters.

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### 1. INTRODUCTION

Advances in active and passive remote sensing open the potential for new parameters measurement in ecology and industrial applications. Microwave radiometry is preferred technique for many remote sensing applications, particularly for measurement of soil and air parameters. Now can be used techniques and algorithms for achieving desired microwave performances, high spatial resolution and accuracy. For example, for soil moisture and salinity sensing the used frequencies are in the range 1-3GHz and for other parameters additional measurement channel at frequencies up to 14GHz are used. The radiometers can be used for airborne remote sensing and ground-base laboratory measurements. The ground-based microwave radiometry is mainly used for estimating temperature, water vapor and cloud liquid profiles in the absence of precipitation. In ecology the most important principle of effective radiometry is that the measurements must be relevant to the physical properties of the studied process parameters. Now many works are dedicated to the theoretical and experimental studies to improve the measurement accuracy by active and passive remote sensing in radiometry

According to algorithms of the multi-channel microwave monitoring discussed in Krapivin [1] and Nitu et al. [2], it is possible to promptly measure environment parameters, the wind speed, sea surface roughness and water temperature which are used to calculate other parameters of the environment. By using these measurements, a mutual control of the accuracy of correction of the estimates of the measured parameters can be obtained.

### 2. TECHNOLOGY OF SOIL-VEGETATION MICROWAVE MONITORING

As is well known, among the types of remote sensing techniques, microwave radiometry proves effective for

observations of environmental parameters [1-5]. However, these observations are a function of different environmental conditions mainly depending on the soil-vegetation systems (SVS) type. That is why it is necessary to develop data processing methods for microwave monitoring that allow the reconstruction of the SVS characteristics with consideration of the soil-vegetation types and that provide the possibility of synthesizing their spatial distribution. The problem of microwave remote sensing of the soil-vegetation cover requires the study of the attenuation of electromagnetic waves (EMW) within the soil-vegetation layer. The solution of the problems arising here is made possible by the combination of experimental and theoretical studies. The soil-vegetation cover commonly is characterized by varied geometry and additional parameters. Therefore, a knowledge of the radiative characteristics of the SVS as functions of time and spatial coordinates can be acquired by means of a combination of on-site measurements and models. General aspects of such an approach have been considered by many authors [1-5]. But these investigations were mainly restricted to the investigation of models describing the dependence of the vegetation medium on environmental properties, as well as the correlation between the morphological and biometrical properties of the vegetation and its radiative characteristics.

One prospective approach to the solution of the problems arising here is GIMS-technology (GIMS=GIS+Model) [5]. A combination of an environmental acquisition system, a model of the functioning of the typical geoecosystem, a computer cartography system, and a means of artificial intelligence will result in the creation of a geoinformation monitoring system for the typical natural element that is capable of solving many tasks arising in the microwave radiometry of the global vegetation cover. The GIMS-based approach, in the framework of the EMW attenuation by the soil and vegetation canopies, allows the synthesis of a knowledge base that establishes the relationships between the

experiments, algorithms and models. The links between these areas have an adaptive character giving an optimal strategy for experimental design and model structure. The goal of this paper is the tasks of high precision reconstructing of the spatial and temporal distribution of the SVS radiative characteristics.

Many investigators support a constructive technology for microwave monitoring of soil and vegetation covers. But greater accuracy of this technology is required for the reason that the soil and various vegetation covers, especially vegetation canopies, are very dynamic and complicated for experimental study or model parametrization. In this respect, there are two aspects. One is connected with the creation of a highly productive technology to estimate the land cover characteristics. The other is connected with the climate change problem through the greenhouse effect [7]. In these cases the GIMS-technology recommends a balanced scheme for the solution of problems of land cover monitoring. To increase the parameters measurement precision the experimental and theoretical studies of attenuation of microwave radiation by soil and vegetation cover is required. It is actually possible to synthesize the experimental dependence between attenuation and a restricted set of soil and vegetation parameters. An estimation of attenuation of microwave radiation by soil and vegetation cover in real time is possible only with the application of microwave models, interpolation algorithms and methods to increase the models precision

### 3. THE INVERSE PROBLEM OF THE MICROWAVE MONITORING

Solution of the correction equations in a general case requires the use of the criterion of discrepancy between theoretical and empirical estimates of the parameters or correlations. Usually for this purpose, a criterion of mean square deviation is used. The reliability and efficiency of determination of solutions for the system of equations relating the theoretical and empirical estimates can be increased if their dispersive characteristics are taken as a criterion of discrepancy of these solutions.

