Lidar Monitoring of Phytoplankton and Organic Matter in the Inner Seas of Europe

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ABSTRACT

A condensed review of applications of lidar-fluorosensor technique in the European inner seas is presented in the paper. The main objects of lidar monitoring were phytoplankton and organic matter ("yellow substance" and oil pollutions). The general principles of the oceanographic lidar technique and instrumentation are discussed, and results of profiling and mapping in the Baltic, Mediterranean and Black Seas (1980-1991) are analyzed. The advantages of lidars are defined by their capacity for active remote high-frequency sampling at space/time scales intermediate between satellite and shipboard observation.

1. INTRODUCTION

In this paper we present a condensed review of our applications of the lidar technique for monitoring of phytoplankton and organic matter (OM) in oceanographic and environmental studies of the European inner seas. The measurements were performed by the use of shipborne lidar systems in the Baltic, Mediterranean and Black seas during several cruises of research vessels during the period of 1980 - 1991.

The objects of our lidar measurements were phytoplankton and (in several cases) dissolved organic matter (DOM), oil and oil products. Since our studies were carried out in the framework of complex surveys, we performed, as a rule, along-track measurements (lidar profiling) during all ship motions within investigated areas between stations, where conventional measurements and sampling were conducted. Real-time data processing provided the possibility for correction of preliminarily stated locations of stations to study peculiarities of special interest detected by lidar measurements. Spatial resolution was defined by the average distance between two successive points of along-track measurements, and it varied in the range from 100 m to 1.5 km depending on the ship rate, equipment capabilities, and the detected local variability of the measured parameters. In most of the cases, a reconstruction of horizontal distributions for measured parameters was performed to obtain two-dimensional maps (lidar mapping).

2. GENERAL PRINCIPLES OF LIDAR FLUORESCENCE MEASUREMENTS IN THE SEA

Oceanographic applications of lidars are based on laser excitation of the near-surface water column and detection of spectra of the return signal. Because of strong attenuation of light in water, most lidar systems are capable of effectively detecting the backscattered signal from the only near-surface water column (less than 10 m even in relatively clear waters in the open sea). In general, there are three important contributions (see Fig. 1) to the spectrum detected: the water Raman scattering (WRS), as well as fluorescence of organic matter and pigments of phytoplankton. Therefore, the lidar technique is potentially capable of providing both qualitative and quantitative information about important environmental, biological and physical parameters: "yellow substance" (Bristow et al., 1985; Reuter et al., 1993; Alberotanza et al., 1994, Chekalyuk et al., 1992a) and oil pollution characteristics (e.g., see Hoge and Swift, 1980; Hengstermann and Reuter, 1990), pigment composition of phytoplankton (Hoge and Swift, 1990; Babichenko, 1994), their concentrations and photosynthesis efficiency (e.g. see Chekalyuk and Gorbunov, 1992b), temperature (Leonard et al., 1979; Raimondi and Cecchi, 1994) and salinity (Bekkiev et al., 1983) of sea water, and light attenuation in the water column (Bristow et al., 1981, 1985). The combination of these capabilities, as well as the capacity for high-resolution day-and-night remote monitoring, could provide a wide range of applications of lidar techniques for studies of biogeochemical and physical processes in the sea (e.g. see Babin et al., 1991), and for environmental monitoring in coastal zones.

The wavelength $\lambda_R = 1/\nu_R$ of the maximum of the water Raman scattering band is defined by the frequency $\nu_L = 1/\lambda_L$ of laser excitation: $\nu_R = \nu_L - \Delta\nu_R$, where $\Delta\nu_R = 3440\text{cm}^{-1}$. As a result, $\lambda_R = 381\text{nm}$ in case of UV excitation with a nitrogen laser ($\lambda_L = 337\text{nm}$), and it would be shifted to the red area ($\lambda_L = 651\text{nm}$, see Fig. 1) with changing the excitation wavelength to $\lambda_L = 532\text{nm}$ (the second harmonic of YAG laser). The width of this band (FWHM) would correspondingly vary from 10 to 18 nm in this case. This allows some optimization of the position of the WRS in the spectra detected by changing the wavelength of excitation.

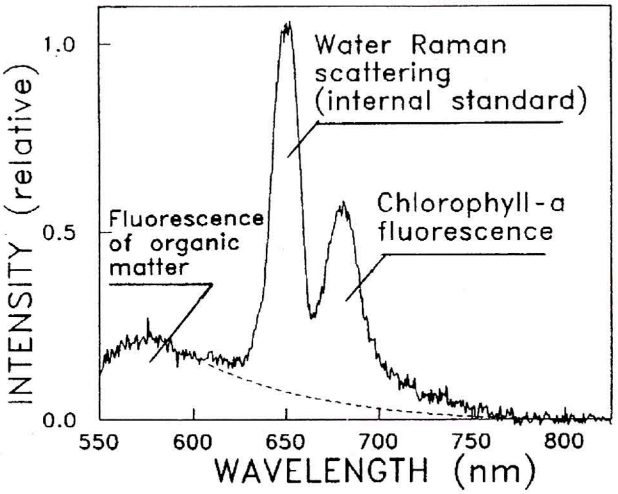


Fig. 1 - A typical spectrum of the return signal from water excited by radiation of a frequency-doubled Nd:YAG laser (wavelength 532 nm).

