

## A SHORE-BASED LIDAR FOR COASTAL SEAWATER MONITORING

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### ABSTRACT

The paper presents a description of a shore based lidar which can play a key role in developing a system for continuous express monitoring of coastal seawater areas. Results of field tests in the region of the Blue Bay (Black Sea, near Gelendzhik) are reported. Echo-signals are obtained with excitation wavelengths of 532, 355 and 266 nm (2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> harmonics of a YAG:Nd laser).

The dependencies of an echo-signal (in this case water Raman scattering) on the sensing distance of the laser beam are investigated. The results obtained appear to correlate well with the theory of laser remote sensing under large incidence angles, in which wind waves are taken into account. In the experiments, laser radiation with 532 nm wavelength at 10 Hz repetition rate, with 10 ns pulse duration and 10 mJ pulse energy was used. The sensing distance was up to 100 m at a sensing angle of approx. 80°. The possibility of increasing the sensing distance up to 0.5-1 km is shown. Therefore, this device can be used for monitoring of bays similar to the Blue Bay or other vitally important areas.

### INTRODUCTION

During the development of methods and means of laser diagnostics of natural waters in the last 25 years, many research groups have demonstrated the unique possibilities of this technique. Now the time has come to devise measuring methods to meet the specific needs for monitoring relevant water areas. A special place in this list is occupied by coastal seawater areas around harbours, recreation zones etc.

Coastal waters have a much more complex and variable composition than open ocean water. There are differences in hydrodynamic processes also. For example, coastal currents along the Black Sea coast of Russia have great importance for pollution transport. That is why the creation of methods and tools for monitoring coastal seawater areas is a very relevant but difficult problem (1).

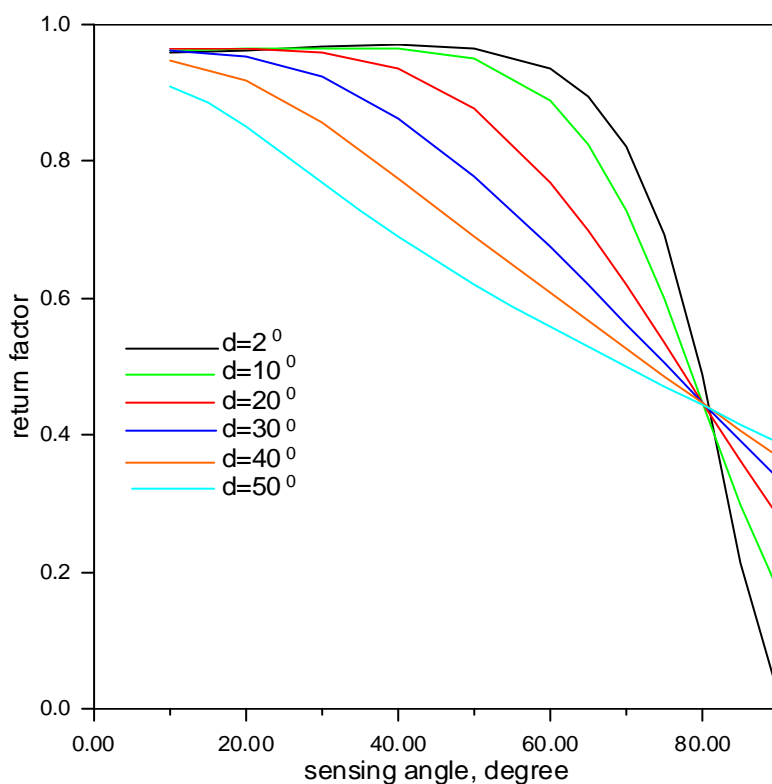
The first element of the monitoring system is a lidar mounted in a sufficiently high building on the shore. The lidar allows for a continuous monitoring of the water surface and the sub-surface layer of the water (and, possibly, of the atmosphere) in the selected area. As shown in (2,3), the remote sensing distance of a lidar for measuring water Raman scattering (and fluorescence of organic compounds in seawater) can be several kilometres. The effectiveness/cost index of a shore-based lidar is substantially higher than that of other methods of continuous monitoring using aircraft, helicopter and ship.

