A method for the continuous measurement of the diffusivity of the natural light field over the sea

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Abstract

This paper discusses a method of measuring the diffusivity of the atmospheric natural light field continuously and automatically even on board a ship in motion. The idea of this method is to remove cyclicly from the photodetector's field of view successive parts of the horizon (one of them including all direct solar radiation), and is implemented by means of a strip diaphragm with fixed dimensions, rotating automatically around the optical axis of a cosine collector.

The usefulness of the strip method was justified on the basis of a comparison with the disc method (the Sun covered by a disc) and comparative error analysis.

1. Introduction

Separating the direct and the diffuse components of the natural solar radiation field is the main element of many approximate solutions to the radiative transfer equation (Chandrasekhar, 1960) in the sea and in the atmosphere (Sobolev, 1975; Bird, 1984). Such a separation is also very useful in the estimation of several optical parameters of the atmosphere included in atmospheric correction models of remotely-sensed data in marine applications (Gordon, 1978, 1981; Sturm, 1981a,b, 1983). The contribution of these components to the total solar radiation can be described by the degree of diffusivity, which is the ratio of the diffuse irradiance component E_d to the total irradiance $E = E_d + E_s$ (E_s – the direct component): $D = E_d/E$.

Defining this ratio in such a way suggests an apparently simple way of determining it by measuring the irradiance in the undisturbed field, repeating the measurement with the Sun's disc covered artifically (see Fig. 1 (A)) or with the remainder of the horizon covered (without the Sun's disc), and calculating the appropriate relationships. The physical problem here is connected with the errors introduced by the limited dimensions of the detector, which do not allow the exact angular dimensions of the diaphragm placed between Sun and detector to be calculated. The technical problem is that it is difficult to fix the diaphragm at the proper spherical coordinate position, because of the latter's dependence on the instantaneous 'Sun-detector' configuration. If it is possible to imagine more or less complicated technical solutions under stationary conditions on land, on a ship sailing across the continually moving sea such solutions become incredibly expensive at the very least. In this paper we suggest a very simple way of avoiding these difficulties by forgoing absolute precision, which is in any case impossible to achieve, as has already been shown.

2. The principle of measurement

Generally speaking, there are two basic elements in the measuring system: the irradiance detector, in which light is received by a flat, usually circular, cosine collector (a Lambert collector), and a diaphragm or aperture, allowing the direct or diffuse component to be removed from the total irradiance. As it is much simpler for practical reasons to use the shadowing diaphragm, this is the one that will be discussed.

In quasi-ideal measurement, the Sun's disc should be covered by a disc during the determination of the diffuse irradiance. This should lie in a plane parallel to that of the cosine collector, and its angular dimensions should be selected in such a way as to throw a shadow over the whole cosine collector surface, but not beyond. In brief, then, the disc throwing the shadow should be of exactly the same shape and dimensions as the cosine collector (see Fig. 1 (B)). Unfortunately, even if these conditions are fulfilled, the quantity measured will be strongly dependent on the absolute dimensions of the disc and its distance from the cosine collector. This is obvious, if we notice that every change in the above dimensions significantly affects the angular dimensions of the disc, which is 'seen' by each element of the cosine collector surface. Because it is very difficult to find an optimum distance for the disc dimensions, one should accept the fact that the measurement principle is of an indicative nature, and concentrate on attempts to standardise it, for example, by keeping to a specified interval of the above dimensions and a constant solid angle of the disc as seen from the cosine collector centre.

