Derivation of remote sensing reflectance of Baltic waters from above-surface measurements

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Abstract

It has been shown experimentally that the remote sensing reflectance can be readily calculated from the total remote sensing reflectance, provided certain external conditions are fulfilled. The first condition concerns the solar zenith distance, which should be limited to the 35–70° range (suitable to the Baltic region). The second condition refers to the sea state, which should display no foam and no vertically directed solar glitter. Under such circumstances some simplifying assumptions were possible, which permitted a proper algorithm, in the form of a linear function, to be worked out. Coefficients of the function are tabled for 10 discrete wavelengths (widened SeaWiFS standard), and are also given analytically as linear functions of the wavelength.

1. Introduction

The remote sensing reflectance R_{rs} (Lee *et al.* 1997, Mueller *et al.* 1997) is an important parameter in marine remote research. This parameter is the ratio of the upward, underwater or water-leaving radiance $L_{uw}(\nu,\, \phi,\, z)$ to the downward irradiance $E_d(z)$, where ν – zenith angle, ϕ – azimuth, z – upward vertical axis of co-ordinates. Commonly, nadir values of radiance at the sea surface are used, so $z = 0$, $\nu = \pi$, the dependence on ϕ disappears and so we have, just above the surface:

$$R_{rs}(0^+) = L_{uw}(\pi,\, 0^+)/E_d(0^+) \tag{1a}$$

or just below the surface:

$$R_{rs}(0^-) = L_{uw}(\pi,\, 0^-)/E_d(0^-). \tag{1b}$$

Sometimes it is convenient to operate with the underwater reflectance R_w, which is more easily measured. This is the ratio of the underwater upward radiance to the downward irradiance above the water. Just beneath the surface we have

$$R_w = L_{uw}(\pi,\, 0^-)/E_d(0^+). \tag{2}$$

The underwater reflectance R_w and the remote sensing reflectance R_{rs} are closely related to the classical irradiance ratio R

$$R = E_u/E_d = Q\, L_{uw}(\pi)/E_d = Q\, R_{rs} = Q\ \ R_w/T_{aw}, \tag{3}$$

where

E_u – upward irradiance,

T_{aw} – surface transmission of downward irradiance, defined as $T_{aw} = E_d(0^+)/E_d(0^-)$,

Q – the radiance distribution function, defined as $Q = E_u/L_{uw}(\pi)$.

R is dependent on the ratio of two inherent optical properties of the water: the absorption coefficient a and the backscattering coefficient b_b (Gordon *et al.* 1975, Morel & Prieur 1977, Gordon *et al.* 1988, Kirk 1991, Lee *et al.* 1996). To a first, rough approximation, the quantities R, R_w and R_{rs} are proportional to the above ratio.

For all their importance, underwater and remote sensing reflectances are hard to determine. This is due to the fact that they cannot be measured directly without contact with the water, or even directly at all in the case of $R_{rs}(0^+)$. Only the total, *i.e.* the water-leaving plus the surface-reflected upward radiance L_u, can be measured remotely from above the sea:

$$L_u(0^+) = L_{uw}(0^+) + L_{us}(0^+). \tag{4}$$

Then, if the downward irradiance above the sea is measured, only the total remote sensing reflectance R_{trs} can be obtained:

$$R_{trs}(0^+) = L_u(0^+)/E_d(0^+). \tag{5}$$

A typical set of experimentally found points relating the underwater reflectance R_w to the total remote sensing reflectance R_{trs} above the water at a fixed wavelength is shown in Fig. 1. At first glance, there is no dependence between these two parameters. However, such a dependence must exist because of well-known and determined physical processes transforming the radiance passing through the water surface. To find the desired relationships, one must take into account these processes, as well as a number of environmental parameters. The method for this is proposed below.

