A physically based technology for processing of water basin remote sensing data

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Abstract — The Modular Inversion Program (MIP) is a processing and development tool designed for retrieval and mapping of hydro-biological parameters obtained from multi- and hyperspectral remote sensing measurements. The architecture of the program binds a set of general and transferable computational schemes in a chain, connecting bio-physical parameters with the measured reflected radiance. The radiative transfer is simulated in MIP for a multilayer atmosphere-ocean system using the FEM method. Results of radiative transfer calculations are stored in a sensor independent form on hard disks avoiding in this way repeated solutions of radiative transfer equation. The adjustment of algorithms to sensor specifications is supported automatically in MIP. The program modules provide for the retrieval of atmosphere and water constituents, estimation of phytoplankton primary production, water column correction and classification of surface substrates. The processing system has been tested and validated on data of surveys of German inland waters performed by several airborne and satellite sensors.

Keywords: remote sensing, inland water, radiative transfer equation, inversion, retrieval, airborne, multispectral

1. INTRODUCTION

The necessary element of any environment management system is a monitoring subsystem which supplies the decision making subsystem with the information about the current state of controlled objects. The specifics of environmental objects, namely their large extent, makes evidently prospective an application for monitoring purposes of remote sensing methods, allowing to obtain surveys of vast spatial regions in short time periods and with comparatively low expenses. An effective use of remote sensing is, however, conditioned by the existence of reliable methodology for processing of instrument readings, transforming the latter into the set of physical, chemical or biological variables which can serve as indicators of the object state.

In the case of water objects the problem of processing of remote sensing measurements is connected to a significant extent with the presence of atmospheric layer between the instrument and the object. The useful signal coming from the water body is highly contaminated by radiance reflected from this layer. Filtering out of the interfering atmospheric reflection is mostly performed basing on synchronous ground-truth observations or using some simplifying assumptions on the formation of resulting radiation field (Austin & Petzold, 1981, Gordon et al, 1988). The first approach is rather laborious and requires a lot of man power. The simplifying assumptions usually give satisfactory results for specific locations and observation conditions, but it is difficult to predict the accuracy of the results if the same method is applied to any other set of measurement data.

The most generally applicable methodology of retrieval of water body parameters from remote measurements must evidently proceed from fundamental physical principles formulated in radiative transfer theory. The basis of this theory is radiative transfer equation (RTE) which, using optical characteristics as intermediate parameters, connects radiation field with physical characteristics of the media. The solution of this equation is, however, a rather complicated problem and in the case of natural media even the calculation of radiation field for the media with known characteristics (the direct problem) can be performed only numerically. The inverse problem, namely the search of media characteristics from the measured radiation field is much more complicated as only iterative approach is possible here, and requires, speaking in general, multiple solution of the direct problem. The proposed technology of processing of the remote sensing images of water objects is aimed on overcoming the above difficulties and creation of a consistent set of computational procedures resulting in the compositional maps of objects under study. The core of this technology is the Modular Inversion Program (MIP).

2. ALGORITHM AND MODULAR STRUCTURE OF MIP

The Modular Inversion Program consists of a set of relatively independent modules implementing physically based algorithms. Such a structure permits substitution of any existing module by its newer version without modification of the program as a whole, so that the latest achievements in the related fields of knowledge can be easily incorporated into the program. MIP modules constitute a continuous chain, which allows one to transform scanner images into various thematic maps, furnishing the decision makers with vivid information about the state of water basin.

The architecture of MIP in general is defined by the choice of iterative inversion of RTE as a basic line of processing scheme.

