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ALGORITHM FOR ESTIMATION OF ELECTROPHYSICAL PARAMETERS OF THE SURFACE BY ITS OWN MICROWAVE RADIATION

Reliable estimation of the electro physical parameters of surfaces using radiometric equipment is an actual area of remote environmental monitoring. The disadvantage of the procedures developed today for assessing the indicated properties of surfaces according to their own thermal radiation, prevents their practical use. In the framework of the statistical theory of detection-measurement based on the results of processing radiometric signals during multichannel reception, an identification method is developed and a decision-making rule were synthesized in favor of any of the hypotheses put forward about the values of the parameters of the observed surface. The methodology for solving the problem and the inherited identification rule meet the criterion of maximum likelihood. A distinctive feature of the synthesized decision-making rule: critical statistics based on the eigenvalues of the covariance observation matrix under multichannel reception conditions. The implementation uses standard computing operations. Moreover, a distribution density of critical statistics obtained because tabulated solving the problem. This circumstance makes it possible to set the required value of the significance level "a priori", therefore, the value of the comparison threshold. Certification of the synthesized test is the rules for deciding in favor of the hypothesis about a given value of the components of the Fresnel reflection coefficient. It was carried out at the level of digital statistical modeling. The significance level was set equal to 0.05 and 0.1. Based on the simulation results, there were analyzed the dependence of the number of correct decisions (the fulfillment of the corresponding hypothesis) on the signal-to-noise power ratio for a given angular parameter of the signal. The performance characteristics obtained at the level of digital statistical modeling of the developed test confirmed, firstly, the conclusions of theoretical studies. Secondly, they give specialists in the field of development of radiometric systems the opportunity to evaluate both the effectiveness of synthesized tests at various numerical values of the probability of an error of the first kind and the complexity of their practical implementation.

Keywords: likelihood ratio logarithm criterion; electrophysical parameters; multichannel reception; level of significance.

Introduction

Reliable estimation of the electrophysical properties of the surface using radiometry methods is a relevant area of remote environmental monitoring [1 - 3].

Disadvantages of the currently developed procedures for estimation of these surface properties in accordance with their own microwave radiation are known. In particular, they are associated with the decision instability and the technical complexity of their practical implementation [4]. The use of the modulation-type radiometers does not solve the problem of effective decision-making, since part of the energy potential of a noise-like signal is virtually unused.

estimation of the surface properties in case of a multichannel radiometric signals reception. Let us assume that the receiving antenna is a linear system of M non-directional

$$(F_0(f, \vartheta) = F_0(f_0, \vartheta) = F_0(\vartheta) = \text{const})$$

elements, equidistantly spaced with a step d along the axis x of the plane XOY . The first element is located at the origin, and the position of the m -th element is determined as

$$x_m = (m-1)d.$$

Problem Statement

The purpose of this work is to create a methodology for solving the problem of reliable

We assume that at an extended radiation source – the surface V – is located at an angular position V_0 (connected with the generalized angle $\vartheta_0 = \sin V_0$), which is the direction of the axis orientation of the

receiving system antenna pattern $F(\vartheta)$ relative to the reference direction. Then, the oscillation $\dot{U}_m(t, \bar{a})$ at the output of the m -th channel of preliminary temporary processing that appears due to the radiation source V from the direction V_0 located in the far-field region of the antenna, can be written as the sum of the signal $\dot{S}_m(t, \bar{a})$ and the interference $\dot{n}_m(t)$ components [5, 6] within the angular sector $\vartheta \in \varphi$ frequency range $|f| \leq F$, and observation interval $t \in (0, T)$:

$$\dot{U}_{m,n}(t, \bar{a}) = \dot{S}_m(t, \bar{a}) + \dot{n}_m(t), \quad (1)$$

$$m = \overline{1, M}.$$

In this case, the first term is connected with the spectral-angular density $\dot{A}(\vartheta, f, \bar{a})$ of the surface radiation V , the frequency response $\dot{K}(j2\pi f)$ of the preliminary temporary processing tract, and the element $\dot{F}_0(f, \vartheta)$ by the ratio [6]:

$$\dot{S}_m(t, \bar{a}) = \int_{-F}^F \dot{K}(j2\pi f) \int_{\Omega} \dot{A}(\vartheta, f, \bar{a}) \dot{F}_0(f, \vartheta) \times$$

$$\times e^{j2\pi \frac{d}{\lambda} (m-1) \vartheta} e^{j2\pi f t} d\vartheta df \times$$

$$\times e^{-j2\pi \frac{d}{\lambda_0} (m-1) \vartheta_0} \quad (2)$$

where λ_0 is the operating wavelength corresponding to the central frequency f_0 of the preliminary processing channel setting, \bar{a} is a vector of electrophysical parameters, which characterize the properties of the radiation surface V .

We consider the frequency characteristics $\dot{K}(j2\pi f)$ of the receiving paths identical:

$$\dot{K}(j2\pi f) = \begin{cases} \dot{K}(j2\pi f), & -F \leq f \leq F, \\ 0, & f < -F \text{ and } f > F. \end{cases} \quad (3)$$

The second term $\dot{n}_m(t)$ in the expression (1) is a random Gaussian process (the channel noise) with a zero mathematical expectation $\langle \dot{n}_m(t) \rangle = 0$, ($m = 1, 2, \dots, M$) and dispersion $2\sigma_0^2$ that is not correlated over the channels of the linear system.

The spectral-angular radiation density $\dot{A}(\vartheta, f, \bar{a})$ is modeled by a Gaussian process with statistical characteristics

$$\langle \dot{A}(\vartheta, f, \bar{a}) \rangle \geq 0;$$

$$\langle \dot{A}(\vartheta_1, f_1, \bar{a}) \dot{A}^*(\vartheta_2, f_2, \bar{a}) \rangle \geq B(\vartheta_1, f_1, \bar{a}) \times$$

$$\times \delta(\vartheta_1 - \vartheta_2) \delta(f_1 - f_2), \quad (4)$$

where $B(\vartheta, f, \bar{a})$ is the radiobrightness of the "area" Ω .

As a result, according to relations (2-4), in such a case when the narrowband condition is satisfied,

$$\langle \dot{S}(t, m, \bar{a}) \rangle = 0;$$

$$\langle \dot{S}(t_1, m, \bar{a}) \dot{S}^*(t_2, n, \bar{a}) \rangle =$$

$$= \int_{-F}^F |\dot{K}(j2\pi f)|^2 \int_{\Omega} B(\vartheta, f, \bar{a}, t) |\dot{F}_0(f, \vartheta)|^2 \times$$

$$\times e^{j2\pi f(t_1 - t_2)} e^{j2\pi \frac{d}{\lambda} (m-n) \vartheta} d\vartheta df \times$$

$$\times e^{-j2\pi \frac{d}{\lambda_0} (m-n) \vartheta_0} \quad (5)$$

In most practically justified cases, approximation [6] takes its valid place:

$$B(\vartheta, f, \bar{a}) \approx B(\vartheta, \bar{a})$$

Further refinement of expression (5) can be based on the Rayleigh-Jeans formula:

$$B(\vartheta, \bar{a}) = K_B \cdot T_B(\vartheta, \bar{a}) \frac{f^2}{c^2} \quad (6)$$

where K_B is the Boltzmann constant, T_B is the brightness temperature of the observed surface, c is the electromagnetic wave propagation speed.

The brightness temperature T_B for vertical (index "v") and horizontal (index "H") polarizations is determined from the expression [7]:

$$T_B(H) = \left(1 - |K_{v(H)}(\varepsilon', \varepsilon'', \vartheta_0)|^2 \right) T_0, \quad (7)$$

where $K_{v(H)}(\varepsilon', \varepsilon'', \vartheta_0)$ are the Fresnel reflection coefficients for a flat surface. The latter in terms of the surface parameters can be expressed in the following way:

$$\left\{ \begin{aligned} K_v &= \frac{\cos(\vartheta_0) - \sqrt{\dot{\varepsilon} - \sin^2(\vartheta_0)}}{\cos(\vartheta_0) + \sqrt{\dot{\varepsilon} - \sin^2(\vartheta_0)}}, \\ K_H &= \frac{\dot{\varepsilon} \cos(\vartheta_0) - \sqrt{\dot{\varepsilon} - \sin^2(\vartheta_0)}}{\dot{\varepsilon} \cos(\vartheta_0) + \sqrt{\dot{\varepsilon} - \sin^2(\vartheta_0)}}, \end{aligned} \right. \quad (8)$$

where $\hat{\varepsilon} = \varepsilon' + j\varepsilon''$.