The *in vivo* chlorophyll-a (*Chl-a*) fluorescence provides the contribution at 685 nm (Fig. 1) with a width (FWHM) of about 20 nm. From this point, the utilization of the second harmonic of YAG laser at 532 nm may be considered as near-optimal for phytoplankton monitoring (Klyshko and Fadeev, 1978). When excited with a UV source, the DOM fluorescence shows an extremely broad band overlapping the whole visible region of the spectrum from UV to the red area (e.g. see Reuter, 1993) and possessing a maximum emission at 440 nm. The spectra of oil products (dissolved or being in film on water surface) can vary in a wide range, depending on the type of product (Hengstermann and Reuter, 1990) and its "water history". In general, relative contributions of the discussed fluorescent bands to the detected spectrum can also vary in a fairly wide range, particularly in coastal waters. It can lead to significant difficulties in spectral processing and data interpretation. In the framework of our research we had no particular purpose of discriminating the contributions of DOM and oil products. Therefore, we measured the intensity of integral blue fluorescence at 440 nm, that can be considered as an indicator of the overall content of organic matter (OM) in sea water.

A conventional approach (Klyshko and Fadeev, 1978; Bristow et al., 1981; Hoge and Swift, 1981) is to normalize the fluorescence contributions to water Raman scattering to exclude affecting the signal by varied detection conditions, such as the distance to water surface, its shape, attenuation of light in the water column, etc.. The so-called "fluorescence parameter" Φ (Klyshko and Fadeev, 1978) is commonly calculated as a ratio of the fluorescence intensity to the WRS one. As the detected WRS signal is proportional to the energy of laser excitation in water column, this parameter Φ reflects the product of the yield of laser-induced fluorescence emission (i.e. the efficiency of fluorescence due to laser excitation) and the concentration of fluorescent substance. Spectral intensities are measured at maxima of the bands, and a subtraction of the "background" provided due to bands overlapping is required to obtain the true values (e.g. see an exponential OM background presented as a dashed line in Fig. 1)

3. SHIPBOARD LIDAR SYSTEM FOR CONCURRENT MONITORING OF PHYTOPLANKTON AND ORGANIC MATTER

Depending on the objectives of particular applications and the stage of instrumentation development, various lidar systems have been constructed and used in our sea-going activity. The common features of those lidars were the use of the optical multichannel analyzer (OMA) for spectral analysis of laser induced response from water, and utilization of a ship as a platform of the lidar system. The first peculiarity was defined by our focusing rather on research than operational aspects at that stage of development, the second one - by the convenience of complementary supporting measurements with conventional shipboard techniques. The use of a pulsed laser as an energy source for generation of response from water allowed us to apply gating of the OMA detector synchronously with laser pulses to exclude the contribution from background (e.g. solar) irradiance to the detected signal. Recently a prototype of the pump-and-probe lidar (e.g. see Chekalyuk and Gorbunov, 1992b) has been developed on that basis. The system is capable of remotely monitoring the efficiency of primary photochemical reactions in algae.

Radiation of the second harmonic of a YAG laser ($\lambda = 532$nm) was utilized for excitation of *Chl-a* fluorescence at 685 nm (see Fig. 1), the third harmonic of the YAG laser ($\lambda = 355$nm) or radiation from a nitrogen laser {($\lambda = 337 nm$) - for excitation of fluorescence from organic matter (dissolved organic matter and oil pollution). The computer provided automated control over the system operations and real-time data processing. The major components of the lidar system (excluding the folding mirror) were mounted inside the ship laboratory. The block diagram of the system we used during lidar monitoring in the Baltic sea is presented in Fig. 2.

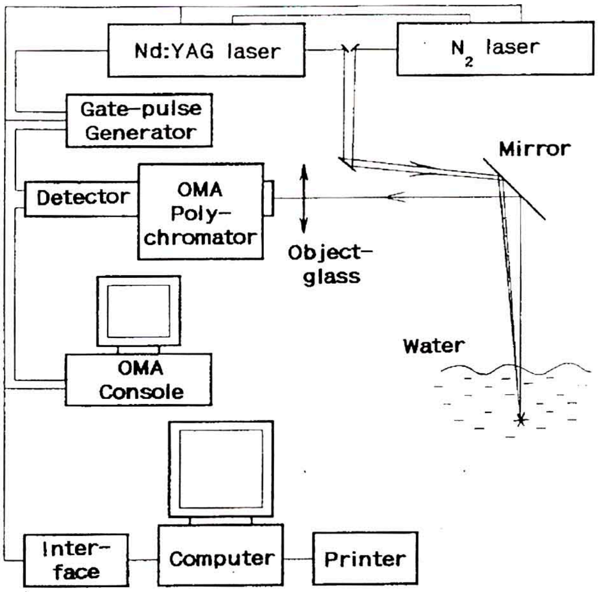


Fig. 2 - Block diagram of the lidar system.

