# Multispectral Ecological Control of Parameters of Water Environments Using a Quadrocopter

**Serhii Kvaterniuk, Vasyl Petruk, Orest Kochan and Valeriy Frolov**

**Abstract** The aim of the work is to improve the methods and means of environmental monitoring of the parameters of aqueous media using a quadrocopter with a multispectral camera. The process of indirect measurement of biomass and pigment parameters of phytoplankton in the near-surface layer of the water objects is investigated. Instrumental and methodical errors of indirect measurements in the near-surface layer of the aquatic environment with the use of the developed means of ecological control are analyzed. The effect of changes in the spectral characteristics of illumination was corrected with respect to the object with known spectral characteristics of the diffuse reflection coefficient. In the course of multiple regression, regression equations were obtained that allow determining biomass and pigment parameters of phytoplankton based on processing of multispectral images. An analysis of measurement errors was used when using the eight-channel multispectral cameras CMS. Optimal wavelengths of spectral channels and their number are selected from the condition of ensuring a minimum value of the total error.

**Keywords** Ecological monitoring · Multispectral measurements · Water · Phytoplankton

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## 1 Introduction

One of the important factors negatively affecting the quality of the surface waters is their anthropogenic eutrophication, which lies in a rapid increase in the trophicity of the water bodies as a result of the arrival of biogenic elements and organic substances in them, in quantities significantly exceeding the usual natural levels. Anthropogenic eutrophication leads to excessive overgrowth of standing reservoirs and an increase in the content of blue-green algae. Phytoplankton is one of the bio-indicators of the ecological status of water bodies in accordance with the EU Water Framework Directive (WFD) 2000/60 [1].

When harmonizing the environmental protection system of Ukraine with EU legislation, it is necessary to improve the monitoring system for anthropogenic pollution of aquatic environments. In this case, it is possible to obtain an integral parameter characterizing the toxic effect of all contaminants present in the water—toxicity, only by the method of biotesting [2–5]. In order to obtain high reliability of ecological control of the toxicity of aquatic environments, it is necessary in this way to select bioindication test objects, their test parameters, and methods and means for their measurement in order to ensure sufficient accuracy of measurement of these test parameters. For further research, phytoplankton was chosen as the test object, and the phytoplankton biomass concentration and the ratio between the main pigment parameters of phytoplankton, chlorophyll a, total chlorophyll and carotenoids in the near-surface water layer were chosen as test parameters.

At the same time, optical methods of control are a promising direction for improving the means of ecological control of phytoplankton biomass in water bodies [6, 7]. In comparison with them, acoustic methods for controlling the parameters of aqueous media have less reliable control [8].

Unmanned aerial vehicles have been used extensively throughout the world since the 1970s to investigate and locate local “bloom spots” for cyanobacteria in the near-surface water layer. The complex solution of the tasks of managing the ecological safety of water bodies requires the improvement of methods and tools for multispectral environmental measurement of water parameters. With the use of a quadrocopter, it is necessary to increase the accuracy of measurements of biomass and pigment parameters of phytoplankton in the near-surface layer of aqueous media using the multispectral method.

## 2 Materials and Methods

Methods of multispectral measurement control occupy an important place in solving applied problems of ecological monitoring of water bodies. However, at present, they are not developed enough and require the continuation of research in order to increase the speed and accuracy. In [7] a proposed method for monitoring the environmental status of water bodies in the parameters of phytoplankton by flow multispectral television measuring analyzer continuous particle when comparing particle image on characteristic wavelengths pigments using a CCD camera with images from the database in real time and determine the number of particles of phytoplankton. In [9] the method used for the multispectral remote satellite environmental control content phytoplankton in aquatic objects, which allowed analyzing the spatial distribution of the concentration of the phytoplankton in aquatic objects with high resolution. The choice of characteristic wavelengths for the study of the phytoplankton samples of reservoirs is determined by the spectral dependences of the relative efficiency of phytoplankton pigment absorption [10].

To investigate the contamination of water bodies with hazardous waste components, as well as to assess the toxicity of water, specialized biosensors have been developed, that allow the detection of heavy metal ions, unsuitable pesticides and other toxic substances in aqueous media [11–14].

