LASER REMOTE SENSING OF PHYTOPLANKTON AND ORGANIC MATTER IN THE SEA WATER

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ABSTRACT:

The method and equipment are based on the measurement of organic substances laser-induced fluorescence and permit to investigate distributions of chlorophyll-a and organic matter as well as phytoplankton (PP) photosynthetic activity (PPA) from a moving carrier (vessel, helicopter, aircraft). The results of our lidar measurements in the Atlantic, Pacific, Indian, and Antarctic oceans as well as the Baltic, Black and Mediterranean Seas are analyzed and generalized. The problems of spatial variability in local, meso- and synoptic scales, PP patchiness, dynamics of PP bloom, organic pollutions in the coastal zone, space correlation with hydrological structures are discussed.

KEY WORDS: Lidar, Phytoplankton, Chlorophyll, Dissolved organic matter, Algae photosynthetic activity.

1. INTRODUCTION

Laser remote sensing is one of intensively developing methods for study of both Earth surface and atmospheric phenomena. When applying to water media it permits to obtain valuable information about some important ecosystems parameters of oceans, seas and internal water bodies (lakes, rivers, etc.). This technique is based on remote detection and spectral analysis of optical response for laser probing of subsurface water layers. Using special lidar (i.e. laser fluoroscensor) equipment it is possible to carry out express measurements from on board a moving carrier (vessel, helicopter, aircraft). As a result of real-time data processing the horizontal distributions of measuring parameters are obtained with a high spatial resolution (up to 100 m).

In our first field experiments (1974-75) phytoplankton, dissolved organic matter (DOM) and oil pollutions have been found as the most convenient objects for laser remote sensing. These objects provide specific fluorescent contributions to spectra detected (Fig.1). In natural conditions the intensities (I_F) of these spectral bands are comparable with water Raman scattering one (I_R). Both organic admixtures fluorescence and water Raman scattering are similarly influenced by the measurements conditions (distance from the water surface, its form, propagation of light within water media, sensitivity of detector, etc.). So the ratio $\Phi = I_F/I_R$ (so called "fluorescent parameter" (Klyshko, 1978)) is independent on these conditions and its value is usually used for quantitative evaluation of admixture fluorescence intensity.

The contribution of phytoplankton to optical response from water media is chlorophyll-a (*Chl-a)* fluorescence. It forms as a by-product of primary photosynthetic processes induced by laser excitation. Now it is possible to make estimations of two important phytoplankton characteristics from lidar monitoring data: chlorophyll-a concentration (*Ca*) and, using our laser remote modification (Chekalyuk, 1991) of *pump-and-probe* technique (Falkowski, 1985), the efficiency of light energy utilization in primary photosynthetic reactions (by measuring relative yield η of *Chl-a* variable fluorescence). The value of this parameter (η) is used not only for phytoplankton photosynthetic activity (*PPA)* estimation but also for correction of monitoring data on diurnal variations of *Chl-a* fluorescence quantum yield (Gorbunov, 1990; Chekalyuk, 1991). One can find the description of this new technique, special double-pulse lidar system and its applications for studies the features of spatial (of local, meso- and synoptic scales) as well as diurnal variability of *PPA* in papers (Chekalyuk, 1991; Gorbunov, 1991, Chekalyuk, 1992a; Chekalyuk, 1992c).

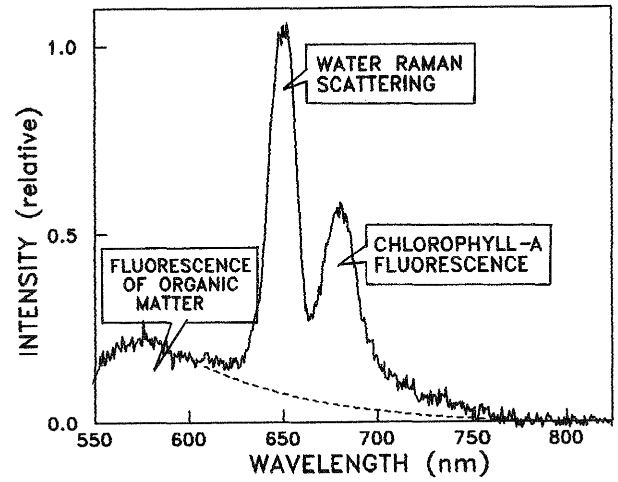

Fig.1 Typical spectrum of backscattered light from water excited by a double-frequency YAG:Nd-laser (excitation wavelength 532 nm).

Carrying out our laboratory and field investigations we paid special attention to the problems of correct estimation of phytoplankton characteristics from lidar remote sensing data. Although the intensity of *Chl-a* fluorescence is obviously proportional to the concentration *Ca*, there exist some factors complicating *Ca* estimation.

