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| IALA Guideline |

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The Measurement of Marine Lights Performance

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# Introduction

This guideline concerns both photometric and colorimetric measurement of marine signal lights and supports IALA Recommendation *R0203 Definitions of Marine Signal Lights Terms of Measurements* [1]. The main body provides further explanations, diagrams and examples to the recommendations given in R0203. They will cover the measurements as well as both processing and presentation of results. These sections are intended for measurement operators with some experience.

An appendix contains further information including both introductory topics, aimed at those newer to light measurement, and more detailed topics to assist readers in obtaining accurate and precise measurements. However, it is unfeasible for a single document to transfer all knowledge and skills required. It is recommended that measurement personnel complete dedicated training courses and read additional material.

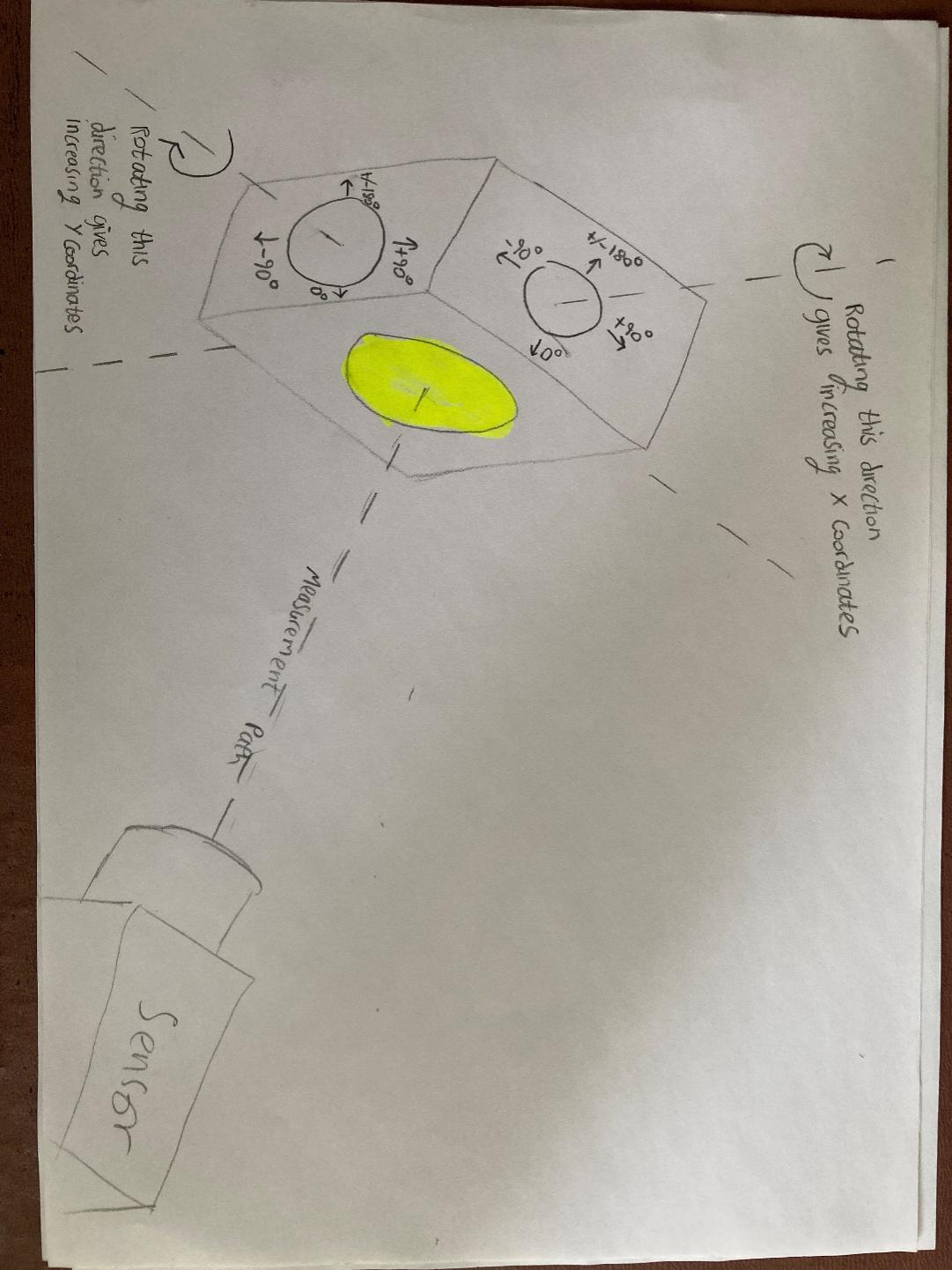
Most of the AtoN light measurement are carried out in the laboratory, where the measurement is more precise than that in the field, so this guideline mainly introduces the laboratory measurement. For the measurement in field, different states may use different methods and APPENDIX 1, Section 6 provides three methods based on different technological approaches.

# Standard measurement conditions

## measurement geometry

In testing, the marine light is referred to as the device under test (DUT). Many individual photometric, spectroradiometric or colourimetric measurements are taken at various positions. During the measurement process, a goniometer is used for producing and measuring the required angular rotation of the DUT. A corresponding coordinate system is used to identify the position of these rotations. R0203 recommends an X-Y coordinate system. This system, illustrated in Figure 1, has the following characteristics:

* The coordinates at the datum position are X = 0° and Y = 0°.
* The X coordinate is the rotation of the DUT about a vertical axis.
* Rotating the DUT clockwise increases the value of X up to a maximum of 180°.
* Rotating the DUT anticlockwise decreases the value of X down to a minimum of -180°.
* The X angle is often referred to as the “horizontal” or “azimuth” angle since the rotation occurs in the horizontal plane.
* The Y coordinate is the rotation of the DUT about a horizontal axis that is perpendicular to the measurement path. Viewing with the measurement sensor to the right of the DUT as in Figure 1:
* Rotating the DUT clockwise increases the value of Y up to a maximum of 180°.
* Rotating the DUT anticlockwise decreases the value of Y down to a minimum of -180°.
* The Y angle is often referred to as the “vertical” or “elevation” angle since the rotation occurs in the vertical plane.
* The axis of rotation and measurement path should intersect. The centre of the DUT should be positioned at this intersection.



1. X-Y Coordinate System

## Ambient conditions

Ambient conditions for indoor measurements should be maintained at a relative humidity of 10 % to 65%. The ambient temperature should be stabilized at 25.0 °C with a tolerance interval of:

* ±1.2 °C for LEDs
* ±3.0 °C for other types of light source.

