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FIELD PERFORMANCE OF THE ST 1000 SPECTROMETER IN PASSIVE OPTICAL REMOTE SENSING OF WATER BODIES

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Abstract. The ST 1000 is a multipurpose fibre optic spectrometer produced by Ocean Optics Inc. It consists of three CCD array spectrometers mounted on the same electronic circuitry board and driven by the electronics of the main spectrometer. The spectral band of our instrument is 350–850 nm with average resolution of 0.5 nm. Light is conducted to the gratings through 2 m long fibre optics. For data acquisition a plug-in board PCMCIA card is used. Integration time, number of scans, and the interval between them can be varied by software provided by the manufacturer. We built a frame for the instrument to carry out field measurements, calibrated the measuring system, and tested the suitability of the instrument for remote sensing of aquatic environments. Comparison with airborne and shipboard remote sensing spectrometers as well as underwater spectrometer data was carried out. Our results show that the ST 1000 spectrometer can be used in remote sensing although it is designed for laboratory measurements.

Key words: optical remote sensing, marine optics, fibre optic spectrometer.

INTRODUCTION

Passive optical remote sensing of water environments started in Estonia two decades ago. The first optical device used was a telespectrometer MS-1, designed at the Institute of Astrophysics and Atmospheric Physics (now Tartu Observatory). Measurements with an MS-1 on board a research vessel were carried out on the Baltic Sea in 1978–82 (Eerme et al., 1983; Arst et al., 1984). Since 1987 another telespectrometer, Pegasus, was used on board a helicopter and a research vessel. The prototype of Pegasus was designed in the institute of VNIIOFI in Moscow (Bacherikov et al., 1981; Lokk et al., 1986) and it was improved step by step by the marine optics group of the Estonian Marine Institute (Miller et al. 1988; Arst et al., 1997).

A replacement to the torn and worn Pegasus was purchased in 1997. The ST 1000 (made by Ocean Optics Inc., USA) was selected as the main unit of our remote sensing instrumentation because of its small size, high resolution, measurement speed, and relatively low cost. First *in situ* remote measurements were carried out on Estonian and Finnish lakes and the southern part of the Baltic Sea in 1997. In the present paper the design criteria, operation, and methodology of the work of ST 1000, the principles of calibration, and accuracy estimations are given. It was possible to carry out simultaneous measurements with other spectral devices: an airborne imaging spectrometer AISA, remote sensing spectrometer FieldSpec, and underwater spectroradiometer LI-1800 UW. Comparative results of these measurements are discussed in the paper.

DESIGN AND OPERATION OF THE ST 1000

Because of different illumination conditions during different measurement series (different time and place, different synoptic situation) it is better to analyse the spectra of the radiance factor, $r(\lambda)$, rather than the spectra of upwelling radiance, $L_u(\lambda)$. The radiance factor can be calculated by the formula:

$$r(\lambda)=\frac{L_u(\lambda)}{E_d(\lambda)/\pi}, \quad (1)$$

where $E_d(\lambda)$ is the downwelling irradiance.

As known, the upward solar radiance above the water surface consists of the radiation reflected from the surface, $L_{u,R}(\lambda)$, and the radiation diffusely backscattered from the water mass, $L_{u,D}(\lambda)$. The first component gives information on the characteristics of the sea surface (undulation, foam, oil pollution, etc.), the second on the optically active substances in the water. Under the conditions where the influence of the sun glitter on $L_{u,R}$ can be neglected, the reflected component can be approximately estimated in the following way:

$$L_{u,R}(\lambda)=0.02L_z(\lambda), \quad (2)$$

where $L_z(\lambda)$ is radiance of the zenith point. It is assumed that 2% of the radiation from the zenith point is reflected back from the water surface.

Thus, the values of $L_u(\lambda)$, $L_z(\lambda)$, and $E_d(\lambda)$ allow us to compute the components of $L_u(\lambda)$, as well as the radiance factor $r(\lambda)$ and its components. Therefore we decided to use a spectrometer that can measure those three parameters simultaneously.

