Sky glint correction in measurements of upward radiance above the sea surface

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Abstract

An experiment has been performed to determine the upward water-leaving radiance by non-contact measurement of the total upward and downward radiance above the sea surface from a moving ship. The method for achieving this aim is described: the radiance meters are both tilted in such a way that the upward radiance meter can 'see' that part of the measured downward radiance which would be reflected if the water surface were smooth and which is not derived directly from solar glitter. Both meters are firmly fixed in a special frame, which ensures that the required orientation is the most probable one. Time records of the measured parameters are analysed. The results are presented in several forms: frequency (histogram) analysis appears to be the most promising one.

1. Introduction

In marine remote sensing, the problem of eliminating the sea surface background is a fundamental one and remains unsolved. Nevertheless, various attempts have been made to find a solution. The earliest and simplest one assumes that in a certain infrared region of the spectrum the upward radiance leaving the water $L_{uw}(IR)$ is equal to zero. Hence, the total upward radiance just above the surface consists entirely of the surface-reflected component (Gordon 1981). Though a useful assumption where clean oceanic waters are concerned, it is inapplicable in turbid coastal waters. A more realistic approach for coastal waters would be to assume that $L_{uw}(IR)$ is not equal to zero but is independent of water properties (Olszewski & Darecki 1999). In neither of these methods does the sky radiance need to be measured. However, this is not the case in the following methods. Lee *et al.* (1997) suggest measuring the sky radiance at a certain zenith angle, then separately removing the Rayleigh and aerosol contributions to the surface reflection, the latter by a special optimisation procedure (Lee *et al.* 1996). The downward sky radiance $L_d(\vartheta_a)$ measured at a fixed zenith angle ϑ_a is also needed in the methods described by Mueller *et al.* (1997) and Hooker *et al.* (1999), and also in this paper. The surface-reflected upward radiance $L_{us}(\pi - \vartheta_a)$ is then calculated from Fresnel's law and can be removed from the total nadir radiance $L_u(\pi)$ after the respective correction factors, as introduced by Morel & Gentili (1996), have been taken into account.

In this paper we describe a method in which selected zenith angles ϑ_a and $\pi - \vartheta_a$ of the measured sky radiance L_d and of its reflected part L_{us} respectively are not fixed in space but only occur most frequently in time. The temporal changes in the downward and upward radiance are then analysed to find the values that fit these angles and which fit the instants when reflecting wave facets are horizontal. It is important here to assume that the wave slope distribution is close to Gaussian. This is certainly true at low wind speeds, at least those not exceeding 10 m s^{-1} (Cox 1974). Our aim is to show that this method, together with appropriate analysis, allows non-contact determination of the upward water-leaving radiance, and that this is possible from a moving ship.

2. Methods and material

The experiment was performed in the open Baltic on 10 September 1999. In the experiment the downward and upward radiance over the sea surface were measured continuously along the ship's course for about 4 hours. They were recorded at four arbitrary points on the course for analysis. Each record lasted 100 sec and consisted of 1000 samples, taken every 100 ms.

Figure 1 shows the general scheme of the measuring system. The radiance meters consist of units with the same optical and electronic parameters as described by Olszewski *et al.* (1995). The only difference lies in the greater number of units and in the altered set of optical filters: the centres of spectral channels were at 412, 443, 490, 510, 550, 589, 625, 665, 683 and 710 nm. The meters were attached to a special frame at a fixed tilt angle, shown in the figure as ϑ_a and equal to 15°. This particular tilt angle was a compromise selected so as to (1) avoid most of the reflected solar rays and (2) be able to interpret the upward radiance as approximately vertical. The cross-section of the solid view angle for both meters was $\gamma = 20°$. The frame was suspended from four long cords fixed to a steering wheel.

