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TOWARDS THE SIMULATION AND INVERSION OF
USER-DEFINED INLAND WATER IMAGING SPECTROMETER DATA

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ABSTRACT

An at-sensor radiance simulation environment based on Hydrolight and MODTRAN-5 was set up for the evaluation of arbitrary combinations of sensors, methods and targets for the investigation of inland water quality. Each L_s simulation requires three MODTRAN-5 runs, whereas two runs are needed for the calculation of the specular reflectance. Simulation results can be used in the preparation of specific algorithms for future sensors, e.g. the Airborne Prism Experiment (APEX), as well as for vicarious calibration, to estimate the noise sensitivity of a specific algorithm or in general project planning.

1. INTRODUCTION

Remote sensing of inland water constituents in optically deep water is done with a wide range of targets, methods and sensors. A simulation environment based on Hydrolight [14] and MODTRAN-5 [1] was set up for the evaluation of arbitrary combinations within these three dimensions.

Common targets in limnic remote sensing cover a wide range of eutrophic or turbid waters such as those in the Netherlands [3] [6], Germany and Poland [13] [18], to clear, oligotrophic waters in the perialpine area [4] [5] [8] [15] [16] or highly absorbing, CDOM-rich waters in Scandinavia [10] [11]. This leads to the emergence of fundamentally different optical conditions for potential applications, including spectral features like the secondary absorption maxima of CHL a and b between 600 and 700 nm in eutrophic water or variations of NIR backscattering in turbid water that affect the prospects of a black target or constant backscattering based atmospheric correction. Further target-specific application constraints include the shape and size of a water body and the topography of its neighborhood, which affect the choice of sensors and the relevance of adjacency effects as observed in the case of Lake Maggiore for example [7] [16].

Suitable methods for water constituent concentration retrieval must be chosen according to such specific optical conditions of the studied water body. Such methods calculate single water properties such as CHL [6] [11] [13] [18], TSM [3] or Secchi depth [11] [18], whereas more complex approaches will retrieve the full set of optically active substances. Furthermore, the use of algorithms may be restricted to certain sensors, such as the neural networks trained for MERIS [17], the secondary CHL absorption band ratios for narrow band instruments [6] or the wide-spread (semi-) empirical approaches [11] [13] [18]. The other large group of analytical inversion algorithms may be applied to arbitrary sensors, but their performance strongly depends on certain instrument properties, such as well-calibrated bands in the blue wavelength for the separation of CHL and CDOM [5] [15].

The choice of sensors includes the terrestrial mapping satellite sensors Landsat-TM5 and SPOT-HRV [3], medium resolution, narrow band satellites such as MERIS [6] [11] [15] [16], MODIS or SeaWiFS, experimental spaceborne satellite sensor such as Hyperion [5] or CHRIS/Proba [13] and several airborne instruments, e.g. AISA [10] [11], Daedalus [8], Hymap [18] or ROSIS [4]. It depends on the requirements of radiometric, spatial, spectral and temporal resolution. The significance of spatial and temporal resolution is relatively obvious, while the consequence of an instrument's radiometric and spectral resolution is often only approximately known in advance. General estimates of this propagation of sensor properties to water constituent products are complicated by variable acquisition conditions, algorithm-specific accuracy properties or the limited quantification of sensor noise.

In order to account for these manifold options in the conception of water constituent retrieval projects, the Hydrolight/MODTRAN-5 simulation environment is built in a way that SIOPs, sensor-specific band widths and positions as well as different types and magnitudes of sensor noise can be defined among other parameters. The primary purpose of this work is the evaluation of the potential of the upcoming APEX imaging spectrometer [9] for water constituent applications, but it can at the same time support decision-makers in the choice of suitable existing or future (e.g. Sentinel's

Ocean and Land Cover Imager OLCI or ENMAP) earth observation sensors for specific projects.

2. METHODOLOGY

The remote sensing reflectance R_{rs} is simulated by means of the Hydrolight radiative transfer model. This numerical model calculates radiance distributions and related quantities like irradiance and reflectance for specified water, illumination and viewing conditions [14]. Several thousand simulation runs were carried out for SIOPs measured in Lake Constance (Austria/Germany/Switzerland) and the Scheldt River near Antwerp (Belgium) in June 2009 [11]. The targets were chosen as examples of typically low reflectivity and CHL-driven constituent concentrations on one hand and generally high reflectivity and TSM-driven reflectance variations on the other hand. The spectral range of both SIOP measurements and accordingly the simulated R_{rs} is 350-950 nm, $R_{rs}=0$ was assumed for larger wavelengths.