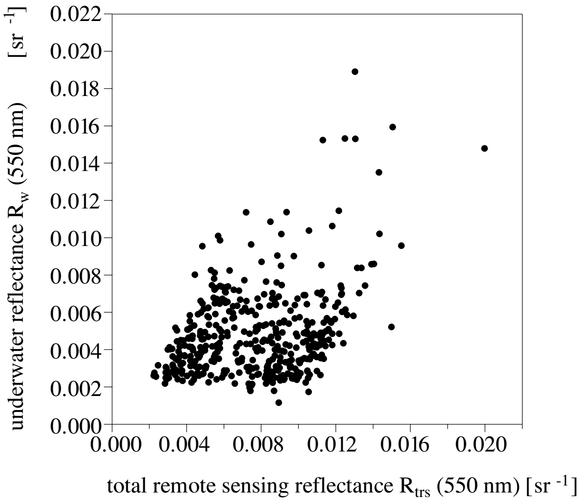

Fig. 1. An unprocessed in-water vs. above-water reflectance data set, measured at wavelength $\lambda = 550\,\text{nm}$ in the Baltic

2. Theory

To find the relationship between the remote sensing reflectance and the total remote sensing reflectance we will take a closer look at the two components of the total upward radiance coming towards the observer, specified in eq. (4). The radiance $L_{uw}(0^+)$ emerging from the water determines the underwater upward radiance crossing the surface with an efficiency given by the transmission $T_{wa} = L_{uw}(0^-)/L_{uw}(0^+)$. The radiance originating at the surface $L_{us}(0^+)$ is that part of the downward irradiance reflected at the surface with coefficient $R_s(0^+) = L_{us}(0^+)/E_d(0^+)$ and is referred to as the surface reflectance. Equations (4) and (5) can now be rewritten as

$$L_u(0^+) = L_{uw}(0^-)\ T_{wa} + E_d(0^+)\ R_s(0^+) \tag{6}$$

and

$$R_{trs}(0^+) = R_{rs}(0^+) + R_s(0^+) = R_w\ T_{wa} + R_s(0^+), \tag{7}$$

or, taking into account the dependence on the light wavelength λ and on environmental parameters,

$$R_{trs}(p_w,\, p_s,\, p_a,\, \lambda) = R_w(p_w,\, \lambda)\ T_{wa}(p_w,\, p_s,\, \lambda) + R_s(p_s,\, p_a,\, \lambda), \tag{8}$$

where the symbols p_w, p_s, p_a stand for the respective sets of parameters influencing the optical characteristics of the water, the sea surface and the atmosphere; the last one includes the solar elevation.

We shall now determine the circumstances under which some essential simplifications are possible. First of all, observation should be strictly limited to the vertical direction. The next condition concerns the solar zenith angle, which should be limited to the 35–70° range. The final limiting condition applies to the sea surface state, which should show no foam and no vertically directed solar glitter. All the above conditions taken together lead to the following simplifying assumptions.

The first assumption refers to the surface transmission of the upward radiance T_{wa}. The combined effect of all these limitations suggests that the permitted wave slopes are rather small, no more than 15 degrees. It then ensues from Snell's law of refraction that the nadir radiance above the surface leaves the water body from a very narrow cone around the vertical. Within such an underwater cone the angular distribution of upward radiance can be regarded as isotropic and thus independent of the water's optical parameters. The surface transmission of radiance will then be determined only by the Fresnel reflection coefficient ρ at almost normal directions and by the refraction coefficient of water n, both weakly sensitive to the light wavelength. Thus the constant, mean value can be taken to be the real transmission

$$T_{wa} = \bar{T}_{wa}(p_w,\, p_s,\, \lambda) = \bar{n}^{-2}(1 - \bar{\rho}). \tag{9}$$