In the following, some features of remote sensing of coastal seawater areas with shore-based lidar are discussed (sect. 2); the results of a calculation of the signal on the sensing distance (sect. 2); a description of the used lidar and its features (sect. 3); and results of lidar field tests, the verification of theoretical results, and the evaluation of the maximum sensing distance, which can be achieved with improved laser energy (sect. 4) are presented.

## THEORY

Main features of shore-based lidar measurements of coastal waters are the widely varying sensing distance and the sensing angle. At a long distance the sensing angle  $q$  (defined as the angle of laser beam incidence versus the normal on the plane water surface) approaches  $90^\circ$ . For example, with our shore lidar station at the Blue Bay (Russian Black Sea coast) the sensing angle varies from  $\sim 78,6^\circ$  to  $88,9^\circ$  if the sensing distance varies from 50 m to 500 m (see sect. 4). In this case, the echo-signal energy cannot be calculated without regard to the processes of reflection and refraction. It may seem that at angles close to  $90^\circ$ , a lidar can hardly detect any optical signal, because of reflection losses and the increase in the sensing distance. However, the surface of the sea is seldom smooth, and it is necessary to take into account waves on the water surface. Due to waves the local angles of incidence may substantially differ from the right angle. Therefore, it is necessary to take into account the effect of waves on the received echo-signal (4).

In (4) the calculation of the return factor  $K(q)$ , which represents the production of propagation coefficients of the laser beam and echo-signal in the presence of waves, is described. The results of the calculation are



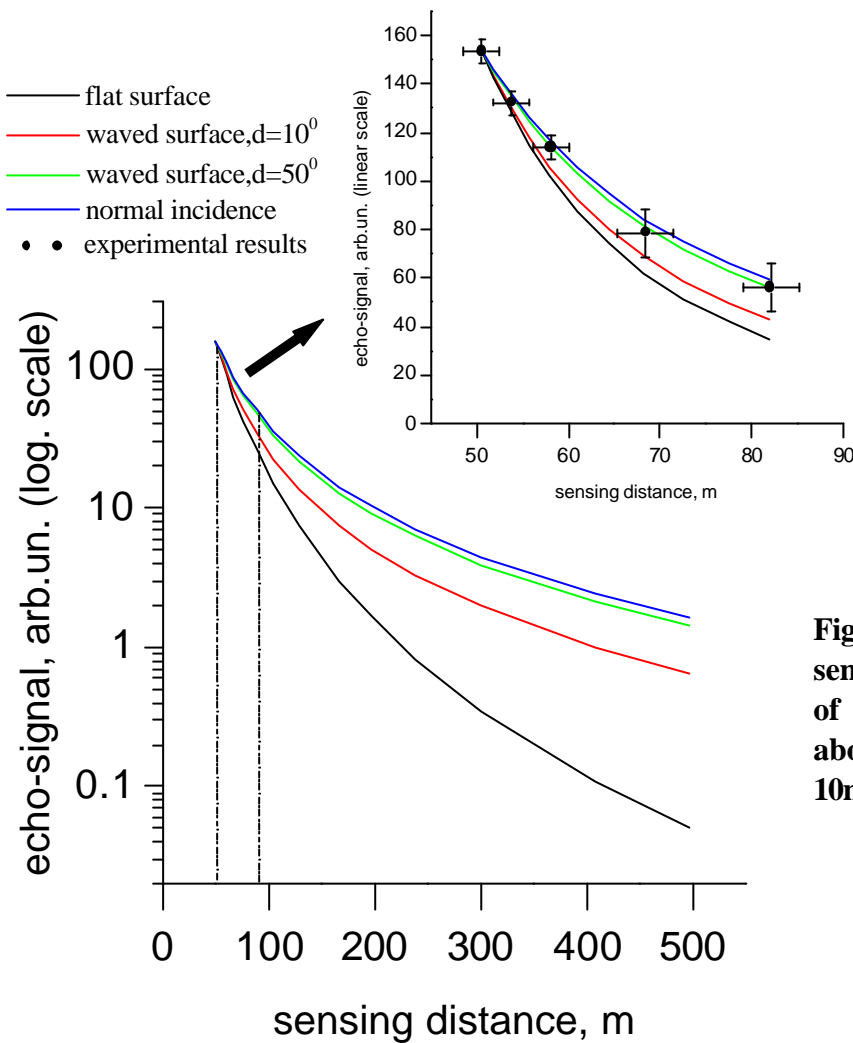
shown in Figure 1, where different curves correspond to different wave levels  $d$  ( $\tan d = S$ , where  $S$  is the dispersion of displacements of the distribution of water surface elements). As can be seen in Figure 1, there is a strong possibility of sensing at large angles. In the case of developed waves, the return factor value is only twice smaller than for normal incidence. So, the achievement of large sensing distances is limited only by the power of the laser radiation and the sensitivity of the detector.

