Mapping of submerged aquatic vegetation with a physically based process chain

Thomas Hege*ab, Anke Bognera, Nincole Pinnelb
abDLR Oberpfaffenhofen, Münchner Str. 20, D-82230 Weßling, Germany;
bTechnical University of Munich, Limnological Station, Hofmark 3, D-82393 Iffeldorf, Germany

ABSTRACT

Mapping the submersed vegetation is of prime importance for the ecological evaluation of an entire lake. Remote sensing techniques are efficient for such mapping tasks, if the retrieval algorithms and processing methods are robust and mostly independent from additional ground truth measurements. The Modular Inversion Program (MIP) follows this concept. It is a processing tool designed for the recovery of hydro-biological parameters from multi- and hyper-spectral remote sensing data. The architecture of the program consists of physical inversion schemes that derive bio-physical parameters from the measured radiance signal at the sensor. Program modules exist for the retrieval of aerosols, sun glitter correction, atmospheric corrections, retrieval of water constituents among others. For the purpose of mapping the bottom coverage in optically shallow waters, two modules have been added to MIP. The first module calculates the bottom reflectance using the subsurface reflectance, the depth and an approximation of the water constituent concentrations as input. The second module fractionalizes the bottom reflectance to three endmembers of specific reflectance spectra by linear unmixing. The three endmembers are specific reflectance spectra of bottom sediments, small growing macrophytes (Characeae) and tall macrophytes such as Potamogeton perfoliatus & P. pectinatus. The processing system has been tested with data collected from the multi-spectral airborne scanner Daedalus AADS1268 at Lake Constance, Germany, for multi-temporal analysis.

Keywords: Remote sensing, inland water, shallow water, macrophyte, retrieval, airborne, multispectral

1. INTRODUCTION

Areas fully mapped in high spatial resolution of submersed littoral vegetation are of prime importance for the ecological valuation of an entire lake. Maps of the submersed vegetation frequently are used for bio-indication tasks. An assessment of such information with traditional methods requires significant effort and expenses in terms of man power and time, because of extensive data collection in the field. In addition, it is often limited to low areal coverage. Particularly in case of large lakes, we are faced with such limitations. At Lake Constance a detailed mapping of submersed macrophytes has been carried out every 10 years by use of aerial photographs and ship based mapping.

For inland waters, operational remote sensing methods have only been used to limited extent to assist in human power intensive surveying and mapping campaigns in the field. One reason could be the difficulty in delivering comparable products of satisfying quality. New methods for monitoring indicative parameters promise to be more efficient, using up-to-date remote sensing technologies like modern sensors in combination with physical based processing schemes (e.g. MIP).

2. MODULAR INVERSION PROGRAM

The Modular Inversion Program (MIP) is a processing and development tool designed for the recovery of hydro-biological parameters from multi- and hyperspectral remote sensing data. The architecture of the program consists of general and transferable algorithms based on physical inversion schemes that derive bio-physical parameters from the measured radiance signal at the sensor. Inverted parameters include e.g. the variable constituents of the atmosphere, the concentration of water constituents and the reflectance characteristics of substrates in shallow waters.

Various program modules are implemented for the inversion and processing of remote sensing data. These modules are partly iteratively coupled. The internal structure of MIP is also modular, so that a separate treatment of different

*thomas.hege@dlr.de; phone (++49) 8153 282716; fax (++49) 8153 281444
functions is possible. The most important internal modules are libraries of algorithms, mathematical derivatives and optimization methods, functions for the interaction of different databases, and program-user-dialog functions.

Program modules exist for the retrieval of aerosols, sun glitter correction, atmosphere and water surface corrections, retrieval of water constituents in optically deep waters, phytoplankton primary production, water column correction and the classification of substrates such as macrophytes and bottom sediments amongst others. The program modules are operated by control files and allow the processing of image data in batch mode. Present MIP developments focus on easy generation and access to needed radiative transfer databases in order to manage hyperspectral image data from different sensors as well.

2.1 Radiative transfer database

In present applications, two radiative transfer databases are used for the aerosol retrieval: the atmospheric correction and the bidirectionality correction of the underwater light field. The databases are generated by a radiative transfer model. Radiative transfer is simulated in a coupled, plane-parallel atmosphere-ocean system, currently by use of the matrix operator method. The model calculates radiances in a vertically inhomogeneous (multilayer) atmosphere-ocean system with respect to all angle dependencies of the sun- and observer-geometry.

