MEASUREMENT OF THE SEA RADIANCE COEFFICIENT WITH A THREE–CHANNEL SPECTROPHOTOMETER FROM ABOARD A RESEARCH SHIP

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We describe here a three–channel spectrophotometer. It was designed to estimate the sea spectral radiance coefficient by simultaneously recording the intensity of radiation upwelling from the sea surface, the radiance of an adjacent sky area, and the sea surface illumination. Most typical measurement results obtained in different areas of the Mediterranean Sea and the Black Sea are presented. The accuracy of this technique for measuring the spectral radiance coefficient is studied. The greatest contribution to the error under conditions of our measurements is due to the lens effect. The total error in the spectral radiance coefficient measurements did not exceed 6–7%.

Measurements of the sea radiance coefficient (SRC)[1] from aboard a moving ship are necessary component of a ground support observations in order to develop the methods for routine monitoring of different areas of the World Ocean.

The technique for such measurements was tested during the 53rd voyage of the research ship *Akademik Kurchatov* in 1994. This technique is based on the use of a three–channel spectrophotometer. The basis for its design is described in Ref. 2. The spectrophotometer is constructed following the scheme of direct measurements and is intended for measurements of the radiance spectral density of radiation coming from the sea plus that reflected from the sea surface (B_{sea}), the radiance of an adjacent sky area (B_{sky}), and the sea surface irradiation (illumination) (E_{ir}) in the 400–700 nm spectral range with the spectral resolution of 2.5 nm.

The sea radiance coefficient can be found from the values measured by the spectrophotometer using the following equation:

$$\rho_\lambda = [K_1 (B_{sea} - K_2 B_{sky})]/K_3 E_{ir}, \quad (1)$$

where K_1 is the coefficient taking into account a nonideal surface of a white reflector (of plastic) located horizontally above the water surface, which scatters solar radiation; K_2 is the Fresnel reflection coefficient; $K_3 = B_f/E_{ir}$ is the calibration coefficient allowing for the transition from the sea surface irradiation E_{ir} measured by the spectrophotometer to the radiance of the calibrating foam plastic screen B_f.

The block diagram of the three–channel spectrophotometer (meter of the sea spectral radiance coefficient) is shown in Fig. 1. It comprises the optical and electronic parts. The optics includes an optical head and a monochromator. In contrast to the spectrophotometer described in Ref. 2, the optical head of this spectrophotometer uses a modulator (commutator of optical channels). It is made as the mirror *4* rotating at a speed of 9 000 r/m with the help of the motor *5* and the device *6*, generating synchronization pulses. The mirror *4* alternatively directs the light fluxes, coming from the three optical channels: B_{sea}, B_{sky}, and E_{ir}, to the entrance slit *10* of the monochromator. The window *1*, the diaphragm *2*, the neutral light filter *3*, and the entrance slit *10* of the monochromator comprise the sky radiance channel B_{sky}; the window *8*, the diaphragm *7*, and the entrance slit *10* of the monochromator do the sea radiance channel B_{sea}, whereas the light collector *15* of the sea surface irradiation (made of milk glass), the neutral light filter *16*, the beam-folding mirror *17*, and the entrance slit *10* of the monochromator form the irradiation channel E_{ir}. In the optical head of the spectrophotometer there is the fourth (dark) channel, which is used to compensate for the background illumination and the dark current of a PMT.

When the modulator is in operation, the device *6* generates the synchronization pulses at the moments of light fluxes passage through the channels B_{sea}, B_{sky}, and E_{ir}, as well as when scanning the dark channel with a mirror *4*.

