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| IALA Guideline |

FRAGMENTARY DRAFT

Marine signal lights

Calculation of Luminous intensity and range

Edition x.x

Document date

Revisions to this IALA document are to be noted in the table prior to the issue of a revised document.

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| Date | Page / Section Revised | Requirement for Revision |
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# Acronyms

# Aims

The aim of this guideline is to give information about the calculations necessary to derive the luminous intensity of an AtoN light from the navigational requirements.

# Introduction

A suitable luminous intensity is one of the basic features of a light. The intensity should be high enough to ensure that the light is visible for navigation as required. It should not be too bright to avoid glare.

Normally the operating expense is strongly influenced by the luminous intensity. A 10-cd-light can be realized by a cheap and small lantern immediately available from stock of a manufacturer. A sector light of about 1 000 000 cd will require a special design and will be produced for a single position.

# Physical basics

## Luminous intensity

The brightness of the light emitted by a signal lantern is expressed with the luminous intensity . The unit is Candela (cd [1]). ‘Luminous intensity‘ and ‘luminous range’ are abbreviated to ‘intensity’ and ‘range’ in some chapters of this guideline.

## Illuminance

The brightness of the light seen by a distant observer is expressed with the illuminance . The unit is Lux (lx [1]).

## Meteorological visibility

The light emitted is attenuated by absorption and scattering in the atmosphere. This attenuation is specified by the ‘meteorological visibility’. Its unit is metres or nautical miles (1 852 metres = 1 nautical mile).

Although meteorological visibility is described by a distance or length, its value does not represent a range to determine the useful distance of a light or a daymark.

There are other ways to describe the attenuation of the atmosphere. These are shown in the Annex.

## Allard’s law

Allard’s law allows the calculation of the illuminance as a function of distance, luminous intensity and the meteorological visibility.

Equation 1 Allard’s law

Where:

is the illuminance at the eye of the observer

is the luminous intensity

is the distance between the light and the observer

is the meteorological visibility (), see IALA dictionary



Figure 1 Quantities for Allard’s law

## Luminous intensity calculations

Rearranging Equation 1 gives an equation to calculate the luminous intensity of a marine signal light.

Equation 2 Luminous intensity calculation

### Minimum luminous intensity

The calculation of the required luminous intensity of a marine signal light is based on the input of

* the maximum distance the light will be used,
* the required illuminance at the eye of the observer
* and a minimum value for the meteorological visibility .

The luminous intensity calculated will be the minimum required luminous intensity .

Equation 3 Minimum luminous intensity

Whereas the maximum distance varies with each light and its position to the waterway, there are values recommended for the illuminance and the meteorological visibility.

### Maximum luminous intensity

At a short distance a light may appear very bright and it may even cause glare. To avoid this, a maximum luminous intensity should be defined. This can be calculated by Allard’s law and

* the minimum distance the light will be used,
* the maximum acceptable illuminance at the eye of the observer to avoid glare
* and a maximum value for the meteorological visibilty .

Equation 4 Maximum luminous intensity

### Design intensity

The calculation of the minimum and maximum luminous intensity normally gives an interval the real intensity should be between:

In many cases the interval is very large . To reduce the expense for a light it is recommended to link the intended luminous intensity during design procedure of a light to the minimum value . However there should be some safety factor between the minimum intensity and the design intensity . It is recommended to choose this factor to 1,5x.

Equation 5 Design luminous intensity

In a few cases the calculated minimum may become larger than the maximum . In that case it has to be decided whether glare at a near position of the observer is accepted or the intensity may be reduced.

# Key values

Beside the maximum and minimum distance the light will be used as an Aid to Navigation, the intensity calculations requires input values for maximum and minimum illuminance and meteorological visibility.

## Minimum illuminance at the observer’s eye

For many years marine signal lights were designed for situations without any additional disturbing lights. The situation has changed and additional lights, interfering with the signal light, have to be considered. The influence of additional lights can be divided in two different aspects.

* background illumination (smooth halo of light produced by scattered light)
* rival lights (appearing as point lights, directly emitted to the observer)



background illumination

rival

lights

leading line

buoys

Figure 2 Marine signal lights, background illumination and rival lights

The influence of background illumination is covered by adjusting the minimum illuminance at the eye of the observer.

