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ABSTRACT:

New technique and special double-pulse LIDAR system for measurements of horizontal distributions of phytoplankton photosynthetic activity are described. By using this technique it is possible to carry out express remote monitoring of sea surface from a board of moving carrier (vessel, helicopter, aircraft) with a high spatial resolution (up to 100 m). Photosynthesis efficiency is estimated by the value of relative yield of chlorophyll-a variable fluorescence. The results of laboratory experiments and the examples of applications in oceanography investigations are reported.

KEY WORDS: Lidar, Phytoplankton, Photosynthetic activity, Fluorescence

1. INTRODUCTION

Due to a unique feature - the ability of photosynthesis phytoplankton may be considered as a key component of sea, ocean and freshwater ecosystems. It forms the base of various trophic chains and provides effective regulation of oxygen and carbon dioxide concentration in water and atmosphere. For solving many ecological problems there exists a need for development of modern methods for measurements of phytoplankton characteristics, such as chlorophyll concentration and photosynthesis efficiency.

In the present paper the remote technique for measuring horizontal distributions of phytoplankton photosynthetic activity is described.

2. RELATIONSHIP BETWEEN PHOTOSYNTHESIS EFFICIENCY AND CHLOROPHYLL-A FLUORESCENCE YIELD.

One of the main factors which determine the phytoplankton photosynthesis efficiency is functional state of reaction centers (RCs) of photosystem 2 (PS2). Under favorable natural conditions the majority of RCs are in open state ensuring high efficiency of light energy utilization in the primary photosynthetic reactions. Unfavorable influences (nutrients depletion, presence of toxic substances, etc.) cause the increase in the share of closed (inactive) RCs and corresponding reduction of photosynthesis efficiency. Thus the ratio of open and close RCs may be considered as a good indicator of photosynthesis efficiency (Falkowski, 1995).

Chlorophyll-a (*Chl-a*) fluorescence emission accompanies the first stages of primary photosynthetic reactions. In fact, it is one of the channels of excitons energy deactivation. The intensity (Φ_o) of *Chl-a* fluorescence includes so called 'constant' (Φ_c) and 'variable' (Φ_v) components. The first one arises when exciton migrating within light-harvesting antenna towards RC after absorption of light quantum. The 'variable' fluorescence forms as a result of charges recombination ($P680^+Pheo^- \rightarrow P680Pheo$) in close (inactive) RCs. Therefore the yield of 'variable' component Φ_v and consequently the yield of total *in-vivo Chl-a* fluorescence $\Phi_o = \Phi_c + \Phi_v$ both depend on the ratio of open and close RCs (as well as photosynthesis efficiency). Thus Φ_o reaches the minimum value (Φ_c) when all the RCs are open and the maximum (Φ_m) when all the RCs are

close.

The so called 'pump-and-probe' fluorescent technique (Falkowski, 1985) for estimation of algae photosynthetic activity in water samples is based on this background. The initial (Φ_o) and maximum (Φ_m) levels of *Chl-a* fluorescence intensities are measured by special lamp excitation and the value of parameter $\eta = (\Phi_m - \Phi_o) / \Phi_m$ ('the relative yield of variable *Chl-a* fluorescence') is used for quantitative estimation of the efficiency of light energy utilization in primary photosynthetic reactions. According to the practice this is good estimation of total photosynthesis efficiency produced by algae. Our analysis has shown that one can use a simple formula for estimation of percentage of active RCs: $N_{act} (\%) \cong 150 \times \eta$.

3. LASER REMOTE TECHNIQUE FOR *IN SITU* MEASUREMENTS

The method we describe is in fact the laser remote modification of contact 'pump-and-probe' lamp technique and ensures the opportunity of carrying out the *in situ* measurements from the board of moving carrier.

The remote measurements are provided by using laser pulses for excitation of *Chl-a* fluorescence in subsurface water layers. This fluorescence is alternately detected as response to excitation by single probing pulses (Fig.1) and by probing pulses following pumping pulses (Fig.2). In the first case original *Chl-a* fluorescence intensity level (Φ_o) is detected, in the second case - maximum one (Φ_m). As a result the value of relative yield of *Chl-a* variable fluorescence $\eta = (\Phi_m - \Phi_o) / \Phi_m$ is determined. The function of pumping laser pulse is to cause the transition of previously open RCs to closed state at the moment of probing pulse action; the function of probing pulse - to induce fluorescence to be detected.

