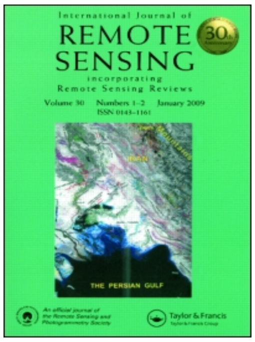

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# Ground truth data on chlorophyll-*a*, chromophoric dissolved organic matter and suspended sediment concentrations in the upper water layer as obtained by LIF lidar at high spatial resolution

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**ABSTRACT**
This article is based on field measurements on the lake Balaton (Hungary) during the three days: 10, 11, and 12 September 2008. The expedition was performed with the aim to test recently developed ultraviolet (UV) fluorescent portable lidar UFL-8 in natural lake waters and to validate it by contact conventional measurements. We had opportunity to compare our results with the Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra spectroradiometer satellite images received at the satellite monitoring station of the Eötvös Loránd University (Budapest, Hungary) to make an attempt of lidar calibration of satellite medium-resolution bands data. Water quality parameters were surveyed with the help of UFL lidar in a time interval very close to the satellite overpass. High resolution maps of the chlorophyll-*a*, chromophoric dissolved organic matter and total suspended sediments spatial distributions were obtained.

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## 1. Introduction

Use of systems based on of laser-induced fluorescence light detection and ranging (LIF lidar) for detecting bio-optical parameters, such as chlorophyll-*a* (chl-*a*) and chromophoric dissolved organic matter (CDOM) in open and coastal ocean studies have a long history (e.g. Farmer et al. 1979; Hoge and Swift 1981; Barbini et al. 1999). Investigations of different bio-optical constituents of the water column in lakes play an important role for monitoring and assessment of the changes of water quality in these waterbodies (Palmer et al. 2013, 2015). Despite the fact that there are various methods and instruments for measuring these parameters (e.g. Abramov et al. 1977; Babichenko, Dudelzak, and Poryvkina 2004; Utkin, Lavrov, and Vilar 2011), using lidar systems in limnological research has been limited, perhaps because of cumbersome lidar equipment, applicable to oceanographic vessels or aircraft rather than small boats used in lakes.

For the total suspended matter (TSM) estimation in upper layer of water, the principle of using the back-scattered laser radiation normalized to the Raman signal has long been

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known (e.g. Fang 1994). Despite this fact, in conventional practice of remote sensing it is rarely used, especially with regard to turbid lake waters (Pelevin et al. 2015). Based on the experience of more than 35 expeditions in the open sea, coastal waters, and fresh lakes, we can state the fact that the signal of back-scattered laser radiation wavelength (355 nm), normalized to Raman wavelength (404 nm), always exhibits strong linear correlation with the concentration of TSM. The mineral matter is making the main contribution to the back-scattered laser radiance due to the shape and particle size. Calibration of the method depends on the granulometric composition of total suspended sediments.

Satellite remote sensing of lakes, estuaries and coastal waters can be an important tool for ecology and conservation research, but needs to be validated against high resolution ground truth data. Lidar methods were used in various open sea regions for satellite data validation, for example, an original lidar-calibrated algorithm for CDOM in the Ross Sea for satellite imagery was developed (Fiorani et al. 2006). Various studies have been conducted on the comparison of lidar measurements and satellite data of Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS), and SeaWiFS radiometers in the open sea (Fiorani et al. 2002, 2004, 2008; Hoge et al. 2003; Ma et al. 2006; Moreno-Madrinan et al. 2010). However, typically, spatial patterns of water quality parameters in relatively small inland water-bodies are changing very fast. Sometimes an area that can be measured is limited due to the rapidly changing weather conditions, for example, wind forcing. During the end of the measurement we might have different weather than in other areas at the beginning of the measurement. This is why limnologists and also coastal zone oceanographers have to use portable and express instruments for quick measurements of ground truth data synchronous with satellite imagery. Furthermore, recent work (Palmer, Kutser, and Hunter 2015) showed that data from satellite sensors for monitoring water features in inland lakes do not have optimal spectral coverage and resolution for many applications over inland waters (e.g. phytoplankton pigment or CDOM retrieval). Thus, the capacity to monitor the water properties of freshwater lakes via small-size lidar systems can be a great help in these studies. Subsatellite applications of portable lidar systems are capable to provide information about water quality of the upper layer in high resolution and satisfactory accuracy (Palmer et al. 2013). It should be noted that the laser ray sounds the aquatic environment directly through the water surface, so in the fluorescent response contributes the surface layer and any thin film located on the surface. For this reason, a remote-sensing lidar system cannot be equivalently replaced by contact flow-through system with fluorometer due to subsurface water intake because of the inevitable presence of waves on the sea surface. In addition, the sensitivity of the LIF lidar technique is higher compared to a flow-through or immersion fluorometers since the powerful laser ray penetrates to a greater depth in the water column, causing the fluorescence of the constituents. The estimated thickness of the water layer from which integrated fluorescence response is registering, varies 0.5–10 m according of water turbidity for ultraviolet fluorescence (UFL) lidar.

