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A MEASURING SYSTEM FOR PASSIVE OPTICAL REMOTE SENSING OF WATER BODIES

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Abstract. A field telespectrometer PEGASUS, designed for passive optical remote sensing of aquatic environment, is described. PEGASUS is a spectrometer with mechanical scanning of the spectrum (in the wavelength range 400–700 nm). It uses a photomultiplier as the light detector for measuring the sea and sky radiance and recording the whole complex of these signals with a PC. The prototype of PEGASUS was designed at the research institute VNIIOFI in Moscow (1981) and later developed by an Estonian marine optics group. Since 1987 this measuring system has been constantly used in the marine optics expeditions of the Estonian Marine Institute and the results obtained have been discussed in many papers. In the present paper the design criteria, operation and methodology of the work of PEGASUS, the principles of its calibration, and accuracy estimations are given.

Key words: optical remote sensing, telespectrometer, marine optics.

INTRODUCTION

Today optical remote sensing is one of the usual procedures of water environment research. It is evident that operative information on a global scale can be given by satellite measurements only. However, also remote measurements from aircraft or ships are valuable and need further development. This is especially important for coastal regions, marginal seas, and inland waters, where numerous suspensions vary in type and amount within short distance and time intervals. Moreover, remote sensing data collected from the near-surface levels are needed for validating and interpreting the satellite data.

For optical remote measurements two methods can be applied, which differ principally in the source of illumination: the passive method where solar radiation reflected from the water surface and backscattered from the water column into the atmosphere is measured, and the active method where a laser system is used as a light source. Both methods are in use in the world scientific experience. The choice of the method depends on the concrete purpose and possibilities. Usually the general idea is to carry out regular measurements above the territories under investigation, giving a contribution to the monitoring data of the natural environment. For an operative collecting of a large number of data and their analysis not only high-quality radiative sensors, but also automatic recording and processing of the measurement results are necessary. Below a field telespectrometer for passive optical remote sensing of aquatic environment is described.

OVERVIEW

Several institutes, which used to belong to the Estonian Academy of Sciences, have carried out investigations of the water environment using the passive optical remote sensing method for more than 15 years (with some intervals). The first optical device used was a telespectrometer MS-1, designed at the Institute of Astrophysics and Atmospheric Physics. During 1978–82 measurements on the Baltic Sea were carried out on board a research vessel (Eerme et al., 1983; Arst et al., 1984). Since 1987 the telespectrometer PEGASUS has been used for optical remote sensing of water bodies. The prototype of PEGASUS was designed in the research institute VNIIOFI in Moscow (Bacherikov et al., 1981; Lokk et al., 1986) and, step by step, improved by our research group (see also Miller et al., 1988). The most essential changes were made in 1994–95, when a new version of the electronic unit was developed. So, a measuring system supported by a computer supplied with a set of programs for measurement control and data processing was designed.

PEGASUS is a spectrometer with mechanical scanning of the spectrum (in the wavelength range 400–700 nm) using a photomultiplier (PMT) as a light detector for measuring the sea and sky radiance and recording the whole complex of these signals with a PC. There are three measuring channels and one reference channel in this optical device, allowing of recording the spectra of solar radiance upward from the nadir point, $L_u(\lambda)$, the sky radiance downward from the zenith point, $L_z(\lambda)$, and the downward spectral irradiance, $E_d(\lambda)$.

As illumination conditions during different $L_u(\lambda)$ measurement series vary (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 $L_u(\lambda)$:

$$r(\lambda) = \frac{L_u(\lambda)}{E_d(\lambda)/\pi}. \tag{1}$$

This explains why the $E_d(\lambda)$ data are needed.

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

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

It is assumed here that 2% of the radiation from the zenith reflects back from the water surface. Thus, the values of L_u, L_z, and E_d allow us to compute the components of L_u, as well as the radiation factor r and its components. Note that actually the value of L_u is influenced by the atmospheric layer between the water surface and measuring instrument, but in case of the low-height measurements (on board a ship or helicopter) it may be neglected.

DESIGN CRITERIA AND OPERATION OF THE TELESPECTROMETER PEGASUS

The system consists of four units connected with each other as shown in Fig. 1:

A. Optical unit (spectrometer, light detector, pre-amplifier, and transmitter of the synchronizing pulses), located inside a 16.5 × 100 cm tube.

