GENERALIZED FORMULATION OF THE PROBLEM ON ESTIMATION OF THE PARAMETERS OF STATE OF NATURAL FORMATIONS BASED ON OPTICAL MEASUREMENTS FROM SPACE

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This paper presents a generalized description of the techniques for quantitative estimation of the state parameters of natural formations states from data of spectral, angular, and polarization measurements with the spaceborne scanning radiometers. This approach differs from earlier formulations of the problem by the separation of spectral reflectivity of layers, in its functional description of the outgoing radiation fields, into two parts. The first one describes interaction of optical radiation with the target volume under study while the second one represents the noise due to direct reflection of incident solar radiation from the upper boundary of the layer. As a result, the use of the proposed techniques enables one to represent each pixel of the image processed, earlier classified using standard procedures of image recognition and scene analysis, in terms of the state parameters obtained from data of sampling ground based measurements, these state parameters being characteristic of a particular class from the image.

Feasibility of solving certain applied problems on estimation of the state of natural formations from their images taken from space is based on the property of spatial distributions of the brighness images of such formations to bear information about their structures, contrasts, difference in conditions of illumination with solar radiation, etc. First techniques of visual decoding of such images, developed yet at early times of airborne photography, were then progressed to interpret and analyze multispectral images with computers. Interactive processing techniques operating with digitized matrices of image equivalents of different spatial resolution came to substitute instrumental and visual processing of images taken from space, so that the task could be formulated of searching for optimal criteria for distinguihing among various natural formations, such as "vegetation indices",[1] "quality index of green color of vegetation",[2] etc.

Another one field of applications of satellite data is related to measurements of angular distributions of brightness, using for this purpose spaceborne radiometers which could scan crosswise, cone–wise, or even along the flight line. The latter mode, tested on some of the pioneer spaceborne systems, was based on the assumption that instant spectral images of one and the same target taken from different angles could noticeably differ from each other, so that some additional features of the objects could be found from such spectral images. Naturally, the overall efficiency of spaceborne instruments, primarily aimed at covering vast territories, was lower in this case.

Meanwhile the demands to spaceborne instrumentation mainly depend on the type of the problem to be solved. Thus, at a high spatial resolution (tens of meters) most often found in the sun–synchronous and polar orbiting systems the width of a strip observed is not large, and the probability of repeated observations of one and the same territory is reduced to once every several weeks, or even to once every several months because of cloud cover. On the contrary, low spatial resolution (e. g., about 1 km) presents an actual possibility of regularly covering the whole globe with observations several times a day.

Thus, an important task in spaceborne studies of the Earth is to provide adequate grounds for using multispectral satellite imaging of different spatial resolution.

Good prospects are expected from advanced spaceborne systems for stereoimaging of one and the same territory from two different platforms and for polarization measurements. It is anticipated that stereoimaging will enable further simultaneous development of multispectral and multiangular techniques, so that the overall efficiency of studying various natural formations from space will be increased. The same may be said about polarization measurements, however their role in expanding informative capacities of spaceborne instrumentation is still unclear.

A particular feature of transverse electromagnetic waves (as distinct from, for example, the acoustic longitudinal scalar waves), which requires their vector description, is that identical objects (such as vegetation, water surface, etc.) look different under the illumination by natural or polarized light. Measurements of polarization of the reflected solar radiation may, therefore, yield additional characteristics of the state of such objects. Multiple scattering of the reflected radiation by atmospheric aerosol results in radiation depolarization so that the task of estimating information content of satellite polarization measurements, e. g., of radiation reflected from the top of forest canopy, is far from being trivial. Possible variations in the state of polarization of outgoing radiation may be caused, in particular, by the presence of a layer of oriented ice crystals of semitransparent cirrus clouds between the object observed and the spaceborne platform, but not by changes in the properties of the surface itself. Hereafter when speaking about forest canopy, we imply the volume interacting with the incident radiation thus controlling the level of signal in the outgoing radiation.

