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RAPID HYDROLOGIC MEASUREMENTS OF UNDERWATER ANGULAR DISTRIBUTION OF LIGHT*

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ABSTRACT

For consistent studies of light propagation in shallow waters the sole use of irradiance meters is insufficient. To know the vertical structure of light fields in the sea it is necessary to measure additional light field parameters such as angular distribution of underwater radiance. Implementation of radiance measurements by the method of angular scanning is proposed. The general principles of optical scanning assembly for investigation of underwater angular radiance distribution are discussed. It is shown that the practical realization of the proposed scanning arrangement allows us to develop simple, reliable and highly informative meters. A device for continuous optical scanning over zenith and azimuth angles is proposed. It is implemented as detachable adapter to a standard wide-range underwater photometer. An example of measurements made in the Gulf of Mexico is presented.

1.0 INTRODUCTION

Long-term bio-optical investigations in various regions of the World Ocean have been made by Smith and Baker (1978), Jerlov (1986), Austin and Petzold (1986), Siegel and Dickey (1987). They demonstrate that properties of a light field are closely related with the concentration of chlorophyll pigments in seawater. As a result, a number of empirical algorithms have been proposed. These algorithms and methods allow to adequately determine concentrations of phytoplankton and other optically active components of a seawater through the *in situ* measurements. These investigations influenced incorporation of the spectral bands used in these algorithms into current satellite sensors. The experience of the long-term hydro-optical investigations was also influenced the instrument design for sea truth measurements.

Taking into account common practices of routine hydro-optical measurements, Austin and Petzold (1986) have proposed to provide basic calibration of the sensors for the SeaWiFS and other projects. The calibration procedure was based on measured vertical profiles of the underwater irradiance. The practical implementation of this type of calibration is quite difficult. First, the accuracy requirements for the irradiance meters are so demanding, that the problems of maintaining shape precision of the light collectors become significant. The necessity for the development of the shape and immersion correction procedures for light collectors is also a vital problem. Also, for the sea truth investigations of shallow waters the measurements of light field's parameters should be even more accurate. This is necessary because the existing bio-optical algorithms, developed for the open oceans, are unsuitable for coastal seawaters and lakes.

In turbid waters, typical to the lakes and the sea coastal zones, the structure of light fields is

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very complex. The light distribution in such areas is influenced by a number of factors. These factors include: refraction and reflection of the light from the water-air boundary, variability and depth stratification of optical properties, resuspension of particular matter of terrageneous origin by the coastal dynamic processes and riverine plume. In shallow waters, especially in the benthic environment, processes that influence distribution of light are even more complicated. They also include reflection and absorption of light by the shallow bottom.

Therefore for *in situ* investigations of light fields in shallow waters it is insufficient to use only underwater irradiance meters. We have to adopt new approaches to measure light field characteristics. These approaches should allow precise measurements of vertical profiles of light radiance at different viewing angles. This radiance distribution fully determines other apparent optical properties. It allows us to calculate all integral parameters of the underwater light field, including diffuse attenuation and reflection coefficients. It also allows us to retrieve some inherent optical properties of water. Measurements of angular radiance distribution are especially important during *in situ* validation of current radiative transfer models in the sea coastal zone.

In situ measurements of the angular radiance distribution are scarce despite its high information capability. This happened because of the significant difficulties in implementing underwater radiance measurements in a multitude of strictly oriented directions. These difficulties are resulted from the present implementation of angular measurements. This implementation consists of rotating a radiance meter in different planes around the axis normal to viewing direction. The simultaneous measurements of current viewing direction and spatial orientation of the instrument are also should be made. Originally, the complete data on angular radiance distribution at different depths were obtained by Tyler (1960) in the Pand-Orey lake. He used a radiance meter that was scanning in a vertical plane with the 10-degree step over the azimuth angle. The device was so complex and fragile that it was absolutely unusable under the marine conditions. Several years later Sasaki (1962), Timofeyeva, (1962) and Kelbalikhanov (1975) created several models of marine probes for underwater angular radiance distribution. However, these devices fail to find wide applications in hydro-optics. Because of their complex design these instruments were bulky and very inconvenient under field conditions. They also were limited in speed and accuracy.