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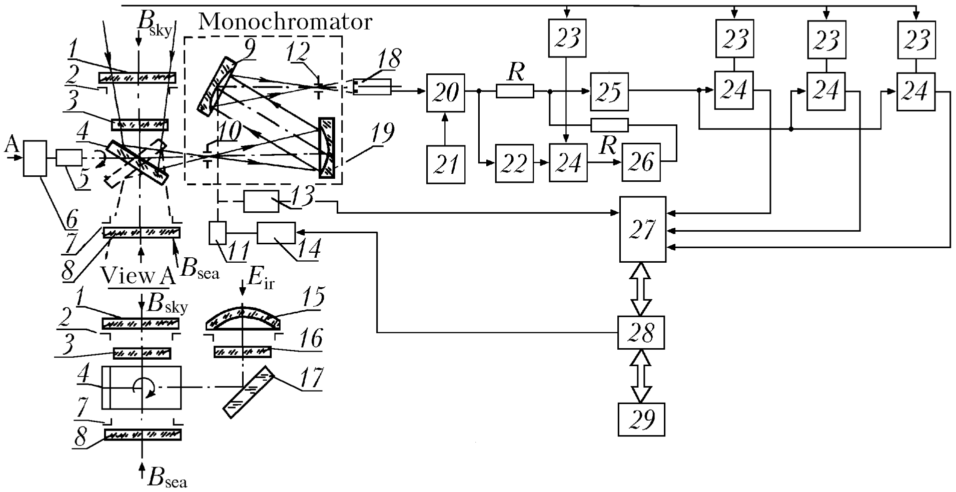

FIG. 1. Functional optoelectronic diagram of the measurer of the sea spectral radiance.

Simultaneously with the commutation of the optical channels, the spectral analysis of the light fluxes is performed. The commutation speed is so high, that signals from all channels are recorded at practically the same wavelength within the monochromator spectral resolution. This allows us to obtain, after an analog processing of signals recorded, the electric signals, proportional to light fluxes dispersed over spectrum in time, at the spectrophotometer exit. Such a way of recording the terms entering into Eq. (1) lowers the error of SRC estimation, caused by the variability of the meteorological conditions during measurements.

The monochromator,[3] being a part of the spectrophotometer, was designed by the Z–shaped Wodsvort scheme on a concave diffraction grating *9* (1200 grooves/mm), which continuously turns about the axis parallel to grooves with the help of a motor *11* and a reducer. An entrance slit *10*, a mirror objective *19*, a diffraction grating *9*, and an exit slit *12* comprise a Z–shaped scheme of the monochromator. The diffraction grating turns in a reversible mode. Direct and reverse runs of the spectral sweep take no more than one minute. A wavelength of the spectral range analyzed is proportional to the diffraction grating turn angle. An electric signal, proportional to the diffraction grating turn angle and, hence, to the wavelength of the spectral range analyzed, is generated in a transducer *13* built around the multiturn wire potentiometer C1–39. The C1–39 potentiometer is of high reliability due to its design and the gold coating of a nichrome wire. The spectrophotometer provides for the mode of setting of a given wavelength of the analyzed spectral range by fixing the position of the diffraction grating. The device *14* switches the spectrophotometer between the modes of continuous scanning over spectrum and setting of a given wavelength. This device is remotely controlled by a command from the control desk or by a program.

The light fluxes recorded, having come through the optical channels B_{sea}, B_{sky}, and E_{ir}, are resolved, by a monochromator, over spectrum. Then a PMT, *18*, FEU-68, installed behind the exit slit *12* of the monochromator, transforms them into the proportional electric signals. These electric signals are then amplified with the matching amplifier *20* built around the operational amplifier KR544UD1A. The PMT operates in a linear mode. Nonlinearity of the PMT performance characteristic is within 0.5% for light fluxes recorded by the spectrophotometer. This is reached by introducing neutral light filters into the channels B_{sky} and E_{ir}, that lowers the PMT maximum current down to 5 μA (the FEU-68 maximum permissible current is 50 μA), and due to relatively large current in the PMT power supply voltage divider (up to 1 mA) which is provided by a high-voltage source *21* (1200 V). The high-voltage PMT power supply voltage divider is mounted on the plate of the matching amplifier *20*.

Then the amplified signal from PMT undergoes analog processing, which consists in compensation for the PMT background illumination and its dark current and in the distribution of PMT pulse signals over the electric channels VB_{sea}, VB_{sky}, and VE_{ir}, corresponding to the optical channels B_{sea}, B_{sky}, and E_{ir}. To this end, at the input of an amplifier–inverter *25*, the PMT signal is added together with the same signal, but inverted in the amplifier *22* and recorded at the moment when there are no light fluxes measured in the channels B_{sea}, B_{sky}, and E_{ir} at the PMT photocathode, i.e. during the scanning of the dark channel with the mirror *4*. For doing this we use a storage *24*. At that instant it is switched on by the corresponding synchronization pulse, coming from the amplifier–generator *23* and stores the value of a signal, proportional to the dark current and the PMT background illumination. Then this positive–polarity signal comes through a follower *26* and a resistor R to the output of the amplifier–inverter *25*, where it is added together with the PMT signal that has a negative polarity. As a result, the signal proportional to the background illumination and the PMT dark current, is subtracted from the net PMT signal. As a consequence, at the output of the amplifier–inverter *25* we have the PMT pulse signals, referred to the zeroth level.