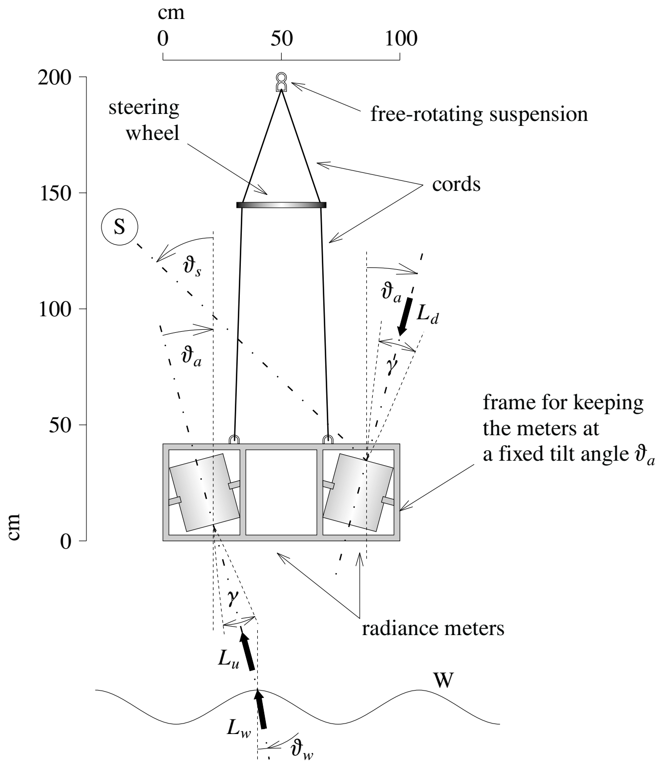

Fig. 1. Diagram of the measuring system; S – sun at zenith distance ϑ_s, azimuth φ_s, W – water surface, γ – angular limit of input radiance (cross section of solid angle), L_d – downward radiance $L(\vartheta = \vartheta_a,\ \varphi = \varphi_s + 180°)$, L_u – upward radiance $L(\vartheta = 180° - \vartheta_a, \varphi = \varphi_s + 180°)$, L_w – underwater upward radiance $L(\vartheta = 180° - \vartheta_w, \varphi = \varphi_s + 180°)$, ϑ_w – Snell's refraction angle

The wheel is suspended from three short cords attached to the deck structure in the ship's bows with the aid of a freely rotating suspension device. The wheel is maintained in the desired azimuth position, *i.e.* in the plane of incidence of solar radiation $\varphi = \varphi_s$ by two cords not shown in the figure. Under gravity, the long cords ought to oscillate around the vertical and around the fixed azimuth. This motion, in turn, affects the orientation of the frame. A photograph of the measuring device in action is shown in Fig. 2.

The map in Fig. 3 gives the positions of the initial (P5) and final (P39) stations of the stationary measurements, as well as the stations A, B, C and D where data were recorded while the ship was in motion. The basic parameters are summarised in Table 1. As far as the irradiance conditions are concerned, the sun was generally visible, but was occasionally veiled by mist. These conditions are presented in Fig. 4 as the diurnal record of visible radiant energy at the sea surface.