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Consider the general problem on formation of the outgoing radiation brightness, paying special attention to its the functional relation to spectral reflectivity, which, in its turn, depends on the parameters characterizing the state of natural formations under study. One of such parameters may be the amount of phitomass, the most important parameter invariant with respect to conditions of observations from space and of solar illumination.[3] We shall consider most complex formations of the type of a spatially distributed forest canopy, the outgoing radiation from which being a combination of at least two components: one directly reflected from the top of the canopy, which does not carry any information on its properties, and another, diffusely scattered by the canopy itself, which bears information about the parameters of the canopy state, such as the above‑mentioned amount of phitomass. In contrast to traditional application of the theory of radiation transfer and allied problems,[4] we now focus upon the functional description of such a problem, aiming at developing new techniques for estimating the state parameters from multispectral, multiangular, and polarization data of remote sensing with our new approximate solutions of both direct and inverse problems of atmospheric optics[5] and auxiliary ground based and airborne support measurements.[3]

MATHEMATICAL FORMULATION OF THE PROBLEM

The principles of image recognition and scene analysis, commonly used to process images taken from space, provide a scientific basis for classification of objects observed in such images. Such a classification results in a representation of a multispectral image in the form of a set of uniform subsets, grouped according to certain decision‑making rules, which allow the elements of an image to be sorted among different classes. Certain "class alphabets", "feature glossaries", and mathematical recognition procedures are used for this purpose. We propose not to use only these traditional data processing techniques, but to reconstruct, as the next step of data processing, the parameters of state of the objects for each identified subset, using selected joint measurements of spectral images of these classes and the relevant parameters of state. The number of such selected "point" measurements or measurements at some surface transsections should, ideally, correspond to the number of classes identified during each processing, that is, each contour of the identified class should have its selected "training" sequence to be further used to solve the inverse problem on reconstruction of the parameters of state. The formation under study for such a problem is some ith class associated with a corresponding uniform subset from the processed image, so that the terms "object" and "class" are equivalent in this respect.

Such new techniques should result, upon implementation, in such a transformation of the classified images, which would make it possible to present each element of the corresponding image in terms of invariant parameters of state, instead of spectral images, sensitive to conditions of illumination and observation, or combinations of measurement channels, such as the above mentioned vegetation indices, which are similarly sensitive to conditions of observations.

Taking into account all the above said, let us write the basic functional L for radiation reflected from the ith object on the Earth's surface, measured in the jth channel of the kth instrument in the form:

$$L^{h,\nu}_{ijk}(z_0;\ \theta,\ \varphi;\ \Delta\theta,\ \Delta\varphi,\ \Delta s;\ M) = \frac{1}{(2\pi)^2}\int\limits_0^{2\pi} d\varphi' \times$$

$$\times \int\limits_0^{\pi} \cos\theta'\, d\theta' \int\limits_{k_1}^{k_2} [S(z_0;\ \lambda) + H(\theta',\ \varphi';\ \lambda)] \times$$

$$\times [\rho^{h,\nu}_i(\theta,\ \varphi;\ \theta',\ \varphi';\ \lambda) + \rho^{(1)}_i(\theta,\ \varphi;\ \theta',\ \varphi';\ \lambda;\ M)] \times$$

$$\times \Pi_{jk}(\Delta\theta,\ \Delta\varphi,\ \Delta s;\ \lambda)\, d\lambda, \qquad (1)$$

where each ith class is characterized by

– measurement conditions (Sun elevation z_0, direct solar radiation S, zenith θ and azimuth φ sight angles, corresponding θ' and φ' angles refer to the diffusely scattered radiation H reaching the instrument) ;

– instrumentation features, such as angular ($\Delta\theta$, $\Delta\varphi$) and spatial (ΔS) resolution, and sensitivity Π at the wavelength λ ;

– spectral reflectivity ρ, which is determined by the external structure of a given class, govering its specific reflectivity for horizontally h and vertically ν polarized light and by its internal properties (the amount of phitomass, M), which causes the mode, in which the radiation interacts with a given natural formation in its different states.

In addition to the above external conditions, under which the ith object presented by a corresponding class in the processed image exists, other factors important for its description based on observations from space are the transmission of the atmosphere and brightness of the atmospheric haze (see below).

The separation into two components $\rho^{h,\nu}$ and $\rho^{(1)}$ of the reflectivity ρ for each class, as presented in this general formulation of the problem, is caused by the necessity to identify the signal $\rho^{(1)}$, bearing information on the properties of the studied formation, against the noise component $\rho^{h,\nu}$, produced by "pure" reflection of radiation from the top of the volume observed. In case of water objects the component $\rho^{h,\nu}$ is determined by Fresnel reflection from the air–water interface. This component also determines the polarization of radiation and the appearance of specularly reflected component, in contrast to backscattered difuse non–polarized radiation $\rho^{(1)}$, which bears information about the content of chlorophyll, suspended particulate matter, etc.