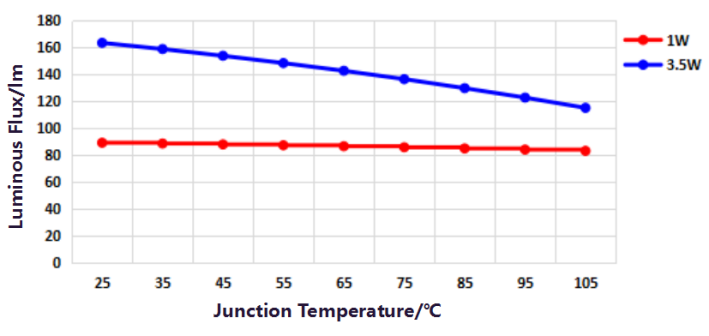
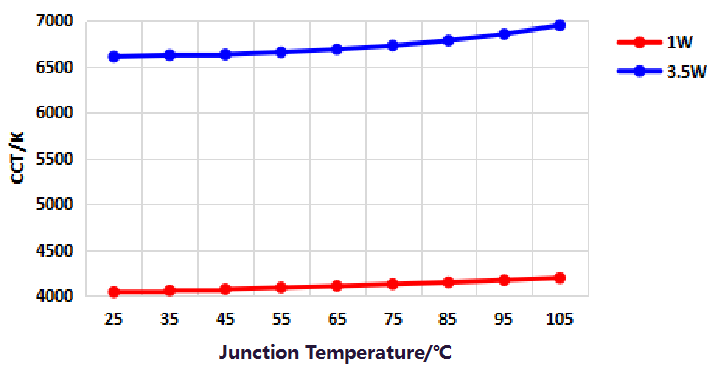
Measurements should be made in still air with a tolerance interval of 0 m/s to 0.25 m/s.

Minimise interference such as smoke, dust, water vapor, mechanical vibration, electromagnetic and light that affect the test accuracy. The laboratory should be a dark room environment with stray light and reflections minimised. Reflections, such as from walls, baffles and other test equipment may be minimised using matte black fabric or paint.

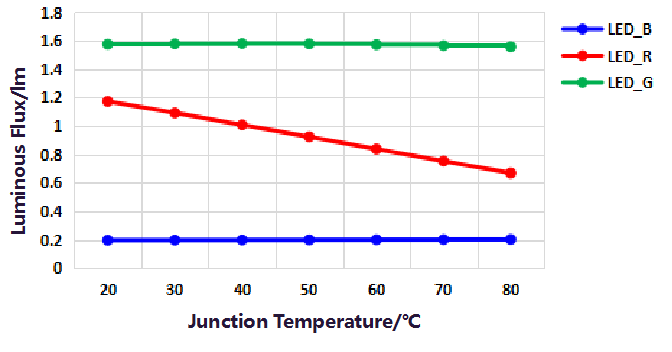
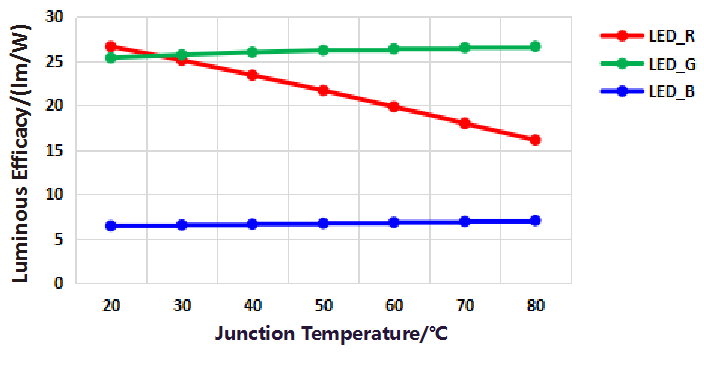
If the above temperature conditions cannot be met, it is recommended to use a correction factor to adjust the results to the standard ambient temperature. The correction factor may be determined from the LED datasheet or experimentally

Figure 2 and Figure 3 provide examples of luminous flux versus LED junction temperature performance curves from an LED datasheet. These are provided as examples and should not be used. Marine AtoN light manufacturers may sometimes provide these for the LEDs used. Where this is not possible, an average of the curves from various LED manufacturers may be used.

The LED junction temperature is not usually known. As such, it must be assumed that the change in luminous flux is linear with temperature and that the junction temperature varies directly with the ambient temperature. Any two points, separated by the same temperature difference as the measurement and standard temperature, can then be selected and the relative luminous flux used to determine the correction factor. These assumptions will introduce errors which should be accounted for in the uncertainty budget (to be covered in an upcoming guideline).

1. Example of luminous flux and CCT variations with temperature of white LED with different power

1. Example of photometric variations with temperature of monochrome LED

Experimental determination is possible if the laboratory can control the ambient temperature for certain measurements but not the suite of measurements required in R0203. For example, the laboratory may be able to measure the total luminous flux in a temperature controlled integrating sphere. In this case, a measurement of this property is taken at both 25° and the temperature at which the test was conducted. The ratio between these measurements can then be used to correct the suite of measurement results in R0203.

The correction factor is determined as shown in Equation 1.

1. Temperature Correction Factor

Where:

is the temperature correction factor

is the total luminous flux at 25° (lumens)

is the total luminous flux at the measurement temperature (lumens)

Similarly, a correction factor can be applied to convert results to service conditions. In this case, to comply with R0203, the results for 25° should also be reported.

In the case of outdoor measurements, the temperature and relative humidity should be noted at the time of the measurement. Any significant changes in ambient conditions during the measurement should be recorded.

## POWER SUPPLY CONDITIONS

For measurements involving equipment powered by a DC power supply, the output voltage and/or current should be maintained within ± 0.2% or better. Ripple voltage should not exceed 0.4% of the DC output voltage.

For measurements involving equipment powered by an external AC power supply, the output RMS voltage or current should be maintained within ± 0.4%. If the rated value is within a range, the median value shall be taken. The AC power supply should have a specified frequency sinusoidal voltage waveform. The RMS summation of the harmonic components, caused by departures from a true sinusoidal waveform, should not exceed 3% of the RMS value of the fundamental frequency. Readjustment of the output voltage may be required during measurements if adequate stabilization is not achieved.

The test voltage should be measured at the supply terminals of the DUT, not at the output terminals of power supply, to avoid errors due to voltage drop by the cables and connectors.

# Measurement preparation

## Mounting

The DUT should be installed on the goniometer and the detector positioned and aligned as necessary. These steps are described below and the resulting setup is illustrated in Figure 4.

The DUT should be positioned on the rotating workbench such that its reference centre (see APPENDIX 1 Section 2.1.) coincides with the X axis of the workbench.

Where possible, the height of the goniometer table should be adjusted so that the reference centre of the DUT is aligned with the Y of the goniometer. If this is not possible, due to the design of the goniometer table, then errors in measurement distance and height caused by tilting the table should be corrected or included in the uncertainty budget.

The DUT should be aligned such that its datum faces the measurement device. This datum should be identified on the perimeter of the DUT to clearly define a direction in the horizontal plane. This may be a manufacturer’s mark or one made by the testing laboratory. Where no datum mark is present, a uniquely identifiable feature of the DUT, for example a cable gland or photocell, may be used for the purpose of a datum. In all cases, the measurement report should note what the datum was.

The centre of the detector aperture should lie along the line normal to the reference centre of the DUT. The alignment process and its associated uncertainty should be part of the documented laboratory procedure. Since the angle of incidence is always close to zero, there is no need to carry out cosine correction.



1. Mounting diagram

Where:

1 is the rotating workbench of goniophotometer.

2 is the photometric centre of the DUT.

3 is the DUT.

4 is the baffle.

5 is the detector.

Some AtoN lights have multiple light-emitting areas with significant separation between. This large separation may mean it is not possible to comply with the requirement for measurement distance given in Section 3.4. In this case, the light should be measured in several steps with each light-emitting area centred accordingly.

In some cases, the exact photometric centre can be unknown and require extensive measurements to determine, which can vary with wavelength or angle. In such cases, a more practical DUT reference centre, based on the device geometry and the size, shape and position of the light source within the DUT, can be used (APPENDIX 1 Section 2.1.)