## 2. Study area

Lake Balaton is the largest shallow lake in Central Europe in area (592 km$^2$) with average depth of 3.2 m. Due to its shallow depth and regular resuspension of bottom sediment, lake Balaton is a vertically well mixed and turbid system, entirely nonstratified, even during the summer season (Likens 2010; Tundisi et al. 2012). In the 1980s, the western part of the lake became hypertrophic, and the central and the eastern basins became eutrophic (Herodek 1986). Nowadays, after some measures have been taken to decrease the nutrient load, the central and the eastern part became mesotrophic while the western part remains eutrophic (Presing et al. 2008). The only major inflow into the lake is Zala River, which flows in the southwestern-most basin. The river is a major source of CDOM because it runs through a system of wetlands. This also caused the southwestern basin of the lake to remain eutrophic, so it is considered that there is a strong longitudinal trophic gradient from SW to NE persists in lake Balaton.

## 3. Materials and methods

### 3.1 *Ultraviolet fluorescence LIDAR (UFL series)*

The instruments of UFL series were developed by the Shirshov Institute of Oceanology and the Russian Electro-Technical Institute (Pelevin et al. 2001). The UFL-8 model was used in the lake Balaton expedition of 2008 for estimation of CDOM, chl-*a* and TSM. UFL takes measurements with sampling rate up to 2 Hz while the boat is travelling. The registration of the measured values is connected to a GPS, so all measurements are geotagged and can be used for interpolating maps of the measured parameters. More detailed information about UFL series lidars and laboratory calibration experiments was previously published (Pelevin et al. 2001; Aibulatov et al. 2008; Palmer et al. 2013; Pelevin et al. 2015). Investigations using UFL-8 in open sea case 1 waters in Atlantic Ocean are described by Koprova et al. (2010), and those in the South China, the Kara, and the Black Seas by Zavialov et al. (2010, 2014).

The UFL-8 gives an opportunity to measure the TSM concentration in addition to chl-*a* and CDOM (Aibulatov et al. 2008). This makes it possible to detect at the same time multiple water quality parameters (chl-*a*, TSM, and CDOM) with the sampling rate of 2 Hz and could be an efficient tool not only in open sea, but also in optically complex lake waters. UFL measures near-surface concentrations optically *in situ*, on a travelling boat, and so it is capable of making a large number of measurements in a short time. In addition, UFL observations could provide accurate estimates in turbid inland waters such as lake Balaton (Palmer et al. 2013).

The instrument analyses return signal from dual excitation (355 and 532 nm) Nd:YAG laser pulses emitted at 2 Hz with energy of 2 mJ are detected across 11 bands in series (355, 385, 404, 424, 440, 460, 499, 532, 620, 651, and 685 nm) on stations simultaneously with water sampling for the instrument calibration, and across four bands at the same time (355, 404, 440, and 685 nm) in transect mode in case of moving boat (Table 1, Figure 1). Fluorescence intensities at 440 and 685 nm and backscattering of the 355 nm laser pulse are normalized to Raman scattering at 404 nm, and then calibrated using a set of laboratory-measured concentrations to derive CDOM, chl-*a*, and TSM concentrations. Since this instrument needs to be calibrated, some water samples have to be collected. Optical measurements usually show high correlation with laboratory analyses on the collected water samples (Pelevin et al. 2015).

**Table 1.** Main parameters of UFL-8 fluorescence lidar.

| | |
|---|---|
| Excitation laser wavelengths | 355 and 532 nm |
| Receiver central wavelength, transect mode | 355, 404, 440, and 685 nm |
| Additional spectral channels | 385, 424, 460, 499, 532, 620, and 651 nm |
| Bandwidth (FWHM) | 10–15 nm |
| Pulse repetition rate | 2 Hz |
| Pulse duration | 6 ns |
| Pulse energy | 2 mJ (355 nm pulse), 2 mJ (532 nm pulse) |
| Telescope | Kepler; adjustable length to target range 1.5–25 m |
| Power supply | 220 V, 50 Hz, 120 W |
| Dimensions; weight | 800 × 550 × 250 mm; 35 kg net |
| Receivers | Photomultipliers |
| Channel filters | Four-channel beam splitter; interference filters |
| Telescope clear aperture | 140 mm |
| ADC frequency | 50 MHz, special energy integrating scheme |
| ADC resolution | 10 bit |


**Figure 1.** UFL-8 lidar on-board Balaton Limnological Institute research boat.

### 3.2 *Laboratory water sample analyses*

Chl-*a* and TSM concentrations, and CDOM absorbance at wavelength 440 nm $a_{440}$ (m$^{-1}$) of all water samples collected during the UFL field campaign were analysed following the standard protocol of the Nutrient Cycling Laboratory of the Balaton Limnological Institute (Iwamura, Nagai, and Ishimura 1970; Cuthbert and Del Giorgio 1992; Svab et al. 2005; Tyler et al. 2006). Chl-*a* concentrations were determined through spectrophotometric analysis following extraction by hot methanol and centrifugation from known volumes. TSM concentrations were determined by weight, following the drying of filtered samples of known volume on pre-dried and weighed GF/C filters (1.2 μm). The concentration of chromophoric dissolved organic matter (CDOM) was determined spectrophotometrically through absorbance measurements with a Shimadzu UV 160A spectrophotometer at wavelength 440 nm (Cuthbert and Del Giorgio 1992).

