

Laser Methods for Measuring the Ocean Surface-Wave Spectrum

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ABSTRACT

We suggest a new method for remote measurement of the statistical characteristics of the sea surface, that is based on a continuous scanning of the sea surface small divergence laser beam and on the measurement of mirror back reflections and distances from specular points. The latter may be considered as a modification of a traditional laser profilometry. Under some assumptions on the statistics of the specular points relation have been found between the spectrum of the measured process and the ocean waves spectrum. A probability analysis of a random series of reflected pulses yields some other statistical characteristics of the sea surface. The theory was confirmed in a series of field experiments with a narrow-beam laser profilometer from an oceanographic tower, an aircraft and from a ship. A calibrated wire gauge was used for the comparative measurements from the oceanographic tower. A good coincidence of measured spectra was obtained up to the frequency of 3 Hz or $\lambda = 15$ cm.

One of the major problems in the remote sensing of the ocean is related to measurement of the characteristics of surface possibilities in investigating the wave interaction in the ocean and in identifying the sea state. The most highly developed technique of ocean remote sensing is based now on the air or space imaging radars. The traditional microwave radar imaging of a sea surface provides data only for a long wave region of the spectrum. The main goal of our work was to achieve better resolution in the high frequency part of the spectrum.

Laser methods of sea probing have been developing since the early 1970's (Olsen, 1970). They are superior to radio oceanography in several aspects. First, one can expect better resolution due to the small divergence of a laser beam in comparison with a microwave beam. That is suitable for the measuring of the small-scale waves. For instance, a sharp-focused laser beam permits to measure waves of a horizontal scale up to 1 mm, while the micro-

wave radar resolution is limited to several meters (Alpers, 1981).

There is also the principal difference between radar and lidar probing in the reflection of signal by the sea. The radar wavelength exceeds those of the capillary waves, and, therefore, various diffraction effects are important here. The laser wavelength is considerable shorter than any surface one, and the mechanism of the laser reflection is responsibly explained in the terms of geometric optics. This aspect gives rise to much simpler relations between the statistics of the lidar return and that of the sea surface.

The two basic laser methods of sea state measurements have been developed up to now. One of them is based on the measurements of the intensity of the reflected light and allows to obtain such average characteristics of a sea state as a mean square slope and a mean square height of the wave field (Bufton, 1983). Another lidar technique is based on the measurements of the wave heights or wave profile and is known as laser altimetry or laser profilometry. Laser measurements of the sea profile can be carried out from an airborne platform (McClain, 1982).

An analysis of the state-of-the-art in these methods revealed that the two techniques have been effectively used for the investigation of sea waves as long as 10 m and more. But in many field experiments it is important to study both large scale and comparatively short waves. A good example of such situation is the interaction between internal and surface waves, where most changes are observed in the high frequency part of the spectrum. So there is need for the further investigations of the laser remote sensing methods for achieving the limiting spatial resolution.

If the laser profilometer is used on the land the spatial resolution will be simply determined by the diameter of the laser spot but this is not true in the case of the sea surface. The thing is that the illuminated sea surface looks

for the distant observer like a number of randomly located small bright spots - or specular points. The bright spots corresponds to the points of backward reflections to the receiver. The density of specular points on the sea surface is approximately 1000 - 10000 per square meter, the diameter less than 100 mcm. If the laser beam diameter of the profilometer is much larger than the average distance between specular points the spatial resolution will be determined by the light spot diameter. We believe that all the earlier airborne experiments in this field have been conducted in this regime. In the opposite case of a small laser spot the resolution will be determined by the average distance between registered specular points. The main result of our research is that the best spatial resolution in the laser profilometry could be obtained with a narrow beam technique at an optimum diameter of a light spot on the surface. Using this technique it is possible to measure practically the whole gravitational part of the surface wave spectrum.

Let a laser beam to be incident upon the sea surface. In the case of phase profilometry the laser beam is amplitude modulated with a frequency f . The return signal is formed by specular points mentioned above. Oceanographers are primarily concerned in the sea spectrum or other statistical data rather than in isolated sea elevation records. The problem is therefore to reconstruct the statistics of an unknown random sea from an experimental discrete samples corresponding to the specular points.