B. Multi-purpose electronic controller AD204, including an intermediate amplifier with a gain switch, analogue to digital converter (ADC), microprocessor-based controller, and a serial interface circuit. The size of the AD204 is 21 × 21 × 3 cm.

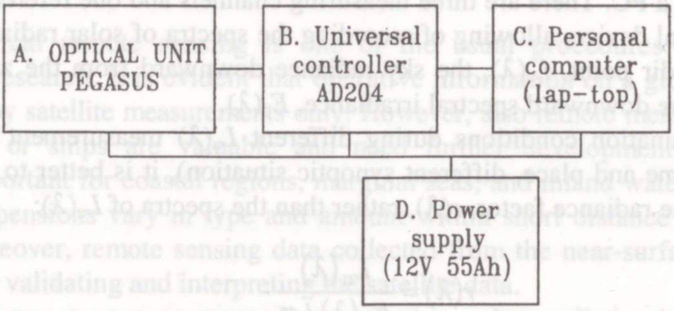

Fig. 1. The main units of the measuring system.

C. Notebook computer which controls the optical unit and is used for data reception and preprocessing (PC).

D. Power supply.

The scheme of the optical unit of PEGASUS is given in Fig. 2 (the optical systems of irradiance and reference channels are shown separately). The operation of this optical unit is briefly described below.

The incident radiation fluxes from the optical channels *1*, 2, and *13* (in the last case over the supplementary mirror *15*) and also from the reference channel *14* are consecutively directed by rotatory mirror *3* to the entrance slit *4* of the

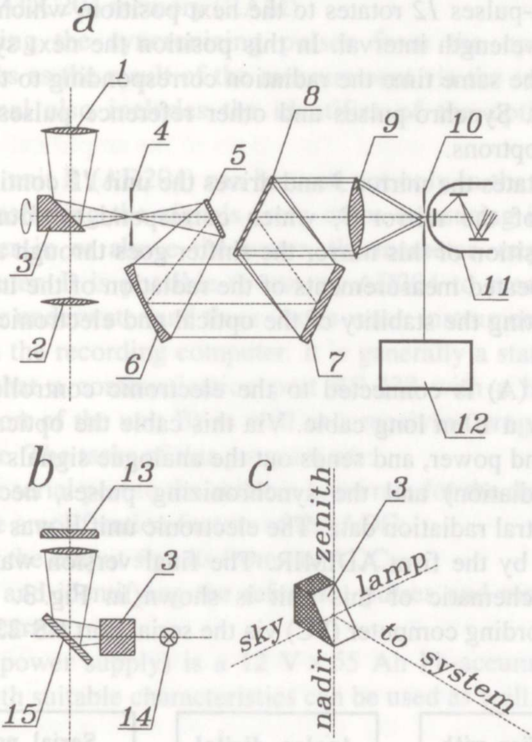

Fig. 2. *a*, Movement of the light rays (coming from the zenith channel) in the optical unit of PEGASUS (elements *4–10* together constitute a monochromator): *1*, objective of the zenith channel; *2*, objective of the nadir channel; *3*, rotating flat mirror; *4*, entrance slit; *5*, flat mirror; *6*, concave mirror; *7*, grating; *8*, flat mirror; *9*, refocusing lens; *10*, scanning slit; *11*, detector (PMT); *12*, drive for the scanning slit and generator of the synchro-pulses. *b*: *13*, diffuser in front of the objective of the irradiation channel; *14*, light source of the reference channel; *15*, flat mirror. *c*: isometric view of rotating flat mirror *3*.

monochromator by means of an optical-mechanical system. The input angle of the radiance channels (*1* and *2*) is approximately 9 degrees. There is a diffuser *13* in the irradiation channel, which is made from fluoroplast-4.