### 3.3 *Field measurements*

In September 2008, measurements were performed during the three days in diverse weather conditions, 10, 11, and 12 September 2008 at sites 1, 2, and 3, respectively. We have selected three study sites on lake Balaton (Figure 2). The Keszthely basin (1) is the easternmost embayment of the lake, and it receives the main tributary, the Zala River. This area is eutrophic, and some spatial patterns were expected due to a current cell which can form in the western part of the bay. The eastern part of the basin is an area where lower trophity waters from the next basin mix with the Keszthely basin waters. The measurements in this area were conducted under conditions of a freshening breeze from the east. The second measurement area (2) was located between the northern and the southern shore in the Szemes basin. We expected no distinct patterns to form in this area, since the bottom is flat and the water quality exhibited no known sharp changes. We sampled this area on a day with practically no wind. Our third area was the straits of Tihany (3), a narrow channel between the northern and southern shore of the lake, where strong seiche-induced currents occur even on calm days. The bottom of the lake has very distinctive topography here (a deep narrow channel in the northern part of the strait), and strong spatial patterns were expected. We registered a relatively strong NW wind during this measurement day.

## 3.4 *Lidar and satellite calibration*

A total of 28 water samples were collected during the three working days on sites 1–3 simultaneously with the lidar measurements, thereby the CDOM, chl-*a*, and TSM concentrations were determined with the widest possible range of concentrations. These results were used to calibrate the lidar measurements with $R^2$ (coefficient of determination) values between 0.90 and 0.95 (Figures 3(*a*)–(*c*)). The first step of calibration was successful in part of UFL-8 lidar data validation.

Second, we made an attempt to validate medium-resolution bands of MODIS/Terra radiometer for obtaining water quality parameters with the help of regional algorithm of data processing. The relative values in Raman units measured by the lidar were

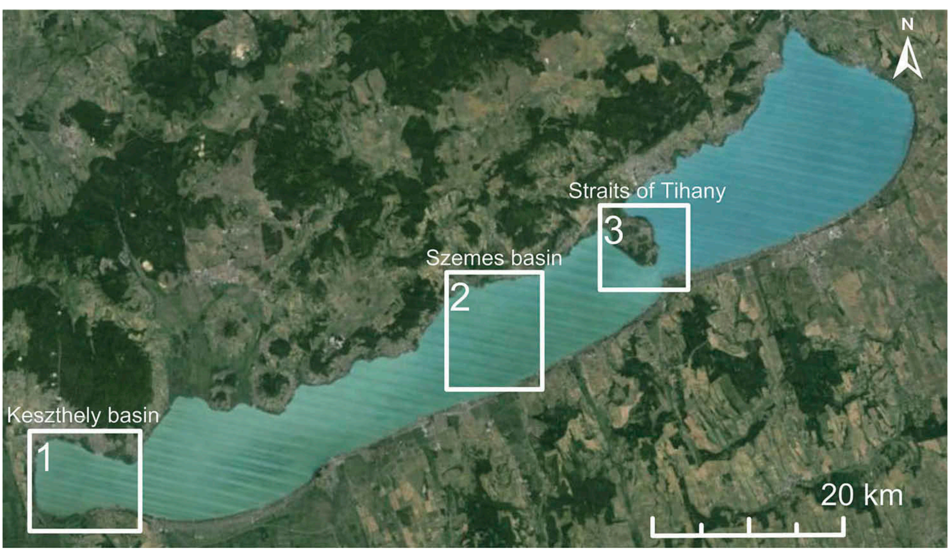


**Figure 2.** Lake Balaton (46° 50′ N, 17° 44′ E) with locations of study sites.

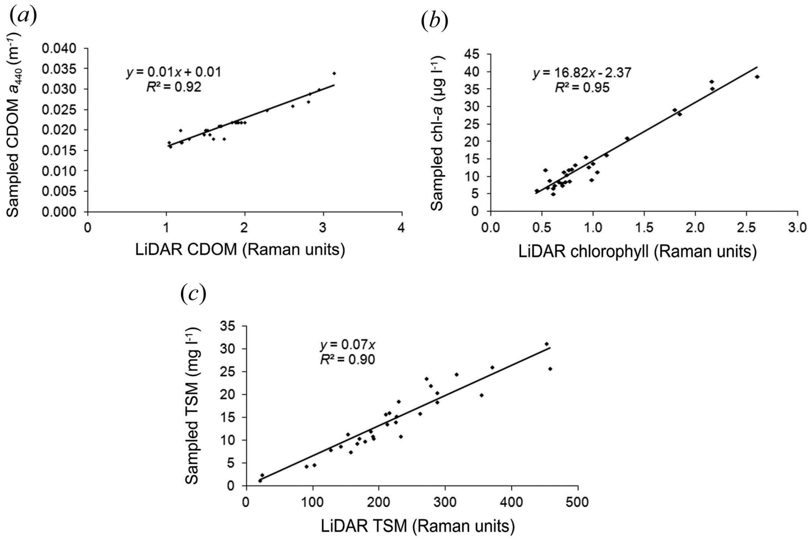


**Figure 3.** Correlations between CDOM (*a*), chl-*a* (*b*), and TSM (*c*) concentrations measured from water samples and by UFL lidar.

