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Radiation of lamp and optimized experiment using artificial light in the Arctic Ocean

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Abstract A winter optical experiment by an artificial lamp was conducted in the Amundsen Bay of Arctic Ocean from November of 2007 to January of 2008. The radiation field emitted from an artificial lamp was measured and is introduced in this paper, and the optimized experiment project is discussed. It is demonstrated that the minimum size allowed of the lamp is determined by both the field of view (FOV) of optical instrument and the measuring distance from the lamp. Some problems that might influence on the experiment result often occur for a simple fluorescent lamp, such as instability, spatial nonuniformity, light divergence, effect of lamp temperature, etc. By the analysis of the light radiation, three kind of measures are proposed to control the quality of the experiment, i. e. keeping consistency of lamp size with FOV of instrument, calibrating in situ downwind, and conducting measurement in effective range. Among them, the downwind calibration is the key step to overcome most problems arose by the lamp. The experiment indicated that the reliable results can be obtained only when the optical measurement is coordinated with the radiation field of artificial lamp. The measured radiation property of the lamp was used to advise the field experiment to minimize measuring error. As the experiment by artificial lamp was the first attempt in the Arctic Ocean, the experience given by this paper is a valuable reference to the correlative studies.

Key words Arctic, Artificial light experiment, radiation of lamp, optical measurement, field of view.

1 Introduction

In the Arctic Ocean, part of the solar energy arriving at the surface is reflected to the space by snow and ice, part of the energy enters sea ice, and part of it penetrates the ice and propagates into the underlying water. Sea ice is a substance formed by phase transition of sea water and with complicated optical properties. These properties determine how the light propagates in the ice and how the solar energy shifts from light to heat[1,2]. Therefore, the optical study about sea ice is important to understanding the energy balance on the earth[3]. Especially in recent years, the sea ice in the Arctic declines very quick[4], and the increased heat flux from air-ice-sea interface influences the climate seriously[5].

There are two main approaches to study the optical properties of sea ice: experiment in laboratories and field measurement. Laboratory experiments study the inherent optical properties (IOPs) of sea ice for the propagation of artificial light[6], while the field experiments measure the apparent optical properties (AOPs) of ice under the natural light conditions[7]. Laboratory experiments use a narrow collimated light beam, whereas in field experiment, the solar radiation is corresponding to a parallel light beam with infinite width. The difference of light source between the approaches results in incomparability of the parameters. Although the IOPs of sea ice are successfully measured by thin light beam in laboratory, it cannot be extended to the parallel light situation. Vice versa, although the field observation reveals the real propagation of light, it is only the result in certain condition and hard to obtain the general IOPs. Up to now, the two kinds of approaches develop separately to solve their respective issues[3].

Sometimes, any of the two approaches is insufficient. For example, the optical parameters for normally projected light is needed, but in the Arctic, the solar height is very low, and the AOPs for normally projected light cannot be obtained neither by laboratory nor field experiments. Otherwise, the lateral propagation and attenuation of light in the interior of the sea ice is concerned, but in the field situation it is impossible to measure as the lateral light flux through a section is bidirectional, and the lateral attenuation cannot be measured by laboratory beams as well.

Therefore, an experiment in the Arctic with artificial lamp is proposed to solve these issues in this study, which combines the advantages in laboratory experiment by artificial light beam and the field observation for natural sunlight. Firstly, the field experiment measures the real sea ice in its original location and the interior structure of sea ice does not change during the experiment. Secondly, an artificial light with larger area instead of a thin light beam in a lab could be adopted to simulate the natural light. So the artificial light experiment is not only a field experiment, but also one that is analogical to the laboratory experiment.