4. LIDAR MONITORING IN THE BALTIC SEA (1984)

The measurements were conducted in May-June of 1984 (39th cruise of R/V 'Academic Kurchatov'). More than 50 along-track lidar measurements performed; the total length of the monitoring route was 8390 km. Laser-induced fluorescence of *in vivo* chlorophyll-a (excitation by the second harmonic of YAG laser, $\lambda = 532$nm) and organic matter (excitation by a nitrogen laser, $\lambda = 337$nm) were detected consequently point-by-point from on board the moving ship. Spatial resolution of the lidar measurements was about 450 m. The integral fluorescent response from the near-surface water layer of 2-5 m was detected.

An example of along-track distribution of *Chl-a* fluorescence is shown in Fig. 3. It was obtained as a result of traversing the Baltic Sea from west to east at the central area to the south-east of Gotland island in the middle of May, 1984. To the east of Gotland island it was found a synoptic area of relatively high *Chl-a* fluorescence with pronounced mesoscale variability. Corresponding maximum values of *Chl-a* concentrations at the surface were about 2.5 µg/l (Fig. 3a), while the values of relative horizontal variability of *Chl-a* fluorescence ranged up to 100-150 % per kilometer (see Fig. 3b).

Maps of horizontal distributions of in vivo *Chl-a* fluorescence of near-surface phytoplankton were reconstructed relying on lidar along-track data, adjusted for diurnal variations of *Chl-a* fluorescence yield. The corresponding maps for 15-30 May and 8-10 June are presented in Fig. 4. In the first case (15-30 May) lidar monitoring was conducted during all motions of the ship between stations, at which the measurements with conventional shipboard techniques were performed. The result was quite detailed knowledge about the current situation in the investigated area. In the second case (8-10 June) the mapping was conducted over a large area during three days of continuous lidar monitoring while the ship followed meandering course from Helsinki to Rostock. That temporal period is comparable with the life time of individual algal cells.

The situation as a whole was determined by the development of the phytoplankton spring bloom, that started late in April. The most interesting feature of the first distribution (Fig. 4a) is essentially mesoscale patchiness in the central and southern parts of the explored region. According to our measurements in various regions of the Ocean, such patch structures of about 10 miles in size are characteristic of the stage of decline of an algal bloom. One can see (Fig. 4b) disappearance of the patch structures in the central area of the Baltic Sea (the region of Gotland hollow) two weeks after the first measurements in May.

Fig. 5 presents a reconstructed map of organic matter spatial distribution based on lidar remote sensing in June of 1984. As in the case of phytoplankton, there was also essential, but more moderate mesoscale variability of the horizontal distribution. The comparison between this pattern and that of Fig. 4b allows us to suppose that organic matter patch

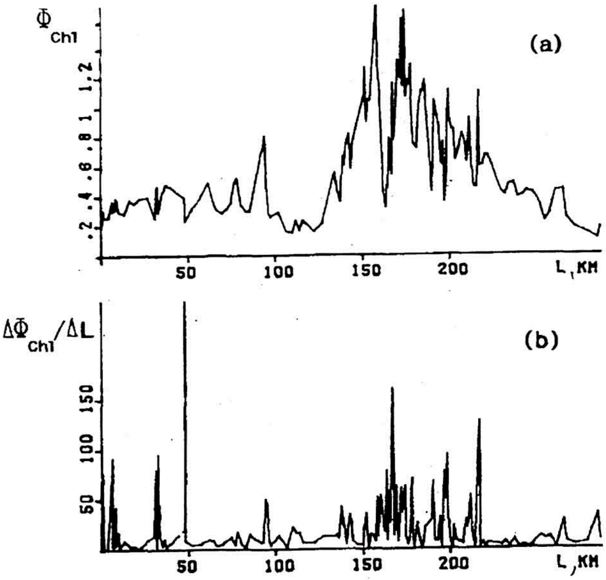


Fig. 3 - Profile of chlorophyll-a fluorescence normalized to water Raman scattering Φ_{Chl} *(a) and its relative horizontal variability per kilometer* $\Delta \Phi_{Chl}/\Delta L$ (b). *Traversing the Baltic Sea from west to east at the central area to the south-east of Gotland island in the middle of May, 1984.*