converted to absolute values using these regressions, and the point-by-point results were interpolated into a raster with a cell size equal to the spatial resolution of the corresponding MODIS/Terra bands. After atmospheric correction and geolocation, the band 9 was used for estimating CDOM (pixel sixe 1 km × 1 km), the ratio of band 3 to band 4 for estimating chlorophyll (pixel size 500 m × 500 m), and band 1 for suspended sediment (pixel size 250 m × 250 m). This allows for a spatial resolution of 1 km × 1 km for CDOM, 500 m × 500 m for chlorophyll, and 250 m × 250 m for suspended sediment (Table 2). For detailed description of MODIS/Terra radiometer, see Chen, Hu, and Muller-Karger (2007); Wong et al. (2008).

We have used the simple algorithms described by Miller and McKee (2004) and by O'Reilly et al. (1998) for the medium-resolution bands. The low resolution bands are routinely used for remote sensing of these parameters on the sea, but lake Balaton is not so large and spatial patterns are too subtle to be measured in these MODIS channels.

We have calculated suspended sediment from band 1, with 250 m resolution, which allowed for the fitting of the regression to the 360 data points, since a large number of MODIS pixels were located in the area we mapped. The satellite measured values fit the lidar-measured values relatively well in each of the days separately, but the lines are not the same due to the lack of atmospheric correction (Figures 4(*a*)–(*d*)). We believe so, because the correlations of UFL data and water samples are strong, although samples

**Table 2.** MODIS/Terra spectral bands used for satellite calibration experiment.

| Band number | Central wavelength (nm) | Bandwidth (nm) | Spatial resolution (m) |
|---|---|---|---|
| 1 | 645 | 620–670 | 250 |
| 3 | 469 | 459–479 | 500 |
| 4 | 555 | 545–565 | |
| 9 | 443 | 250 | 1000 |

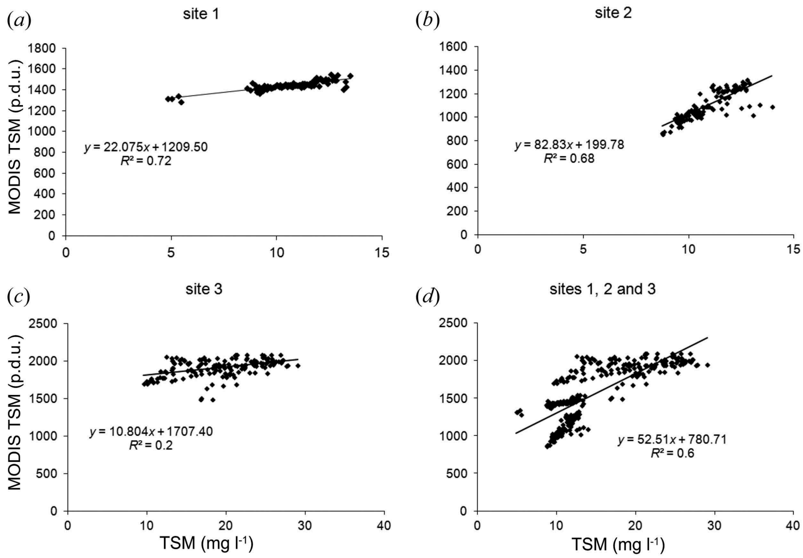


**Figure 4.** Correlations of TSM concentrations measured by UFL at different sites (*a*–*c*) and at all study sites (*d*) with MODIS satellite data, band 1, 250 m × 250 m resolution. Lidar data is averaged within each MODIS pixel (p.d.u. – procedure defined units).

were taken during the three days on all study sites together. The other problem of the suspended sediment calibration was that with these weather conditions, we were not able to measure the whole range of suspended sediment values that normally occur in lake Balaton. We have measured values between 10 and 30 mg $l^{-1}$, but a water sample we recently took after a three-day storm contained 80 mg $l^{-1}$ of suspended sediment, and we found values up to 300 mg $l^{-1}$ in the sediment.

We have calculated chlorophyll using the ratio of band 3 to band 4, which are 500 m resolution bands, this way we could fit our regression to 170 points. We observed chlorophyll maximum during the autumn, and the lake has a strong trophic gradient, so the problem we encountered was not about the range, but about the lack of atmospheric correction (Figures 5(*a*)–(*d*)).

The fitting of a CDOM algorithm was also attempted, but we only found and were able to use CDOM algorithms for the low resolution bands. The measured CDOM concentrations did not show any significant correlation with the CDOM concentrations estimated from the MODIS images, which is probably caused by the low number of satellite data points due to low resolution. Since the main source of CDOM, the Zala River forms a plume that usually runs close to the shore, it cannot be separated from the shore pixels, and this means that the satellite data can only cover the variation of CDOM in the lake, which is very low.

