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DOUBLE BEAM SPECTROPHOTOMETER FOR SIMULTANEOUS MEASUREMENT OF THE UPWELLING SEA RADIANCE AND THE INCIDENT SEA IRRADIANCE

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ABSTRACT

The article describes the structure and the operation principle of the spectrophotometer developed on the basis of a compact rapid monochromator with one input port and two output ports and a radiometric unit where upwelling radiation radiance and sea surface irradiance channels are located. A new approach to measurements of spectral characteristics of upwelling radiation of sea based on combination of advantages of a double beam photometer with a photomultiplier and a direct-reading photometer with a high-stability silicon photodiode for its absolute adjustment in energy units is implemented.

Keywords: marine desk spectrophotometer, instrumental measurements, spectral radiance factor

1. INTRODUCTION

The main parameter of water quality monitoring from outer space is spectral radiance factor of water layer $R_{rs}(\lambda)$ (SRFWL) determined by spectral radiance concentration (SRC) of upwelling radiation at upper boundary of the atmosphere measured by spectral radiometers of ocean colour satellite scanners. SRC is a secondary optical characteristic of waters and depends on features of marine water and irradiation of water surface [1]:

$$R_{rs}(\lambda) = \frac{L_w(\lambda, 0^+)}{E_d(\lambda, 0^+)}, \tag{1}$$

$$L_{wN}(\lambda) = R_{rs}(\lambda) \cdot F_0(\lambda), \tag{2}$$

where $L_w(\lambda, 0^+)$ is the SRC of upwelling water layer; $E_d(\lambda, 0^+)$ is the spectral irradiance concentration (SIC) on the sea surface; 0^+ shows that the parameter is measured directly above the sea surface; $L_{wN}(\lambda)$ is the normalised SRC of upwelling water layer; $F_0(\lambda)$ is the SIC from the Sun on the outer boundary of Earth atmosphere (at average distance between the Earth and the Sun).

Using SRF values, both primary optical characteristics of water and content of optically active components (phytoplankton pigments, dissolved organic matter and mineral particles) can be defined. This became possible due to development of semi-analytical and empirical algorithms which establish relation between one or several bio-optical characteristics and SRF or normalised SRC of upwelling sea water. Enhancement of these algorithms, in turn, is related to performance of field measurement requiring application of highly precise spectrophotometers.

In-situ measurements are required also for validation of upwelling water layers values SRC obtained on the basis of satellite data. The procedure of concordance of the latter with the values obtained in actual conditions is an important and mandatory element of remote sensing of ocean from space [2, 3], which requires large-scale sub-satellite measurements.

The sea truth (sub-satellite) measurements are performed using stationary platforms, buoy stations and vessels [4–9]. The measurements performed using stationary platforms are capable to provide long dynamic series of data for one area, usually in waters with optical properties varying insufficiently, which is important for compensational adjustment of satellite data. The vessel measurements, on the contrary, are required for short-term measurements in the waters of seas and oceans with optical properties varying significantly. That is why they are extremely important for development of bio-optical algorithms.

The existing contact methods are based on measurements of SRC upwelling water layers (UWL) directly above or under the sea surface [4–10]. Each of them has its own advantages and disadvantages. The vessel spectrophotometers most often apply the method of measurement of UWL SRC directly above the sea surface. The total sea SRC $L_{tot}(\lambda)$ measured in this case is a sum of UWL SRC ($L_w(\lambda, 0^+)$) and spectral concentration (SC) of the sky radiation reflected by the sea. To separate these components, the device should contain two relevant optical channels and the third one for measurement of SIC on the sea surface [7–10].

In foreign practice, three identical spectrophotometers simultaneously measuring the total SRC of the sea, the SRC of sky radiation and SIC of the sea surface are used for vessel measurements [7–9]. In this case, there is a disadvantage due to necessity of absolute calibration of each optical channel which is hard to be performed with high precision both in conditions of expedition and in stationary metrology laboratories due non-availability of relevant spectral radiation standards.

