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SIMPLE RED-BEAM ATTENUATION METER FOR SEA TRUTH MEASUREMENTS

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ABSTRACT

Red beam attenuation is useful in analyzing profiles of remotely sensed hydrooptical parameters and for accurate resolution of the vertical structure of chlorophyll and suspended particles. Hence, the development of a probing red beam attenuation meter has practical interest. Auto-collimating optical schematics with a cat's eye have been used in the meter developed. The instrument is intended for application both as an independent device and as a module for oceanographic systems. High accuracy with minimal size and power consumption are realized by using electro-optical semiconductors. The dual beam principle of stabilization with negative optical feedback for the light emitting diode (LED) is applied. The exponential shape of LED modulated impulses causes the instrument output to be proportional to beam attenuation. By placing the optical attenuator into the reference beam one can compensate for pure water absorption and measure the volume scattering coefficient. The optical base of the cat's eye can be varied from 50 cm on down. The device is not sensitive to ambient light.

1.0 INTRODUCTION

Unlike the apparent optical properties of sea water, inherent optical properties are steady characteristics of a scattering medium, independent of both the ambient light conditions and the spectral changes due to light penetration into deep sea water. Knowledge of the inherent optical properties substantially improves the quality of the physical interpretation of under-satellite measurements and permits to improve methods for the solution to inverse problems of marine optics. Therefore, besides compulsory light field measurements, the SeaWiFS Pre-launch Science Working Group has recommended additional measurements of inherent optical properties.

At the Marine Hydrophysical Institute of Ukrainian Academy of Sciences and at Naval Research Laboratory, Stennis Space Center, MS, USA methods and instruments for the measurement of beam attenuation are the most advanced. For a long time such instruments were used in performing field hydrooptical investigations. The choice of the beam attenuation coefficient as an additional parameter which is essential in carrying out under-satellite optical measurements is not accidental. Because the attenuation coefficient is the sum of the absorption and scattering coefficients, it contains information about the features of these parameters in various waters. The most important features, investigated to the present time, are as follows:

1. In the beam attenuation spectrum, absorption bands from suspended particulate matter

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become barely distinguishable due to compensating changes in scattering. This was shown in theoretical accounts by Morel and Bricaud (1981) with the use of Mie scattering theory to biological particles. The shape of the absorption spectrum of yellow substance is reproduced in the beam attenuation spectrum practically without distortions and is described by an exponential dependence (Jerlov, 1961):

$$\sim \exp(-0.015\lambda), \qquad (1)$$

2. In the red band the absorption both by particulate matter and by yellow substance is negligible. Detailed investigation of these features required the development of new instruments as well as the improvement of existing instruments for beam attenuation measurements. When performing under-satellite experiments, these instruments will allow not only to measure vertical profiles of beam attenuation and light scattering coefficients, but they also will essentially complement conventional biochemical observation with detailed data of their stratification, and will also provide an opportunity to take samples at optimal depths.

2. METHODS

For a long period of time the transparency of upper layers was evaluated using the Secchi disk depth. Despite the extreme simplicity of these measurements, their application is limited due to the intense influence of ambient light and surface conditions on the measured data. Besides, the transparency evaluation of sea water by means of Secchi disk depth is not applicable to cases when it is important to know the vertical distribution of the tramsparency. As a parameter more fully describing the light attenuation, it is convenient to use the beam attenuation of sea water. A number of beam attenuation meters (or transparency meters) which use various optical and photo-electric layouts have been developed (Zhiltsov and Nikolaev, 1980; Lee, 1980; Vinokurov, Migulya, Prikhach and Shishkin, 1988; Anonymous, 1989). Most of them are based on a method which consists of measuring the beam attenuation coefficient c averaged over a water path l defined by the instrument optical base:

$$F = F_0 \exp(-c\,l), \qquad (2)$$

where F_0 and F are the light fluxes before and after traversing the water path. The measurement accuracy of the beam attenuation coefficient by this method is defined mainly by the instability of the elements in the photo-electric circuits and by such geometrical parameters as the light source collimation angle, the photodetector acceptance angle and the length of the optical base. Because of the instability of the elements in the photo-electric circuits, the error could be diminished by the choice of an appropriate photo-electric layout. Other factors have different influences on the accuracy of beam attenuation measurements in natural waters with various turbidity and they require specific attention in each particular case. The calculations of optimal light source collimation angle and photodetector acceptance angle are made by taking into account the given accuracy and the shape of the volume scattering function. In this case the selection of optimal measurement conditions can be made only with a change of optical base length. Because of the elongated shape of the sea water volume scattering functions the light source collimation and the photodetector acceptance angles should be extremely small. This leads to a very stringent requirement to maintain optical alignment of the instrument which is frequently moved from air to water and back. In the former meters optical schematics did not always fulfill these requirements; therefore a partial misalignment, forced by external factors, occurred. It is possible to explain the data discrepancy of different instruments by this fact. In former meters the opportunity to change the optical base length is not stipulated for the same reason and they are intended for measurements of beam attenuation of the scattering medium only for a limited range of optical characteristics variations.

3.0 A NEW PRINCIPLE FOR BEAM ATTENUATION MEASUREMENT

Modern requirements imposed on instruments for measurement of absorption coefficient and beam attenuation are high, and to meet them it is necessary to develop a new design concept and to apply innovative decisions. The minimum instrument characteristics adopted by SeaWiFS Project Working Group for the measurement of inherent optical properties are shown in Table 1.

Hence, for spacecraft sensor calibration and validation, it is necessary to develop a new beam attenuation design which would first have high resistance to the influence of various factors and, second, allow changes of the optical base length even in field conditions. One such realization (Lee, 1980) is offered by the Laboratory of Optical Oceanography of Marine Hydrophysical Institute and its main feature is application of auto-collimating optical schematics with a cat's eye as a reflecting element. With such optical schematics a measured medium fills the space between the illuminator and the cat's eye, which reflects the incident light precisely in the opposite direction, irrespective of prism orientation. In this auto-collimating optical schematic the beam alignment is not changed when a slight deviation of prism position occurs. Therefore it is possible to smoothly change the length of the optical base of the beam attenuation meter by simply moving the prism along the optical axis, as long as the instrument alignment is not affected. Hence, the opportunity arises to dramatically expand the range of beam attenuation measurement . It is even possible to measure under optimum conditions with the same relative error over a range of environments characterized by drastic changes in optical properties.

The opportunity to easily change the optical base length over wide ranges allows to measure absolute values of the beam attenuation. It is enough to conduct measurements of the same medium for two various bases which are short enough to be regarded as single-scattering paths. In this case, the necessity to correct for the reflectance change of the glass surface situated in the water is eliminated. At the present time, this correction is performed in a theoretical manner for each particular optical design. Whereas the value of the correction considerably exceeds the beam attenuation of pure water, mistakes in its determination frequently are the main reasons for the high additive component in the resulting error. This circumstance was the main obstacle to high measurement accuracy for beam attenuation absolute values.

Another advantage of auto-collimating schematics with a cat's eye as a reflecting element is that it does not appreciably respond to minute deviations of beams when it comes into contact with the measured medium, and also to various deformations of optical details and of mechanical units making up the instrument optical base. Therefore, the occurrence of instrument misalignment

Table 1. Instrument characteristics for measurement of inherent optical properties

Instrument characteristics	
Spectral Resolution:	410, 443, 490, 520, 510 and 670 nm
Bandwidth:	10 nm
Accuracy:	0.005 m^{-1}
Precision for λ < 650 nm:	0.002 m^{-1}
Precision for λ > 650 nm:	0.005 m^{-1}
Stability width:	≥ 0.005 m^{-1}
Temperature:	0°-25° (centigrade)
Sampling interval:	> 4 samples m^{-1}
Source Collimation Angle:	< 5 mrad
Detector Acceptance Angle:	< 20 mrad
Depth Capability:	200 m

during operation is excluded, a situation which has important significance for measurements in field conditions, especially at large depths where water pressure is high.

The auto-collimating optical schematics with a cat's eye as a reflecting element was applied in a simple meter for measurement of sea water beam attenuation. It is intended for wide application, both as an independent instrument and as a component of various oceanological mounting: STD sounds, towed apparatus, buoy and moored stations. In such routine devices the main requirement is to achieve high accuracy at minimal dimensions and power consumption. An optimal combination of these requirements can be reached if such a compact low consumption meter is realized on the basis of electro-optic semiconductor elements as both light source and photo-receiver. Nevertheless, until recently, the use in hydrooptics of electro-optic semiconductors was constrained because of the low output power of the light-emitting diodes over the visible spectrum, especially the blue-violet band, where the sensitivity of photo-diodes is also minimal. Another reason for the limited application of electro-optic semiconductors is their significant temporal and temperature instability, hindering high accuracy of measurements. To avoid these limitations the development of instruments for transparency measurement only in the red spectral band is employed, using various electronic ways of stabilization of the properties of the light emitting diode (LED). A typical example of such a transparency meter using semiconductor elements is a transmissometer presently manufactured by Sea Tech, Inc. The instrument is designed as a beam photometer and suffers from the typical limitation of this method of measurement. Besides, the optical schematics applied in this meter are very sensitive to minute deformations in the illuminators and design elements composing its measuring base.