Radiometric problem solving requires an aggregate analysis of instant array "responses" on the input influences. In doing so, at the moment $t_k = k\Delta t$

$\Delta t = \frac{1}{2F}$, $2FT = K$, $k = \overline{1, K}$ we obtain M – a dimensional observation vector:

$$\bar{U}_k = \bar{S}_k + \bar{n}_k \quad (9)$$

Here,

$$\begin{aligned} \bar{U}_k^T &= [\dot{U}_1(k\Delta t, \bar{a}), \dot{U}_2(k\Delta t, \bar{a}), \dots, \dot{U}_M(k\Delta t, \bar{a})]; \\ \bar{S}_k^T &= [\dot{S}_1(k\Delta t, \bar{a}), \dot{S}_2(k\Delta t, \bar{a}), \dots, \dot{S}_M(k\Delta t, \bar{a})]; \\ \bar{n}_k^T &= [\dot{n}_1(k\Delta t), \dot{n}_2(k\Delta t), \dots, \dot{n}_M(k\Delta t)]. \end{aligned}$$

A comprehensive description of the process (9) is given by the covariance matrix

$$\|R_{mn}\| = \langle \bar{U}_k \bar{U}_k^T \rangle = \langle \bar{S}_k \bar{S}_k^T \rangle + 2\sigma_0^2 I_M. \quad (10)$$

where the symbol "+" represents the Hermite conjugation, the dimension of the diagonal matrix $I_M = \text{diag}(1, 1, \dots, 1)$ is $M \times M$, and $m, n = \overline{1, M}$.

On the basis of (5), we write elements $R_{mn}^{(c)}$ of the signal component R_{mn} at the time points t_k ($k = 1, 2, \dots, K$) in the following way:

$$\begin{aligned} R_{mn}^{(c)} &= \langle \dot{S}(t_k, m, \bar{a}) \dot{S}^*(t_k, n, \bar{a}) \rangle = \int_{-F}^F |\dot{K}(j2\pi f)|^2 \times \\ &\times \int_{\Omega} B(\vartheta, \bar{a}) |\dot{F}_0(f, \vartheta)|^2 e^{j2\pi \frac{d}{\lambda} (m-n) \vartheta} d\vartheta df \times \\ &\times e^{-j2\pi \frac{d}{\lambda_0} (m-n) \vartheta_0}. \end{aligned}$$

The detailed expression above allows to factorize the covariance matrix as follows:

$$R(\bar{a}) = (\Lambda \Psi \Lambda^+) + 2\sigma_0^2 I_M. \quad (11)$$

In this expression, the elements of the direction-finding matrix $\Lambda = \text{diag}(1, \lambda, \lambda^2, \dots, \lambda^{M-1})$ are connected with direction ϑ_0 to the conditional "center" of the observation Ω by the equation

$$\lambda = e^{-j2\pi \frac{d}{\lambda_0} (m-n) \vartheta_0} \quad (12)$$

and

$$\Psi = \begin{bmatrix} B_{11} & B_{12} & \dots & B_{1M} \\ B_{21} & B_{22} & \dots & B_{2M} \\ \dots & \dots & \dots & \dots \\ B_{M1} & B_{M2} & \dots & B_{MM} \end{bmatrix} \quad (13)$$

is a correlation matrix of the intensities, elements of which

$$\begin{aligned} B_{mn} &= \int_{-F}^F |\dot{K}(j2\pi f)|^2 \int_{\Omega} B(\vartheta, \bar{a}) |\dot{F}_0(f, \vartheta)|^2 \times \\ &\times e^{j2\pi \frac{d}{\lambda} (m-n) \vartheta} d\vartheta df \end{aligned} \quad (14)$$

are the components of the radiobrightness area.

