*Proceedings of the Second **International Airborne Remote Sensing Conference and Exhibition:***
Technology, Measurement & Analysis, Vol. II, San Francisco, California, USA
Publication by Environmental Research Institute of Michigan (ERIM), ISSN 1076-7924.

POLAR NEPHELOMETER FOR SEA TRUTH MEASUREMENTS*

Vladimir I. Haltrin
Naval Research Laboratory, Ocean Sciences Branch, Code 7331
Stennis Space Center, MS 39529-5004, USA. e-mail: <haltrin@nrlssc.navy.mil>

Michael E. Lee, and Oleg V. Martynov
Optical Oceanography Laboratory, Marine Hydrophysical Institute of Ukrainian National Academy of Science
2 Kapitanskaya St., Sevastopol, Crimea, 335000, Ukraine. e-mail: <ocean@mhi2.sebastopol.ua>

ABSTRACT

The SeaWiFS Pre-launch Science Working Group pointed out the importance of *in situ* measurements of the volume scattering function for sea water. Thus a need has arisen for the development of a new polar nephelometer which can support such measurements, because presently used instruments are not adequate to this task. We propose here a new approach to measure the volume scattering function, in which a light source and photodetector are fixed and angle deviation is implemented via rotation of a special periscope prism with three reflecting facets. The shape of this special periscope prism together with precisely adjusted dimensions allow the detection of the scattered radiance practically over the full angular range including the case of direct beam attenuation measurement. This approach gives us the opportunity to develop a fast and compact polar nephelometer, capable of measuring the volume scattering function over the full angular range using modern systems of data acquisition, managing and processing.

1.0 INTRODUCTION

The SeaWiFS Pre-launch Science Working Group has developed and adopted a number of propositions for SeaWiFS validation and algorithm development (Mueller and Roswell, 1992). These propositions cover the main principles and strategy for sea truth hydrooptical measurements.

Previous nephelometers had complex optical and mechanical designs because their angular deviation was provided by rotating a bulky light source or photodetector unit around the axis going through the scattering volume. One must take into account that higher angle resolution requires larger dimensions for both the light source and photodetector units. Therefore, when one needs to provide measurements of the full volume scattering function for both large and small angles, multiple problems will arise in the development of a convenient design for practical purposes. That is the reason the schematic illustrated in Fig. 1 was mainly used in laboratory nephelometers or in meters placed in underwater vehicles (Tyler and Roswell, 1964), where design requirements and instrument size are much lower than for *in situ* devices (Tyler and Richardson, 1958). The need to solve these problems for submersible instruments has resulted in the fact that polar nephelometers were only created for large angles and for scattering measurements. For small angles other instruments based on small-angle techniques were used. It should be noted that the problems

* Presented at the Second International Airborne Remote Sensing Conference and Exhibition, San Francisco, California, 24-27 June 1996.

associated with improving instruments and methods for *in situ* scattering measurements were not given sufficient attention for a long period of time. In hydrooptics, for this reason, instruments created more than twenty years ago and based on schematics suggested by Petzold (1972), Jerlov (1961), Kullenberg (1968) and others were still employed until recent times. Another meter of the same time period (Man'kovsky, Semenikhin and Neuymin, 1970) and later ones (Afonin and Basharin, 1975) had insignificant distinctions. Though the above-mentioned instruments allow the acquisition of qualitative data, they are rather obsolete and do not satisfy the modern requirements concerning the optical apparatus for under-satellite investigations. Due to low angular resolution the old meters cannot measure the full volume scattering function and are restricted to large-angle measurements. Scatterance data for small angles are extrapolated by parabolic (Spielhaus, 1965) and other laws (Morrison, 1970) or are retrieved from two or three values obtained by the small-angle range technique (Petzold, 1972; Kelbalikhanov and Krasovsky, 1972; Kopelevich, Mashtakov and Burenkov, 1975). Other limitations are low accuracy, long measurement time, and output which is inconvenient for collecting and storing in modern systems of data acquisition. The instruments are bulky and, hence, not convenient for field conditions.