The second simplification involves the surface reflectance R_s. Under the same circumstances as before, the downward irradiance, reflected vertically, comes from a cone that includes a section of sky around the zenith but not the area around the sun. The radiance distribution in this cone is generally far from isotropic, but since direct sun rays are absent, it can be averaged to a single value dependent on the optical state of the atmosphere rather than on the sea surface state, which merely narrows or widens the cone. Moreover, the reflection of such radiance can be averaged, as it is dependent only on the quasi-normal Fresnel coefficient and atmospheric parameters, especially the solar elevation. So again, the mean value instead of the real one can be introduced:

$$R_s(p_a,\, \lambda) = \bar{R}_s(p_a,\, p_s,\, \lambda). \tag{10}$$

Substituting (9) and (10) in (8) we have

$$R_{trs}(p_w,\, pa,\, \lambda) = R_w(p_w,\, \lambda)\ T_{wa} + R_s(p_a,\, \lambda) \tag{11}$$

which indicates that under the circumstances assumed, the total remote sensing reflectance R_{trs} becomes independent of the state of the sea surface. These external conditions and the assumptions emerging from them are discussed in greater detail in a separate section.

Another important set of assumptions can be inferred from the optical properties of pure water: they concern the effect of the strong absorption of light in the red and near-infrared parts of the spectrum (Smith & Baker 1981, Pope & Fry 1997). This effect causes the emergent upward radiance to fall considerably. Hence, in the IR there is a wavelength λ_0 for which almost all upward radiance is due to surface reflection and is thus more closely dependent on external conditions than on seawater parameters. In this simplification we further assume that the dependence of the underwater part of the upward IR radiance $L_{uw}(\lambda_0)$ on the water properties is so weak that it can be neglected. It should be emphasised at this juncture that in contrast to some other standard correction procedures, we do not ignore the value of $L_{uw}(\lambda_0)$, merely its dependence on the seawater properties and surface state. Equation (11) can therefore be written in the form

$$R_{trs}(p_a,\, \lambda_0) = R_w(\lambda_0)\ T_{wa} + R_s(p_a,\, \lambda_0). \tag{12}$$

Since, according to our earlier assumptions, the surface reflectance R_s depends only on the atmospheric parameters p_a and the wavelength λ, we can extract from $R_s(\lambda)$ a part dependent on its IR value $R_s(\lambda_o)$ using the hypothetical functions f_1 and f_2, which must also depend only on p_a and λ:

$$R_s(p_a,\, \lambda) = f_1(p_a,\, \lambda)\ R_s(p_a,\, \lambda_0) + f_2(p_a,\, \lambda). \tag{13}$$

Functions f_1 and f_2 are simply a means to obtain the final solution. At fixed atmospheric conditions and a fixed wavelength, eq. (13) expresses a linear relation between $R_s(\lambda)$ and $R_s(\lambda_o)$; f_1 is then the slope, and f_2 the intercept of this relation.

Taking eqs. (11)–(13) and introducing the temporary notation

$$\begin{aligned} Y = R_s(p_w,\, p_a,\, \lambda) &= R_{trs}(p_w,\, p_a,\, \lambda) - R_{rs}(p_w,\, \lambda) = \\ &= R_{trs}(p_w,\, p_a,\, \lambda) - R_w(p_w,\, \lambda)\ T_{wa}, \end{aligned} \tag{14a}$$

$$X = R_{trs}(p_a,\, \lambda_0), \tag{14b}$$

we find that

$$Y = f_1(p_a,\, \lambda)\, X - f_1(p_a,\, \lambda)\, R_{rs}(\lambda_0) + f_2(p_a,\, \lambda). \tag{15}$$

We see that the coefficient at X is the slope and that the remainder of (15) is the intercept in the straight-line equation

$$Y = a_1\, X + a_0, \tag{16}$$

where

$$a_1 = f_1(p_a,\, \lambda), \tag{17a}$$

$$a_0 = f_2(p_a,\, \lambda) - f_1(p_a,\, \lambda)\ R_{rs}(\lambda_0). \tag{17b}$$

The values of Y consist of the total remote sensing reflectance and of the underwater reflectance being investigated, while X signifies the total remote sensing reflectance at a fixed IR wavelength λ_0. According to eq. (17),