From the expressions (11) - (14) it follows that all available information about the observed surface properties is concentrated in the components of the matrix $R(\bar{a})$. Therefore, the main task can be formulated in the following way. It is required to make a classification decision on whether a surface belongs to the class of surfaces with parameters $\bar{a} = \bar{a}_m$ based on the set of observations with the above statistical characteristics.

Solution of the problem

In case of the real measurement conditions, the covariance matrix $R(\bar{a})$ of the observed vector

$\bar{U}_k^T = [\bar{U}_1, \bar{U}_2, \dots, \bar{U}_k]$ where "T" is the transpose sign, is unknown. In this case, the likelihood function

$P\left\{\frac{\bar{U}_k}{R(\bar{a})}\right\}$ of a set of independent vectors

\bar{U}_k ($k = \overline{1, K}$) takes the following form regarding to the unknown $R(\bar{a})$:

$$P\left\{\frac{\bar{U}_k}{R(\bar{a})}\right\} = \pi^{-MK} \left| R^{-1}(\bar{a}) \right|^K e^{-\sum_{k=1}^K \bar{U}_k^+ R^{-1}(\bar{a}) \bar{U}_k}. \quad (15)$$

We introduce the notation

$$\tilde{S} = \frac{1}{K} \sum_{k=1}^K \bar{U}_k \bar{U}_k^+, \quad (16)$$

which is a selective covariance matrix.

In this case,

$$\ln P \left\{ \frac{\bar{U}_k}{R(\bar{a})} \right\} = -MK \ln \pi - K \ln |R(\bar{a})| - KS_p \left(R^{-1} S \right). \quad (17)$$

Let us assume that H_m is a hypothesis of receiving a signal from the direction ϑ_0 of an area with its "length" Ω and parameters \bar{a}_m :

$$H_m : R(\bar{a}_m) = R_m = 2\sigma_0^2 + \Lambda \Psi_{\bar{a}_m} \Lambda^+. \quad (18)$$

The strategy of choosing the optimal likelihood ratio according to the logarithm criterion and the rule for identifying selective matrixes \tilde{S} and $R(\bar{a})$ lie in the fulfillment of the hypothesis H_n ($n = 1, 2, \dots, m, \dots$).

$$2 \ln l_n = -2 \ln \frac{P \left[\frac{\bar{U}_k}{R(\bar{a}_n)} \right]}{P \left[\frac{\bar{U}_k}{R(\bar{a}_n)}, H_n \right]}, \quad (19)$$

which prescribes formation of a classification procedure that ensures a minimal critical statistics $2 \ln l_n$ at a given set of values \bar{a}_n ($n = 1, 2, \dots, m, \dots$).

Here, $R(\bar{a}_n)$ is an estimate of the maximum likelihood $\tilde{R}(\bar{a}_n)$, $\max P \left[\frac{\bar{U}_k}{R(\bar{a}_n)}, H_n \right]$ is a value of the likelihood observation function calculated under the assumption that the hypothesis is H_n valid.

It is not difficult to show that equation (19) can be transformed into the following form:

$$2 \ln l_n = 2K \left[Sp \left(\tilde{S} \cdot \tilde{R}_n^{-1} \right) - \ln \left| \tilde{S} \cdot \tilde{R}_n^{-1} \right| - M \right]. \quad (20)$$

Here, in order to shorten the expression, we introduce the notation $\tilde{R}(\bar{a}_n) = \tilde{R}_n$.

Using the known relations connecting the trace SpT and the determinant $|\tilde{T}|$ of the matrix \tilde{T} with its own values, we obtain

$$2 \ln l_n = 2K \sum_{i=1}^M \left(\frac{S_i}{V_i} - \ln \frac{S_i}{V_i} - 1 \right). \quad (21)$$

Here, S_i and V_i are the i -th own values of the matrixes \tilde{S} and \tilde{R}_n respectively.