2.0 METHODS

The most complete understanding of the scattering properties of sea water one can obtain by measurements of volume scattering functions over the full angular range spans from several tens of minutes to angles close to 180°. It is very important to provide accurate measurements of this important light scattering property when carrying out complex field oceanographic investigations in the visible range of spectrum. In the simplest case, the typical scheme behind volume scattering function measurements can be illustrated by Fig. 1. For this case it is possible to express the angular scattering coefficient $\beta(\theta)$ in the direction θ in the following form:

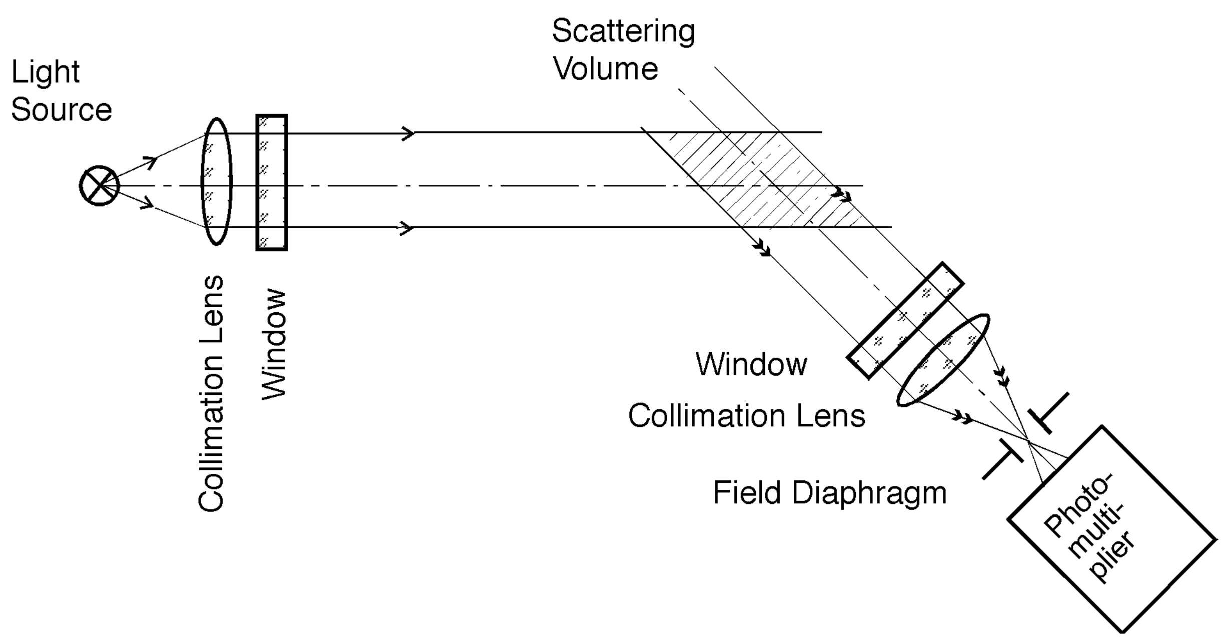

Fig. 1. Old schematic for volume scattering function measurements

$$\beta(\theta) = I(\theta) / E\,V(\theta), \tag{1}$$

where $I(\theta)$ is the light intensity, scattered by the volume $V(\theta)$ in the direction θ and E is the scattering volume irradiance. Since modern photodetectors measure, practically speaking, radiant fluxes, it is more convenient to write Eqn. (1) in terms of the exiting and scattered radiant fluxes. Scattered flux $F(\theta)$ can be expressed as a function of the optical assembly parameters of the scattering meter as follows:

$$F(\theta) = I(\theta)\Omega \exp(-c\,r), \tag{2}$$

where Ω is the viewing angle of the photodetector in radians, c is the beam attenuation coefficient and r is the distance between the center of the scattering volume and the photodetector. The irradiance E determined by the light flux F_0 penetrates into the sea water and is attenuated along the water path r_1 from the light source to the center of the scattering volume:

$$E = (F_0/S)\exp(-c\,r_1), \tag{3}$$

where S is the normal cross-section area of the exiting light flux. Combining Eqs. (1), (2) and (3) we get:

$$\beta(\theta) = \frac{S\,F(\theta)}{F_0\,\Omega\,V(\theta)} \exp[-c(r + r_1)]. \tag{4}$$

The necessity will arise for additional measurements of F_0 and c when the determination of absolute values of the scattering coefficient in a given direction is desired, but the opportunity to perform these measurements does not always realize itself. Therefore the measurements of the angular distribution of scattered light are usually made in arbitrary units. If the polar nephelometer has the additional requirement of measuring the direct beam attenuation for $\theta = 0°$ by the same photodetector, then its calibration for absolute values of $\beta(\theta)$ will be fulfilled by Kullenberg's method. In this case, in accordance to Bouguer's law, the light received by the photodetector will be determined by:

$$F(0) = F_0 \exp[-c(r + r_1)]. \tag{5}$$

From Eqs. (1) and (5) we derive:

$$\beta(\theta) = \frac{S\,F(\theta)}{F(0)\,\Omega\,V(\theta)}. \tag{6}$$

Obviously, the simultaneous measurements of scattered and direct attenuated fluxes allow the easy determination of the absolute values of $\beta(\theta)$, because other variables in equation (6) are known from the geometrical parameters of the optical assembly.