As the Arctic summer is bright, the artificial light experiment can only be conducted in the nights of spring and autumn, and in the day in wintertime. The experiment can be operated for much more hours in a winter day, however, the field expedition in the winter Arctic is quite rare. A year-round Canadian expedition of the Circumpolar Flaw Leads (CFL) Studies was implemented in the Beaufort Sea and Amundsen Gulf (www.ipy-cfl.ca). The authors of the paper participated the 2007/2008 winter cruises for the artificial light experiment. It is addressed by this study that a successful experiment with artificial light is a result in using a suitable lamp, understanding the property of light field, and adopting an appropriate experimental project. In this paper, the properties of the light field and thereby the optimal experimental project are discussed. As this field experiment using an artificial light in the Arctic is the first attempt, the results in this paper are expected to be valuable to the similar studies in future.

2 Spectrum and light field of a fluorescent lamp

2.1 *Spectrum of the fluorescent lamp*

The spectrum of the lamp must include the main spectral bands of solar radiation, but the spectral radiation intensities of the lamp are not necessary to be consistent with that of solar radiation, as only the attenuation rate is measured during the artificial light experiment. Among various lamps, the spectra of the xenon lamp and fluorescent lamp are close to the solar spectrum only. The light source for the experiment should be as stable, uniform, antijamming, and portable as possible for the in situ use. The xenon lamps with stabilization and uniformity systems are all heavier than 150 kg, being difficult to use in the field experiment on sea ice. The light field of the general xenon lamp is neither stable nor uniform compared to that of the fluorescent lamp. The fluorescent lamp is relatively better in the stability, uniformity, and portability. The spectrum of the fluorescent lamp is not consistent well to the solar spectrum as shown in Figure 1, but the radiation intensities are strong enough for the artificial light experiment. An exception wavelength is at 312 nm, which shows the relative weak radiation in violet bands. So the choice to use the fluorescent lamp as an artificial lamp is suitable.

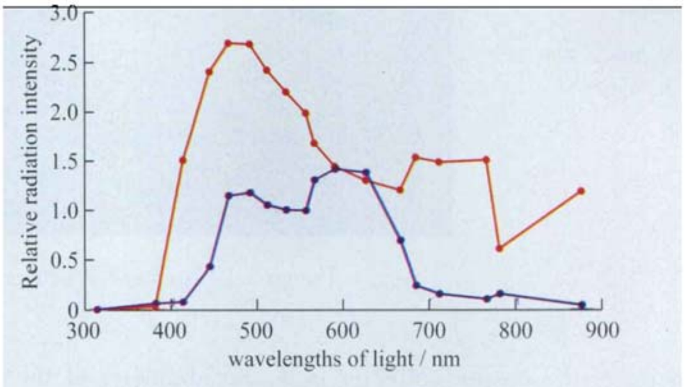


Fig. 1 The comparison between artificial (blue line) and natural (red line) light spectra. The result expressed by red line was measured for sunlight at Amundsen Bay (69°52.301'N, 126°32.541'W) in Nov. 16, 2007. The blue line is a measurement to the lamp.

2.2 *Consistency of the field of view of the instrument with the size of lamp*

The magnitude of the artificial lamp is determined by some factors, such as the field of view (FOV) of the instrument, the maximum thickness to be measured, the marginal effect of the lamp, etc. The larger FOV of instrument and the thicker ice need larger lamp. And the lamp should be large enough to keep the marginal effect off when the instrument is put under the center of the lamp.

Usually the optical instruments for irradiance measurement are with hemispheric FOV to receive the radiation from upper hemisphere, suitable to natural light. In the situation of artificial lamp with limited size of the lamp, the radiation emits only from a small solid angle, so the FOV of instrument should be reduced for reliable measurement. The FOV of the instrument could be adjusted by mounting a foreoptics in front of the instrument[8] as designed and shown in Figure 2, where the black body is the PRR800/810 profiler, and the upper surface of the instrument is a cosine collector. The foreoptics is a sleeve with a small hole, inside which the wall is painted black to avoid the reflection.