## Settings

The settings of the DUT should be configured as appropriate for the purpose and type of measurement. For intensity versus time measurements, the flash character and intensity of the light might be set to represent an intended application or to some benchmark as a general quality check. For intensity versus angle measurements, it is often convenient (to increase measurement speed) or necessary (because of measurement system capability) to set the light to a fixed character.

To avoid overheating, some lights will/must be set to output a reduced intensity when set to a fixed character. This will cause the intensity values to differ between angular and temporal results. To avoid confusion, the cause of this difference should be noted with the results. Section 4.2, contains an optional normalisation method useful to avoid confusion related to this intensity difference.

## Warm-up

All measurement equipment requiring electrical power should be switched on and allowed to warm up in accordance with the manufacturers’ operating instructions or calibration certificates before commencement of any tests or measurements. In the absence of such guidance, the measurement facility should evaluate the performance of measurement equipment to determine the required warm up period to prevent drift for each piece of equipment.

Before measurement, the measured AtoN light shall be run at the power supply condition in Section 2.3 and at the specified character for a sufficient time to ensure stability. The detector is used to continuously monitor the output of the measured AtoN luminaire, which can be determined as stable when the following conditions are met:

The light output is measured every 5 minutes. After three consecutive measurements, if the relative difference of the maximum and minimum readings of light output is less than 0.5% of the last reading.

When the DUT is switched to a different light character or colour for subsequent measurement, the stability should be judged again according to the above condition before measurement. Record the stabilization time for each measurement.

Some AtoN lights may automatically reduce their power to avoid overheating. This may not occur instantaneously but after some time due to increasing temperature of the light. Care should be taken to ensure appropriate settings and warm up time to produce a stable output.

## Measurement distance

Before commencing a measurement, the minimum measurement distance of the DUT should be estimated. Provided the measuring distance is relatively large compared to the size of the light source (greater than fifteen times as a rule of thumb), this method is simple and accurate for unfocused light sources. However, when measuring light beam projection apparatus, such as a light source and lens or mirror system, much greater measuring distances are required to ensure an error free result when using this method.

The minimum measurement distance can be determined by measuring the luminous intensity at several different distances from the DUT, always on the same radial coordinate, and assessing the distance beyond which the resultant measured intensity is consistent [28].

For example, when the AtoN luminaire is in the steady light state, the initial distance between the photometer and the AtoN luminaire is 20 times the diameter of the lens of the measured AtoN luminaire. Then, move the photometer so that the relative distance between the photometer and the reference centre of the AtoN luminaire increases by 1 m each time, and measure the luminous intensity accordingly until that the relative difference of the maximum and minimum readings is less than 0.5% of the last reading within three consecutive measurements. In practice this will be restricted to small sealed beacons, whose component parts are not measurable.

For ball shaped light sources in a parabolic mirror, which may be used for old search lights, in cases where the sizes of optical components are known, the determination of minimum measurement distance involves calculating the crossover distance. John W. T. Walsh described a method for determining crossover distance in his book on Photometry[8], as follows:

1. Crossover Distance

Where:

*d* is the crossover distance (m);

*f* is the focal length of optical system (m);

*R* is the radius of the optic aperture (m);

*r* is the radius of the light source (m).



1. Crossover Distance

An approximation of crossover distance can be obtained by the formula:

1. Crossover Distance – approximation 1

The approximation only holds good for an optical lens system with a collection angle of approximately 63°. If the collection angle is markedly different, the full formula, as prescribed by Walsh, should be used.

Equation 2 is good for circular optical apparatus with a spherical light source but when the optical system is larger in one dimension than another; for example, a rectangular lens with a cylindrical light source, the vertical and horizontal crossover distance will be different. In this case, the formula can be expressed as follows:

1. Crossover Distance – approximation 2

Where:

*d* is the crossover distance (m);

*f* is the focal length of the optical system (m);

*H* is the height of the optic aperture (m);

*h* is the height of the light source (m).

1. Crossover Distance – approximation 3

Where:

*d* is the crossover distance (m);

*f* is the focal length of the optical system (m);

*H* is the width of the optic aperture (m);

*h* is the width of the light source.

Both the crossover distances of height and width should be calculated and the greater of the two used. For an omnidirectional beacon, only the vertical crossover is relevant, therefore only Equation 3 is relevant.

For a precision sector projector, the crossover distance may be expressed as follows [27]:

1. Crossover Distance – Precision Sector Projector

Where:

d is the crossover distance (m);

R is the radius of the optic aperture (m);

*α* is the requested angular resolution (radian).

**The minimum measurement distance may be taken as twice the calculated crossover distance.**

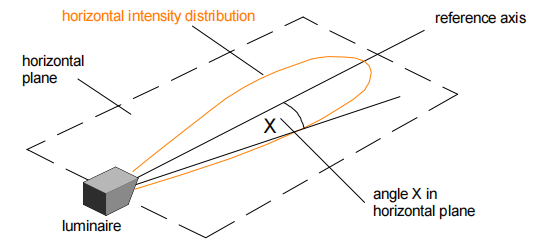
If the minimum measurement distance exceeds the length of the measurement light path, measurement should be made using of the two methods described in APPENDIX 1 1.3 and APPENDIX 1 1.4.

# Measurement of marine signal lights

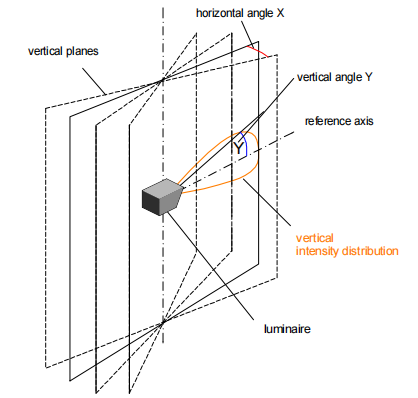
## Luminous intensity versus angle

### general

The measurement of luminous intensity versus angle is usually carried out by using a goniophotometer. According to the measurement geometry described in Section 2.1, for marine signal lights, the preferred angles on which the luminous intensity depends are named X/Y. With the use of X and Y, there is only one horizontal plane (Figure 6) and for each angle X in this horizontal plane there is a vertical plane (Figure 7). The reference axis may be chosen arbitrarily, but it is recommended to put it in the horizontal plane and for pencil beam light in or near the direction with maximum intensity and it should lie at the junction of vertical and horizontal planes. All angles should be referenced to this axis. X is in the range of -180° to +180° and for Y it is -90° to +90°.



1. Horizontal angle X



1. Vertical angle Y

With the goniophotometer, the luminous intensity distribution *I=I(X, Y)* is measured.

For omnidirectional light, the goniometer of the goniophotometer should take rotating scanning at an angle interval of no more than 0.1° on the vertical plane and no more than 1° on the horizontal plane.

For directional and rotating beacons and sector light, the goniometer should take rotating scanning at an angle interval of no more than 0.1° on the vertical plane and no more than 0.1° on the horizontal plane.

For AtoN lights array based which is composed of multiple light-emitting areas, the luminaire should be measured in several steps with each light-emitting area centred accordingly. The result of the angular dependence of the luminous intensity of each light-emitting area are added to obtain the luminous intensity distribution of the entire AtoN light.