4.0 PRINCIPLE OF VOLUME SCATTERING COEFFICIENT MEASUREMENT

The important advantage of the proposed two-beam principle for red beam attenuation measurement is that it permits easy access to measurement of the volume scattering coefficient *b*. In the use of one-beam meters this characteristic can only approximately be calculated.

The volume scattering coefficient is one of the main hydrooptical characteristics. First, this variable is one of the parameters in the radiation transfer equation and, hence, determines the law of propagation of light in the sea; secondly, it appears to be the best way to evaluate the scattering property of sea water suspended particulate matter. Therefore it is possible by means of volume scattering coefficient measurements to obtain information about sea water particulate matter content. Other existing methods (filtration and weighing, study of particle size distribution by Coulter counters, special opto-electronic sensors and video cameras (Morel, 1983) are not more accurate at the present time and require expensive and complex instruments (Ivanoff, 1978). Besides, knowledge of the volume scattering coefficient is necessary for calculations of yellow substance concentration from remotely sensed data.

The most widespread methods for the determination of the volume scattering coefficient (Kopelevich, 1975) are :

1. method of the volume scattering function integration,
2. nephelometric method,
3. method of direct measurements.

The volume scattering function integration method uses the following equation:

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta \, d\theta, \qquad (3)$$

where $\beta(\theta)$ is the volume scattering function. It should be taken into account that, owing to the elongated shape of the volume scattering function of sea water in the forward direction, from 10 to 40 % of the scattered light can be found in the angular range from 0 to 1 degree. As a rule, for cases when *in situ* measurements of the volume scattering function do not involve measurements over small angles, the errors in determining the volume scattering coefficient by these method is 20% or less.

The nephelometric method is based on the determination of an empirical relation between the volume scattering function measured under one or several fixed angles and the volume scattering coefficient. The theoretical accounts made by Kopelevich (1975) have shown that application of a single angle of 6 degrees leads to an error of 16 %, use of two angles (1 and 45 degrees) decreases the error up to 15 %, while three angles (1, 6, 45 degrees) give an error of 9 %.

The known method of *in situ* measurements of the volume scattering coefficient offered by Jerlov (1961) has a shortcoming, because the method of calibration of a real instrument is not clear.

The proposed direct method of measurement of the red volume scattering coefficient gives the opportunity to easily reach high accuracy of measurements and to circumvent the above limitations of the other methods.

As is well known, beam attenuation is the sum of the absorption coefficient a and the scattering coefficient b:

$$c = a + b. \tag{4}$$

Taking into account the contribution from various components it is possible to write:

$$c = a_w + a_p + a_y + b_w + b_p, \tag{5}$$

where the subscripts w, p, and y stand for pure water, suspended particles and yellow substance, respectively.

The values of a_w and b_w are calculated theoretically and are known with high accuracy. The particle absorption coefficient is determined by phytoplankton pigment absorption, and in the red band of the visible spectrum does not exceed 2-4 % from measured values of beam attenuation (Shifrin, 1988). As already mentioned, the absorption by yellow substance decreases exponentially with increasing wavelength and becomes negligible in the red band. Hence Eqn. (5) can be accurately approximated by:

$$c = b_p + const. \tag{6}$$

When performing the two-beam measurement the constant in Eqn. (6) can easily be compensated by the insertion into the reference beam of a precisely calibrated optical attenuator. Thus, in this case the device for red beam attenuation measurement gives the possibility of directly measuring the particle volume scattering coefficient in the red band of the visible spectrum. The value of the particle volume scattering coefficient is related to the total particle concentration C_p by the equation:

$$C_p = k_1 b_p, \tag{7}$$

where k_1 is a factor of proportionality depending on the measured wavelength, total number of particles and particle size distribution. In spite of the fact that the total concentration and particle size distribution vary from location to location, these changes have an insignificant effect on the value of the constant k_1. And with absolute calibration of the instrument it is possible to measure total particle concentration.