The radiation from the entrance slit of the monochromator is reflected by the flat mirror *5* to the concave mirror *6*, which directs the collimated beam onto the plain grating *7*. Then, over the flat mirror *8*, this (almost) monochromatic radiation goes into the refocusing lens *9*. This lens forms the image of the spectrum (from the channel under consideration) on the scanning slit *10*, which is moving by means of the drive *12* and cuts off a part (width of 5–6 nm) from the spectrum. The PMT (FEU-84, Russian production) is placed behind this scanning slit (*11*). Simultaneously with the spectrum scanning the disc placed in the generator of synchro-pulses *12* rotates to the next position, which is represented as the following wavelength interval. In this position the next synchro-pulse is encountered and at the same time the radiation corresponding to this wavelength interval is measured. Synchro-pulses and other reference pulses are generated optically by opened optrons.

The DC motor rotates the mirror *3* and drives the unit *12* continuously. There are four positions of the mirror *3*, which correspond to four measurement channels. In each position of this mirror the shifter goes through all wavelengths of the spectrum. Repeated measurements of the radiation of the internal lamp *14* are necessary for testing the stability of the optical and electronic system during the whole operation.

The optical unit (A) is connected to the electronic controller (B) and the power supply (D) by a 10 m long cable. Via this cable the optical unit receives the control signals and power, and sends out the analogue signals (corresponding to the measured radiation) and the synchronizing pulses, necessary for the decoding of the spectral radiation data. The electronic unit B was outlined by our group and designed by the firm ADIMIR. The final version was completed in spring 1995. The schematic of this unit is shown in Fig. 3. The unit B is connected to the recording computer (PC) via the serial port RS-232.

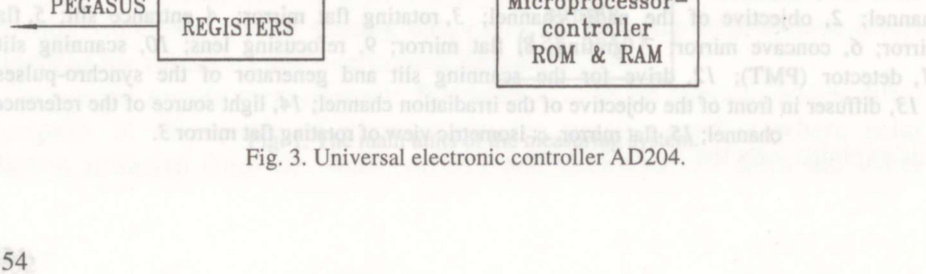

Fig. 3. Universal electronic controller AD204.

Information of four types is transferred from unit A to unit B:
(1) starting pulse of one full measurement cycle (four optical channels);
(2) starting pulse of one cycle of the scanning slit;
(3) synchro-pulses, determining the wavelength intervals in the spectra;
(4) analogue signal from the PMT.

The analogue signals from the unit A are amplified and converted to digital form in the unit B, in accordance with the synchronizing pulses. As the radiant flux energies from the directions of the sea and the sky are quite different, it may be necessary to change the amplification factor at switching from one channel to another. It is possible to adjust amplification factors by PC separately for each optical channel at the beginning of the measurements. The amplification factors are saved in the ADC204 memory (RAM).

After receiving the syncronizing pulses from the optical unit, AD204 outputs two bytes as the result of the measurement via the serial port to the PC. The output signal also includes the identifier of the optical channel under consideration.

Note that the unit B (AD204) can be used not only in the PEGASUS system, but also for transferring the signals from other measuring instruments (e.g., a radiation receiver in or above the water, thermometer, oxygen meter) to the recording computer. It is possible to use an AD204 to receive simultaneously signals from four underwater and three above-water instruments.

The unit C is the recording computer. It is generally a standard one, the only requirement is that a communication port RS-232 with a baud rate of 38400 (similar to the port of the unit B) as well as a receiving program for the AD204 must be available. The tasks of this program are:
(1) tuning the serial port to the suitable baud rate for the data transfer;
(2) setting the amplification factors of the ADC;
(3) collecting the output signals from the ADC;
(4) detecting and identifying the reference pulses and recording the data on the information carrier.

The unit D (power supply) is a 12 V × 55 Ah Pb-accumulator. Some other power supply with suitable characteristics can be used as well.