Let the proper emission of the sea be measured simultaneously with the help of  $n$  radiometers, each operating at a fixed wavelength  $\lambda_j$  ( $j=1, \dots, n$ ). As a result at the moment  $t_i$  at the output of each radiometer the values  $Z_{ij}$  ( $i=1, \dots, M$ ) are fixed, so that

$$Z_{ij} = T_j + \xi_{ij}$$

where  $T_j$  is the brightness temperature of a sea site at the wavelength  $\lambda_j$ , and  $\xi_{ij}$  is the random value (noise) with the zero mean and dispersion  $\sigma_j^2$ .

Let the correlation between the brightness temperature and  $m$  parameters of the sea be linear:

$$\begin{aligned} A_{11}x_1 + \dots + A_{1m}x_m &= T_1 + \xi_1 \\ A_{n1}x_1 + \dots + A_{nm}x_m &= T_n + \xi_n \end{aligned} \quad (1)$$

where  $A_{ij}$  are the coefficients determined in the regime of monitoring the sea site with the known parameters  $\{x_i\}$ . The

$x_i^*$  parameter should be estimated for the  $x_i^0$  parameters so that, first, the average  $x_i^*$  coincided with the accurate solution of the system (1), that is,  $\bar{x}_i^* = x_i^0$  ( $i=1, \dots, m$ ), and second, a dispersion of the  $x_i^*$  estimate was at a minimum, that is,  $D[x_i^*] \leq D[\tilde{x}_i]$ , where  $\tilde{x}_i$  is the estimate of the  $x_i^0$  parameter obtained by any other method.

And finally, third, let the procedure of estimation of the  $x_i^*$  parameters be as simple as possible and permit to judge about the best discrete set of radiometric channels needed to realize the two conditions above.

Let the totality of the  $x_i^*$  estimates meeting these conditions be  $\sigma$ -solution of the system of linear equations with the disturbed right-hand part. Multiply step by step the  $i$ -th solution of the system (1) by  $c_{1i}, \dots, c_{mi}$ , and let

$$\sum_{i=1}^n c_{ji} A_{il} = \delta_{jl} \quad (2)$$

Where

$$\delta_{jl} = \begin{cases} 1 & \text{for } j = l \\ 0 & \text{for } j \neq l \end{cases}$$

As a result, we have

$$x_1^0 = \sum_{i=1}^n c_{1i} T_i, \quad \tilde{x}_1 = \sum_{i=1}^n c_{1i} T_i + \sum_{i=1}^n c_{1i} \xi_i, \quad D[\tilde{x}_1] = \sum_{i=1}^n c_{1i}^2 \sigma_i^2$$

For  $\tilde{x}_i$  ( $i \geq 2$ ) we write similar relationships. Derive an auxiliary expression:

$$\varphi(c_{11}, \dots, c_{1n}) = \sum_{i=1}^n c_{1i}^2 \sigma_i^2 + \mu_1 \left( \sum_{i=1}^n c_{1i} A_{i1} - 1 \right) + \sum_{j=2}^m \mu_j \sum_{i=1}^n c_{1i} A_{ij}$$

Where  $\mu_j$  are the non-estimated Lagrange multipliers. Putting first derivative functions  $\varphi$  to zero, we obtain:

$$2c_{1k} \sigma_k^2 + \sum_{j=1}^m \mu_j A_{kj} = 0 \quad (k=1, \dots, n)$$

These equalities together with conditions (2) form the system  $(m+n)$  of equations whose solution enables one to find desired

optimal values of  $c_{ij}^*$ . As a result,  $D[x_1] = -\mu_1 / 2$ , and the remaining  $\mu_j$  ( $j \geq 2$ ) values meet a system  $m \times n$  of equations:

$$\begin{aligned} \sum_{j=1}^m \mu_j \sum_{i=1}^n A_{ij} A_{i1} \sigma_i^{-2} &= -2 \\ \sum_{j=1}^m \mu_j \sum_{i=1}^n A_{ij} A_{il} \sigma_i^{-2} &= 0, \quad (l=2, \dots, m) \end{aligned}$$