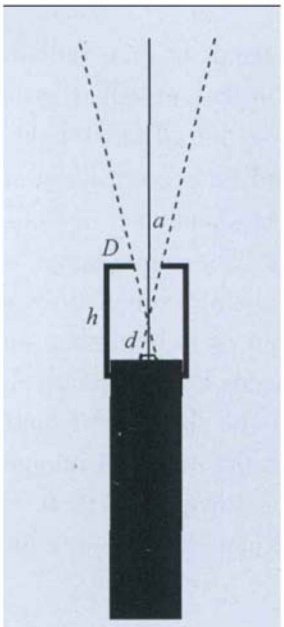


Fig. 2 Sketch of the foreoptics

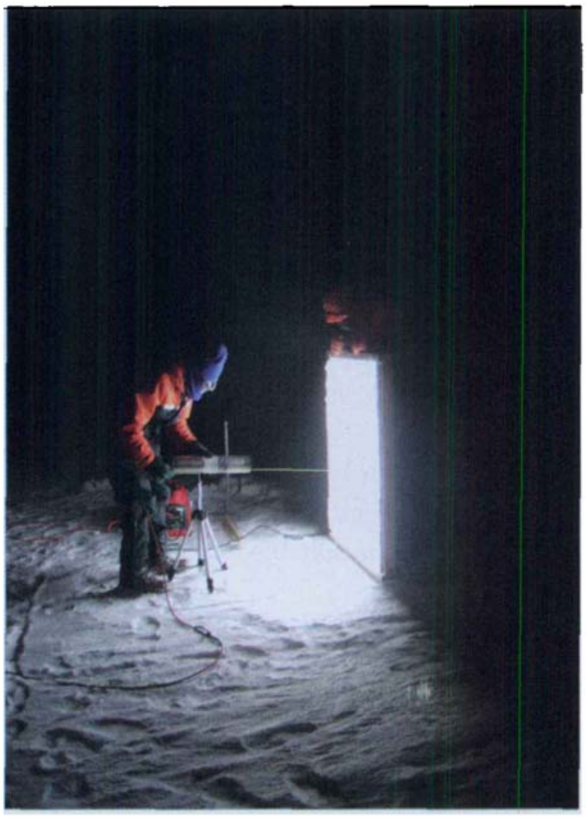


Fig. 3 The artificial lamp and in situ calibration.

Let the diameter of the cosine collector is d, the diameter of the hole of foreoptics is D, and the length of the sleeve is h, then

$$\frac{d/2}{\tan(\alpha)} + \frac{D/2}{\tan(\alpha)} = h \tag{1}$$

Where the half FOV is

$$\alpha = \tan^{-1}\left(\frac{D + d}{2h}\right) \tag{2}$$

If the distance from instrument to the lamp is H, the scale of the light source should be

$$L = \frac{H(D + d) + hD}{h} \tag{3}$$

It shows that the size of the lamp could be smaller for thinner sea ice, smaller hole and longer sleeve. A smaller size of the lamp is more convenient for field observation. Under the condition of a certain maximum thickness of sea ice, the only possible ways to decrease the size of lamp are to reduce the hole diameter and to extend the length of the foreoptics. However, the smaller hole will reduce the arriving optical flux and the measurement accuracy for thicker ice, and the longer sleeve will be more inconvenient to the field observation. Therefore, the design for the foreoptics is a compromise in these factors. For a measurement for 1 m thick ice ($H = 1$ m), taking $d = 2.8$ cm, $h = 10$ cm, $D = 5$ cm, the half FOV will be $21.3°$, and the minimum width of the lamp is 78 cm. In other words, the size of the lamp must be greater than 78 cm for a measurement for 1 m thick ice.

Based on above calculation, ten of the fluorescent lamp tubes of 40 W for low temperature are used to make the lamp with the shining area of 1.30 m by 0.96 m as shown in Figure 3. The weight of the lamp is only 20 kg, convenient for field experiment. The minimum length of the lamp is 0.96 m, and ±9 cm positioning error of the instrument is allowable for the accurate measurement of 1 m thick ice. On the sea ice, the lamp was powered by a power generator for long lasting working in cold environment.