It is known [8] that when the hypothesis H_n is fulfilled, the statistics (20) has a χ^2 distribution with $V-1$ degrees of freedom in its asymptotics, where V is the dimension of the vector \bar{a}_n ($n = 1, 2, \dots, m, \dots$). Therefore, solution of the stated problem (in fact, the problem of detecting signals with parameters that characterize the properties of the observed surface) is reduced to testing the hypotheses H_n ($n = 1, 2, \dots, m, \dots$) on the basis of critical statistics (20) for a given set of values \bar{a}_n ($n = 1, 2, \dots, m, \dots$), which is defined by the values V_i ($i = 1, 2, \dots, M$).

Using the methodology described above, we can propose the following technological procedure for implementing the observed process of making a classification decision on whether a surface belongs to the category of surfaces with specified electrophysical parameters (in the text, with a given permittivity). It is necessary to form an estimate \tilde{S} for the covariance matrix $\tilde{R}(\bar{a}_n)$ of the spatio-temporal signals received from the direction ϑ_0 of the given M - channel system according to the rule (16). In order to do so, it is required to calculate the critical statistics $2 \ln l_n$ on the basis of "test" V_i and estimated S_i ($i = \overline{1, M}$) values, and compare it with threshold $\chi_{a,t}^2$ selected from the tables χ^2 , which show the distributions over a given significance level α and the number $t = V-1$ of degrees of freedom. If $2 \ln l_n > \chi_{a,t}^2$, the discrepancy is considered as significant, and the hypothesis H_n is rejected.

After that, the following subsequent hypothesis H_{n+1} is verified. If at some step, for instance, m , $2 \ln l_n \leq \chi_{a,t}^2$ for the first time, the following decision is made: the observed process is resulted from the surface radiation with its parameters. The verification procedure is terminated.

Effectiveness of the synthesized test was verified using the digital statistical modeling with the following initial data: $M = 9, d = \lambda, \vartheta_0 = 30^\circ, K = 10^3, a = 0, 1$. For the sake of simplicity, we considered that the input signals have vertical polarization and are received from a uniform area. Also, the reception channels were considered as certified.

The nature of the change in statistics $2\ln l_x$, which occurred when changing parameters ε' and ε'' of the test surface (with true $\hat{\varepsilon} = \varepsilon'_m - j\varepsilon''_m, \varepsilon'_m = 20, \varepsilon''_m = 30$), is shown in Figures 1.

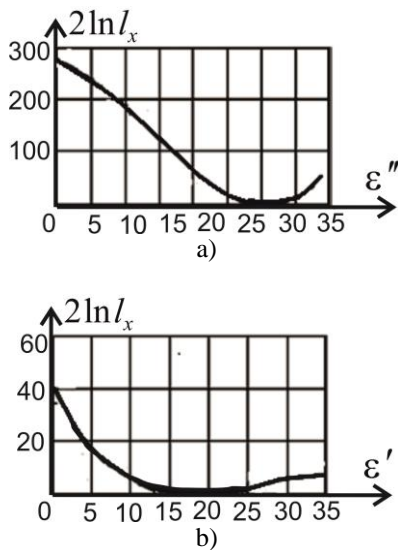


Fig. 1. Dependence of the value $2\ln l_x$ on the parameters of the investigated surface: a – when $\varepsilon'' = 30$; b – when $\varepsilon' = 20$

The ordinate values were obtained by averaging 100 experiments for $\mu = R_{mm}^c / 2\sigma_0^2 = 30$. The solid line shows dependences obtained after regressive processing of the experimental results. Dependence of probability P_{count} on the “identification” of the investigated surface with the test one as a function of change $\varepsilon', \varepsilon''$ when $K = 3 \cdot 10^2, 10^3$ is shown, accordingly, on Fig. 2. Here, the ordinate value is obtained by averaging 100 experiments.