The first group of factors is connected with the natural variations of *in situ Chl-a* fluorescence quantum yield due to changes in algae species composition, nutrients limitation, sunlight illumination, etc. In accordance with our latest results (Gorbunov, 1992) some of this factors can affect not only the so called 'variable' component of *Chl-a* fluorescence, but also the 'constant' one. Taking into consideration these factors seems to be important not only for correct lidar data interpretation, but for any *Chl-a* fluorometric technique.

The second group of factors is defined by the features of powerful pulse laser excitation, first of all - by *saturation* of *Chl-a* fluorescence caused by singlet-singlet annihilation of excitons migrating within light-harvesting antenna. According to our laboratory and field experiments and theoretical study of this phenomena (Bunin, 1992; Chekalyuk, 1992) the saturation effect may reduce the *Chl-a* fluorescence quantum yield up to 2-3 times and it is necessary to take it into account for correct estimation of *Chl-a* concentration from lidar data.

Problems of correct phytoplankton photosynthetic activity estimation from lidar sensing data are discussed in (Gorbunov, 1991).

Concerning the problems of lidar measurements of dissolved organic matter and oil pollutions it is necessary to note that the main difficulties of their interpretation are defined by the complex nature of these objects and insufficient knowledge about fluorescence formation processes under laser excitation. It complicates the estimations of practically important characteristics (organic carbon concentration, oil film thickness, etc.) on the base of lidar remote sensing data. Serious problems of interpretation are also arisen because of overlapping of broad fluorescent bands of DOM and oils. There is some progress in solving of these problems in the recent time (Patsaeva, 1991).

It is necessary to note that some useful conclusions one can make on the base of analysis of monitoring data of integral fluorescence of DOM and oils. This is the approach we used in our field measurements on shipboard lidar monitoring presented in this paper.

2. SHIPBOARD LIDAR SYSTEM

For some years we have been involved in developing shipboard lidar systems for remote sensing of seawater. In principle there is no considerable differences between shipboard and aircraft or helicopter based lidar systems. They consist from tree main parts: laser for water excitation, optical system for collecting, detecting and spectrum analysis of optical response from the water media, and computer system for data processing. The main peculiarities of these systems are distance from the water surface (≃ 10 m in the first case; ≃ 100-1000 m in the second one) and rate of the carrier (≃ 10 km/hour for vessel; ≃ 100-1000 km/hour for aircraft). It defines some differences in power of lasers used for water excitation, constructive features of optical system, and space resolution of lidars.

We believe the shipboard lidar systems possess some advantages over the airborne ones, especially at the stage of development of technique and equipment. Their construction and exploitation are not so expansive and, that is more important, there exists the useful opportunity to compare lidar data with results of measurements being carried out by using other techniques and to stop the carrier for complex detailed investigation (including use of sampling) of detected by lidar monitoring features of special interest.

Block diagram of our modern shipboard fluorescent lidar system is presented at Fig.2. It consists of two pulsed 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 components of the 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.

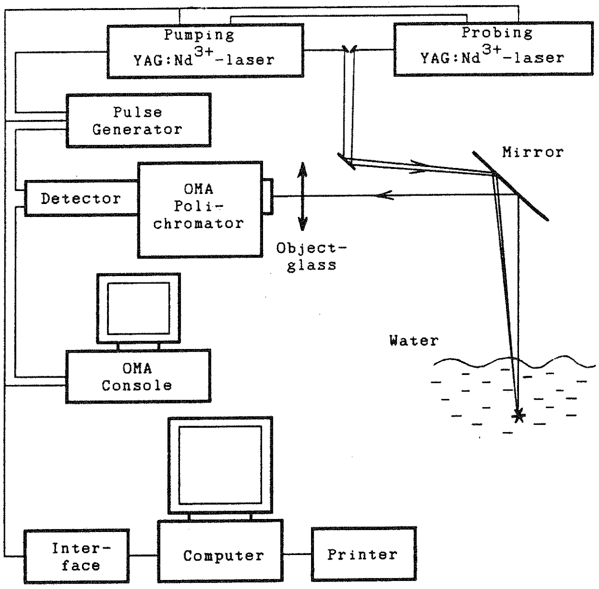

Fig.2 Block diagram of shipboard lidar system for remote sensing of phytoplankton and organic matter.

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 measurements of *Chl-a* fluorescence maximum level under probing pulses excitation (Chekalyuk, 1992c). The second laser generates probing pulses for phytoplankton (532 nm; 10 ns; 0.5 MWt) as well as DOM and oils (355 nm; 10 ns; 0.4 MWt) fluorescence excitation. Time delay between pumping and probing pulses in double-pulse mode is about 30-40 μs (Gorbunov, 1991). Our estimation 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 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 the 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.

