CONSTITUTION OF AN AUTOMIZED PROCESSING CHAIN TO ANALYSE A MERIS TIME SERIES OF SWISS LAKES

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ABSTRACT:

The physically based Modular Inversion & Processing System (MIP) is used in an automized processing chain for inland water constituent retrieval from MERIS level 1B data. Preprocessing routines are used to automatically convert the ESA generic data products into MIP input data format. Water/land masking, atmospheric correction and water constituent retrieval are accomplished by simple batch executables from MIP. The accuracy of the constituent retrieval mainly depends on the spectral fit between the image input data and the radiative transfer model results extracted from a database. Therefore, thresholds and initial values for model fitting have to account for all occurring lake specific temporal variations and need careful adjustment.

1. INTRODUCTION

Monitoring of water quality in lakes is required as an integral part of water resource management, in order to guarantee the sustainable use of water and to track the effects of anthropogenic influences. Simultaneously, adequate monitoring is required to report the effects achieved by management programs.

For most of the large glacial and fluviglacial lakes in the Swiss midland and south of the Alps, in situ water quality monitoring was established in the 1950s or 1960s. The data gathered since then reveals a period of over-fertilisation, with pronounced lake specific phosphorus concentration maxima between 1970 and 1985, followed by an ongoing decrease (Liechti, 1994). These monitoring programs are directed by cantonal, interregional and international authorities, and carried out by either the authorities themselves or respective research institutes.

Within ESA’s APEX airborne imaging spectrometer experiment project (Nieke et al., 2005), it is planned to monitor the water quality of lakes and coastal areas using high spectral and spatial resolution data. First flights of APEX are planned 2008. An APEX level 2/3 processor chain is currently implemented and a limnology and coastal processor is under development (Schläpfer, 2007). In order to test the approach and algorithms, MERIS and other sensor data is applied to provide a sound validation tool for future semi-automatical data retrieval and processing.

The MERIS instrument onboard ENVISAT offers increased potential to support established monitoring programs by means of remote sensing. MERIS level 2 water constituent products were found not to be accurate for inland waters (Gege and Plattner, 2004). However, remarkably improved results were achieved by customizing retrieval algorithms to lake specific properties (Giardino and Gomarasca, 2006). Moreover, methods were found that allow the integration of MERIS derived concentrations with in situ measurements (Miksa et al., 2006; Heege, 2000), using the Modular Inversion & Processing System (MIP) (Heege and Fischer, 2004).

In this work, a processing chain to automatically derive water constituents from MERIS level 1B data for Swiss lakes is built around MIP. MIP is well automatable as it performs image based aerosol retrieval and atmospheric correction in advance of the water constituent retrieval. Still, the large number of input variables for atmospheric correction and constituent retrieval require accurate adjustment in terms of the high regional and temporal variability of inland water.

2. DATA

2.1 Satellite imagery

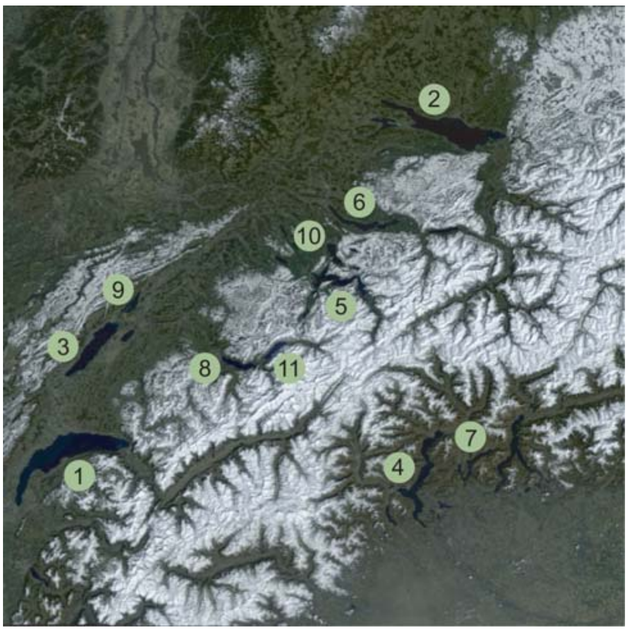

Figure 1. RGB composite of MERIS channels 8/6/3 (681/620/490 nm), acquired 29 March 04. Lake numbers refer to Table 1.