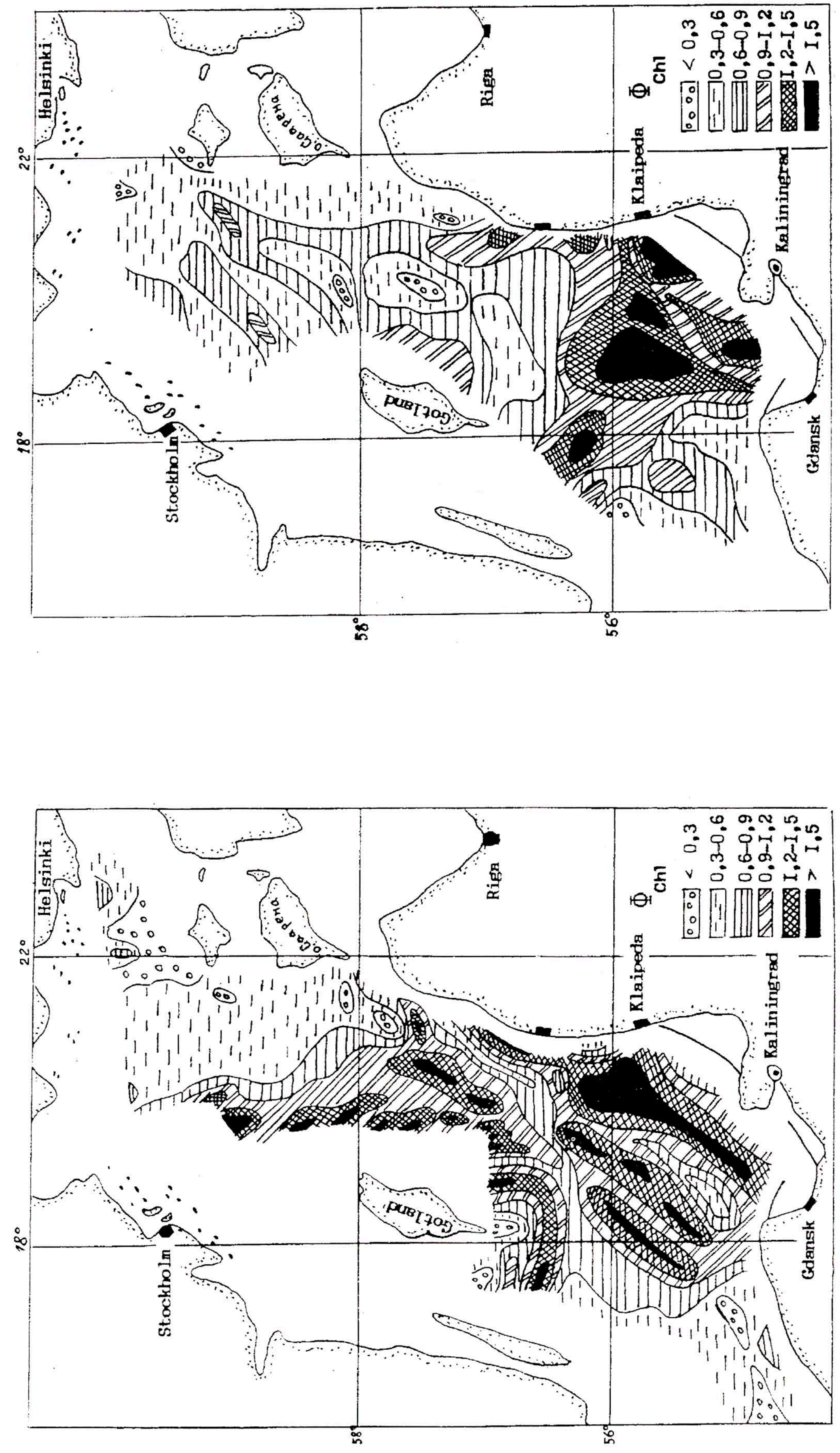


Fig. 4 - Distributions of in vivo chlorophyll-a fluorescence normalized to water Raman scattering Φ_{Chl} *in the near-surface layer of the Baltic Sea. Lidar monitoring on May 15-30 (a) and June 8-10, 1984 (b).*

structures in the southern part of the area had a natural origin and were directly related to phytoplankton bloom patchiness in that region. Another apparent feature of the organic matter pattern was the significantly increased concentrations of organic matter in the vicinity of industrially active coastal regions (Stockholm, Helsinki, the coast of the former Soviet Union). Obviously, the dominating component of detected organic matter in those areas was of anthropogenic origin (organic and oil pollutions), which is proved by reference to corresponding peculiarities in the chlorophyll distribution (Fig. 4b).

The temporal variability of detected distributions was studied at various time scales (from hours to month). Diurnal rhythms of Chl-a fluorescence were measured by lidar sounding at several specific stations (Chekalyuk et al., 1992c), and the *Chl-a* fluorescence data were adjusted for the observed diurnal variations. Relying on comparison of the adjusted *Chl-a* fluorescence detected at more than 50 intersection points of the ship track, the time of divergence for horizontal distributions of phytoplankton were evaluated. For the major part of the examined area it was found, that the averaged relative difference D increased from 18% to 26% and 36% with respective increases in time lapse between point measurements from 1 to 8...12 and 13...18 days. Taking into account a "constant" contribution from the measurement error (15%), one can roughly estimate the rate of distribution divergence as 1.2% per day. It is significant that initial data, unadjusted for diurnal variations, did not indicate any monotonic rise of D with time.