Results of the angular dependence of the luminous intensity should be graphically presented to clearly illustrate the performance of the lantern. Graphs should be linear and annotated to identify causes of irregularities in the intensity measurements, such as shadowing due to filament supports, effects of lens seams, etc. If possible, try to give detailed data in tabular form , such as giving the table of luminous intensity versus angle.

### Vertical Divergence

IALA Recommendation *R0203* gives the following definition:

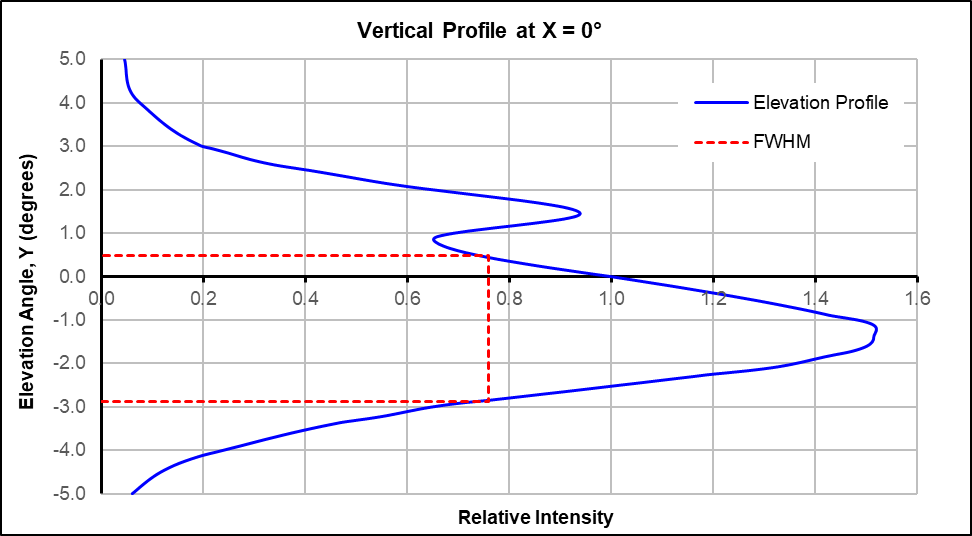
“The average of all measured Full Width Half Maximum (FWHM) values shall be reported as the vertical divergence, along with the maximum deviation of the maximum intensity from an elevation of Y = 0°.”

These parameters are calculated from a light’s luminous intensity versus elevation angle profiles. An example profile plot, annotated with the FWHM, is shown in Figure 8.

Example results for an omnidirectional light are shown in Table 1. In this example three elevation profiles are summarised, each taken at a different azimuth coordinate. The second row of results (X = 0°) corresponds to the profile shown in Figure 2; these should be compared to aid understanding.

The FWHM is the angle between the points where the plot crosses 50 % of the peak intensity. It is possible that the intensity of the plot drops below 50 % of the peak and then rises above, giving multiple crossing points. In this situation, the innermost angle on each side of the peak is used.

Table 1 shows the angle at which the maximum intensity occurs in each vertical profile. From these, the angle with the greatest magnitude (positive or negative) is presented as the maximum deviation of the maximum intensity from an elevation of Y = 0°.



1. Example luminous intensity versus Vertical Profile
2. Example Vertical Profile Summary

|  |  |  |
| --- | --- | --- |
| Azimuth Measurement Angle (X) | FHWM | Angle of Maximum Intensity. |
| -120° | 2.95° | -0.45° |
| 0° | 3.30° | -1.20° |
| 120° | 3.05° | 0.15° |
|  |  |  |
| Vertical Divergence | 3.10° |  |
| Maximum deviation from 0° |  | -1.20° |

The angular range of each measurement should be chosen based on the beam shape and the intended application. For example, over the required viewing range of the light or until the intensity drops to a low value. In Figure 8 the intensity is plotted down to approximately 3 % of the maximum.

The minimum number and location of vertical profiles to measure for different AtoN lights are as follows:

* For an omnidirectional light: measure in three vertical planes. These should be equispaced and include the datum vertical plane, i.e. with horizontal angle X = -120°, X =0°, X = +120°.
* For a sector light: for each sector, measure as given below.
  + For sectors ≤120°, measure one vertical plane in the centre of that sector.
  + For sectors >120° and ≤240°, measure in two vertical planes equispaced in that sector.
  + For sectors >240°, measure in three vertical planes equispaced in that sector.
* For a directional light: measure in the datum vertical plane, i.e. with X = 0°.
* For a rotating light: measure one vertical plane in each individual beam. Measure at the point where the peak intensity of that beam lies on the horizontal profile.

In all cases, additional vertical profiles may be necessary to investigate any irregularities in the horizontal profile.

The profile in Figure 8 has been normalised to the intensity at datum (X = 0°, Y = 0°). This normalisation is optional, and each and the testing organisation may choose whether to present absolute or normalised intensity values and what to normalise to. If normalising, all beams should be normalised to a common value as this allows for meaningful comparison between them.

### Horizontal Divergence

IALA Recommendation *R0203* gives the following definition:

“The Full Width Half Maximum (FWHM) values as measured along the horizontal plane shall be reported as the horizontal divergence. If the intensity does not fall to half maximum at any point around the light, then the horizontal divergence is 360°.”

These parameters are calculated from a light’s luminous intensity versus horizontal angle profile. An example profile plot, annotated with the FWHM, is shown in Figure 9.

The FWHM is the angle between the points where the plot crosses 50 % of the peak intensity. It is possible that the intensity of the plot drops below 50 % of the peak and then rises above, giving multiple crossing points. In this situation, the innermost angle on each side of the peak is used.



1. Example Luminous Intensity Versus Horizontal Profile

**The angle range of plotting the profiles for different AtoN lights are as follows:**

* For an omnidirectional light, a graph of the horizontal profile should be plotted over ±180º from the vertical reference plane or datum.
* For a sector light, graphs of the horizontal profiles should be plotted over the Sector Width.
* For a directional light, a graph of the horizontal profile should be plotted over at least the intended arc of utilization of the sector or to the points where the intensity falls below 1% of the maximum, whichever is the greater.
* For a rotating light, a graph of the horizontal profile should be plotted between the points where the intensity falls below 1% of the maximum. For rotating beacons with more than one emitted light beam, the results of all beams should be shown.

### Specification Peak Intensity

IALA Recommendation *R0203* gives the following definition:

“**Omnidirectional light:** the intensity is defined as the 10th percentile of the intensity measured around the entire light at an elevation of Y=0°.”

“**Directional light without a required boundary:** the intensity at the optical centroid axis of the light”

“**Sector intensity:** the intensity is defined as the 10th percentile of the intensity measured within the Sector Width at an elevation of Y=0°.”

“**Rotating optic:** This is the peak intensity of the individual beams when the optic is not rotating.”

From the above definition, the specification peak intensity can be calculated from the horizontal luminous intensity versus angle profile. The specification peak intensity is used to scale the effective intensity, this is discussed in Section 4.2.3.1

## Luminous INTENSITY versus time

### Measurement of Luminous Intensity Versus Time

To determine the flash duration or effective intensity of a flashing AtoN light operating at a chosen character, the luminous intensity versus time profile must first be measured. The following sub sections discuss approaches and considerations.

#### Sampling Considerations

The aim when sampling the intensity versus time waveform is to capture the relevant features of the waveform with negligible error. Marine lights often produce flash waveforms that require careful consideration to ensure this. For example, the pulse width modulation (PWM) used to drive LEDs or the short flashes from rotating optics may require a high sampling frequency.