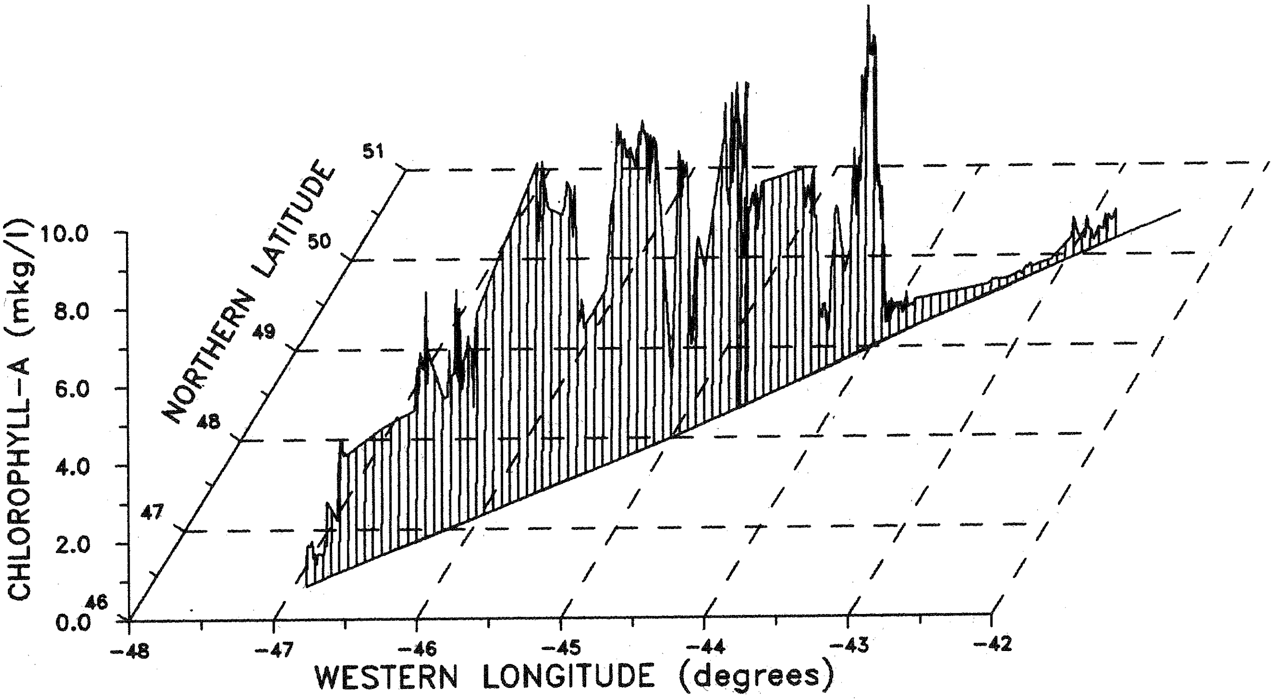

Fig.3 Results of laser remote sensing of phytoplankton on the route A (see fig.4). The North-Western Atlantic, April 20-21, 1990.

The IBM-compatible computer interfaced with OMA and 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 optimize 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.

3. RESULTS AND DISCUSSION

Our first experimental measurements on shipboard lidar sensing were carried out in the Atlantic (1975) and Pacific (1977) oceans. Systematic lidar fluorescent monitoring of phytoplankton was carried out in the Black Sea (1980, 1981, 1988, 1991), Baltic Sea (1984), South Atlantic and the Antarctic Region (1985, 1989), Indian ocean (1988), North-Western Atlantic (1990) and the Mediterranean Sea (1991). The horizontal distributions of organic matter (DOM and oils) fluorescence were measured in the Baltic Sea (1984) and in the Black Sea (1991) simultaneously with phytoplankton fluorescence monitoring. The problems of spatial and temporal variability, phytoplankton patchiness and dynamics of bloom, features of horizontal distributions in the coastal zones, correlation of detected distribution features with hydrological structures have been studied during these measurements. It is necessary to note that in this paper we do not have an aim of detailed analysis of this complex phenomena. Our main purpose is to make condensed review of some results and applications of shipboard lidar in sensing of phytoplankton and organic matter in the seawater.

