ASSESSMENT OF THE PARAMETERS OF SOIL STATE FROM OPTICAL MEASUREMENTS PERFORMED WITH SATELLITE SCANNING SYSTEMS

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New results of assessment of soil fertility index from multispectral aerospace images are shown as a development of a concept of the soil brightness and the quality index of green color of vegetation. Some examples are presented which demonstrate the influence of inaccurate information about the atmospheric properties, measurement errors, and a number of other factors on the accuracy of reconstruction of the humus content in ploughed soil.

INTRODUCTION

In the solution of new problems of atmospheric optics related to remote sounding of the earth's surface from space it is important to understand the principles of formation of a spectral image of vegetation and soil in the field of outgoing optical radiation. The statement of the problem on transformation of reflected radiation at altitudes up to the top of the atmosphere and reconstruction of the parameters of soil–vegetative cover is described in Ref. 1. The accuracy estimates are given in Ref. 2 for the solution of corresponding inverse problems of atmospheric optics on reconstruction of the amount of vegetation phytomass (biomass).

In this paper we give some results of the solution of a similar problem in assessing the main index of soil fertility from space, keeping in mind that soil reflectivity is sensitive to the humus content when the most part of soil is ploughed.[3] The below–considered examples describe measurements carried out by the MSS apparatus, LANDSAT (USA), and its analog – the MSU–E multispectral scanning system of the Soviet satellite "Kosmos–1939".

PROBLEM STATEMENT

The concept of the B and G coordinates[1,2] makes it possible to assess remotely not only the vegetation parameters (first of all, the amount of phytomass) but also the soil parameters, in particular, the humus content H in soil.

In general, as has already been noted in Ref. 1, it is necessary to know the phase function of reflection from the surface. However, the surface may be considered as quasi–isotropic[1,4] in many cases, and we may restrict our consideration to simpler Lambertian surfaces.

As is well known,[3] the reflectance of soil depends on a number of factors: its chemical and mineralogical composition (the content of humus and compounds of ferric oxides, silicic acids, etc.), type of soil and its moisture content, structure of its surface (degree of cultivation), and structure of illuminating flux (i.e., illumination of the surface by the direct and scattered solar radiation) depending on cloudiness, atmospheric turbidity, and solar zenith angle.

Our challenge is to obtain the values of typical parameters (soil brightness B and quality index of green color of vegetation G), which characterize the state of the investigated continental objects observed from the top of the atmosphere. It can be done by modeling of the outgoing radiation fields in the "ground–atmosphere" system and by using the real experimental dependences of spectral reflectance on various factors[3] supplemented with definite atmospheric models[1] instead of the pure model representation[1] (as is often the case[4]). In processing of multispectral satellite images these parameters of the states of the objects (in the given case these are ploughed fields) are calculated from the real digitized images as certain combinations of measuring channels of satellite scanning radiometers with the known coefficients relating B and G with the spectral brightness L_1 and L_2 in two corresponding channels. These coefficients are typical of the employed tutorial samples in the form of dependences obtained in Ref. 3. In this connection the accuracy of reconstruction of the unknown parameters H affecting the functionals measured onboard satellites can be founded for the proposed scheme combining the data of modeling and monitoring.

The dependences of the parameters B and G for the nadir direction on the humus content H in dry chernozem, dark–grey forest, and sod–podzolic soil shown in Fig. 1 were calculated by us from the data obtained in Ref. 3 after their corresponding classification, systematization, and subsequent convolution with the sensitivity function for the second and fourth channels of the MSS apparatus. The representative discrete distributions of the parameter B as a function of H are associated with the discrete representation[3] of the initial reflection spectra measured from low–flying aircrafts as functions of humus content which is most typical of the above–considered soil types and comprises 4–6% in chernozem soil, 2–4% in dark–grey forest soil, and less than 2% in sod–podzolic soil. Here we do not discuss the quality of representation of the employed initial data (spectral reflectance as a function of the main index of soil fertility) but simply use the dependences obtained in Ref. 3 to justify the accuracy of the solution of inverse problems on reconstruction of the parameter H from the satellite data based on the given tutorial sample taking the distorting effect of the atmosphere into account. It can be seen from Fig. 1 that while the values of G vary slightly with H, the dependence of B on G is quite pronounced. Moreover, the inverse dependence of the brightness on turbidity of the atmosphere for dark and light soil is distinctly pronounced: the value of B increases with atmospheric turbidity[1,2] (haze brightness) for chernozem and decreases for lighter podzolic soil what corresponds to the data of Ref. 5.