5.0 AUTO-COLLIMATING ELECTRO-OPTIC SCHEMATICS OF BEAM ATTENUATION MEASUREMENT

In the red beam attenuation meter for *in situ* investigation the two-beam principle of measurement with negative feedback through an optical channel and auto collimating optical schematics with a cat's eye as a reflecting element is applied. The structure meter schematics is shown in Fig. 1. The main elements of the schematics are divided into two channels: measuring and reference.

The measuring channel contains a generator of exponential impulses, a differential amplifier, LED, an amplifier and photodiode, an input diaphragm, mirror, beam splitter, illuminator-objective and a cat's eye. The reference channel contains a reference voltage, comparator, an amplifier and photodiode, an optical attenuator, LED, mirror and beam splitter.

The beam attenuation meter works in the following manner. Light from an LED is divided by the beam splitter into two beams. After the beam splitter the measuring beam is collimated by the illuminator-objective into a parallel beam and goes into the investigated medium, where it traverses a distance up to a cat's eye, is reflected by it, passes across the medium again in the opposite direction, and through the same illuminator-objective comes back inwards into a hermetic case. Inside the hermetic case, the light is attenuated by water, reflected by the splitter and in turn by the mirror, focused into the measuring diaphragm center and further drops on one of the photo-cathode of a two-element photodiode.

The reference beam is formed from the LED light which is reflected by the beam splitter before the output diaphragm. A mirror reflects the reference beam and sends it through the optical attenuator to the second photo-cathode of a two-element photodiode.

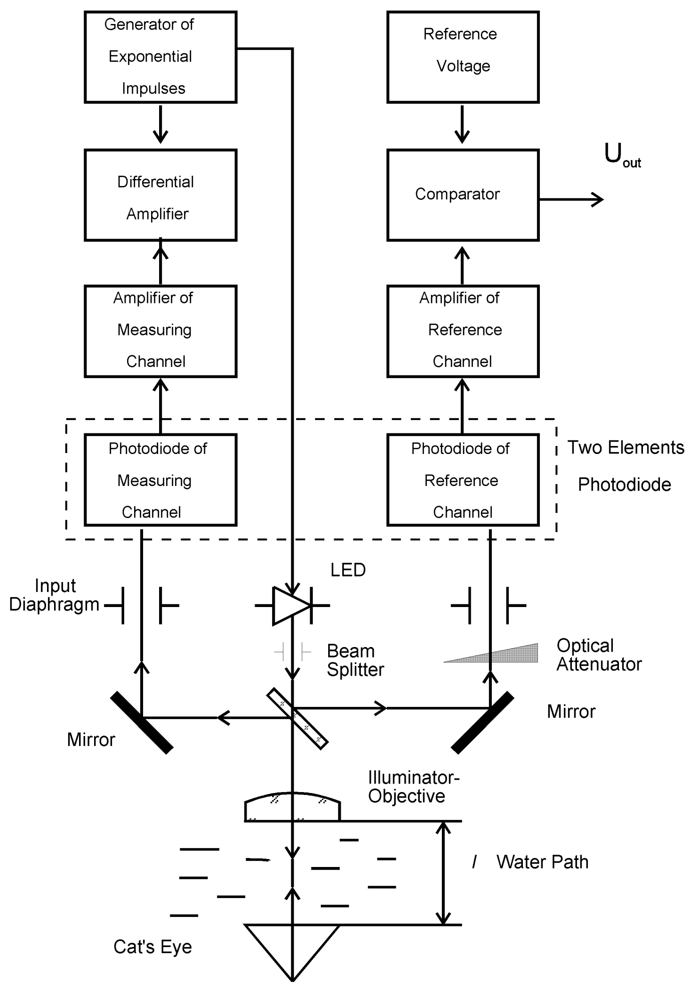

Figure 1. Red Beam Attenuation Meter Structure Schematic

While developing this optical schematics, attention was focused to the question of reference and of measuring the mutual influence of the beams. To separate these two beams all cases of potential interference were carefully considered, and optical shielding of beams by mechanical screens is provided.