3.0 A NEW PRINCIPLE FOR VOLUME SCATTERING FUNCTION MEASUREMENT

In connection with preparations for under-satellite experiments concerning international projects in remote sensing of the ocean from space such as PRIRODA and SeaWiFS, polar nephelometers which are free of most of the above mentioned limitations have been developed at the Marine Hydrophysical Institute. The limitations could be overcome by application of the new measurement schematic of the volume scattering function shown in Fig. 2, which provides angular deviation via rotating a specially designed periscope prism. The prism turns around the photodetector assembly axis going through the center of the scattering volume. The main advantage of the offered schematic is that the light source and photodetector units are fixed during the measurement process. The special shape of the periscope prism and its precisely adjusted dimensions gives us the opportunity to measure scattered light practically over the full angular range including the case of direct beam attenuation measurements. For the latter, the scanning arrangement is significantly simplified and becomes compact. Since the light source and the photodetector units are fixed, increasing their dimensions (length) does not result in significant design complexity. Therefore the opportunity to achieve high angular resolution and accordingly to provide the full volume scattering function measurements without using the small-angles range technique is offered. A halogen lamp with a small-sized filament which provides a 500-lumen light flux is employed in the nephelometer. This lamp, coupled with the 95-mm-focus lens, provides light flux with a divergence lower than 30'. This flux, denoted by the single arrows on Fig. 2,

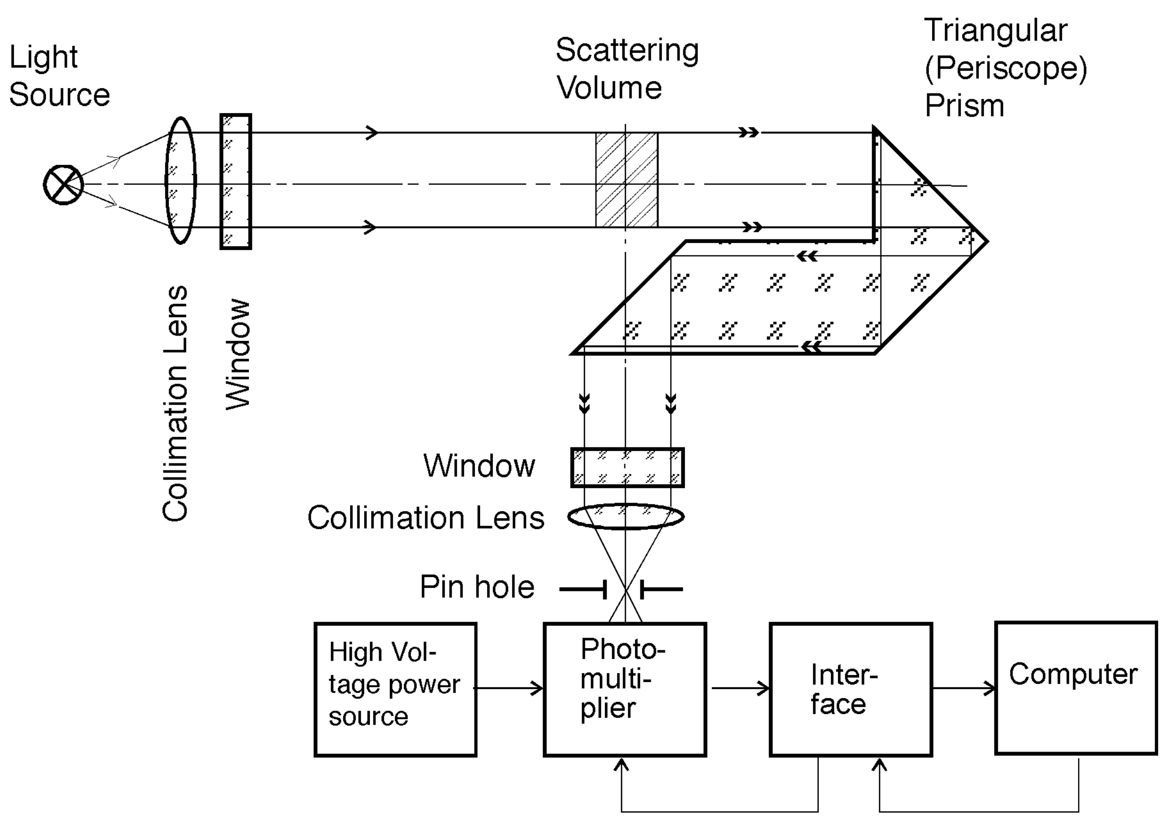

Fig. 2. Proposed schematic for volume scattering function measurements.

