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Calculation of the remote sensing reflectance based on the total upwelling radiance measured from the ‘Optik’ Tu-134 aircraft laboratory

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ABSTRACT

A method has been developed for calculating the spectral remote sensing reflectance based on the total upwelling radiance measurements, carried out from the ‘Optik’ Tu-134 aircraft laboratory over the Kara Sea on September 10, 2022. Data on the spectral downwelling irradiance and the reference remote sensing reflectance were obtained during synchronous under-aircraft measurements from the R/V ‘Akademik Mstislav Keldysh’. To calculate the remote sensing reflectance, a simple two-parameter formula is proposed (with the relative error of 7%), the application of which allows one to separate the reflected from the surface radiation and take into account the variability of sky conditions due to the influence of variable cloudiness.

Keywords: remote sensing reflectance, water-leaving radiance, sea surface reflection, ‘Optik’ Tu-134 aircraft laboratory, Arctic seas

1. INTRODUCTION

The spectra of the remote sensing reflectance $R_{rs}(\lambda)$ carry information about the bio-optical characteristics of the seawater surface layer, the values of which are widely used in estimates of the biological productivity of the ocean, for environmental monitoring and ocean heat content calculations. At present, satellite ocean color scanners are the main source of such data, which makes it possible to conduct research on a wide spatial and temporal scale. The practice of using satellite data on the remote sensing reflectance in the Arctic shows that, for a number of reasons, these data often have high errors associated with atmospheric correction uncertainty[1]. To refine the atmospheric correction algorithms, as well as to validate the results of their work, sub-satellite measurements of the remote sensing reflectance are carried out. Such measurements are usually performed on ship expeditions, from offshore platforms (AERONET-OC) and using buoys (MOBY, BOUSSOLE). The advantage of airborne measurements is the significantly greater spatial coverage and correspondingly more validation data. Airborne measurements are quite rare due to their high cost, although they have been carried out for more than half a century[2]. In this paper, we present a method that makes it possible to calculate the $R_{rs}(\lambda)$ from the data of airborne measurements of total upwelling radiance $L_t(\lambda)$ and synchronous shipboard measurements of the downwelling irradiance $E_d(\lambda)$, and the results of its application are presented.

2. MATERIALS AND METHODS

The field data were obtained during an under-aircraft experiment performed during the 1st stage of the 89th cruise of the R/V ‘Akademik Mstislav Keldysh’ (AMK) on September 10, 2022 in the southwestern part of the Kara Sea. The total upwelling radiance spectra $L_t(\lambda)$ were obtained using a PSR-1100f spectroradiometer with a spectral range of 320–1100 nm and a spectral resolution of <3 nm, installed on board the Tu-134 “Optik” laboratory aircraft[3]. The spectra were recorded when the receiver was set to nadir, the angle of the field of view of the receiver lens was 4°, the recording was carried out once every 15 seconds, which, at an aircraft speed of about 120 m/s, corresponds to a spatial data resolution of 1.8 km. On board the vessel we measured the values of the downwelling spectral irradiance at the sea surface level (RAMSES spectroradiometer: spectral measurement range – 300–950 nm, spectral resolution - 3 nm, registration of the spectrum every 5 minutes) and the seawater remote sensing reflectance (PRO-1 floating spectroradiometer: spectral measurement range – 390-700 nm, spectral resolution – 2 nm).

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The measurements were carried out in calm weather (wind speed was about 1 m/s). The sky was covered with translucent stratocumulus clouds. The solar zenith angle was 67°. The map of the aircraft route and the position of the ship at the time of under-aircraft operations (station 7440) are shown in Figure 1. For calculations, only points obtained at flight altitudes below 100 m (circled points in Figure 1) were used, which makes it possible to ignore the influence of the atmosphere.