2.0 METHOD FOR MEASUREMENTS OF ANGULAR RADIANCE DISTRIBUTION

To eliminate above mentioned shortcomings we should drop the idea of rotating the whole instrument. We can achieve measurements of radiance distribution in different directions by scanning over the angle of a receiver. To demonstrate this idea we consider a scanning system for underwater radiance distribution measurements proposed by Lee and Sherstyankin (1975).

The arrangement for continuous scanning over zenith and azimuth angles is schematically shown in Fig. 1. The axis ON, originated in the center O of the horizontally placed circle 1, is directed to the zenith. The second circle 2 rolls without sliding over the circle 1. Its plane is always perpendicular to the plane of the first circle. In the center O at 45° angle to the plane of the circle 1 the mirror is installed. This mirror reflects light from the scattering medium to the second mirror. This second mirror is installed at point O_1 at 45° angle to the axis ON on the level $OO_1 = O_2F$. It directs light to the third mirror located at point O_2. The third mirror reflects light to the photoreceiver. The second and the third mirrors form a periscope. Mutual rotation and movement of the mirrors allow to perform spatial scanning. The law of this scanning depends on diameters of the circles and number of revolutions.

To analyze this scanning method let us derive some equations. Let us assume that we scan over a sphere of such large radius $r >> O_1O_2$ that the parallax effect, caused by the mirrors biased on the distance O_1O_2, is negligible. With such an assumption it is convenient to adopt polar coordinates with the scanning system located in the center of this coordinate system.

The polar angle θ $(0 \le \theta \le \pi)$ is measured from the zenith direction. In this case for the zenith angles $0 \le \theta \le \pi/2$ all measurements are conducted in an upper hemisphere, and for the angles $\pi/2 < \theta \le \pi$ they are conducted in a lower one. The azimuth angle φ $(0 \le \varphi \le \pi)$ is measured from any fixed direction in a horizontal plane.

Let us define that at the initial moment the mirrors are located in such a way that the photoreceiver detects light propagating at the angles $\theta = 0$ and $\varphi = 0$. At some point, as a result of revolving, the measured light spot moves the way $S = BF$ along an arch of the circle 1; that way is equal to the distance FD along an arch of the circle 2. Since the path S is determined by the angles θ and φ (See Fig. 1), we can write the following functional dependencies for the viewing angles:

$$\varphi = 2\pi\left|\frac{S}{l_1} - \mathrm{int}\left(\frac{S}{l_1}\right) + 0.5\left|\sin\left[\frac{\pi}{2}\mathrm{int}\left(\frac{2S}{l_2}\right)\right]\right|\right|, \quad \theta = 2\pi\left|\frac{S}{l_2} - \mathrm{int}\left(\frac{S}{l_2}\right) - \left|\sin\left[\frac{\pi}{2}\mathrm{int}\left(\frac{2S}{l_2}\right)\right]\right|\right|, \qquad (1)$$

here S is the way passed by a rolling touching spot of the circles 1 and 2, l_1 and l_2 are circumference lengths of these circles. Let us introduce the definition for the gear-ratio *i*:

$$i = l_1 / l_2 = k / m, \qquad (2)$$

here *k* and *m* are integers that have no common multipliers. In this case the path S is an univalued function of angles θ and φ only, with the restrictions defined by the formula:

$$S = m l_1 = k l_2. \qquad (3)$$

If the gear-ratio *i* is known, Eqn. (4) allows us to specify the limits of non-repetitious scanning. For example, when the lengths of circles 1 and 2 are divisible and $m = 1$ or $k = 1$, the scanning without repetition occurs only during one revolution of the larger circle.

Equations (1) give us the law of scanning in the parametric form. Let us investigate the scanning patterns for different values of gear-ratio. The estimates are made for the following gear-ratio values: *i* = 1, 2, 3, 4, 1/2, 1/3, 1/4 and 1/5. The results of these calculations are shown in Fig. 2. The figure displays equatorial plane projection of the intersection points of the viewing direction with the sphere of radius *r*. The projections from the upper hemisphere are shown with solid lines. The projections from the lower hemisphere are shown with dotted lines. The common feature of all considered cases is following: at odd gear-ratios *i* the projections from the upper and lower hemispheres coincide; at even gear-ratios *i* projections are mirror images of each other.