An important feature of described technique is the normalization (Klyshko, 1978) of detected fluorescence intensity by the intensity of water Raman scattering (Fig.1,2) excited by the same laser pulse in the same probing volume of water. It excludes (Klyshko, 1978) the influence from geometry and registration conditions, incessantly changing during the measurements from the moving carrier.

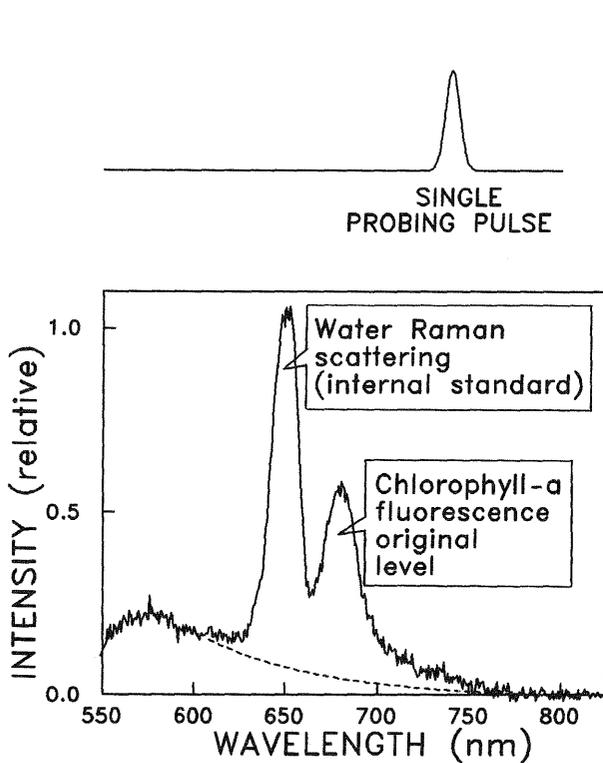


Fig.1 Spectrum of backscattered light from water excited by single laser pulse (excitation wavelength 532 nm).

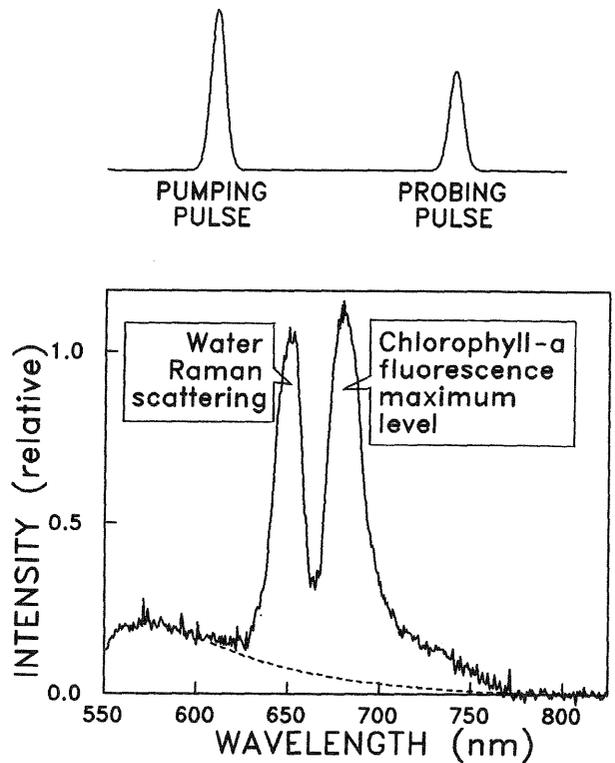


Fig.2 Spectrum of backscattered light from water excited by a probing laser pulse following a pumping one with a delay 40 μ s.

4. DOUBLE-PULSE SHIPBOARD LIDAR SYSTEM

Block diagram of our modern shipboard fluorescent lidar system is presented in Fig.3. It consists of two pulse YAG:Nd-lasers for water excitation, the optical system including optical multichannel analyzer (OMA) for water response detection and spectrum analysis and computer for control of the system and data processing. All the components of lidar (excluding turning mirror) are mounted inside laboratory of a research vessel. Laboratory porthole is used for output of laser irradiance and input of backscattered response from the water.