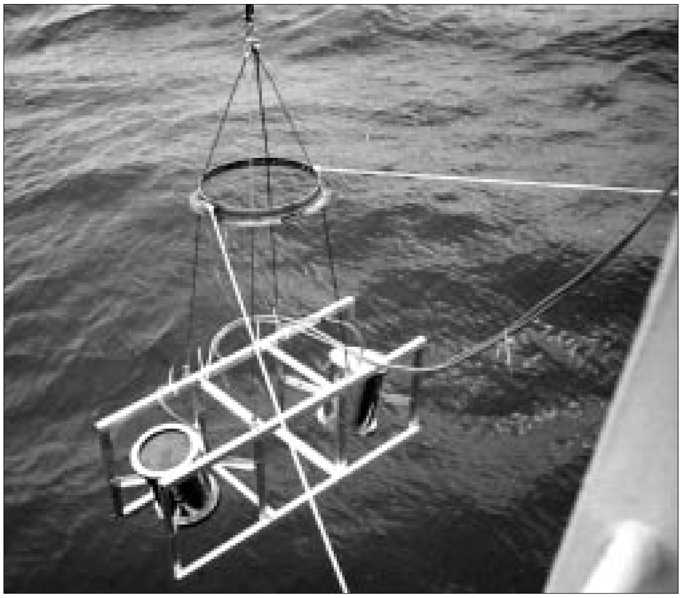

Fig. 2. Photograph of the measuring device

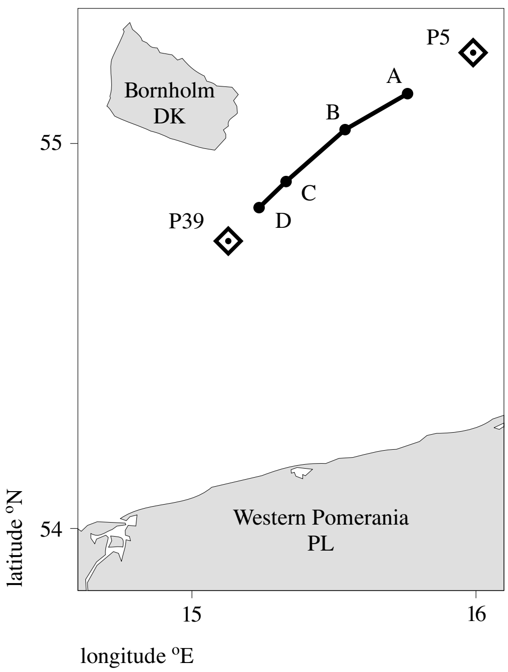

Fig. 3. Data recording stations and course of r/v 'Oceania' during continuous non-contact measurements of upward and downward radiance on 10 September 1999

Table 1. Basic parameters of the experiment on 10 September 1999

Station	Position lat. °N	long. °E	Time GMT [h:min]	Solar zenith angle ϑ_s [°]	Sea state [°B]	Kind of measurement
P5	55.233	15.985	06:40–06:50	∼70	0–1	stationary, *in situ*
A	55.122	15.755	08:26	58.66	0–1	non-contact, on run
B	55.032	15.541	09:32	53.06	1	non-contact, on run
C	54.892	15.331	11:03	50.03	1–2	non-contact, on run
D	54.832	15.244	11:41	50.68	1–2	non-contact, on run
P39	54.743	15.133	12:50–13:00	∼53	1	stationary, *in situ*

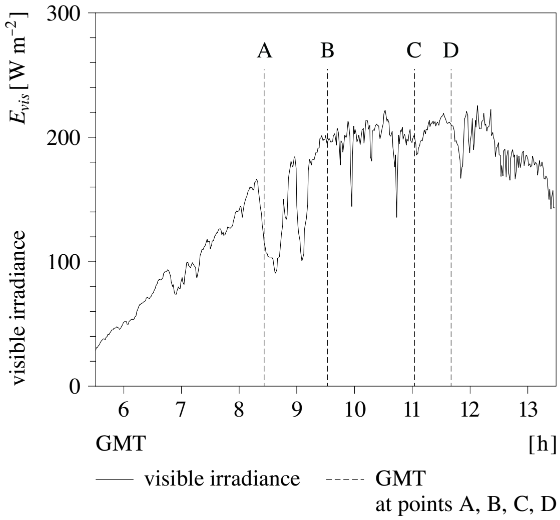

Fig. 4. Time record of irradiance E_{vis}(400–700 nm) at the sea surface during the experiment

The stationary measurements were carried out in order to obtain values of the investigated parameters by the standard *in situ* method before and after the main four-hour run. The downward vertical radiance above and below the sea surface was measured with an MER 2040 spectroradiometer in the ten spectral bands mentioned previously. The radiance just below the surface was determined by Darecki's (1998) method following the self-shading correction procedure given by Gordon & Ding (1992) and Zibordi & Ferrari (1995).

3. Results and method of analysis

The spectral ratio of the upward water-leaving radiance to the total upward radiance above the water at points A, B, C, D, the final result of the experiment, had to be calculated. The total upward radiance was measured directly, whereas the underwater radiance was taken to be the difference between the total and that reflected at the water surface, calculated from the Fresnel reflection of the measured downward radiance.

An example of the rough input data recorded during 100 sec during the ship's motion near point A is shown in Fig. 5. It also shows the record of the run-averaged downward radiance. This parameter was chosen as a reference because of the lack of downward irradiance data. Hence, all further presentations apply to radiance normalised with the above factor.