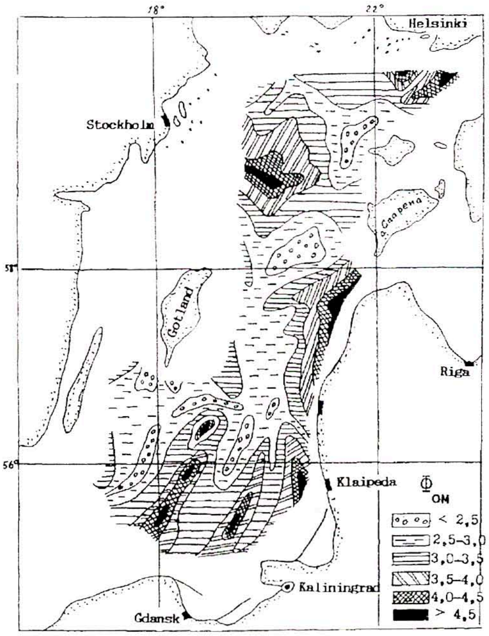


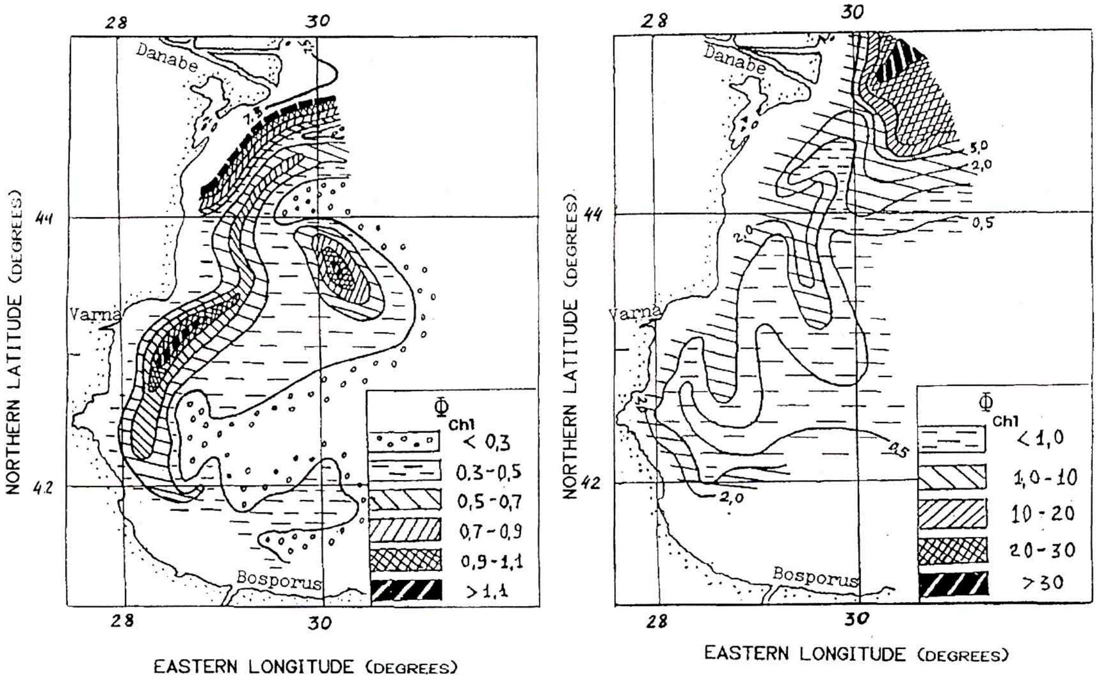
Fig. 5 - Lidar mapping of organic matter fluorescence normalized to water Raman scattering Φ_{OM}. *The Baltic Sea, June 8-10, 1984.*

5. LIDAR MONITORING IN THE BLACK SEA (1980-81, 1991)

Seasonal variability of the horizontal distribution of phytoplankton was studied by means of lidar monitoring over large area in the western part of the Black Sea in 1980-81. The reconstructed patterns of *Chl-a* fluorescence horizontal distributions are presented in Fig. 6. In October of 1980 (Fig. 6a) the mosto strictly feature was the considerable increase in biological productivity along the coastal zone, probably caused by autumn upwelling. In May 1981 (Fig. 6b) the intensive spring bloom of phytoplankton with dominating influence of spring runoff from the Danube river was found and investigated in the area. The maximum intensities of laser-induced *Chl-a* fluorescence were 30 times higher in comparison with those measured in the area in October, 1980 (see Fig. 6), indicating a corresponding increase in phytoplankton biomass during the spring bloom.

14 parallel route measurements (each of 20 miles long) were carried out in the Russian coastal zone of the Black Sea (see Fig. 7) in August, 1991 (Chekalyuk et al., 1992d). The objective of that study was to provide a fast evaluation of the environmental situation within that zone. The noteworthy feature of those measurements was the concurrent monitoring of both *Chl-a* and organic matter distributions. The shipborne lidar system used here was based on a commercially available lidar manufactured by RADIAN R&D Centre (Moscow, Russia). The radiations of the second (λ = 352nm) and the third (λ = 355nm) harmonics of a YAG laser were used for excitation of Chl-a and organic matter fluorescence, respectively. Relying on monitoring data, the regional patterns of *Chl-a* concentration and organic matter fluorescence have been reconstructed (Fig. 8).