**Figure 1 Return factor versus sensing angle at different levels of the waving  $d$  (4).**

To carry out a field verification of these theoretical conclusions, we calculate dependencies of the echo-signal on the sensing distance  $R$  for a shore-based lidar. In Figure 2, the results of these calculations are presented for three cases: a) for laser beam incidence on a flat surface; b) for laser beam incidence on a real sea surface at different levels of waving ( $d=10^\circ$ ,  $d=50^\circ$ ); and, for comparison, c) for the case of normal incidence of the laser beam on a flat surface where the echo-signal depends on sensing distance as  $R^2$  (this case corresponds to the ideal case of sensing the hypothetical ocean surface without waves from board an aircraft).

## CHARACTERISTICS OF THE LIDAR

The shore-based lidar described in this paper consists of a source of pulse laser radiation with four wavelengths, a receiver of echo-signal and a PC.



**Figure 2. Echo-signal versus sensing distance  $R$  for distances of 50 to 500 m. The lidar height above the sea surface is about 10m.**

### The source of pulse laser radiation

In this variant of a lidar, a YAG-Nd laser built by the company RDI "POLYUS" with frequency multiplier was used. The laser consists of a generator and an amplifier. In the generator, the three-pass scheme was used. For this reason, the YAG-Nd crystal has the form of a parallelepiped (SLAB). The crystal size is 100x8x5 mm. For effective conversion of the laser basic frequency to the higher harmonics (2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup>), a small divergence of the laser beam should be provided. To achieve this, the lowest cross-section mode was picked out by a diaphragm, and it provided the necessary divergence of about 0,5 mrad. At the generator output, the beam diameter was 3,5 mm. Before the amplifier was put in place, the beam was expanded up to 6 mm by means of a telescope to avoid the risk of a destruction of the active element. A YAG-Nd crystal with cylindrical shape and 6 mm diameter was used as the amplifier. After the amplifier, the laser beam fell into a special box with non-linear elements, where transformation of the laser radiation frequency to the second, the third and the fourth harmonics was performed. A KTP crystal was used as the doubler, a KDP crystal as the tripler, and a BBO crystal as the doubler of the second harmonic. To change from the mode of second harmonic generation to the mode of third and fourth harmonics generation consisted of a 90° turn of the KTP crystal and of placing the corresponding crystal (KDP or BBO) on the beam path. All crystals were mounted in specially prepared holders that allowed to change the harmonic easily.