The graph in Fig. 3 illustrates the operating characteristics of the synthesized test: the dependence of the probability P of the area “identification” when $\varepsilon' = \varepsilon'_m = 20, \varepsilon'' = \varepsilon''_m = 30$ on the signal-to-noise ratio μ at the significance levels $\alpha = 0,1$ and $\alpha = 0,5$, the number of time samples and the number of experiments equal to 300 and 100 respectively.

Analysis of the experimental results makes it possible to estimate the effectiveness of the developed method for solving the classification problem.

Conclusion

A method for identifying the electrophysical properties (state) of natural environments depending on changes in their defining parameters for multi-channel passive remote sensing systems has been developed.

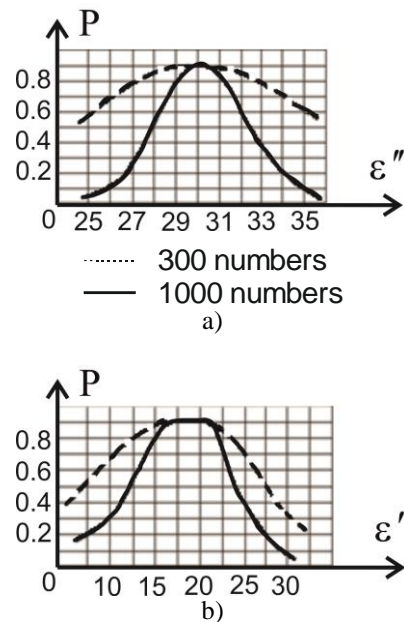


Fig. 2. Dependence of the probability of the investigated surface identification on the deviation of its parameters from the reference one: a – when $\varepsilon'' = 30$; b – when $\varepsilon' = 20$

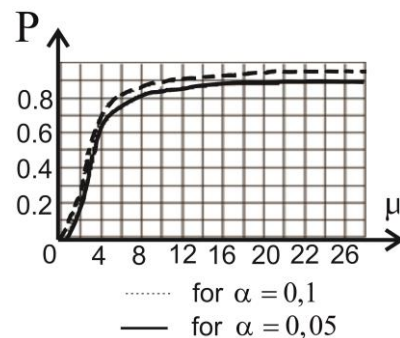


Fig. 3. Dependence of the probability of investigated surface identification on the signal-to-noise ratio (at the point of reference parameters)

It has been proved that this methodology and its identification technologies meet the conditions of the maximum likelihood criterion: they allow to make rules that guarantee a given certainty of the decision-making for a fixed level of errors of the first kind.

The operating characteristics obtained by using the digital statistical modeling of the developed test, first of all, confirm the conclusions of theoretical studies. Secondly, they give the specialists in the field of passive radio engineering system development the opportunity to estimate both the effectiveness of these tests for various numerical probability values of the first kind errors and the degree of difficulty in their implementation.

References (GOST 7.1:2006)

1. A layer-averaged relative humidity profile retrieval for microwave observations: design and results for the Megha-Tropiques payload [Text] / R. G. Sivira, H. Brognier, C. Mallet, Y. Oussar // *Atmospheric Measurement Techniques*. – 2015. – P. 1055-1071.

2. Дифференциальные радиотепловые методы восстановления профиля влажности атмосферы с борта космических аппаратов [Текст] / В. В. Стрелядкин, Е. В. Пашинов, А. В. Кузьмин, Е. А. Шарков // *Исследование земли из космоса*. – 2017. – № 2. – С. 64-76.

3. Relationship between deformational activity of the surface and electric properties of materials [Text] / S. E. Refinkina, R. A. Denisov, A. A. Morozov, V. I. Surin // *Modern problems of theory machines*. – North Charleston, USA, 2016. – No. 4. – P. 177-183.

4. Волосюк, В. К. Синтез алгоритмов оптимальных оценок электрофизических параметров поверхностей при синхронных флуктуациях колебаний различных поляризацій [Текст] / В. К. Волосюк, В. Ф. Кравченко, В. Н. Пустовойт // *ДАН РАН*. – 2001. – Т. 377, № 1. – С. 34-37.

5. Фалькович, С. Е. Оценка параметров сигнала. [Текст] / С. Е. Фалькович. – М.: Сов. радио, 1970. – 336 с.