3 Artificial lamp and the test of the light field

3.1 *Stability of radiation intensity of the lamp*

The lamp with stable radiation is benefit to the measurement. Some factors are the source to cause the variation of the radiation intensity, such as the variation of the radiation ability of the fluorescent lamp tubes, the instable radiation in cold condition, and the instability of the power. The temporal variation of the lamp radiation for different spectra under the indoor condition is shown in Figure 4. It is indicated that the radiation intensity experienced three stages of quick enhancing, short equilibrium and slow weakening. The variation of radiation intensity looks good enough to be an experimental light source as the regular variation embodies a dynamic stability, which can be calibrated reliably. But the result obtained under indoor condition is impossible to extend to outdoor conditions of low temperature. Therefore, the radiation intensity is impossible to be forecasted in advance by experienced statistics, and repeated in natural condition. It will be verified that the instability of the light need to be overcome by in situ calibration.

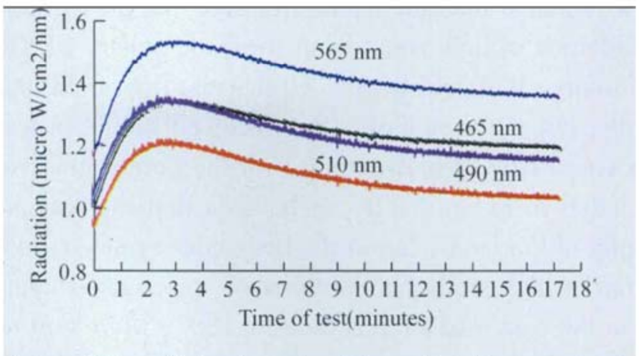


Fig. 4 Temporal variation of the radiation intensity of the artificial lamp under the indoor condition.

3.2 *Uniformity of the light field*

Some steps were adopted to optimize the uniformity of the light field. Firstly, the backboard of the lamp was painted white to enhance the reflection of light emitted form the fluorescent tubes, which made the light field more uniform. Secondly, the front transparent board was made by a kind of small crystal grids with the size of 5 mm, which play a good role to uniform the emitted light. There are some other factors to make the nonuniformity of the light field, including the nonuniformities arose by the lamp structure, the arrangement of the fluorescent tubes, and the brightness of each tube. The measurement reflecting these factors is shown in Figure 5.

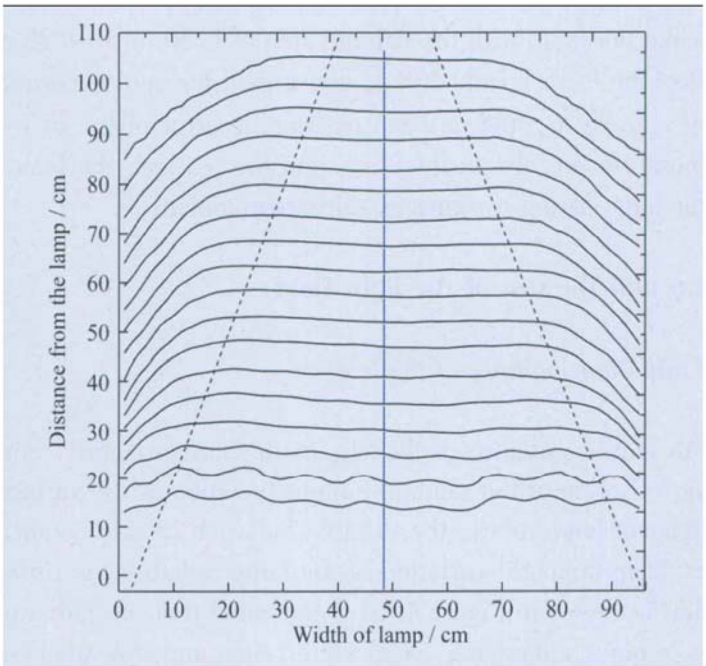


Fig. 5 Radiation nonuniformity of artificial lamp and the effective measuring scope. Light intensity section across the lamp with the normal interval of 5 cm. The amplitudes of the lines express the 50 times´ anomaly of radiation intensity.