Using the value of the gear-ratio *i* of the scanning as a parameter it is possible to divide the full set of scanning curves into two types:

1) the family of curves with $i > 1$, that corresponds to the scanning over planes close to the meridian ones, with the simultaneous rotation around the polar axis; and
2) the family of curves with the gear-ratios $i < 1$, that corresponds to the scanning over the latitude with the simultaneous change of polar angle.

In the case when $i = 1$, projections imposed on each other form a circle that touches the center of coordinates. For the information acquisition this gear-ratio is unacceptable because we are recording only a few directions of the angle φ on the hemisphere with $0 < \varphi < \pi$, and none for the hemisphere with $\pi < \varphi < 2\pi$

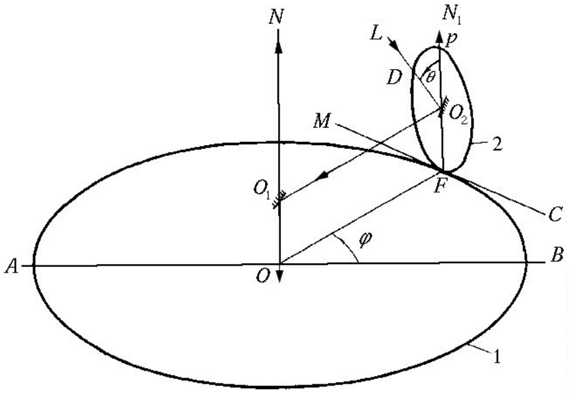

Fig. 1. Schematic of the arrangement for the continuous scanning over zenith and azimuth angles.

When $i > 1$ the equatorial plane projections of the intersections of viewing direction with the surface of a sphere form curves that are similar to leminiscate. The number of petals N in these curves are defined by the formula:

$$N = 2mk. \tag{4}$$

According to the Eqn. (4) an average step of the azimuthal scanning $\Delta\varphi$ is equal:

$$\Delta\varphi = \frac{2\pi}{N} = \frac{\pi}{mk}. \tag{5}$$

From the Eqn.(5) it is clear that the step $\Delta\varphi$ diminishes with the increase in the gear-ratio or with the decrease in the ratio k/m.

For $i < 1$ projections form curves that are similar to cardioid. In this case the larger the difference between m and k the more detailed is the scan. For the gear-ratio larger than 1, the sounding in the whole solid angle of 4π occurs as an interleaved sequence of scan cycles over vertical angles with simultaneous rotation over azimuth by a step divisible to a number of cycles. Clearly, with the increase of gear-ratio the information capability of scanning will also increase. In practice, because of mechanical restrictions, it is impossible to increase the gear-ratio above certain level. The amount of information on radiance distribution measured at integer values of gear-ratio is also limited because all scan cycles over vertical angles with the azimuth period of 2π completely repeat each other. If necessary, this limitation can be bypassed by using fractional values of gear-ratio. In this case each subsequent cycle of scanning occurs at different viewing angles; and it does not overlay the previous trajectory. So the information on angular radiance distribution increases with time. Moreover, one cycle of scanning over vertical angles allows to evaluate space structure of a light field over the whole solid angle. Each subsequent scan enhances and multiplies the information already received. Therefore, for scanners with fractional gear-ratio the information on angular radiance distribution can be acquired with any degree of detail.

