INVERSE PROBLEMS OF ATMOSPHERIC OPTICS: APPLICATION TO AN ASSESSMENT OF THE BIOSPHERIC PARAMETERS FROM SPACE

V.V. Kozoderov and V.S. Kosolapov

Institute of Computer Mathematics of the Russian Academy of Sciences, Moscow
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Accuracy of vegetation biomass retrieval and effects of various factors of the developed model and measurement errors on it are studied using polynomial approximation of biomass in the quality index of green color of vegetation obtained for every pixel of multispectral satellite images. Estimates of the corresponding reconstruction errors are given.

In Ref. 1 the authors presented a new concept of analysis of multispectral satellite images, i.e., the concept of the B^* and G^* coordinates, which made it possible to separate soil and vegetation components of radiation emitted by the "atmosphere–vegetation–soil" system (here B^* is the soil brightness and G^* is the quality index of green color of vegetation).

We derived the expressions for B^* and G^* in terms of the radiation received by the apparatus placed onboard a satellite in two measuring channels $L_{1,2}^*$ of the visible and IR spectral regions, respectively, using the simplest model describing the effect of the atmosphere on the radiation reflected by a "soil–vegetation" system for anisotropic surfaces and more simplified relatively isotropic (Lambertian) surfaces. The latter can include, in the first approximation, a wide class of surfaces, given that the following conditions are satisfied: the solar zenith angles $h_\text{А}$ are large, the viewing angles are smaller than 30° and are not much different from the nadir, and the azimuthal viewing angles φ are close to 90 and 270° (i.e., are far from the plane of solar vertical).

There is the evidence for the relation between B^*, G^*, and the amount of the vegetation biomass M (t/ha) (Fig. 1). This generates a need for solving inverse problems of retrieving M from the data of satellite and aircraft multispectral measurements, whose linear combinations for each pixel of aerospace image are specified by the coordinates B^* and G^* reduced to the top or corresponding altitude of the atmosphere. It is a new type of inverse problems of atmospheric optics for which the atmosphere is an interfering factor imposing its own limitations on the accuracy of retrieving the vegetation biomass (M). This second stage of image processing is preceded by the first more traditional stage of image classification at which uniform soil and vegetation are classified in the images being processed based on various mathematical procedures and decision rules. The second stage of thematic interpretation involves an assessment of quantitative parameters describing the state of the separated classes. One of these parameters is the vegetation biomass M.

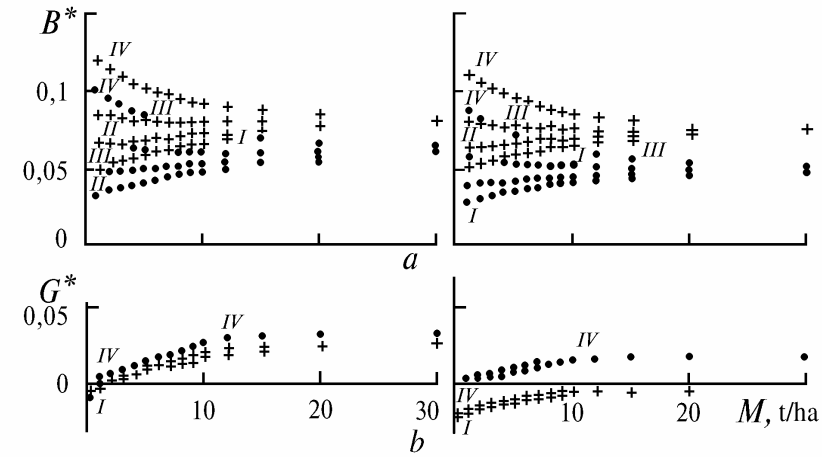

FIG. 1. A plot of indices B^*(a) and G^*(b) vs the vegetation biomass for the second and fourth channels of the MSS (to the left) and the first and third channels of the MSS (to the right) near the Earth's surface (dots) taken from Ref. 2 and at the top of the turbid atmosphere (crosses). Soil: chernozem (I), dark chestnut soil (II), sod–podzolic soil (III), and sierozem (IV).

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The present paper is concerned with the accuracy of retrieving the vegetation biomass from the coordinates B^* and G^* at the top of the atmosphere.