Pulses of the first laser (irradiance wavelength - 532 nm; pulse duration - 10 ns; pulse power - 3.5 MWt) are used as pumping one to cause the transitions of phytoplankton reaction centers to closed state for the measurements of *Chl-a* fluorescence maximum level under probing pulses excitation. The second laser generates probing pulses for phytoplankton (532 nm; 10 ns; 0.5 MWt) fluorescence excitation. The time delay between pumping and probing pulses in double-pulse mode is about 30-40 μ s. Our estimations and field experiments have proved that described pulses parameters ensured required characteristics of irradiance in the upper layers of seawater (down to 2-5 m of depth) if the distance from lidar to water surface is about 10-15 m.

The construction of optical system ensures coincidence of pumping and probing beam in the same water volume and collection of backscattered optical response at the input aperture of OMA polychromator. The turning mirror is mounted at falseboard of a vessel. The most important part of detection system is the Optical Multichannel Analyzer (OMA) produced by Princeton Applied Research (EG&G, USA) and intended for spectral analysis of optical response from the water. Outstanding operational

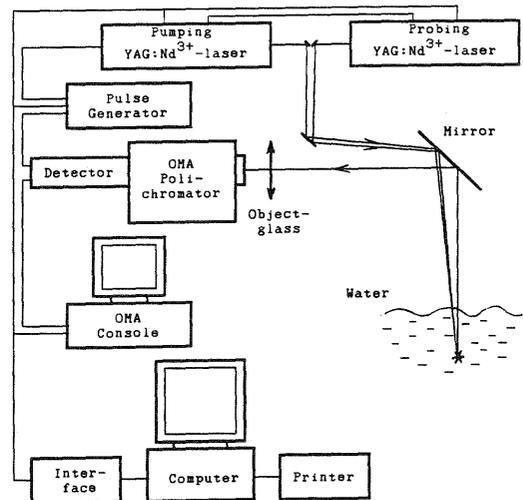


Fig.3 Block diagram of lidar system for remote sensing of phytoplankton photosynthetic activity and chlorophyll-a concentration.

characteristics and reliability of this equipment were tested during more than a dozen expeditions in tough environmental conditions (including tropics and the Antarctic region). The OMA detector is gated by 50 ns pulses synchronized with probing laser pulses, so the system is insensitive to natural sunlight illumination of water surface. This technique enabled us to carry out nonstop day-and-night route measurements of more than 1000 km long.

The IBM-compatible computer interfaced with OMA and

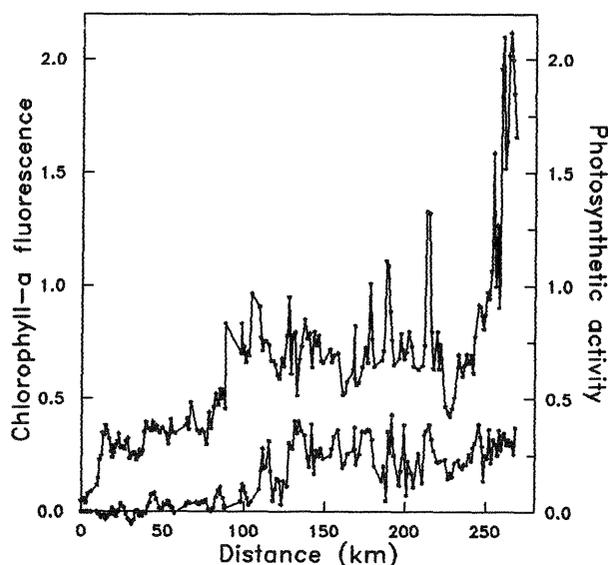


Fig.4 Results of simultaneous laser remote sensing chlorophyll-a fluorescence intensity and phytoplankton photosynthetic activity. The Black Sea, April of 1991.

lasers automatically controls all operations of the lidar system and ensures real-time data processing. Special software was developed to carry out lidar measurements in various modes. Average time duration of one measurement circle (lasers activation, water response spectrum accumulation, data processing) is about 20-30 seconds, ensuring horizontal space resolution of about 100-150 m under boat rate of 10 miles per hour. Spectrum accumulation time is usually about 5-10 seconds, so calculated value of fluorescent parameter Φ is averaged over the distance of 25-50 m. There exist a possibility to change time period between two consequent measurements to vary the mode of lidar activity depending on detected variability of measured parameter. Thus, by measuring from a moving vessel point by point laser induced fluorescence intensity of water admixtures, it is possible to study not only fine structures of their horizontal distributions but also features of meso- and synoptic scales.