Rival lights are treated in this document at a later step (See Chapter 6).

The minimum illuminance at the eye of the observer depends on the background illumination found at the position of the light. Traditionally the values in Table 1 are used to define the minimum illuminance.

Table 1 Minimum illuminance at the eye of the observer

|  |  |  |
| --- | --- | --- |
| Background | Relevant lights |  |
| Lights for nighttime use |  |  |
| - no background illumination | all lights except leading lights |  |
| - no background illumination | leading lights |  |
| - minor background illumination (how do we handle leading lights?) | all lights |  |
| - substantial background illumination  (how do we handle leading lights?) | all lights |  |
| Lights for daytime use | all lights |  |

Although it is still acceptable to use the table, there are two aspects, which may require a more detailed investigation.

* The definition of the background is not based on physical quantities and cannot be measured. It is only based on the estimation of an observer (mariner).
* The ratio between the different values for the illuminance is 10 and therefore the minimum luminous intensity may increase by a factor 10 or 100, when it is assumed to have background illumination. This may lead to very intense and expensive lights. This can be solved by introducing intermediate steps.

A formula for the calculation of the required illuminance as a function of the background luminance has already been used for many years. Its main purpose was for daytime lights only. However the values of the formula fit very well to the existing values from Table 1, so it can be interpreted as an interpolation of these values.

Equation 6 as a function background luminance

Where:

is the background illuminance near the light in

Remark:

There is a difference about 20% when the value is calculated from Equation 6 with or drawn from Table 1. It is suggested that with no background illumination the value (Table 1) is used and if background illumination is considered and can be measured () Equation 6.

Measuring background illuminance:

The background luminance can be measured with a luminance meter. A luminance meter has an ocular where the object to be measured is marked by a circular reticle. The luminance of the surface inside the reticle is measured.



reticle

leading line

halo

Figure 3 Measuring background luminance

Measurement procedure should take into account that

* the meteorological visibility has a medium value of 4 to 10 M during measurement,
* the measuring field (reticle) should be placed nearby the signal light,
* the measuring field (reticle) should not contain rival lights (point lights),
* the measuring field (reticle) should be illuminated uniformly
* the measurement distance should be near the minimum distance .

## Maximum illuminance at the eye of the observer

The maximum illuminance is defined in Table 2 with two values depending on background illumination.

Table 2 Maximum illuminance at the eye of observer

|  |  |
| --- | --- |
| background illumination |  |
| * none | 0.01 |
| * present | 0.1 |

When a background illumination is relevant for the minimum illuminance the value should be used, and only when there is no background illumination.

## Minimum meteorological visibility

The nominal range of a light is defined for a meteorological visibility of 10 nautical miles (18 520 m). However, in many regions this visibility does not occur for a long period, so the light may be not visible at maximum distance.

To improve the visual performance of a light, it is recommended to define a minimum visibility for the intensity calculations, which is lower than 10 M.

On the other hand, it is not suitable to design a signal light for fog situations, except for very short range lights to mark obstacles (fog lights, range ≈ 200 - 400 metres).

To achieve both aspects, the minimum meteorological visibility for luminous intensity calculation should be in the interval .

Equation 7 Recommended values for minimum meteorological visibility

The value used for intensity calculations may be linked to the category for the availability of an AtoN (IALA Recommendation O-130). For example an authority may use for lights of CAT1 and for CAT3.

However the availability objective of more or equal than 97% will not be achieved due to atmospheric visibility conditions.

*At this step we could fix some recommended values for .*

*Example:*

*for CAT 1*

*for CAT 2*

*for CAT 3*

## Maximum meteorological visibility

The maximum visibility is used to estimate glare from a near position. In a ‘worst case scenario’ this calculation should be done for a very good meteorological visibility.

is the preferred value for this purpose.

Some administrations use ‘infinity’ instead (). In this case Allard’s law cannot be used, but .

# Rival lights

With the calculation described in chapter 4 and 5, an intensity for the marine signal light is determined. However there may be other lights (rival lights) in the vicinity of the marine signal light, showing the same or a higher intensity.

This may influence the recognisability of the marine signal light.

Rival lights may be:

* illumination of ports, roads and buildings,
* navigation lights on vessels,
* aeronautical lights,
* road traffic lights,
* other marine signal lights.