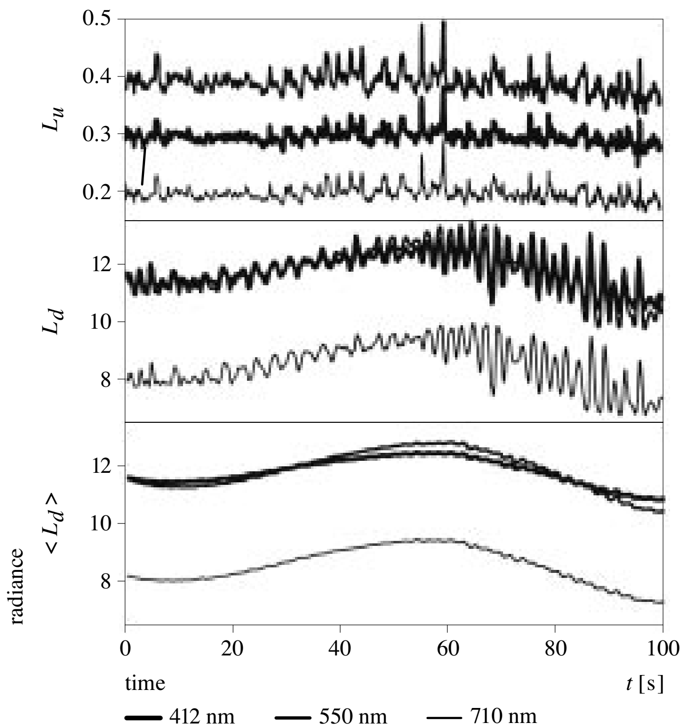

Fig. 5. Time record of upward radiance L_u, downward radiance L_d and downward radiance $< L_d >$ run-averaged with a gate of 10 seconds width, all recorded at station A at three wavelengths: 412, 550, 710 nm

Normalised values of the total upward radiance at points A and D in the blue, green and red parts of the spectrum are presented as examples of input data in Fig. 6. They have been chosen because of the distinct difference in their time record. At point A, where wave motion was minimal and the solar altitude low, solar glitter is practically invisible. This is the reverse of the situation at point D, where the waves were somewhat higher and the sun's altitude so high that some reflected solar rays entered the optical input of the upward radiance meter and recorded. The consequences of this difference will be discussed below.

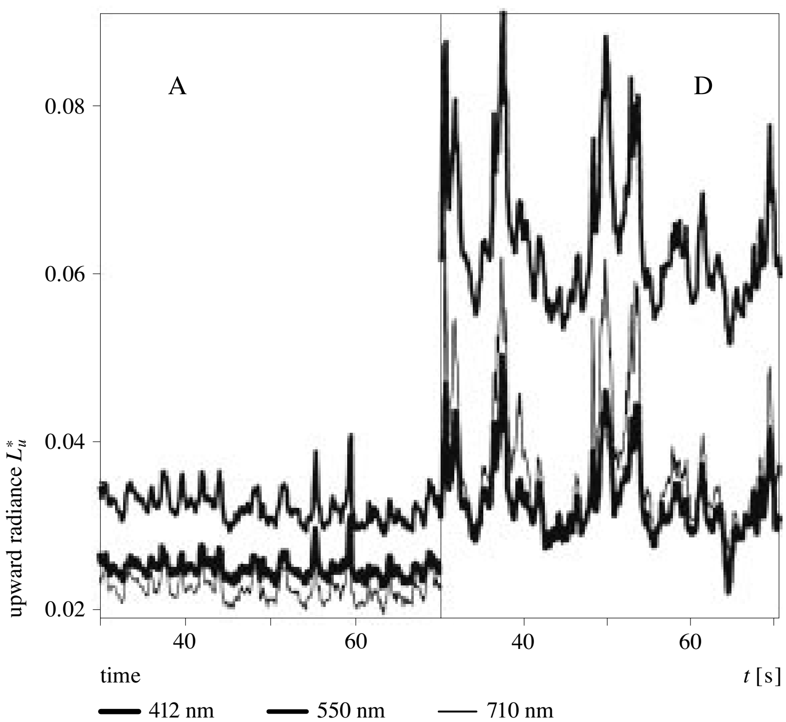

Fig. 6. Comparison of time record of relative upward radiance $L_u^* = L_u / < L_d >$ at stations A and D at three wavelengths: 412, 550, 710 nm

All spectral values of the upward and downward relative radiance at points A, B, C, D were analysed statistically to obtain the mean, standard deviation and modes. The modes were assumed to be the most realistic values because, owing to the force of gravity, the suspended measuring device is most likely to hang vertically. Thus, the downward radiance was most probably measured at a zenith angle of 15°, as was the upward radiance at the same angle from the zenith. Moreover, according to what was said in the Introduction, the most probable slope of the water surface is zero. Such a reflecting surface should reflect light incident from a zenith angle of 15° into a zenith angle of $180° - 15° = 165°$, appropriate to the optical input of upward radiance meter.