Russian practice applies vessel photometers measuring total SRC of the sea, SRC of sky radiation and sea surface SIC alternately (with high frequency) by means of one photo detector (PMT) via different optical channels [11]. The disadvantage of this method is low precision of absolute measurements of the said values in wide ranges of their magnitudes. This is caused by the fact that, first, the signals of radiance and irradiance channels differ from each other by one or two orders of magnitude, and second, depending on the illuminance conditions (clouds, sunny day), these signals may be changed by several orders of magnitude, and these changes may occur simultaneously and several times in the course of measurement. So, high precision absolute measurement of two spectral magnitudes by the PMT, highly depending on illumination conditions, is difficult because of necessity to maintain continuity of PMT sensitivity for a long period of time. Moreover, definition of absolute values requires separate calibration of each optical channel and, as mentioned above, impossibility to obtain more precise calibration in conditions of expedition, which lowers precision of measurements.

Application of a differential photometer [12] measuring SRFWL allows to increase precision of measurements significantly since it does not require absolute optical channels calibration and provides optimal conditions for operation of PMT. But in order to validate SRC upwelling sea water layer, which is defined by using satellite data, and for a number of application tasks, it is also important to know absolute values of SRC for upwelling sea layer and SIC for sea surface apart from SRFWL.

This article proposes a new approach to measurements of spectral characteristics of upwelling radiation of sea based on combination of advantages of a double beam differential photometer with a photomultiplier as a photo detector [12] and a direct-reading photometer with a high-stability silicon photodiode for its absolute calibration in energy units. The structure of a marine desk multifunctional spectrophotometer (MDMS) based on the proposed approach allowing measurements both SRFWL and absolute values of sea surface SIC, which are used for recovery of absolute values of upwelling sea water layers SRC, is described.

2. THE STRUCTURE OF THE MARINE SHIP-BASED MULTIFUNCTIONAL SPECTROPHOTOMETER

MDMS (Fig. 1) contains a photometric unit installed on the slit of the M150 monochromator and a photoelectric module (Fig. 2).

The photometric unit (Fig. 2) contains two optical channels for measurement of upwelling sea water layers SRC and sea surface SIC respectively. The first one is made in the form of an optical head *4* consisting of a lens *3* and a mirror *5* deflecting radiation beam by 90°. The focal distance of the lens *3* is 180 mm and it is determined by the selected structure of the photometric unit; the lens is made of KV fused quartz glass with high transparency within the whole set spectral range of (350–800) nm. The diameter of the lens, 54 mm, is calculated with consideration of necessity of concordance between the angle of view of the sea radiance channel and the monochromator relative aperture. For the purpose of mounting convenience, the mirror *5* is made in the form of an ellipse with axial dimensions of 52×74.5 mm and of fused quartz glass too. The optical head *4* is capable to be rotated so that it provides SRC measurements of upwelling water layer and sky radiation SRC between nadir and zenith. For this purpose, the optical head is mounted on the cover *8* of the body of the photometric unit by means of a rotary joint *6* with a waterproof gasket *7*. The rotating structure of the optical head also allows it to select the area of sea surface free of sun glares in the course of measurements.

The SIC sea surface measurements channel (Fig. 2) consists of a flat cosine collector *2* and of a glare shield *13*. Without taking additional measures, at high radiation angles of incidence (exceeding 60°), due to relation between the reflectance factor of the flat surface of the collector and this angle, distortion of cosine distribution of the measured signal occurs. Due to this fact, the relevant recommendations of [13] were taken into account in design of the cosine collector (Fig. 3). The mounting seat for the cosine collector is a socket on the body of the photometric unit, which forms the required angle of view equal to 85° and provides the height of the collector above the body equal to 2 mm. The cosine collector itself is a disk with diameter of 38 mm and thickness of 3 mm made of MS-13 frosted glass glued together with a disk made of KV fused quartz with diameter of 40 mm and thickness of 3 mm. By means of this disk, the collector is mounted to the body of the photometric unit leak-proof. Such structure of the collector provides formation of spatial characteristic with inaccuracy not exceeding 8 % [13].