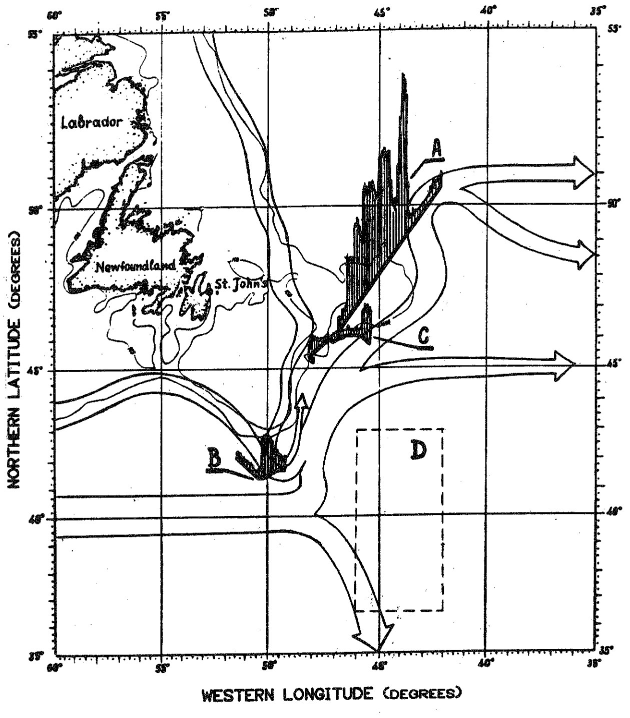

Fig.4 Map of the Nort-Western Atlantic. Some routes of phytoplankton remote sensing are shown.

3.1 Profiling and mapping. Spatial variability of phytoplankton distributions

On the first stage of lidar sensing data processing the horizontal distribution profiles of measured parameters are calculated. By analyzing such profiles it is possible to make preliminary esti-

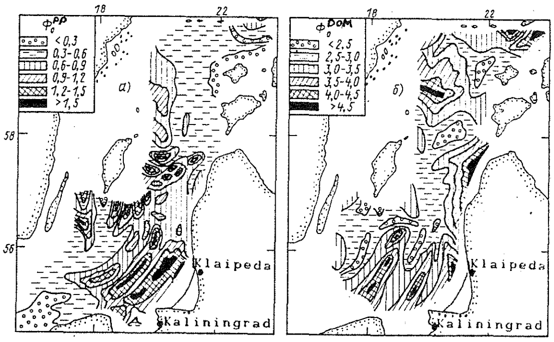

Fig.5 Distribution of chlorophyll-a fluorescence intensity (left) and organic matter that (right) in subsurface layer of the Baltic Sea. May 1984.

mation of the situation along the route of sensing, to select the areas of special interest for further investigations, to study characteristics of spatial and temporal variability. By processing of data measured at parallel routes within selected area one can reconstruct a map of horizontal distribution for characteristics investigated.

An example of profile of chlorophyll-a fluorescence is presented in Fig.3. It was obtained by lidar remote sensing in the North-Western Atlantic on the 20-21 of April, 1990. The position of this profile on region map one can find in Fig.4. The most interesting feature of presented profile is enormous area of powerful spring bloom of phytoplankton in the center. Furthersample analysis showed that this bloom had been caused by *Phaeocystis sp.* algae. There was considerable patchiness within the bloom area with mesoscale quasi-periodical structures. According to our estimations based on lidar sensing and laser measurements of relative yield of variable *Chl-a* fluorescence, *Chl-a* concentration reached 8...6 μg/l and phytoplankton photosynthetic activity was also high (up to 80..90% of reaction centers were active) within the patches. On the contrary, *Chl-a* concentration reduced down to 0.5...1 μg/l accompanying by corresponding reduction of photosynthetic activity (only 35...50% reaction centers were active) in the areas between patches.

Using our lidar technique we have observed the similar quasi-periodical structures of phytoplankton horizontal distribution with patch dimension of 6-10 miles and period length of 15-30 miles in various regions of the Ocean. Often such patch structures arise at the stage of bloom degradation. In March-April of 1988 we studied dynamics of patchiness from arising to its full disappearing in the central area of the Black Sea. One year before the famous PEX-experiment (May-June of 1984) we had observed (Demidov, 1987, Demidov, 1988) patch structures development in the central and South-Eastern Baltic Sea on the final stages of spring bloom (Fig.5). Similar phenomena were detected (Fig.6) to the North from Elephant island (South Shetland islands, Atlantic sector of Southern ocean) in December, 1985 (Demidov, 1988).

Quantitative analysis of spatial variability one can carry out using profiles obtained by lidar monitoring (Demidov, 1987). The example of such approach is shown in Fig.7, where we presented horizontal distribution of relative variability of *Chl-a* fluorescence and frequency spectrum of this parameter calculated for lidar profile crossing the Baltic Sea in central area to the South from Gotland island (May, 1984). The highest values of relative variability (up to 100-150 %/km) were detected in the region of considerable patchiness near Gotland hollow to the South-East from Gotland island (Fig.5).