(1) Nonuniformity arose by the structure of the lamp

Part of the nonuniformity of the light field is caused by structure of the lamp, which can be detected by a radiance measurement. However, as the radiation light field is concerned rather than radiation of light source, an irradiance meter (PRR800/810) is used to measure the nonuniformity. It should be noticed that the light field measured by PRR800 is not the real light field, but is the radiation flux received by the instrument. Measuring the standing lamp by moving PRR810 horizontally with the normal interval of 0.05 m, the result for 490 nm is plotted in Figure 5. It can be seen that the maximum flux is not at the spot opposite the center of the lamp, but at the both sides symmetrically. It is caused by the side frame of the lamp, which shifts part of the aside propagated light to normal direction. The radiation angle in the center of lamp is close to 180°, while that near both sides is only more than 90° to produce higher energy density. The positions with the maximum irradiance are close to the margins of the lamp when the instrument is near the lamp, but move to the center when the instrument is moved away from the lamp.

(2) Nonuniformity arose by arrangement of fluorescent tubes

The diameter of the fluorescent lamp tube is 4 cm and the distance between tubes is 6 cm, which causes alternate intensity oscillation. The light field has been smoothed by the highly reflecting backboard and the front crystal board, but the oscillation is still obvious when close to the lamp (Figure 5). The nonuniformity becomes unclear when the distance from the lamp is more than 35 cm, which means that it is not necessary to consider this nonuniformity in measurement the ice thicker than 35 cm.

(3) Nonuniformity arose by the brightness of the fluorescent tubes

In making the lamp, the brightness of the fluorescent tube is supposed to be the same. Nevertheless, the differences of fluorescent materials, using times, and voltage added probably produce the difference in radiation intensity, which is also inevitable for a lamp arranged by multiple fluorescent tubes. Both radiation intensity peaks shown in Figure 5 are not equal with the left one being higher, though the distribution of the tubes is symmetric. This difference is speculated to be caused by the radiation difference of the tubes.

(4) Errors arose by the nonuniform radiation

The errors caused by nonuniformities of light field mentioned above are similar and can be analyzed simultaneously. The maximum, minimum, mean, standard deviation, maximum deviation rate of the radiation intensity measurement for 490 nm wavelength are listed in Table 1, where the unit is $\mu W/cm^2/nm$. At the position 1 m away from the lamp, the effective measuring range is about 18 cm (± 9 cm) with the maximum deviation rate of 1.14%. The closer to the lamp, the larger the effective range is. The maximum deviation rate about 3% appears at the positions close to the lamp, which is accurate enough to the in situ experiment. In fact, the deviation rate will be much less than 3% as the instrument was always positioned accurately under the center of the lamp.

Table 1. Error analysis for the nonuniformity of artificial light in the effective measuring scope

Distance from lamp (cm)	maxima	minima	mean	deviation	Maximum deviation rate%
100	1.170	1.157	1.164	0.004	1.14
95	1.173	1.167	1.170	0.002	0.49
90	1.182	1.171	1.174	0.004	1.01
85	1.184	1.179	1.181	0.001	0.38
80	1.193	1.186	1.188	0.002	0.60
75	1.199	1.188	1.191	0.003	0.92
70	1.207	1.196	1.199	0.003	0.94
65	1.215	1.203	1.208	0.004	0.99
60	1.219	1.211	1.214	0.002	0.68
55	1.228	1.214	1.219	0.004	1.19
50	1.236	1.225	1.229	0.003	0.96
45	1.242	1.228	1.234	0.006	1.20
40	1.240	1.226	1.231	0.003	1.11
35	1.247	1.230	1.237	0.006	1.39
30	1.247	1.235	1.242	0.005	1.01
25	1.251	1.229	1.239	0.007	1.80
20	1.263	1.225	1.239	0.012	3.00
15	1.265	1.229	1.244	0.012	2.92

3.3 Divergence of the light field

Attenuation of the light field is usually caused by absorption, scattering and divergence. In the case of natural light, the divergence is not obvious as the sunlight comes from infinite. However for artificial light, the light field weakens with distance, which might be caused by divergence. Using a parallel light might avoid the divergence, but for an area of lamp about 1 square meter it is very difficult to produce the parallel light as the lens will be too big and heavy to carry on the sea ice. The light source without lens system cannot produce parallel beam and the divergence of the light field is inevitable.