RECONSTRUCTION OF THE AMOUNT OF BIOMASS FROM MULTICHANNEL SATELLITE IMAGES

By virtue of the relationship between B^*, G^*, and M (Fig. 1) we attempted to reconstruct M from satellite (or aircraft) images using the dependence of the type

$$M = C_0^*(n, \kappa, r, \theta, h_\odot) + C_1^*(n, \kappa, r, \theta, h_\odot)G^* +$$

$$+ C_2^*(n, \kappa, r, \theta, h_\odot)B^* + C_3^*(n, \kappa, r, \theta, h_\odot)G^*B^* +$$

$$+ C_4^*(n, \kappa, r, \theta, h_\odot)G^{*2} + C_5^*(n, \kappa, r, \theta, h_\odot)B^{*2} + \dots , \quad (1)$$

where n determines the type of atmospheric conditions ($1 \le n \le 4$); κ specifies the type of apparatus; r is the soil parameter which allows for the soil type, moisture, fertility, and so on; θ is the viewing angle; and, $h_\odot$ is the solar zenith angle.

However, such attempts failed. It turned out that the obtained coefficients C_i^* depend strongly on various parameters determining the state of the soil–vegetation–atmosphere system, e.g., on atmospheric turbidity, soil type, moisture, etc. Taking into account that variability of B^* attendant to changes in the above–mentioned parameters of the system under study, as a rule, far exceed its variability caused by variations in M (Fig. 1) as well as the fact that due to the poor control over imaging conditions, M is frequently reconstructed with the use of inappropriate coefficients $C_i^*(n, \kappa, r, \theta, h_\odot)$, it is easy to understand that the parameter B^* (and its coefficients) is the source of gross errors, and it would be rationally to use the M dependence on G^* only

$$M = C_0^*(n, \kappa, r, \theta, h_\odot) + C_1^*(n, \kappa, r, \theta, h_\odot)G^* +$$

$$+ C_2^*(n, \kappa, r, \theta, h_\odot)G^{*2} + \dots \quad (2)$$

in place of formula (1).

To find the coefficients C_i^*, we used a standard program for determining the coefficients of the overdetermined system of linear algebraic equations. As calculations showed, the best results in reconstructing M with a sufficiently good *a priori* estimate of the above–mentioned parameters can be obtained with the higher–degree polynomials in Eq. (2). However, the degree of polynomials higher than four and poor controllability of the system parameters may deteriorate the results of reconstruction of the parameter M, especially for large values of M.

Depicted in Fig. 2 are the systematic errors in reconstructing the parameter M (winter wheat is used as a vegetation reasoning from the test data array obtained in Ref. 2 for spectral reflectance as a function of the amount of vegetation biomass) averaged over the soil types and moisture contents, i.e., in reconstructing the parameter M with the use of appropriate coefficients C_i^* from the data of the AVHRR apparatus and of the first and third and second and fourth channels of the MSS apparatus given that the polynomials of the third and fourth degree were used for approximation in Eq. (2). The systematic errors are seen to be small, especially with the use of polynomials of the fourth degree, and are no more than 3–5% for $M > 3$ t/ha. With lower degree of approximation the systematic errors become somewhat larger but for the most cases they do not exceed 10–12% regardless of the type of apparatus being used.

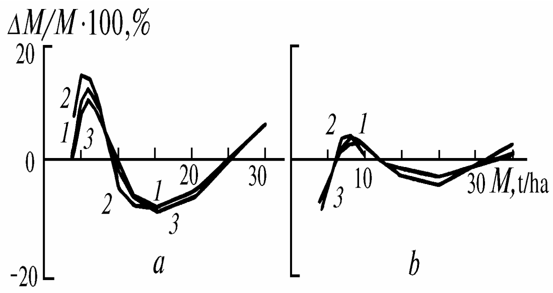

FIG. 2. Theoretical systematic errors of the proposed method of reconstructing the amount of vegetation biomass for the AVHRR apparatus and the second and fourth and first and third channels of the MSS (curves 1, 2, and 3) in the case of approximation of the parameter M in terms of G by polynomials of the fourth (a) and third (b) degrees.*

It should be noted that since the coefficients C_i^* are dependent on a number of characteristics of the soil–vegetation–atmosphere system, the inappropriate coefficients C_i^* may be used to reconstruct the parameter M under conditions of poor controllability of the system characteristics at the instant of imaging. To study the effect of each of these parameters, we may employ the coefficients C_i^* obtained under certain average atmospheric conditions and types and moisture content of soil, etc., i.e., inappropriate coefficients for reconstruction of the parameter M. [Recall that in Ref. 1 we examined four states of atmospheric turbidity: strong (a and b), moderate (c), and weak (d).]