The described scanning system also allows to accomplish strictly azimuth scanning. To do this it is necessary to change mechanical arrangement so that after each full turn-over of periscope around the vertical axis the second mirror is discretely switched to a given angle. This case gives us a new way of scanning Such scanning may be regarded as one of specific cases for infinitely

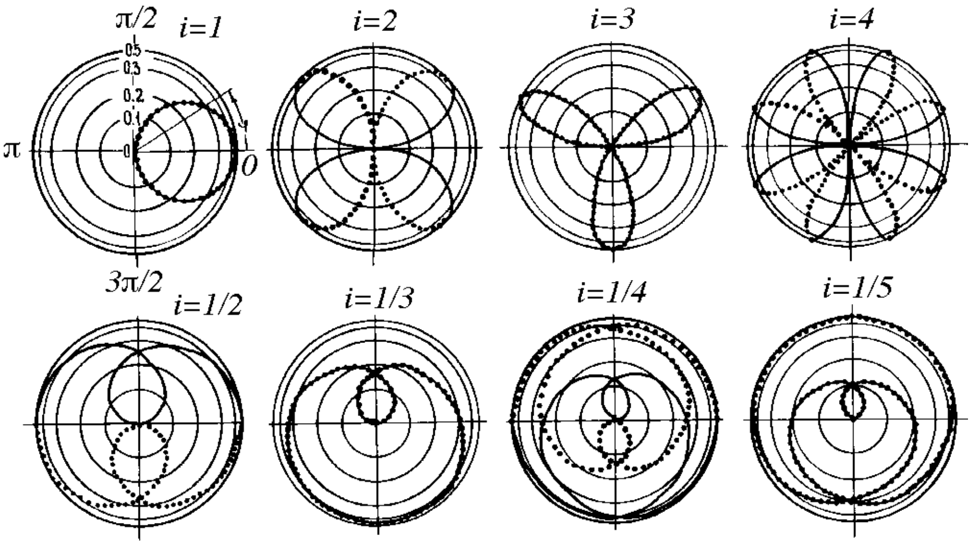

Fig. 2. Scanning laws for various gear-ratios *i*.

small gear-ratios. Now during a rotation of the periscope around the vertical axis a continuos scanning occur over the azimuth at any fixed values of zenith angle. After the completion of a scan with one zenith angle the scanner is switched to a new angle and so on consecutively for all angles starting from zenith to nadir.

Each of the described scanning methods has its advantages and limitations. The choice of the method is determined by the purposes of investigations. The main advantage of the first method is in the fact that even partial scanning gives some information on the light field in an investigated point. The first method also gives an opportunity to collect very detailed data on angular radiance distribution by accumulation of the information with time. The shortcoming of this method is the relative complexity of measured data processing. The second method is convenient due to the simplicity in processing of received information. By using this method we can determine the light field parameters only after the full cycle of scanning.

These methods of scanning have been practically implemented using detachable adapters to the standard submersible irradiance photometer. They also have been successfully tested under various marine conditions.

3.0 DESIGN OF THE SCANNING RADIANCE METER

Proposed scanning method allows to create various underwater radiance meters: from miniature meters for experiments in tanks, filled with artificially created scattering medium, to submersible devices for measurements in seas and lakes. Clearly, the instrument designs may vary widely. Below we give the descriptions of two implementations of scanning radiance meters.

The first implementation consists of a periscope tube, installed in a specially designed gear-wheel arrangement. This arrangement ensures both rotation of the whole periscope over azimuth and, compelled by this rotation, simultaneous rapid rolling of an input mirror around the periscope axis. To implement this the moving parts of the horizontally located periscope are coupled kinetically with a pair of conical gear-wheels with mutually perpendicular rotation axes. The design of a detachable adapter for continuous scanning over zenith and azimuth angles is shown in Fig. 3. The input mirror 2 is built into the rim 5 together with the small conic gear-wheel 6 and is fixed on the end of periscope tube 4 on a bearing. Therefore this mirror can simultaneously rotate around the tube axis and reflect light to the output mirror 1. On the side of output mirror 1 the periscope edge is fixed to a bearing that is placed over the center opening of large motionless gear-wheel 7 in such a way that the tube axis is parallel to the radius of the large gear-wheel. The periscope tube rotates over the large gear-wheel and causes a coupled small gear-wheel to roll over the large gear. The rotation of the periscope tube is caused by the electric motor 3, installed over that tube and placed into a hermetic case. As the instrument works, the small gear-wheel, coupled with the input mirror, continuously rolls over the large one. As a result, the scanning in a vertical plane under a continuously changing azimuth angle is accomplished. Thus, the optical axis will make a complex movement consisting of a rotation in the vertical plane and a movement along the circle with a radius being equal to a half of the radius of the gear-wheel 7. Diameters of gear-wheels 6 and 7 are chosen in such a way that during one full periscope rotation the mirror 2 makes twelve rotations around the horizontal axis. Consequently, the graphic projection of points of intersections of the viewing line with a unit-radius sphere on the equatorial plane is imaged to twenty-four petals of a leminiscate, that are distributed uniformly over all directions.