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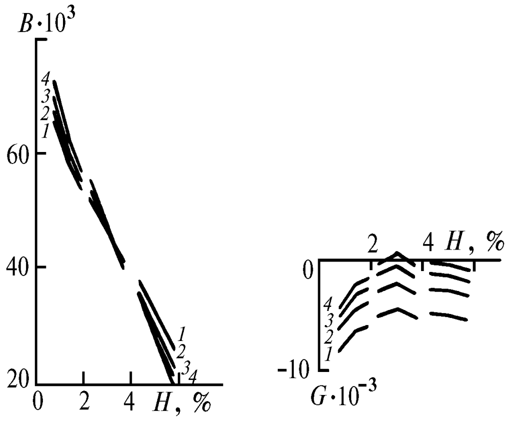

FIG. 1. Quantities B and G vs humus content H for three types of soil and four degrees of atmospheric turbidity changing from a strongly turbid state (1) (the type a *in Ref. 1) to a transparent one (4) (the type* d *in Ref. 1).*

This gives us grounds to keep the polynomial dependence of H on B, as the most informative and unique characteristic, for assessing the humus content in soil from the data of two–channel satellite measurements. This polynomial dependence was previously used by us for reconstruction of the vegetation biomass M (see Refs. 1 and 2). It is given by the formula

$$H = C_0(\kappa, r, l, n) + C_1(\kappa, r, l, n)B + C_2(\kappa, r, l, n)B^2 + \dots, \quad (1)$$

where κ is the type of measuring apparatus, r is the soil type, l is its moisture content, and n characterises the type of atmospheric conditions.

Since the dependence of B on H is nearly linear (see Fig. 1), it is obvious that we can restrict ourselves to two or three coefficients C_i in expansion (1). These coefficients are determined from the data of *a priori* simultaneous measurements of the spectral brightness coefficients (SBC) of soil and the values of H corresponding to them (the same approach was used in Ref. 2 to calculate the corresponding coefficients for reconstruction of vegetation biomass).

THE INFLUENCE OF VARIOUS FACTORS ON THE ACCURACY OF RECONSTRUCTION OF THE HUMUS CONTENT IN SOIL

Such often encountered factors as poor (or lacking at all) monitoring of the atmospheric conditions, soil type, moisture content in soil, state of the surface (its cultivation) at the instant of imaging as well as neglect of the real anisotropy of soil reflectance (phase function of reflection from the surface), solar zenith angle, viewing angle, inaccurate data on the angular coordinate of imaging, instrumental errors, and errors in *a priori* data have most pronounced effect on the accuracy of the above–described remote method of reconstruction of the humus content in soil. In the last case we are dealing with the initial data used for calculation of the coefficients $C_i(\kappa, r, l, n)$ as well as involved in the parameters of four employed atmospheric states P_n and D_n where P is the atmospheric transparency, D is the brightness of atmospheric haze, and n is the type of atmospheric turbidity.[1] First of all it should be noted that systematic errors (approximation errors) are small and less than 2–3 % in most cases when the appropriate coefficients of reconstruction are used.