Both databases were calculated with optical parameters for a midlatitude summer standard atmosphere. The first database was generated for an atmosphere-ocean system with a Lambert reflector of defined reflection \( R_L \) at 1 cm depth. Therefore, for the first database the underwater radiance was assumed to be isotropic. The water surface was modelled as flat, so that no sun glitter contributed to the upwelling radiances. The free parameters of the database are three types of aerosols \( \tau_i \), \( \tau_s \), \( \tau_d \) (continental, maritime, urban), each with 4 optical depths between 0.01 and 0.5 (at 550 nm), 7 reflection values for \( R_L \) (\( \lambda \)) between 0 and 0.6, 17 observer altitudes \( h \), 17 azimuth differences \( \Delta \phi \) between sun and observer, 8 sun zenith \( \theta_{sun} \) and 8 observer zenith angles \( \theta \). For applications presented here, the database currently contains 21 wavelength-bands \( \lambda \) in order to simulate the spectral bands 1-6 and 9 of the airborne DAEDALUS-Scanner (6 channels in the visible, 1 at 1600 nm). \( L \) values were calculated as a function of \( \lambda, h, \tau, \Delta \phi, \theta \) and \( R_L \) values. Intermediate values, as needed in the inversion scheme, are calculated by a multidimensional spline.

The second database is needed to correct reflectance values \( R_L \) due to the bidirectionality of the underwater light field to \( R = E_{up}/E_{down} \) as function of \( \lambda, h, \Delta \phi, \theta, \theta_{sun} \) and the water constituents. Values of \( Q = E_{up}/\|E_{down} \| \) were calculated with a standard atmosphere as described above, but with a fixed medium aerosol concentration and an expanded water body.

The inversion scheme consists of several separate program modules as shown in figure 1 and 2. The first stages comprise atmospheric and surface corrections, giving the underwater irradiance reflectance \( R \). The two databases are required, firstly relating pairs of measured radiance values \( L \) to underwater radiance reflectance values \( R_L \), and secondly for providing the angularly-dependent Q-factor to convert radiance reflectance into irradiance reflectance \( R \).

<table>
<thead>
<tr>
<th>symbol</th>
<th>meaning</th>
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<tbody>
<tr>
<td>( \lambda )</td>
<td>wavelength</td>
</tr>
<tr>
<td>( h )</td>
<td>sensor altitude</td>
</tr>
<tr>
<td>( \theta )</td>
<td>observer zenith angle</td>
</tr>
<tr>
<td>( \theta_{sun} )</td>
<td>sun zenith angle</td>
</tr>
<tr>
<td>( \Delta \phi )</td>
<td>azimuth diff. obs.-sun</td>
</tr>
<tr>
<td>( a )</td>
<td>absorption coefficient</td>
</tr>
<tr>
<td>( b, b_h )</td>
<td>scattering-, backscatter-</td>
</tr>
<tr>
<td>( k )</td>
<td>&amp; extinction coefficient</td>
</tr>
<tr>
<td>( a_s, b_s, b_h )</td>
<td>specific coefficients</td>
</tr>
<tr>
<td>( z )</td>
<td>water depth</td>
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<table>
<thead>
<tr>
<th>symbol</th>
<th>meaning</th>
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<tbody>
<tr>
<td>( E_{down} )</td>
<td>irradiance (downwelling)</td>
</tr>
<tr>
<td>( L_{up} )</td>
<td>radiance (upwelling)</td>
</tr>
<tr>
<td>( A )</td>
<td>bottom albedo</td>
</tr>
<tr>
<td>( R )</td>
<td>subsurf. diff. reflectance ( R = E_{up}/E_{down} )</td>
</tr>
<tr>
<td>( R_{\infty} )</td>
<td>deepwater subsurf. diff. reflectance</td>
</tr>
<tr>
<td>( Q )</td>
<td>subsurf. rad. bidirectionality ( Q = E_{up}/L_{up} )</td>
</tr>
<tr>
<td>( P )</td>
<td>phytoplankton pigments</td>
</tr>
<tr>
<td>( SM )</td>
<td>suspended matter</td>
</tr>
<tr>
<td>( Y )</td>
<td>yellow substance</td>
</tr>
<tr>
<td>( DN )</td>
<td>digital number/grayvalue</td>
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Table 1: Symbols and acronyms
2.2 Retrieval modules

Radiometrically calibrated remote sensing data are inputted into MIP. After extraction of track specific look-up tables from both databases, the retrieval and correction modules can be applied (see Fig. 1 and 2).