For biological assessment of water toxicity, there are a number of methods and means using different test organisms. In particular, the methods of biological assessment of water toxicity are proposed in [15], Mclnnis [16], using *ceriodaphnia* (*Ceriodaphnia* affinis Lilljeborg), as test objects, as a measure of the physiological state of the *ceriodaphnia*, the number of living mobile ceridiophony is used. The disadvantage of the device is the possible errors of the operator when calculating the number of mobile daphnia. The multispectral method is more suitable for measuring parameters of aqueous media with phytoplankton or higher aquatic plants. In [17], the multispectral method was used for rapid non-destructive testing of objects that differ only in the presence of certain biochemical markers. In [18], the multispectral method is used for remote sensing and environmental control of the environment based on a multiwave lidar, which during the scanning of the surface by a laser forms an array of multispectral images. In [19], algorithms for processing multispectral images are proposed that allow increasing the resolution and determining the spatial distribution of certain pigments in inhomogeneous media with greater accuracy. The analysis of existing optical methods for monitoring the parameters of water environments showed their imperfection and the inability to solve an applied problem for the needs of environmental monitoring, which necessitated the improvement of methods and tools for multispectral environmental measurement control. The essence of the method of multispectral measurement control is the analysis of digital images of the investigated object, obtained in several spectral ranges [20–22]. Similar approaches are also used for environmental monitoring of noise in different spectral ranges [23]. Conditionally, spectral television measurements are divided into one-spectral (panchromatic, number of channels $N = 1$), multispectral (number of channels $2 \leq N \leq 99$), hyperspectral (number of channels $100 \leq N \leq 999$) and ultraspectral (number of channels $N > 1000$). After processing the obtained array of multispectral images, it is necessary to indirectly measure the parameters of heterogeneous aqueous media in each pixel of the image. This is done on the basis of solving the inverse optical problem taking into account the mathematical model of inhomogeneous aqueous media [24–26]. Mathematical models of light transformation in the near-surface layer of inhomogeneous aqueous media take into account the concentrations of the main pigments, the structural features of the near-surface layer, the wavelength of the incident radiation, and the degree of its polarization. The method of experimental studies and environmental measurement control based on the processing of multispectral images of an object obtained by a CCD camera at characteristic wavelengths must ensure with high reliability the control of the state of the object and its near-surface structure. Measurement of the concentrations of the main pigments in the near-surface layer of inhomogeneous aqueous media is carried out by analyzing the array of multispectral images of the test object and comparing them with an array of multispectral images of model media with known concentrations of pigments obtained under certain defined experimental conditions.

The processing of the results of multispectral measurements can be performed using a neural network or a neural-fuzzy network, which will allow the surface to be divided into segments with different phytoplankton biomass values or the ratio between its pigments [26, 27]. The coordinates in the multispectral n-dimensional space are determined on the basis of the spectral characteristics of the radiation sources, filters, photomatrix and the object of control. When using multispectral cameras with light filters at the inputs of photomatrix elements, the system of equations for determining the coordinates in the n-dimensional multispectral space:

$$\begin{cases} M_1 = \sum_{i=1}^{i_{\max}} P(\lambda_i) s_1(\lambda_i) R_d(\lambda_i) \Delta\lambda, \\ M_2 = \sum_{i=1}^{i_{\max}} P(\lambda_i) s_2(\lambda_i) R_d(\lambda_i) \Delta\lambda, \\ \qquad \ldots \\ M_n = \sum_{i=1}^{i_{\max}} P(\lambda_i) s_n(\lambda_i) R_d(\lambda_i) \Delta\lambda, \end{cases} \tag{1}$$

where $P(\lambda_i)$—spectral characteristic of a radiation source, $s_n(\lambda_i)$—spectral characteristic of the nth channel of the multispectral camera, $R_d(\lambda_i)$—spectral characteristic of diffuse reflection coefficient of a research object.