Fig. 3 shows the second variant of the detachable adapter. It can be implemented in such a way that it ensures continuous scanning over azimuth angle with discrete changes in zenith angle. To do this, instead of a small conic gearwheel a spur wheel 6 is built into a rim. On the periscope case 4 a special mechanism is mounted. This mechanism turns the spur wheel and the mirror 2 on one tooth after each periscope rotation around the vertical axis. In this case the scanning is implemented in steps over circular zones at equal zenith angle intervals, starting from zenith to nadir.

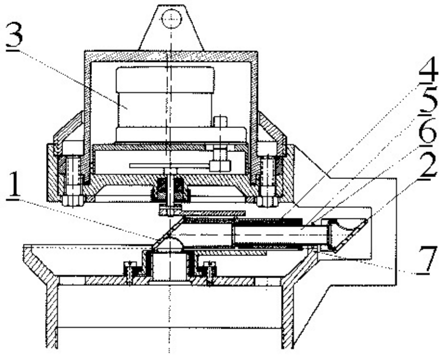

Fig. 3

A scanning detachable adapter is mounted on the illuminator of wide-range photometer in such a way that the periscope's output mirror directs light, reflected by the source mirror, through an aperture in the bearing of the photoreceiver. For spatial stabilization of scanning radiance meter a flat stabilizer made of a transparent material is attached. It orients the instrument over the azimuth by the flow of water. The underwater vertical position of the instrument is insured with the additional weight attached with a cable to the bottom of radiance meter case.

4.0 RESULTS OF TRIAL MEASUREMENTS

Trial measurements of the angular radiance distribution are convenient to conduct in the tropical part of the ocean In tropics the light measurements can be made up to maximum sun heights in waters with high transparency and homogeneity. The lack of vertical stratification allows to carefully trace changes in light field characteristics with depth. Fig. 4 shows samples of an angular radiance distribution measured by the described scanning radiance meter in the Caribbean Sea. The curves represent cross-sections of a radiance distribution in planes close to the vertical plane of the sun. They are taken at various depths in the most penetrating band of light spectrum. The horizontal axis shows the values of the zenith angle θ , that change from $-\pi$ to π. The values of the azimuth angle φ are also shown. Along the vertical axis the relative values of the underwater radiance are plotted in a logarithmic scale.

As shown in Fig. 4, in a clear day, the underwater radiance distribution curve in the upper layers is extended in the direction of the sun. The radiance maximum in the vertical plane of the sun is observed as a peak in the direction of the refracted beam. In a plane, that is perpendicular to the sun vertical plane, the underwater radiance maximum coincides with the vertical direction, but it has smoother shape. For all other cross-sections, the shapes are intermediate between the two discussed extreme forms. The peculiarities of the angular radiance distribution that are observable in relatively turbid waters only near the surface, are seen in clean ocean waters up to depths of several tens of meters. In the curves of angular distribution sharp reduction of radiance is visible near the angle of total internal reflection $\theta = 48.6^\circ$. The clearly pronounced bend exist at $\theta = 90^\circ$: it is formed by the light ascending from below and totally reflected from the surface. In the intermediate zone minor details of the angular structure are gradually smoothed, and the bend at $\theta = 90^\circ$ disappears. The angular distribution in all planes has a smoother form, but still keeps stretching in the direction of the refracted beam. As depth increases further, the shape of the angular radiance distribution stabilizes, with the values of radiances decreasing exponentially.