Fig. 1. Exterior of the marine desk-based multifunctional spectrophotometer (MDMS)

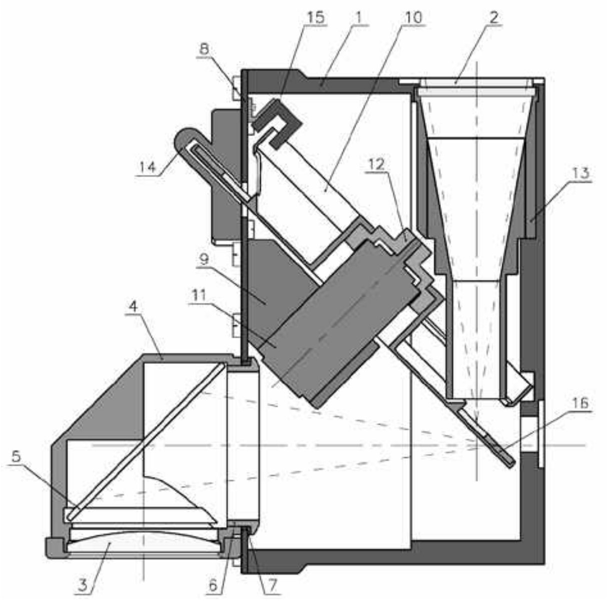

Fig. 2. Structure of the radiometric unit of MDMS

By means of the rotating modulator *10* three beams get into the monochromator from the SRC of upwelling water layers and SIC of sea surface channels by turns at high speed: one from the SRC channel and two others from the SIC channel (Fig. 2). The modulator *10* is a disk with gaps and sectors made of dark polished glass *16*. Reflective coating is applied to surfaces of the polished sectors. This makes the radiation from the irradiance collector reflect in the form of two beams with one of them reflecting from the polish surface of the sector and the other one reflecting from the reflective coating, which multiplies intensity of the second beam by many times. The modulator *10* is rotated by micro electric motor *11* (DC hollow anchor collector motor DPR-42-F1–03 type and motor speed 4500 rotations/min). This motor has an important distinction for marine field devices, as it is designed for continuous operation and has a long service life. On the inside of the body cover *8*, there is a photon-coupled pair *15,* which generates synchronous impulses at the moment each beam gets into the input port of M150 monochromator. Outside the cover part of the modulator *10* is protected by a waterproof casing *14*.

For elimination of background illumination, the case *1* of the photometric unit and all plastic parts are made of black graphite-filled caprolon and the modulator *11* and all other parts made of duralumin are blacking by galvanizing.

The photometric unit is mounted on the input port of the universal compact M150 monochromator-spectrograph manufactured by SOLAR LS

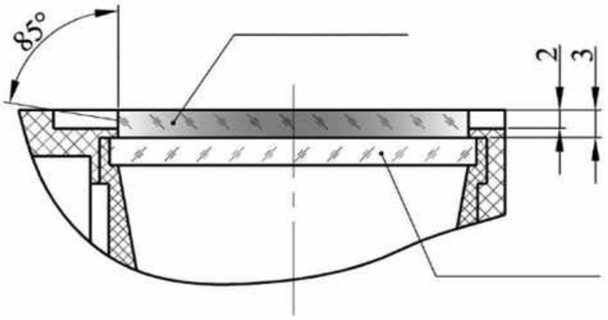

Fig. 3. Structure of the flat cosine collector of MDMS

[14]. M150 contains one input port and two output ports. The entrance slit is automatic, blades opening width is controlled by means of the device software. Both exit slits are equipped with precision focusing devices and superfine adjustment of the width of exit slits is performed manually by means of micro screws.

As shown in Fig. 4, both direct sun radiation and radiation diffused by sky get into the cosine collector *1* of the sea surface SIC channel. Inside the body of the photometric module, the radiation from the cosine collector *1* moves along the glare shield (item *13* in Fig. 2) and gets on the mirror sector *5* via the relevant slit of the modulator *4*. The upwelling radiation from the sea gets on the plano-convex lens *2* of the radiance channel. The optical head of the radiance channel is capable to rotate around the body of the photometric module, which allows directing it to the area of sea surface free of sun glares. The radiation beam from the plano-convex lens *2* (shown by three arrows) is redirected by an elliptical flat mirror *3* and, after passing the relevant slit of the modulator *4*, is focused in the relevant part of the entrance slit of the monochromator *7*.