Figure 3 shows the errors in reconstruction of the parameter M with the use of the coefficients of the third type of the atmosphere c (soil and its moisture content strictly correspond to measurement conditions) for two types of apparatus of the second and fourth and first and third channels of the MSS. The errors are quite large and reach 40–60% for the second and fourth channels and 80–160% for the first and third channels of the MSS (in the last case they are caused by the strong influence of atmospheric conditions on the first short–wave channel, see also Fig. 1). As follows from Fig. 3, the coefficients C_i^* used for reconstruction of the parameter M under certain average atmospheric conditions do not always provide high accuracy of reconstruction of the parameter M. When certain minimum amount of (approximate) information about the state of the atmosphere (below we give a scheme of determining the appropriate type of the atmosphere at the instant of imaging) is available, the coefficients C_i^* not only for one, but also for two or even three types of the atmosphere can be used to restore M. Then the obtained values of M are averaged thereby decreasing the errors in their reconstruction. Moreover, if we may specify the probability t_n of one or other state of the atmosphere, then we must use these weighting coefficients t_n in averaging of the reconstructed values of M_n. Thus the corresponding curves in Fig. 3 will approach the abscissa, i.e., zero error of reconstruction (in this case for the c atmosphere). Shown in Fig. 4 are the results of reconstruction of the parameter M for the same types of apparatuses as in Fig. 3 using the coefficients C_i^* determined for two types of the atmosphere (one of which exactly corresponds to the real state of the atmosphere). It is easy to see that the errors in reconstruction M for any type of the atmosphere do not exceed 15–20% for the second and fourth and 25–35% for the first and third channels of the MSS (and only for the d atmosphere the errors in the last case can increase up to 60–80%). In those cases in which certain intermediate state of the atmosphere is observed, e.g., between c and d, the use of the coefficients C_i^* for the c and d atmospheres will give close–to–zero errors in reconstruction of the parameter M. Thus it follows from comparison of the results shown in Figs. 3 and 4 that the minimum volume of *a priori* or any other information about the current state of the atmosphere at the instant of imaging from satellite reduces the errors in reconstruction of the vegetation biomass.

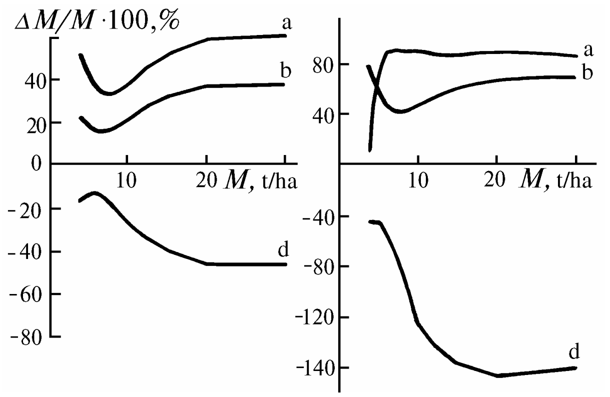

FIG. 3. The effect of inexact knowledge of the atmospheric properties (types a, b, and d) at the instant of imaging on the reconstruction of the vegetation biomass with the help of the approximation coefficients corresponding to the atmospheric conditions of the type c for the second and fourth (to the left) and first and third (to the right) channels of the MSS.

REMOTE MONITORING OF THE STATE OF THE ATMOSPHERE

It is evident from the foregoing discussion that continuous and desirably remote monitoring of the state of the atmosphere could substantially decrease the errors in reconstruction of the parameter M. The proposed scheme of such monitoring is simple and does not require any complementary apparatus.

Let among many objects in a scanned image of the region under study the objects with $M = 0$ be present apart from vegetation, e.g., some ploughed plots of land (or dirt roads). These plots also possess zero near–ground values of the parameter G (because all soil points lie along the B axis). By substituting then the brightnesses of these objects L_1^* and L_2^* measured onboard satellite into the expression

$$G = a_1^{*g} L_1^* + a_2^{*g} L_2^* - (a_1^{*g} D_1 + a_2^{*g} D_2) ,$$

derived in Ref. 1 (recall that D_j is the atmospheric haze brightness in the jth channel of the apparatus), and by sequential sampling of the four parameters P_1, P_2, D_1, and D_2 for each of the above–introduced states of the atmosphere a, b, c, and d and of the corresponding coefficients $a_{1,2}^{*g}$ we find the set of these parameters for which G is closest to zero. It is essential that the instrumental resolution should be sufficiently high and the identification of such objects should be reliable.