To distribute the PMT pulse signals over the electric channels, the synchronization pulses are used, which come through the amplifier–generators *23* to the controlling inputs of the storages *24*, whereas the amplified PMT pulse signals come to their signal inputs. At the outputs of the storages *24* we thus have the constant voltages, proportional to light fluxes coming through the optical channels B_{sea}, B_{sky}, and E_{ir}. Without light fluxes these voltages are minimal due to their reference to the zeroth level and are determined by PMT noise and a drift (temperature, temporal, etc.) of the operational amplifiers, which are parts of the storages *24* and serve as output and matching devices.

As a result, constant voltages, proportional to light fluxes, are generated at the spectrophotometer output. These voltages together with the voltage proportional to the wavelength of the spectral range analyzed are fed to the analog-to-digital converter *27*, which is controlled by an IBM PC/AT computer *28*. The specialized computer program computes the values of SRC, which are then displayed and stored in a recording system *29* in real time.

Before performing measurements of the sea spectral radiance coefficient in the expedition, the device's spectral scale has been graduated using interference light filters. As a result, the operating wavelength range has been found, which is from 400 to 700 nm.

The channels of the sea radiance and the sky radiance have also been calibrated. To make correct measurements, these channels should necessarily be identical in their optical parameters (it is provided by the spectrophotometer design), and the transmission (amplification) ratios of the electric channels should be equal.

The channel of sea irradiation was calibrated in the following way. The device was installed above a horizontal foam plastic screen, irradiated by the sun. And the sea irradiation channel was directed onto it. A neutral light filter with a known transmission coefficient was introduced into the channel. The spectra of B_{f} and E_{ir} signals were recorded, and thus the above-mentioned coefficient K_3 was obtained.

Let us now estimate the error of SRC determination following the above technique under conditions of our experiments. Main contributions to the resultant error are given by the following errors: the error σ_ρ^{ins} determined by the instrumental error of recording the radiance and the irradiation in the three channels ($\sigma_{B_{\text{sea}}}$, $\sigma_{K_2 B_{\text{sky}}}$, $\sigma_{E_{\text{ir}}}$); the error σ_ρ^{c} arising when estimating the blackness coefficient K_1 of the diffuse reflector and the transmission ratio K_3 in calibration, the errors σ_ρ^{n}, σ_ρ^{ref}, and $\sigma_\rho^{\text{lens}}$ due to nonuniform brightness of the sky area reflected, as well as the sea roughness. Let us estimate the values of these components as far as our experimental conditions are concerned. The value of σ_ρ^{ins} can be found from the expression

$$\sigma_\rho^{\text{ins}2} = [K_1/(K_3\,E_{\text{ir}})]^2\,(\sigma^2_{B_{\text{sea}}} + \sigma^2_{K_2\,B_{\text{sky}}}) + \rho^2\,(\sigma^2_{E_{\text{ir}}}/E^2_{\text{ir}}). \quad (2)$$

The spectrophotometer design gives $\sigma_{B_{\text{sea}}} = \sigma_{K_2 B_{\text{sky}}} = \sigma_{E_{\text{ir}}} = \sigma_B$. The additive component of this error has been measured at completely closed channels and was 2.5 mV. The multiplicative component due to nonlinear transformations in the optoelectronics was no more than 0.005 for the dynamic range used. The signals varied from 0.5 to 5 V. Having substituted these values into Eq. (2), we find that the instrumental error does not exceed $2\cdot10^{-4}$ for small SRC and $3\cdot10^{-4}$ for large SRC ($\rho \sim 0.05$).

The calibration coefficients were determined accurate to at least 3% of their values, therefore the error $\sigma_\rho^{\text{c}} < 0.03\rho$. Moreover, this error is systematic and does not affect the SRC spectral dependence.