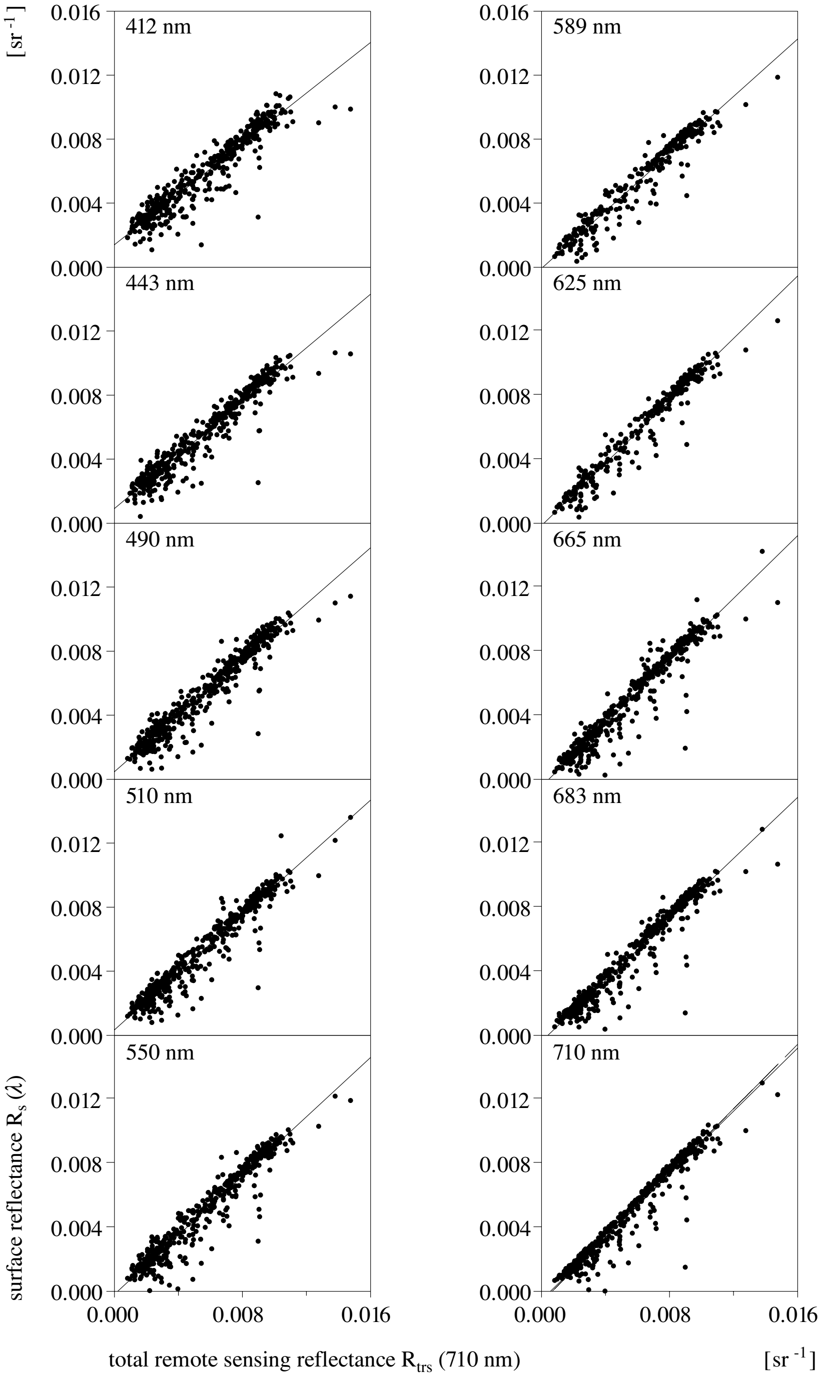

Fig. 2. Sets of reflectance data gathered in the Baltic at ten wavelengths and processed according to eq. (18). The solid lines denote linear regressions; the dashed line at 710 nm denotes the regression with a slope coefficient $a_1 = 1$