6. Фалькович, С. Е. Оптимальный прием пространственно-временных сигналов в радиоканалах с рассеянием [Текст] / С. Е. Фалькович, В. И. Пономарев, Ю. В. Шкварко; под ред. С. Е. Фальковича. – М.: Радио и связь, 1989. – 296 с.

7. Радиолокационные методы исследования Земли [Текст] / Ю. А. Мельник, С. Г. Зубкович, В. Д. Степаненко и др.; под ред. Ю. А. Мельника. – М.: Советское радио, 1980. – 264 с.

8. Большев, Л. Н. Таблицы математической статистики [Текст] / Л. Н. Большев, Н. В. Смирнов. – М.: Наука, 1983. – 416 с.

References (BSI)

1. Sivira, R. G., Brognier, H., Mallet, C., Oussar, Y. A layer-averaged relative humidity profile retrieval

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АЛГОРИТМ ЩОДО ОЦІНЮВАННЯ ЕЛЕКТРОФІЗИЧНИХ ПАРАМЕТРІВ ПОВЕРХНІ ЗА ДАНИМИ ЇХ ВЛАСНОГО РАДІОТЕПЛОВОГО ВИПРОМІНЮВАННЯ

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Достовірне оцінювання електрофізичних параметрів поверхонь за допомогою радіометричної апаратури являється актуальним напрямком дистанційного моніторингу оточуючого середовища. Недоліки розроблених на сьогоднішній день процедур оцінювання зазначених властивостей поверхонь за даними їхнього власного радіотеплового випромінювання перешкоджають їх практичному використанню. В рамках статистичної теорії виявлення-вимірювання за результатами обробки радіометричних сигналів при багатоканальному прийомі розроблено метод ідентифікації та синтезовано правило прийняття рішень на користь будь-якої з висунутих гіпотез про величини параметрів поверхні що спостерігається. Методологія вирішення задачі і правило ідентифікації, що впливають з неї, відповідають критерію максимальної правдоподібності. Відмітна особливість синтезованого правила прийняття рішень: критична статистика формується на основі власних значень коваріаційної матриці спостережень в умовах багатоканального прийому. При реалізації використовуються стандартні обчислювальні операції. Крім того, щільність розподілу критичної статистики, отримана в результаті рішення задачі, табульована. Ця обставина дає можливість в «априорі» задавати необхідну величину рівня значущості, а, отже, величину порога порівняння. Атестація синтезованого тесту – правила прийняття рішення на користь гіпотези, що висувається про задану

for microwave observations: design and results for the Megha-Tropiques payload. *Atmospheric Measurement Techniques*, 2015, pp. 1055-1071.

2. Strelyadkin, V. V., Pashinov, E. V., Kuz'min, A. V., Sharkov, E. A.. Differentsial'nye radioteplovye metody vosstanovleniya profilya vlazhnosti atmosfery s borta kosmicheskikh apparatov [Differential radio thermal methods for reconstructing the atmospheric humidity profile from spacecraft]. *Issledovanie zemli iz kosmosa – Research of the earth from space*, 2017, no. 2, pp. 64-76.

3. Refinkina, S. E., Denisov, R. A., Morozov, A. A., Surin, V. I. Relationship between deformational activity of the surface and electric properties of materials. *Modern problems of theory machines*, North Charleston, USA, 2016, no. 4, pp. 177-183.

4. Volosyuk, V. K., Kravchenko, V. F., Pustovojt, V. N. Sintez algoritmov optimal'nyh otsenok elektrofizicheskikh parametrov poverhnostej pri sinhronnykh fluktuatsiyah kolebanij razlichnykh polarizatsij [Synthesis of algorithms for optimal estimates of the electrophysical parameters of surfaces under synchronous fluctuations of vibrations of various polarizations]. *DAN RAN*, 2001, vol. 377, no. 1, pp. 34-37.

5. Fal'kovich, S. E. *Otsenka parametrov signalov* [Estimation of signal parameters]. Moscow, Sov. Radio Publ., 1970. 336 p.

