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CALIBRATION OF A MARINE RADIANCE AND COLOUR INDEX METER

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Abstract

A method for radiance calibration by means of a standard lamp only, without any diffusing surface, is presented. The method maps the opening solid angle of the radiance meter, and the spectral calibration factor may be found by the instrument's response to the input from the lamp. The linearity is also calibrated, and the calibration factor in water and the colour index correction is determined.

Contents

1. Introduction

In nature the variation of radiance is considerable. On a clear day at noon the radiance from the sun at 450 nm may be

$$2{\cdot}10^4 \text{ W m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1},$$

while the radiance from the sky may vary in the range

$$0.05 - 1.0 \text{ W m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}.$$

On a summer day, just beneath the surface of the Oslofjörd, the radiance from nadir at 450 nm may be of order

$$10^{-3} - 10^{-2} \text{ W m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1},$$

while on a cloudy day in December the same radiance at noon may be as low as

$$10^{-5} \text{ W m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}.$$

Radiation equipment which is designed for atmospheric conditions, will then measure in a range which is quite different from that of the marine radiance meter, and therefore a direct comparison between such instruments will often not be possible.

While reference lamps for irradiance can readily be purchased, standard sources of radiance in the appropriate marine range do not seem to be manufactured.

The diffusing and reflecting properties of magnesium oxide are fairly well known (Woronkoff and Pokrowski, 1923, Harrison, 1946, Benford et al., 1948, Carr and Zimm, 1950, Middleton and Sanders, 1951, Tellex and Waldron, 1955), and it is possible to irradiate a disk covered with such material with the light from a standard lamp. However, a satisfactory method to reduce the radiance from this kind of a disk to the marine signal level was not found in our investigation.

Instead a procedure in two steps was applied. First a reference meter designed for atmospheric use with a wide range was calibrated. Then the actual marine radiance meter was either compared directly with the reference meter, or it was calibrated by means of a lamp spectrum measured by the reference instrument.

The calibration constants presented in this paper will only have local significance, but the simple methods which are described may perhaps also be of interest to other readers. The calibration experiments took place during the autumn of 1989. They were first presented in an internal report in November, 1989.

2. Light sources and instruments

2.1. Standard lamps and reference instruments

Two different kinds of primary references were used. The first was a standard halogen lamp of 12 V, 100 W, at the Norwegian Radiation Protection Authority, calibrated at the Swedish National Testing and Research Institute. The second was a Li-Cor Quantum Sensor, Model Number LI-190SB from the Li-Cor, Ltd., Nebraska. This sensor had been spectrally calibrated by the company.

The lamp and sensor were tested against each other. At a distance of 49.2 cm the lamp was supposed to produce a quanta irradiance in the interval 400-700 nm of $1.230 \cdot 10^{17}$ quanta m^{-2} s^{-1}. According to the quantum sensor the irradiance was $1.21 \cdot 10^{17}$ quanta m^{-2} s^{-1}, which is 2 % higher and of the same order as the error of reading.

The results of a spectral comparison are given in Table 2.1. In this test the quantum sensor was provided with external interference filters of presumed known transmittance. It is seen that while the measured irradiance may differ by ± 7 % from the lamp values, the mean ratio between the two different sets is 1.00. The differences may have several causes, but the most likely ones are errors in filter transmittances and non-linearities in the recording device which occur when the signals are weak and the readings are less than one third of the full scale.

It was decided to apply the spectral curve of the standard lamp as the basic reference throughout this work.

The reference radiance meter was a simple construction intended for atmospheric measurements, and consisted of a Gershun tube with an opening toward the light at one end, and a silicon detector of model type S351A with radiometric filter from United Detector Technology, California, at the other end. The tube could also be connected with the Li-Cor sensor.

TABLE 2.1. Comparison of the standard lamp and the Li-Cor sensor at the Norwegian Radiation Protection Authority, October 4, 1989.

Wavelength nm	Lamp irradiance mW m^{-2} nm^{-1}	Li-Cor sensor mW m^{-2} nm^{-1}	Lamp / Li-Cor sensor
450	5.67	5.83	0.97
520	11.0	12.0	0.92
550	13.6	13.4	1.01
620	22.9	21.3	1.07
Mean value			1.00

A halogen lamp at the Institute of geophysics, similar to the one at SIS, was used as a substandard. The reference instrument was directed towards the lamp at a distance of 50 cm, and the irradiance was measured at 15 wavelengths. The irradiance was then calculated by means of the calibration factors which are presented later in Table 3.1 of Chapter 3.3.

The corresponding spectral irradiance distribution at a distance of 3.36 m, which will be needed in Chapter 4.5, is shown in Figure 1, for two different lamp currents. Both currents were reduced below the ordinary value in order to obtain a suitable magnitude of the signals.