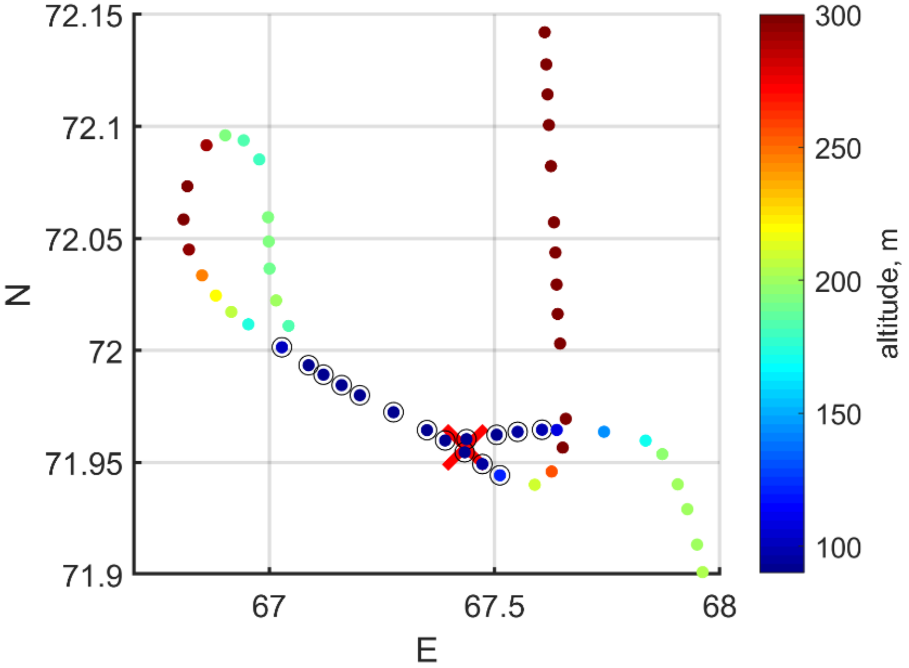

Figure 1. Scheme of the experiment. The dots indicate the position of the Tu-134 aircraft at the time of registration of the radiance spectra, the color indicates the flight altitude; the cross is the ship's position (station 7440). For calculations, we used data obtained at altitudes below 100 m (circled). The Kara Sea, September 10, 2022.

3. RESULTS

To calculate the values of $R_{rs}(\lambda)$, the formula is used:

$$R_{rs} = \pi \frac{L_u}{E_d} = \pi \frac{L_t - L_{sky}}{E_d} \tag{1}$$

where L_u is the water-leaving radiance, L_t is the total upwelling radiance (including both radiations reflected from the surface and water-leaving radiance), L_{sky} is the radiance reflected from the sea surface. The radiances and downwelling irradiance in this equation depend on the wavelength λ, which is not shown explicitly.

There is not enough information about the radiation reflected from the surface to directly calculate the desired value. It depends on various factors, such as cloud cover parameters, sun height, wind speed, and the state of the rough sea surface[4,5]. It is proposed to eliminate the influence of all these factors by a simple two-parameter formula:

$$R_{rs} = a \frac{\pi L_t}{E_d} + b \tag{2}$$

where a is a scaling factor that takes into account the L_u acquisition geometry and changes in illumination conditions that have occurred between upwelling and downwelling fluxes measurements. The b/a ratio should be considered as an ‘integral’ Fresnel coefficient, which takes into account the contribution of the downwelling radiation reflected from the surface.

The selection of the values of these coefficients was carried out by the least squares method in comparison with the ‘reference’ spectrum of the seawater remote sensing reflectance, measured using a floating spectroradiometer. The result of the calculation ($a = 0.22$, $b = 0.005$) is shown in Figure 2. The relative error in estimating R_{rs} from aircraft data was 7%.

It is important to note that the resulting value *b/a* = 2.3% corresponds to the value of the Fresnel coefficient for close to the nadir viewing angles.