## 4. Results

Our measurement cruises took place in the first week of September, because that is the usual period of an algae bloom at the end of the summer. Previously calibrated on water samples lidar's data points were used to interpolate the following maps in Surfer

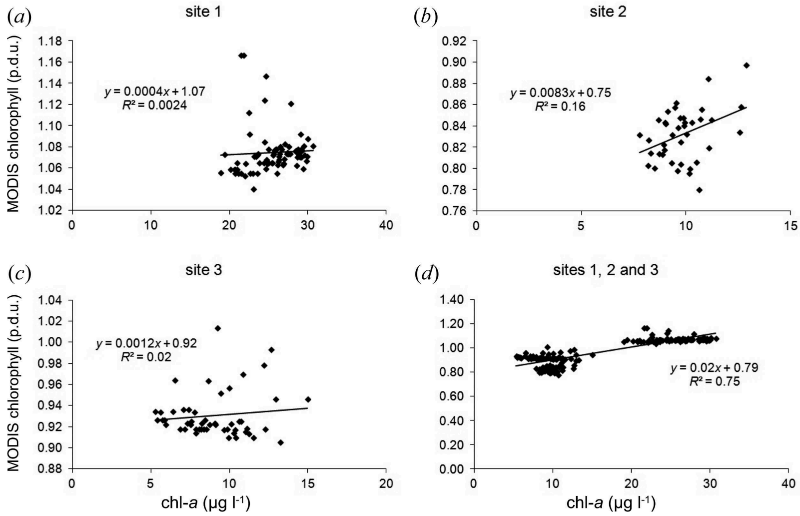


**Figure 5.** Correlations of chl-*a* concentrations measured by UFL at different sites (*a*–*c*) and at all study sites (*d*) with MODIS satellite data, the ratio of band 3 to band 4, 500 m × 500 m resolution. Lidar data is averaged within each MODIS pixel.

software using natural neighbour and Kriging interpolation techniques and a spatial resolution of 10 m. Each map was created by one day measurements in the highest sun conditions because lidar measurements where conducted in the time of satellite sensing, about noon.

The first measurement area, the Keszthely basin, shows relatively small variations of CDOM, except for the mouth of the Zala river. The river runs through a constructed wetland, so its water has a very low chlorophyll and sediment content, but is extremely rich in CDOM. This pattern can be seen on the map (Figure 6).

The chl-*a* map of the area shows that, generally, the shallower water is richer in chlorophyll and there might be a circulation in the western part of the bay driven by the wind. Figures 7(*a*) and (*b*) show low chl-*a* water from the neighbouring basin entering from the southeast, and maybe the chlorophyll-rich swath in the middle of the basin

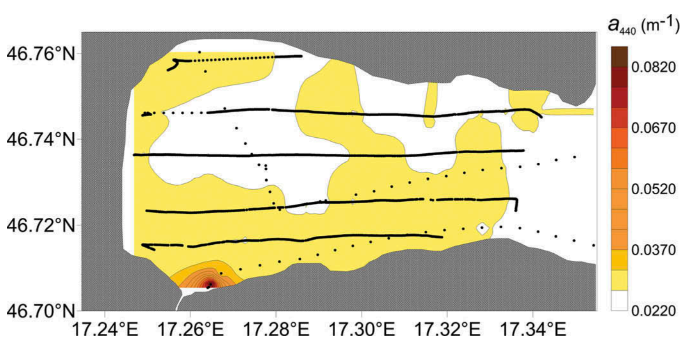


**Figure 6.** CDOM distribution pattern in Keszthely area (site 1) measured by UFL.

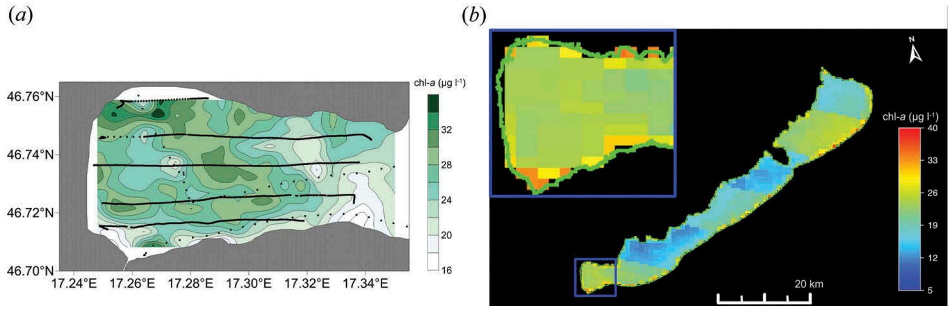


**Figure 7.** Spatial distribution of chl-*a* concentrations measured by UFL (*a*) together with MODIS, the ratio of band 3 to band 4, 500 m × 500 m resolution (*b*) in Keszthely area (site 1).

running from North to South separates two circulation cells. The chl-*a* concentration values vary between 16 and 35 µg $l^{-1}$.