coefficients a_0 and a_1 depend upon external conditions. Nevertheless, experiments have shown that the latter dependence is rather weak and, in some ranges of the conditions, can be neglected. Now, returning to the reflectance symbols, and taking eqs. (14) and (17) into account, we can rewrite eq. (15) as

$$R_s(\lambda) = a_1(\lambda)\ R_{trs}(\lambda_0) + a_0(\lambda). \tag{18}$$

The linear approximation (18) is very well substantiated by experimental data; it will be discussed later (see Fig. 2). To explain the physical significance of coefficients a_0 and a_1, it is preferable to rewrite eq. (18) as

$$R_s(\lambda) = a_1(\lambda)\ R_s(\lambda_0) + a_1(\lambda)\ T_{wa}\ R_w(\lambda_0) + a_0(\lambda). \tag{19}$$

Coefficient $a_0(\lambda)$ stands for the surface reflectance R_s at λ, diminished by part of the total remote sensing IR reflectance R_{trs}. This diminished value can be approximately regarded as part of the underwater IR reflectance R_w after the zenithal IR radiance has been neglected, or as part of the surface IR reflectance R_s after the emergent IR radiance has been neglected. Coefficient $a_1(\lambda)$ can be thought of as the ratio of surface reflectances R_s at λ and λ_0, if the same part of the underwater IR reflectance R_w as above balances the reflectance defined as $a_0(\lambda)$. Inspection of eqs. (18) and (7) shows that for the reference wavelength λ_0, coefficient $a_1(\lambda_0) = 1$ and then coefficient $a_0(\lambda_0)$ is equal to the negative remote sensing reflectance $R_{rs}(\lambda_0)$ above the water. So we can write

$$R_s(\lambda_0) = R_{trs}(\lambda_0) - R_{rs}(\lambda_0,\ 0^+). \tag{20}$$

Having determined experimentally the coefficients $a_0(\lambda)$ and $a_1(\lambda)$, we can obtain the final form of the algorithm to find the remote sensing reflectance R_{rs} or the underwater reflectance R_w

$$R_{rs}(\lambda, 0^+) = R_w(\lambda)\ T_{wa} = R_{trs}(\lambda) - a_1(\lambda)\ R_{trs}(\lambda_0) - a_0(\lambda). \tag{21}$$

3. Materials and methods

The experimental part of this work is based on measurements of the remote sensing reflectance and underwater reflectance made in the central and southern Baltic from r/v 'Oceania' (50 metres in length) from June 1993 to September 1997, excluding winter and mid-summer. The measurement points were almost evenly spread all over the Polish Zone of the Baltic and yielded 439 data sets. Unfortunately, the grid of these points is too dense to be shown distinctly on a map of the region.

Measurements were made using a MER 2040 spectrophotometer (Biospherical Instruments USA) at ten spectral channels: 412, 443, 490, 510, 550, 589*, 625*, 665, 683, 710 nm (*since Sept. 1994). Each data set contained values of the upward radiance and downward irradiance, both above and below the water. In accordance with the assumed limits of the external conditions, only data with the solar zenith angle at $< 70°$ were collected; the upper limit of 35° resulted from geographic position. Other optical conditions – cloudiness, the level of irradiance and its diffusivity – were limited only by the spectrophotometer's sensitivity. Hydrodynamic situations with strong wave motion and foam were avoided for the reasons given in the discussion and conclusions.

The spectrophotometer was placed above the water and immersed from a 6 m-long boom on the sunny side of the after part of the ship. The self-shading effect on upward radiance was corrected using the procedures proposed by Gordon & Ding (1992), modified by Zibordi & Ferrari (1995), which take the meter and detector diameters, the solar elevation and the radiance attenuation coefficients into consideration.