57 MERIS datasets covering the years 2003 to 2006 in approximately fortnightly temporal resolution are analysed. The data was delivered as level 1B full resolution quarter scenes ("imagettes"), measuring 1153 square pixels at a nominal ground resolution of 260x290 m. The ground area represented by each imagette has almost the size of Switzerland, covering all lakes that are large enough for analysis (Fig. 1).

The data are geolocated but not geometrically corrected. It comes as at-sensor radiances, without atmospheric correction applied, but a large set of metadata is provided within the files delivered in the proprietary PDS format (ESA, 2006). For further processing, the PDS files were converted to HDF, making use of the batch executable "pds2hdf" contained in ESA's free EnviView application (Brooker et al., 2002).

2.2 Water quality reference data

In situ data from governmental water quality monitoring programs is used to compare the results from MIP processing where they coincide with ENVISAT overflights. Furthermore, knowledge of the methods currently used in water quality monitoring and the physical connectivity of measurements taken by either method is crucial in order to integrate results from satellite remote sensing in common ongoing monitoring programs.

The monitoring programs for the 11 largest Swiss lakes are administrated by 9 different cantonal departments or regional authorities (Tab. 1). Continuous chlorophyll-a (chl-a) and biomass measurements are collected in 10 of these lakes by 8 different departments and research institutes (see Acknowledgements). The methods used for chl-a determination are based on 20 m composite samples (Utermöhl, 1958), on sample profiles (DEV, 1986) or on fluorescence probe profile measuring (Turner Designs, 2004).

	Lake Name	Area (km^2)	Freq. (d)	Chl-a method	Depth (m)
1	Geneva	580	14	Probe profile	0-10
2	Constance	536	14	Probe profile	0-10
3	Neuchâtel	215	30	Composite sample	20
4	Maggiore	210	14	Composite sample	20
5	Lucerne	114	30	(Chemistry only)	-
6	Zurich	88	30	Probe profile	0-10
7	Lugano	49	14	Sample profile	0-10
8	Thun	48	30	Composite sample	20
9	Biel	40	30	Composite sample	15
10	Zug	38	30	Probe profile	0-10
11	Brienz	30	30	Composite sample	20

Table 1. Water monitoring data routinely collected in the 11 largest Swiss lakes (Fig. 1).

Empirical methods to correlate 20 m chl-a depth composite sample results to remote sensing data exist (Heege, 2000) and in an analysis of MERIS data of Lake Constance, they were found to be quite accurate (Miksa et al., 2006). But varying depth distribution of chl-a concentrations is thereby not considered and may cause large deviations. The remotely sensed chl-a values can only be considered accurate, if the maximum concentration is located near the surface. In the probe profile data for chl-a in Lake Geneva in 2003 for example, 5 out of the total 18 profiles show significantly higher values in positions below 2 m than above.

Fluorescence probe profile data resolves depth in intervals of 0.5 to 1 m, but the brightness of the underwater light field in the top layer leads to inaccurate results just below the surface. For Lake Constance for example, values from surface to 2 m depth are extrapolated from deeper layers. This implies the assumption of small chl-a concentration variation with depth, similar to composite sample data. Additionaly, the results from an instrument intercomparison campaign showed that the chl-a concentratioin results from 8 different fluorescence sondes diverge by more than 20% in average (GBL, 2006). Thus, the question how in situ data from both methods are best compared to chl-a values retrieved from MERIS data has to be addressed in future work.