penetrates into the water through the flat illuminator and irradiates the scattering volume. During measurements of the volume scattering function, the scattering volume varies steadily from a maximum value at scattering angles $0°$ and $180°$ to a minimum at $90°$. For clarification purposes, the scattering volume for scattering at $90°$ is represented in Fig. 2 by a filled rectangle, and the prism position is shown for the beam attenuation measurement. With an accuracy sufficient for practical application the scattering volume variation for large angles can be defined by the equation

$$V(\theta) = V(90°)/\sin(\theta), \qquad (7)$$

where $V(90°)$ is the scattering volume in the $90°$direction, defined by the optical assembly parameters. As the scanning motor rotates, scattered light is continuously directed by the periscope prism into the hermetic case of the photoelectric assembly. The scattered light path is marked by double arrows. Light which passes through the illuminator is focused by an objective into the center of pin hole, and then is directed onto the photo-multiplier photo-cathode. The acceptance angle of the photodetector, determined by both the objective focus and the pin hole diameter, is chosen somewhat greater than the source collimation angle and is equal to 40'. The scattering volume function measurement is performed under continuous turning of the periscope prism; therefore, two registrations of the volume scattering function from $10°$ to $175°$ take place during a full prism turn. The intensity of the direct attenuated flux is measured at 0 on the water path from the light source illuminator to the prism input faucet. The limitation of the volume scattering function measurement at small-angles range is defined by the angular resolution of the nephelometer, and for large angles is caused by the transverse dimension of the prism cutting the light source emitting flux. It is known that the scattering volume dependence on scattering angle diverges from the sine law over the small-angles range. To avoid this influence on measured data the collimated light flux is formed a few times wider than the received one. In this case the volume scattering function measurements at small angles down to 5 degrees take place over a constant scattering volume and further down over a scattering volume obeying the sine law.

4.0 METHOD OF MEASUREMENT OF SCATTERED LIGHT IN A WIDE DYNAMIC RANGE

The main problem in the development of a polar nephelometer photoelectronic circuit is the very large dynamic range of the scattered light intensity. Due to the elongated shape of the volume scattering function this range can reach seven or more orders of magnitude. To provide accurate measurements of intensity over such a wide range, light attenuation by means of a combination of diaphragm and standard neutral filters which reduce light flux at certain times is generally used. Taking into account the difficulties in developing such a design this method of measurement is preferred for laboratory instruments or for submersible instruments measuring the volume scattering function at a few discrete angles. In instruments with uninterrupted angle deviation photomultipliers with a logarithmic mode the negative feedback through the photomultiplier power source is usually employed (Bogushevsky, Lee and Sherstyankin, 1973). This photometer schematic, despite its relative simplicity, allows for easy expansion of its dynamic range to the required 7 to 8 orders of magnitude, but the accuracy and stability of the resulting measurements are very low. With the aim of avoiding the contradictions of the existing wide dynamic range photometers, we propose an automated method for multistage control of the photo-multiplier sensitivity. The main feature of the method is that the photomultiplier output signal after amplification goes to one of the inputs of the multifunctional interface card placed into the personal computer. This card allows not only fast analog-to-digital conversion with a high accuracy but also produces a photomultiplier control signal for changes in its sensitivity. It is possible to divide the whole dynamic range into several bands where the photomultiplier output signal varies by no more than an order of magnitude or any other convenient value. As a result it is possible to establish a linear working mode for the photomultiplier with a high accuracy of data measurements over a wide dynamic range. The information recording, the management process of measurements and the pre-processing of data into physical values allows to make all these operations practically simultaneously. This method can be implemented using any type of photomultiplier via control of its sensitivity by varying the photomultiplier high voltage. But this method of sensitivity control has a large time constant associated with it. The time constant is firstly defined by the duration of the photo-cathode transitional process, caused by the discrete change of the photomultiplier supplied voltage. Secondly, the time constant is determined by the inertia of the high voltage power source, itself controlled by the low voltage output of the interface card.

That’s why the application of specially designed photomultipliers is more convenient. For example, the anode assembly of the FEU-101 photomultiplier is designed in such a manner that the photomultiplier sensitivity can vary from negligible to maximal under a controlling voltage from 0 to 15 volts. Using this type of photomultiplier and principle described we have developed a wide dynamic range photometer which can measure 8 orders of intensity with an accuracy of 5% of measured value.