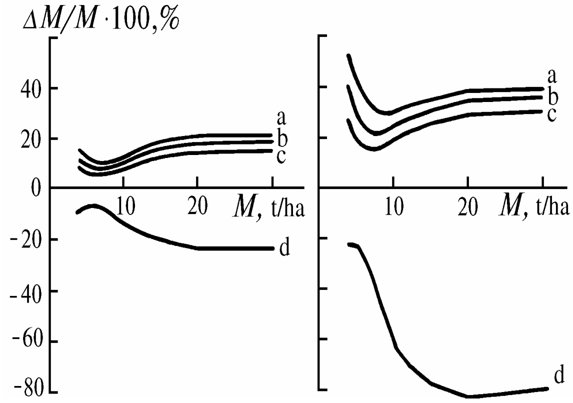

FIG. 4. Decrease of the errors in reconstruction of vegetation biomass from the data of multispectral satellite measurements with the use of complementary information about optical state of the atmosphere at the instant of imaging (designations as in Fig. 3).

If it is impossible or difficult to use a soil–dirt object for determining the state of the atmosphere, it is possible to use any imaged water surface. Since the spectral coefficients of water–surface brightness are negligible, the radiation received by the satellite is primarily determined by the haze brightness[1] ($L_1^* \approx D_1$). This allows one to find the entire set of interconnected parameters $P_{1,2}$ and $D_{1,2}$ based on one of the parameters (D_1), i.e., to determine the state of the atmosphere.

The calculations indicate that practical implementation of the above–mentioned scheme is difficult due to the instrumental errors. As a result, $G \approx 0$ could hold for some neighboring atmospheric parameters $P'_{1,2}$, $D'_{1,2}$, and $a_{1,2}^{*g'}$. Some way out is invoking a large number (20–30) of soil measurements. After their averaging the random instrumental error substantially decreases.

EFFECT OF VARIOUS FACTORS ON THE ACCURACY OF RECONSTRUCTION

The accuracy of reconstruction of the parameter M deteriorates not only due to the effect of the atmosphere but also due to different errors caused by inexact knowledge of the soil type and moisture content. Thus, e.g., when the coefficients of inappropriate types of soil are used, the errors do not exceed 10–15%. However, they may increase up to 20–25% for completely dry soil. The errors in reconstruction of the parameter M do not exceed 5–10% when the moisture content of dark soil (chernozem) is not controllable; however, they can reach 15–18% for brighter soil (sodpodzol or sierozem).

The effect of instrumental errors on the accuracy of reconstruction of the parameter M has also been studied. It turned out that these errors are different in different channels for different types of measuring apparatuses and depend on atmospheric conditions. Thus, e.g., the first (short–wave) channel of the MSS is strongly affected by the atmosphere; therefore, in the first and third channels of the MSS the errors in reconstruction of the parameter M in the strongly turbid atmosphere (type a) increase and can exceed 100% with an instrumental error of

~ 20 % in the first channel. In the longer–wave channels the atmosphere affects weaker the accuracy of reconstruction, and the total level of errors decreases especially in the first channel, while the effect of the second channel, as a rule, is stronger than that of the first channel. Figure 5 demonstrates the effect of measurement errors in the second and fourth channels of the MSS apparatus on the accuracy of reconstruction of the parameter M (under atmospheric condition of the type b). Thus the requirements for the measurement error of the second channel are more stringent (3–5%) than that of the first channel (5–10%). Under these conditions the 20% error in reconstruction of the parameter M can be achieved.

One of the most important points of our spaceborne method of estimating the parameters of soil–vegetation cover is the use of definite *a priori* information in the form of the dependence of spectral reflectance on biomass M (see Ref. 2). This *a priori* information enables one to calculate the coordinate coefficients $a^{*bg}_{1,2}$ (the coefficients of transformation from the coordinates L^*_1 and L^*_2 into the coordinates B^* and G^*) as well as the retrieval (approximation) coefficients C^*_i, whereby the biomass of vegetation M can be reconstructed for each pixel of the image being processed.