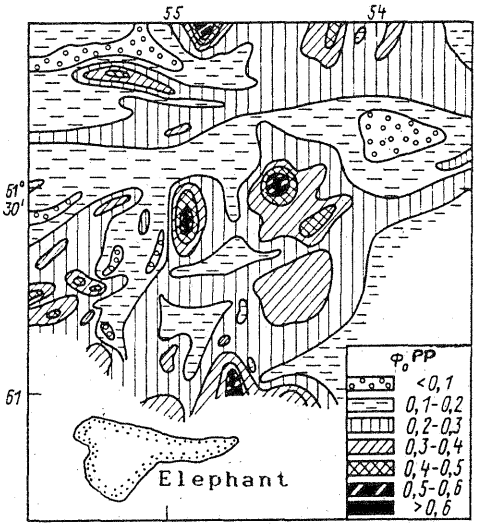

Fig.6 Distribution of nearsurface phytoplankton fluorescence intensity to the North from Elephant island (South Shetland islands, Atlantic sector of Southern ocean) December, 1985.

3.2 Correlation of phytoplankton distributions with hydrological structures

It is well known that phytoplankton, being living object, is sensitive in high degree to such environment factors as nutrients concentration, light, temperature, etc. Therefore there exists correlation between the features of phytoplankton characteristics spatial distribution and hydrological structures (upwellings, streams, rings, frontal zones, etc.) defining the character of water masses movement in subsurface layers. By using lidar technique it is possible to investigate these phenomena in various spatial scales (from 1 to 1000 km). Working in various region of the Ocean we have accumulated considerable material in this field, but within the limits of this paper we shall try to illustrate the opportunities of lidar technique using an example of our measurements in the North-Western Atlantic.

Fig.4 shows the locations of some profiles of lidar monitoring and the area of detailed mapping we carried out in that region, as well as the scheme of the Labrador and Gulf Streams. This profiles are presented at fig.3,12,13. Analyzing this figures one can obviously conclude that the situation with phytoplankton fluorescence (*Chl-a* concentration) was quite different within and outside the warm waters of the Gulf Stream. In fact we have observed moderate bloom within the Gulf Stream (*Chl-a* concentrations of 1...2 μg/l) separated from the outside by the sharp frontal zone (*Chl-a* fluorescence has been changed by a factor over the distance of 3-5 miles).

The analysis of the situation within mapping region (Fig.4) proved (Chekalyuk, 1991; Gorbunov, 1991; Chekalyuk, 1992c) that there had been observed good spatial correlation between the locations of many mesoscale features of phytoplankton photosynthetic activity distribution measured by laser technique

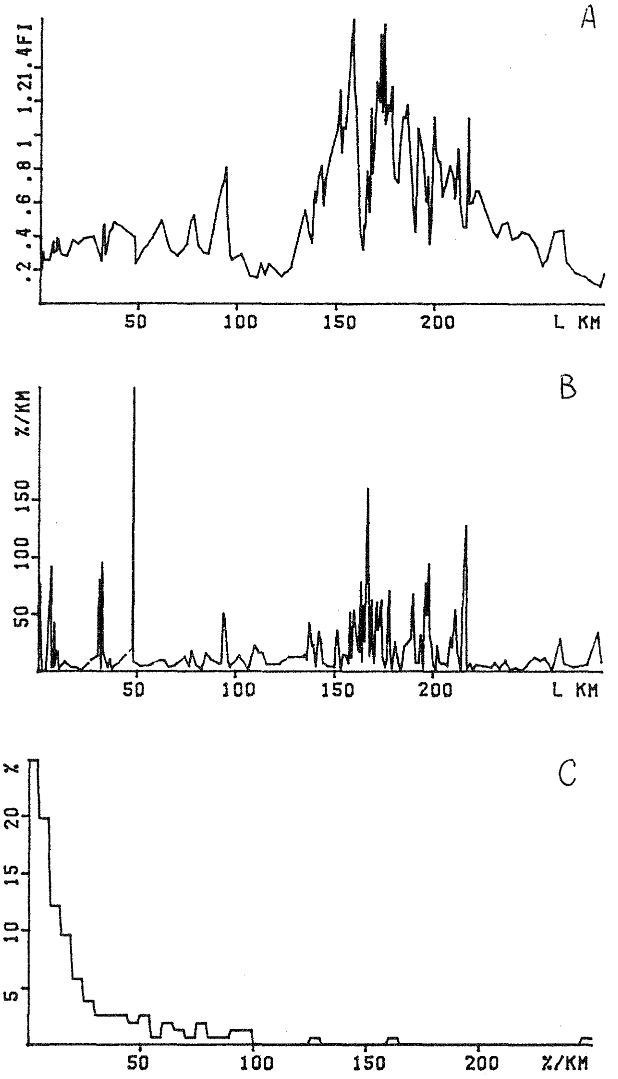

Fig.7 Horizontal distribution of *Chl-a* fluorescence (A), its relative variability (B) and frequency spectrum (C) of this parameter calculated for lidar profile crossing the Baltic Sea in central area to the South from Gotland island (the Baltic Sea, May 1984).

and hydrological structures. The central area of highest activity had coincided with location of powerful and stable anticyclonic ring of synoptic scale. The correlation between distribution of *Chl-a* concentration and hydrological parameters was not so strong.