## 3 Experimental Procedure

Spectral characteristics of the coefficient of diffuse reflection on the surface of the natural aqueous medium were calculated in [24–26] in the small-angle approximation for such parameters of phytoplankton: the biomass of phytoplankton varies from 17.7 to 35.4 mg/l; the ratio between chlorophyll a and total chlorophyll in phytoplankton is 0.8; the ratio between carotenoids and total chlorophyll 0.27. The content of chlorophyll in the raw mass of phytoplankton is assumed to be 0.5%. Spectral characteristics of the absorption index, scattering index and anisotropy factor for an aquatic environment without phytoplankton, but with the presence of suspended particles of organic origin, are introduced into the mathematical model by means of approximation from the results of experimental studies [28]. Similar studies were also conducted to study the effect of hazardous components of industrial and domestic waste on water bodies using bioindication on phytoplankton [29–35]. The effect of localized absorption of radiation as a function of the shape and size of the absorbing phytoplankton particles and the presence of higher aquatic plants in the aquatic environment is accounted for by correction factors calculated on the basis of experimental studies and numerical modeling [36–43]. The diffuse reflection coefficient R was calculated in the quasi-single-scattering approximation [44]. It includes small-angle light propagation to the scattering point, single scattering in the "backward" direction, and again small-angle propagation in the opposite direction.

As a source of radiation, natural solar radiation is used, the averaged spectral characteristic of the radiation density of which, taking into account the absorption in the atmosphere, is shown in Fig. 1, a. Multispectral environmental monitoring uses eight-channel multispectral CMS cameras (Silios Technologies, France) with the following main parameters [45]: CMS-C spectral range from 400 to 700 nm, CMS-V—550–850 nm, CMS-S—650–950 nm; the resolution of the monochromatic channel is 1280 × 1024 pixels; the resolution of spectral channels 426 × 339 pixels; the size of one pixel is 5.3 µm; bit depth of analog-to-digital converter 10 bits; exposure time from 10 µs to 2 s; weight 59 g. The spectral sensitivity characteristic of the multispectral cameras of the CMS series is shown in Fig. 1b–d. The results of calculating multispectral parameters from known spectral characteristics when phytoplankton biomass is changed and using eight-channel multispectral cameras of the CMS series of various types, are shown in Fig. 2.

Since the spectral characteristics of natural solar radiation at the water surface level are constantly changing, it is necessary to normalize the results of multispectral measurements from the quadrocopter relative to an object with known spectral characteristics, for example, a floating platform with a white diffusely reflecting surface with a barium sulfate coating. The necessity of always getting a part of this surface into multispectral images reduces the real resolution of the camera. For indirect measurement of the phytoplankton biomass according to the results of multispectral measurements are used only normalized values multispectral parameters.

The results of calculating multispectral parameters from known spectral characteristics when changing the pigment parameters of phytoplankton and using eight-channel multispectral cameras of the CMS series of various types are shown in Fig. 3.

## 4 Results and Discussion

The solution of the inverse optical problem for the determination of phytoplankton biomass in aqueous media based on the results of multispectral measurements is carried out by means of multiple regression in the program STATISTICA 6.0. Using stepwise regression, we will analyze multispectral parameters that make it possible to determine the biomass of phytoplankton more accurately (Table 1).