As a check of the irradiance values the colour temperature of the spectrum was calculated. If the lamp radiates as a black body, the irradiance in the visible part of the spectrum will be given by Planck's law in the approximated form

$$E_\lambda(\lambda) \approx A\ \lambda^{-5}\ e^{-\frac{B}{T\lambda}} \tag{2.1}$$

where $E_\lambda(\lambda)$ is spectral irradiance, λ is wavelength, A is a constant which depends upon the area of the filament and the distance to the lamp, T is filament temperature in degrees Kelvin, and B is the radiation constant 14388 μm K. The equation may also be written

$$\ln[\lambda^5\ E_\lambda(\lambda)] \approx \ln A - \frac{B/T}{\lambda} \tag{2.2}$$

If the expression on the left side of (2.2) is used as the ordinate, and $1/\lambda$ as the abscissa, the observations should fall on a straight line, and the temperature could be calculated from the slope of the line. Figure 2 illustrates that the colour temperature of the lamp is only slightly different for the two series. In Series 1 the temperature is $T = 3200\ K$, while the reduced lamp current in Series 2 gives $T = 3116\ K$. The good fit between the points and the lines indicates that the obtained spectra are reasonable.

2.2. The marine radiance and colour index meter

The instrument was designed optically and electronically by Niels K. Højerslev and Henning Hundahl at the University of Copenhagen, primarily to measure colour index, and was manufactured by Dansk Havteknik. It consists of a cylinder of height 14 cm and diameter 14 cm, where the bottom is a glass window. Three channels look downwards through the window. The radiance from nadir passes the window, an interference filter, and a lens and pinhole system before it meets a photo diode. The signals are read off on deck by means of a cable and a recording unit. A more detailed description has been given elsewhere by Højerslev and Larsen (1980).

3. Calibration of the reference instrument

3.1. Linearity of the reference instrument

In order to test the linearity of the reference instrument, several methods to vary the amount of incident radiation were tried, but finally it was decided that the only accurate way was to vary the distance between the instrument and the light source.

The institute building has at its top floor an open air terrace, which receives very little artificial light from its surroundings. A stabilized halogen lamp of *100 W* was placed at one end of the terrace, and the distance from it was marked on the floor for each meter with a chalk. The measurements were made on the night of October 26, 1989, which was dark and calm.

Since all parts of the light source was contained within the angle of view of the radiance meter, it was acting as an irradiance meter during this experiment.

For each meter between 1 and 28 meters the instrument was directed towards the lamp, adjusted to maximum signal, and read off.

The signal of the background light was found by keeping a ruler between the lamp and the radiance meter, so that the shadow was coverings the entrance of the instrument. The difference between the first and the last signal is the signal due to the direct lamp light. Usually the background signal was negligible.

The instrument was then taken back to the 1 meter distance, and supplied with a filter which reduced its signal to the former value at 28 meters. A new series was then recorded between 1 and 28 meters. Since the signals are supposed to be inversely proportional to the squares of the distances, the instrument would be tested in a region of variation from 1 to $(1/28^2)^2 \approx 10^{-6}$, that is over 6 decades. The measurements showed that the UDT sensor was linear within the whole of this region.

3.2. Solid angle of the reference instrument's field of view

The most simple type of a radiance meter consists of a tube with a field stop at one end and a detector at the other end. A good geometric approximation to the solid angle "seen" by the detector in this kind of instrument will be the area of the field stop divided by the square of the distance between stop and detector.

Our reference instrument has been constructed as described above. The area of the field stop is 72.4 mm^2, and the distance from the field stop to the LI-COR detector is 42 mm. The solid angle Ω should then be

$$\Omega = 72.4/(42^2)\ \text{sr} = 0.0410\ \text{sr}.$$

This result is commented below.

When the optical system is more complex than the described tube, the solid angle may be found by a method where the effective field of view of the instrument is mapped. The radiance meter will then be placed at a distance y from an optical bench, with its direction normal to the bench, at the same horizontal level as the lamp, as illustrated in Figure 3. If the lamp, which can move along the optical bench, has been shifted a distance x to the side, the distance r between instrument and lamp will be given by

$$r^2 = x^2 + y^2 \tag{3.1}$$

As the lamp is gradually moved sideways, the background light will start to influence and eventually dominate the signal of the radiance meter. The background signal was found, as described in the former chapter, by shading the direct light to the instrument with a ruler. The magnitude of this signal ranged typically from 3-4% (lamp in center) to 100% (lamp outside field of view). For each value of x the signal or reading should be corrected for the change in distance by multiplying it with the ratio

$$\frac{r(x)^2}{r(0)^2} = \frac{x^2 + y^2}{y^2} \tag{3.2}$$

To each value of x corresponds the angle Θ (Figure 3) given by

$$\tan\theta = \frac{x}{y} \tag{3.3}$$

Beyond a certain value of x or θ the signal drops markedly and becomes identical with the background signal. The experiment may then be terminated.

We have now a set of observations which defines the corrected reading $R(\theta)$ as a function of θ. The effective solid angle Ω_{eff} of the instrument may then be found from the expression

$$\Omega_{eff} = \frac{1}{R(0)}\int_{2\pi} R(\theta)\, d\Omega = \frac{2\pi}{R(0)}\int_0^{\pi/2} R(\theta)\sin\theta\, d\theta \tag{3.4}$$

When this method was applied to the reference meter with the Li-Cor detector, the effective solid angle was found to be $\Omega_{\text{eff}} = 0.0402$ sr. The difference from the geometric estimate above is only 2 %, which corresponds to the accuracy of the readings. This also indicates that the geometric estimate is quite adequate for simple instruments like the reference meter. On the other hand, for more advanced instruments like the marine radiance meter, where the solid angle is defined by a lens and field stops, the mapping method described above, has to be applied.