3. METHODS

3.1 Image preprocessing

After conversion of the MERRIS datasets to HDF format, specific IDL routines are used to extract single image clippings for each lake (Fig. 2). The output is saved in MIP-readable BIL-files and respective input file structures for MIP retrieval modules (Fig. 3, *Image Preprocessing*).

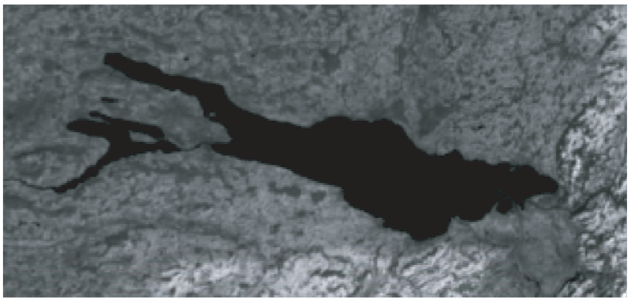

Figure 2. Mission input data: Lake Constance clipping from MERIS scene 29.3.04, depicted as channel 14 (885 nm) greyscale.

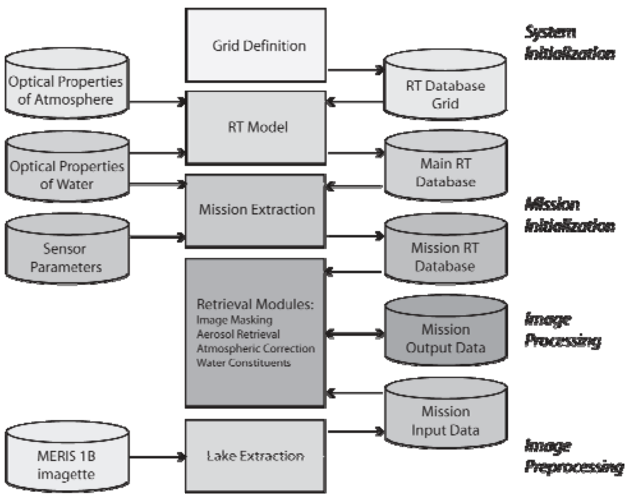

Figure 3. Flow chart of input imagery preprocessing (lower workflow) and MIP processing (upper workflow).

Darker shading indicates direction of work (modified from Miksa et al., 2006).

The clipping areas are set according to the longitude and latitude grid values contained in the image metadata. The grid point positioning values in MERIS metadata were found to deviate in an order of tenths of degrees from map values. Thus, reliable extraction of single lakes is possible for large, detached lakes such as Lake Geneva and Constance. Smaller, adjacent lakes could be extracted as clusters where they are found to be qualitatively similar. In cases where they have to be separated (i.e. Lake Thun and Lake Brienz), the shorelines contained in the metadata must be used with simple geometric positioning routines. Such routines identify a lake's relative position within the grid, making use of its size and the shape of surrounding shoreline patterns in its neighbourhood. Other parameters taken from metadata for further use in MIP processing are time and date of acquisition and observation angles. The elevation metadata differs by hundreds of meters for some lakes, obviously due to coarse resolution (i.e. in mountain valleys). A constant value for each lake is used instead. The metadata of the original images contain two different sets of calibration gain factors, which do not occur periodically but are indicated in the file names. The files labelled "PNIPA" and "PNUPA" contain calibration gain factors somewhat higher than those in files labelled "PNEPA". The application to the respective scenes was implemented in the preprocessing routines.