The spectrometer ST 1000 consists of three fibre optic CCD array spectrometers mounted on the same electronic circuitry board. One of the spectrometers (Master) is equipped with full necessary hardware and the other two (Slave 1 and Slave 2) are driven by the Master spectrometer's hardware. All three CCD arrays are identical: 1024 element lines, 12.5×14 μm per element, signal to noise ratio 1000:1.

Diffraction gratings can be ordered from the manufacturer for measuring any 500 nm wide spectral band within 320 to 1050 nm range. Two spectrometers are needed if one wants to measure with full range. The software makes it possible to operate with these two spectrometers like with a single wide band spectrometer.

We selected wavelengths 350–850 nm for all three channels of our instrument because other wavelengths are strongly absorbed by water. Spectral resolution of the spectrometers is about 0.5 nm. Three optical cables, each 2 m long, are used to transport light from the necessary directions to the spectrometers.

The digitizing of the signal takes place in an analogue-to-digital converter mounted in the PCMCIA data acquisition board (DAQCard-700) connecting the ST 1000 with a notebook PC. The integration time of measurements can be varied by the software from 40 to 4000 ms. The time interval between the measurements can also be selected by the software, but the minimum interval between two scans depends on the integration time used.

It is possible to use averaging of measured spectra by the spectrometer software, but some of the spectra could be distorted due to a sun glint or some other factors. Therefore, we recorded a number of spectra and averaging was carried out after correct spectra had been selected visually. In 1997 the integration time used was 80 ms and only less than 1% of the total number of spectra were distorted; however, the importance of visual checking of the measured spectra increases with the integration time.

The main units of the measuring system with an ST 1000 spectrometer are shown in Fig. 1.

We designed a special frame (see Fig. 2) into which the ST 1000 is mounted for remote sensing measurements. The spectrometer with a power supply unit and a PC are in a suitcase fixed to the aluminium frame with a telescopic tube. The optical head, where the input ends of fibre optics are fixed, is in the end of the tube of adjustable length. One of the measuring channels is equipped with a cosine sensor for measuring downwelling irradiance, the other two are equipped only with a fibre face fixing.

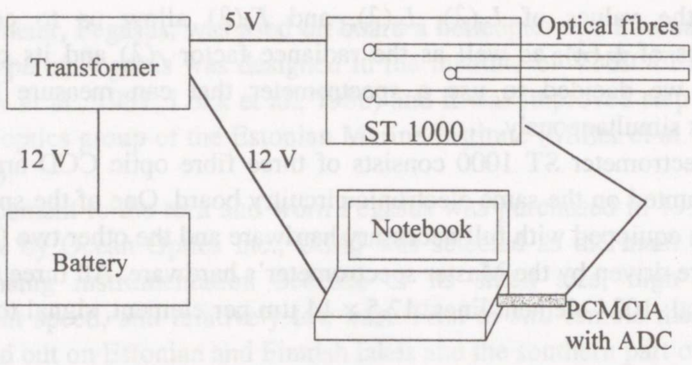

Fig. 1. The main units of the measuring system with the ST 1000 spectrometer.