3.3 Temporal variability analysis of horizontal structures

By carrying out repeated lidar measurements in the region of special interest it is possible to study temporal variations of horizontal distributions of detected parameters in various temporal scales (from diurnal to seasonal). The example of seasonal variability of *Chl-a* distribution in the western Black Sea is presented in Fig.8. In the autumn the main feature of the pattern was *Chl-a* maximum located along the whole western coastal zone and probably caused by autumn upwelling phenomenon in this area. In the spring the powerful bloom caused by Danube river spring water carrying out dominated in this area.

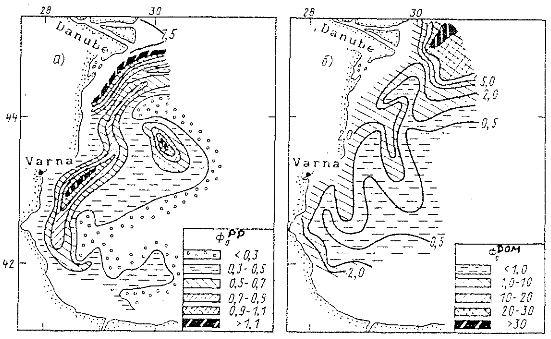

Fig.8 Distribution of nearsurface phytoplankton fluorescence intensity in western region of the Black Sea in October of 1980 (left map) and May 1981 (right map).

In order to study the stability of investigated horizontal structures we compared the results of repeating measurements in selected local points. By statistical processing of the results of more than 100 of such measurements in the Baltic Sea we tried to estimate life time of detected structures in different parts of the search area. As a quantitative measure for estimation we used an average value D of relative difference between the first and second measurements in the same point. It was found (Demidov, 1987) that the value of this parameter D increased from 18% to 26% and 36% under corresponding growing of time intervals between point measurements from 1 to 8...12 and 13...18 days. Taking into consideration "constant" contribution to this values from the measurement error ($\simeq$ 15%) one can roughly estimates from this data the time of distribution divergence as 1.2% per day. At the same time the similar analysis carried out for the South-eastern part of investigated area (see Fig.5) showed that the patch structures mentioned above were stable during at least 25 days (D = 15%, comparable with measurement error). The similar stable patchiness has been observed later near Elephant island, South Atlantic (Fig.6). We believe the problems of stability of such patch structures as well as their arising and evolution are one of the most interesting questions for investigation by shipboard lidar technique in cooperation with traditional methods of hydrobiology.

One of the factors complicating interpretation of lidar sensing data is diurnal variations of *in vivo* *Chl-a* fluorescence, observed by some authors (Kiefer, 1973; Karabashev, 1975; Gorbunov, 1990; Chekalyuk, 1992a). It leads to corresponding modulation of fluorescent remote sensing data (as well as any *in situ* fluorescent technique) and should be taken into account for correct estimations of studying parameters, e.g. *Chl-a* concentration distribution.

This phenomenon may be defined both diurnal variations of *Chl-a* concentration in subsurface layer and regulation of *Chl-a* fluorescence quantum yield. Using special laser technique we investigated this phenomena both in lab and in field conditions, including direct *in situ* measurements in various regions of the Ocean. It was found that in many cases the main reason of diurnal fluorescence variations was dominated contribution of fluorescence efficiency regulation caused by sunlight illumination.

Fig.9 shows a typical curve of *Chl-a* fluorescence yield diurnal rhythm we measured in the Black Sea in the spring of 1988. The fluorescence yield