The suspended sediment concentration pattern shows some similarity to the chl-*a* pattern, the NW-SE 'swirl' can be observed (Figures 8(*a*) and (*b*)). All three parameters show this faint, but distinguishable feature, so it is probably related to a larger scale current.

The second study area, the Szemes basin was sampled on a completely flat calm day. Theoretically, absolutely nothing should have been measurable, but on the map of CDOM, some patterns are visible (Figure 9). We have to note, however, that there are only very small differences among the measured values that build the pattern, the $a_{440}$ range being from 0.20 to 0.24 $m^{-1}$. The map of this day might show some CDOM-rich water 'leaking' from the reed stands in the little bay on the northern shore. It also shows some small areas of locally high concentration which would have dissipated if the wind would have been stronger. Local high values area is difficult to explain but the tendency that the CDOM values are higher in the vicinity of the north shore can be explained by a weak N–S surface current, which continues in an N–S circulation.

On a sunny, calm day like this, if local algae growth maxima occur, they are not dissipated by wave and current action. The spots on the chl-*a* map of this area do not correlate with the bathymetry or the suspended sediment or CDOM pattern (Figures 10 (*a*) and (*b*)). Such spots have also been observed on the ocean with this instrument, so

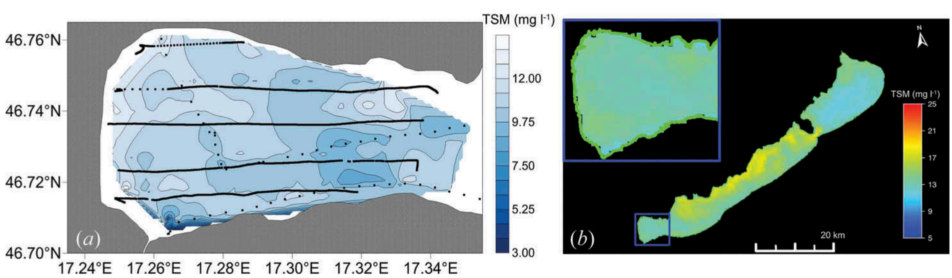


**Figure 8.** Spatial distribution of the TSM concentration measured by UFL (*a*) together with MODIS, band 1, 250 m × 250 m resolution (*b*) in Keszthely area (site 1).

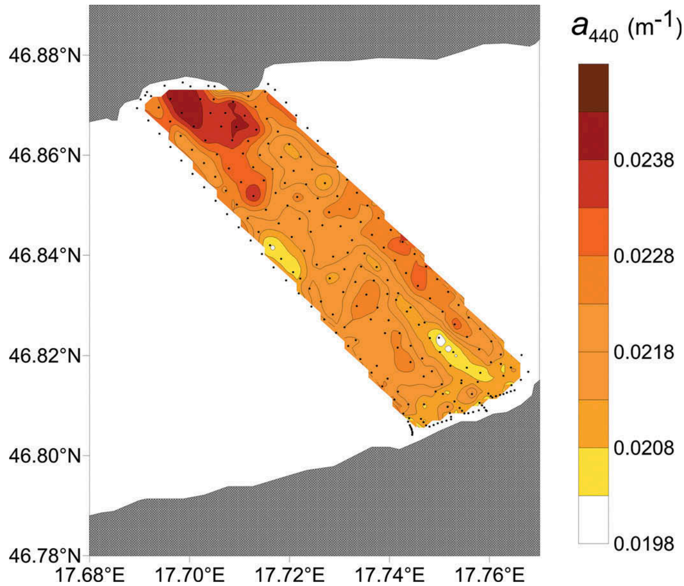


**Figure 9.** CDOM distribution pattern in Szemes region (site 2) measured by UFL.

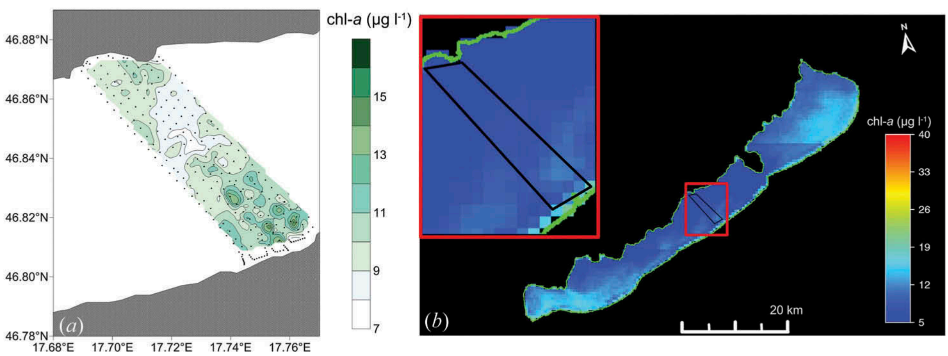


**Figure 10.** Spatial distribution of chl-*a* concentrations measured by UFL (*a*) together with MODIS, the ratio of band 3 to band 4, 500 m × 500 m resolution (*b*) in Szemes region (site 2).

we suppose this is a widespread small-scale phenomenon that only this and similar instruments are capable of measuring.