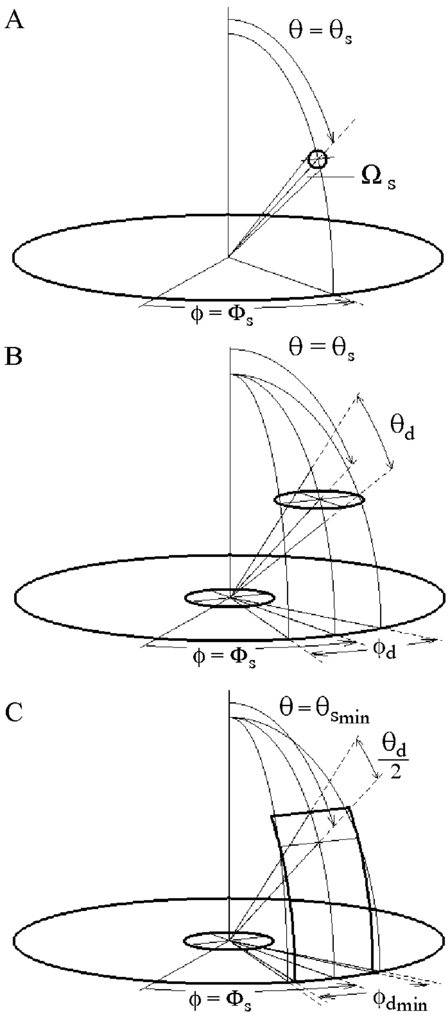

Fig. 1. The geometry of different methods of determining the natural light field diffusivity – the symbols of the angles are explained in the paper;
A – quasi-ideal measurement by means of a detector – collector, assumed to be a point, and a circular diaphragm, the angular dimensions of which are equal to the dimensions of the Sun's disc;
B – measurement by means of a circular diaphragm and a cosine collector (both projected by two small ellipses) having the same linear diameters;
C – Measurement by means of a strip diaphragm, the linear width of which is equal to the diameter of the cosine collector (small ellipse). The great ellipse is a projection of the circumference around which the diaphragm is moving

The suggested method of measurement takes all the above remarks into account. The fundamental principle on which the measurement is based involves forgoing entirely the covering of the Sun's disc by means of its geometrical projection. Instead, we propose that a strip rotating around the optical axis of a cosine collector and lying on the surface of a hypothetical hemisphere surrounding the cosine collector at some distance (see Fig. 1 (C)) should act as an instantaneous diaphragm. The strip is equal in width to the diameter of the cosine collector, its bottom edge lies in the cosine collector plane, and its top edge at the zenith angle, which is no smaller than the minimal solar zenith angle during measurements. Even though the strip covers the Sun exactly, it will always cover some other part of the horizon as well.

3. Analysis of the errors inherent in the method

In order to assess the quality of the suggested method, we have compared three sets of diffusivity measurements obtained in a hypothetical light field of the same radiance distribution $L(\theta, \phi)$. This overlaps the direct sun-ray field creating the irradiance E_s, where θ, ϕ are respectively the zenith angle and the azimuth in a spherical coordinate system, the centre of which is at the cosine collector centre and whose axis is also the optical axis of the measuring system (normal to the flat sea surface).

For the first set, the reference system, the degree of diffusivity is calculated under the following conditions: the cosine collector is assumed to be a point, and the angular dimensions of the shadowing disc are equal to those of the Sun (Fig. 1 (A)).

For the second set, the degree of diffusivity is calculated on the assumption that the linear dimensions of the shadowing disc and the cosine collector are the same (Fig. 1 (B)), and that their reciprocal distances differ. θ_d and ϕ_d are respectively the zenith and the azimuth angular dimension of the disc in relation to the cosine collector centre.

Finally, for the third set, the sought-after quantity is calculated in accordance with the assumptions of the method proposed (Fig. 1 (C)). The distances between the shadowing strip and the cosine collector centre are the same as in the previous set. The linear width of the strip is constant, the angular width ϕ_d takes the minimal value for its base and depends on the zenith angle: $\phi_d = \phi_{d_{\min}} / \sin\theta$. The upper edge of the strip determines the zenith angle of the Sun $\theta_{s_{\min}}$ diminished by the angle $\theta_d/2$, and its horizontal position – the azimuth ϕ_p.