It has been noticed when recording the signals B_{sea}, B_{sky}, and E_{ir} that when two channels B_{sky} and E_{ir} give, as one would except, a slightly noisy signals, recorded from the channel B_{sea} is a fluctuating signal with a mean amplitude of variations about 10% of the mean signal value. Under conditions of our experiments these fluctuations were caused by the lens effect on the sea surface (the effect of double focusing).[4] Really, if the conditions for SRC measurements are optimal: the open sun ($\odot^2$), the sun elevation $30° \le h_\odot \le 60°$, cloudless conditions at least within the solid angle ±45° from the zenith, sea disturbance of 0÷1 degree, the sight line being at an angle no more than 10° from the vertical, the influence of the nonuniformity of the brightness field of the sky area reflected upon the error of SRC determination is small. The deviation of the Fresnel reflection coefficient, occurring at a rough surface under these conditions, from 0.02 is also insignificant, therefore the error of SRC determination when calculating the fraction of reflected radiation in the net signal is also much smaller than the instrumental one: (σ_ρ^{n}, $\sigma_\rho^{\text{ref}} \ll \sigma_\rho^{\text{ins}}$). At the wind speed above 4 m/s the influence of these factors upon the error of SRC determination grows and can be taken into account following Refs. 5 and 6.

As to the lens effect, when performing measurement from aboard a research vessel even at the optimal observation conditions it is well pronounced due to small sea area falling into the device's field of view. This effect causes the fluctuation of the signal in the B_{sea} channel. The influence of the lens effect upon the error of SRC determination can be decreased by averaging several records of the B_{sea} spectral dependence ($\sigma_\rho^{\text{lens}} = \left(\dfrac{K_1\,B_{\text{sea}}}{K_3\,E_{\text{ir}}}\right)(\overline{\sigma_{B_{\text{sea}}}/B_{\text{sea}}})$). Owing to this procedure the relative error of SRC determination was decreased down to 5%, that, however, is greater than both calibration and instrumental errors. Thus, the resultant error of SRC estimation did not exceed 6–7%.

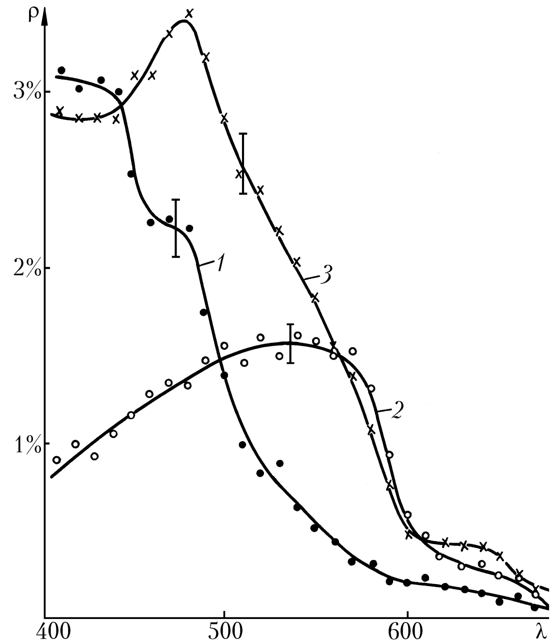

FIG. 2. Spectral dependences of the sea radiance coefficient measured with the three-channel spectrophotometer from aboard the research ship Akademik Kurchatov *(53rd voyage, 1994) in the Aegean Sea (1), the Sea of Marmara (2), an the Black Sea (3).*

The measurements were performed from aboard the research ship being in motion in the Mediterranean and Black Seas. All dependences obtained can be divided into three groups. Most typical results are shown in Fig. 2. Transparent waters are characterized by the dependence of the type *1* (the Aegean Sea), whereas for turbid waters the dependence of the type *2* is typical (the Sea of Marmara). In addition, the dependence of the intermediate type was observed: the waters have low transparency and maximal SRC values are observed in the green spectral range due to relatively high chlorophyll concentration (curve *3*, the Black Sea).

Thus, the measurements from aboard a moving ship with the three-channel spectrophotometer give a possibility of obtaining the spectral dependence of the sea radiance coefficient accurate to 6–7%. These spectral dependences can be used to identify the type of waters by the classification[7] and to estimate the chlorophyll concentration, contents of suspended matter and other components of the sea waters.

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