6. Fal'kovich, S. E., Ponomarev, V. I., Shkvarko, Yu. V. *Optimal'nyj priem prostranstvenno-vremennykh signalov v radiokanalakh s rasseyaniem* [Optimal reception of spatio-temporal signals in radio channels with scattering]. Moscow, Radio i svyaz' Publ., 1989. 296 p.

7. Mel'nik, Yu. A., Zubkovich, S. G., Stepanenko, V. D. i dr. *Radiolokatsionnye metody issledovaniya Zemli* [Radar methods of Earth exploration]. Moscow, Sovetskoe radio Publ., 1980. 264 p.

8. Bol'shev, L. N., Smirnov, N. V. *Tablitsy matematicheskoy statistiki* [Tables of mathematical statistics]. Moscow, Nauka Publ., 1983. 416 p.

величину складових коефіцієнта відбиття Френеля, проведено на рівні цифрового статистичного моделювання. Рівень значущості задавався рівним 0,05 і 0,1. За результатами моделювання проведений аналіз залежності числа правильних рішень (виконання відповідної гіпотези) від співвідношення сигнал/шум по потужності при заданому кутовому параметрі сигналу. Робочі характеристики, отримані на рівні цифрового статистичного моделювання розробленого тесту, по-перше, підтвердили висновки теоретичних досліджень. По-друге, дають можливість фахівцям в області розробки радіометричних систем оцінити як ефективність синтезованих тестів при різних числових значеннях ймовірності помилки першого роду, так і складності їх практичної реалізації.

Ключові слова: критерій логарифма відношення правдоподібності; електрофізичні параметри; багатоканальний прийом; рівень значущості.

АЛГОРИТМ ДЛЯ ОЦЕНИВАНИЯ ЭЛЕКТРОФИЗИЧЕСКИХ ПАРАМЕТРОВ ПОВЕРХНОСТИ ПО ДАННЫМ ИХ СОБСТВЕННОГО РАДИОТЕПЛОГО ИЗЛУЧЕНИЯ

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Достоверное оценивание электрофизических параметров поверхностей с помощью радиометрической аппаратуры является актуальным направлением дистанционного мониторинга окружающей среды. Недостатком разработанных на сегодняшний день процедур оценивания указанных свойств поверхностей по данным их собственного радиотеплового излучения, препятствует практическому их использованию. В рамках статистической теории обнаружения-измерения по результатам обработки радиометрических сигналов при многоканальном приёме разработан метод идентификации и синтезировано правило принятия решений в пользу какой либо из выдвигаемых гипотез о величинах параметров наблюдаемой поверхности. Методология решения задачи и вытекающие из неё правило идентификации отвечают критерию максимального правдоподобия. Отличительная особенность синтезированного правила принятия решений: критическая статистика формируется на основе собственных значений ковариационной матрицы наблюдений в условиях многоканального приёма. При реализации используются стандартные вычислительные операции. Кроме того, плотность распределения критической статистики, полученная в результате решения задачи, табулирована. Это обстоятельство даёт возможность в «априори» задавать требуемую величину уровня значимости, а, следовательно, величину порога сравнения. Аттестация синтезированного теста – правила принятия решения в пользу выдвигаемой гипотезы о заданной величине составляющих коэффициента отражения Френеля, проведено на уровне цифрового статистического моделирования. Уровень значимости задавался равным 0,05 и 0,1. По результатам моделирования проведён анализ зависимости числа правильных решений (выполнение соответствующей гипотезы) от соотношения сигнал/шум по мощности при заданном угловом параметре сигнала. Рабочие характеристики, полученные на уровне цифрового статистического моделирования разработанного теста, подтвердили, во-первых, выводы теоретических исследований. Во-вторых, дают возможность специалистам в области разработки радиометрических систем оценить как эффективность синтезированных тестов при различных числовых значениях вероятности ошибки первого рода, так и сложности практической их реализации.

Ключевые слова: критерий логарифма отношения правдоподобия; электрофизические параметры; многоканальный приём; уровень значимости.

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