Figures 2 and 3 show the effect of the atmosphere on the accuracy of reconstruction of the humus content in soil for dry and moisten soil (Figs. 2*a* and 3*a*) and for cultivated soil (Figs. 2*b* and 3*b*). The coefficients $C_i(\kappa, r, l, n)$ correspond to the third type of the atmosphere (type *c* in Ref. 1) and dry and dense soil for different channels of the MSS apparatus. It can be seen that the effect of the atmosphere itself (for dry and dense soil) on the accuracy of reconstruction of humus content of soil is not as strong as that of vegetation biomass.[2] In general, the error does not exceed 10% for the second and fourth channels and 20% for the first and third channels of the MSS for chernozem soil, while for podzolic soil it is 20–25% for the second and fourth channels and 10–12% for the first and third channels of the MSS. In addition, it should be noted that the sign of the error in strongly turbid and transparent atmospheres is changed in going from dark (chernozem) soil to light (podzolic) soil. This is associated with different effect of the atmospheric turbidity on the brightness B for dark and light soil (see Fig. 1), and thus we will underestimate the reconstructed quantity H for dark soil and overestimate it for lighter soil if haze (turbidity) appears. Occurrence and neglect of moistening and cultivation of soil affect stronger the accuracy of determination of H. This effect is most pronounced in the case of less fertile (podzolic) soil for which the error in determining the value of H can reach 100% and more.

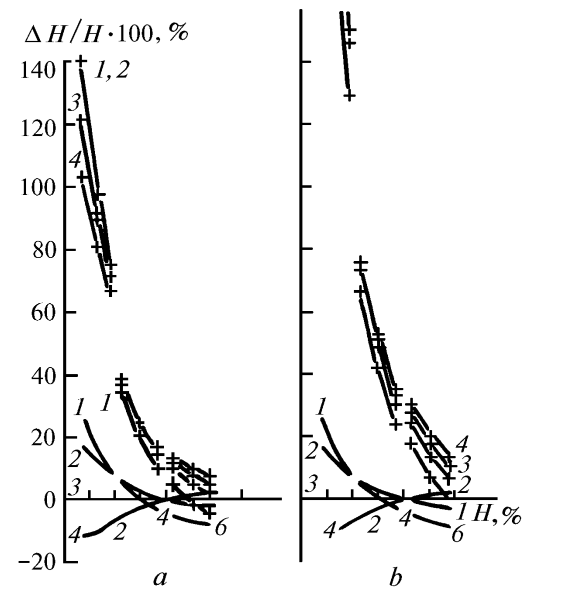

FIG. 2. Influence of inaccurate information about the properties of the atmosphere [the types a *(1),* b *(2),* c *(3), and* d *(4)] obtained at the instant of imaging when the humus content in dry soil (solid curves) is reconstructed with the use of the approximation coefficients for the atmosphere of the type* c *for the second and fourth channels of the MSS apparatus. The corresponding errors in reconstructing H with the use of the same coefficients under conditions of soil moistening up to the* 50 *percent level of the normal moisture capacity (a) and of cultivation (roughness) of soil surface (b) are shown by crosses.*

As can be seen from Figs. 2 and 3, these errors are somewhat less for the first and third channels than for the second and fourth channels of the MSS. Since cultivation and moistening cause always soil darkening, the sign of the error in determining H is always positive, i.e., its effect is opposite to that of haze in the case of relatively dark soil. As a consequence, their total error decreases and, generally speaking, can have one or another sign depending on the possible combinations of these factors. It is seen from Figs. 2 and 3 that reconstruction of the values of H with fair accuracy is possible only for chernozem and partially for forest soil in the case of poor monitoring of the atmospheric conditions, moisture content, and surface state. In the case of podzolic soil adequate monitoring of the above–indicated soil and atmospheric characteristics is required. In so doing measurements in the second and fourth channels are more suitable for reconstruction of H for chernozem soil while in the first and third channels of the MSS – for podzolic soil.

The errors in reconstruction of H for forest soil appear to be relatively small (4–7%) when the coefficients $C_i(\kappa, r, l, n, \Theta)$ characterizing the chernozem soil are used; however, they can reach 30–50% in podzolic soil (Θ is the zenith viewing angle).