Let $\xi(t)$ be a stationary random function of the surface elevation in time or in space in the case of a moving platform. The discretization of $\xi(t)$ by random sequence produces a new random function $\eta(t)$

$$\eta(t) = \xi(t_i) \text{ at } t_i \leq t \leq t_i$$

where t_i - is the moment of its reflection. The quantity $\tau = t - t_i$ is known as a reverse time of a pulse process. The transformation of the correlation function and spectrum at the four-dimensional probability density

$$P\{\xi[t_1 - \tau(t_1)], \xi[t_2 - \tau(t_2)], \tau(t_1), \tau(t_2)\}$$

For the independent from ξ Poisson process the transformation is (Boyer, 1986):

$$S_\eta = (S_\xi + S_0) \frac{1}{1 + (2\pi f \tau)^2},$$

where f - is frequency, S_ξ is process ξ spectrum, S_η process - η spectrum, τ Poisson process time constant,

$$S = 4 \int_0^\infty S_\xi(f) \frac{(2\pi f)^2 \tau_0^3}{1 + (2\pi f \tau)^2} df$$

From this relation one can see that if $S_\xi(f_1) < S_0$ for some frequency f_1 than

$$S_\xi(f) \approx \left[1 + (2\pi f \tau_0)^2 \right] S_\eta(f) - \left[1 + (2\pi f_1 \tau_0)^2 \right] S_\eta(f)$$

The latter is true for our case due to the fact that ocean waves spectrum is limited.

Knowing f_1 , τ_0 and $S_\eta(f)$ it is possible to reconstruct the spectrum of the initial process.

Our measurements of the statistics of specular points performed from the oceanographic tower showed sea specular glitter is described rather well by the Poisson statistics, that allows us to apply the suggested algorithm for reconstruction the sea spectrum. For the Poisson process

$$P_0(\tau) = \frac{1}{\tau_0} \exp\left(-\frac{\tau}{\tau_0}\right)$$

where $P_0(\tau)$ is the distribution of time intervals between pulses. This distribution can be obtained experimentally, that gives the quantity τ_0 . S_0 is determined from the measurements of $S_\eta(f_1)$ at the high frequency part of the spectrum.

To study the statistics of the laser reflection from the sea surface we have designed a lidar based on 15 mW CW He-Ne-laser. The intensity of the beam was amplitude modulated with a frequency 40 MHz that corresponded to the uncertainty range in wave height measurements of 3.75 m. The reflected signal was registered by a photo multiplier. Than the signal was processed by a detector of envelope and phase including DISA 56 N 11 Type Mean Value Meter and Bruel & Kjaer 7005 Spectrum Analyzer. Spectrum transformation was performed by a personal computer. The experiments have been conducted from the oceanographic tower located in the Black Sea 500 m off the Crieman Coast. Nearly 100 measurements were performed under various weather conditions. The distance between the receiving telescope and the sea surface was 16 m. The experiments were accompanied by in situ measurements with a calibrated wire gauge.

Depending on the weather conditions and light spot diameter it was possible to measure the surface wave elevation spectrum up to the frequencies of 0.5 - 2.0 Hz. the upper limit of the frequency range depends on the white noise density S_0 and on the lidar noise. The latter

can be diminished by increasing the laser output power and the narrowing of the bandpass of the receiving filter. For the diminishing of S_0 it is necessary to increase the average frequency of registered pulses by increasing of the diameter of the light spot. But the latter leads to the diminishing of the spatial resolution of the lidar. So there is a possibility for the optimization of the process under discussion. In a whole, the experiment showed that using this technique it is possible to measure practically the whole gravitational part of the surface waves spectrum at the wind velocities of 5 - 12 m/s.

REFERENCES

- Alpers W.R., Ross D.B., and Rufenach C.L., 1981, J. Geophys. Res. C86, 6481 - 6498.
- Boyer L. and Searby G., 1986, J. Appl. Phys., v.60, 2699.
- Buften J.L., Hoge F.E. and Swift R.N., 1983, Appl. Opt., v.22, 2603.
- McClain C.K., Chen D.T. and Hart W.D., 1982, J. Geophys. Res., v.87, 9509 - 9512.
- Olsen W.S. and Adams R.M., 1970, J. Geophys. Res., v.75, 2185.