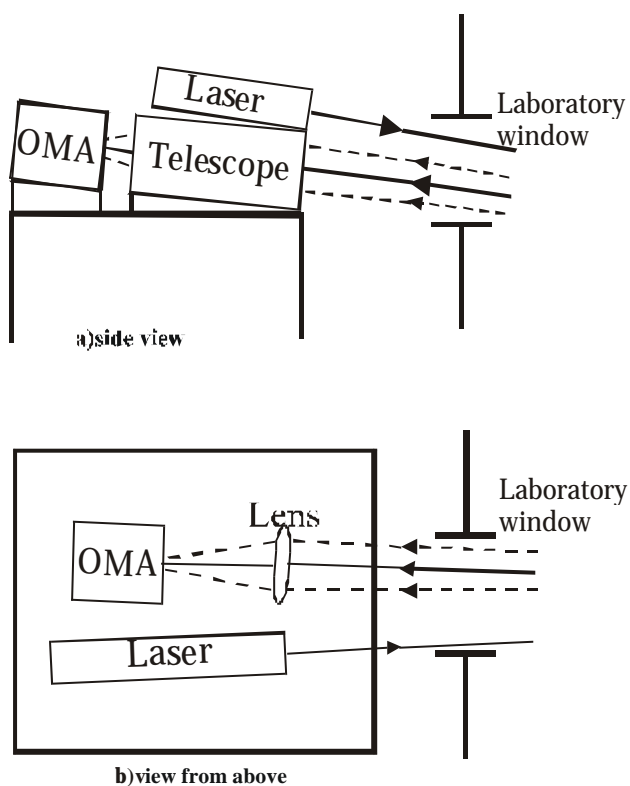
In our experiments, the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> harmonics were used (note that for some tasks, for example, for the determination of oil films on the water surface the main emission of the YAG:Nd laser with a wavelength of 1064 nm can be useful). The laser parameters are listed in Table 1.

**Table 1: Characteristics of the laser**

	pulse energy , mJ	average power, mW	pulse power, MW	repetition rate, Hz
$\lambda=532$ nm	80	800	8	10
$\lambda=355$ nm	30	300	3,5	10
$\lambda=266$ nm	20	200	3	10

### The receiver

For detecting the signal and its spectrum two optical multichannel analysers were used: an OMA-1 (PARC, USA) or an OMA assembled with an UV-enhanced CCD camera (by DeltaTek, Russia) and of a polychromator EG&G model 1226. For focusing the radiation to the OMA slit, two quasi-coaxial schemes



were used: with focusing by a lens or by a telescope (Figure 3). The lens had a focal length of  $F = 46$  cm and an aperture (diameter) of  $D = 12.5$  cm; the Cassegrain telescope had  $F = 1$  m and a diameter of the main mirror of  $D = 30$  cm. The lens and the telescope focused the incident radiation to the OMA entrance slit being 0.5 mm wide and 5 mm high.

To obtain the spectra, up to 2000 cycles of signal accumulation were performed (each 33 ms long). So, recording one spectrum took up to 60 sec. At daylight, the OMA were used in the gating mode to improve the signal-to-noise ratio.

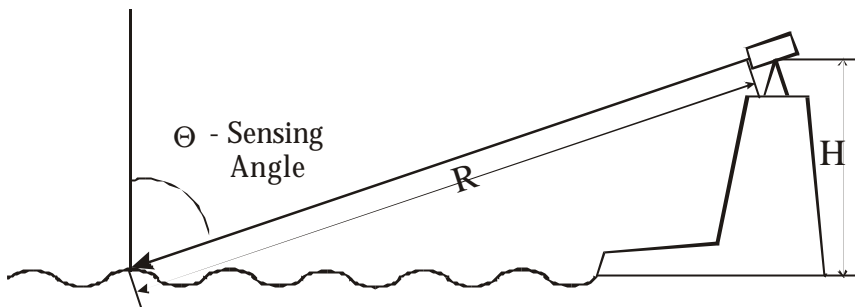
**Figure 3: Schemes of remote sensing of coastal water by means of shore based lidar with telescope (a) and with lens (b).**

The spectral sensitivity of the OMA-1 ranges from 350 to 700 nm. It was possible to detect radiation spectra under excitation by the second harmonic ( $I_{exc} = 532$  nm) and by the third harmonic ( $I_{exc} = 355$  nm) of YAG-Nd laser. To detect radiation spectra under excitation by the fourth harmonic ( $I_{exc} = 266$  nm) of YAG-Nd laser, the OMA with UV CCD camera from DeltaTek was used. This camera has sensitivity in the range of 250-900 nm.