The sampling frequency must be sufficiently high to ensure the sampling captures relevant features of the flash waveform. However, higher sampling frequencies create more data which then increases storage and computational demands. It is therefore beneficial to find a balance between the two.

To avoid aliasing of higher frequencies, a low pass filter should be used between the photometer output and analogue to digital converter. The cutoff frequency of the filter should be set to a maximum of half the sampling frequency.

It is often useful to take an exploratory measurement of a flash waveform at a high sampling rate and filter cutoff frequency. The resulting waveform can be examined and the sample and filter frequency reduced or increased as required. Effective intensity and flash duration calculations can be performed on the various exploratory measurements and compared to ensure the selecting settings cause negligible error. Once the suitable frequencies have been determined, the exploratory measurements need not be repeated for subsequent lights with the same or very similar waveforms.

Note that changes to the PWM duty, for example because a change in programmed output intensity, or PWM frequency can significantly change the sample requirements. Waveforms with higher PWM frequencies, or with PWM duties further from 50 % have smaller “features”. This will require higher sample rates to sufficiently capture the features.

Usually there are two kinds of photometers based on different sampling rates: conventional photometer and fast photometer. The sampling rate of the fast photometer is much higher than that of the conventional photometer, so for measurement of luminous intensity versus time, the fast photometer should be used except for some laboratories whose goniophotometer equipped with only conventional photometer, in which case a fast photometer is still needed (see the Conversion measurement method described in Section 4.2.1.3).

#### Direct Measurement Method

With the AtoN light to set to the required rhythmic character, use the fast photometer of the goniophotometer to measure the instantaneous intensity versus time profile of the AtoN light.

#### Conversion Measurement Method

If it is not possible to place the fast photometer but only the conventional photometer at the fixed point of the goniophotometer mentioned in the direct measurement method to measure the instantaneous intensity versus time profile of the AtoN light, the conversion measurement method can be used.

With the AtoN light set to a fixed character, check that the stabilisation requirements of Section 3.3 are met. If they are not, this method cannot be used. Take a measurement of the fixed intensity .

Use a fast photometer to collect the fixed illuminance of the AtoN light at any position. Set the AtoN light to the rhythmic light state. After stabilization, use the fast photometer to measure the instantaneous illuminance versus time profile of the AtoN light at the same position. Calculate the luminous intensity versus time profile of the AtoN light by the formula:

1. Luminous Intensity Profile Versus Time

Where:

is the luminous intensity profile versus time;

is the illuminance profile versus time;

is the fixed luminous intensity of the AtoN light (cd);

is the fixed illuminance of the AtoN light at one position (lx).

#### Considerations for Stationary and Rotating Lights

For AtoN light signals that are flashed by eclipsing or switching the light source, the instantaneous luminous intensity profile versus time (flash profile) should be plotted with the luminous versus time. The plot should include the entire cycle of the flash character, illustrating both the on and off periods. Secondary plots may be used to illustrate any short-duration fluctuations of the instantaneous luminous intensity.

For rotating beacons where the instantaneous luminous intensity is plotted against time by allowing the beacon to rotate under its own power, plots should show the luminous intensity profile against time for one complete revolution of the beacon. Secondary plots should also be used to illustrate individual emitted beams in greater detail.

Based on the horizontal distribution diagram of the luminous intensity of the rotating light measured in the non-rotating state (that is, the luminous intensity versus angle) and the rotating rate of the rotating beacons (that is, the angle versus time), the horizontal angular luminous intensity variation may be converted to a time-dependent luminous intensity profile at specific rotation rates for calculation of the effective intensity and flash duration.

### Flash Duration

IALA Recommendation *R0203* gives the following definition:

“The duration of the measured flash profile should be taken from the point in time when the intensity first exceeds 50% of the peak intensity value to the point in time when the intensity finally falls below 50% of the peak intensity value. The end of a flash should be considered as when the intensity falls below 5% of the peak intensity value for more than 100 ms.”

This parameter is calculated from a light’s luminous intensity versus time profile. An example profile plot, annotated with the flash duration, is shown in Figure 10.



1. Example Luminous Intensity Versus Time Profile

In cases where LED lights may have intensity spikes, pulse width modulation (PWM), a convolutional method may be used to determine the flash duration , see APPENDIX 1 3.9.

### Effective Intensity

The response of an observer’s visual system to a flashing light will vary depending on the flash’s luminous intensity, duration and shape. The luminous intensity of a fixed character that appears equal in intensity to the flash is known as the effective intensity. The effective intensity is used to determine the range of the light.

IALA Recommendation *R0204* and Guideline *G1135* provide methods to either calculate or estimate the effective intensity of a flashing light from the luminous intensity versus time profile of its flash. For an AtoN light exhibit a fixed character, the steady intensity of the light is used directly.

According to R0203, the effective intensity shall be based on the Specification Peak Intensity. Calculation of the Specification Peak Intensity from the luminous intensity versus angle profiles is described in Section 4.1.4. There are two possible approaches to base the effective intensity on this:

1. Select a coordinate on the angular profiles where the intensity is equal to the Specification Peak Intensity. Measure the luminous intensity versus time profile at this coordinate and calculate the effective intensity as in IALA Recommendation *R0204*.

Or,

1. Measure the luminous intensity versus time profile at the datum (or other arbitrary) coordinate and calculate the effective intensity as in IALA Recommendation *R0204*. Using the angular profiles, determine the ratio between the specification peak intensity and the intensity at the chosen measurement coordinate. Scale the effective intensity by this ratio. Thus,
2. Scaling Effective Intensity

Where:

is the Effective Intensity (cd)

is the effective intensity, taken at the datum position.

is the specification peak intensity (cd), determined from the intensity versus angle profiles.

is the luminous intensity at the datum position, taken from the intensity versus angle profiles.

### Nominal Range

The nominal range of a light is determined by the effective intensity, or the steady intensity of a light with a fixed character. Having determined either of these, the corresponding nominal range can be determined by applying one of the methods described in IALA Recommendation *R0202*.

## Colour and Sectors

### Signal Colour

The measurement of the colour of a light source in the laboratory is carried out by one of two methods: either by use of a tristimulus colorimeter (see APPENDIX 1 Section 4.1), or a spectroradiometer (see APPENDIX 1 Section 4.2). The results from either method should be reduced to x, y coordinates that enable a colour point to be plotted on a CIE 1931 chromaticity chart [24].

For the light with only one color or the same color, the overall color of the light can be measured at close range or by placing the AtoN light in an integrating sphere. However, if the angular dependence of colour is being measured (for example of a sector light), a goniometer may be employed to facilitate the measurement of colour against angle on which the light source may be rotated about its light centre and several measurements carried out at different orientations.

To ensure that a light source fully and evenly illuminates the measurement aperture, a diffuser or integrating sphere may be used. If the measurement angle needs to be small, then either the measurement distance should be increased or the measurement aperture should be decreased. At greater measurement distances, the lower levels of illuminance at the measurement aperture may increase measurement uncertainty considerably due to instrument noise. At least three colour measurements should be taken at different points within the arc of utilisation. The results of all measurements should be reported.