The suspended sediment values show a strong correlation with the bathymetry (Figures 11(*a*) and (*b*)). The amount of sediment is very low in areas deeper than 3.5–4 m, both on the north and the south shores. The lake floor has a slight slope from the North to the South, and a sandbank with a relatively steep face on the southern shore. We have no explanation for the local high in the middle between the two shores.

On site 3, we had a relatively strong force-4 wind from the NW, the typical wind direction on lake Balaton. We measured in the straits of Tihany, which is a narrow area where water is exchanged between the two adjoining basins. The topography of the lake bottom is distinctive: on the northern area of the strait, a deep 'trench' connects the two basins, which is formed by the currents. There is a large submerged sandbank near

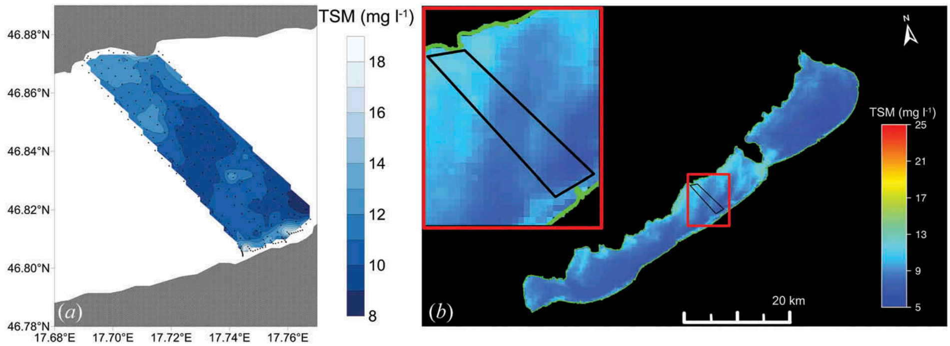


**Figure 11.** Spatial distribution of the TSM concentration measured by UFL (*a*) together with MODIS, band 1, 250 m × 250 m resolution (*b*) in Szemes region (site 2).

the southern shore that is deposited by a backwater that usually forms, and there is another elongated deep area near the southern shore to the West of the sand bank.

The lake has a CDOM gradient from the West to the East (Figure 12), and the map of the CDOM absorbance (though also in a very narrow range) shows not only relatively CDOM-rich water from the West flowing into the East, but also the low-CDOM water from the East entering the West, probably due to a current–countercurrent system in the strait. The image also implies that the trench near the southern shore is formed by eastern basin water (low CDOM) flowing towards the West.

The chl-*a* values correlate quite well with the suspended sediment concentrations in the areas further away from the shore (Figures 13(*a*) and (*b*)). This is probably caused by the fact that the upper layer of the settled sediments on the lake bottom is relatively rich in benthic algae, and these probably get regionally resuspended, causing chlorophyll and sediment highs in the same place. In the areas near to the shore, perhaps somewhat deeper layers of the sediment get also resuspended, because we cannot observe similar correlations.

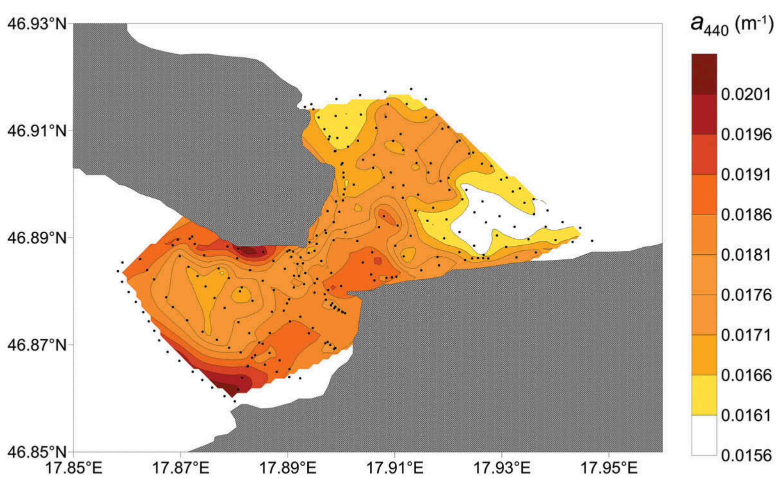


**Figure 12.** CDOM distribution pattern in straits of Tihany area (site 3) measured by UFL.

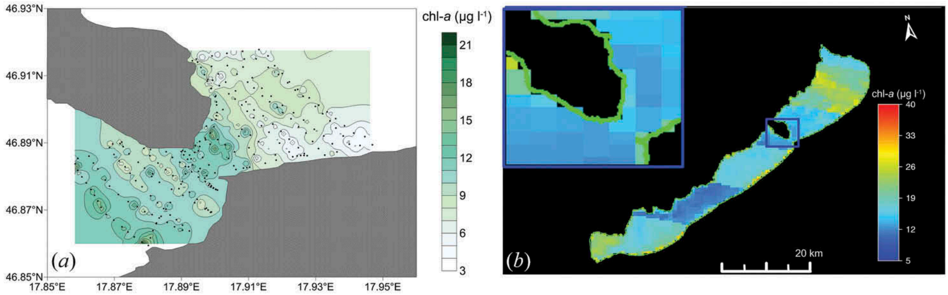


**Figure 13.** Spatial distribution of chl-*a* concentrations measured by UFL (*a*) together with MODIS, the ratio of band 3 to band 4, 500 m × 500 m resolution (*b*) in straits of Tihany area (site 3).