For  $m=2$  we have:

$$c_{1,k}^* = \left( A_{k1} \sum A_{i2}^2 / \sigma_i^2 - A_{k2} \sum_{i=1}^n A_{i1} A_{i2} / \sigma_i^2 \right) \Delta^{-1} \sigma_k^{-2}$$

$$c_{2,k}^* = \left( A_{k2} \sum A_{i1}^2 / \sigma_i^2 - A_{k1} \sum_{i=1}^n A_{i1} A_{i2} / \sigma_i^2 \right) \Delta^{-1} \sigma_k^{-2}$$

$$\Delta = \sum_{i=1}^n A_{i1}^2 \sigma_i^{-2} \sum_{i=1}^n A_{i2}^2 \sigma_i^{-2} - \left( \sum_{i=1}^n A_{i1} A_{i2} \sigma_i^{-2} \right)^2$$

$$x_j^* = \sum_{i=1}^n c_{ji}^* Z_i, \quad (j = 1, 2);$$

$$D[x_1^*] = \Delta^{-1} \sum_{i=1}^n A_{i2}^2 \sigma_i^{-2} \quad D[x_2^*] = \Delta^{-1} \sum_{i=1}^n A_{i1}^2 \sigma_i^{-2}$$

For the real use of this algorithm in the radiometric monitoring system the following arrangement can be suggested. Put between the radiometers' outputs and respective inputs of the microprocessor in series the  $n$ -channel commutation unit and  $n$  units of dispersion calculation. At the radiometers' inputs we plug in switches, which are connected through a control unit with the first group of outputs of the microprocessor, and to the second group of the microprocessor's outputs are linked up the resolver, whose second group of outputs is connected, respectively, with the radiometers' outputs. Each unit to calculate dispersion consists of the in-series connected quantizers of the mean value calculator, divisor, summator and second divisor, and the quantizer's output is connected with the second input of the summator. The resolver consists of identical channels, each containing a summator,  $n$  outputs of which are connected with  $n$  multipliers. Some inputs of the multipliers form the first group of the resolver's inputs, others – the second group of its inputs, the number of channels being equal to the number of the parameters to be measured.

Figures 1-3 gives principal schemes that realize this algorithm. Figure 1 shows the structural scheme of an arrangement to measure the parameters of geophysical and hydrophysical objects. The scheme in Figure 3 explains the structure of the unit to calculate dispersion. The resolver is characterized in Figure 2. The apparatus operates as follows. When radiometers 1 are calibrated, the signals  $Z_{ij}$  from their outputs through the multi-channel switching unit 2 enter the unit 3 of the dispersion calculator. The antennas are switched off from radiometers. In unit 3 the dispersion is calculated using the algorithm

$$\sigma_j^2 = \frac{1}{M-1} \sum_{i=1}^M (Z_{ij} - M_j)^2 \quad M_j = \frac{1}{M} \sum_{i=1}^M Z_{ij}$$

The  $M_j$  parameters are calculated in the units of the mean calculations. The summator calculates the sum