For such complex formations as forest ecosystems, $\rho^{h,\nu}$ determines the external parameters of a given system, such as its structure and conditions of solar illumination, for example, crown spread, tree stand density, upper surface roughness, leaf orientation in the upper layer, their mutual shading, etc. The internal structure of the canopy is characterized by the corresponding values of $\rho^{(1)}$, depending on its density, interaction of radiation penetrating under the canopy, and that exiting its top, canopy transmission in both directions, etc. It is natural that signal $\rho^{(1)}$ is much lower than $\rho^{h,\nu}$ for a dense canopy. The publications available do not contain reliable data on conditions when these values are comparable or noticeably differ from each other. Basically it is believed that understanding of this problem can be reached via precise measurements in the ground field experiments.

Intuitively, it is understandable that the more cohesive is forest canopy, and the higher is its density, the more difficult it is to recover the informative signal on the amount of phitomass M from the data of remote sensing. When solving such an inverse problem on estimation of M for steppe grassy vegetation it appeared possible to combine these two components into one.[3] The necessary proofs of the feasibility to solve such a problem for forest vegetation may apparently be obtained from high precision measurements of the vertical profiles of radiation and of the forest canopy itself in the ground field experiments.

The values of $\rho^{h,\nu}$ are associated with the so–called bidirectional distribution reflectance functions (BDRF)[3] although available measurements, e. g., using the PARABOLA (Portable Apparatus for Radiation Bidirectional Observations of Land and Atmosphere) instrumentation yield the joint effect of the directional reflection and diffuse radiation escaping from the forest canopy or any other natural formation. The new formulation of the problem on quantitative estimation of the parameter M requires new instrumental sets for making ground support experiments.

Within such a problem formulation the value of the degree of polarization $(L^h / (L^h + L^\nu))$ is only a complementary feature describing the structure of the top of forest canopy rather than its internal structure. If the canopy is dense ($\rho^{(1)} \to 0$) the dependence of L on M becomes insignificant, and we have a standard formulation of the problem in place of proposed one. In other limiting case, when $\rho^{h,\nu} \to 0$, polarization measurements loose their meaning. The latter case is however highly improbable in practice, since there always exists some reflection from the top of the canopy.

METHODS OF SOLVING DIRECT AND INVERSE PROBLEMS

From the standpoint of seeking optimal spectral features suitable for estimating the state of natural formations and optimizing measurement channels of scanning spaceborne radiometers, the concept of using such combinations of channels as "soil brightness" B and "quality index of green color of vegetation" G (see Ref.6) seems to be quite natural. In contrast to the initial formulation of the problem, our updated version refers to a maximum use of complementary ground support measurements in the general computational scheme for the coefficients which relate (B, G) to (L_1, L_2) in the linear combinations of the two selected channels (1 and 2).

Our studies are an alternative to the already mentioned concept of vegetation indices, which are combinations of satellite data without any relation to other ground support measurements. The information content of our combinations is higher than that of vegetation indices, since we involve more measurement data, thus reducing the ambiguity in the results of final analysis.

Naturally, invocation of additional data does not necessarily results in an increase of the information content of a given set of remote sensing data (much can depend on the value function of such additional data for a given problem). However, our attempt to make maximum use of the existing data bases (for example, on boreal forests) is a positive development for geoinformational systems (GIS) and for GIS–technologies of data processing and interpretation, independent of the type of measurement data.

In the generalized formulation of the problem the roles of former $L_{j=1}$ and $L_{j=2}$ (see the left–hand side of Eq. (1)) in our expressions for B and G

$$B = a_1^{(B)} L_1 + a_2^{(B)} L_2; \tag{2}$$

$$G = a_1^{(G)} L_1 + a_2^{(G)} L_2, \tag{3}$$

where matrices $\hat{A} = \begin{pmatrix} a_1^{(B)} & a_2^{(B)} \\ a_1^{(G)} & a_2^{(G)} \end{pmatrix}$ are obtained from synchronous data of remote (spaceborne) and ground measurements at selected test sites or transsections using the least–square technique, are played by the differences:

$$\tilde{L}_{j=1} = L^{h,\nu}_{i,j=1,k} - \bar{\rho}^{h,\nu}_{i,j=1,k} ;$$

$$\tilde{L}_{j=2} = L^{h,\nu}_{i,j=2,k} - \bar{\rho}^{h,\nu}_{i,j=2,k} ,$$

where

$$\bar{\rho}^{h,\nu}_{ijk} = \frac{1}{(2\pi)^2} \int_0^{2\pi} d\varphi' \int_0^{\pi} \cos\theta' \, d\theta' \int_{k_1}^{k_2} [S(z_0; \lambda) +$$