With the UDT detector in the reference instrument the solid angle was determined by the last method above to be $\Omega_{\text{eff}}=0.0286$ sr.

It may be added that if the irradiance $E_\lambda(\lambda,0)$ received by the instrument when $x=0$ is known, the calibration factor f_a, or the inverse radiance sensitivity of the instrument in air, is readily given by

$$f_a = \frac{L_\lambda(\lambda,0)}{R(0)} = \frac{E_\lambda(\lambda,0)}{\Omega_{eff}\, R(0)} \tag{3.5}$$

3.3. Spectral sensitivity of the reference instrument

When the light source is contained within the field of view of the radiance meter, the instrument acts as an irradiance meter. The spectrum of the standard lamp at the Norwegian Radiation Protection Authority was recorded by means of 16 interference

TABLE 3.1. Irradiance calibration factors for the reference instrument with the UDT and Li-Cor sensors, November 14, 1989.

Peak transmittance of interference filter nm	UDT sensor $mW\ m^{-2}\ nm^{-1}/\mu W$	Li-Cor sensor $mW\ m^{-2}\ nm^{-1}\ /\mu mol\ m^{-2}\ s^{-1}$
352	12.3	
370	9.10	
405	4.74	
406	5.63	
431	4.91	
446	3.33	37.9
472	3.40	35.6
485	2.62	26.9
516	2.98	27.6
555	3.46	28.8
575	2.93	25.4
602	2.78	22.2
613	2.57	19.8
647	3.39	23.9
668	4.30	32.4
690	3.16	120

filters in front of the reference instrument equipped with the UDT sensor. The calibration factors for irradiance, which are the ratios between the spectral irradiances (mW m^{-2} nm^{-1}) and the recorded signals (μW) are presented in Table 3.1. Similar values for the readings with the Li-Cor sensor (μmol m^{-2} s^{-1}) are also shown.

The peak wavelength of the interference filters was found by measurements in a Hitachi Perkin-Elmer spectrophotometer at the Norwegian Institute for Water Research. This instrument calibrates its wavelengths against a line in the spectrum of a deuterium lamp.

The radiance calibration (Table 3.2) is obtained by dividing the two last columns in Table 3.1 with the corresponding solid angles found in Chapter 3.2.

TABLE 3.2. Radiance calibration factors f_a for the reference instrument with the UDT and Li-Cor sensors, based on Table 3.1.

Peak transmittance of interference filter nm	UDT sensor mW m^{-2} nm^{-1} sr^{-1} /μW	Li-Cor sensor mW m^{-2} nm^{-1} sr^{-1} /μmol m^{-2} s^{-1}
352	430	
370	318	
405	166	
406	197	
431	172	
446	116	924
472	119	868
485	91.6	656
516	104	673
555	121	702
575	102	620
602	97.2	541
613	89.9	483
647	119	583
668	150	790
690	110	2930

4. Calibration of the marine radiance and colour index meter

4.1 The ratio between the "expanded" and "normal" scales

The deck and recording unit of the marine instrument presents the radiance signal as a digital value. The upper limit for this value is 1999. In order to expand the range of measurements the recording unit is supplied with two scales: a "normal" and an "expanded" scale.

More than fifty parallel recordings at the two scales show that the same radiance will produce a reading at the normal scale that is 5.61 times higher than the reading at the expanded scale. Thus 1 digital unit at the expanded scale corresponds to a radiance which is 5.61 times higher than the radiance which produces 1 digital unit at the normal scale. The total range of the instrument becomes 1 - 11214 digital normal units.

Unless otherwise stated, all digital units which appear in the text refer to the normal scale.

4.2. Wavelength of the channel's peak sensitivity

The relative spectral sensitivity curves of the different channels in the marine instrument were found by using the double beam monochromator in a Shimadzu spectrophotometer as the light source. One beam was directed towards one of the channels by means of a mirror, while the other beam illuminated the reference instrument. For each wavelength the signals of the two meters were recorded, and since the spectral sensitivity curve of the UDT sensor is fairly flat, the relative spectral sensitivity within each channel of the marine instrument could be calculated. The wavelengths of the spectrophotometer were checked with the interference filters mentioned in Chapter 3.3.

The results are shown in Figure 4. It was difficult to adjust the mirror to obtain maximum response in the different channels, which means that the values of the different curves can not be compared. It is seen, however, that the peak sensitivities lie at 445 nm, 514 nm, and 546 nm respectively, while the band width for all three channels is about 17 nm.

4.3. Linearity of the marine instrument

The linearity of the marine radiance meter was tested against the reference instrument. The latter was provided with an interference filter of the same peak wavelength as in the marine instrument. The two instruments were then directed towards the evening sky and read off while the sun was setting. The result at 514 nm is presented in Figure 5. No significant deviations from linearity can be detected. Similar results were obtained at 445 and 546 nm.

4.4. Solid angle of the marine instrument's field of view

The method of calibration has been described in Chapter 3.2. During the calibration of the marine radiance meter y was 336 cm while x varied between + 50 cm and - 50 cm. The observations at 514 nm are presented in Figure 6. The effective solid angle for all three channels was found to be 0.0206 steradians in air. The effective half opening angle $\Theta_{a,eff}$ in air can be found from

$$\Omega_{a,eff} = 2\pi \int_0^{\theta_{a,eff}} \sin\theta_a \, d\theta_a = 2\pi[1 - \cos\theta_{a,eff}] \tag{4.1}$$

which makes $\Theta_{a,eff}$ equal to 4.64° for the marine meter.