3.2 MIP processing

MIP uses a main radiative transfer database, built from simulation results of a coupled, plane-parallel atmosphere-water model, currently by use of the FEM-method (Kisselev and Bulgarelli, 2004). The main database contains optical properties for atmosphere, water surface and constituents, that allow optimization of fit between modelled and measured spectra in a later step. In order to process input data from different lakes, the database had to be supplemented with atmospheric optical properties accounting for different elevation levels (Fig. 3, *System Initialization*). For MIP batch processing, specific mission radiative transfer databases are extracted for each lake clipping, accounting for its specific flight geometry (Fig. 3, *Mission Initialization*). EOMAP provided batch executable modules from MIP, which perform simple (meaning non-iterative) unsupervised land/water masking, atmospheric correction and chl-a, yellow substance (y) and suspended matter (sm) retrieval. We optimise a single set of input variables for each lake. This set is supposed to be as representative as possible for the total 57 acquisition dates. The optimisation of input variables was started with Lake Constance, where most previous knowledge exists.

For land/water masking, estimates of aerosol type (continental, maritime, rural), aerosol optical thickness (AOT, at 550 nm) and water constituents are used. Thresholds for land/water discrimination are derived from simulated, Q-factor corrected underwater reflectances in channels close to 730 and 800nm and applied to the image croppings. The output files contain unchanged at-sensor radiances above water surfaces and zero values above land surfaces (Fig. 4) (Heege, 2000).

Channels 13 (865 nm) or 14 were found to be most suitable for atmospheric correction. The masked radiances (Fig. 4) serve as input files, and the same aerosol type estimate as for land/water masking is used. Again, underwater reflectance in the selected channel is calculated and Q-factor corrected, using estimated initial values of water constituent concentrations. The concentration of the estimated aerosol type is then retrieved for each pixel, connecting the calculated underwater reflectance to the measured at-sensor radiance in the respective channel. The output is written in Q-corrected subsurface reflectance. The channel used for aerosol retrieval results in constant, low values. Channels at shorter wavelengths however can now be used for water constituent retrieval. (Fig. 5).

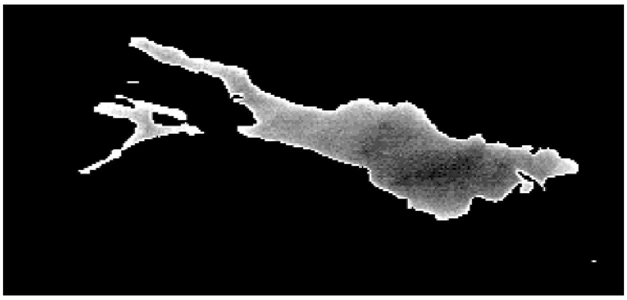

Figure 4. Scene from Figure 2 after land/water masking, depicted as channel 14 contrast enhanced greyscale. Brightness indicates atmospheric influence.

Figure 5. Scene from Figure 2 after atmospheric correction, depicted as channel 4 (510 nm) contrast enhanced greyscale. Brightness indicates high subsurface reflectance.

The subsurface reflectances in channel 1-9 (412-735 nm) are finally used for the retrieval of the water constituents chl-a, y and sm. Therefore, initial values and maximum, minimum and tolerance thresholds for each parameter are estimated. Weighting factors can be set for each channel in use. By means of a Simplex algorithm, the simulated subsurface reflectance for varying constituent concentrations is then fitted with the subsurface reflectance from atmospherically corrected image pixels (Heege, 2000).

4. DISCUSSION

The land/water masking functionality of MIP is much more sensitive to aerosol concentration estimates than to aerosol type. When continental AOT is changed from 0.05 to 0.1, the number of pixels masked as water for Lake Constance drops by more than 5% in 15 of the 57 clippings. However, most land/water masks change only marginally. When changing aerosol type from continental to maritime , the number of pixels masked as water increases on two dates (25.5.04 and 28.7.05) by more than 5%. In order to keep as many pixels as possible for subsequent processing steps, higher aerosol concentrations were not examined in detail and maritime aerosol type was preferred.