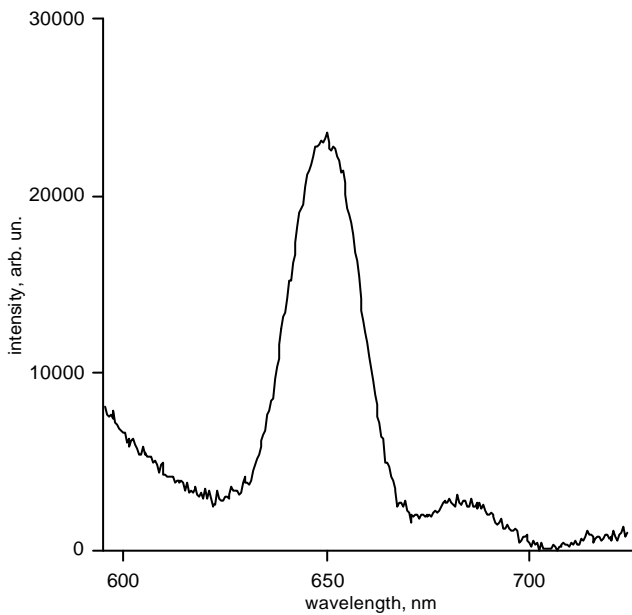
### FIELD TESTS OF THE LIDAR

The lidar was tested in the Blue Bay (Black Sea, near Gelendzhik). It was mounted in the laboratory on the 3<sup>rd</sup> floor of a building standing on the shore, so the lidar height above the sea surface was about 10 m (Figure 4). The sensing distance varied from 50 to 80 m, which corresponds to a change of the sensing angle from 78.6 to 83°. To evaluate the lidar quality, the water Raman scattering signal obtained under sensing of coastal sea areas at 532 nm wavelength, and for an evaluation of theoretical conclusions, the dependence

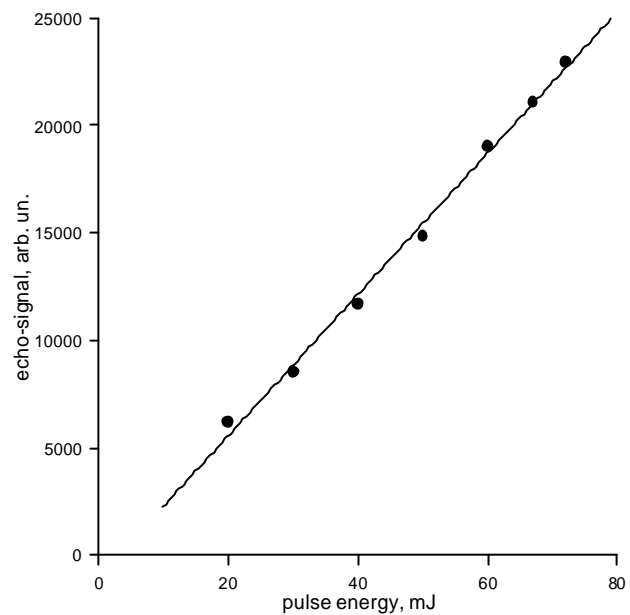
of echo-signal on sensing distance was used. With  $I_{exc} = 532$  nm the phytoplankton fluorescence band appears in the spectrum of the echo-signal besides the water Raman scattering band (Figure 5). With  $I_{exc} = 355$  nm and  $I_{exc} = 266$  nm, the spectra of the echo-signal included the fluorescence band of passive organic admixtures (aquatic humic substance, proteins, oil pollution etc) (1,5).