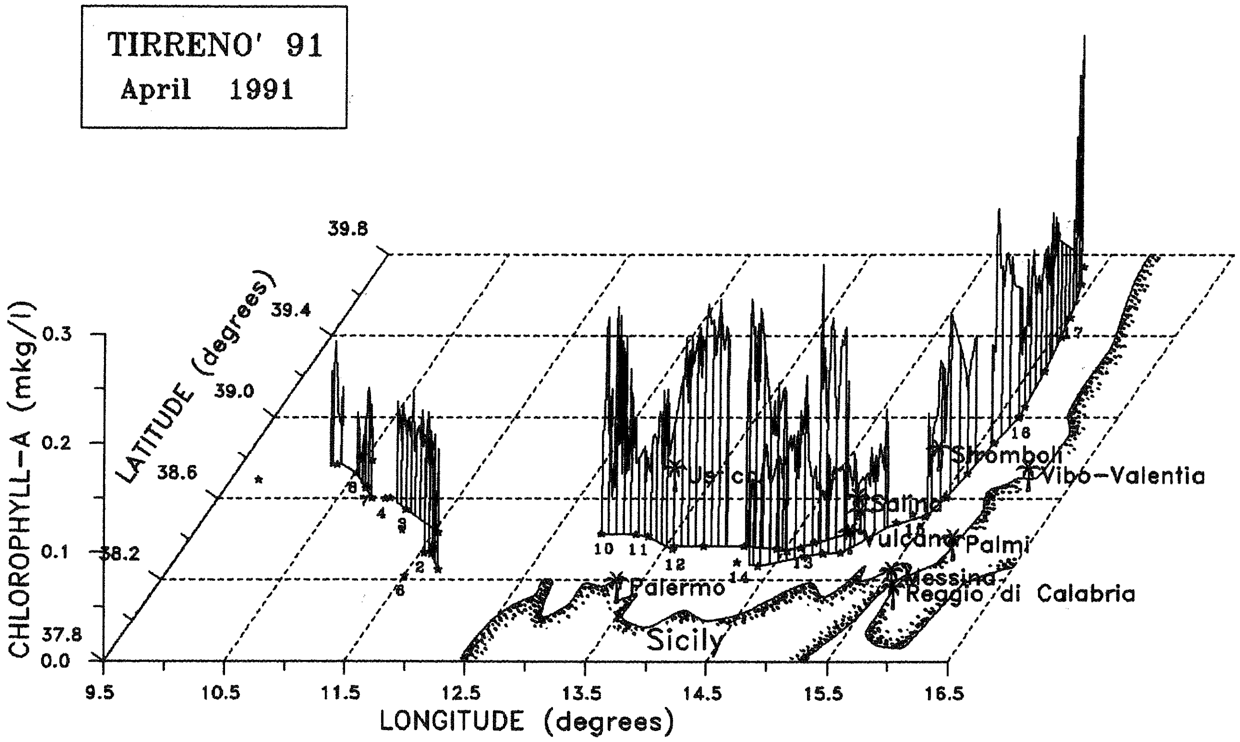

Fig.10 Nearsurface phytoplankton chlorophyll-*a* distribution along the coastal zone of South Italy.

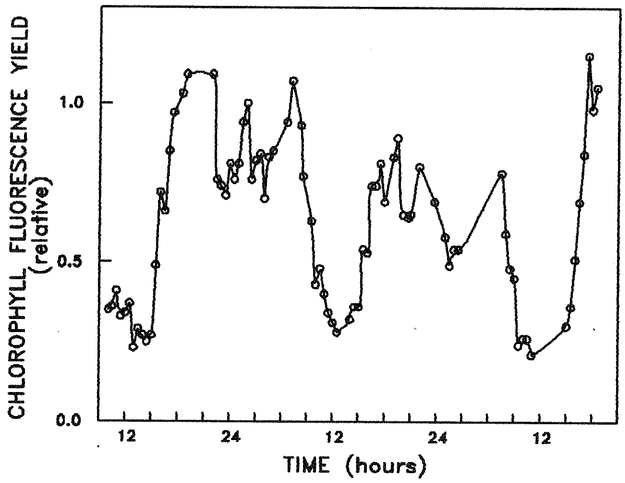

Fig.9 Diurnal rhythm of nearsurface phytoplankton fluorescence yield. The Black Sea, April of 1988.

reached its maximum values at night and minimum ones in the daytime. Our investigation has shown that the max/min ratio of *Chl-a* fluorescence yield and correspondingly the depth of modulation of fluorescent sensing data may vary from 3 to 1 depending on the functional state of algae photosynthetic apparatus. Field measurements have proved that the main mechanisms of regulation were photoinhibition of primary photosynthetic reactions and energy-dependent quenching of *Chl-a* fluorescence under sunlight illumination variations (Gorbunov, 1990; Gorbunov, 1992).

In the recent time we have developed the new approach for correction of lidar sensing data taking into account these diurnal variations. It is based on simultaneous remote measurements of both original *Chl-a* fluorescence and relative yield of variable fluorescent component using our new