$$+ H(\theta', \varphi'; \lambda)] \, [r_i^{h,\nu}(\theta, \varphi; \theta', \varphi'; \lambda) \, \Pi_{jk}(\Delta\theta, \Delta\varphi, \Delta s; \lambda) \, d\lambda, \tag{4}$$

are reflectivities of the ith volume in the jth channel of the kth instrument for the horizontal (h) and vertical (ν) polarizations, averaged over the angles (θ', φ') of radiation incidence and spectral channels $\Delta\lambda$ with their boundaries (λ_1, λ_2). Different sets of matrices $\hat{A}$ for different sets of i, k, h, ν characterize different non–spectral properties of the studied classes of natural formations.

Understanding of the laws of the formation of spectral images, that is, linking theory and experiment, one should recall that, along with averaging over angular coordinates of the incoming radiation and over the spectral channels of instruments used, there necessarily takes place averaging of obtained values of $\tilde{L}$ over the horizontal coordinates, within the field–of–view angles $\Delta\theta$ and $\Delta\varphi$ of the instruments used with a spatial resolution Δs:

$$<\tilde{L}(<M>)> = \int_{\Delta\theta} \int_{\Delta\varphi} \int_{\Delta s} \tilde{L} \, [\Delta\theta, \Delta\varphi, \Delta s, M(s)] \, ds \, d\varphi \, d\theta, \tag{5}$$

where the averaged values of $<\tilde{L}>$ characterize separate elements of resolution of a given instrument within each selected class, which then only depend on θ and φ. The apparent paradox of averaging over the instrument field of view covering certain area Δs is caused by the need to know the law of transforming a "point" into an "area". Finally, one needs for some *a priori* data on the average values and on the corresponding spatial variances characterizing given class or type of natural formations.

Averaging of the values of $\tilde{L}$ calls necessarilly for similar averaging of M within the same contours of the objects under study from the classified images. The next step in studying the processes of formation of spectral images of various natural formations from spaceborne observations concerns atmospheric transformations of data on $<\tilde{L}>$ so that these data may be reduced to the upper boundary of the atmosphere, using corresponding models, usually associated with the models of radiation transfer.[4]

Our orientation on the maximum use of ground measurements for processing data of spaceborne measurements calls for a wide application of ground spectrophotometric measurements of the atmospheric transmission (which characterizes exponential extinction of the direct solar radiation) and the earlier derived functional relations between the atmospheric transmission in a given spectral range and brightness of the atmospheric haze, that is, radiation scattered in the atmosphere that does not reach the Earth's surface.[5]

As it follows from the above said, one may exclude $L_{ijk}^{h,\nu}$ and $\bar{r}_{ijk}^{h,\nu}$, independent of $<M>$, from the initial satellite data, so that the remaining right–hand side of Eq. (1) composed of $\bar{r}_{ijk}^{(1)}$, similar Eq. (4), may then be subjected to the same standard transformations that we have used earlier to demonstrate the potential capabilities of the proposed technique in its application to grass vegetation cover.[3] Here we face one more paradox. The values of $<M>$ obtained from the data on $\bar{r}_{ijk}^{(1)}$, do not depend on polarization. Note that, on the one hand, the values of $\bar{r}_{ijk}^{(1)}$ characterize our *a priori* data on the relation of this part of reflectivity to the vegetation biomass, and, on the other hand, they are presented by the specific values of $<L>$ for test sites within the processed images. This paradox results from the fact mentioned above, that polarization measurements (e. g., of the forest canopy) yield valuable information on the structure of the top of that canopy, but are not informative on its internal structure. As a result of implementing the proposed techniques, we increase the overall number of approximation coefficients which relate $<M(z = 0)>$ to $<G(z = H)>$, while following the same sequence of steps of estimating $<M>$ value

$$<M(z = 0)> = C_0 + C_1<G(z = H)> + \dots , \quad (6)$$

where $z = 0$ corresponds to the Earth's surface; $z = H$ is the upper boundary of the atmosphere, and averaging of $G(z = H,\ z_0,\ \theta,\ \varphi,\ M)$ takes place in the above sense for specific $\hat{A}$ matrices, determined by the values of i, k, h, and ν. Note that transformations of the spectral signatures in the atmosphere during occuring at a transition from $z = 0$ to $z = H$, such signatures being integral for the chosen channels, follow the same transformations of the type

$$<\tilde{L}_j(z = H)> = <\tilde{L}_j(z = 0)\ P_j + D_j>$$

for some specific i, k, h, and v. Here P is the atmospheric transmission, and D is the brightness of the atmospheric haze; they are presented by the corresponding transformation matrices, different for the h and ν components of polarized radiation.[4] Thus, the theoretical grounding of solving the above applied problem is fully considered.