Due to the refraction of the light rays, the marine instrument will receive light from a smaller solid angel $\Omega_{w,eff}$ in water. This angle can be expressed as

$$\Omega_{w,eff} = 2\pi \int_0^{\theta_{w,eff}} \sin\theta_w \, d\theta_w \tag{4.2}$$

where θ_w is the angle between the incident ray in water and the normal to the window of the instrument. The angle in water is related to the corresponding angle in air by Snell's law of refraction

$$\sin\theta_a = n_w \sin\theta_w \tag{4.3}$$

where n_w is the refractive index of sea water. Differentiation of this law gives

$$\cos\theta_a \, d\theta_a = n_w \cos\theta_w \, d\theta_w \tag{4.4}$$

With the last two expressions $\Omega_{w,eff}$ can be written

$$\Omega_{w,eff} = 2\pi \int_0^{\theta_{w,eff}} \sin\theta_w \, d\theta_w = \frac{2\pi}{n_w^2} \int_0^{\theta_{a,eff}} \sin\theta_a \frac{\cos\theta_a}{\cos\theta_w} \, d\theta_a \tag{4.5}$$

Since the ratio between the cosines in this integral is very close to 1, the solid angle in water can be approximated by

$$\Omega_{w,eff} \approx \frac{2\pi}{n_w^2} \int_0^{\theta_{a,eff}} \sin\theta_a \, d\theta_a = \frac{\Omega_{a,eff}}{n_w^2} \tag{4.6}$$

With $n_w = 1.34$, $\Omega_{w,eff}$ becomes 0.0115 steradians. The half opening angle in water is then found to be 3.46°.

4.5. Spectral calibration by means of a standard lamp

In order that the signals should not become too high for the marine radiance meter, the distance from the halogen lamp was chosen as 336 cm. The spectrale irradiance distribution $E_\lambda(\lambda)$ of the lamp at this distance has already been presented for two different lamp currents (Figure 1). The curves show the irradiance values that the marine instrument receives at 445, 514, and 546 nm, respectively. The corresponding values of radiance $L_\lambda(\lambda)$ are given by

$$L_\lambda(\lambda) = \frac{E_\lambda(\lambda)}{\Omega_{a,eff}} \tag{4.7}$$

where $\Omega_{a,eff}$ is the solid angle of the channels in air, equal to 0.0206 steradians according to Chapter 4.4.

The instrument was directed towards the lamp and adjusted to produce the maximum signal, U_{max}. By shading the direct light the background signal U_b was found. The sensitivity S of the channels was then obtained from

$$S = \frac{U_{\max} - U_b}{L_\lambda(\lambda)} \tag{4.8}$$

The sensitivity is given in units of d.u./(μW m^{-2} nm^{-1} sr^{-1}), where d.u. means a recorded digital unit of the radiance meter. However, a more practical quantity may be the calibration factor f_a defined as the inverse value of the sensitivity, which is the factor that the observation should be multiplied with in order to obtain the radiance.

TABLE 4.1. Calibration factor f_a of the marine instrument in air, based on irradiance from a standard lamp.

Date	μW m^{-2} nm^{-1} sr^{-1} / d.u.		
	445 nm	514 nm	546 nm
Oct.21	1.47	1.09	1.00
Oct.31	1.58	1.04	0.94
Nov.2	1.47	1.08	0.96
Nov.15	1.47	1.10	0.97
Nov.15	1.47	1.11	0.98
Nov.15	1.41	1.08	0.95
Mean value	1.48	1.08	0.97
Stand. dev.	0.06	0.02	0.02

The results from the two mentioned series as well as from others are presented in Table 4.1. It is seen that the variation between the series is only a few percent.

4.6. Calibration by comparison with the reference meter

The obvious way to check the calibration of a radiance meter is to direct it towards a diffuse light source together with a reference instrument. If the values agree, we are likely to trust the instruments. However, if they do not agree, the question may become which one of the instruments that should be trusted. Even if the original calibration of the reference meter was correct, the instrument may have changed since the calibration. This possibility increases with increasing time.

In our case the reference meter was calibrated during the same process as that of the marine instrument, so that the time factor may be neglected. Since the reference meter has a sensitivity range more adapted to common light sources, its calibration should perhaps be more reliable.

It is important that the peak sensitivities of the two instruments lie as close as possible, and preferably at the same wavelengths. The interference filters applied with the atmospheric radiance meter have peak transmittances at 446, 516, and 555 nm respectively. The applied diffuse light sources were blue or gray skies and white paper, illuminated by a lamp. The blue sky has the disadvantage that the spectrum shows a pronounced dip at 430 nm and a top at 450 nm (Kondratyev, 1969, p.367).

TABLE 4.2. Calibration factors f_a of the marine radiance meter found by comparison with the reference meter.