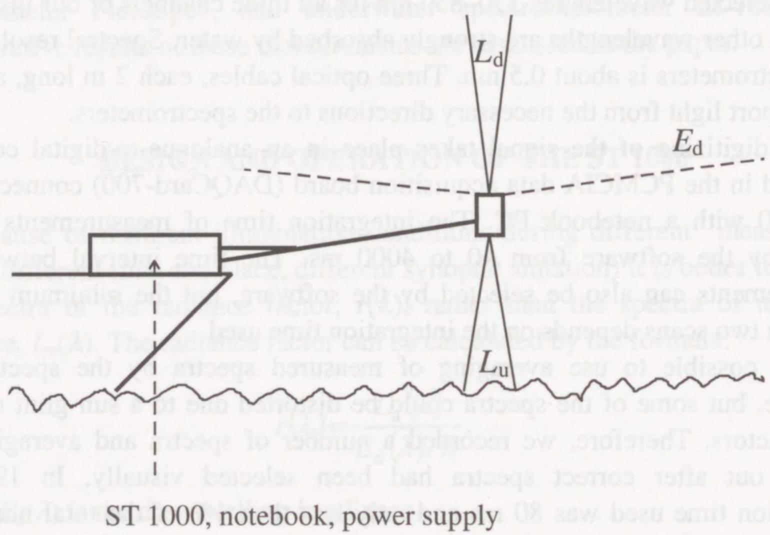

Fig. 2. Measuring system with the ST 1000 spectrometer on board a boat.

The output of the ST 1000 is spectra of L_u, E_d, and L_z in the instrument's own units (0–4096). An example of an L_u spectrum is shown in Fig. 3. Calibration of the instrument is needed if one wants to obtain results in physical units. Wavelength calibration of all three spectrometer channels was provided by the manufacturer, but radiometric calibration must be carried out using the real configuration (with optical fibres, cosine sensors, etc.) of the system.

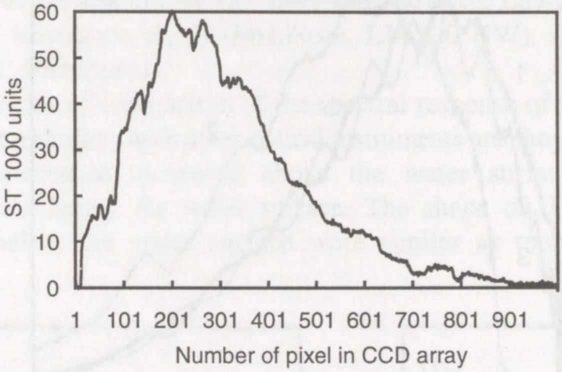

Fig. 3. Sample spectrum of raw data. Upwelling radiance measured on the southern part of the Baltic Sea.

CALIBRATION

Optical radiometry standards and methods in Estonia are based on the experience and instrumentation of the former Space Research Laboratory of Tartu Observatory (Veismann, 1996). Detailed descriptions of the spectral irradiance standard sources, standard detectors, and calibration techniques are also given in special publications of National Institute of Standards & Technology (formerly National Bureau of Standards).

A system of radiometric and photometric standards for Estonian regional calibration laboratory at Tartu Observatory and the University of Tartu is proposed with the emphasis on traceability, cross-linking, and its future improvement. The detector standards include the photodiode trap detectors, designed and investigated at the University of Tartu together with Helsinki University of Technology (Veismann et al., 1994).

The background and principles of investigation and calibration of remote sensing instrumentation was discussed in a previous publication (Arst et al., 1997). Here we will describe the new details and changes in the methodology.

The lamp FEL must be operated at a specified calibration current 8.2 A to produce the calibration irradiance. A water-cooled 1 kW supply and voltage meters were designed and used.

The irradiance calibrations are provided directly from the FEL lamp at the nominal 50 cm distance. For the calibration of the radiance measuring channel a diffuser screen made from a commercially available Russian-made diffuse reflectance material fluoroplast-4 was used. Fluoroplast-4 is a Teflon-like white polytetrafluoroethylene material. In the visible part of the spectrum it has good reflectance and near-Lambertian spatial distribution.