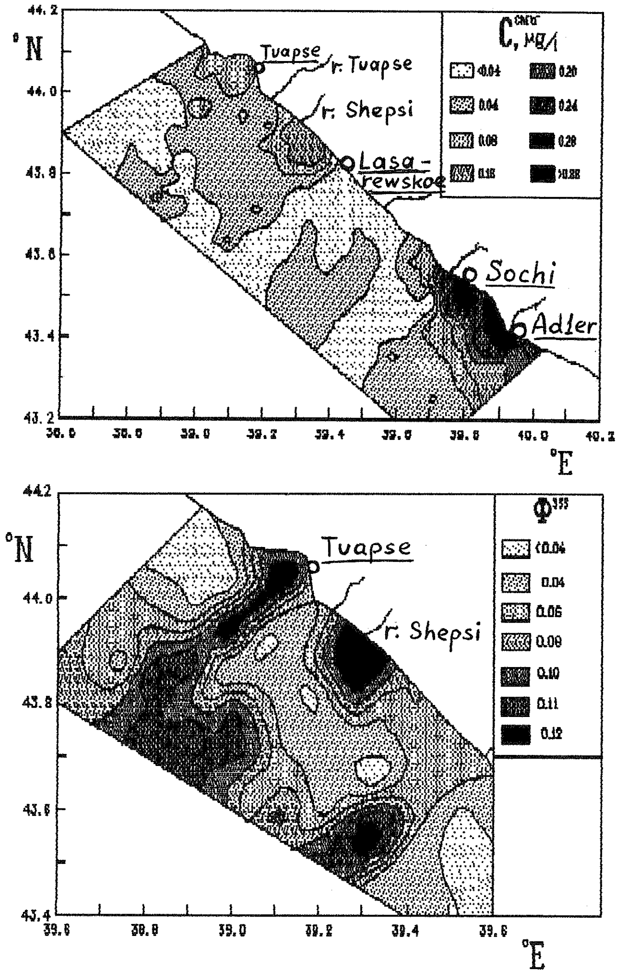

Fig.11 Distributions of chlorophyll-a (upper map) and organic matter (lower map) in the Russian coastal zone of the Black Sea. August, 1991.

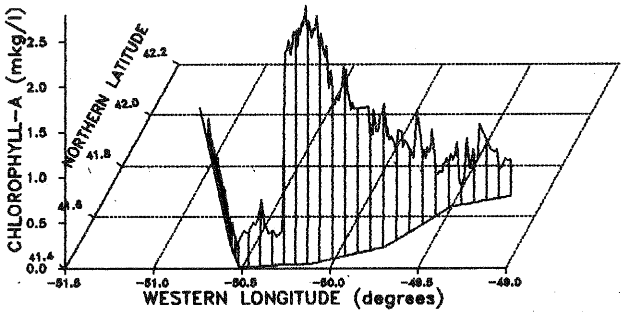

Fig.12 Results of laser remote sensing of phytoplankton on the route B (see fig.4). The North-Western Atlantic, April 30, 1990.

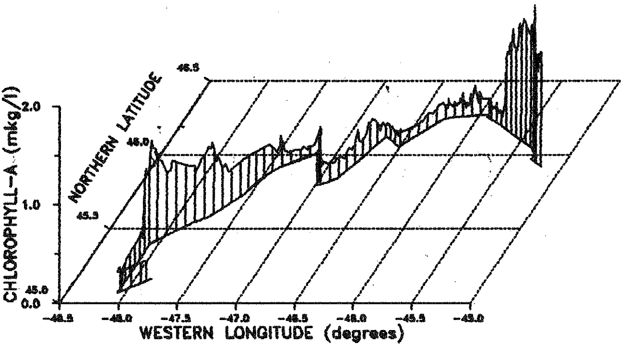

Fig.13 Results of laser remote sensing of phytoplankton on the route C (see fig.4). The North-Western Atlantic, May 30, 1990.

double-pulse lidar technique (Chekalyuk, 1991). The correction factor is calculated from the second parameter value.

3.4 Laser monitoring organic matter and phytoplankton in the coastal zones

Laser remote sensing may be effectively used for coastal zone monitoring. By using lidar technique it is possible to study biological productivity as well as organic matter and oil pollution distributions in that specific areas. The example of profile of *Chl-a* distribution along the coastal zone of South Italy is shown in Fig.10. These data were obtained by us in April, 1991 under the program of joint Italo-Russian project "TIRRENO'91".

More effective way is simultaneous monitoring of laser induced fluorescence of both *Chl-a* and organic matter (dissolved organic matter and oil). Comparison of such measurements may give a valuable information about ecological situation in the coastal zones. Fig.11 presents the results of shipboard lidar mapping in the Russian coastal zone of the Black Sea (August, 1991). The maps were obtained as a result of data processing of measurements which had been carried out for 14 profiles perpendicular to the coast line. The width of the search zone is about 20 miles. One can see the influences of the coastal features (cities, villages, small rivers, etc.) on the detected distributions.

4. CONCLUSION

We believe the data presented in this paper show shipboard lidar sensing as a powerful technique for investigation both spatial distribution and temporal variability of phytoplankton and organic matter in the seawater. The future development of this technique by means of phytoplankton photosynthetic activity measurements will considerably expand the field of lidar applications (estimation of primary production by remote sensing, remote seach of hydrological structures, calibration of satellite data, etc).

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