The symbols of the Sun's position are common to all sets: Φ_s – the azimuth, Θ_s – the zenith angle, $\Theta_{s_{\min}}$ – the minimal zenith angle; the same applies to the symbol for the Sun's solid angle: Ω_s.

For the first set we have the following relationships:

a) the measured diffuse irradiance E_{dm1} (the disc covers the Sun):

$$E_{dm1} = E_d - \Delta E_d, \tag{1}$$

where

$$E_d = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L_d(\theta, \phi) \cos\theta \sin\theta d\theta d\phi, \tag{2}$$

$$\Delta E_d = \int_{\Omega_s} L_d(\Theta_s, \Phi_s) \cos\Theta_s d\Omega, \tag{3}$$

and $\Delta E_d \ll E_d$.

b) the measured total irradiance E_{m1} (without disc):

$$E_{m1} = E_d + E_s = E. \tag{4}$$

For the second set, corresponding to the measurement method indicated by the number 2, we have:

a) the measured approximate diffuse irradiance E_{dm2} (the disc covers the Sun):

$$E_{dm2} = E_d - \Delta E_{d2_{\max}}, \tag{5}$$

where

$$\begin{aligned} \Delta E_{d2_{\max}} \cong & \int_{\phi=\Phi_s-\phi_d/2}^{\Phi_s+\phi_d/2} \int_{\theta=\Theta_s-\theta_d/2}^{\Theta_s+\theta_d/2} L_d(\theta, \phi) \cos\theta \sin\theta d\theta d\phi = \\ & \int_{\phi'=-\phi_{d_{\min}}/2}^{\phi_{d_{\min}}/2} \int_{\theta=\Theta_s-\theta_d/2}^{\Theta_s+\theta_d/2} L_d(\theta, \phi') \cos\theta d\theta d\phi, \end{aligned} \tag{6}$$

and $\phi' = (\phi - \Phi_s)\sin\theta$.

The minimal azimuthal width $\phi_{d_{\min}}$ of a shadowing disc with constant linear dimensions determines the width of a disc with an actual width of ϕ_d, lowered to the level of the horizon ($\phi_{d_{\min}} = \phi_d \sin\Theta_s$); the angles $\phi_{d_{\min}}$ and θ_d are approximately inversely proportional to the distance of the disc from the cosine collector centre r: $\phi_{d_{\min}} \sim 1/r$, $\theta_d \sim 1/r$.

b) the measured total irradiance E_{m2} (without the disc)

$$E_{m2} = E_d + E_s = E. \tag{7}$$

Finally, for the third set corresponding to the proposed method of measurement, indicated by the number 3, we have:

a) the measured approximate diffuse irradiance E_{dm3} (the strip covers the Sun, $\phi_p = \Phi_s$):

$$E_{dm3} = E_d - \Delta E_{d3_{\max}}, \tag{8}$$

where

$$\begin{aligned}\Delta E_{d3_{\max}} \;\cong\; & \int_{\phi=\Phi_s-\phi_d/2}^{\Phi_s+\phi_d/2}\int_{\theta=\Theta_{s_{\min}}-\theta_d/2}^{\pi/2} L_d(\theta,\phi)\cos\theta\sin\theta d\theta d\phi = \\ & \int_{\phi'=-\phi_{d_{\min}}/2}^{\phi_{d_{\min}}/2}\int_{\theta=\Theta_{s_{\min}}-\theta_d/2}^{\pi/2} L_d(\theta,\phi')\cos\theta d\theta d\phi'. \end{aligned} \tag{9}$$

b) the measured approximate total irradiance E_{m3} (the strip covers not the Sun but the darkest part of the horizon, $\phi_p <> \Phi_s$):