The specular reflectance R_{spec} is accounted for with a sequence described by [2], where R_{spec} is calculated from the reflectivity of a water surface at defined illumination/observation geometry and illumination conditions (Eq. 1), and can be derived by two MODTRAN runs.

$$R_{spec} = \pi \cdot r(\theta_v) \cdot \frac{L_{ad}(\theta_v, \varphi_v)}{E_{ad}} \qquad (1)$$

Where θ_v is the refracted observation zenith angle below the surface according to Snell's Law, and φ_v are the viewing zenith and azimuth angles, respectively, L_{ad} is the downwelling radiance from the sky segment directly seen in the specular reflectance (i.e. from θ_v and 180°-φ_v), E_{ad} is the downwelling irradiance, both just above the water surface. The surface reflectivity $r(\theta_v)$ is given by the Fresnel reflection function (Eq. 2).

$$r(\theta_v) = \frac{1}{2} \left\{ \left[\frac{\sin(\theta_v - \theta_w)}{\sin(\theta_v + \theta_w)} \right]^2 + \left[\frac{\tan(\theta_v - \theta_w)}{\tan(\theta_v + \theta_w)} \right]^2 \right\} \qquad (2)$$

Where θ_w is the perpendicular incidence occurs, $r(\theta_v)$ is calculated with the refraction index n_w instead (Eq. 3).

$$r(0) = \left(\frac{n_w - 1}{n_w + 1} \right)^2 \qquad (3)$$

L_{ad} is calculated by the first MODTRAN run. The downwelling irradiance above the water surface E_{ad} is calculated by means of a surface reflectance assumption R' (Eq. 4) and the second MODTRAN run for the upwelling radiance above the surface, L_{au}.

$$E_{ad} = \frac{\pi \cdot L_{au}(R')}{R'} \qquad (4)$$

The influence of a spectrally constant R' as found negligible by [2] was investigated by running two MODTRAN simulations for the downwelling flux above two surfaces of R'=0 and 0.05. The ratio of the two fluxes shows that maximum deviations occur towards short wavelengths and may lead to an underestimation of E_{ad} at wavelengths where $R_{app}>R'$, and vice versa. The difference in E_{ad} is lower than 1.5% although ΔR' is twice as high as to be expected for the Scheldt, and five times for Lake Constance. Since this error in E_{ad} affects only the specular part of the apparent reflectance, the effect should indeed be negligible.

The third MODTRAN run for L_s is carried out for the R_{app} calculated as the sum of the Hydrolight R_w and the R_{spec} from the two previous MODTRAN runs (Eq. 5).

$$R_{app} = R_{rs} + R_{spec} \qquad (5)$$

In this step, the internal convolution function of MODTRAN is used to define arbitrary instrument band models based on their response functions. The APEX sensor response was applied for preliminary tests, as it covers the full spectral range between 380-2500 nm. Furthermore, another module enables the application of noise by means of arbitrary multiples of a band-wise specified level, which will then be appended to the MODTRAN simulated L_s as additive, subtractive or random noise.

3. PRELIMINARY RESULTS

Example R_{rs} simulation results for the SIOPs and concentrations (Table 1) measured in the Scheldt and Lake Constance are given in Figure 1.
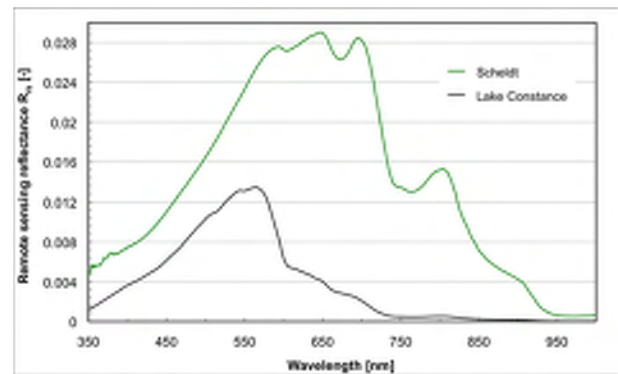

Figure 1: R_{rs} simulations for concentrations and SIOPs measured in the Scheldt and Lake Constance.

Table 1: List of the concentrations used in the simulation of the R_rs in Figure 1.

	$CHL[mg/m^3]$	$TSM[g/m^3]$	$CDOM[m^{-1}]$
Scheldt	16.60	77.70	0.33
Lake Constance	1.33	0.44	2.03

The different concentration ranges and SIOPs result in two challenging test datasets, which bear the same modeling constraints, but consist of independent optical features and require specific parameterizations of inversion algorithms. A comparison of the Lake Constance Hydrolight simulation with ASD and RAMSES R_{rs} measurements is given in Figure 2. The agreement is relatively good regarding the general magnitude of the spectrum, considering that the in situ R_{rs} and Hydrolight input parameters were measured in a reference site that was at a few hundred meters from the intercomparison measurements. It seems that the ASD measurements are relatively unreliable between 350-450 nm. Considerable variations also occur in the critical 600-700 nm wavelength range. Normalization with e.g. the reflectance at 550 nm would remove most of these variations among the ASD and RAMSES measurements. The Hydrolight simulated R_{rs} at last is lowest in the blue and highest in the red. This could be due to a decrease in the $a_{CDOM}:a_{CHL}$ ratio between the reference and intercomparison site, but must in any event be reconsidered in the future.
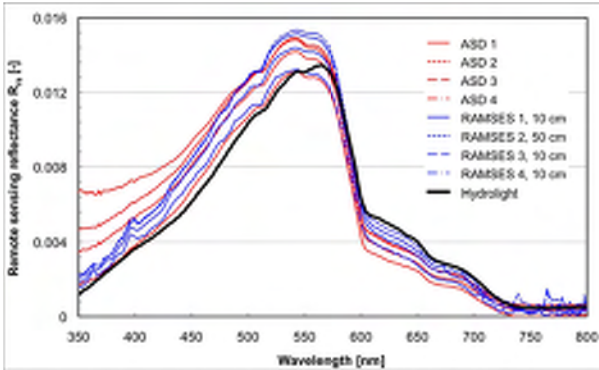

Figure 2: Comparison of VITO's ASD and DLR's RAMSES spectrometer, carried out on Lake Constance. Hydrolight data refers to SIOPs and concentrations of an adjacent test site.