The divergence is generated by the increasing radiation area with the distance from the lamp. The divergent light beam can also be used to the optical experiment[9] as long as its divergence is clearly known. The Allard Law[10] in atmosphere expresses the light divergence from a point source, and the radiation intensity is inversely proportional to the square of the distance from the lamp. The spatial distribution of radiation intensity is complex and cannot be describe by a simple function.

In Figure 6, two curves represent both measurements of PRR810 for the radiation variations from the center of the lamp: measurement moved normally from the lamp (red line) and the central values of the across section (blue line). Both curves are well consistent. The radiation intensity deceased when the distance from the lamp increased. As the attenuation of atmosphere to the light is quite weak, the decline of the intensity is mainly arisen by the divergence of the light field. The decrease with distance is not linear, the further the distance is, the stronger the decrease becomes. 9.1% of the radiation was attenuated within distance of 1 m. However, it is not necessary to know clearly the divergence of the light field, as the impact of it can be eliminated by the field calibration, as described latter.

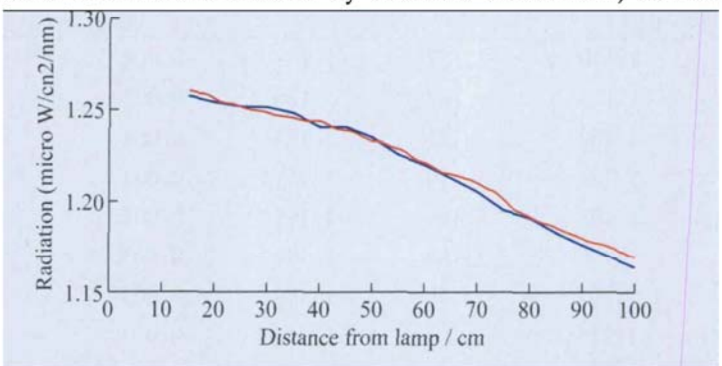


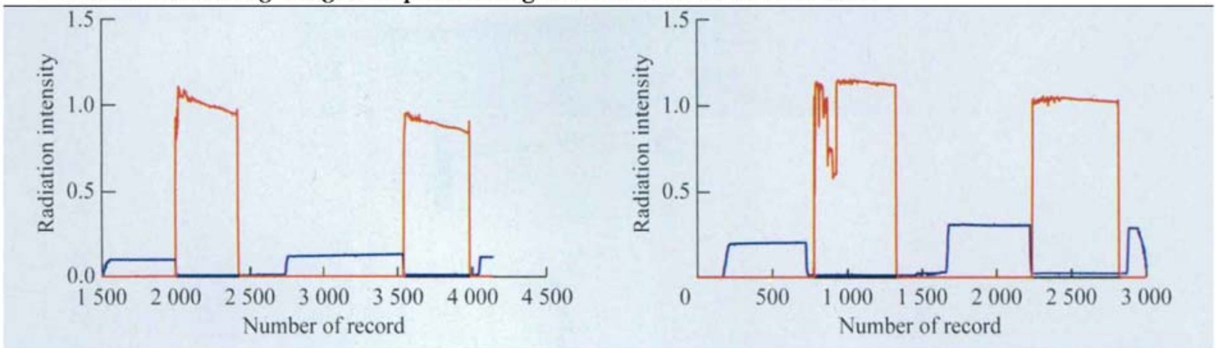
Fig. 6 The experiment result for light divergence from the artificial lamp. The radiation variations in the center of the lamp when the PRR800 was moved normally from the lamp (red line) and across the lamp (blue line).