$$E_{m3} = E - \Delta E_{d3_{\min}}, \tag{10}$$

where

$$\begin{aligned}\Delta E_{d3_{\min}} \;\cong\; & \int_{\phi=\phi_p-\phi_d/2}^{\phi_p+\phi_d/2}\int_{\theta=\Theta_{s_{\min}}-\theta_d/2}^{\pi/2} L_d(\theta,\phi)\cos\theta\sin\theta d\theta d\phi = \\ & \int_{\phi'=-\phi_{d_{\min}}/2}^{\phi_{d_{\min}}/2}\int_{\theta=\Theta_{s_{\min}}-\theta_d/2}^{\pi/2} L_d(\theta,\phi')\cos\theta d\theta d\phi', \end{aligned} \tag{11}$$

and $\phi' = (\phi - \phi_p)\sin\theta$, $\Delta E_{d3_{\min}} \ll E$. The angular width of the strip $\phi_{d_{\min}}$, and the difference $\theta_d/2$ between the minimal solar zenith angle and the edge of the strip (keeping the linear dimensions constant), are approximately inversely proportional to its distance from the cosine collector centre r: $\phi_{d_{\min}} \sim 1/r$, $\theta_d \sim 1/r$.

The degrees of diffusivity for these sets are:

$$\begin{aligned} D_{m1} &= E_{dm1}/E_{m1} \cong E_d/E = D, \\ D_{m2} &= E_{dm2}/E_{m2} = (E_d - \Delta E_{d2_{\max}})/E, \\ D_{m3} &= E_{dm3}/E_{m3} = (E_d - \Delta E_{d3_{\max}})/(E - \Delta E_{d3_{\min}}) \cong \\ &\cong (E_d - \Delta E_{d3_{\max}})/E, \end{aligned} \tag{12}$$

and the errors in relation to the real values are:

$$\begin{aligned} &(D_{m1} - D)/D \cong 0, \\ &(D_{m2} - D)/D = -\Delta E_{d2_{\max}}/E_d, \\ &(D_{m3} - D)/D \cong -\Delta E_{d3_{\max}}/E_d. \end{aligned} \tag{13}$$

Two very important conclusions emerge from these relations. Firstly, the relative error of measurement is almost independent of the direct irradiance component E_s. Secondly, the diffusivity calculated by one of the methods proposed is always lower than its real value.

In the real sky radiance distribution, the maximum is always directed towards the Sun, hence the symbol $\Delta E_{dn_{\max}}$ for the part of the sky removed by covering the Sun with the circular diaphragm (n = 2) or the strip (n = 3). The greater the relative value of this covered part, the greater the measurement error. In order to estimate this error, two hypothetical cases of the radiance distribution described by the extreme values $\Delta E_{dn_{\max}}$ are considered; between them there is a real radiance distribution.

The first of these cases is the isotropic one, which is only possible if there is no absorption and the number of scatterings in the atmosphere is infinite. In such a case the relative value of $\Delta E_{dn_{\max}}/E_d$ reaches a minimum, and depends only on the dimensions of the disc or strip and on the Sun's altitude. It can be calculated from eqs. (6) or (9) as

$$K_{i2} = \Delta E_{id2_{\max}}/E_{id} = (\phi_{d_{\min}}/\pi)\cos\Theta_s \sin\theta_d/2,$$
$$K_{i3} = \Delta E_{id3_{\max}}/E_{id} = (\phi_{d_{\min}}/\pi)[1 - \sin(\Theta_{s_{\min}} - \theta_d/2)]. \tag{14}$$

The second extreme case could be the complete lack of scattering. The relative value of $\Delta E_{dn_{\max}}/E_d$ in this case would be maximum and equal to 1. But taking into account the fact that this situation deviates widely from actual environmental conditions, allowances are made for single light scattering in the atmosphere, and it is assumed that the maximum possible natural value of $\Delta E_{dn_{\max}}/E_d$ fulfils this moderated condition. This value can be calculated from expression (6) or (9), but apart from the geometrical parameters, environmental parameters are also needed, especially the atmospheric phase function and the optical thickness. For the time being we write the sought-after value symbolically in a similar way to (14):

$$K_{sn} = \Delta E_{sdn_{\max}}/E_{sd}. \tag{15}$$

The subscripts *i, s* appearing in formulas (14) and (15) symbolise the assumptions of isotropy and single light scattering respectively, made during the determination of the sky radiance distribution.