The modulator *4* inclined at angle of 45° alternately directs the radiation beams through the gaps in the 90° sector from the said optical channels to the entrance slit of the monochromator *7*. The photon-coupled pair (item *15* in Fig. 2) generates synchronous impulses at the moment each beam gets into the slit. Opposite to the modulator slit, through which the beam from the SIC sea surface channel goes, there is a reflective sector *5* (made of dark glass) divided into two parts: the upper one with frontal reflective coating and with reflectance 98 % and the lower one without coating and with reflectance about 5 %. The radiation beam from the SIC channel is divided into two beams after being reflected from the reflective sector: the upper one, more intensive (shown with one arrow) and the lower one, with intensity less by order of magnitude (shown with two arrows) each of which is redirected to the relevant part of the entrance slit of the monochromator *7*. Additionally, in order to divide the beams from the SIC channel into the upper one and the lower one, there is a thin light-dividing plate (not shown) opposite the entrance slit of the monochromator *7*.

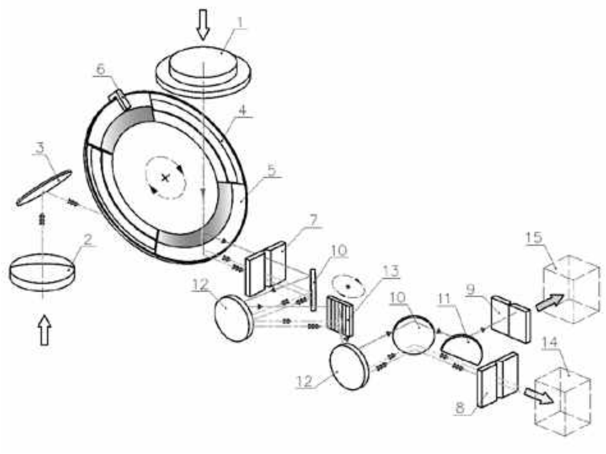

Fig. 4. Optical scheme of MSMS

The lower beam from the SIC channel is aligned with the optical axis of the beam from the SRC channel by the lower part of the reflective sector *5* (for convenience, these beams are dislocated in relation to each other in Fig. 4). These beams are alternately directed to the exit slit *8* of the monochromator where they get into the photoelectronic unit with PMT *10* thus implementing the scheme of the double beam photometer with one photo detector. After PMT, the signals from the SRC and SIC channels (lower beam of radiation) get into the recorder and then into the analogue unit (not shown) for SRFWL determination by finding ratio between these signals. With ratio between the signals of two channels measurements, it is not necessary to maintain continuous sensitivity of PMT, which is necessary in case of absolute measurements of SRC and SIC. By means of feedback from the recorder, the PMT splitter is supplied with slowly changing high voltage which adjusts sensitivity of PMT proportionately with average value of signals thus providing optimal operation conditions for the photo detector of the double beam spectrophotometer.

In the monochromator, the spectrum of the upper beam of radiation from the SIC channel is scanned and the beam is reflected by the mirror *11* to the second slit of monochromator *9* where it gets into the photoelectric unit with a high-stability silicon photodiode *12* thus implementing the scheme of the direct-reading photometer for absolute measurements of sea surface SIC.

As a result of measurements, the electronic unit obtains voltages equal to absolute values of SIC and SRFWL which allow us to recover absolute values of upwelling sea water SRC at the stage of digital processing.

For absolute measurements of sea surface SIC, a high-stability photodiode for precision measurements is used. The signal from the photodiode is amplified and transferred to a computer via a communication line for its digitalisation, visualisation and further registration. Development of the electric diagram of the SIC channel is currently at the stage of optimisation with consideration of opportunity to apply required components by various manufacturers.

3. CONCLUSION

A new approach to measurements of spectral characteristics of upwelling radiation of sea based on combination of a double beam photometer with a photomultiplier (as a photo detector) and a direct-reading photometer with a high-stability silicon photodiode for its absolute adjustment in energy units is proposed. First, this approach significantly increases precision of measurements since it does not require absolute calibration of optical channels and provides optimal conditions for PMT operation; second, it allows absolute values of SIC and SRFWL to measure simultaneously and uses them further for determination of absolute values of upwelling sea water SRC at the stage of digital processing.

MDMS applying the proposed method may be used for measurement of spectral characteristics of radiation upwelling from the sea layer in field expedition studies both on a vessel moving and on hydrological stations.

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