A licensed SigmaPlot program was used to process the data, and all the statistical parameters are in accordance with this program (SigmaPlot 4.0 for Windows, 1997). Only the results from the full-size data base were finally taken into account. Any attempt to separate the total data set into sub-sets according to season, region or light conditions yielded statistical parameters of consideraby lower quality.

4. Results

The basic form for visualising the results are sets of points connecting the surface reflectance R_s at ten wavelengths with the total remote sensing reflectance R_{trs} at 710 nm (Fig. 2). The sets are obtained by calculating the data in accordance with the theory, summarised in eq. (18). Linear regressions are shown in Fig. 2 as solid lines, while at $\lambda = \lambda_0 = 710$ nm the linear regression with slope coefficient $a_1 = 1$ is added (the dashed line). This last regression fits eq. (20) and is shown together with the 'no constraints' regression as evidence of the very good similarity between the two lines. Detailed parameters of the above data sets and regressions will be found in Table 1. Since the standard errors are small and the correlation coefficients high, the regression coefficients from Table 1 can be regarded as good enough and used directly in algorithm (21).

To improve the quality of algorithm (21), an attempt was made to find the analytical form of the regression coefficients spectrum. Again, the linear fit was found to be the best one:

$$a_i(\lambda) = C_{i0} + C_{i1}\ \lambda; \qquad (i = 0,\ 1). \tag{22}$$

The results of such fitting are shown in Fig. 3 and presented in Table 2. Almost all the points in Fig. 3 lie within the limits determined by their

Table 1. Statistical parameters of the processed data sets: λ – wavelength; n – size of sample; a_0, a_1 – coefficients of linear regression $R_s = a_1\,R^o_{trs} + a_0$, where $R^o_{trs} = R_{trs}$ (710 nm)

λ [nm]	n	$a_0 \pm$ S.E.	$a_1 \pm$ S.E.	S.E.E.	r
412	439	0.0014 ± 0.0001	0.7896 ± 0.0132	0.0008	0.9443
443	439	0.0009 ± 0.0001	0.8361 ± 0.0120	0.0007	0.9581
490	439	0.0005 ± 0.0001	0.8746 ± 0.0122	0.0007	0.9600
510	439	0.0003 ± 0.0001	0.8965 ± 0.0120	0.0007	0.9632
550	439	–0.0002 ± 0.0001	0.9194 ± 0.0130	0.0008	0.9589
589	282	–0.0001 ± 0.0001	0.8956 ± 0.0143	0.0007	0.9663
625	282	–0.0002 ± 0.0001	0.9697 ± 0.0135	0.0007	0.9738
665	439	–0.0004 ± 0.0001	0.9725 ± 0.0133	0.0008	0.9617
683	439	–0.0004 ± 0.0001	0.9477 ± 0.0122	0.0007	0.9657
710	439	–0.0005 ± 0.0001	0.9784 ± 0.0124	0.0008	0.9666
		–0.0007 ± 0.0001	1.0000 ± 0.0125	0.0008	0.9663

Explanations:
S.E. – standard error,
S.E.E. – standard error of the estimate,
r – correlation coefficient.

Table 2. Statistical parameters of linear regression $a_i(\lambda) = C_{i0} + C_{i1}\,\lambda$, describing the dependence of the coefficients a_0 and a_1 on the wavelength λ

a_1	$C_{i0} \pm$ S.E.	$C_{i1} \pm$ S.E.	S.E.E.	r
a_0	$(3.450 \pm 0.408)\ 10^{-3}$	$(–5.845 \pm 0.708)\ 10^{-6}$	0.0002	0.9486
a_1	$(5.592 \pm 0.425)\ 10^{-1}$	$(\ 6.209 \pm 0.737)\ 10^{-4}$	0.0229	0.9444

Explanations as Table 1.

standard errors and the standard error of the estimate. Some exceptions to this may be due to our not taking into account an unknown systematic error. This ought to be quite small but is none the less possible, because, despite all due care having been taken during the measurements, the occasional recording of the sun's glitter, badly averaged by the meter's relatively long time constant, was unavoidable. There may also be differences between the time responses of each channel, as well as errors in the energetic and spectral calibration. Correction of self-shading is not very accurate either. Even if all the errors are negligible when taken separately, their combined effect at the measuring point cannot be ruled out.