2.2.1 Aerosol retrieval:

The atmospheric parameter retrieval module calculates the aerosol optical depths $\tau_1$, $\tau_2$, $\tau_3$ of three different aerosol types simultaneously from bidirectional remote sensing measurements over case II waters $^3$. The algorithm optimises the aerosol optical depth concentrations by equalizing the underwater reflectance values that are estimated from an input set of bidirectional radiance measurements. Therefore, the set of bidirectional radiance values must be taken over the same ground element or – in the case of the DAEDALUS scanner – from a +/-43° field of view over a homogeneous deep water body. For applications shown below, homogeneous areas in the Pelagial zone of upper Lake Constance mapped by DAEDALUS were used for the aerosol estimation. This set of aerosol optical depths was used for the atmospheric correction of all flight strips of the survey. The time difference of litoral flight strips to the one used for aerosol retrieval is up to 2 hours, the distance up to 10 km.
2.2.2 Atmospheric & surface correction:

The resulting radiances at sensor altitude \( L \) can now be converted into subsurface reflectances \( R^\prime \). Since the radiances contain no (more) sun glitter, the conversion can be performed by a multidimensional interpolation of the sampling points of the first database. A bidirectional correction for the underwater light field is applied to calculate \( R = R^\prime \frac{\pi Q(\lambda, \Delta \phi, \beta, \theta, \psi; \lambda, \theta_s, \phi_s)}{M, P, Y} \) using the second database. \( Q \)-factors are calculated for deep water but applied also for data over shallow water. By comparison with in situ measurements in different locations, systematic errors of more than 30% to the used \( Q \)-factors were observed. Apart from this, the retrieved underwater reflectance just below the water surface shows good agreement with hyperspectral underwater measurements. Furthermore, the calculated underwater reflectance of three overflights in 2000, 2001, and 2002 match each other well (Fig. 4).

2.2.3 Retrieval of water constituents:

Using the underwater reflectance \( R^\prime \), it is now possible to obtain the concentrations of water constituents in deep water areas. This is achieved by an iterative fitting algorithm to adjust modelled and measured underwater reflectances. Modelling of \( R \) utilises the relation \( R_\infty = f b_0/(a+b_0) \) from Gordon. The specific optical absorption and scattering coefficients of the water constituents for Lake Constance are used. In case no in situ measurements are available, the calculated water constituents from the deep water zone near the shore line are used as input for the water body correction in the littoral zone.

2.2.4 Water body correction:

This module corrects the influence of the water body on the irradiance reflectance by use of the optical depth for each pixel. The bottom albedo \( A \) is calculated as function of the subsurface reflectance \( R^\prime \), the water depth \( z \) and the concentrations of water constituents. Concentrations of water constituents were kept constant over each flight track. By use of the inherent optical properties of the water constituents, the (theoretical) underwater reflectance for deep water \( R_{\infty} \) and the diffuse vertical attenuation coefficient \( k \) are calculated. The water depth \( z \) is extracted from a digital bathymetry map for each pixel along with actual water level information. Bottom albedo spectra \( A \) are calculated according to Maritorena et al. with enhancements by Albert: \( A = (R - R_\infty) \exp(2kz) + R_\infty \) (formula simplified). For tall macrophytes, this correction results in unrealistic reflectance spectra, because the effective water depth in reality is not equal to the depth extracted from the digital bathymetry map (see Fig. 5). Nevertheless, these spectra were used without further correction for the spectral unmixing of the bottom albedo. This results partially in classification errors at depths greater than 3m, as will be seen later.
Figure 4: Subsurface irradiance reflectance over tall macrophyte P. *Perfoliatus* at 0.1m depth after atmospheric- and surface correction in MIP. Multitemporal comparison of data from three overflights in 2000, 2001 and 2002. The continuous line shows the ground truth measurement of the irradiance reflectance, calculated from the hyperspectral radiometer RAMSES (TRIOS).