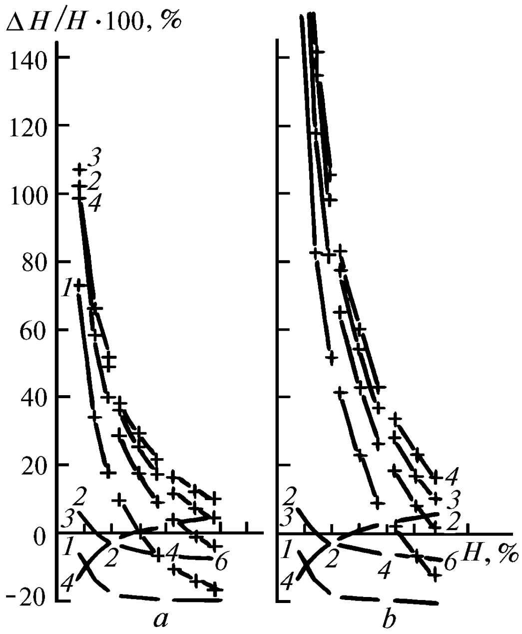

FIG. 3. The same dependences as in Fig. 2 for the first and third channels of the MSS apparatus.

When the viewing angle Θ is unknown or inaccurately known in the case of isotropic (Lambertian) surfaces, using, for example, the nadir coefficients $C_i(\ldots, \Theta = 0)$, we obtain that the errors in reconstruction do not exceed 5% for objects observed at $\Theta \sim 15°$ for the second and fourth channels and 10% – for the first and third channels of the MSS. However, at large angles of observation these errors can be rather large, and it is necessary to take into account the angular dependence of the coefficients $C_i(\ldots, \Theta)$ (for example, the errors in reconstruction of H are of the order of 20% at $\Theta \sim 45°$ for the second and fourth channels and reach 45–60% for the first and third channels of the MSS).

Neglect of the surface anisotropy can introduce gross errors into the reconstructed quantity H, especially at large measurement angles Θ. These errors can reach 20–25% for chernozem soil and 70–80% for podsolic soil even in the case of relatively low degree of anisotropy of the surfaces (less than 20%).

The errors in the initial data (*a priori* data), which are used for calculation of the reconstruction coefficients $C_i(\kappa, r, l, n, \Theta)$ are quite noticeable. For example, 10 percent systematic errors in the SBC's can result in 5–6 percent error in H for chernozem soil and more than 30 percent error for podzolic soil.

The proper choice of the nodal points H_i determining the values of the coefficients C_i of reconstruction of humus content in soil may affect the accuracy of determination of H in addition to the value of the SBC. This may, in its turn, strongly affect the errors caused by other factors. The problem in this case comparing, for example, to the reconstruction of vegetation biomass is in the fact that for determining the coefficients C_i no more than three or four points can normally be used in connection with the narrow range of variation of H in each of soil types. Therefore, any error (even not very large one) in determining the position of each of the points H_i can markedly affect the results. This requires careful measurements and reasonably complete volume of initial data array employed for determining the coefficients C_i.

Errors in determining the atmospheric parameters $P_{1,2}$ (transparency) and $D_{1,2}$ (haze brightness) characterizing four chosen states of the atmosphere[1,2] included in the *a priori* data and used in calculations of the coefficients $C_i(\kappa, r, l, n, \Theta)$, less noticeably affect the accuracy of reconstruction of H. Thus, 10 percent errors in determining $D_{1,2}$ introduce the errors less than 4–6% for chernozem and forest soil and less than 8–10% for podzolic soil into the determination of H. The 5% errors in determining $P_{1,2}$ result in the errors in reconstruction of H which are less than 5–6% for chernozem and forest soil and less than 13% for podzolic soil.