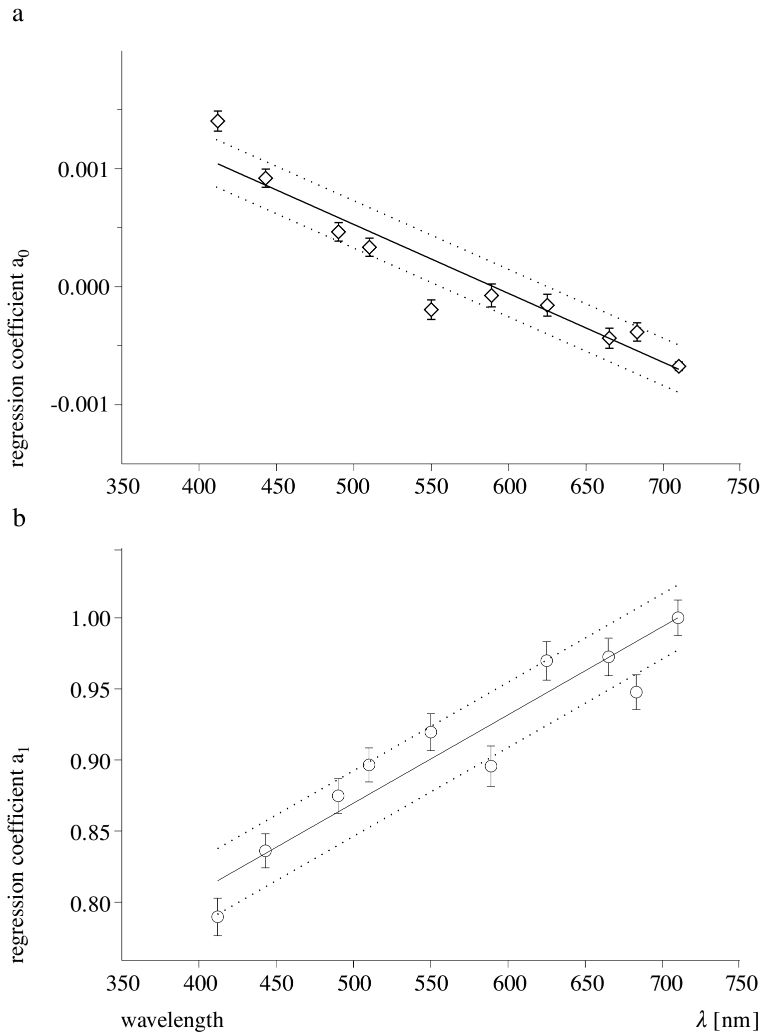

Fig. 3. Linearly interpolated spectrum of regression coefficients a_0 (a) and a_1 (b). The solid lines indicate the regressions given by eq. (22); the dotted lines are the limits of the standard error of the estimate (S.E.E.); vertical bars denote standard errors

5. Discussion and conclusions

The range of circumstances and the resulting assumptions considered here require further explanation. The upper limit of the solar zenith angle of 70° was quite simply imposed in order to diminish the errors due to the low signal level, shading, a rapid increase in reflection, and so on. The lower limit of this angle (35°) is due entirely to the geographic position of the Baltic, where the lowest latitude is around 54°N. This would have yielded a minimum solar zenith distance of somewhat less than 35°, but in fact there was no such case in the data sets. Indeed, more than 90% of the data were obtained at solar zenith angles in excess of 45°. This means that noon-time measurements on several days around the longest day of the year were largely omitted, the reason being to avoid direct sun rays reflected towards the observer. Such solar glitter dramatically raises the level of surface reflectance, whereas underwater reflectance remains unchanged. This would clearly have a very adverse effect on the possibility of deriving the last parameter from remote measurements.