## Illumination of areas, roads and buildings

These lights should have a light cone (luminous intensity distribution) which covers the illuminated surface only. When done properly, there will be no direct light into the direction of the waterway. Only scattered light should be visible, which is added to the background illumination (halo).

However, in many situation there will be some direct light pointing into the direction of the waterway and interfering with a marine signal light (Figure 4).



Figure 4 A rival light

In that case the operator of the illumination equipment should be contacted and measures should be taken to remove the direct light.

This can be done either by rotating the lantern to move the light cone away from the waterway or by introducing cut-off-screens (Figure 5).



Figure 5 Using a cut-off-screen to remove direct light

## Navigation lights on vessels

The navigation lights on vessels are defined by IMO COLREGs, Rule 22 and Annex I [2]. In many situations navigation lights (on a vessel) and marine signal lights (light house, beacon, buoy) may be easily distinguished by the flash characters, as navigation lights normally are steady burning lights and signal lights are flashing.

However, this is not always true and therefore it makes sense to look at the intensities of the navigation lights and harmonize them with the signal lights.

The top light of a navigation light is the most intense light on a vessel and its luminous intensity is linked to the length of a vessel.

Table 3 Luminous intensity of navigation lights on vessels

|  |  |  |
| --- | --- | --- |
| length of a vessel | luminous intensity (white, top) | luminous intensity (green, red) |
| L < 12 m | approx. 4.3 cd | 0.9 cd |
| 12 m ≤ L < 50 m | 12 - 52 cd | 4.3 cd |
| L ≥ 50 m | approx. 94 cd | 12 cd |

Remark: IMO does not use the IALA definition on nominal range.

To compete with navigation lights, there should be a minimum luminous intensity defined for a marine signal light.

It is recommended that the luminous intensity of a marine signal light should not be less than the minimum value given in Table 4. For example, when a minimum intensity for a lighted buoy is calculated, the value should be replaced with .

Table 4 Minimum luminous intensity of a marine signal light

|  |  |
| --- | --- |
| Type of light | minimum luminous intensity |
| Lights on a buoy | 5 cd |
| Beacon / Light house | 10 cd |
| Leading Light | 50 cd |

## Other signal lights

Aeronautical lights, road traffic signal lights and other marine signal lights may cause confusion with the signal light, the calculations are done for.

If it is not possible to remove direct light, which is going to the waterway, the intensity of the marine signal light may be increased beyond the design intensity (chapter 4.5.3).

An example is shown in Figure 6. The marine light is a sector light with three sectors. The coloured area shows the positions the sector light is used by the mariners. Next to the marine light there is a high intensity aeronautical light.

To ensure that the marine signal light will compete with the aeronautical light, the illuminance of the marine light should be at least the same as for the aeronautical light. The calculation should be done with Allard’s law with the minimum visibility chosen in chapter 5.3. and some relevant positions.



Figure 6 Intensity check for a rival aeronautical light

In the example the observer is on a vessel in the white sector. The distance to the sector light is (marine light) and to the aeronautical light is (rival light).

The illuminance at the eye of the observer produced by the marine light at minimum visibility is:

.

The illuminance at the eye of the observer produced by the aeronautical light at minimum visibility is:

.

The illuminance produced by the marine light should be equal or greater than the illuminance of the aeronautical light:

.

This gives the inequation:

.

Rearranging the formula gives a minimum value for the luminous intensity of the marine signal light.

Equation 8 Inequation for the intensity of a marine light considering a rival light

.

The luminous intensity of the rival light has to be reported by the operator.

Some typical values are given in the

Table 5 Intensity of road traffic and aeronautical signal lights at night

|  |  |  |  |
| --- | --- | --- | --- |
| Purpose | Type | Luminous intensity | Characteristics |
| Aeronautical obstacle lights [3] | Low-intensity, Type A, red, fixed | 10 cd | omnidirectional |
| Low-intensity, Type B, red, fixed | 30 cd | omnidirectional |
| Medium intensity, Type A, white, flashing | 2000 cd | omnidirectional |
| Medium intensity, Type B,  red, flashing | 2000 cd | omnidirectional |
| Road traffic lights [4] | Green, Red, Yellow | 25 - 200 cd | pencil beam |

# PHOTOMETRIC LUMINOUS INTENSITY

The luminous intensity calculated in the chapters above is an intensity, which should be guaranteed, when the light is in operation. It is called in-situ-intensity in this chapter.