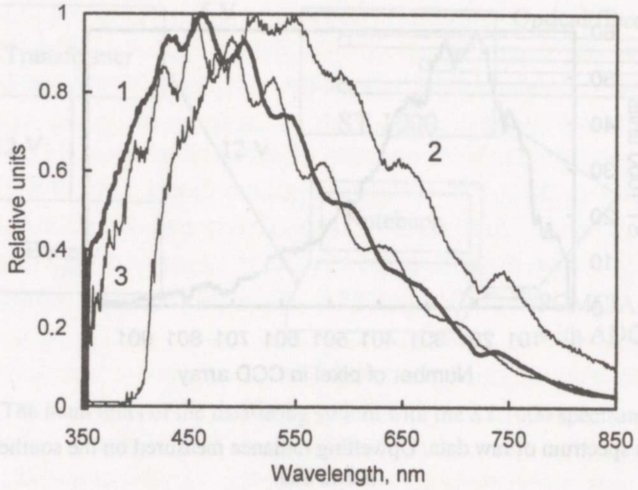

Fig. 4. Relative spectral sensibility of the channels of the ST 1000 spectrometer. 1, Master; 2, Slave 1 with diffuser; 3, Slave 2.

The spectral calibration was provided by a Russian-made quartz–mercury PRK lamp for medical purposes. The distinct peaks at 365, 404/407, 436, 546, 578, and 737 nm are in the spectral range of our ST 1000 spectrometer and can be used for wavelength calibration of the instrument.

It must be noted that, limited by the 12 bit A/D converter, a maximum of 4096 radiometric resolution levels are feasible into one exposed spectrum. Really the noise limited dynamic range is 1 : 1000.

The relative spectral sensibility of the spectrometer with optical fibres and cosine sensors is shown in Fig. 4. It must be noted that the cosine sensor absorbed UV radiation and part of the visible light up to 420 nm. The cosine sensor diffuser was replaced by a better diffuser after the first calibration whereas we are interested in obtaining water reflectance for the photosynthetically active radiation (400–700 nm) region.

COMPARISON OF THE ST 1000 WITH OTHER OPTICAL INSTRUMENTS

The ST 1000 spectrometer was used simultaneously with other optical instruments in field experiments carried out on Estonian, Finnish, and Swedish lakes during summer 1997. The other optical instruments included an airborne imaging spectrometer AISA (some Finnish lakes), an underwater spectrophotometer LI-1800 UW (Estonian and Finnish lakes), and a FieldSpec portable remote sensing spectrometer (Lake Erken, Sweden).

Comparable parameters are the upwelling radiance, $L_u(\lambda)$ (AISA, FieldSpec), downwelling irradiance, $E_d(\lambda)$ (FieldSpec, LI-1800 UW), and reflectance, $r(\lambda)$ (LI-1800 UW, FieldSpec).

Two examples of comparison of the spectral response of the ST 1000 (waters with different turbidity) with other optical instruments are shown in Figs. 5 and 6.

Water reflectance measured above the water surface is 0.544 of the reflectance just below the water surface. The shape of the spectra measured above and below the water surface were similar as seen in Fig. 6, but the

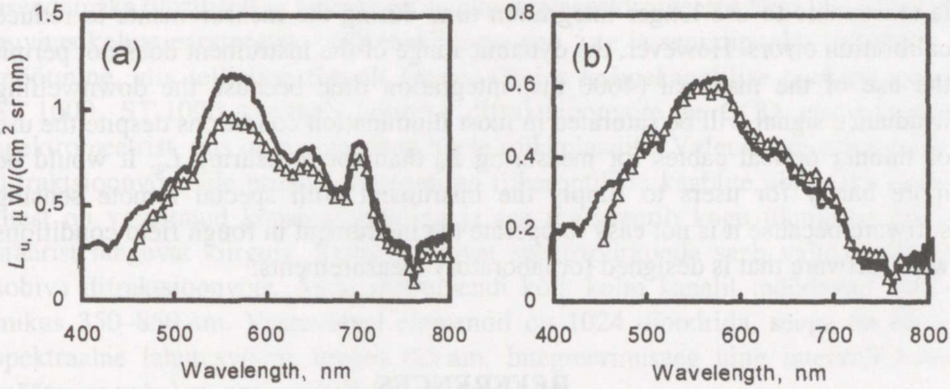

Fig. 5. Comparison of upwelling radiance measured by an airborne imaging spectrometer AISA and the spectrometer ST 1000 on board a boat on Lake Lohjanjärvi on 11 August 1997 at measuring stations P2 (a) and P5 (b). Solid line, ST 1000; triangles, AISA.