For most of the area (Fig. 8a), the *Chl-a* concentration varied from 0.02 to 0.1-0.2 mg/m^3. The more marked increase in *Chl-a* concentration was observed near towns (Tuapse, Lasarevskoe, Sochi) and river mouths (Shepsi, Shakhe rivers). The analysis has shown that the local increase of biological productivity in the Sochi-Adler area was caused by a strong hurricane and storm that had struck that region several days before the measurements. The distribution of organic matter (Fig. 8b) clearly indicates the influence of pollution, in particular in the Tuapse-Lasarevskoe region due to the contribution from Shepsi river. In the bay area to the north of Tuapse there was some marked increase in organic matter content; the patch structure was found relatively far from the coast without any corresponding indication in the *Chl-a* pattern (Fig. 8a).



(a) (b)

Fig. 6 - Lidar study of seasonal variability of chlorophyll-a fluorescence (Φ_{Chl}) distribution in near-surface water layer in the western part of the Black Sea. (a) - October 1980, (b) - May 1981.

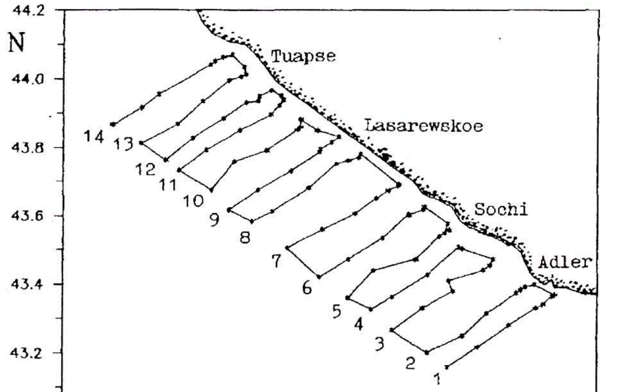


Fig. 7 - The scheme of the route of lidar monitoring in the Russian coastal zone of the Black sea in August, 1991.

6. LIDAR BIOMONITORING IN THE MEDITERRANEAN SEA (1991)

The measurements were conducted in the framework of the joint Italian- Russian project "TIRRENO'91" in April, 1991 on board the R/V 'Moskovski Universitet'. The map of the area and the routes of lidar remote sensing are presented in Fig. 9. Along-track profiles of *Chl-a* concentration (e.g. see Fig. 10-12) were reconstructed on the basis of lidar measurements of *Chl-a* fluorescence adjusted for diurnal variations in *Chl-a* fluorescence yield. Correction factors were calculated from measurements of variable *Chl-a* fluorescence with the lidar pump-and-probe technique (Chekalyuk and Gorbunov, 1992b, 1993), taking into account the current values of solar irradiance.

The distinctive peculiarity of the Tyrrhenian Sea (as well as the major part of the Mediterranean as a whole) is relatively low values of phytoplankton biomass, and correspondingly - of *Chl-a* concentration. With respect to lidar biomonitoring, it manifests itself in strong requirements imposed upon the accuracy of measurements of the spectra and spectral data processing. From this standpoint, the use of optical multichannel analyzer is of great importance. Special software has been developed for quantitative perfect calculation of fluorescence parameter Φ (the intensity of fluorescence band normalized to water Raman scattering, see Klyshko and Fadeev, 1978) in this particular situation, when the intensities of *Chl-a* fluorescence were as low as 0.01-0.03 in some cases relative to WRS.

According to data, of lidar monitoring the *Chl-a* concentration varied from 0.03-0.1 µg/l in the open part of the Tyrrhenian sea (e.g. the northern part of the *Chl-a* profile