$$\sum_{i=1}^M (Z_{ij} - M_j)^2$$

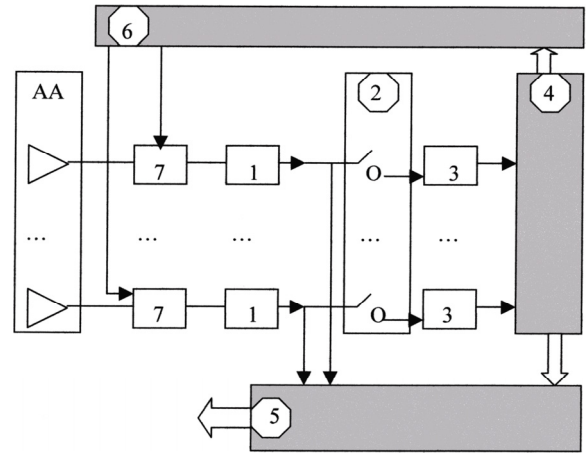


Fig. 1. The structural scheme of the arrangement to measure the geophysical and hydrophysical parameters in the regime of the microwave monitoring. Notations: 1 – radiometers; 2 – commutation unit; 3 – unit of dispersion calculation; 4 – microprocessor; 5 – resolver; 6 – control unit; 7 – switches; AA – antennas admittance.

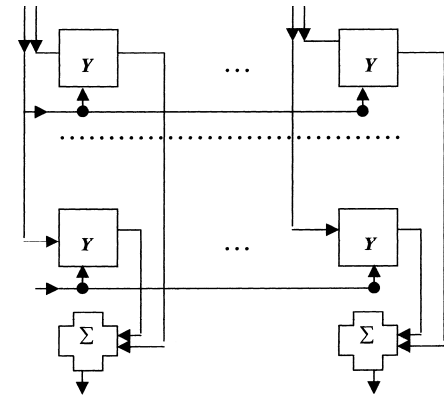


Fig. 2. Resolver. Note: Y – multiplier, Σ – summed.

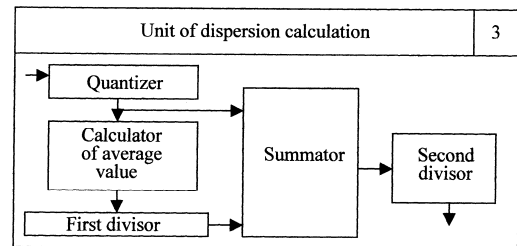


Fig. 3. Scheme of operations in the unit of dispersion calculation.

The calculated values  $\sigma_j^2$  enter the microprocessor 4 to calculate partial coefficients  $c_{ji}$ . From the first group of its outputs they enter the resolver 5 where they are used to solve a system of equations, and from the second group of outputs they enter the control unit 6 which forms the signal that switches off radiometers 1, for which the partial coefficients are equal or close to zero, that is, the information channels automatically get excluded. At the same time, the systems of equations to be solved get compressed. This step makes it possible to contract not only the volume of calculations but

also to increase the accuracy of estimating the parameters of the sounded objects of the environment.

After determination of dispersions, the commutator 2 blockades the input of data from non-information channels. The data from information channels enter the resolver 5. The signal at the multiplier's output corresponds to the value of one of the parameters to be estimated.

An approach to the inverse problem of the microwave monitoring considered by Krapivin [1] is based on assumption of the linear functional correlation between radiobrightness contrasts and characteristics of the monitored object. The search of analytical relationships relating the radiobrightness temperature of the environment to its thermodynamic and electrophysical characteristics covers more general classes of the functional models. The most general form of such dependence is as follows:

$$T_{bi} = \kappa_i \int_0^\infty T(h) \gamma_i(h) \exp \left[ - \int_0^h \gamma_i(x) dx \right] dh \quad (3)$$

where  $T(h)$  is the thermodynamic profile of the environment,  $T_{bi}$  is the radiobrightness temperature at the frequency  $\nu_i$ ,  $\gamma_i(h)$  is the profile of the absorption coefficient of the environment,  $\kappa_i$  is the emissivity of the environment.

Relationship (3) makes it possible using  $T(h)$  and  $\gamma_i(h)$  to find  $T_{bi}$  (direct problem) and by  $T_{bi}$  to calculate  $T(h)$  and  $\gamma_i(h)$  (inverse problem). The proposed method to solve these problems is based on the use of  $T(h)$  and  $\gamma_i(h)$  and their derivatives at the point  $h=0$  with some additional limitations resulting from the transformations made below. Write the relationship (3) in the form:

$$T_{b\lambda} = -\kappa_\lambda \int_0^\infty T(h) dF_\lambda(h) \quad (4)$$

Where

$$F_\lambda(h) = \exp \left[ - \int_0^h \gamma_\lambda(x) dx \right]$$

$\lambda$  is the wavelength.