The generator of exponential impulses produces a continuous sequence of decreasing exponential impulses U_g with stable parameters (amplitude U_0, frequency and a time constant τ).

$$U_g = U_0 \exp(-t/\tau). \qquad (8)$$

These impulses go to the differential amplifier input. A signal $U_m(t)$ from the output of the measuring channel amplifier is connected to another input of this differential amplifier. The output signal of the differential amplifier controls the light intensity of the LED. When the amplification of the differential amplifier is very high the voltage to its inputs will be equal:

$$U_g(t) = U_m(t). \qquad (9)$$

On the other hand, U_m is provided by the LED light flux F_{LED}:

$$U_m = S_m F_{LED} \exp(-2cl), \qquad (10)$$

where c is the beam attenuation coefficient, l is the instrument measuring base length, S_m is a factor of transformation of the light flux to a signal voltage of the photodiode. From Eqns. (9) and (10) we deduce the expression for the LED light flux:

$$F_{LED} = \frac{U_m}{S_m \exp(-2cl)} = \frac{U_g}{S_m} \exp(2cl). \qquad (11)$$

From Eqn. (11) the voltage, defined by F_{LED}, at the output of the reference signal amplifier is:

$$U_r = S_r F_{LED} = S_r \frac{U_g}{S_m} \exp(2cl), \qquad (12)$$

where S_r is a factor of transformation of the light flux to the signal voltage of the photodiode. Since the electrical parameters of the channels are identical we assume, that $S_r = S_m$. Then from Eqns. (8) and (12) we have

$$U_r = U_0 \exp(2cl - t/\tau). \qquad (13)$$

In accordance with Fig. 2, for the moment at time t_p, when the voltages at the inputs of the comparator become equal $\left(E_0 = U_r(t_p)\right)$, we can write:

$$E_0 = U_0 \exp\left(2cl + t_p/\tau\right), \qquad (14)$$

where E_0 is the reference voltage of the comparator and t_p is the time for the comparator action.

We take the logarithm of Eqn. (14) to obtain

$$t_p = \left[2\,c\,l + \ln\left(U_0/E_0\right)\right]\tau, \qquad (15)$$

and finally we can write:

$$t_p = 2\,c\,l\,\tau + const.$$

If the value of U_0 approaches E_0, then *const* will approach zero. Thus the output signal of the comparator is a sequence of impulses with a duration proportional to the beam attenuation coefficient *c*.

6.0 CONCLUSION

The proposed principle of measurement of beam attenuation and volume scattering coefficients are realized in a single small-sized instrument with the help of modern electro-optical elements. The applied auto-collimating optical schematics with a cat's eye as a reflecting element has allowed to simplify the determination of the correction for the reflectance change of glass surfaces situated in water. This circuit also permits easy changes in the wide limits of the instrument optical base length and to solve such a problem as the definition of the absolute value of the beam attenuation coefficient by measurements of the same water sample at two fixed bases. The variable base of the instrument allows us to expand the range of beam attenuation measurements, so that measurements can always be performed under optimal conditions with an equal relative error.

The two-beam principle of measurement of red beam attenuation permits a new direct method of measurement of the volume scattering coefficient. The proposed direct method of measurement of the red volume scattering coefficient also permits high accuracy of measurement and avoids the limitations of other methods.

The instrument is intended for application both as an independent device and as a module for oceanographic systems.

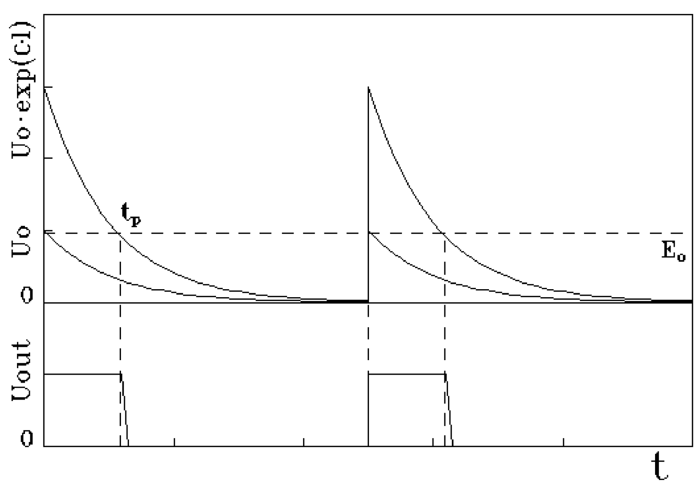

Figure 2. Explains the Work of Red Beam Attenuation Meter.

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