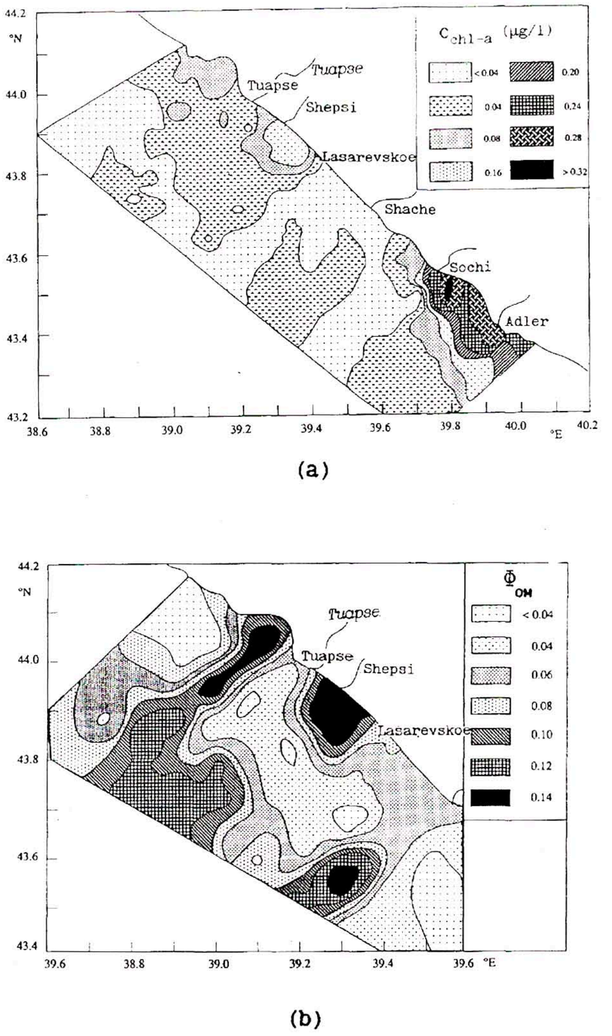


Fig. 8 - Distributions of chlorophyll-a concentration C_{Chl-a} *(a) and organic matter fluorescence* Φ_{OM} *(b). Russian coastal zone of the Black Sea. August, 1991.*

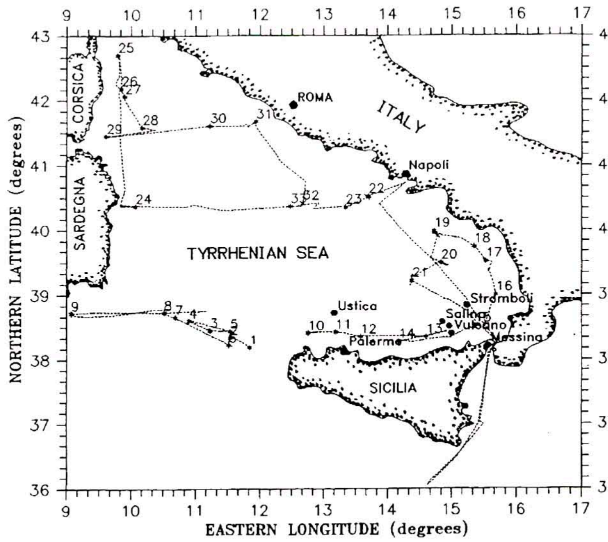


Fig. 9 - Map of the Tyrrhenian Sea and the route of shipborne lidar monitoring of phytoplankton in April of 1991. Stations are indicated in by numbers.

presented in Fig. 11) to 0.15-0.3 µg/l in more productive coastal zones (Fig. 10-12). As a whole, the horizontal distribution of *Chl-a* concentration was fairly homogeneous in the open parts of the sea (Fig. 10, 11), while we observed high spatial variability at both meso- and local scales along the coastal zones of Southern Italy (Fig. 11, 12) and Corsica (Fig. 10). The diurnal variations of phytoplankton photosynthetic activity and *Chl-a* fluorescence yield caused by variations in solar irradiation in near-surface water layer were studied during three-days of measurements at a specific point near the coastal zone (Gorbunov and Chekalyuk, 1992).

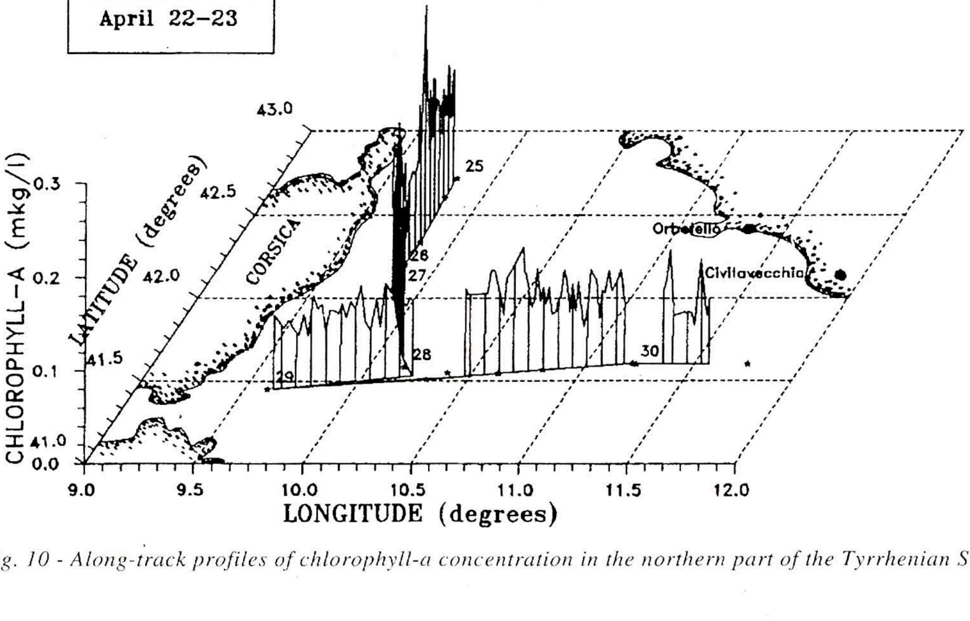


Fig. 10 - Along-track profiles of chlorophyll-a concentration in the northern part of the Tyrrhenian Sea.