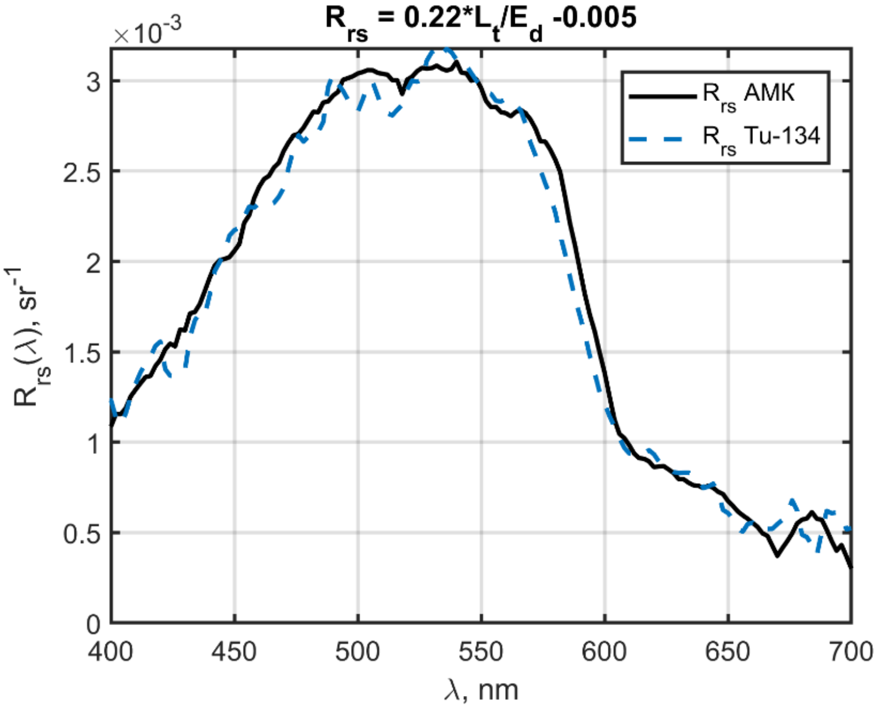

Figure 2. The result of the spectral seawater remote sensing reflectance calculation in comparison with the synchronously obtained data of the floating spectroradiometer performed onboard the R/V ‘Akademik Mstislav Keldysh’ (AMK).

4. DISCUSSION

Apparently, the main drawback of the resulting simple model is the assumption that reflection from the surface is nonselective. It was shown in[5] that the values of the reflection coefficients from the sea surface for wavelengths of 400 nm and 800 nm can differ significantly, which is primarily due to waves. Our experiment was carried out in almost calm conditions, which made it possible to neglect the influence of waves and wind. In addition to changing the shape of the sea surface these factors can lead to the formation of sea foam which significantly affects surface albedo. It is known that large errors in the measurement of R_{rs} values arise due to the variability of cloudiness parameters. For example, it was shown in[4] that the influence of this factor caused up to 86% of errors in the results of R_{rs} measurements on the transatlantic transect performed in 2018. At the time of obtaining the data used in this work, the state of the cloud cover was not favorable, however, it did not experience significant changes, which made it possible to obtain fairly accurate data on the seawater remote sensing reflectance.

Further development of the technique involves the use of only data on the total upwelling radiance obtained from the aircraft. The first step towards this is the parametrization of the downwelling irradiance changes due to different cloudiness conditions. An example of one of the possible approaches to achieve this goal is shown in Figure 3.

5. CONCLUSION

A method has been developed for calculating the values of the seawater remote sensing reflectance from the total upwelling radiance spectra, obtained from an aircraft, and the downwelling irradiance spectra, measured from a ship during an under-aircraft experiment. The results of comparison with the "reference" values of the measured quantity under variable cloudiness in calm weather showed good agreement (the relative error is 7%). In the future, it is planned to tune the model to take into account the influence of the state of the sea surface, characterized by wind speed, as well as to perform calculations without using field data on the downwelling irradiance.

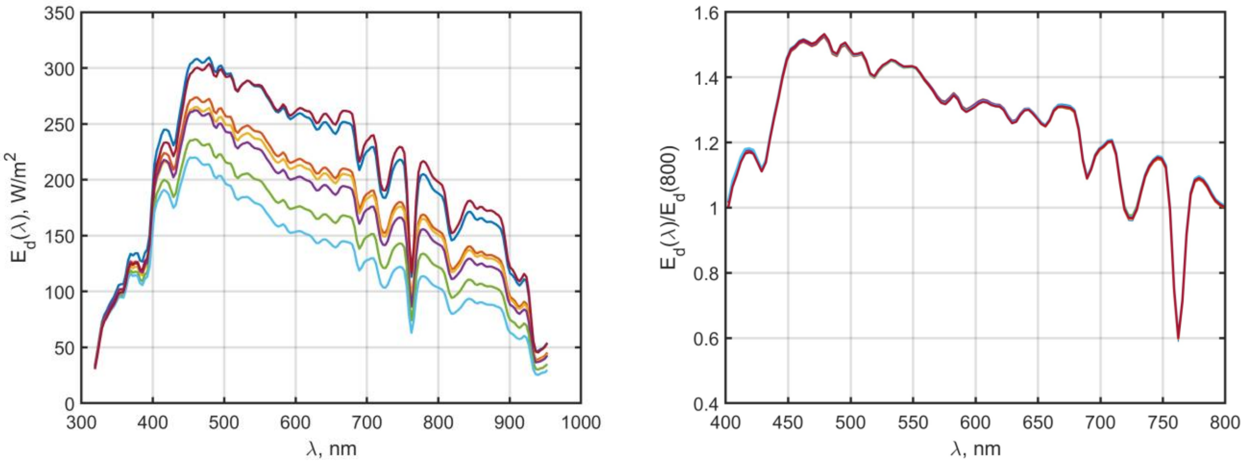

Figure 3. The result downwelling irradiance parametrization. Left: measured E_d spectra; right: converted with accordance to different cloud conditions and normalized at 800 nm spectra. The Kara Sea, September 10, 2022.

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