The colour of an LED is likely to change during its operation as the device current warms the junction. This means that there may be a significant colour difference between an LED exhibiting a rhythmic character with a low duty cycle and one exhibiting a high duty cycle character (e.g. occulting) or continuous light. It is recommended that an average of the colour over the duration of the flash be taken. When the tristimulus colorimeter is used, multiple measurements can be taken within the period of the flashing light to take the average; when the spectroradiometer is used, the integration time can be set as the the period of the flashing light, that is, the average color within this time can be obtained.

Further guidance on basic colorimetry can be obtained from CIE publications [14], [24], [30], [33] and [34].

The measured colour of the light should be reported in x, y coordinates according to the CIE 1931 chromaticity chart. Compliance with the appropriate IALA colour region should also be reported with reference to IALA Recommendation *R0201*.

If all points lie within the recommended boundary, results may be shown as a scatter plot on a chromaticity chart. However, if there are deviations in colour from the recommended regions, a Cartesian plot of x, y chromaticity against angle is preferable because the angles at which deviations occur can be seen.



1. Scatter Plot of Red LED AtoN Light over 360°

### Sectors

A sector light usually display different colours for different sectors, so the colour of the sector light varies with angle. For example a sector light with white, red and green sectors, the colour should be measured in at least three points within each coloured sector. The results of all measurement should be reported.

There are several key parameters for a sector light, such as sector colour boundary, sector intensity boundary, sector width, sector boundary, and sector of uncertainty whose definition are given by IALA Recommendation *R0203*. These parameters are calculated from a sector light’s luminous intensity and colour versus horizontal angle profiles. An example profile plot, annotated with the these parameters, is shown in Figure 12.

In this example, the **Red Sector Colour Width**, taken between the Red Sector Colour Boundaries, covers 1.5° from -56.9° to -55.4°. The **Red Sector Intensity Width** which is the angle interval across the full width half maximum (FWHM) intensity (i.e. taken between the Red Sector Intensity Boundaries), covers 1.4° from -56.6° to -55.2°. Therefore, according to the definition of Sector Width given by IALA Recommendation *R0203*, the **Red Sector Width** covers 1.2° from -56.6° to -55.4°.

The **Green Sector Colour Width**, taken between the Green Sector Colour Boundaries, covers 1.8° from -54.8° to -53.0°. The **Green Sector Intensity Width** which is the angle interval across the full width half maximum (FWHM) intensity (i.e. taken between the Green Sector Intensity Boundaries), covers 1.2° from -54.6° to -53.4°. Therefore, the **Green Sector Width** covers 1.2° from -54.6° to -53.4°.

Since the Red Sector Width and Green Sector Width have been determined, as the **Sector of Uncertainty** should be the angle between the adjacent Sector Width, so the Sector of Uncertainty between the red and green sectors covers 0.8° from -55.4° to -54.6°.

The **Red/Green Sector Boundary**, which should be taken as the centre of the Sector of Uncertainty, is -55.0°.

**IALA R0201 Red**

**IALA R0201 Green A**

-57.0

-56.8

-56.6

-56.4

-56.2

-56.0

-55.8

-55.6

-55.4

-55.2

-55.0

-54.8

-56.6

-54.6

-54.4

-54.2

-54.0

-53.8

-53.6

-53.4

-53.2

-53.0

Luminous Intensity

Horizontal Angle

(degress)

Colour

FWHM

FWHM

10% of Maximum

Red Sector Colour Width

Green Sector Colour Width

**Green Sector Width**

**Angle of**

**Uncertainty**

Red Sector

Intensity Width

Green Sector

Intensity Width

**Red Sector Width**

Angle of

Uncertainty

10% of Maximum

Angle of

Uncertainty

**Red/Green Sector Boundary**

**Green/Blank Sector Boundary**

**Blank/Red Sector Boundary**

1. Plot of Colour and Luminous Intensity Versus Horizontal Angle of Red and Green Sectors

When carrying out measurements of sector lights it is important to bear in mind the accuracy of alignment of the measurement datum point. If the resolution of the angular measurement is 0.1 degrees, it is necessary for the datum point to be aligned with the measurement instrument to better that half that resolution angle. The angular uncertainty of this datum alignment should be quoted along with the measurement results.

It may be necessary for the horizontal angular information given in the results, i.e. that reported from the goniometer, to be replaced with the bearing from seaward of the intended location of the light. In this case, care should be taken to align the goniometer datum with the cardinal points of the compass and, where possible, to show bearings of landmarks intended for alignment.



1. Plot of Colour and Luminous Intensity Versus Horizontal Angle of Red and Green Sectors



1. Plot of Colour and Luminous Intensity Versus Horizontal Angle of Red and Green Sectors

# Definitions

The definitions of terms used in this Guideline can be found in the *International Dictionary of Marine Aids to Navigation* (IALA dictionary) at <http://www.iala-aism.org/wiki/dictionary> and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

In addition, for this document the following definitions are relevant:

# abbreviations

DUT Device Under Test

# references

1. IALA. (2022) Recommendation R0203 Definitions of Marine Signal Lights Terms of Measurement.

# Further reading

Any texts that are recommended to the reader without direct reference in the text should be listed within this section using the same syntax as the reference list. Sources should be listed using the **Further reading** style.

1. Einstein, A. (1905) Relativity: The Special and General Theory of Relativity
2. Idle, E. (1984) The Galaxy Song
3. Further Technical Guidance
   1. The Measurement Laboratory
      1. Overview

In order to obtain the accurate photometric and colorimetric performance of the AtoN light, standard measurement conditions are specified in the mainbody of this guideline. Besides these, there are also some other matters that require attention, such as the way to control stray and ambient light, the method to extend the optical path length when the minimum measurement length can’t be met.

* + 1. Stray and ambient light control

Stray light control includes eliminating reflected light of the DUT, from walls, floors, and other surfaces, from reaching the photodetector. Ambient light control includes eliminating or reducing the amount of light from sources other than the DUT. The impact of ambient light may be determined by removing power to the DUT and recording the output of the photodetector. The impact of both elements may be determined by taking measurements with the DUT on, but with the direct light path occluded by a screen just larger than the light source aperture, as illustrated in Figure 16. The measured value of the ambient and stray light should be deducted from the measured value of the DUT.



1. Stray light reduction by absorbing screens



1. Arrangement to determine ambient and stray light
   * 1. Folded Path Measurement

When the minimum photometric distance (see Section 3.4) exceeds the maximum length of the light path of the available measurement space, one or more plane mirrors, sufficiently large as to generate a full image of the DUT, may be placed at the end of the light path. The photometer may be used to measure the light signal reflected from the mirror.

It is recommended to use a front-surfaced mirror with a very accurate flat surface, high reflectance and flat spectral reflectance to minimize losses and geometrical distortion of the reflected image.

However, the use of a mirror may result in a change to the spectral correction factor, SCF (see section 8.4). Measurement of a reference source, directly and over the folded path, of similar spectral output to the DUT, may be used to determine overall losses and spectral distortion produced by the mirror. If the minimum measurement distance still exceeds the folded measurement length, measurements should be made using the method described in APPENDIX 1 Section 1.4.



1. Folding mirror schematic

The reflection angle of the mirror should be as small as possible to reduce the influence of polarization; more than one mirror can be set to return the light path. The diameter of the folding mirror should be slightly larger than the cross-sectional size of the light path formed at this position .