3.4 Impact of the lamp temperature on the radiation intensity

It was found that the radiation intensity decreased quickly during the calibration measurement as shown by the red line in Figure 7a. This phenomenon was not understood, until once it was no change when calibration was conducted leeward (or downwind, with the back of the lamp facing the wind) (Figure 7b), showing that the cooling during the calibration induced the intensity variation. Since then, the calibration is always conducted leeward to get good measurement result in frequent stormy and low temperature conditions.

3.5 Weakening near the margin of lamp and effective measurement range

For the flat lamp, the radiation intensity at the area close to the margin will decrease by the loss of scattering and imbalance of the radiation, which is called "margin effect". For given boundary conditions and lamp parameters, the margin effect could be simulated by resolving the Maxwell Equation. It can also be measured by a radiance instrument. But the best way is to measure in an area being not influenced by margin effect, which is called "effective measuring range" as shown by the two dashed diagonal lines in Figure 5. The effective measuring range becomes smaller as the distance from the lamp increases. In fact it is not necessary to know the margin effect thoroughly. What needed to be known is only the effective measuring range for positioning the underwater instrument.



(a) (b)

Fig. 7 the impact of lamp's temperature on the radiation intensity. Calibration results at (a) upwind and (b) downwind conditions for both surface (red line) and underwater (blue line) instruments.

4 Quality control of the measurement by artificial lamp

Effective approaches are necessary to overcome the shortcomings of the lamp as introduced above and to ensure the reliability of the measurement. The most important approach is so called field calibration.

4.1 Field calibration

If a light source keeps the stable radiation intensity in any environmental condition, the radiation distribution could be measured in a laboratory, which is called the laboratory calibration. However, as stated in section 3 the radiation intensity is varied irregularly, and thus the field calibration is necessary. Field calibration is to measure the irradiance in air at the same distance with the under ice measurement before or after field measurement. It means that the field measurement is to measure the radiation flux penetrating the ice (Figure 8a), whereas the field calibration is to measure the radiation flux penetrating the air with the same thickness (Figure 8b).

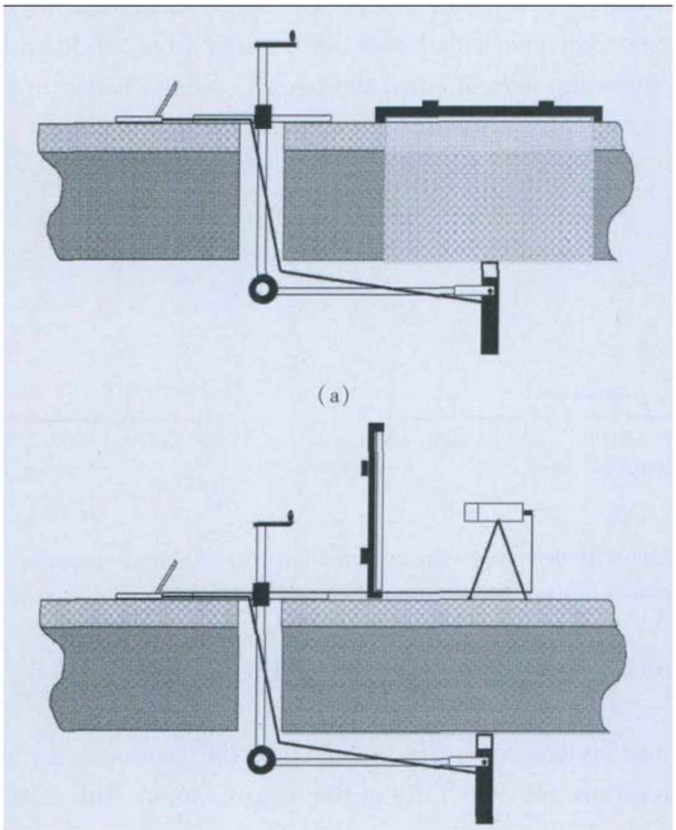
The field calibration can solve the following problems:

(1) Radiation instability. Even though the radiation intensity is instable and oscillates slowly, the instability can be offset if the field calibration can be conducted just before or after the measurement.