The relative value of the part of the real horizon radiance covered by either the strip or disc method, will fulfil the condition

$$K_{in} < \Delta E_{dn_{\max}}/E_d < K_{sn}. \tag{16}$$

According to (13), the above formula yields the condition limiting the range of possible values of the real diffusivity D, depending on its value D_{mn} measured by the n-th method:

$$D_{\min} = D_{mn}/(1 - K_{in}) < D < D_{\max} = D_{mn}/(1 - K_{sn}). \tag{17}$$

The value of diffusivity most closely approaching reality is determined from the mean value $< D >$ and the relative error δ_n:

$$D =< D > (1 \pm \delta_n), \tag{18}$$

where

$$< D >= 0.5(D_{\max} + D_{\min}), \tag{19}$$

$$\delta_n = 0.5(D_{\max} - D_{\min})/ < D > . \tag{20}$$

4. The results of the simulations

In order to assess the utility of measuring the light-field diffusivity by means of a moving strip, the measurement errors were calculated according to eq. (20). The relative errors obtained (δ_3) were then compared to the errors calculated for the disc method (δ_2). The sky radiance distribution, required in order to determine the function K_{sn}, was calculated under the condition of single light scattering in the atmosphere from the following relationship (Jerlov, 1976):

$$L_d = E_0 \cos\Theta_s \frac{p(\Psi)[\exp(-\tau/\cos\Theta_s) - \exp(-\tau/\cos\theta)]}{\cos\Theta_s - \cos\theta}, \tag{21}$$

where

$\cos\Psi = \cos\Theta_s \cos\theta + \sin\Theta_s \sin\theta \cos(\phi - \Phi_s)$,

$p(\Psi)$ – the atmospheric phase function,

τ – the total optical thickness of the atmosphere,

E_0 – the scalar irradiance of the external limit of the atmosphere.

The simulations were carried out in the visible spectrum, and for this range of wavelengths the total optical thickness τ was assumed to be the sum of the scattering optical thickness of air molecules (τ_R) and the scattering optical thickness of aerosol particles (τ_A). The resultant phase function was then the weighted mean of the molecular p_R and aerosol p_A phase functions:

$$p(\Psi) = [p_R(\Psi)\tau_R + p_A(\Psi)\tau_A]/\tau, \tag{22}$$

where p_R and p_A took the following forms (Guzzi *et al.*, 1987):

$$p_R(\Psi) = 0.75(1 + \cos^2\Psi), \tag{23}$$

$$p_A(\Psi) = \frac{(1-g_1^2)a}{(1+g_1^2 - 2g_1\cos\Psi)^{1.5}} + \frac{(1-g_2^2)(1-a)}{(1+g_2^2 + 2g_2\cos\Psi)^{1.5}}. \tag{24}$$

The parameters a, g_1, g_2 defined the type of aerosol used in the evaluation of the scattering process and, according to Gordon *et al.* (1983), $a = 0.985$, $g_1 = 0.713$, and $g_2 = 0.759$ for the marine aerosol.

The aerosol optical thickness of the atmosphere was assumed to be as follows (Shifrin, 1992): for the atmosphere over the ocean $\tau_A = 0.07$ (Pacific Ocean), for the atmosphere over the sea $\tau_A = 0.28 - 0.18$ (Mediterranean Sea).

The molecular optical thickness was determined on the basis of the following relation (van Stokkom and Guzzi, 1984):

$$\tau_R(\lambda) = 0.0088\lambda^{-4.15+0.2\lambda}, \tag{25}$$

where

λ – the wavelength in μm. The geometrical parameters selected for these calculations were:

– the Sun's position:

$\Phi_s = 0° = 0,$

$\Theta_s = 30°, 60° = \pi/6, \pi/3,$

$\Theta_{s_{\min}} = 30° = \pi/6;$

– the Sun's angular diameter:

$\Delta\Theta_s \cong 32' \cong \pi/360;$

– the azimuth of the darkest part of the horizon:

$\phi_p = 180° = \pi;$

– the minimal angular dimensions of the disc in method No. 2 and the strip in method No. 3:

$\phi_{d_{\min}} = \theta_d = 10°, 5°, 2° = \pi/18, \pi/36, \pi/90.$

The final results of the simulations are listed in Tab. 1.