Figure 3 depicts L_s simulation results with varying CHL, TSM, AOT and flight altitude, for the SIOPs measured in Lake Constance. Other parameters that were varied are observation and illumination angles, CDOM, aerosol type, ground altitude, ozone content and water vapor as well as several others that are less relevant and will remain constant in future sensitivity studies, where we will examine the concentration ranges that can be retrieved by means of different inversion algorithms (e.g. [8] [11]) and parameterizations.
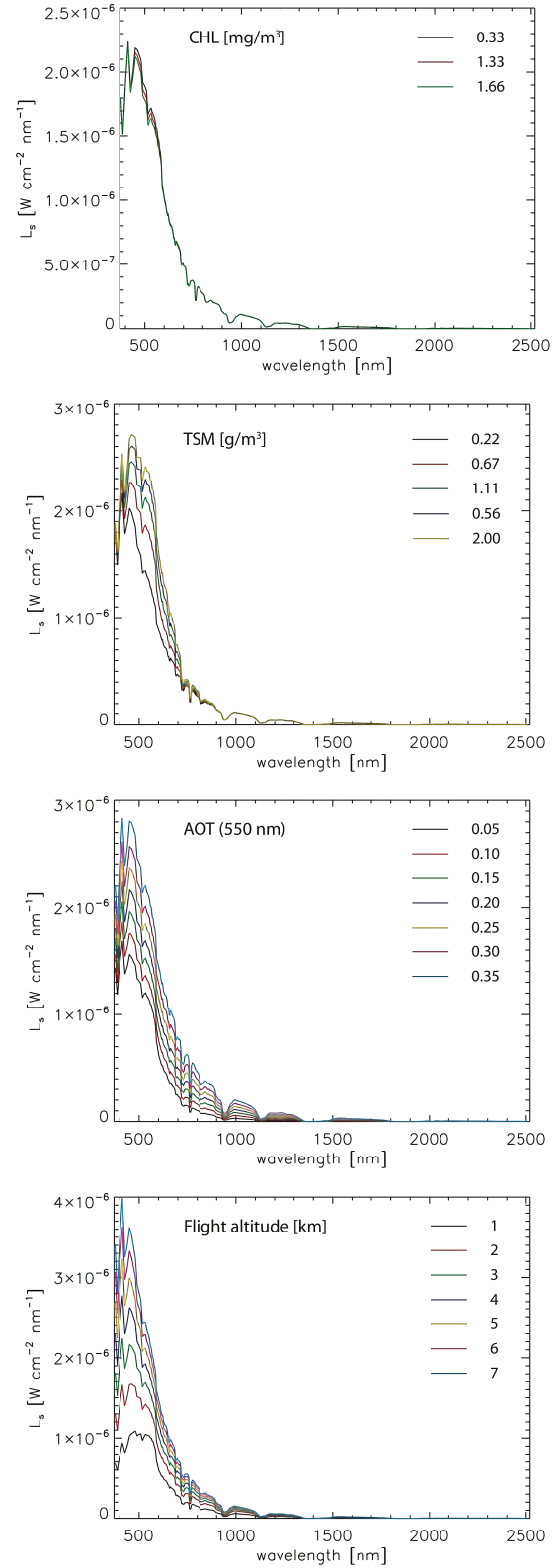

Figure 3: Parameter variations calculated with the Hydrolight/MODTRAN simulator, with L_s convolved for the APEX sensor response.

Other application possibilities lie in the comparison of different sensors, e.g. in the enhanced spectral range of OLCI compared to MERIS, or in the investigation of the water constituent retrieval accuracy at different noise levels for a specific sensor. Finally, the simulator was also used for the vicarious calibration of APEX test imagery with in situ measured reflectances of both aquatic and terrestric targets, whereas the R_{spec} calculation can be switched off in the latter case.

4. CONCLUSIONS

The Hydrolight/MODTRAN simulation environment is a solid basis for future sensitivity studies. The decrease in processing time needed by the latest MODTRAN version also allows the simulation of much larger numbers of variations, which was a critical constraint with earlier versions. Only little is known about the impact of different noise models on the performance of our inversion algorithms, a wide range of noise types and a flexible noise scaling where therefore introduced in the procedure. Altogether, it is a simple but handy tool, although it may not account for the full complexity of the optical conditions in inland water remote sensing, neglecting e.g. adjacency effects.

5. ACKNOWLEDGEMENT

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