Although the probability distributions of downward and upward radiance could be found for each separate case, the forms of these distributions were distinctly different, depending on the sea surface state and solar altitude. With a calm sea and low solar altitudes (at point A, for instance) they were almost symmetrical and close to the Gaussian. With increasing wave motion and solar altitude (allowing some solar glitter to be recorded, as at point D) the distributions become asymmetrical and far from the normal, especially with respect to upward radiance. No specific formula for a smooth transfer between the above kinds of distribution has been found. That is why we assumed the modes of unknown probability distributions as being approximately equal to the most frequent values, derived directly from relevant histograms. In the histograms the start of the first bucket and

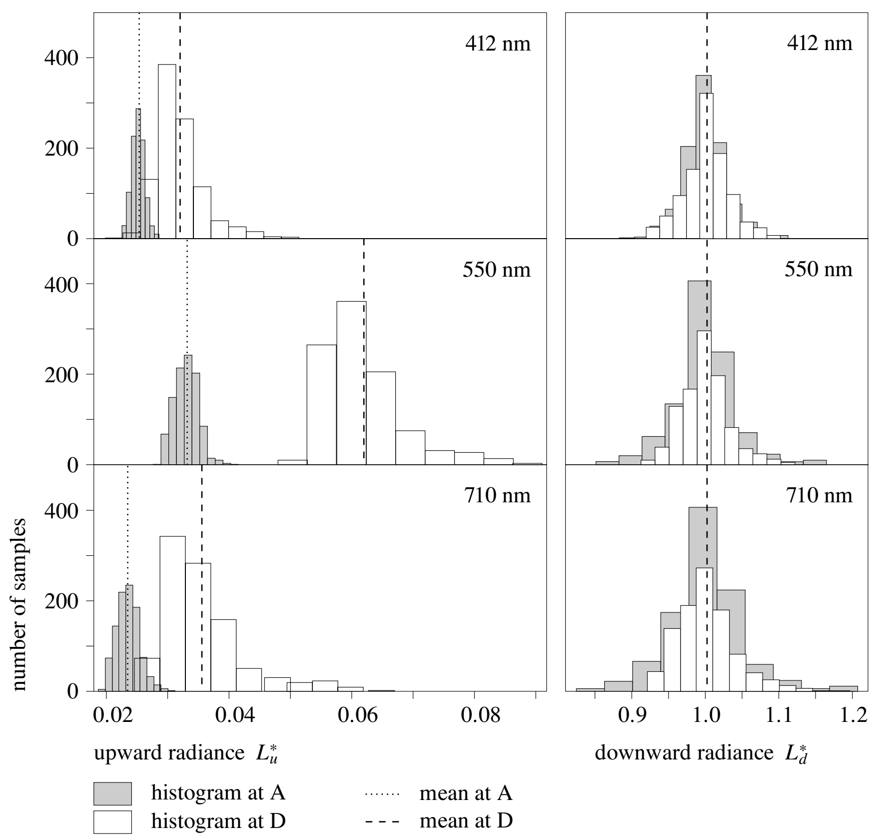

Fig. 7. Comparison of histograms and mean values of relative upward radiance $L_u^* = L_u / < L_d >$ and relative downward radiance $L_d^* = L_d / < L_d >$ obtained at stations A and D at wavelengths 412, 550 and 710 nm (total number of samples $N = 1000$)

the bucket width were found automatically to obtain (1) a total number of buckets not less than ten, and (2) the maximal quantity of samples contained in single bucket. Some of the histograms obtained for records at points A and D are presented in Fig. 7, where all the above-mentioned features are evident.

The final results of the experiment are summarised in Fig. 8. This shows spectra of that part of the underwater radiance in the total above-water upward radiance calculated for the mean and most probable values of the total upward and downward radiance. This last is reflected from the water surface with a reflection coefficient corresponding to an angle of incidence of 15°. Distinctive differences between the mean and modes appear only at points C and D, where the waves and solar altitudes were higher than at points A and B (see Table 1). Nevertheless, the modes at each point are well within the standard deviation limits. Both values could be acceptable, but we consider the modes to be more realistic. While the shape of the spectrum remains almost unchanged, the maximum value of the