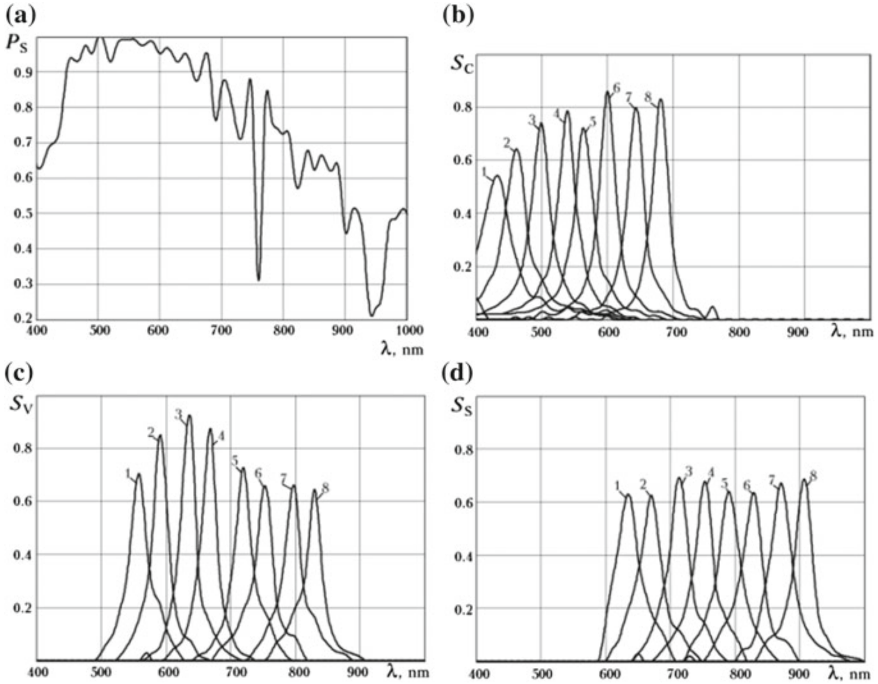

**Fig. 1** Normalized spectral characteristics: **a** natural solar radiation, **b** the sensitivity of the spectral channels of the CMS-C camera (400–700 nm), **c** the sensitivity of the spectral channels of the CMS-V camera (550–850 nm), **d** the sensitivity of the spectral channels of the CMS-S camera (650–950 nm)

In the course of multiple regression for the indirect measurement of phytoplankton biomass in water bodies using the CMS multispectral cameras, the following regression equations were obtained:

$$\begin{aligned} B_{CMS\_C} = {} & 0.057154618 - 0.475979 M_{C\_7\_642} - 0.472422 M_{C\_5\_563} \\ & - 0.287206 M_{C\_6\_600} + 0.355161 M_{C\_2\_461} - 0.343838 M_{C\_4\_536} \\ & + 0.237081 M_{C\_1\_430}, \end{aligned} \tag{2}$$

$$\begin{aligned} B_{CMS\_V} = {} & 0.058691384 - 0.196036 M_{V\_4\_669} - 0.283101 M_{V\_6\_752} \\ & - 0.150405 M_{V\_8\_829} - 0.1319 M_{V\_7\_795} - 0.122064 M_{V\_5\_719} \\ & - 0.118101 M_{V\_3\_635}, \end{aligned} \tag{3}$$

$$\begin{aligned} B_{CMS\_S} = {} & 0.062431853 - 0.330180 M_{S\_5\_790} - 0.283269 M_{S\_6\_827} \\ & - 0.170174 M_{S\_7\_871} - 0.138106 M_{S\_3\_713} - 0.107677 M_{S\_4\_752} \\ & + 0.153303 M_{S\_1\_635} - 0.12637 M_{S\_2\_669}, \end{aligned} \tag{4}$$

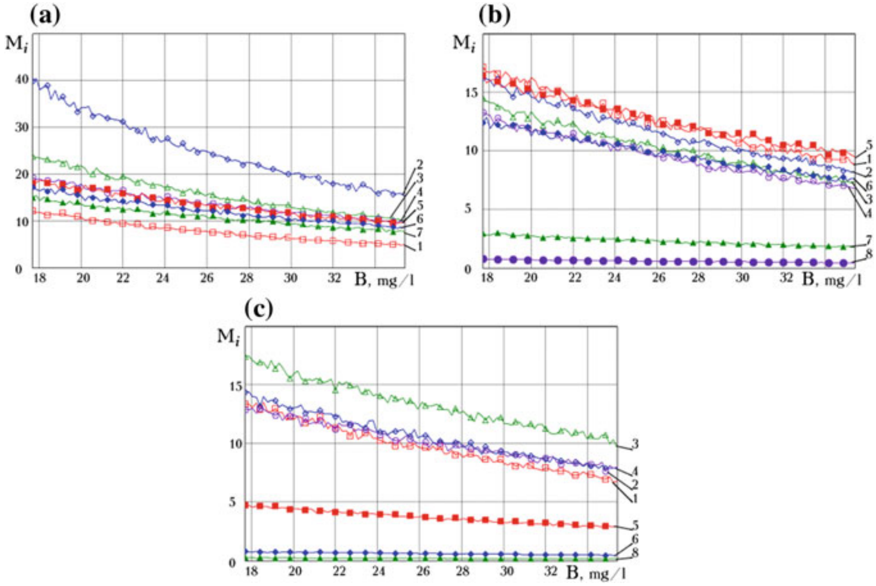

**Fig. 2** Dependence of multispectral parameters upon changes in phytoplankton biomass from 17.7 to 35.4 mg/l and using multispectral cameras of the CMS series: **a** CMS-C, **b** CMS-V, **c** CMS-S

where $B_{CMS\_C}$, $B_{CMS\_V}$, $B_{CMS\_S}$—the biomass of phytoplankton determined with the help of multispectral cameras CMS-C, CMS-V, CMS-S; $M_{i\_j\_k}$—multispectral parameters of camera of ith type, jth spectral channel, kth wavelength in nm.