The effect of sun glitter was neglected in the beginning, but it was soon found to be a major source of errors. It will have to be taken into account for improvement of the processing chain. Images acquired at large eastward observation zenith angles, high illumination zenith angles and high wind speed above water surface are often contaminated by specular surface reflectance. This leads to increased at-sensor radiances and therefore to erroneous processing results, affecting for example almost a third of the data for Lake Constance. The sun glitter contamination can not be corrected, thus it leads to a reduction of the temporal resolution of satellite based observation.

In first tests on Lake Constance, the processing chain worked smoothly, but most of the processing outputs for the 57 MERIS datasets did not resist closer examination. In about a third of the cases, resulting chl-a concentrations are clearly out of the expected range from 0.5-15 µg/l. In most other cases, a comparison between modelled and measured spectra suggests that further optimisation of the input values used in the processing chain would lead to a significant increase in accuracy. To support such input estimates, extensive reference data is available for Lake Constance (Heege, 2000; Gege, 1994). However, the assumptions considered appropriate in precedent research on Lake Constance have changed over time. If this is due to an actual change in water constituent mixture, this rises the question, if and to what extent occasional updates of input variables through reference measurements are required in order to ensure persistent data quality from remote sensing methods in the future.

The automatic extraction of chl-a concentrations from single image pixels corresponding to certain in situ sampling sites on the lake was found complicated due to the error of the positioning information in the MERIS metadata. An attempt to approximate the sampling location from its position relative to the southern, northern and eastern shore of the lake failed, because in many datasets, not the entire lake is visible. A test for the fraction of the lake represented in the clipping was implemented. More sophisticated positioning and possibly interpolation procedures have to be introduced to avoid further decrease of temporal resolution due to fractional cloud coverage and scenes only partly affected by sunglitter.

The influence of adjacency effects causes an increase in accuracy with increasing distance from the shorelines. This is visible in AOT calculations from the atmospheric correction module. It was also found in previous work, that satellite measurements matched best with reference data from the sampling site Fischbach-Uttwil in the lake's center, compared to sites closer to the shore like in the Bay of Bregenz or Lake Überlingen (Miksa et al., 2006). Therefore, correction of adjacency effects has to be taken into account, not only to improve the accordance with water quality monitoring measurements, but also to enable the derivation of accurate results in cases where not the entire lake can be analysed, as described above.

5. OUTLOOK

Currently, the scenes where the water constituent retrieval for Lake Constance failed are evaluated individually. In most cases, changing the initial values of system variables will lead to sound results. Proper analysis of the values found in this way should then allow a synthesis towards an automatable set of input values, that accounts for the temporal variation. This procedure will be repeated for the other lakes presented in this work, in order to find out how atmosphere and water constituents vary in time and space, and how such effects can best be accounted for. Only if these problems are approached, remote sensing can reliably contribute to inland water quality monitoring programs.

The 57 datasets were chosen in order to achieve measurement intervals of about two weeks. More datasets with little cloud coverage are available, but were not taken into account because the temporal coverage seemed satisfactory. Regarding the reduction in temporal resolution caused by sun glitter, it remains to be seen if additional MERIS data could sufficiently compensate for data gaps, or if the integration of other sensors such as MODIS would be necessary to achieve a fortnightly coverage, which seems desirable according to current in situ monitoring.

Apart from the simple retrieval presented here, MIP also offers a module for processing iteratively. In this coupled mode, the results of precedent module iterations are used as initial values in subsequent calculations. This might possibly reduce some of the errors introduced by variable estimations, but it also leads to additional complexity and increased processing time. Therefore, its implementation might be an option at a later date, but is not decided yet.

To facilitate the integration of results from remotely sensed data into current in situ monitoring, further work on the comparability to in situ data is necessary. It has to be examined, if data measured by submerged fluorescence probes correlates with satellite image derived measurements in a similar way like 20 m composite samples do. As the remote sensing signal originates from the top layer, where fluorescence probe data is known to be erroneous, there might even be potential for a reasonable combination of both methods by establishing a transfer function. In any case, combined in situ and satellite data acquisition would be necessary to address this issue.

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