Date	Light source	μW m^{-2} nm^{-1} sr^{-1} / d.u.		
		445 nm	514 nm	546 nm
Oct.2	Blue sky	-	1.20	-
Oct.5	Grey sky	-	-	0.92
Oct.8	Blue sky	1.47	1.19	1.15
Oct.8	Blue sky	1.47	1.27	1.05
Oct.20	White paper	1.61	1.18	1.19
Oct.20	White paper	1.67	1.20	1.14
Oct.26	Blue sky	1.43	1.12	0.94
Mean value		1.53	1.19	1.07
Stand. dev.		0.10	0.05	0.11

Mean values of the calibration factor according to different series of measurements are presented in Table 4.2. The mean values are 3-10 % higher than the corresponding ones in Table 4.1, but the variation, expressed by the standard deviation, is also larger .

4.7. Calibration factor in water

The mean values of the results in Tables 4.1 and 4.2 are presented in Table 4.3. The possible error of the mean value is estimated statistically from the standard deviation s and the total number of values N as $s/N^{1/2}$. Systematic and constant errors in the measurements will not be covered by this estimate.

Since the instrument receives the radiance through a flat glass window, a fraction ρ_a of the nadir radiance, given by

$$\rho_a = \left(\frac{n_g - 1}{n_g + 1}\right)^2 \approx 4.0\% \tag{4.9}$$

where $n_g \approx 1.50$ is the refractive index of glass, will be reflected at the glass/air interface.

In water, however, the reflection at the glass/water interface will be reduced to

$$\rho_w = \left(\frac{n_g - n_w}{n_g + n_w}\right)^2 \approx 0.3\% \tag{4.10}$$

At the same time the radiance which passes from water through the glass window to the internal air of the instrument, will be spread out into a larger solid angle and be reduced by the factor $1/n_w^2$, as given by (4.6). The calibration factor f_w of the instrument in water is then

$$f_w = f_a \frac{1 - \rho_a}{1 - \rho_w} n_w^2 = f_a \left(\frac{n_g + n_w}{n_g + 1}\right)^2 n_w \approx f_a\ 1.73 \tag{4.11}$$

The mean values of this factor are presented in Table 4.4.

If the nadir radiance is measured just beneath the surface, we are often more interested in the value that the radiance will obtain after having passed from water to air through the water/air interface. It will then suffer a reflection loss of about 2% (Gordon, 1969, as quoted by Austin, 1974) and be reduced by the factor $1/n_w^2$. We may then apply directly the calibration factor f_{wa}

$$f_{wa} \approx f_w \frac{0.98}{n_w^2} \approx f_a\ 0.94 \tag{4.12}$$

The resulting values are given in Table 4.5.

It has been observed that in clear weather, if the instrument is lowered close to the ship's side in the Oslofjord, the effect of the ship is to reduce the radiance with about 13, 11, and 7%, at 445, 514, and 546 nm, respectively.

Even more serious is the self-shading effect of the instrument. According to Gordon and Ding (1992) the error will mainly depend upon the solar altitude and the product ar, where a is the absorption coefficient of the water and r is the instrument radius. Values of this error for observations in the Oslofjord have been presented elsewhere (Aas and Sørensen, 1994), but as an example it may be mentioned that the average correction of the observed radiance value at 445 nm was about 50 %.

The effects of ship and instrument shadow have not been taken into account in the tables presented in this paper.

TABLE 4.3. Mean calibration factor f_a of the marine radiance meter in air, based on Table 4.1 and 4.2.

	μW m^{-2} nm^{-1} sr^{-1} / d.u.		
	445 nm	514 nm	546 nm
Mean value	1.50	1.14	1.02
Estimated error	0.02	0.02	0.03

TABLE 4.4. Mean calibration factor f_w of the marine radiance meter in water, based on Table 4.3.

	μW m^{-2} nm^{-1} sr^{-1} / d.u.		
	445 nm	514 nm	546 nm
Mean value	2.59	1.97	1.76
Estimated error	0.04	0.03	0.05

TABLE 4.5. Calibration factor f_{wa} for calculating the radiance transmitted to air, from the radiance reading just beneath the surface.

	μW m^{-2} nm^{-1} sr^{-1} / d.u.		
	445 nm	514 nm	546 nm
Mean value	1.41	1.07	0.96
Estimated error	0.02	0.02	0.03

5. Colour index

5.1. Correction of the recorded colour index

In addition to the radiance readings the marine radiance meter also gives direct instantaneous values of the colour index F, due to a small computer in the deck unit. In fact, the main purpose of the instrument has been to measure F. The colour index was originally defined by Jerlov (1974) as the ratio between the blue and green radiances from nadir beneath the surface of the ocean:

$$F_1 = \frac{L(445)}{L(514)} \tag{5.1}$$

The instrument gives a second colour index, defined as

$$F_2 = \frac{L(445)}{L(546)} \tag{5.2}$$

From these indices a third index may be calculated:

$$F_3 = \frac{F_2}{F_1} = \frac{L(514)}{L(546)} \tag{5.3}$$

According to Table 4.4 the observed colour indices should be multiplied with certain correction factors, in order to get the true indices. These factors are given in Table 5.1.

TABLE 5.1. Correction factors for the observed colour indices.

Colour index	F_1	F_2	F_3
Correction factor	1.32	1.47	1.12

5.2. Direct and indirect measurements of the colour index

In a single set of observations of L and F the ratio between the observed radiances will usually differ from the directly observed colour index. The possible error of a radiance observation may become rather large, e.g. more than 50 %, due to wave action, while the error of the direct colour index readings usually is of order 2-10 %.