Table 1. The relative error δ_n in the measurement of light-field diffusivity by means of a circular diaphragm (n = 2) or a strip diaphragm (n = 3), calculated theoretically for selected geometrical and environmental parameters

n	θ_s	$\theta_d = \phi_{d_{\min}}$	$K_{in} \times 100$	δ_n $\lambda = 440$ nm τ_A=0.07	550 nm 0.07	670 nm 0.07	440 nm 0.26	550 nm 0.20	670 nm 0.18
2	$\pi/6$	$\pi/18$	0.4195	0.0081	0.0124	0.0168	0.0163	0.0195	0.0221
2	$\pi/6$	$\pi/36$	0.1049	0.0022	0.0033	0.0048	0.0044	0.0050	0.0060
2	$\pi/6$	$\pi/90$	0.0168	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002
2	$\pi/3$	$\pi/18$	0.2422	0.0086	0.0134	0.0185	0.0166	0.0208	0.0246
2	$\pi/3$	$\pi/36$	0.0606	0.0023	0.0035	0.0049	0.0044	0.0055	0.0065
2	$\pi/3$	$\pi/90$	0.0097	0.0000	0.0001	0.0002	0.0002	0.0002	0.0003
3	$\pi/6$	$\pi/18$	3.2078	0.0287	0.0392	0.0505	0.0459	0.0545	0.0602
3	$\pi/6$	$\pi/36$	1.4953	0.0139	0.0186	0.0239	0.0218	0.0255	0.0287
3	$\pi/6$	$\pi/90$	0.5724	0.0056	0.0076	0.0096	0.0086	0.0102	0.0117
3	$\pi/3$	$\pi/18$	3.2078	0.0206	0.0359	0.0522	0.0437	0.0574	0.0696
3	$\pi/3$	$\pi/36$	1.4953	0.0108	0.0181	0.0266	0.0223	0.0293	0.0352
3	$\pi/3$	$\pi/90$	0.5724	0.0006	0.0024	0.0043	0.0025	0.0040	0.0056

5. Conclusions

On the basis of the results presented in Tab. 1, it is evident that the maximum relative error of the measurement for the range of parameters assumed does not exceed 7% for the proposed 'strip' method and 2.5% for the 'disc' method (under the same conditions). Obviously, any decrease in the width of the strip reduces this error.

As far as the range of error is concerned, the accuracy of measurement is quite sufficient. Moreover, the main ideas of this method – continuous and automatic measurement, and the maximum stability of its parameters – are implemented under natural marine conditions, even on board a ship in motion.