METHODOLOGY OF THE WORK

Before starting the real measurement cycles, a test of the whole system must be carried out. It is quite enough to switch on the main power and motor for a short time. After starting the program and tuning the data-transfer baud rate, the spectrum of the control lamp is displayed on the screen of the computer. Then the telespectrometer is placed into the working position, the shutters of the measuring channels are removed, and the measurements can be started. During one measurement cycle (1–2 s) the spectra in all the four channels are scanned.

Because of the instability of the radiation signals (influence of clouds, sun glitter, wind, and movement of the ship or helicopter) one cycle is not enough to obtain the necessary data. The final results must be obtained by averaging not less than 20 individual spectra. However, a suitable amplification factor for each channel must be determined earlier. A few measurement cycles are sufficient for this. The amplification factor must guarantee a "normal" shape of the spectrum: its amplitude has to be not less than 50% of the maximum value, but it cannot be too large to fit into scale. The selection of the amplification factor is an iterative process.

After the amplification factors are determined, the real measurements can be started. During the measurement cycles the data are collected and stored into the memory of the recording computer. These results must be visually controlled, by checking averaged spectra of all three channels on the screen of the PC. The output of the unit C should be recorded in an unchanged form on floppy or hard disks with some identifying data (place and time of measurements, measurement conditions, special remarks) added. The values of the amplification factors of the ADC are also recorded on a disk. Further data processing and analysis of the results will be carried out later using programs developed for this purpose. The real values of the averaged radiation spectra in the energy units are obtained using the corresponding calibration coefficients, which are found by the calibration procedure.

CALIBRATION

The principles and methods of the radiometric calibration of remote sensing apparatus are described in the monograph by Wyatt (1978). Calibration of the marine radiance and colour index meters has also been described in the literature (Hoge et al., 1986; Aas 1993a, b). The calibration of telespectrometer PEGASUS bases on the experience and instrumentation of the Space Research Laboratory of the Institute of Astrophysics and Atmospheric Physics (now Tartu Observatory) (Veismann et al., 1993; Veismann, 1995).

The major objectives of the calibration of an electro-optical instrument relate to the measurement of incident flux from a remote source of radiation. Geometry for the transfer of flux from the source (object) area to the collector (teleradiometer input) area is described in the monograph by Wyatt (1978). The spectral flux incident $\Phi(\lambda)$ upon a teleradiometer input surface A from a uniform extended object into solid angle Ω is given in terms of the spectral radiance, $L(\lambda)$, as

$$\Phi(\lambda) = L(\lambda) A \Omega \,. \tag{3}$$

The sensibility of the instrument depends on the parameters such as the optical through-put, the transmittance and reflectance of the mirrors, lenses, filters, gratings, etc., and the detector sensitivity. These parameters are not determined by design considerations and not all of them are known, therefore it is possible to obtain the system performance

$$U(\lambda)=\mathrm{f}\left[L(\lambda)\right]. \tag{4}$$

For a linear spectroradiometric sensor

$$U(\lambda)=K(\lambda)L(\lambda), \tag{5}$$

where $K(\lambda)$ is the calibration constant.

The radiometric calibration involves exposing the instrument to the given light levels in two configurations. For the irradiance configuration the diffuser input of the instrument is illuminated by a DXW standard lamp at a distance of 50 cm. The irradiance calibration constant $K_1(\lambda)$ is determined by

$$K_1(\lambda)=\frac{E(\lambda)G(\Theta,\varphi)}{U_1(\lambda)}, \tag{6}$$

where $E(\lambda)$ and $G(\Theta,\varphi)$ are respectively the spectral irradiance and the goniometric characteristic of the lamp, and $U_1(\lambda)$ is the instrument output voltage. The goniometric characteristic of the lamp is included to take into account the inhomogeneity in the lamp output across the solid angle subtended by the instrument diffuser during the irradiance calibration. For FEL lamps the average value of the goniometric characteristic is approximately 0.998.

The DXW quartz-halogen, tungsten lamps are coiled filament commercial lamps (Stair et al., 1963). The spectral irradiance of the DXW lamp is provided by the Optronic Labs traceable to the NIST at 10 nm intervals between 250 and 350 nm and at 50 nm at longer wavelengths. A five-step interpolation between these points was made by Optronics. The irradiance scale transfer uncertainty is 0.5% in the visible region. Detailed descriptions of standard sources of spectral irradiance and calibration techniques are given in an NBS special publication (Walker et al., 1988).