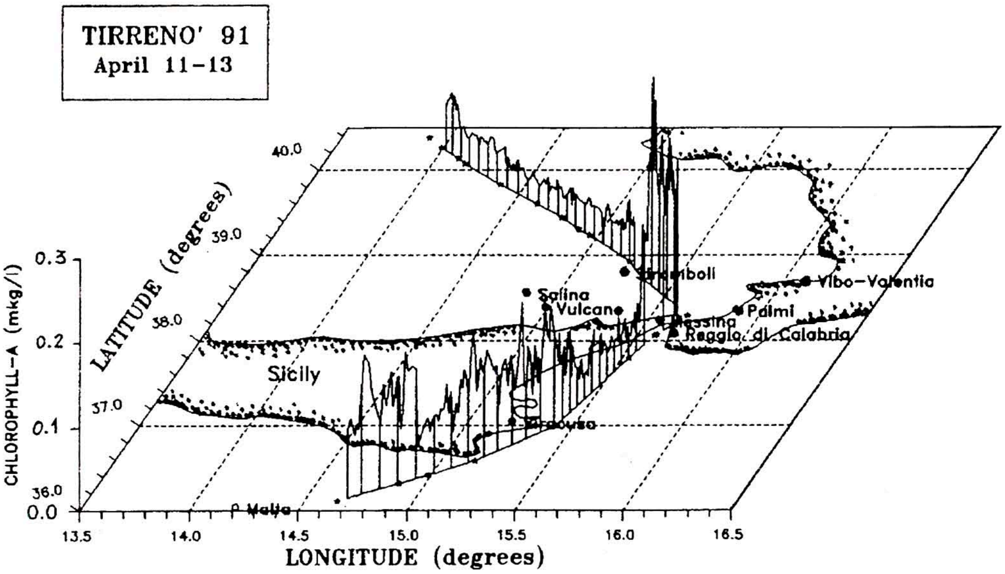


Fig. 11 - Along-track profile of chlorophyll-a concentration measured on the traverse from Malta island to the Gulf of Naples through Messina Strait.

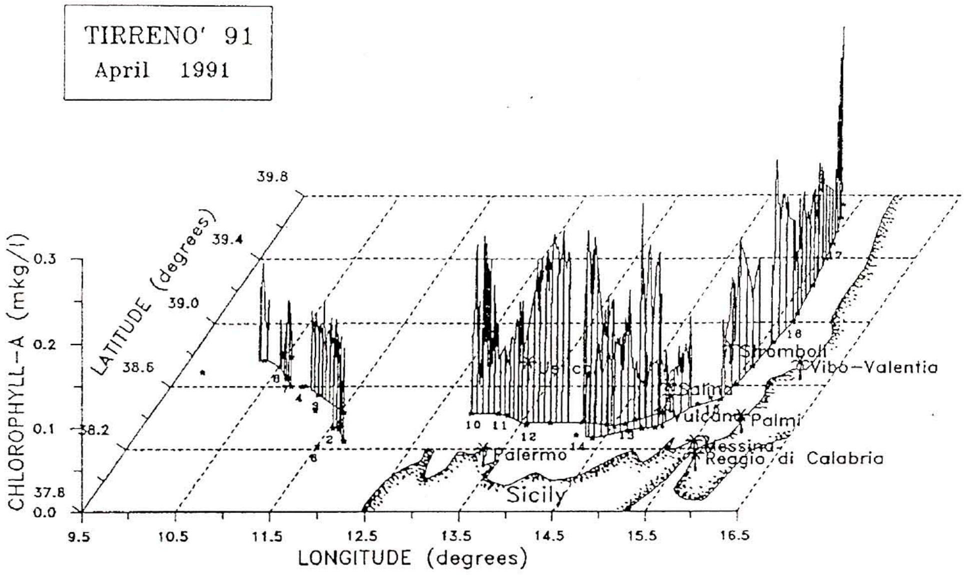


Fig. 12 - Horizontal distribution of chlorophyll-a concentration along the coastal zone of South Italy. March 28 - April 9, 1991.

CONCLUSION

The lidar technique has been applied to studies of spatial and temporal variability of phytoplankton and organic matter, algal patchiness and dynamics of blooms, as well as features of horizontal distributions in the coastal zones of European inner seas. Although the main objective of the conducted research was the development of lidar methodology and instrumentation per se, the results obtained clearly indicate the potential of the lidar technique in this field.

The advantages of the lidar technique in marine applications are:

(1) capability of remote real-time monitoring over large areas (up to synoptic scale) with a high spatial resolution (about 100 m);
(2) relatively weak dependence upon weather conditions;
(3) capability of day-and-night continuous measurements;
(4) full automation of measuring and primary data processing.

The lidar technique therefore may be considered as a powerful tool for both environmental monitoring in coastal zones and for process studies in the sea. Nevertheless, a number of problems (e.g. see Chekalyuk and Gorbunov, 1993) must be solved to allow the transfer of laser remote sensing from the research environment to operational use in marine and coastal applications.

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