APPLIED ASPECTS OF IMPLEMENTING NEW TECHNIQUES

Proceeding from the theoretical formulation of the problem to applications of the proposed techniques, we would like to note the following:

– It is need the angles (z_0, θ, φ) to be known, at which every pixel of the image was taken, to make classification in the above sense. This requirement is a standard item of any software now used for processing of obtained from space images;

– Differences between the initial brightness and the reflectivity (4) of the upper boundary of a volume layer (such as forest canopy) have to be calculated for each test site typical for the corresponding class in the image, thus filtering signal off noise background presented in the form of such differences; such a filtering only becomes possible due to high–precision ground measurements at test sites;

– For each test site, the matrices $\hat{A}$ are computed by the least squares technique to characterize the relation between these differences and $<G>$ ($<B>$ for the case of soil cover) for any pair of spectral channels of a spaceborne instrument; these matrices contain the functional relations between the data of remote sensing and the parameters of state (such as vegetation biomass, for example), expressed in terms of measured reflectivities at selected test sites in corresponding spectral channels;

– Thus obtained matrices $\hat{A}$ are then modified to be transformed with the account for measurement data on atmospheric transmission and its functional relations to haze brightness over each test site;

– For each test site the process of training by the obtained matrices $\hat{A}$ involves the use of corresponding matrix values with the account for specific geographical coordinates and measurement conditions, such training should result in transformation of the current values of $<\tilde{L}>$ and $<G>$, already filtered off by the above techniques, according to their information content, into the values of $<M>$ for each element of the image, using an individual training set for every such element. Note that the general problem on optimal interpolation of "point" data from test sites over the contours of homogeneous subsets from the corresponding classes is an integral part of the inverse problem solution to reconstruct $<M>$ values.

Significant part of data from ground support measurements is quite ordinary for ground based field experiments at observational networks. These are the direct (S) and scattered (H) incident solar radiation (note, however, that spectral measurements are needed, in contrast to the commonly used integral data being collected at networks), spectral behavior of the atmospheric transmission (P); and, vegetation biomass (in particular, the amount of phitomass M).

The latter measurements are often associated with the quantitatively more apparent leaf area index (LAI). In particular, standard field measurements of the vertical profile of spectral radiation in forest canopy (presented as the ratio of radiation reaching a given level inside the canopy to that incident on its upper boundary) include LAI in the exponent characterizing the extinction of radiation. In this sense, updating the requirements to necessary spectral measurements of the vertical profiles of radiation inside the canopy should enable one to separate out the "informative" portion of outgoing radiation from its "parasitic" component.

Measurements similar to those of BDRF, mentioned above, are not so common. Such measurements at selected test sites are also necessary to implement the proposed techniques of quantitatively estimating parameters of state from multispectral spaceborne imaging.

To understand how separate resolved elements, characterizing a selected class of natural formations, are formed, one needs for additional information on the degree to which every given test site is representative for the whole class described by the same $<M>$ and $<\tilde{L}>$ (including average <BDRF>) and by their spatial variances.

The principal scientific problem here lies with understanding the laws by which spectral images of various objects are formed at the level of separate resolved elements. To do this, one would need for an input to regional data bases compiling the data of field experiments from observational networks, from biospheric reservations, etc. GIS technologies, which integrate relevant data bases, provide the ground for implementing such techniques and presenting multispectral images in terms of the parameters of state, invariant to conditions of imaging of various natural formations. Such new informative and methodological possibilities could serve as a basis for well–grounded solutions of the problems on the regional and global changes.

CONCLUSION

We propose in this paper a generalized formulation of the problem on quantitative estimation of the parameters of state of natural formations from multispectral images obtained from space in their combination with the selected complementary remote and ground based measurements at test sites chosen within the images processed. The basis for solving such a task is formed by the techniques normally applied to the direct and inverse problems of atmospheric optics, which functionally describe the fields of outgoing radiation depending on spectral reflectivity, the latter partially characterizing the external structure of corresponding natural formations. The other part of the description depends on the parameters of state of such formations, to be reconstructed using the techniques proposed for processing remote sensing data. We have also considered some aspects of implementing such techniques, and show how separate elements of the classified images may be presented in terms of their parameters of state, measured at test sites.

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