During the radiance calibration the instrument views an external extended source, a fluoroplast-4 (Russian-made Teflon) plate (diffuser of known reflectance), which is illuminated normally by a calibrated spectral irradiance standard DXW (Fig. 4). The spectral radiance calibration constant $K_2(\lambda)$ is determined by

$$K_2(\lambda)=\frac{E(\lambda)\rho(\lambda,\Theta)}{\pi U_2(\lambda)}, \tag{7}$$

where $E(\lambda)$ is the standard source irradiance and $U_2(\lambda)$ is the instrument response in volts. The bidirectional reflectance distribution function $\rho(\lambda,\Theta)$ is a measure of the deviation of the fluoroplast-4 plate from a purely Lambertian surface, where Θ is averaged over the instrument's field of view. The fluoroplast-4 spectral reflectance (≈ 0.85) was published by Khazanov and Krajman (1975) and experimentally measured by Tartu Observatory. The data obtained show that the normal direction from instrument to diffuser is not suitable because the spectral reflectance of the fluoroplast has in this case a maximum. It was estimated that an angle of about 30 degrees would be optimal.

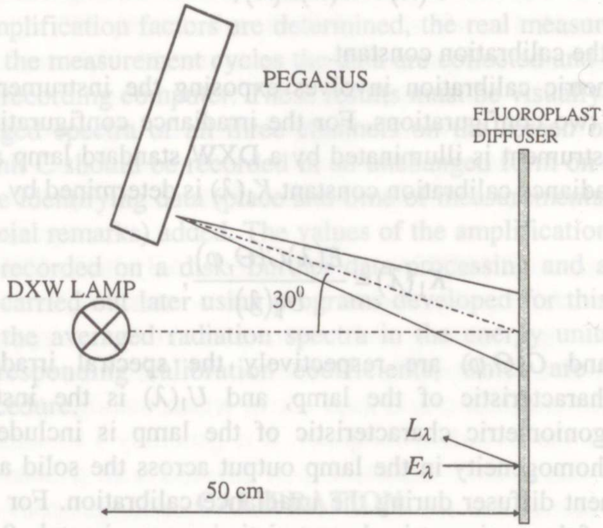

Fig. 4. Calibration of the radiance (L_λ) and irradiance (E_λ) channels of the telespectrometer PEGASUS.

ON THE ACCURACY OF PEGASUS MEASUREMENTS

As known, measurement errors are generated by numerous factors. As to the accuracy of PEGASUS measurements, the following main sources of errors can be mentioned:

(1) Instability of the synchro-pulses, which brings about an incorrect indication of wavelength, leading thus to the deformation of the measured spectra.
(2) Instability of the light flux of the calibration lamp and errors in the determination of the distances between the lamp, screen, and PEGASUS.
(3) Instability of the PMT (FEU-84) voltage.
(4) Errors due to occasional incorrect functioning of some mechanical unit of the instrument.
(5) Electronic noise.

These errors may be called "instrumental" and they do not depend on the properties of the object under investigation. Our rough estimates show that the first source causes an about 5% error in the measurement results (obtained by sky channel spectra, taking into account both the calibration procedure and the measurements in the nature). The error due to the second source is estimated at about 4%, the third and fourth both account for about 2%. The absolute value of the electronic noise is the same for all channels; consequently, its relative value is different for each channel and we cannot give its percentage for the whole instrument (all channels together). Because of the electronic noise the relative error of the measurement results increases with the decreasing of the measured radiation.

We must remember that the telespectrometer is often under strong mechanical impact: transportation from lake to lake, shaking of the ship due to storm, etc. Therefore, there may be some additional loss of accuracy due to hard outdoor conditions. This group of measurement errors includes also those caused by rocking of the instrument (causing a change in the measurement direction) on rough sea, the influence of the shadow of the vessel or some other object, the hauling of the vessel during the measurement. These errors are difficult to estimate.