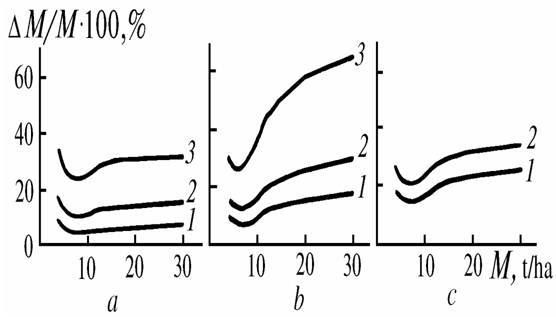

FIG. 5. Effect of measurement errors of the MSS apparatus (in the second and fourth channels) on the accuracy of reconstruction of vegetation biomass: a) with measurement errors δL_1 in the second channel being equal to 5, 10, *and* 20%, *respectively (curves 1–3); b) with δL_2 for the first channel being equal to* 3, 5, *and* 10% *(curves 1–3); and, c) with δL_1 = 5% and δL_2 = 3% (1) and δL_1 = 10% and δL_2 = 3% (2).*

It is natural to expect that for some reasons such *a priori* information would contain some errors. These may be, e.g., neglect of anisotropy of soil–vegetation objects, solar zenith angles, cloudiness, atmospheric turbidity, errors in measuring the biomass of vegetation, random (fluctuational) and systematic instrumental errors.

The errors in measuring the spectral coefficients of brightness $\rho(\lambda, M)$ can be divided into systematic and random as well as the errors in measuring the parameter M and spectral errors.

Our calculations (Fig. 6) indicate that for the MSS apparatus the systematic errors of about 5% in determining the relation between ρ_k and M (disregarding the reasons for their appearance) result in the errors in reconstruction of the parameter M from the satellite data varying from 5 to 15% (with M), but for the AVHRR apparatus these errors increase up to 15–28%.

For random (alternating) 3% errors in the *a priori* relation between ρ and M, the errors in reconstruction of the parameter M are 5–7% for the MSS and 10–15% for the AVHRR.

With a ~ 3 % random error in measuring ρ vs. λ (spectral distortion) additional errors appear in reconstructing the parameter M which are equal to 3 % for the second and fourth channels of the MSS, to 5% for the AVHRR, and to 6–9% for the first and third channels of the MSS.

The other pieces of important *a priori* information are the four interrelated atmospheric parameters $P_{1,2}$ and $D_{1,2}$ for the above–introduced four atmospheric states a, b, c, and d.

It is entirely possible that the real relation (interrelation) between the quantities $P_{1,2}$ and $D_{1,2}$ will be somewhat different from the one found in our studies (unfortunately, such data are few in number and these relationships must be determined more accurately).

The calculations show that when the parameter D_1 is determined with an error of 10% (and the remaining three parameters are determined exactly), the error in reconstruction of the parameter M does not exceed 5–10% for the second and fourth channels of the MSS, 10–15% for the AVHRR, and 30–40% for the first and third channels of the MSS (due to high sensitivity of the first channel of the MSS to atmospheric turbidity).

When the error in determining D is about 10%, the errors in reconstruction do not exceed 5–7% for any type of apparatus.

When the errors in determining the values of P_1 are about 5%, the errors in reconstruction of the parameter M can reach 6–13% in the second and fourth channels of the MSS and AVHRR and 10–15% in the first and third channels of the MSS. When uncertainties in determining P_2 are about 5%, the errors in estimating M can be 10–20% for the second and fourth channels of the MSS and AVHRR and 15–25% for the first and third channels of the MSS. With increasing errors in determining P_1 and P_2 a linear growth of the errors in reconstructing the parameter M is observed. It should be noted that since the errors of the same sign in determining P_1 and P_2 (as well as in determining D_1 and D_2) lead to the errors in reconstruction of the parameter M of different signs, partial mutual compensation of corresponding errors in reconstruction of the parameter M takes place when simultaneous errors of the same sign appear in determining P_1 and P_2 (D_1 and D_2). All the foregoing about the effect of different factors on the accuracy of the estimates is depicted in Fig. 6. Solid line here denotes the range of possible errors under relatively favourable conditions for manifestation of the effect of the corresponding errors (with lower but real level of manifestation of there factors, with the use of the most appropriate apparatus, and so on), dashed curves stand for maximum possible errors.