Using stepwise regression, we analyze the multispectral parameters that allow the most accurate determination of the pigment parameters of phytoplankton. An example of the results of calculating multiple regression for the indirect measurement of the ratio between chlorophyll and total chlorophyll phytoplankton from multispectral measurements using CMS-C camera, is shown in Table 2.

In the course of multiple regression, the following regression equations were obtained for the indirect measurement of the ratio between chlorophyll and total phytoplankton chlorophyll in an aqueous medium using the CMS multispectral cameras:

$$\begin{aligned} Chl\_a/Chl_{CMS\_C} &= 0.287843623 + 0.209036M_{C\_4\_536} + 0.195614M_{C\_5\_563} \\ &\quad + 0.149845M_{C\_7\_642} + 0.140127M_{C\_6\_600} + 0.110152M_{C\_1\_430} \\ &\quad + 0.133364M_{C\_2\_461} + 0.112934M_{C\_3\_499}, \end{aligned} \tag{5}$$

$$\begin{aligned} Chl\_a/Chl_{CMS\_V} &= 0.29904534 + 0.18592M_{V\_2\_593} + 0.21701M_{V\_1\_560} \\ &\quad + 0.153637M_{V\_5\_719} + 0.12818M_{V\_7\_795} + 0.111973M_{V\_8\_829} \\ &\quad + 0.157482M_{V\_3\_635} + 0.087702M_{V\_6\_752}, \end{aligned} \tag{6}$$