Considering the measurement errors and their dependence on wavelength we must take into account also the sensibility curve of PEGASUS (determined mainly by the sensibility of FEU-84), the DXL lamp energy curve, and the radiative properties of the objects under investigation. The sensibility curve of PEGASUS and the energy curve of the DXL lamp are presented in Fig. 5. These data show that the maximal errors are expected in the regions 400–430 and 650–700 nm (in the first interval the lamp's energy is small and the calibration coefficient errors are maximal, the second interval is characterized by small sensibility of the instrument). As known, the radiation from the sky and the sea decreases towards both borders of the 400–700 nm spectrum. This supports the above conclusion.

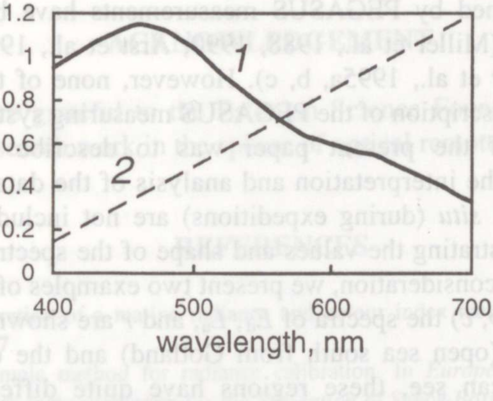

Fig. 5. The spectral distribution of the sensibility factor of the PEGASUS (*1*) and the energy of the calibration lamp (*2*) (in relative units).

We tried to estimate the reliability of the PEGASUS data also by comparing them with the results obtained by other investigators. Comparisons for the irradiance channel were the easiest to do: there exist numerous measurement or model calculation results of the irradiance spectra in the literature (Jerlov, 1976; McCartney & Unsworth, 1978; Bird et al., 1983; Arst et al., 1984; Hisdal, 1986; Dera, 1992). The comparisons showed that in most cases we can expect an about 5% accuracy. However, in the conditions of a thick cloud cover (very low irradiance values) or quickly varying illumination, errors may be bigger. Taking into account that the signal from nadir (L_u value) is about 50–100 times smaller than E_d/π, the corresponding relative error of L_u should be estimated at not less than 20%, but at the borders of the interval 400–700 nm it is probably bigger.

One more source of errors should be noted. It is sun glitter, which may essentially increase the signal from nadir. The sun glitter (from nadir) appears when the solar zenith angle is small enough and the sea is rough enough. If the influence of the sun glitter to L_u is remarkable, then formula (2) is not applicable (Arst et al., 1990) and the values of $r(\lambda)$ obtained with and without sun glitter are not comparable. Fortunately, this influence is almost independent of the wavelength. This means that the spectrum preserves its shape and we can work using normalized (to some wavelength) spectra.

SOME EXAMPLES OF MEASUREMENT RESULTS

The measuring system described above has been constantly used by the marine optics group of the Estonian Marine Institute (since 1987, i.e. until and after each step of reconstruction). The measurements were carried out during the expeditions to the Baltic Sea, Lake Peipsi, and other Estonian lakes as well as to some Finnish lakes. The main objective has been to investigate the possibilities of solving the passive optical remote sensing inverse problem for the conditions of turbid waters.

The results obtained by PEGASUS measurements have been discussed in some earlier papers (Miller et al., 1988, 1990; Arst et al., 1992, 1993; Arst & Kutser, 1994; Kutser et al., 1995a, b, c). However, none of these publications contains a detailed description of the PEGASUS measuring system.

The objective of the present paper was to describe PEGASUS as a measuring system. The interpretation and analysis of the data set, obtained by the measurements *in situ* (during expeditions) are not included in this paper. However, for demonstrating the values and shape of the spectra of the radiation characteristics under consideration, we present two examples of the measurement results. In Fig. 6 (*a*, *b*, *c*) the spectra of E_d, L_u, and r are shown. One example is for the open Baltic (open sea south from Gotland) and the other is for Lake Võrtsjärv. As one can see, these regions have quite different Secchi disk transparencies and also the values of L_u, and r as well as their spectral distributions are remarkably different.