The example of simultaneous lidar route monitoring using double-pulse technique is presented in Fig.4. The measurements were carried out in the Black Sea in 1991. One can note considerable mesoscale variability of both *Chl-a* fluorescence and phytoplankton photosynthetic activity.

5. LASER MEASUREMENTS IN THE NORTH-WESTERN ATLANTIC

The first tests of laser method for phytoplankton photosynthetic activity measurements have been carried out in the spring of 1990 in the North-Western Atlantic. As a result we have obtained the valuable information about the character and scales of horizontal variability of the photosynthetic activity and *Chl-a* concentration (Fig.5).

Due to complex hydrobiological situation in the area the values of η varied from 0.2 (low activity, 30% RCs are active) to 0.65 (high activity, 95% RCs are active). The comparison of Fig.5a with Fig.5b can show that the central area of highest photosynthetic activity coincided with position of the powerful and stable anticyclonic ring of synoptic scale. One can see good space correlation between positions of many mesoscale features of photosyn-

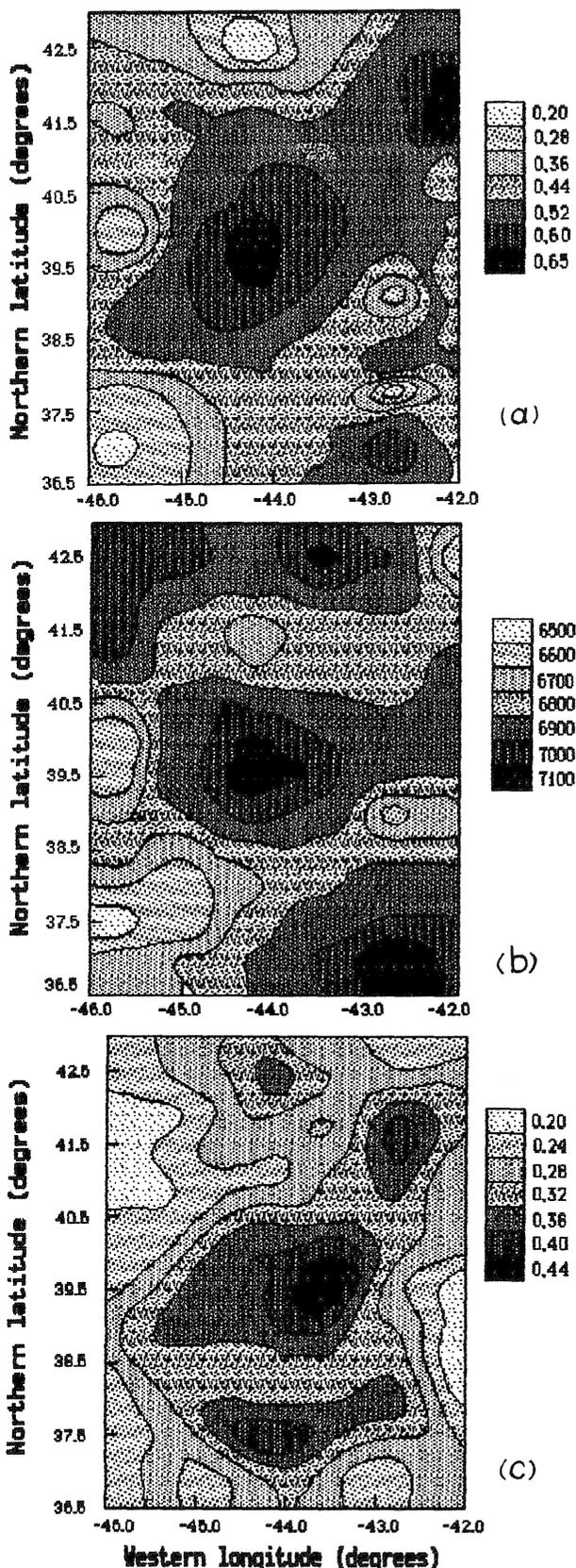


Fig.5 The horizontal distribution of phytoplankton photosynthetic activity in subsurface layer (a), dynamic height (b) calculated using hydrological data from 0 m up to 2000 m depth and characterizing the flows of water masses, and chlorophyll-a concentration (c). The North-Western Atlantic, May, 1990.