Usually, it is not the luminous intensity, which is measured in a light laboratory.

Two aspects have to be considered.

* A service condition factor   
  This factor includes the degradation of the luminous intensity caused by the aging of the light source, and dirt or salting of the lanterns.  
  The service condition factor is used for the minimum intensity values only. The maximum intensity is estimated for a ‘worst-cas-scenario’ (avoid glare) and therefore it should estimated that the lantern was not aged and has the full intensity.  
  For many years IALA proposed to assume that the intensity reduction should be taken as 25% of the measured value in a laboratory ().
* The flash characters  
  Many lights are measured with fixed light and operated with different flashes. As the apparent intensity depends on the flash character, it has to be calculated from the variation in time of the luminous intensity.

The measured luminous intensity of a signal light is now called photometric luminous intensity . It may vary with the horizontal and vertical angle and with time .

## Horizontal and vertiCal Intensity distributions

The description of an angular intensity distribution may be done with several coordinate systems, which are directly linked to the goniometer used for measuring.

The most suitable system is described in the CIE Publications No 43 (goniometer type A) and No 70 (goniometer type 1). The angle is used to describe the distribution in a horizontal plane (when , Figure 7) and the vertical distribution (Figure 8).



Figure 7 Geometry for horizontal luminous intensity distribution



Figure 8 Geometry for vertical luminous intensity distribution

The main advantage of this geometry is that for each horizontal angle a vertical intensity distribution exists and cuts the horizontal plane for .

## Specification of a luminous intensity distribution

### Horizontal distribution

The horizontal luminous intensity distribution depends on the sector the light is used. An example is shown in Figure 9. A light should be visible over a horizontal sector of size and is used in a distance from to . The aim is then to get values for the minimum and maximum photometric luminous intensity distribution. These values can then be measured in a light laboratory for a specific lantern to proof that it fulfils the requirements for the marine signal light (Figure 9).



Figure 9 Nautical requirements and horizontal luminous intensity distribution

Remark:

The signal light in the example above is not a sector light, which shows well defined sectors. So the light radiated outside the horizontal angle is accepted as long as it does not cause glare (maximum intensity). For a sector light this may not be true.

### Vertical distribution

The required vertical intensity distribution depends on the maximum and minimum observer height ( , ), the mean tidal range at the minimum distance .



Figure 10 Nautical requirements and vertical luminous intensity distribution

The minimum value is calculated by:

Equation 9 Minimum vertical divergence angle (general case)

.

In many cases the calculated angle is very small (<2°) and may be hard to adjust in practice. As for the intensity it is advised to have a safety factor 1.5x.

Equation 10 Minimum vertical divergence angle (for small angles <2°)

.

The minimum vertical angle can be used in different ways.

* For a projector sector light, the intensity distribution is nearly a rectangle (Figure 11). The vertical angle is then chosen as the angle range, where the intensity is equal or higher than the minimum intensity.



Figure 11 Minimum vertical angle for a projector sector light

* For other lights it may be sufficient to choose the as the minimum value for ‘full width half maximum (FWHM)’ or ‘full width tenth maximum (FWTM)’ of the vertical intensity distribution.



Figure 12 Vertical intensity with the angles FWHM and FWTM

## Measured intensity

The measured intensity is given by the functions below.

Steady burning light:

Flashing light :

## Steady burning lights

For steady burning lights the in-situ-intensity can be calculated from the nominal photometric intensity with:

Equation 11 in-situ-intensity, steady burning lights, design values

Equation 12 In-situ-intensity, steady burning lights, minimum values

(with intensity reduction)

As stated before the maximum value for the intensity is based on a ‘worst-case-scenario’, which assumes that the lantern is new. Therefore the service condition factor is not included or taken as ‘1’.

Equation 13 In-situ-intensity, steady burning lights, maximum values

(without intensity reduction)

## fast Switching lights

For a fast switching light the flash profile has a rectangular shape. For example, a flashing light shows two flashes (1) and (2) with different size (Figure 13).



Figure 13 Rectangular flash shape

The length of the shortest flash in seconds is used to calculate the apparent intensity and then the in-situ-intensity of the light (the formula uses a time constant ).