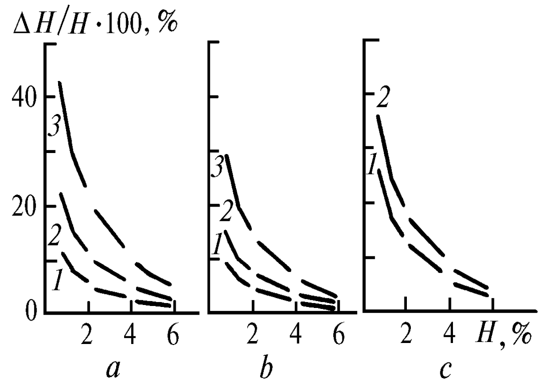

FIG. 4. Influence of the instrumental errors of the MSS apparatus (the second and fourth channels) on the accuracy of reconstruction of the humus content in ploughed soil: a) measurement errors δL_1 for the second channel are equal to 5 (1), 10 (2), and 20% (3); b) δL_2 for the fourth channel are equal to 3 (1), 5 (2), and 10% (3); c) $\delta L_1 = \delta L_2 = 5\%$ (1), $\delta L_1 = 10\%$ and $\delta L_2 = 5\%$ for the atmospheric conditions of the type a *(2).*

Figure 4 shows the effect of instrumental errors on the accuracy of determining H in soil for the second and fourth channels of the MSS. These errors are dependent on the atmospheric state and increase (especially in shorter–wave channel) with atmospheric turbidity. In our previous paper[2] devoted to the reconstruction of vegetation we presented analogous figure showing effect of instrumental errors for the second and fourth channels of the MSS and atmospheric conditions of the type *c*. There the influence of the fourth channel was much stronger than that of the second channel. In this example of the strongly turbid atmosphere the influence of the shorter–wave channel intensifies, and therefore the errors in determining H for the second channel are larger than for the fourth channel. Figure 4 shows the largest errors for the first (the least transparent) state of the atmosphere. It can be seen that even the instrumental errors (~ 10%) in the first and second channels introduce the errors into the determination of H which are less than 10% for chernozem soil. The errors in determining H in this case increase up to 16% for forest soil and can reach 20–25% for podzolic soil, even for the five–percent instrumental error. The use of the first and third channels of the MSS apparatus for the strongly turbid atmosphere will introduce more pronounced errors into determination of the quantity H because the first shorter–wave channel is to a greater extent subjected to the effect of the atmosphere. In this case the instrumental errors (~ 10%) result in the errors in determining the quantity H which are less than 12–14% for chernozem soil and reach 20% for forest soil. The errors in determining H can reach 30–35% for podzolic soil for the five–percent instrumental error.