* + 1. Zero Length Measurement
       1. introduction

Zero-Length Photometry is a methodology for approximating far-field conditions in a short distance. The principal technique of Zero-Length Photometry is the use of a paraboloidal mirror to optically place the detector at an infinite distance from the source and thus out of the near field. An incoming plane wave, incident upon a concave paraboloidal mirror is converted to a converging spherical wave. The resulting image is measured by a detector at the focal point of the mirror [12]. The Illuminating Engineering Society (IES) has presented this as an alternative method for photometric measurement of searchlights [13]. Figure 18 illustrates a Zero-Length Photometry system.

The mirror should be able to focus collimated rays from all sections of the mirror face to a spot no greater than the aperture of the photometer, while excluding off-axis rays. The diameter of the mirror should be greater than the largest dimension of the optical components of the item under test. A front-surfaced mirror is recommended to minimize losses. As with a folding mirror, the relative spectral reflectivity of the mirror should be measured and used in the calculation of the spectral mismatch correction factor.



1. Zero-Length photometry system

The angular resolution depends on the focal length f and the size of the measurement aperture of the photometer head (see Figure 19).



1. Zero-Length geometry showing angular resolution

As an approximation the angular resolution can be expressed as follows:

1. Approximation of angular resolution

Where:

is the measurement angle in radians;

e is the diameter of the measurement aperture;

f is the focal length of the photometer head.

* + - 1. OFF-AXIS ZERO-LENGTH PHOTOMETRY

The photoreceptor may be removed from the direct path of the light signal from the item under test by use of an off-axis paraboloidal mirror. This is especially important when measuring smaller optics, where the amount of obscuration may be a substantial proportion of the light signal. Tilting a centred system will achieve the same result, albeit with an increase in measurement uncertainty.



1. Off-Axis Zero-Length Geometry
   * + 1. CALIBRATING OR CHARACTERISING THE ZERO-LENGTH SYSTEM

Theoretically, all of the on-axis, collimated rays striking the paraboloidal mirror will be gathered at the focal point of the mirror. Actually, there will be losses due to the overall spectral reflectivity of the mirror, non-uniformity of the mirror’s reflective coating, and aberrations in the curvature of the mirror. The following method may be used to determine the losses through the zero-length setup. Measure the illuminance from a stable light source at various distances from the photometer. Placing the source in a light box with a variable aperture will allow for generation of a very small source, so that the illuminance may be found to follow the photometric distance law within the limits of the measurement path. Precise alignment of the light box with the detector is required. The lamp current should be monitored and controlled. Make a series of measurements at distances beyond the minimum distance required for the photometric distance law to apply. Determine the intensity of the source and variance from the series of measurements. Move the light box to the goniometer and align with the mirror and the photometer. Monitor and control the lamp current as the illuminance () is measured through the zero-length system. Using the intensity determined from the direct measurements (), calculate the ‘corrected’ length of the light path.

1. ‘Corrected’ length of the light path

Where:

is the luminous intensity obtained by direct measurement (cd);

is the measured illuminance in Zero-length system (lx);

is the corrected length of the optical path(m).

The corrected light path length of the zero-length setup, , is then used to calculate the luminous intensity of the DUT. Determination of the corrected light path length of the zero-length setup should be carried out whenever new data are to be recorded. Changes to the corrected length that cannot be accounted for in the uncertainty budget should be examined to determine if they are caused by some systematic error or equipment malfunction.

The variance recorded during the series of direct measurements of the light box includes the effects of a significant proportion of the elements that comprise the total uncertainty budget of the zero-length photometry setup. The variance may be used as the unexpanded uncertainty for those elements.

* 1. The Device Under Test
     1. Overview

The DUT should be checked to ensure that it is in good operating condition. Its optical system should be outfitted with the appropriate light source, which may be supplied by the manufacturer or be a standard laboratory test lamp if the light source is separable, and focused (if required) in accordance with the manufacturer’s instructions or standard laboratory procedure.

The DUT should be selected for close conformance to design dimensions, rated power consumption, and rated lumen output. Manufacturing tolerances between individual lamps of the same manufacturer’s specification may be very large causing a correspondingly large variation in the intensity of a beacon. Parameters such as filament coil spacing and size also impact greatly on the intensity distribution, therefore close inspection and selection is recommended.

When a lampchanger is included as part of the test item, lamps should be installed in all positions of the lampchanger where they might impact on the photometric output of the DUT. Lamps should be seasoned by running them for a few tens of hours prior to initial use [11]. Note that all light sources, particularly LEDs and discharge lamps, may require several hundred hours of operation (ageing) prior to being used for measurement purposes.

* + 1. Reference centre

The reference centre of the light source within the DUT is usually based on the geometric centre of the area that emits light, i.e., the centroid of the geometric shape of the luminous area.

In practical applications, the reference centre of a navigation light device can usually be taken as the centre of the three-dimensional figure of the outline of the light-emitting surface. For omnidirectional beacon lights, the geometric centre of the lens is used as the reference centre (in most cases, it is the intersection of the vertical centre axis of the beacon light and the horizontal centre plane of the lens). For beacon lights with directional light, the centre point of the light-emitting surface of the light-emitting surface is used as the reference centre.

* 1. Photometry
     1. Photometric distance law

According to the Photometric Distance Law proposed by Lambert in 1760, the illuminance is inversely proportional to the square of the distance to the point light source. In the case of oblique light, the illuminance is directly proportional to the cosine of the angle between the beam direction and the normal of the illuminated surface. The illuminance on the receiving surface of the illuminance meter is determined by:

1. Photometric Distance Law

Where

is the illuminance on the receiving surface of the luxmeter ( lx );

is the luminous intensity of the measured AtoN light ( cd );

is the distance from the light source center of the measured AtoN light to the receiving surface of the luxmeter ( m );

is the included angle between the beam in the measured direction of the AtoN light and the normal of the receiving surface of the luxmeter.

When using a goniophotometer to measure luminous intensity, is generally equal to zero, so the above equation becomes:

1. Photometric Inverse Square Law

The measurement of luminous intensity is carried out by measuring the illuminance produced by a beacon at a distance *d* away from a photoreceptor and then determined by Equation 12.



1. Photometric Distance Law

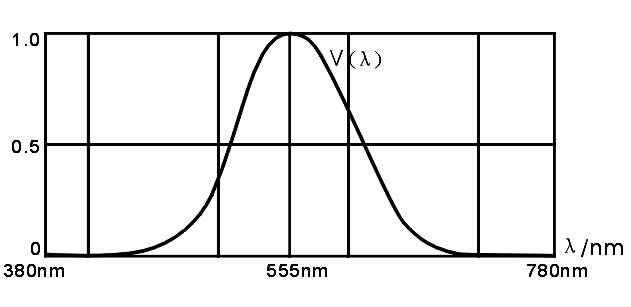
The arrangement above can be modified by introducing a folding mirror or by using Zero-Length Photometry (see APPENDIX 1 Section 1.3, Section 1.4).

* + 1. Measurement by Photometer
       1. measurement principle

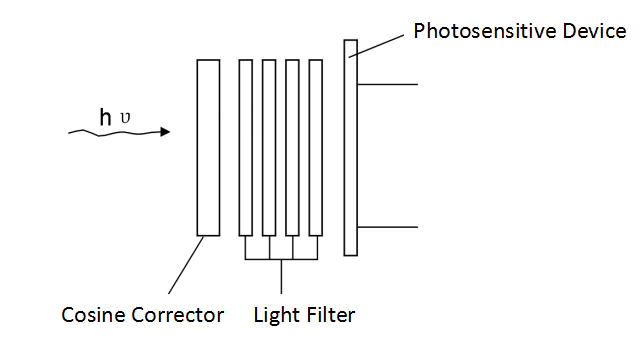
Photometers are used to measure photometric quantities. A photometer typically comprises a photoelectric sensor, a V(λ)-correction filter, and a precision aperture.