Equation 14 In-situ-intensity, fast switching light, minimum values

Equation 15 In-situ-intensity, fast switching light, maximum values

## Arbitrary Flash Profile

*HOW DO WE HANDLE THAT?*

*THE AIM IS DO GET A LUMINOUS INTENSITY WHICH CAN BE USED TO DESCRIBE A LIGHT BEFORE IT IS AVAIABLE!*

## Calculation of the required photometric luminous intensity

In most cases a single value for the intensity (nominal value) shown a horizontal sector is derived from the measurement.

This should be the minimum value measured in the horizontal range and for .

Steady burning light:

Flashing light:

# Obstructions and geographical range

*Height of the light:*

*mention the geographical range and check for obstructions*

# Standard Design Methodology

The standard procedure to derive the required luminous intensity or intensity distribution from the nautical requirements is shown in this chapter.

When a light has sectors with different distances and , it may be useful to repeat the calculations for each sector.

When the differences between the sectors are not too large, the calculation may be done with the largest value of and the lowest for .

## Step 1

Find the nautical requirements of light, which are described by

* the colour,
* the flash (minimum flash duration is ),
* the minimum distance ,
* the maximum distance ,
* the sector (described by angles and )

## Step 2

Fix the essential parameters for calculation.

* minimum illuminance at the eye of the observer
* maximum illuminance at the eye of the observer
* minimum meteorological visibilty

## Step 3

Calculate the in-situ-intensity with Allard’s law.

* with

## Step 4

If necessary adjust the calculated minimum value according to chapter 6.2 and Table 4.

## Step 5

Check for rival lights. If rival lights have to be considered, calculate a new minimum intensity according to chapter 6.3 and Equation 8.

## Step 6

Calculate the photometric intensity.

### Steady burning light

with .

### Fast switching light (rectangular flash profile, LED)

with and .

### Lights with arbitrary flash profile

HOW DO WE HANDLE THAT?

## Step 7 (Optional)

Calculate the required vertical divergence with the tools in chapter 7.2.2.

## Step 8 (Optional)

Calculate the minimum height of the light considering the geographical range and obstructions between the light and the observer.

## Finish

Add information about the horizontal sector the light is used for.

* minimum photometric intensity
* maximum photometric intensity
* design photometric intensity
* required vertical divergence (optional)
* minimum height of the light (optional)

# Examples FOR INTENSITY CALCULATIONS

WE COULD PROVIDE 5 EXAMPLES HERE.

## Example 1

## Example 2

## Example 3

## Example 4

## Example 5

# LUMINOUS RANGE CALCULATION

The calculations described above have the aim to determine the photometric luminous intensity of a light from the required viewing distances .

Range calculation is just the opposite way .

viewing distance

parameters

background illumination

rival lights

luminous intensity

in-situ / photometric

intensity calculation

measured luminous

intensity

Parameters

Flash profile

parametric range

nominal range

range calculation

Figure 14 Intensity versus range calculation

1. Alternative Presentations of Allard’s Law

All calculations are based on Allard’s law. It calculates the illuminance of a signal light at the observer’s eye depending on the meteorological visibility and the distance between the light and the observer.

However very different presentations of this law are published. To avoid errors these different presentations are shown in the following sections.

The preferred version nowadays should use SI-units (International System of Units).

* 1. Physical presentation

A physical presentation of Allard’s law is given in Equation 22.

Equation 23 Allard’s Law, physical presentation

Where:

*E(d)* Illuminance at the eye of the observer

*I* Luminous intensity of the light

*z* exponential factor describing atmospheric absorption and scattering (extiction)

*d* distance between light and observer

In practice, there are alternative ways of characterizing the prevailing atmosphere as follows.

* 1. Allard’s lay using atmospheric transmissivity T

Atmospheric transmissivity (T) is defined as the ratio of the luminous flux transmitted by the atmosphere over a unit distance to the luminous flux which would be transmitted along the same path in a vacuum.