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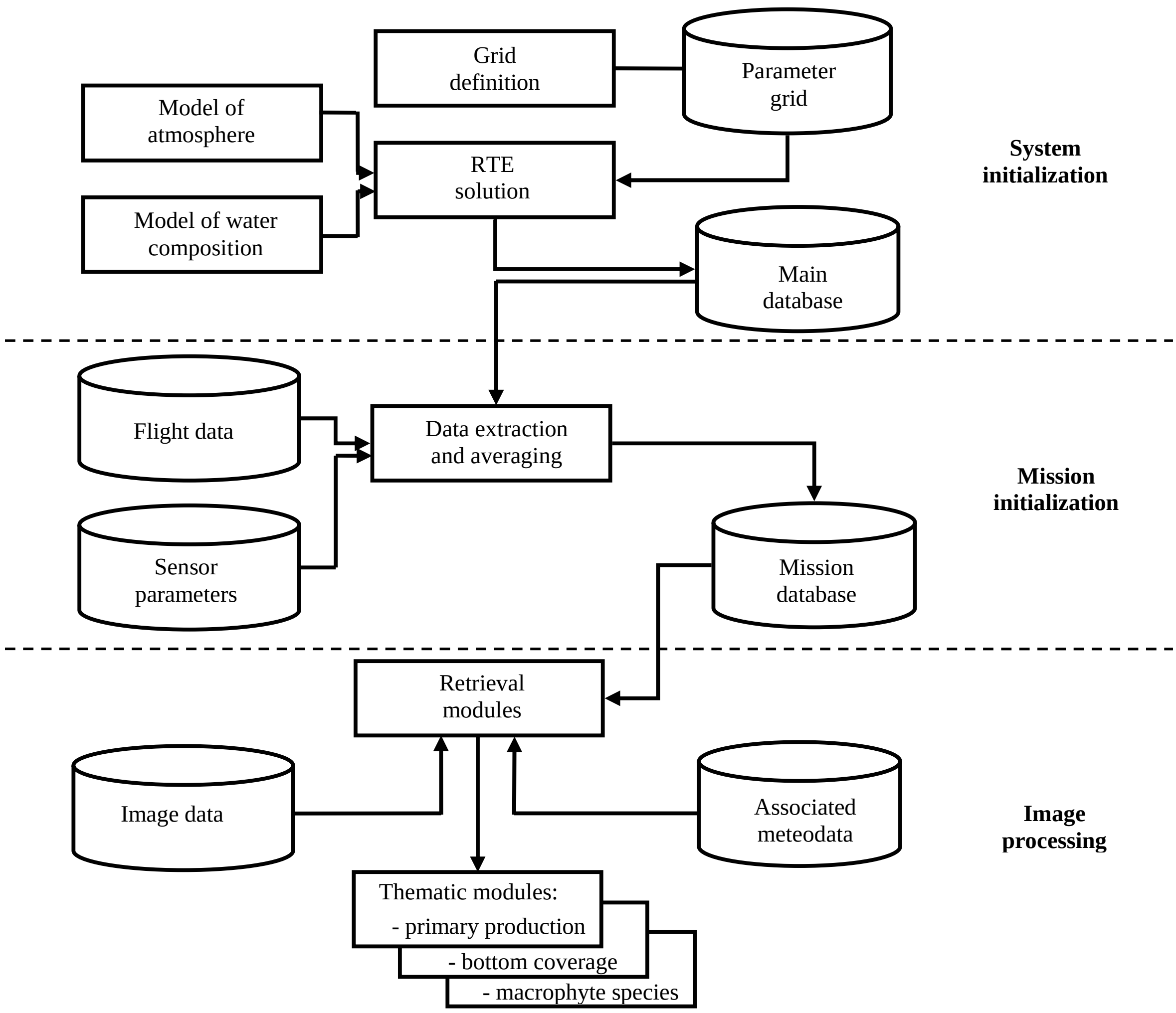

Figure 1. MIP processing diagram.

According to this choice the modules for the realization of the following functions are included in the program:

- modeling of atmosphere;
- modeling of water composition;
- solving of RTE, including multiple scattering and all effects at air-water interface;
- retrieval of media properties;
- thematic treatment.

2.1. Modeling of the atmosphere

As inversion of RTE is an ill-posed problem, it must be regularized in some way. The aim of regularization is to reduce the dimension of the unknown vector and one of the methods of doing that is to take into account the correlations between its components. In the application to the inversion of RTE it means that the sought distribution of the values of optical characteristics of the media in space and wavelength must be considered as not arbitrary, but corresponding to one of the distributions of microphysical properties of the media that can exist in nature. Accordingly, in the process of iterative inversion of RTE the next trial point in the space of optical parameters should be chosen from the set of these possible distributions. The fulfillment of this requirement in the case of the search of appropriate atmospheric parameters is provided by the atmospheric model module.