(2) Divergence of light. Even though the radiation intensity is divergent, the field calibration could offset the effect of divergence, as the divergence of light in the same distance is consistent.

(3) Also, as the spatial positions for both measurement and calibration are equal, the spatial nonuniformity of the lamp can be solved by field calibration.

Therefore, the field calibration overcomes the problems arose by instability of light source and the spatial nonuniformity of radiation intensity to ensure the quality of measurement.



(b)

Fig. 8 sketch for field measurement and calibration. (a) measure under sea ice; (b) calibration in air.

4.2 *Accurate positioning the instrument*

During the measurement for transparence of sea ice, the instrument under sea ice cannot be seen, and the only indicator is the mark on the sticks emerged above the ice, which always brings error to the measurement. In the experiment, the position of the under-water instrument is determined accurately by both ways: accurately indicating the orientation of stick and distance from margin of the lamp. Thus, the instrument is under the center of the lamp within effective range, as ±9 cm positioning error is allowed for 1 meter thick ice.

4.3 *Total error arose by the light field structure*

As discussed above, the way to control the measurement quality is to minimize the error arose by various factors. Table 2 lists the possible error sources, the method to improve them, and the error level. The approaches adopted are cataloged into three types: (1) the matching of the size of the lamp and the FOV of the instrument; (2) field leeward calibration; (3) measuring in effective range. If these error sources are effectively controlled, the maximum error can be controlled less than 3%, which satisfies the measurement.

Table 2. Quality control of measurement for an artificial lamp

	Error source	Approach for quality control	Maximum error
1	Spectrum difference of artificial light source	No error for measuring the attenuation rate	0
2	Size of the lamp and the FOV of the instrument	Sufficient large lamp for a smaller FOV of instrument	0
3	Temporal variation of radiation of the light source	Field calibration	0
4	Spatial nonuniformity of the lamp	Keep measurement and calibration positions are consistent	<3%
5	Divergence of the light field	Field calibration	0
6	Impact of the temperature of the lamp on radiation intensity	Field leeward calibration	0
7	Impact from the marginal effect	Measuring in effective range	0

Besides the errors arose by measurement, there will be errors during the data analysis, which is not discussed in this paper.

5 Results and discussions

A winter optical experiment by an artificial lamp was conducted in the Amundsen Bay of the Arctic Ocean from November of 2007 to January of 2008 by a Canadian icebreaker, Amundsen. The radiation field emitted from the artificial lamp is measured and introduced in this paper. It is demonstrated that a successful field experiment with artificial lamp is a result by using a suitable light source, better understanding the property of the light field, and making a correct experimental project. In this study, the property of radiation intensity and the possible errors are analyzed to direct the field experiment.

The in situ artificial light experiment is a field experiment, but analogous to a laboratory experiment. In order convenience the field task, the size of the lamp should be as small as possible. It is demonstrated that the minimum size of the lamp is determined by both the field of view (FOV) of optical instrument and the measuring distance from the lamp. The FOV of the instrument could be reduced by a foreoptics mounted in front of the instrument.

Some problems that might influence on the experiment often occur in the case of simple fluorescent lamps, such as instability, spatial nonuniformity, light divergence, effect of lamp temperature, etc. By the analysis about the light radiation, three measures are proposed to control the quality of the experiment, i. e. keeping consistency of lamp with FOV of instrument, leeward calibrating in situ, and measuring in an effective range. Among them, the leeward calibration is the key step to overcome most problems arose by the lamp.

The experiment indicated that the reliable results can be obtained only when the optical measurement is coordinated with the radiation field of artificial lamp. The measured radiation feature of the lamp was used to advise the field test to minimize measuring error. As the experiment by artificial lamp was the first attempt in Arctic Ocean, the experience given by this paper is a valuable reference to the correlative studies in future.

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