Equation 24 Transmissivity (luminous flux)

Where:

T atmospheric transmissivity (dimensionless)

luminous flux at the unit distance after passing through the atmosphere

theoretical luminous flux at the unit distance after passing through a vacuum

unit distance

Because the ratio of the luminous fluxes in Equation 23 is the same as the ratio of the corresponding illuminance values, Equation 23 can be rewritten as

Equation 25 Transmissivity (illuminance)

Where:

illuminance at the unit distance after passing through the atmosphere

theoretical illuminance at the unit distance after passing through a vacuum

Inserting expressions for and from Equation 22 into Equation 24, and noting that for , Equation 24 becomes

Equation 26 Transmissivity and exponential factor

Combining Equation 22 and Equation 25 yields

Equation 27 Allard’s law using transmissivity

* 1. Allard's law using the transmissivity TM for 1 nautical mile

The unit distance for transmissivity is chosen to be one nautical mile. Expressed in all metric units equation 5 takes the form

Equation 28 Allard's law using the transmissivity TM for 1 nautical mile

Where:

*E(d)* illuminance at distance d in metres

*I* luminous intensity in candela

*TM* atmospheric transmissivity [dimensionless] for 1 nautical mile

*d* distance in metres

*dU* unit distance that corresponds to the transmissivity [here: 1852 m]

In older publications the distance *d* is expressed in nautical miles. Using the fact that one nautical mile equals 1852 metres and suppressing the unit distance in the exponent Equation 27 can be written as

Equation 29

Where d is the distance in nautical miles.

Simplifying and suppressing all units yields

Equation 30 Allard’s law using nautical miles for the distance

Where:

*E(d)*  illuminance at the eye of the observer in lm/m2 [lx]

*I* luminous intensity of the light [cd]

*TM* transmissivity for one nautical mile of the atmosphere

*d* numerical value of the distance in nautical miles

* 1. Meteorological Visibility

The meteorological visibility is an alternative way to describe the extinction of the atmosphere, which in the development above is quantitatively characterised by the atmospheric transmissivity.

Meteorological visibility is the greatest distance at which a black object of suitable dimensions can be seen and recognized by day against the horizon sky, or, in the case of night observations, could be seen and recognized if the general illumination were raised to daylight level.

By definition the relationship between the meteorological visibility (*V*) and the transmissivity *TM* is

Equation 31 Meteorological visibility

Where:

*V* meteorological visibility in nautical miles

*TM* transmissivity [dimensionless] for one nautical mile

*dU* unit distance of 1 nautical mile

*ln* natural logarithm

Suppressing the unit distance yields:

Equation 32 Meteorological visibility in nautical miles

* 1. Allard’s Law based on Meteorological Visibility

It is recommended in the IALA dictionary that the atmospheric extinction be described by using meteorological visibility V rather than the transmissivity TM.

Allard's law can be expressed using meteorological visibility V by combining Equation 27 and Equation 30.

Equation 33 Allard’s law using meteorological visibility

Where:

*E(d)*  illuminance at the eye of the observer [lx]

*I* luminous intensity of the light [cd]

*d* distance in metres [m]

*V* meteorological visibility in metres [m]

In older publications the distance *d* and the visibility *V* are expressed in nautical miles. Equation 32 then becomes

Equation 34 Allard’s law using meteorological visibility and nautical miles

Where:

*E(d)* illuminance at the eye of the observer [lx]

*I* luminous intensity of the light [cd]

*d* distance in nautical miles

*V* meteorological visibility in nautical miles

the units (not shown) associated with (3.43×106) are m2/M2

The required intensity of a light is calculated from the range with

The calculation of luminous range and the required intensity is based on Allard’s law.

Keep the background information of E-200 part 2.

Further information for the required illuminance depending on the background luminance.

Can we use equation 13 of E-200 part 2 for calculations of the required illuminance at night?

Give information on rival lights.

Give information on a suitable minimum visibility for intensity calculations.

2 to 5 M

1. References
2. CIE 18.2 The Basis of Physical Photometry ( International Commission on Illumination, 1983)
3. Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs), International Maritime Organization
4. Convention on International Civil Aviation, Annex 14, Aerodromes, Volume 1, Aerodrome Design and Operations
5. ISO 16508:1999 / CIE S 006.1/E-1998 Road Traffic Lights - Photometric Properties of 200 mm Roundel Signals
6. CIE Publication No 43 Photometry of Floodlights
7. CIE Publication No 70 The Measurement of Absolute Intensity Distributions