In the present version of MIP the model of atmosphere, i.e. the range of and relations between possible values of atmospheric parameters, follows the main features of the model adopted in MODTRAN code (Abreu & Anderson, 1996). This choice cannot be considered optimal in any way, but this model is widely known in the scientific community, well tested and provides for the enough variety of atmospheric conditions. As an extension of MODTRAN model, not only pure aerosol types (urban, rural, maritime or tropospheric) are allowed, but also their arbitrary mixtures.

2.2. Modeling of water composition

The model of water composition serves the same aim as the model of the atmosphere. Scattering, backscattering and absorption coefficients of water bulk are expressed as a linear combination of corresponding normalized optical properties of water species with concentrations as weighting factors. At any rate three types of species are used (chlorophyll, suspended matter and yellow substance), but arbitrary number of them can be included in necessary cases. Spectral curves of species characteristics are considered location dependent that allows taking into account the specifics of water object biota.

2.3. RTE solving

The requirements to RTE solver for modeling observations of water bodies in MIP are rather strict. The solution have to be obtained with high accuracy as only small part of total reflected radiance is reflected by water bulk and is in reality the useful signal. At the same time the computer time consumption must be low as it is necessary to perform multiple solution of RTE in order to make the iterations converge. The solver based on finite element method (Kisselev et al, 1994, 1995, Bulgarelli et al, 1999) is found to be the most appropriate for this purpose. The obtained solutions of RTE are stored in special databases in order to avoid repeated calculations (see next section).

2.4. Retrieval of media properties

The retrieval of media properties, i.e. the inversion of RTE, is performed by fitting the simulated sensor channel radiances to those observed. The search of media parameters, providing for the best fit, is performed by the downhill simplex method.

When calculating the channel radiances at sensor height for the trial state of the media, the water bulk is emulated by an orthotropic pseudoreflector, being characterized in this case by a single parameter. This pseudoreflector substitutes only the water mass, whereas surface effects, namely Fresnel reflection and refraction, are treated exactly. This assumption is acceptable because of the low reflectivity of a water bulk and allows optimizing the size of MIP databases.

The value of pseudoreflector albedo is connected in MIP with the subsurface reflectance. The relationship between these two values is given by Q-factors, i.e. the ratios of subsurface flux to intensity, which are estimated also by solving the RTE for realistic media. The obtained subsurface reflectance makes it possible to define total scattering, backscattering and absorption coefficients of water medium (Gordon et al, 1975) which in turn are related to the water species concentrations.

2.5. Thematic treatment

In order to have the possibility to supply the data to the final user in a convenient form, the modules for mapping some derived values are included in the system. The phytoplankton production rates are estimated basing on surface chlorophyll concentration, incident radiation of PAR (photosynthetically available radiation), and the vertical diffuse attenuation coefficient in the surface layer of the water column. (Heege et al, 2003). Modules for retrieval of the bottom coverage are also included in the system. After separating zones without vegetation, macrophyte species are classified using the spectral derivative analysis of their reflectances (Pinnel et al, 2004).

3. TECHNOLOGY OF DATA TREATMENT IN MIP

Although the implementation of finite element method provides for fast solving of direct problem of radiative transfer, this step of RTE inversion remains time consuming. Bearing in mind that MIP is being created for routine processing of a large number of remote sensing data, the results of radiative transfer modeling are stored in special MIP databases, avoiding in such a way laborious repeated calculations.

MIP databases contain radiation data both with high spectral resolution and with channel responses of specific sensors. The high resolution database, further called main database, contains data for a reasonable interval of values of observation geometry parameters, such as solar angles, observation heights, view angles and azimuths, and different media parameters. The set of media parameters is defined by the choice of the models of the media. The values of each parameter, for which radiation data are stored (the parameter grid), and the spectral resolution of the data are defined by the user in the process of building the database.