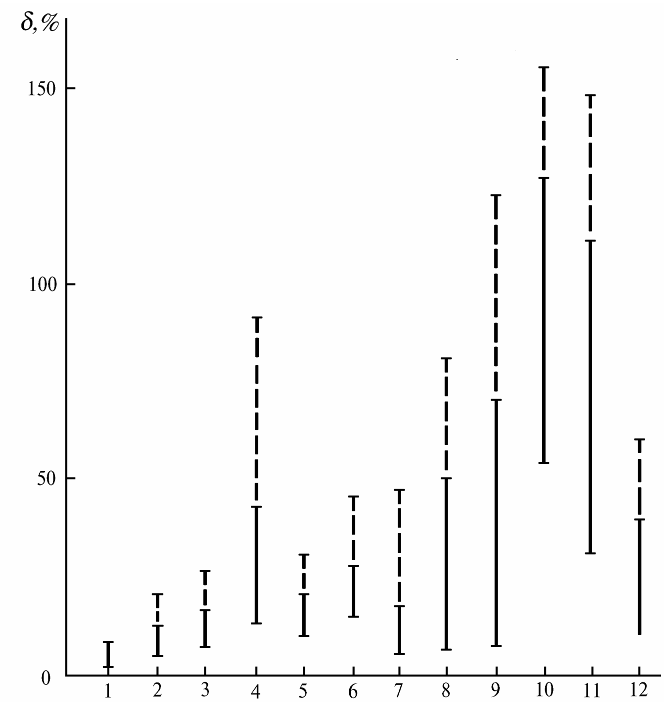

FIG. 6. Effect of various factors on the errors in reconstruction of the vegetation biomass. Numbers along the abscissa indicate the theoretical accuracy of the method (1), effect of uncontrollable soil moisture (2), effect of inexact knowledge of the type of soil at the instant of multispectral satellite imaging (3), effect of inexact knowledge of the optical state of the atmosphere (4), difference between the initial model and the employed reference model[2] (5), effect of the errors of the employed atmospheric transmittance model (6), neglect of the real viewing angle (7), neglect of the solar zenith angle at the instant of imaging (8), neglect of real nonorthotropic reflection (9), lack of stage of classification of multispectral images (10), neglect of seasonal evolution of spectral image of vegetation in the process of reconstruction (11), and the effect of random measurement errors of spaceborne apparatus (12).

The following factors have the greatest impact on the errors in reconstruction of the parameter M: (1) lack of monitoring (identification) of the type of vegetation and, as a consequence, the use of the coefficients C_i^* for inappropriate types of crops for reconstruction of the parameter M; 2) neglect of seasonal evolution of vegetation (their reflecting characteristics); and 3) neglect of anisotropy of reflection (when the above–mentioned conditions of quasi–isotropy are not fulfilled).

The above–mentioned first stage of processing of aerospace images is the subject of refining of the first two factors at the instant of imaging which reduces the effect of these factors at the second stage of parameter evaluation implemented for the given classes of seasonal evolution of vegetation and current state of soil. The effect of the third factor is minimized for solar–synchronous polar–orbital satellite data when the difference between azimuthal viewing angles and azimuthal angles of the sun for scanning spaceborne systems is close to 90 and 270° at which the reflection anisotropy of soils and vegetation is not so pronounced as in the plane of solar vertical.[2] Insufficient controllability of the state of the atmosphere and solar zenith angles at the instant of imaging somewhat weaker affect the results of reconstruction of the parameter M but still remain of great concern. It is necessary here to minimize the level of uncertainty in the knowledge of these factors for more appropriate choice of the coefficients C_i^*.

The remaining factors under unfavourable conditions can also deteriorate the results of assessment of the parameter M but their effect is much weaker than those mentioned above.

CONCLUSION

The outlined new method of quantitative estimate of the parameters of soil and vegetation from multispectral aerospace images opens up new possibilities for monitoring of the biosphere from space. The real capabilities of this method have been shown for formulating the requirements for the accuracy of satellite measurements with allowance for sensitivity of the B^* and G^* parameters to the above–mentioned ones for the model under study. Further technological promotion of the method will allow one to obtain an objective estimate of the state of soil and vegetation with subsequent analysis of the errors in reconstruction of the state parameters for each pixel of the processed aerospace images.

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