It may be interesting to see if there is a systematic difference between the two ways of determining the colour index. From 383 observations in the Oslofjord and the Skagerrak the mean value of the difference

$$F_{observed} - F_{calculated}$$

was found to be 0.0055 in digital units. This was only 2 % of the mean value of the colour index, and is less than the power of resolution of 0.01. Thus the actual error in the calculated value of F seems to be distributed at random with zero as its mean value.

Still there is a possibility that the observer may be reading systematically too high or too low values of the radiance, but this can not be detected by the test above.

5.3. Adjustment of radiance by means of colour index

The higher accuracy of the colour index may be utilized to improve the accuracy of the radiance. Let us assume that the observed colour index F is correct, and defined by

$$F = \frac{L_1}{L_2} \tag{5.4}$$

where L_1 and L_2 are the true radiances at wavelengths *1* and *2*.
We may further relate the true radiances to the observed radiances L_{o1} and L_{o2} by

$$L_1 = L_{o1} + \epsilon_1 \tag{5.5}$$

$$L_2 = L_{o2} + \epsilon_2 \tag{5.6}$$

where ϵ_1 and ϵ_2 are correction terms.

The expressions (1), (2), and (3) constitute three equations with the four unknowns L_1, L_2, ϵ_1 and ϵ_2. A fourth equation may be obtained by the method of least squares. By means of (1)-(3) the sum of the squares of the corrections may be written

$$\begin{aligned} \epsilon_1^2 + \epsilon_2^2 &= (L_1 - L_{o1})^2 + (L_2 - L_{o2})^2 \\ &= (FL_2 - L_{o1})^2 + (L_2 - L_{o2})^2 \end{aligned} \tag{5.7}$$

The sum will obtain its minimum value for a certain value of L_2. This is found by differentiating the right part of the expression with regard to L_2 and setting the derivative equal to zero. The result becomes

$$L_2 = L_{o2} \frac{1 + F\dfrac{L_{o1}}{L_{o2}}}{1 + F^2} \tag{5.8}$$

By means of (1) L_1 is then given as

$$L_1 = L_{o1} \frac{1 + \frac{L_{o2}}{L_{o1}F}}{1 + (1/F)^2} \tag{5.9}$$

According to the expressions (5) and (6), the true radiances will be represented by the observed ones when the ratio L_{o1}/L_{o2} is equal to F. When the ratio differs from F, corrections will be added. These corrections can be expressed explicitli by

$$\epsilon_1 = L_{o1} \frac{\frac{L_{o2}}{L_{o1}F} - \frac{1}{F^2}}{1 + \frac{1}{F^2}} \tag{5.10}$$

$$\epsilon_2 = L_{o2} \frac{\frac{L_{o1}F}{L_{o2}} - F^2}{1 + F^2} \tag{5.11}$$

When the radiance is observed at three wavelengths and two colour indices are recorded, similar correction terms may be obtained by the same method.

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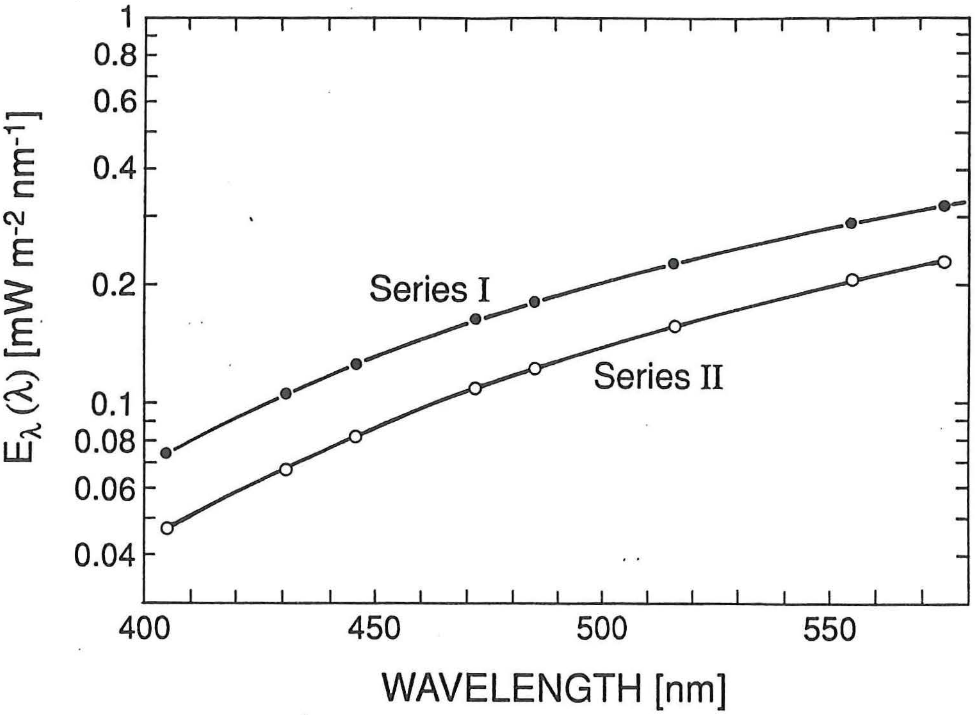

Figure 1. Irradiance distribution of the halogen lamp with two different lamp currents.