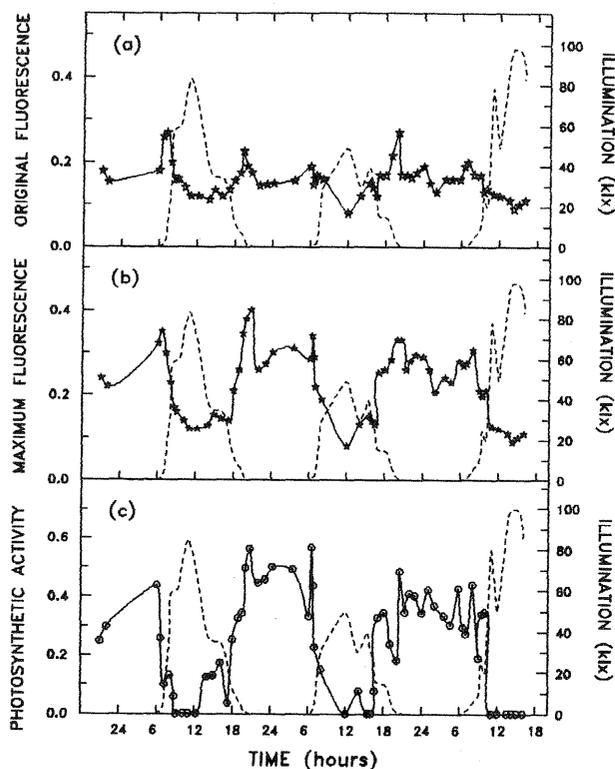


Fig.6 Diurnal rhythms of phytoplankton fluorescence intensity at original level (a) and maximum one (b), and photosynthetic activity (c). The Mediterranean Sea, April of 1991.

thetic activity and dynamic height distributions. Generally the more were values of activity the higher were values of dynamic height.

By comparing Fig 5c with Fig 5a and Fig 5c one can conclude that correlation between the positions of *Chl-a* distribution features with the features of distributions being discussed was not so strong. There was also an area of relatively high *Chl-a* concentrations (up to 0.5 $\mu\text{g}/\text{l}$) located in center of the region, but its position was displaced to the east from the center of the ring.

6. *IN SITU* MEASUREMENTS OF DIURNAL RHYTHMS OF PHOTOSYNTHETIC ACTIVITY AND CHLOROPHYLL FLUORESCENCE

The described technique was also successfully applied for *in situ* investigations of diurnal rhythms of phytoplankton photosynthetic activity and its fluorescence intensity from the board of a vessel. In April, 1991 in the Mediterranean Sea we have carried out special field measurements. Typical time behavior of Φ_0 , Φ_m and $\eta = (\Phi_m - \Phi_0) / \Phi_m$ is shown in the Fig.6. It has been obtained during three days of nonstop measurements. An analysis of the results has shown that the main causes of such variations were photoinhibition and energy-dependent quenching of *Chl-a* fluorescence under influence of natural sunlight illumination variations.

According to our field and laboratory studies, *Chl-a* fluorescence intensity measured by means of lidar technique is modulated due to fluorescence yield diurnal variations described above. Therefore for correct estimation of *Chl-a* concentration on the base of lidar data it is necessary to take into account this diurnal modulation. Its depth of modulation (the ratio of the night maximum values to day minimum ones) may vary from 1 to 3 depending on

the ratio of open and close reaction centers. By using double-pulse lidar technique it is possible to estimate the amplitude of diurnal modulation from the values of measured *Chl-a* variable fluorescence relative yield. Such approach was applied for correction of lidar data presented in Fig.5c.

CONCLUSION

The first applications has proved the potential abilities of presented double-pulse lidar technique for study of marine phytoplankton. As a conclusion we'd like to note that this technique may be used not only for applications described here but also for estimation of phytoplankton primary production as well as for study of photosynthetic activity of higher plants.

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