Integrating (4) by parts, we obtain:

$$T_{b\lambda} = \kappa_\lambda \left[ T_0 + \int_0^\infty T'(h) F_\lambda(h) dh \right] = \kappa_\lambda [T_0 + J_1] \quad (5)$$

Let  $J_1=0$ , then  $T_{b\lambda} = \kappa_\lambda T_0$ . If  $dT(h)/dh=0$ , then  $J_1=0$ . Therefore find conditions under which  $J_1=0$ . Let the following relationships be valid:

$$\gamma_\lambda(h) \equiv c_\lambda > 0, \quad T(h) = \sum_{k=0}^n B_k h^k \quad (6)$$

It follows from (6) that if the coefficients  $B_k$  meet the condition:

$$\sum_{k=1}^n k! \frac{B_k}{c_\lambda^k} = 0 \quad (7)$$

then  $J_1=0$ .

Integrating (5) by parts, we obtain:

$$T_{b\lambda} = \kappa_\lambda \left[ T_0 + \frac{T'_0}{\gamma_\lambda(0)} + \int_0^\infty \frac{T''(h) \gamma_\lambda(h) - \gamma'_\lambda(h) T'(h)}{\gamma_\lambda^2(h)} F_\lambda(h) dh \right] \quad (8)$$

Equate the integral in (8) to zero. It gives

$$T(h) = c \int \gamma_\lambda(h) dh$$

where  $c$  is an arbitrary constant. The integral in (8) will be equal to zero if

$$\sum_{k=2}^n B_k k(k-1) k! c_\lambda^{1-k} = 0 \quad (9)$$

Further integrating of (8) by parts gives

$$T_{\lambda\lambda} = \kappa_\lambda \left[ T_0 + \frac{T'_0}{\gamma_\lambda(0)} + \left( \frac{T'}{\gamma_\lambda(h)} \right)' \frac{1}{\gamma_\lambda(h)} \Big|_{h=0} + J_3 \right]$$

Where

$$J_3 = \int_0^\infty \frac{T'''(h) \gamma_\lambda(h) - 3T''(h) \gamma'_\lambda(h) - T'(h) \gamma''_\lambda(h) + 3T'(h) [\gamma'_\lambda]^2}{\gamma_\lambda^4(h)} F_\lambda(h) dh$$

This integral will be equal to zero at

$$T(h) = c \int \gamma_\lambda(h) \int \gamma_\lambda(u) du dh \quad (10)$$

If the condition (6) is not met then  $J_3 \neq 0$  at

$$\sum_{k=3}^n B_k k(k-1)(k-2) k! c_\lambda^{2-k} = 0$$

With the process of integration of (8) continued  $N$  times, we obtain

$$T_{\lambda\lambda} = \kappa_\lambda \left[ \sum_{k=1}^N P_k(0) + \int_0^\infty P'_N(h) F_\lambda(h) dh \right] \quad (11)$$

Where

$$P_1(h) = T(h), \quad P_2(h) = T'(h)/\gamma_\lambda(h), \dots, \quad P_k(h) = P'_{k-1}(h)/\gamma_\lambda(h)$$

But

$$J_N = \int_0^\infty P'_N(h) F_\lambda(h) dh = 0$$

For

$$\sum_{k=N}^n B_k k(k-1)\cdots(k-N+1)k!c_\lambda^{N-1-k} = 0, \quad (n > N)$$

Consider the case when

$$\gamma_\lambda(h) = \exp\{c_\lambda h\}$$

From (10) we obtain:

$$T(h) = \sum_{k=0}^{N-1} B_k \exp[kc_\lambda h]$$

Now we move on to the inverse problem. Let measurements be made at wavelengths  $\lambda_1, \dots, \lambda_N$ . Solve the equation:

$$P'_{N-1}(h) = c\gamma_\lambda(h)$$

and find

$$P_{k-1}(h) = \int \gamma_\lambda(h) P_k(h) dh, \quad (k = 1, \dots, N)$$

Let  $\gamma_\lambda(h) = \varphi(\lambda)\psi(h)$ , that is, the dependence of the absorption coefficient on the frequency and depth of the layer be divided by the product of the known function  $\varphi(\lambda)$  and an unknown function  $\psi(h)$ . As a rule, the function  $\varphi(\lambda)$  is set from the empirical table and its analytical approximation can be constructed. Then, excluding from (10) the second right-hand term (it is equal to zero), we write the relationship:

$$T_{b\lambda} = \kappa_\lambda \sum_{k=1}^N T^{(k-1)}(0) F_k[\varphi(\lambda), \psi^{(N-k-1)}(0), \dots, \psi'(0), \psi(0)] \quad (11)$$

and the solution of the inverse problem is reduced to the solution of a system of algebraic equations with regard to functions:

$$T(0), T'(0), \dots, T^{(N-1)}(0), \psi(0), \dots, \psi^{(N-1)}(0)$$

Consider the case  $\psi(h) = \text{const}$ , that is,  $\gamma_\lambda = \varphi(\lambda) > 0$ . Equation (11) is re-written:

$$T_{b\lambda} = \kappa_\lambda \sum_{k=1}^N T^{(k-1)}(0) / \varphi^{(k-1)}(\lambda) \quad (12)$$

In the simplest version, if  $T_{b\lambda}$  was measured at  $N$  different wavelengths  $\{\lambda_i; i=1, \dots, N\}$ , then the determinant of the system (12) will be equal to:

$$\Delta = \prod_{i=1}^N \kappa_i \prod_{i>k} [\varphi(\lambda_i) - \varphi(\lambda_k)] / [\varphi(\lambda_i)\varphi(\lambda_k)]$$

If  $\varphi(\lambda_i) \neq \varphi(\lambda_k)$  with none of combinations  $i \neq k$ , then  $\Delta \neq 0$  and the system (12) has a single solution. Now let

$$\psi(h) = h^m$$

then it follows from (10) that

$$T(h) = \sum_{k=0}^{N-1} B_k h^{k(m+1)}$$

and we obtain a system of algebraic equations

$$P_k(0) = (m[k-1])! \dots! b_{k-1} / \varphi^{k-1}(\lambda)$$

with the following determinant:

$$\Delta = \prod_{i=1}^N \kappa_{\lambda_i} \prod_{p=1}^N [m(k-1)]^{N+1-p} \prod_{i>k} [\varphi(\lambda_i) - \varphi(\lambda_k)] / [\varphi(\lambda_i)\varphi(\lambda_k)]$$

The case when the function  $\psi$  is approximated by a polynomial is considered in a similar way.

For a given application a set of soil vegetation-related parameters are to be generated with specific time and space resolutions to use as the basis for the calculation of EMW attenuation by the vegetation layer. Available remote monitoring data are to be used as input information for algorithms and models to synthesize the spatial-temporal distribution of the attenuation effects. Field observations are the initial stage to determine the important properties of the vegetation cover. Many problems exist in providing the model descriptions of biological and physical processes which operate on different timescales. The tasks of describing EMW attenuation by the vegetation cover has timescales ranging from less than a second to hours or days and also has various spatial scales. Consequently, a parametrical description of the EMW attenuation by the vegetation cover demands an enormous number of experimental observations, the planning of which depends on the model type and the vegetation component under investigation. That is why the effective synthesis of the final results into given space-time scales may be realized by application of GIMS-technology [1,7, 8-10]. This allows one to solve the problem of scaling the *soil-vegetation-atmosphere* model and to describe the radiative transfer processes on a scale from that of individual plants or small plots to large-scale biomes.

#### 4. CONCLUSIONS

The effective collection and processing of the data in monitoring systems in ecology is based on use of simulating modelling, collection and processing of the information. These systems represent a structure uniting the computers of various classes, data bases and advanced problem oriented software. Creation of such systems demands the development of formalized description of the information flow and unique methodology of its processing to assure a high precision data using. By using the radiometers for parameter measurements, is very important a mutual control of the accuracy of correction of the estimates of the measured parameters.

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