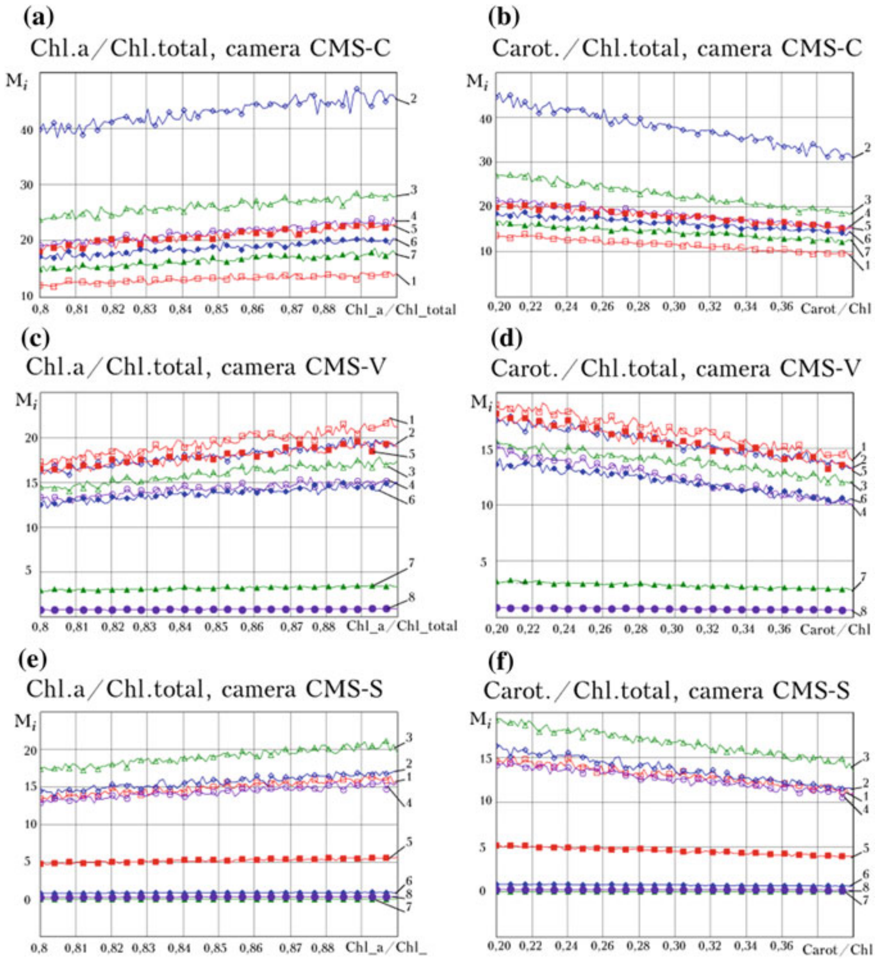

**Fig. 3** Dependencies of multispectral parameters when changing pigment parameters and using multispectral CMS cameras

$$\begin{aligned} Chl\_a/Chl_{CMS\_S} = {} & 0.236112976 + 0.198943 M_{S\_3\_713} + 0.190275 M_{S\_2\_669} \\ & + 0.173474 M_{S\_5\_790} + 0.148602 M_{S\_4\_752} + 0.134188 M_{S\_6\_827} \\ & + 0.144415 M_{S\_8\_906} + 0.063497 M_{S\_1\_635}, \end{aligned} \tag{7}$$

where $Chl\_a/Chl_{CMS\_C}$, $Chl\_a/Chl_{CMS\_V}$, $Chl\_a/Chl_{CMS\_S}$—ratio chlorophyll a/total chlorophyll of phytoplankton, determined using multispectral cameras CMS-C, CMS-V, CMS-S; $M_{i\_j\_k}$—multispectral parameters of camera of ith type, jth spectral channel, kth wavelength in nm.

**Table 1** Results of multiple regression calculation for multispectral measurements

| N | λ, nm | F | $\delta_m$, % | R |
|---|---|---|---|---|
| *Camera CMS-C* (400–700 nm) | | | | |
| 1 | 642 | 4144 | 0.08 | 0.988 |
| 2 | 642, 563 | 3012 | 0.07 | 0.992 |
| 3 | 642, 563, 600 | 2134 | 0.07 | 0.993 |
| 4 | 642, 563, 600, 461 | 1721 | 0.06 | 0.993 |
| 5 | 642, 563, 600, 461, 536 | 1473 | 0.06 | 0.994 |
| 6 | 642, 563, 600, 461, 536, 430 | 1261 | 0.06 | 0.994 |
| *Camera CMS-V* (550–850 nm) | | | | |
| 1 | 669 | 5077 | 0.0717393 | 0.990 |
| 2 | 669, 752 | 3993 | 0.0574001 | 0.994 |
| 3 | 669, 752, 829 | 2982 | 0.0542694 | 0.995 |
| 4 | 669, 752, 829, 795 | 2378 | 0.0526532 | 0.995 |
| 5 | 669, 752, 829, 795, 719 | 1966 | 0.0518029 | 0.995 |
| 6 | 669, 752, 829, 795, 719, 635 | 1648 | 0.0516476 | 0.995 |
| *Camera CMS-S* (650–950 nm) | | | | |
| 1 | 790 | 5508 | 0.07 | 0.991 |
| 2 | 790, 827 | 4191 | 0.06 | 0.994 |
| 3 | 790, 827, 871 | 3336 | 0.05 | 0.995 |
| 4 | 790, 827, 871, 713 | 2644 | 0.05 | 0.996 |
| 5 | 790, 827, 871, 713, 752 | 2156 | 0.05 | 0.996 |
| 6 | 790, 827, 871, 713, 752, 635 | 1797 | 0.05 | 0.996 |
| 7 | 790, 827, 871, 713, 752, 635, 669 | 1562 | 0.05 | 0.996 |

**Table 2** Multiple regression calculation results for indirect measurement of the ratio between chlorophyll and total chlorophyll

| N | λ, nm | F | $\delta_m$, % | R |
|---|---|---|---|---|
| 1 | 713 | 661 | 1.1 | 0.933 |
| 2 | 713, 669 | 655 | 0.78 | 0.965 |
| 3 | 713, 669, 790 | 673 | 0.63 | 0.977 |
| 4 | 713, 669, 790, 752 | 681 | 0.55 | 0.983 |
| 5 | 713, 669, 790, 752, 827 | 644 | 0.51 | 0.986 |
| 6 | 713, 669, 790, 752, 827, 906 | 604 | 0.48 | 0.987 |
| 7 | 713, 669, 790, 752, 827, 906, 635 | 522 | 0.48 | 0.988 |