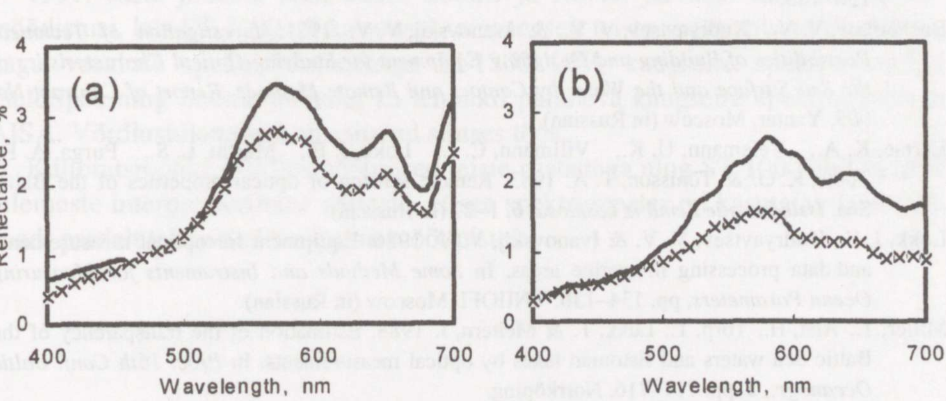

Fig. 6. Comparison of reflectance calculated from data of an underwater spectrophotometer LI-1800 UW and from ST 1000 spectra on Lake Lohjanjärvi on 11 August 1997 at measuring stations P2 (a) and P5 (b). Solid line, remote sensing reflectance calculated from LI-1800 UW underwater measurements; x, the ST 1000 reflectance spectra.

remotely measured reflectance was higher than expected. It can be explained by reflection from the water surface (measured by ST 1000) and possible changes in illumination during the underwater measurements. The delay between the measurements of upwelling and downwelling irradiance may have been about 15 min and the values of upwelling radiance were close to the sensibility of the LI-1800 UW spectrophotometer.

Our results show that the ST 1000 fibre optics spectrometer can be used in remote sensing studies above the water bodies on board a research vessel although the instrument was originally designed for laboratory measurements. It is reasonable to use longer integration time during the measurements to reduce calibration errors. However, the dynamic range of the instrument does not permit the use of the maximal (4000 ms) integration time because the downwelling irradiance signal will be saturated in most illumination conditions despite the use of thinner optical cables for measuring E_d than for measuring L_u. It would be more handy for users to supply the instrument with special remote sensing software because it is not easy to operate the instrument in rough field conditions with software that is designed for laboratory measurements.

REFERENCES

Arst, H., Eerme, K. & Purga, A. 1984. On the brightness coefficient of the Baltic Sea. *Deutsche Hydrogr. Zeitschr.*, **37**, 221–233.

Arst, H., Käärmann, L., Arst, G., Veismann, U. & Kutser, T. 1997. A measuring system for passive optical remote sensing of water bodies. *Proc. Estonian Acad. Sci. Biol. Ecol.*, **46**, 3, 150–163.

Bacherikov, V. V., Kudryavtsev, V. V. & Ivanovskij, V. V. 1981. *Investigation of Technical Possibilities of Building and Designing Equipment for Studying Optical Characteristics of the Sea Surface and the Water by Contact and Remote Methods. Report of Contract No. 003*. Yantar, Moscow (in Russian).