**Figure 4: Geometry of remote sensing by shore-based lidar.  $H=10$  m,  $R=50$  m  $\rightarrow$   $q = 78,6^\circ$ ,  $R_{max}=500$  m,  $\rightarrow$   $q = 88,9^\circ$ .**



**Figure 5: Emission spectrum of seawater at 532 nm excitation wavelength obtained with remote sensing in the Blue Bay**



**Figure 6: Echo-signal versus laser pulse energy.**

First, a verification of the linearity of the water Raman scattering signal dependence on the laser beam energy was carried out. The results of this verification are shown in Figure 6. In the  $R=50-80$  m distance region the echo-signal detected by means of the lens was the same as the echo-signal detected with the Cassegrain telescope. Then the following investigations were carried out:

**Dependence of the echo-signal on the sensing distance.**

As shown in sect. 2, the wave effect on the echo-signal can manifest itself depending on the sensing angle  $\theta$  and therefore on sensing distance. In Figure 2, where the theoretical results are shown, the experimental points are plotted at varying  $R$  from 50 to 80 m. As can be seen, they are close to the dependence corresponding to the waving factor  $d=40-50^\circ$ , and they strongly deviate from the dependence corresponding to the incidence of laser beam on a flat horizontal surface. Note that this procedure can be used for determination of the waving factor. To achieve better precision in these measurements, the range of change of distance  $R$  must be expanded.

### Evaluation of maximal sensing distance limit.

The lidar provided a maximum pulse energy of 80 mJ at 532 nm wavelength and a maximum average power of 0.8 W at 10 Hz pulse repetition rate. To evaluate the maximum sensing distance which can be potentially achieved using the shore-based lidar with improved energetic characteristics, we carried out the following experiment. At 50 m sensing distance we reduced the energy and detected the echo-signal. It was found that the minimal energy of the laser beam required for signal detection was 10 mJ (average power 0.1 W). To achieve a sensing distance of 0.5 km, the average power should be increased 100-fold (in according to Figure 2). Therefore, due to the experimental results described above an average power of 10 W is required. Such a value of the average power can be achieved either by increasing the pulse energy to 1 J at 10 Hz repetition rate, or by simultaneously increasing the repetition rate (for example, to 50 Hz) and the pulse energy (to 0.2 J, if the repetition rate is increased to 50 Hz). YAG:Nd lasers (with frequency multiplier) with such parameters have been commercially produced for a long time (for example, by the RDI "POLYUS"). Quite big sizes, mass, energetic consumption and the necessity of a power cooling system are no problems for a shore-based lidar (unlike airborne and shipborne lidars (3)). Note that the sensitivity of the echo-signal detector can be increased in comparison with the sensitivity of our lidar. Therefore, we can predict achieving the sensing distance of 1 km as a realistic value for a shore based lidar. This fact agrees with the estimations obtained in papers (2,3). Note again that at the sensing distance  $R=1$  km and a lidar height above the sea surface of  $H=10$  m, the sensing angle is  $89,5^{\circ}$ , when detecting the echo-signal with the lidar characteristics specified above are achieved only due to the presence of waves on the sea surface.

In the case of sensing by radiation with wavelengths of 355 nm and 266 nm at 50 m sensing distance, the water Raman scattering signal (maxima of their bands are at  $I_{RS} = 290$  and 403 nm, respectively) does not differ much from the echo-signal with  $I_{exc}=532$  nm ( $I_{RS} = 650$  nm), since the average power of the 3<sup>rd</sup> and 4<sup>th</sup> harmonics radiation is 3 and 4 times less than that of the 2-nd harmonic radiation, respectively (see table). This is due to the water Raman scattering cross-section being proportional to  $(I_{ex})^{-4}$ . Therefore, the conclusions obtained above for sensing by  $I_{exc}=532$  nm are also valid for the wavelengths of the 3<sup>rd</sup> and 4<sup>th</sup> harmonics.

### CONCLUSIONS

In this report an experimental confirmation of theoretical conclusions on remote sensing using a shore-based lidar is presented. Emphasis is given on large incidence angles close to  $90^{\circ}$ . On the basis of results obtained with a three-wavelength lidar with comparably low average power at a sensing distance of less than 100 m it is demonstrated that a 1 km sensing distance can be achieved using industrial YAG:Nd lasers.

### ACKNOWLEDGEMENTS

This work was supported by INTAS (project N96-2063) and the Russian Federal programmes "Integration" (project N475) and "World Ocean" (project N6.10).

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