In the course of multiple regression, the following regression equations were obtained for the indirect measurement of the relationship between carotenoids and total phytoplankton chlorophyll in an aqueous medium using the CMS multispectral cameras:

$$\begin{aligned} Carot/Chl_{CMS\_C} = {} & 0.904790007 - 0.195685M_{C\_3\_499} \\ & - 0.185798M_{C\_2\_461} - 0.180862M_{C\_1\_430} \\ & - 0.092616M_{C\_6\_600} - 0.12339M_{C\_5\_563} \\ & - 0.108316M_{C\_7\_642} - 0.12995M_{C\_4\_536}, \end{aligned} \tag{8}$$

$$\begin{aligned} Carot/Chl_{CMS\_V} = {} & 0.990208189 - 0.18979M_{V\_4\_669} \\ & - 0.147313M_{V\_1\_560} - 0.143672M_{V\_6\_752} \\ & - 0.119588M_{V\_8\_829} - 0.132849M_{V\_5\_719} \\ & - 0.122272M_{V\_7\_795} - 0.098624M_{V\_2\_593} \\ & - 0.06482M_{V\_3\_635}, \end{aligned} \tag{9}$$

$$\begin{aligned} Carot/Chl_{CMS}\_S = {} & 0.976892083 - 0.208828M_{S\_3\_713} \\ & - 0.212616M_{S\_2\_669} - 0.115506M_{S\_5\_790} \\ & - 0.172868M_{S\_4\_752} - 0.159507M_{S\_6\_827} \\ & - 0.143343M_{S\_8\_906}, \end{aligned} \tag{10}$$

where $Carot/Chl_{CMS\_C}$, $Carot/Chl_{CMS\_V}$, $Carot/Chl_{CMS\_S}$—ratio carotenoids/ total chlorophyll of phytoplankton, determined using multispectral cameras CMS-C, CMS-V, CMS-S; $M_{i\_j\_k}$—multispectral parameters of camera of ith type, jth spectral channel, kth wavelength in nm.

Let's analyze the instrumental component of the error of multispectral measurements when using multispectral cameras of the CMS series with a bit depth of 10 bits and a signal-to-noise ratio of 60 dB. In this case, the analog-to-digital conversion error arises due to a finite number of allowed signal levels for level quantization $\delta_{ADCccd}$ and instrumental error due to the presence of noise and random interference in the camera $\delta_{noice\_ccd}$. We compute instrumental error due to the presence of noise and random noise in the multispectral camera:

$$\delta_{noice\_ccd} = \frac{100\%}{10^{D_{s/n}/20}} = \frac{100\%}{10^{60/20}} = 0.1\%. \tag{11}$$

The quantization error $\delta_{ADCccd}$ with a large number of discharges can be described by a rectangular distribution law corresponding to the equal probability density of the quantization error in the range $\pm h_q/2$, where $h_q$ is the quantization step. Taking into account the maximum and minimum signal levels on the elements of the matrix:

$$\delta_{ADCccd} = \frac{F_H}{2 \cdot F_{Xmax} \cdot 2^n} 100\% = \frac{1}{2 \cdot 2^{10}} 100\% = 0.049\%. \tag{12}$$

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The average value of the quantization error:

$$\delta_{SD\_ADCccd} = \frac{\delta_{ADCccd}}{\sqrt{12}} = 0.014\%. \tag{13}$$

Let us determine the random component of the measurement error of each coordinate in n-dimensional multispectral space on the basis of the root-mean-square values of components:

$$\delta_{rand.Mi} = \sqrt{\delta^2_{noise\_ccd} + \delta^2_{SD\_ADCccd}} = \sqrt{0.1^2 + 0.014^2} = 0.101\%. \tag{14}$$

The random component of the measurement error is determined by the random components of the measurement error in each of the spectral channels, so the total random component of the error of the indirect measurements will be determined by the random errors of the corresponding multispectral parameters in the regression equation:

$$\delta_{instr} = \sqrt{\sum_{i=1}^{N} \delta^2_{rand.Mi} + 2\sum_{i=1}^{N} \sum_{j<i} R_{ij}\delta_{rand.Mi}\delta_{rand.Mj}}, \tag{15}$$

where $\delta_{rand.Mi}$, $\delta_{rand.Mj}$—the random error component in the ith and jth channel; $R_{ij}$—the correlation coefficient between the multispectral parameters obtained after multiple regression; $N$ is the total number of channels.