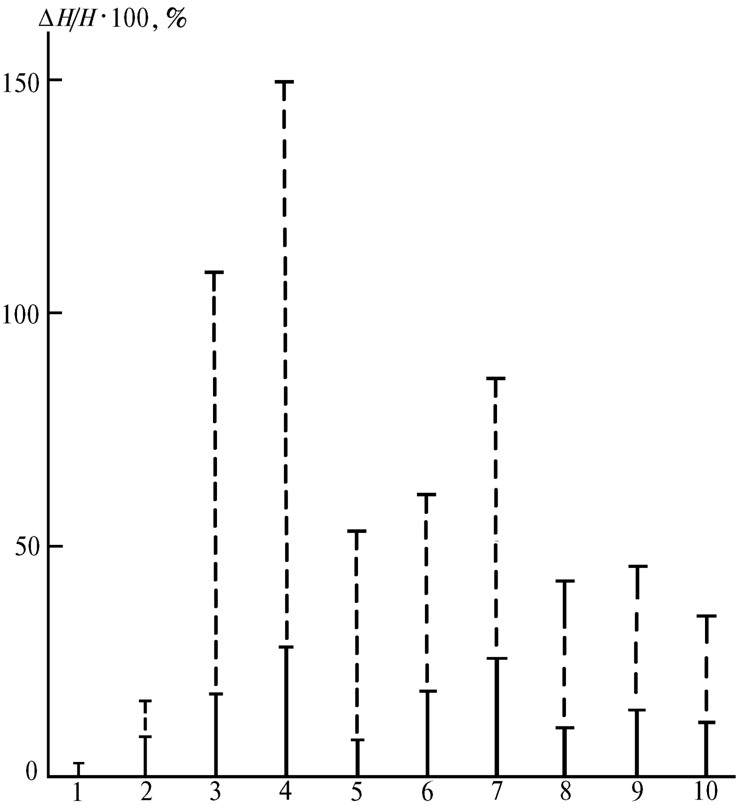

FIG. 5. Influence of various factors on the errors in reconstruction of the humus content in soil. 1) Theoretical accuracy of the method, 2) influence of the inaccurate information about the atmospheric conditions at the instant of imaging, 3) influence of uncontrollable conditions of soil moistening, 4) neglect of cultivation conditions (roughness) of the soil surface, 5) effect of the inaccurate information about the soil type at the instant of imaging, 6) neglect of the real viewing angle, 7) neglect of possible nonorthotropic reflection, 8) deviation of the initial model from the employed reference model,[3] 9) influence of the inappropriate model of the atmospheric transparency and its inaccurate relation to the atmospheric haze, and 10) influence of the random instrumental errors of the satellite apparatus.

Figure 5 shows all the above–mentioned factors and magnitudes of the introduced or possible errors. As can be seen from the figure, even the maximum errors are small for almost all factors for chernozem soil and are less than 15–17%. Only uncertainty of such factors as a surface state and surface anisotropy of soil can introduce more noticeable errors into the reconstruction of H, and thus, they require more attention and control. As to podzolic soil, the majority of characteristics of the atmosphere, surface, etc. require high accuracies of measurements without which the problem of reconstruction of the humus content in such a soil cannot be solved.

CONCLUSION

By the example of the new proposed methods for assessing the parameters of the dry land surface (the amount of vegetation phytomass and soil fertility index) from multispectral aerospace images we have first shown the real accuracies of reconstruction of the above–indicated parameters based on the tutorial samples obtained in subsatellite experiments. Here we have founded the accuracies of quantitative reconstruction of the above–considered parameters over the large areas within the limits of individual pixels of the satellite apparatus (which is about 40 m for the satellite MSS apparatus) in contrast to the preceding qualitative estimates. The influence of various factors on the accuracies of quantitative assessment of soil and vegetation parameters has been shown. Among these factors are inappropriate models, inaccurate information about the state of the atmosphere and state of soil–vegetative cover at the instant of spaceborn imaging, variability of atmospheric characteristics and conditions of solar illumination, fluctuational errors of measurements, etc. The models developed in this manner, which determine sensitivity of the results of reconstruction of the parameters to the errors in determining the environmental factors, justify the permissible errors at the individual stages of satellite and subsatellite measurements. These models provide the assessment of the state parameters with the assured accuracy resulting from the individual stages of obtaining the selected measurements and real instrumental errors.

REFERENCES

1. V.V. Kozoderov and V.S. Kosolapov, Atmos. Oceanic Opt. **5**, No. 8, 550–554 (1992).

2. V.V. Kozoderov and V.S. Kosolapov, Atmos. Oceanic Opt. **6**, No. 5, 316–320 (1993).

3. P.P. Fedchenko and K.Ya. Kondrat'ev, *Spectral Reflectance of Some Types of Soil* (Gidrometeoizdat, Leningrad, 1981), 232 pp.

4. K.Ya. Kondrat'ev, V.V. Kozoderov, P.P. Fedchenko, and A.G. Topchiev, *Biosphere: Methods and Results of Remote Sounding* (Nauka, Moscow, 1990), 224 pp.

5. K.Ya. Kondrat'ev, V.I. Binenko, L.N. D'yachenko, et al., *Albedo and Angular Characteristics of Reflection from Underlying Surface and Clouds*, ed. K.Ya. Kondrat'ev (Gidrometeoizdat, Leningrad, 1981), 232 pp.