Taking solar glitter into account leads to further problems involving the sea surface state. On applying the law of reflection to vertical observations and to the minimum solar zenith angle, we can assume that surface slopes below about 15° are enough to efficiently reduce reflection of the image of the sun and its surroundings. Fortunately, the same condition will suffice in order to avoid another adverse factor – surface foam. This disrupts reflectance in three ways. Firstly, it acts as a Lambertian reflecting surface. Somewhat akin to glitter, this also enlarges the level of surface reflectance, but here by widening the solid angle of the descendant radiance up to the whole upper hemisphere, including the sun. Secondly, the foam screens part of the radiance entering the water, although this effect is not of much importance. The third and most serious factor is the almost total instantaneous screening of the emergent radiance.

Now we can move on to the two important assumptions allowed by the limits of the external conditions. Both concern the radiance distribution. The first refers to the underwater upward radiance. Here the question arises whether its distribution can really be regarded as isotropic. Let us see what happens if we retain the maximum permitted wave slopes at 15°, and the direction of observation remains strictly vertical. A simple calculation using Snell's law of refraction in which the water-air coefficient of refraction $n = 1.34$ yields the maximum width of the underwater cone, from which the radiance crosses the surface towards the zenith, of *ca* 3° around the vertical axis. The distribution of radiance within such a small solid angle can be safely regarded as constant (see *e.g.* Højerslev & Aas 1997).

According to the second assumption, when the optical state of the atmosphere is fixed, the radiance reflected towards the zenith by the water surface does not depend much on the sea state. Within the limits of the permitted wave slopes, this assumption means that we substitute the real incident radiance in a cone of up to 30° around the zenith for its mean value, which does not change when the cone narrows as the sea becomes calm. This approximation is not as good as that of the underwater upward radiance but is still quite acceptable for two reasons. Firstly, the sun is always well beyond the cone, so the radiance distribution is not as sharp as in the vicinity of the sun. Secondly, the highest and lowest values of this radiation usually lie on opposite sides of the cone (since the principal maximum of the sky's radiance in the plane of incidence of the sun's rays always occurs towards the sun, whereas the principal minimum lies perpendicular to the above direction), so the mean must lie somewhere between these sides, not far from the zenith. This is also the case for cloudy conditions, because then the time-averaged radiance distribution is usually flatter than that of a cloudless sky.

All the above conditions are of theoretical significance, important for a better understanding of the relations obtained. Actually, some of them could not have been observed, which is why the final errors were greater. Nevertheless, the method used in this work for determining the remote sensing reflectance gave very good results. Their high quality is due to the small standard errors of the suggested approximations and the high correlation coefficients of not less than 0.94. The important practical property of the proposed solution is its global approach to the data, which takes no account of the conditions under which they were obtained (with the exception of certain initial limits). This is a very useful property for rapid, automatic measurements made from a moving ship, helicopter or aircraft.

Apart from the advantages of a global approach, the results could be improved if some quantitative parameters describing the optical state of the atmosphere were introduced into the calculations. For instance, this would enable only the cloudless conditions necessary for satellite measurements to be taken into account. Here, an attempt to do so has been made using a criterion involving the irradiance level and solar elevation. This gave rise to changes in the coefficients (but not the form) of the algorithms, but the statistical quality obtained was far from satisfactory. One cause of the poor results could have been the size of the data base, which was insufficiently subdivided. More probably, however, the reason was the wrong criterion for recognising the optical state of the atmosphere. In subsequent work we suggest adding a criterion involving the ratio of diffuse to total irradiance, which also can be measured semi-automatically (Olszewski *et al.* 1995).

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