For the three-channel means the instrumental component of the error, taking into account the correlation coefficients between the results of measurements from different channels, was 0.303%, for four-channel means 0.35% and for the six-channel means 0428%. The total error in measuring the biomass of phytoplankton will be determined by the sum of the instrumental and methodological errors:

$$\delta_{gen} = \delta_{instr} + \delta_m. \tag{16}$$

In this case, the value of the total error in measuring the biomass of phytoplankton for three-channel means—0.367%, for four-channel means 0412% and for six-channel means 0.487%. An analysis of errors in multispectral measurements of the pigment parameters of phytoplankton in aqueous media is given in Table 3.

Therefore, since the instrumental component of the measurement error increases with the number of channels, than decreased methodical component of error, then the total biomass measurement error of the phytoplankton will increase with the increase in the number of spectral channels of the multispectral control. When measuring the ratio between chlorophyll a and total phytoplankton chlorophyll using multispectral cameras, a minimum total error is obtained for a three-channel measuring instrument using a CMS-C type camera and operating wavelengths of 536, 563 and 642 nm. When measuring the ratio between carotenoids and total chlorophyll of phytoplank-

**Table 3** Analysis of errors in multispectral measurements of pigment parameters of phytoplankton in aqueous media

| N | $\delta_{instr}$, % | CMS-C | | CMS-V | | CMS-S | |
|---|---|---|---|---|---|---|---|
| | | $\delta_m$, % | $\delta_{gen}$, % | $\delta_m$, % | $\delta_{gen}$, % | $\delta_m$, % | $\delta_{gen}$, % |
| *Chlorophyll a/Chlorophyll total* | | | | | | | |
| 1 | 0.175 | 0.897 | 1.072 | 0.849 | 1.024 | 1.058 | 1.233 |
| 2 | 0.247 | 0.658 | 0.905 | 0.64 | 0.887 | 0.777 | 1.024 |
| 3 | 0.303 | 0.562 | 0.865 | 0.539 | 0.842 | 0.634 | 0.937 |
| 4 | 0.35 | 0.529 | 0.879 | 0.51 | 0.86 | 0.549 | 0.899 |
| 5 | 0.391 | 0.503 | 0.894 | 0.482 | 0.873 | 0.506 | 0.897 |
| 6 | 0.428 | 0.476 | 0.904 | 0.459 | 0.887 | 0.478 | 0.906 |
| 7 | 0.463 | 0.459 | 0.922 | 0.449 | 0.912 | 0.476 | 0.939 |
| *Carotenoids/chlorophyll total* | | | | | | | |
| 1 | 0.175 | 0.981 | 1.156 | 1.062 | 1.237 | 1.161 | 1.336 |
| 2 | 0.247 | 0.695 | 0.942 | 0.791 | 1.038 | 0.805 | 1.052 |
| 3 | 0.303 | 0.575 | 0.878 | 0.673 | 0.976 | 0.668 | 0.971 |
| 4 | 0.35 | 0.528 | 0.878 | 0.616 | 0.966 | 0.592 | 0.942 |
| 5 | 0.391 | 0.5 | 0.891 | 0.568 | 0.959 | 0.533 | 0.924 |
| 6 | 0.428 | 0.471 | 0.899 | 0.533 | 0.961 | 0.5 | 0.928 |

ton, the minimum total error is obtained for a three-channel facility using a CMS-C type camera and operating wavelengths of 499, 461 and 430 nm.

## 5 Conclusion

The method of ecological control of biomass concentration and pigment parameters of phytoplankton in the near-surface layer of natural water media is improved in measurements using a quadrocopter with a multispectral camera. A solution of the inverse optical problem for determining the biomass of phytoplankton in natural aqueous media was obtained based on the results of multispectral measurements using the eight-channel multispectral CMS cameras (Silios Technologies) and corresponding regression equations were obtained. Comparing the values of the methodological error in measuring phytoplankton biomass for the cameras of this series, operating in different wavelength ranges, the smallest error value is obtained for the camera, operating in the range of 650–950 nm (CMS-S). Comparing the values of the methodological error in measuring the pigment parameters of phytoplankton for cameras of this series operating in different wavelength ranges, the smallest error value was obtained for a camera that operates in the range 400–700 nm (CMS-C). There was analyzed a methodical and tool change component of the phytoplankton biomass measurement error by increasing the number of spectral channels. Optimum wavelengths of spectral channels and their number for indirect measurement of biomass and pigment parameters of phytoplankton in natural water media are selected from the condition of ensuring the minimum value of the total error.

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