All the results also show the trophic gradient along the lake, with the highest chlorophyll concentration at Keszthely being 36 and 16 μg $l^{-1}$ around Tihany.

The suspended sediment concentrations here also show relatively good correlations with the bathymetry. The very deep area shows less suspended matter than the area above the sandbar (Figures 14(*a*) and (*b*)). There are some very high sediment concentrations on the western side of the narrows near the southern shore, which is the area most affected by the breaking waves. The red bar of high sediment concentration does not run along the deepest channel between the two shores, but runs a little bit to the south, in shallower water. There is an area of higher turbidity that extends along the wide ridge of deposited sediment to the east of the channel, and a plume of low sediment concentration also on the eastern side that runs along the deeper channel near the southern shore and extends to the west all the way to the ferry harbour of the southern shore.

It is also interesting to note the very high sediment concentration we found on site 3 because of the high wind. In the eastern basin of the lake, the sediment concentration in windy conditions is similar to the turbidity near Szemes (site 2) we measured the previous day when it was calm. We found extremely high turbidity to the west of the straits of Tihany.

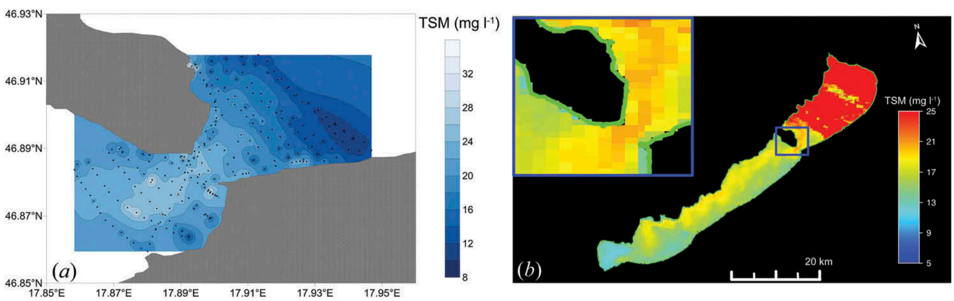


**Figure 14.** Spatial distribution of the TSM concentration measured by UFL (*a*) together with MODIS, band 1, 250 m × 250 m resolution (*b*) in straits of Tihany area (site 3).

## 5. Conclusions

Our results clearly show that the resolution provided by laboratory measurements on a few water samples does not resemble actual conditions in the lake, and it would be more efficient to measure these parameters less accurately but in a better spatial distribution with the lidar.

The UFL instrument has a great potential for being used for collecting ground truth data for satellite remote sensing of these parameters. Its measurement accuracy is comparable to classic water sample measurements, the measurement speed is high and large areas can be surveyed in a time interval very close to the satellite overpass.

The UFL-measured CDOM concentrations did not show any correlation with the CDOM concentrations estimated from the MODIS/Terra low-resolution band 9. Chl-*a* concentrations measured by lidar and estimated from MODIS images as a ratio of medium-resolution band 3 to band 4 showed a relatively strong correlation, and the relatively fine spatial resolution makes detection of patterns possible, although cross-track striping artefacts occurring in the used bands have to be corrected. TSM (mostly suspended sediment) concentrations measured by lidar and estimated from MODIS medium-resolution band 1 show a remarkably strong correlation for each study site separately, and the 250 m × 250 m spatial resolution shows fine patterns of local currents and eddies.

The main problem with the atmospheric correction is the fact that the medium-resolution bands are not routinely used for water quality measurements as they were primarily designed for the land surface sensing, and atmospheric correction schemes designed for land applications (e.g. Kaufman et al. 1997). The selection of medium-resolution bands does not contain infrared channels that are suitable for estimating the water content, and the black pixel approach (Ding and Gordon 1995) does not work in turbid waters where no channel has zero reflectance. A robust atmospheric correction scheme cannot be based on the data we collected during a three-day trial run. The problem with day-to-day difference of regression for TSM requires further investigation. It may be appropriate to use multi-band algorithms in which there are relations of spectral bands to reduce the influence of the atmosphere changing.

Although the satellite calibration attempt was not fully successful, our three-day trial measurement showed that the UFL lidar is a promising tool for measuring the small-scale spatial patterns of chl-*a*, TSM, and coloured dissolved organic matter. The high resolution and good spatial coverage of the instrument allows very small scale structures to be mapped. It is also suitable for the collection of satellite ground truth data needed to create regional satellite data processing algorithms, but it is necessary to use an existing one or develop a new method for the qualitative atmospheric correction of the medium-resolution MODIS bands.

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