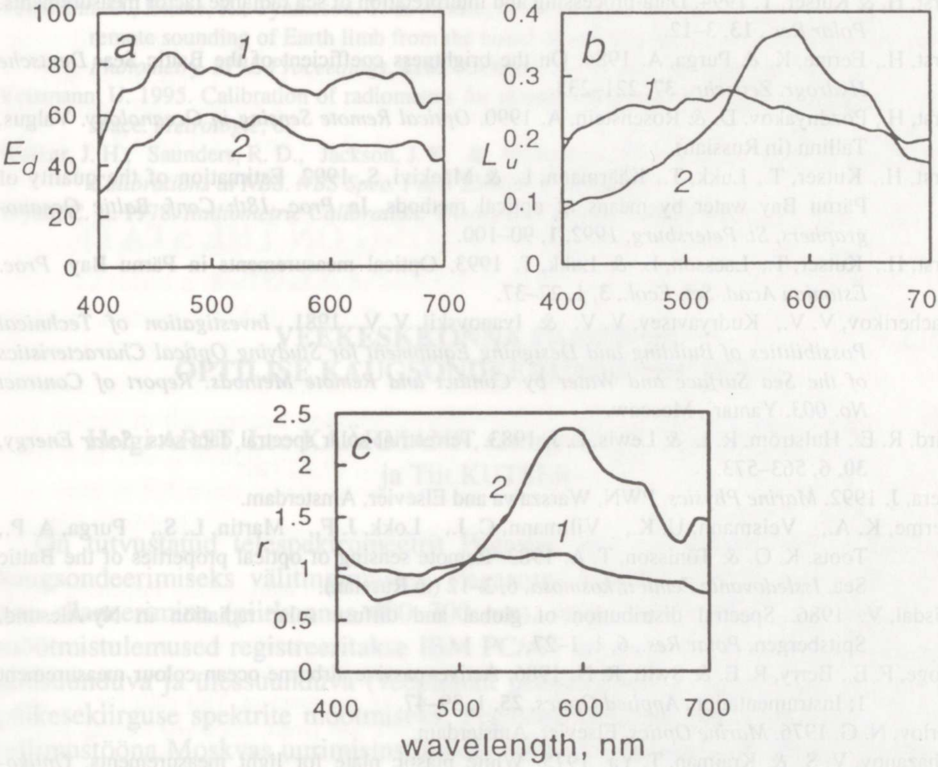

Fig. 6. Two examples of the PEGASUS measurement results: *1*, Baltic Sea, 4 September 1995, the solar zenith angle $\vartheta_0 = 54°$, 8 Cu, Secchi disk depth SD = 5 m; 2, Lake Võrtsjärv, 31 July 1995, $\vartheta_0 = 65°$, clear sky, SD = 0.7 m: *a*, the spectra of downward irradiance E_d (in $\mu\text{Wcm}^{-2}\text{nm}^{-1}$); *b*, the spectra of upward from nadir point radiance L_u (in $\mu\text{Wcm}^{-2}\text{nm}^{-1}\text{sr}^{-1}$); *c*, the spectra of radiance factor *r* (%).

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VEEKESKKONNA PASSIIVSE OPTILISE KAUGSONDEERIMISE SÜSTEEM

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On tutvustatud telespektromeetrit Pegasus, mis on ehitatud veekeskkonna kaugsondeerimiseks välitingimustes. Pegasuses toimub valgusspektri mehaaniline skaneerimine (piirkonnas 400–700 nm), valgusdetektoriks on fotokordisti, mõõtmistulemused registreeritakse IBM PC/AT arvuti abil. Aparaat on mõeldud allasuunduva ja ülessuunduva (veepinnalt peegeldunud ja veest tagasi hajunud) päikesekiirguse spektrite mõõtmiseks. Pegasuse esialgne katseeksemplar valmis tellimustööna Moskvas uurimisinstituudis VNIIOFI, hiljem ehitas seda ümber ja täiustas Eesti Mereinstituudi mereoptika rühm. Alates 1987. aastast on seda mõõtekompleksi korduvalt kasutatud Eesti Mereinstituudi ekspeditsioonidel ja tulemuste põhjal avaldatud mitmeid publikatsioone. Käesolevas artiklis on kirjeldatud aparatuuri plokke, töö põhimõtteid ja metoodikat ning kaliibrimist, ühtlasi on antud ülevaade võimalikest mõõtevigade allikatest.