5.0 DATA INTERPRETATION

Measurements of the angular radiance distribution with depth also allow quantitative evaluation of integral properties of the light field. These properties are easily computable from underwater angular radiance distribution. The advantage of deriving integral properties over their direct measurements by flat half-spherical or spherical light collectors consists in the ability to avoid many errors. The main sources of such errors are the immersion effect and the deviation of light collector characteristics from the cosine or the spherical ones.

To compute various parameters of the light field we need to find the downward E_d and upward E_u irradiances and the scalar irradiances from above E_d^0 and from below E_u^0. Other integral parameters of the light field can be found as various combinations of these parameters. For the case of arbitrary radiance distribution $L(z,\theta,\varphi)$ the values E_d, E_u, E_d^0, and E_u^0 are calculated by the equations given, for example, in Jerlov (1986) or Haltrin and Weidemann (1996).

At present time these integral properties of the light field are measured with irradiance meters that have light collectors made from opaque scattering materials. Depending on the shape of a light collector they have acceptance characteristics close to cosine, or spherical one. The deviation of the real acceptance characteristic from the ideal one leads to the errors of measurements of the integral characteristics, especially for the upward irradiances. Moreover, when the scattering plastic material, used in irradiance collectors, is placed into the water, the transmission of a collector surface will change due to the immersion effect. So, if the device is calibrated in the air, the errors related to the immersion effect are introduced.

The integral characteristics of light field, computed from *in situ* measurements of underwater angular radiance distribution, does not have these additional errors. Therefore the scanning meter of the underwater angular radiance distribution can be recommended as a standard device for the SeaWiFS project of instrument inter-calibrations. In this case it is possible to conduct joint measurements of the same optical characteristic in identical conditions with the light collector characteristics from the cosine or the spherical one. For the derivation of integral light field properties the knowledge of spatial orientation of scanning radiance meter is not required. Then the results of the computations with the equations given in Jerlov (1986) or Haltrin and Weidemann (1996) can be compared with the results of irradiance meter measurements.

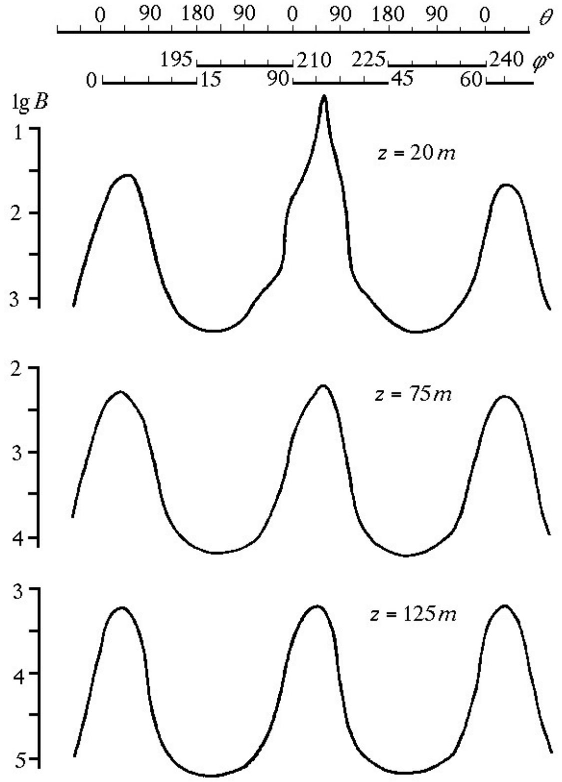

Fig. 4. A Sample of measurements by the scanning radiance meter.

6.0 CONCLUSIONS

Optical marine scanning assembly, described here, allows to develop simple and highly informative angular radiance distribution meters with predetermined characteristics. These meters are capable to effectively measure light radiance distribution even in complex conditions of coastal shallow waters and lakes. The implementation of these devices can transform the angular radiance distribution measurements in different waters from the unique ones to the routine procedures. The simultaneous increase in the efficiency of hydro-optical investigations is also expected.

In the future, these instruments can be adopted for collecting a ground truth information for the purposes of optical spaceborne data processing. Such investigations are especially valuable in regions where current bio-optical algorithms are not applicable and, therefore, careful studies of a light field structure are necessary.

7.0. ACKNOWLEDGMENTS

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