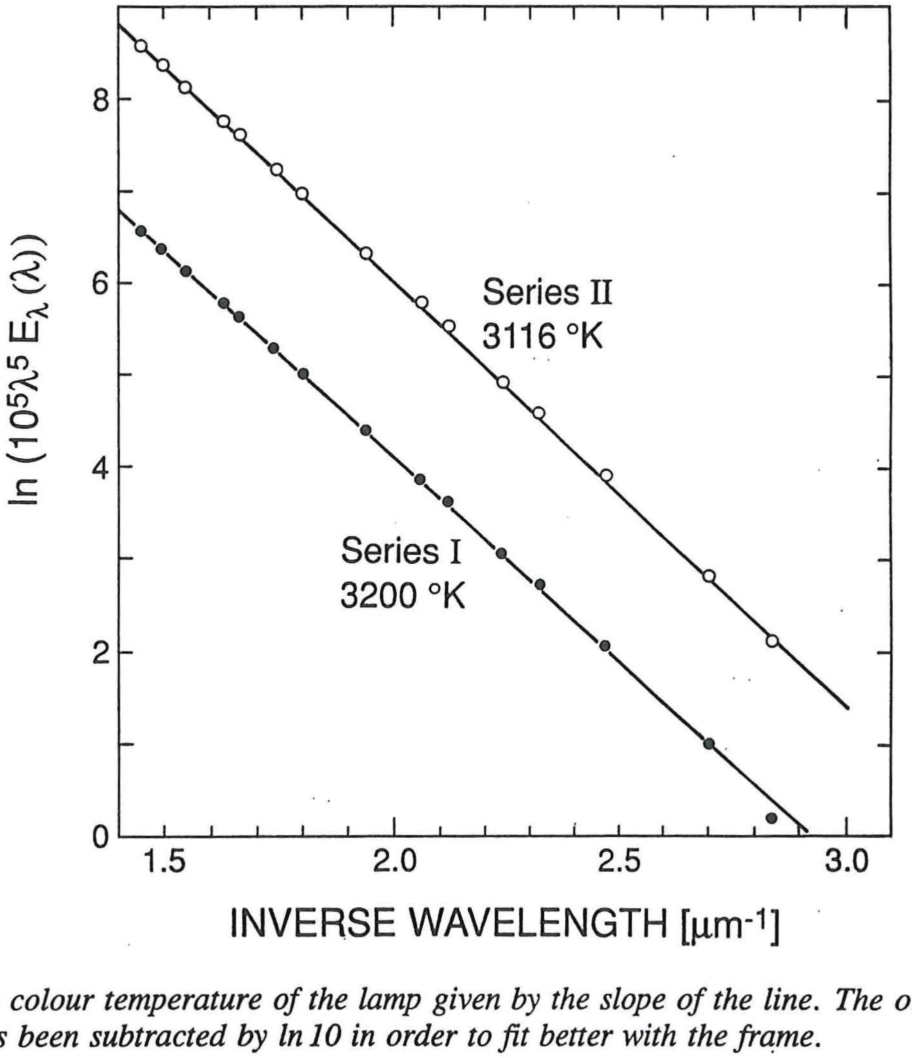

Figure 2. The colour temperature of the lamp given by the slope of the line. The ordinate of Series I has been subtracted by ln 10 in order to fit better with the frame.

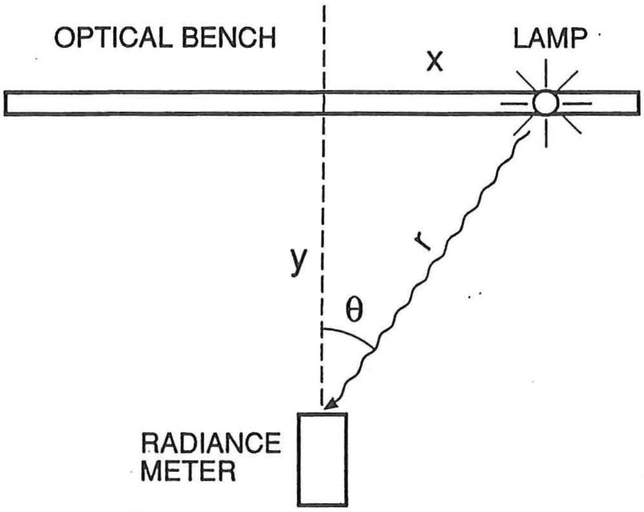

Figure 3. Set-up for the mapping of a radiance meter's field of view.