5.0 POLAR NEPHELOMETER DESIGN

In the instrument photodetector assembly, the light source and motor of the angular scanner are placed in three separate hermetic cases, mutually oriented at $90°$ with respect to the working volume of the nephelometer, and tightly fixed by means of a light trap assembly. The periscope prism is coupled to the console rotating in the scanning plane, so that its output facet is close to the illuminator of the photodetector assembly, and the input facet center strictly aligned with the light source axis when the scanning angle is $0°$. The rotation transfer from motor to prism is executed by an elastic belt to avoid light cutting in the working volume over the full angular range. To eliminate incident natural light the nephelometer working volume is surrounded by a light trap composed of labyrinth partitions of light absorptive material. The partitions are placed so that the incident light is effectively eliminated and the investigated sea water penetrates freely into the working volume. Good exchange and careful hashing of the water in the measuring volume is implemented by the rotation of the periscope prism which plays a role similar to a propeller. Besides this the light trap partitions exclude the opportunity for glint appearance on the design elements and the light source and photodetector illuminators. For additional shielding from backward reflectance and scattering, a few supplementary diaphragms are installed into the light source and photodetector units.

6.0 CONCLUSION

The proposed and adopted principles above for the measurement of the volume scattering function of sea water give us the opportunity to develop a fast and compact polar nephelometer, capable of measuring the volume scattering function over the full angular range using modern systems of data acquisition, managing and processing.

7.0 ACKNOWLEDGMENTS

This work is supported by Ukrainian National Agency of Marine Researches and Technology Theme: “Instrument Building”, section: Development of Mooring Station of Module Design for Marine Ecological Investigations and by Russian Space Agency through the Institute of Radioelectronics of Russian Academy of Sciences Project/Proposal Title: Russian-American Project “ALFA” “Development of optical models, algorithms and of data processing techniques of space color scanners for the ecological monitoring of marine environment”. The authors also wish to thank continuing support at the Naval Research Laboratory through the Littoral Optical Environment Program (LOE 6640-06) and Walton E. McBride III for useful help. This article represents NRL contribution NRL/PP/7331–96-0005.

8.0 REFERENCES

E. I. Afonin and V. A. Basharin “A Laser Polar Nephelometer with Continuous Scanning by Angle.” (in Russian), *Marine Hydrophysical Research*. Publ. by MHI, Sevastopol, No. 1 (68). p. 129-139, 1975.

A. P. Bogushevsky, M. E. Lee, and P. P. Sherstyankin “Marine Wide Range Logarithmic Photometer.” (in Russian), *Marine Hydrophysical Research*. Publ. by MHI, Sevastopol, No. 2 (61). p.7-12, 1973.

N. G. Jerlov, “Optical Measurements in the Eastern North Atlantic.” *Medd. Oceanogr. Inst. Goteborg*, Ser. B., 8, pp. 40, 1961

B. F. Kelbalikhanov and E. S. Krasovsky “Hydronephelometer for *in situ* Measuring the Optical Characteristics of the Sea.” (in Russian), in: *Optics of the Ocean and the Atmosphere*. ed. K.S. Shifrin, Nauka, Leningrad, p. 113-120, 1972.

O. V. Kopelevich, U. L. Mashtakov and V. I. Burenkov, 1975. “Investigations of Vertical Structure of Sea water Scattering Properties by Means Submersible Small Angle Scatterance Meter.” (in Russian), In: *Hydrophysical and Optical Study in the Indian Ocean*. Moscow, Nauka, p. 54-60, 1975.

G. Kullenberg, “Scattering of Light by Sargasso Sea Water.” *Deep-Sea Res*., v. 15, p.423-432, 1968.

V. I. Man’kovsky, V. M. Semenikhin and G. G. Neuymin “Marine Submerged Nephelometer.” (in Russian), Sevastopol. *Marine Hydrophysical Research*. Publ. by MHI, Sevastopol, No. 2(48). p. 171-181, 1970.

J. L. Mueller and R. W. Austin, “Ocean Optics Protocols for SeaWiFS Validation.” *SeaWiFS Technical Report Series*, Vol. 5, pp. 44, 1992

T. J. Petzold, *Volume Scattering Functions for Selected Ocean Waters*. SIO Ref., 72-28, pp. 79, 1972.

J. E. Tyler and W. H. Richardson, “Nephelometer for the Measurements of Volume Scattering *in situ*.” *J. Opt. Soc. Amer.*, v. 48, No. 5, 1958.

J. E. Tyler, and W. A. Roswell, “A Scattering Meter for Deep Water.” *Appl. Opt.*, v. 3, No. 5, pp. 886-895, 1964.