Figure 5: Irradiance reflectance of different bottom types, calculated from DAEDALUS-scanner using the water body correction module. The retrieved values are used as specific bottom spectra by the spectral unmixing module. Arrows denote the impact of the water body correction for the tall macrophytes, where the actual effective water depth to the upper edge of vegetation (0.1m) is not equal to the bottom depth stored in the elevation map (2.5m). This causes an unrealistic reflectance spectrum for the tall macrophytes.
In the case of Lower Lake Constance, relatively low concentrations of water constituents of were found in July 2000, 2001, 2002. Such concentrations are typical for summer season in this isolated lake section: suspended matter SM varied between 0.8 and 2 mg/l, Chlorophyll P between 2 and 5 µg/l. Gelbstoff absorption a$_s$(410) is about 0.32 l/m at 410nm. Inside of this range, errors introduced by incorrect water constituent concentrations are less dominant than differences between the digital bathymetry map and the actual depth. The agreement between bottom reflectances retrieved from DAEDALUS and those measured by underwater hyperspectral radiometer RAMSES is not yet perfect. Partly negative bottom reflectance values of up to 2% were retrieved by MIP for channel 2-5. These were corrected by introducing a constant offset over the whole scene.

2.2.5 Spectral unmixing of bottom albedo:

This module is used for the classification of albedo spectra of the lake bottom (output from the module described below) in shallow water areas. It fractionalizes the bottom albedo into three endmembers, each with distinct bottom coverage, by linear unmixing. For this purpose, specific reflectance spectra of the three endmembers are used. The specific spectra (Fig. 5) are extracted from test areas with known purity of bottom cover for uncovered sediment, tall macrophytes (here *P. perfoliatus*), and for small growing macrophytes (here: *Characeae*). The unmixing is performed by downhill simplex minimisation with regularization for unphysical coverage values.

3. APPLICATION

The processing system has been tested with data collected from the multi-spectral airborne scanner Daedalus AADS1268 (11 channels, 5 VIS channels at 435, 485, 560, 615, 660nm, FOV +/- 43°) at Lake Constance, Germany. The Daedalus data were gathered between 2000 and 2002 and processed at the DLR, Oberpfaffenhofen. Preprocessing (calibration, masking, georeferencing) was performed using the image analysis software XDIBIAS developed at DLR. Channels 1-6 were used for processing in MIP, but only channels 2-5 were ultimately utilized in the spectral unmixing module for the retrieval of the bottom coverage. Channels 1 and 6 are often too unstable for automatized image processing.

A classification of macrophytes in shallow waters near Island Reichenau (Lake Constance) can be seen in figure 6. Daedalus imagery collected in 2000, 2001 and 2002 has been uniformly processed for multi-temporal analysis with MIP. The result contains classes of small growing macrophytes (*Characeae*) in green, tall macrophytes (here: mainly *Potamogeton perfoliatus & pectinatus*) in red and bottom sediments in blue (see color triangle). Mixed picture elements contain more than a single class, e.g. *Characeae* and bottom sediment. The sum of the bottom coverage in each pixel is always 100 %. Because of the different growth height, the two macrophyte groups *Characeae* and *Potamogeton* could be separated very well within the spectral limitations of the Daedalus sensor. Small spatial changes in submerged vegetation coverage between 2001 and 2002 can be recognised, but the essential features remain stable and comparable. Thus the applicability of the processing scheme on different images and dates is shown. The bottom coverage could be mapped down to a depth of 4.5 m, the maximum depth to which plausible reflectance spectra have been derived after water depth correction. For some areas covered by tall macrophytes (Potamogeton P.) and of a depth between 3 and 4.5 m, the algorithm delivers non-defined values (grey image pixels in Fig. 6). This is due to the error introduced by the wrong water column correction for tall macrophytes (see 2.2.4). Regardless, a comparison of three different overflights in 2000, 2001 and 2002 shows that the specific reflectance spectra of the three bottom types largely remain constant. This is a good indicator for the transferability of the procedure. Extensive ground truth measurements are analyzed currently for validation purposes. A further discrimination of macrophyte species is desirable and might be possible using hyper-spectral data. Algorithms using the information of hyper-spectral sensors by physical inversion are currently under development.

4. OUTLOOK

Results of an automated general approach for the retrieval of the distribution of submerged vegetation in littoral zones have been presented. They show promising potential for further research in the field of airborne and satellite remote sensing over shallow water targets. This approach forms the basis for future developments in precise automated methods. Consequently, remote sensing could become an economical monitoring technology for inland waters, with respect to managing nature restoration, rehabilitation and conservation. By use of physical based algorithms, a general transferability to data from different water types and seasons is possible. However, further research needs to be done to stabilize and improve the retrieval procedures (e.g. to develop accurate algorithms for species recognition in shallow
waters or to derive growth height of aquatic plants from remote sensing data as an indicator for biomass). Transferability of this method still has to be tested on different lakes.

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