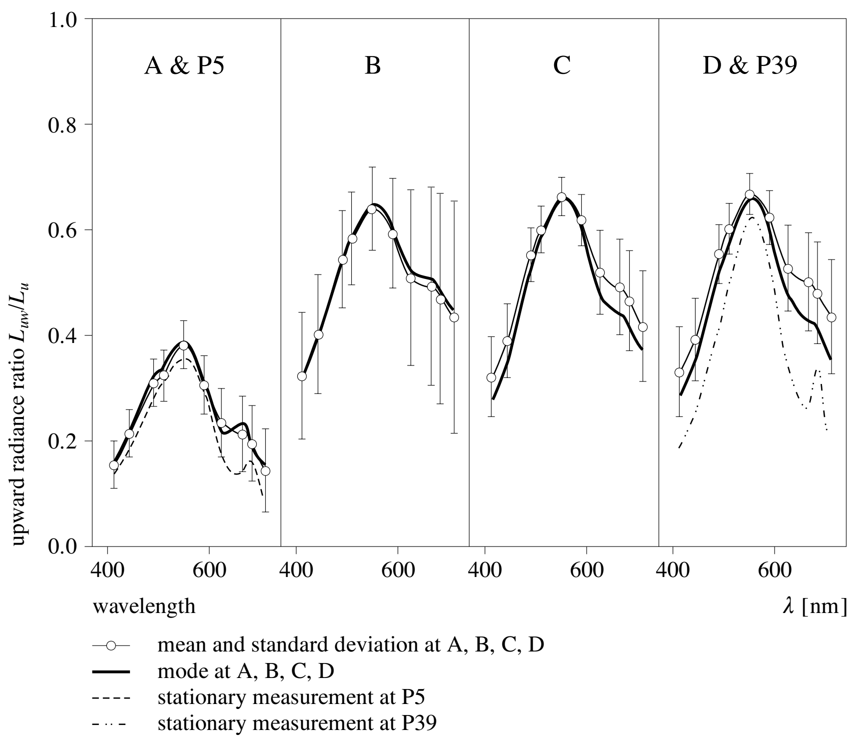

Fig. 8. Spectra of the ratio of the upward water-leaving radiance L_{uw} to total upward radiance L_u above the water surface, calculated from the data recorded at stations P5, A, B, C, D and P39

ratio investigated (in the green band) rises from 40% at point A to above 60% at other points. This is certainly caused by different water properties, because the *in situ* measurements at stations P5 and P39, not very far from points A and D respectively, displayed the same features. For technical reasons the stationary measurements were not carried out at exactly the same stations and times as the non-contact measurements, so they cannot strictly be regarded as verifications. They are only meant to show that the results obtained during the ship's movement using the method outlined here are quite realistic, and coincide roughly with other data from this area. This statement is also supported by the results of long-term stationary measurements, described in the following paragraph.

4. Conclusions

The method presented in this paper provides good estimates for the proportion of water-leaving radiance in the total upward radiance, measured over the sea surface for a calm or moderate sea state. As one can see in Fig. 9, the results are roughly coincident with the average values gathered during several years in the Baltic using direct *in situ* methods.

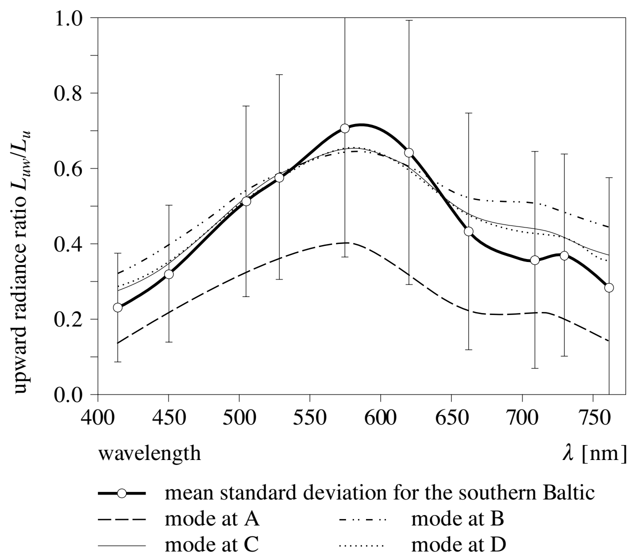

Fig. 9. Spectra of the upward radiance ratio L_{uw}/L_u at stations A, B, C and D compared with the mean spectrum for the southern Baltic in 1993–97

The principal and almost sole source of errors here is uncertainty about (1) the vertical orientation of the device's main axis and (2) the horizontality of light-reflecting patches on the sea surface. A reduction in either of these aspects of uncertainty would yield much more precise results, but to achieve this would not be easy. The second source is practically impossible to eliminate under natural conditions, but some improvement in accuracy here should not be ruled out entirely. On the other hand, to fix the orientation of the measuring device is technically possible, but very costly and complicated. The most realistic solution seems to be to 'sense' this orientation and to select the duration of its verticality. Precisely this solution might be a further effective step along the way to reducing the surface background in remote sensing.

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