Databases with modeled channel responses, further called mission databases, are created for the treatment of images obtained during a specific flight. Channel responses are calculated as weighted with channel response functions averages of the high resolution radiances, the latter being extracted from the main database. It is assumed that solar angle, height, direction and pitch angle do not change during the flight, so the only parameter, characterizing the measurement geometry in mission databases, is scan angle. The set of media parameter remains the same as in the main database.

Two types of data are stored in both main and mission databases. These are radiances in the atmosphere for various directions and heights over the air-water interface and Q-factors, calculated for various directions of subsurface radiance. The calculation of radiances in the atmosphere is performed substituting the water bulk by a pseudo-reflector with varying albedo value, the latter being one of the main database parameters. Q-factors are calculated for typical atmospheric conditions and varying water composition.

The main database is created before the beginning of observation data processing by consecutive calls of RTE solver. Treatment of a specific image begins from building the mission database for geometric parameters of the flight and used sensor. In the process of further retrieval of media parameters MIP modules interact with this mission database, extracting and interpolating its data and obtaining the best fit with measured radiances. MIP processing diagram in a simplified form is presented in fig. 1.

Functionality of MIP is supported by a special image processing system XDibias, developed in the German Aerospace Center (Mueller et al, 2002). XDibias is used in MIP applications for calibration and georeferencing of images, supplying necessary information for building corresponding mission databases. Visualization tools of XDibias also allow performing manual analysis of data quality and combining the images obtained in several flights.

4. RESULTS

The first version of MIP was successfully used for the retrieval of water constituents in Lake Constance basing on the data of multi-spectral airborne scanner DAEDALUS (Heege & Fischer, 2004). In its present form MIP was applied for the treatment of the data obtained from airborn scanner HYMAP and satellite scanner CHRIS (Miksa et al, 2004, Pinnel et al., 2004).

The example below shows the results of inversion of CRIS observations of Lake Constance on the 19th of September, 2003. Molecular composition of the atmosphere was assumed to correspond to midlatitude summer state and aerosol was presented by a mixture of maritime, rural and urban components, optical depth of each component being retrieved as a result of inversion. Also three parameters of water body, namely concentrations of chlorophyll, suspended matter and yellow substance (the latter with some restrictions) were retrieved. The first step consisted in the determination of the aerosol and suspended matter concentrations using measurements in the wavelength region above 750 nm. Then the obtained values were used for the retrieval of water constituents basing on the radiation data for lower wavelengths. The last step was to use the whole spectral region and all parameters to check the retrieved values. The first two channels of CHRIS (at about 410 and 440 nm) were not used for the inversion as direct modeling in this region of the spectra revealed the discrepancies between measurement and simulation results, the nature of which was not quite clear and could be attributed to the inadequacy of MODTRAN model of the atmosphere or to the inaccuracy of CHRIS calibration.

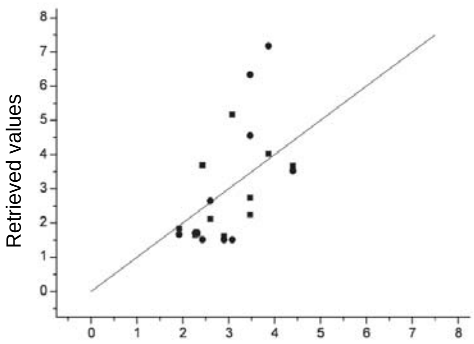

Figure 2. Comparison of measured and retrieved chlorophyll concentrations (mg/l) for different CHRIS along track scanner orientation angles: ■ – 0°, ● – 36°.

Fig. 2 demonstrates the comparison of measured and retrieved chlorophyll concentrations. As it can be expected, the scattering of points is higher for larger inclinations of view direction that is evidently connected with the increased influence of reflection by the atmosphere. The average relative error of retrieval is 33%. Although this is a high value, but if one takes into account that the error of the reference biochemical methods is only about twice lower and that it was impossible to use the remote measurements in the blue region of the spectra, which is highly important for chlorophyll determination, the result can be considered acceptable. However, it is clear that the improvement of atmospheric model is desirable.

The mean difference between measured and retrieved values of suspended matter in these experiments was 16% and that for yellow substance was 26%, both being in the margins of the error of biochemical methods, which were used for verification of retrieval results.

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