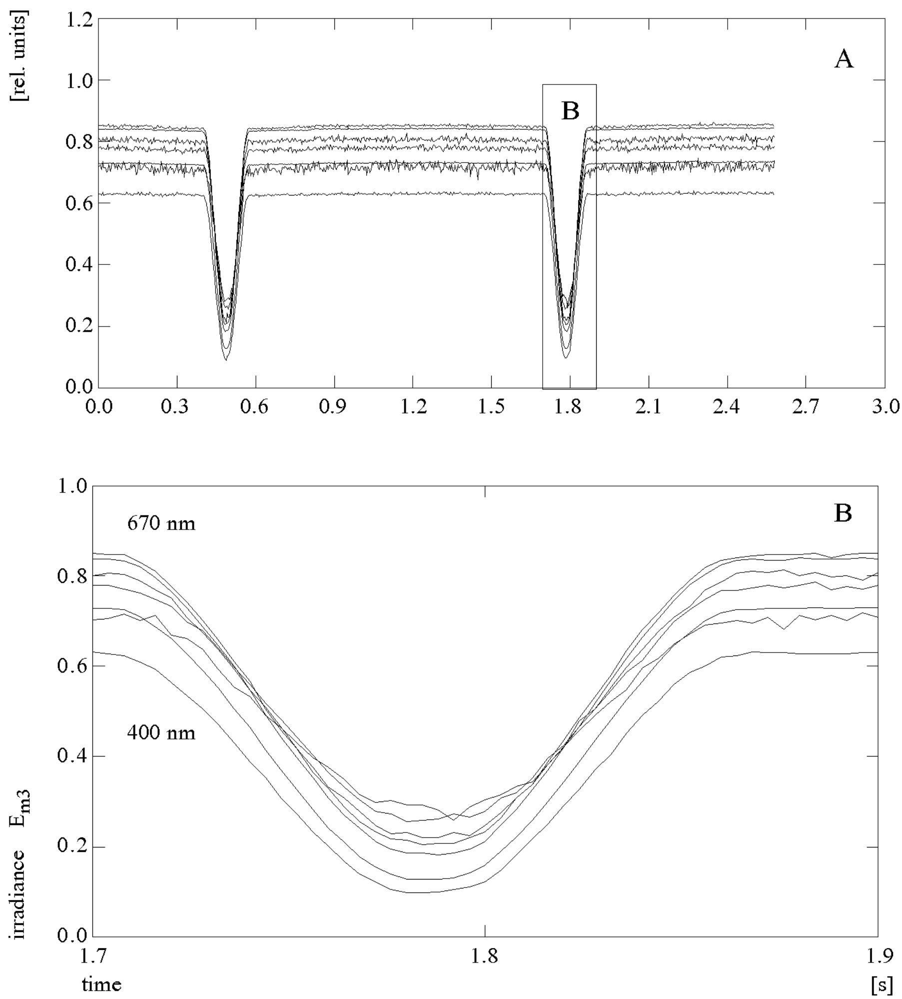

Fig. 2. An example of irradiance recording, measured by means of a moving strip; A – the whole measurement cycle: the minimal values correspond to the instants when the Sun is covered by a strip; the segments between the minimal values concur with the period in which only a part of the scattered radiation of the horizon is cut off; B – The part including the minimal value of a function and its immediate vicinity – an extended time-scale is used in the lower figure

An example of recording irradiance by means of the strip method in order to determine the degree of diffusivity, is shown in Fig. 2. The measurements were carried out on board a moving ship, simultaneously in seven spectral channels across the visible spectrum (for the range of wavelengths from 400 nm to 670 nm). The main parameters of the measuring system were assumed as follows:

- the linear width of the strip and the cosine collector diameter were each 20 mm;
- the angular dimensions of the strip as seen from the cosine collector centre, *i.e.* the distance from its base to its top edge and the width of its base were 60° and 10° respectively;
- the period of rotation of the strip was *ca* 1.3 s, with the possibility of adjustment from 1 to 5 s.

The minimal values of the function, shown on the figure, appeared when the Sun was covered by the strip and corresponded to the stage of determination of the diffuse irradiance component. The points corresponding to the distance centres between the minimal values concurred with the stage of determination of the total irradiance, because at that time the strip covered the part of the horizon opposite the Sun's azimuth, assumed to be the darkest one. The enlarged part (B), corresponding to the minimal value of the function and its immediate vicinity, is shown in order to supply documentary evidence for the ease of differentiating and selecting suitable measuring points. In practice it is implemented, as is the whole registration, by the appropriate computer programme.

The measurements, in agreement with the method discussed, were carried out under various and sometimes very difficult hydrometeorological conditions. However, it was possible at all times to keep a check on the level and the variability of the sought-after parameter. The only manual (not automatic) activity required in this process was the occasional correction of the time of the measuring cycle, which depended on the mean period of the ship's maximum inclinations.

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