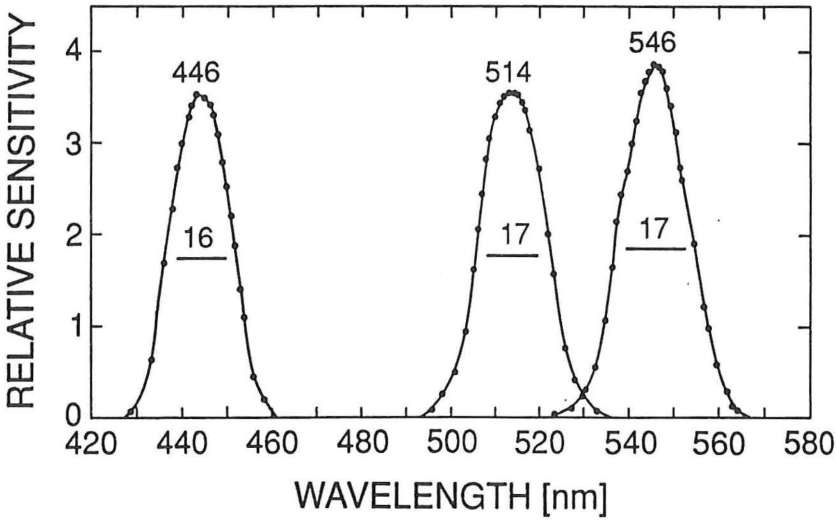

Figure 4. Relative spectral sensitivity of the different channels of the marine instrument.

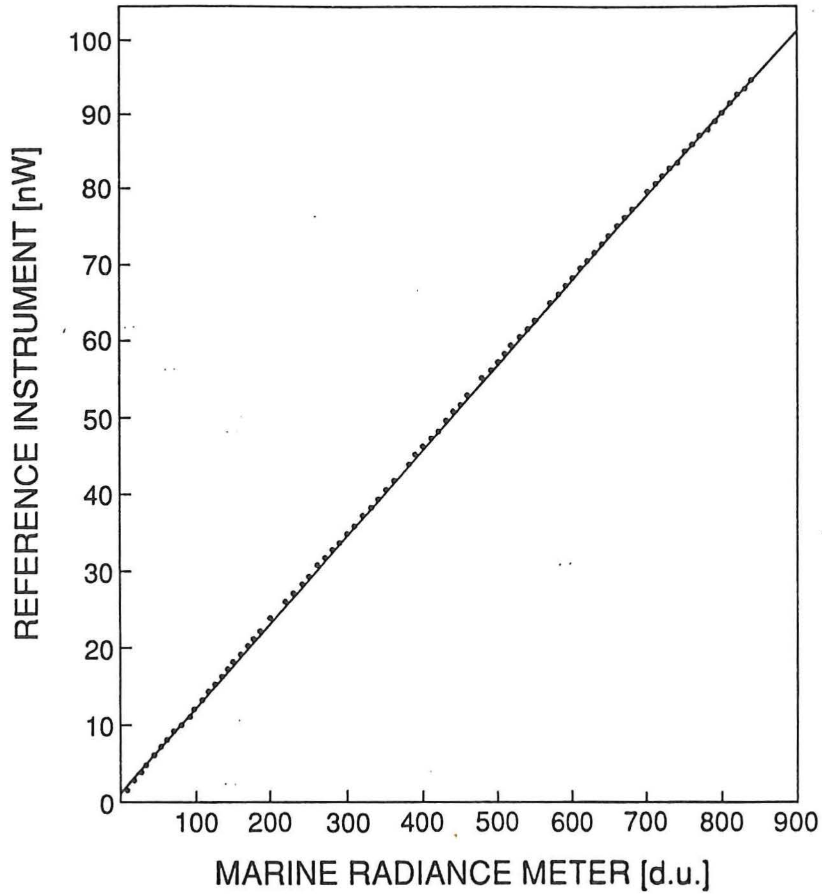

Figure 5. Linearity of the marine instrument at 514 nm tested againts the reference instrument.

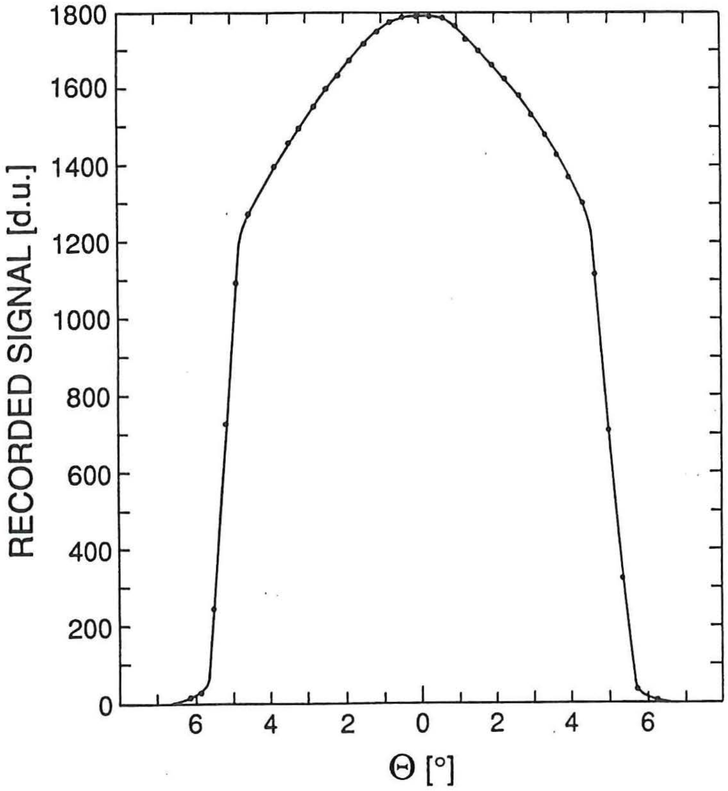

Figure 6. Angular response $R(\theta)$ of the marine instrument.