Eerme, K. A., Veismann, U. K., Villmann, C. J., Lokk, J. F., Martin, L. S., Purga, A. P., Toots, K. O. & Tõnisson, T. A. 1983. Remote sensing of optical properties of the Baltic Sea. *Issledovanie Zemli iz kosmosa*, **6**, 1–27 (in Russian).

Lokk, J. F., Kudryavtsev, V. V. & Ivanovskij, V. V. 1986. Equipment for optical measurements and data processing in marine areas. In *Some Methods and Instruments for Measuring Ocean Parameters*, pp. 134–136. VNIIOFI, Moscow (in Russian).

Miller, T., Arst, H., Torp, T., Lukk, T. & Meitern, J. 1988. Estimation of the transparency of the Baltic Sea waters and Estonian lakes by optical measurements. In *Proc. 16th Conf. Baltic Oceanogr.*, **2**, pp. 711–716. Norrköping.

Veismann, U. 1996. Calibration of radiometers for remote sensing of the Earth's atmosphere from space. *Metrologia*, **32**, 6, 671–674.

Veismann, U., Pehk, M. & Kübarsepp, T. 1994. Standards for radiometric calibration of electro-optical devices in Estonia. In *Proc. Baltic Electronics Conference*, pp. 187–194. Tallinn.

SPEKTROMEETRI ST 1000 KASUTAMISEST KAUGSEIRES

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Seeria ST 1000 spektromeetrid on konstrueeritud mitmete ülesannete lahendamiseks, kuid kaugseire ei kuulunud algselt nende hulka. Spektromeetri väikesed gabariidid (20 × 20 × 5 cm), lühike mõõteaeg (40–4000 millisekundit) ja suhteliselt odav hind (alates 1600 USD) ajendasid meid seda riista hankima asendamaks füüsiliselt ja moraalselt aegunud telespektromeetrit Pegasus. Et meid huvitas kolme parameetri – päikesekiirguse voo, vee ja seniidipunkti heleduse – mõõtmine, siis tellisime firmalt Ocean Optics kolmekanalilise spektromeetri ST 1000. ST 1000 koosneb kolmest difraktsioonvõre ja CCD vastuvõtjaga spektromeetrist, mis on monteeritud ühele trükkplaadile. Valguskiirgus juhitakse difraktsioonvõredele erineva diameetriga fiiberoptiliste kaablite abil. Üks kaablitest on varustatud koosinusanduriga ja see registreerib kogu ülemisest poolsfäärist langevat kiirgust. Registreeritavat spektripiirkonda saab valida tellides sobiva difraktsioonvõre. Meie instrumendi kõik kolm kanalit mõõdavad vahemikus 350–850 nm. Vastuvõtval elemendil on 1024 dioodrida, seega on riista spektraalne lahutusvõime umbes 0,5 nm. Integreerimisaeg ning intervall kahe mõõtmise vahel on programmiliselt muudetavad.

Sellise konfiguratsiooniga ST 1000 on ainueksemplar, millele on lisatud ka koosinusvastuvõtja. Seetõttu on tähtis mõõteriista kaliibrimine energeetilistesse ühikutesse ning tehase poolt antud lainepikkuste kalibratsiooni kontrollimine. Seda protseduuri on kirjeldatud käesolevas artiklis.

1997. aasta jooksul tehti Eesti, Soome ja Rootsi järvedel mitmeid optilisi mõõdistusi, kus ST 1000 oli kasutusel samaaegselt teiste spektraalsete riistadega, nagu veealuse spektrofotomeetriga LI-1800 UW, kaugseire spektromeetriga FieldSpec ning Soome järvedel ka lennukil paikneva kaugseire spektromeetriga AISA. Võrdlustulemused on esitatud siinses töös.

Kalibratsioonid, võrdlusmõõtmised teiste riistadega ning ST 1000 abil saadud tulemuste interpreteerimine näitasid, et see spektromeeter on kasutatav laeva või paadi pardalt tehtavatel kaugseire mõõtmistel.