The V(λ)-correction filter is applied to make the spectral responsivity of the photometer approximate the CIE standard luminous observer's spectral luminous efficiency function V(λ) (see section 4.2). The photometer converts light signals into electrical signals, and its electrical output is amplified to provide readings that can be calibrated into luminous values.

The output of the photometer is proportional to the photometric quantity. After calibration with a standard reference, the photometer can measure absolute photometric values.



Spectral Response



1. Principle of measurement by photometer
   * + 1. Spectral Mismatch Errors

Errors may occur when measuring a light source of different spectral distribution to the one used to calibrate the photometer because of differences between the spectral response of the photometer and the response of the standard photometric observer V(λ), as shown in Figure 23, Figure 24. Such errors are called ‘spectral mismatch errors’ and can be quite large at certain wavelengths, typically in the red and blue regions where the photometer is least sensitive. Light sources with a narrow spectral distribution (e.g. coloured LED) are more likely to produce large errors than broad-spectrum white light sources.



1. Spectral Plot showing Differences between Typical Photometer Response and V(λ)



1. Expanded Section of Spectrum Highlighting Photometric Error in Figure 23
   * + 1. Spectral Mismatch Correction

If the light source being measured has a spectral power distribution that is significantly different from the calibrating light source, especially if it has a narrow band of distribution (such as LED sources), spectral correction should be undertaken. For the white light source being measured, although it is strongly recommended, it is not necessary to correct the spectral mismatch error. For the coloured light source being measured (such as red, green and blue monochromatic light), the spectral mismatch error must be corrected.

An accepted method of correction is by use of a spectral correction factor (SCF) [6], as given by:

1. Spectral correction factor

Where:

is the spectral power distribution of the DUT, which can be measured by the spectroradiometer described in APPENDIX 1 Section 3.3 ;

is the spectral data of the CIE Illuminant A;

is the relative spectral responsivity of the photometer.

Using this equation, the correction factor can be obtained for any light source of known spectral power distribution. If a calibrated light source is being used as a reference, its spectral power distribution may be substituted for.

If the SCF cannot be obtained, a strict alternative method can be used to obtain the correction factor: a calibrated spectroradiometer and photometer is used to measure the photometric value of the AtoN light respectively in the same position and the same luminous state of the measured light source, then the correction factor is calculated according to Equation 14. The corrected photometric value is obtained by multiplying the measurement value of the photometer by the correction factor. For DUT with two or more colors, photometric correction shall be carried out for each color separately.

1. Correction factor

Where:

is the photometric value of the DUT measured by a calibrated spectroradiometer;

is the photometric value of the DUT measured by a photometer;

is the correction factor of the photometer for the DUT.

The correction factor will have an associated uncertainty derived from the spectral measurement process and the pertinent calibration details of equipment used in the measurement.

* + 1. Measurement by Spectroradiometer
       1. Measurement Principle

Photometric quantities can also be measured using a spectroradiometer, within which the light is divided into different wavelengths, and the amount of light at each wavelength or wavelength interval is measured by a receiver. Thus the spectroradiometer is an instrument for measuring radiometric quantities in narrow wavelength intervals over a given spectral region. Depending on their structure, spectroradiometers can be categorized into mechanical scanning and array-based types, as described in APPENDIX 1 Sections 3.3.2 and 3.3.3 below. The obtained spectral radiometric values are weighted by the luminous efficiency function *V*() for photopic vision to obtain photometric values (as defined in section 4.5 for luminous flux, section 4.7 for luminous intensity, section 4.9 for illuminance, etc.).

Spectrophotometric measurements do not have spectral mismatch errors, but it's important to note that wavelength errors and stray light within the spectroradiometer can introduce measurement errors, thereby affecting the accuracy of photometric measurements.

Further guidance on spectroradiometers can be obtained from CIE publications [14], [24]. (CIE 233:2019、CIE 250:2022 .)

* + - 1. Mechanical Scanning Spectroradiometer

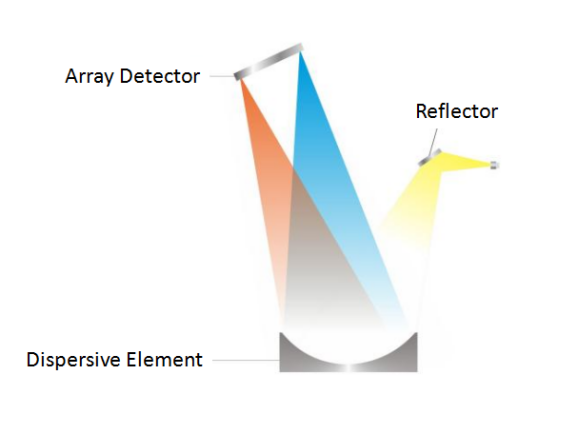
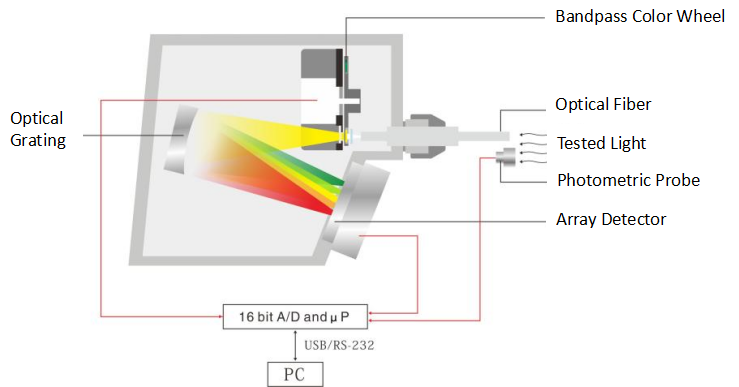
Scanning spectroradiometers combine a monochromator and a single-channel detector. For example , the Czerny-Turner monochromator shown in Figure 25 has a radiometer head (usually a photodiode or photomultiplier tube) coupled to the output slit. The monochromatic light emitted in the exit slit is then measured by the single-channel detector.

Typically, the diffraction grating is turned in increments and a radiometric measurement is taken at each incremented step. Such devices are quite slow and may not be suitable for flashing light sources and modulated light sources. They are however, capable of great accuracy but can be prone to mechanical instability and need frequent calibration.



1. Schematic of Czerny-Turner Stepping Monochromator
   * + 1. Array-based Spectroradiometer

An array-based spectroradiometer uses a monochromator that is fixed and where the output slit is replaced by an array of charge-coupled devices (CCD) that act as individual radiometric receptors for each waveband. CCD record the amount of charge, which is dependent on the exposure time to the light being measured. This exposure time is commonly known as integration time, which can be varied to accommodate varying levels of light input.



1. Schematic diagram of array spectroradiometer
   * 1. Calibration by Substitution with Calibrated Light Source

Calibrated sources, while not required when a calibrated photometer is used, are useful for making comparative measurements [21]. The comparative method of measurement is sometimes known as ‘measurement by substitution’, where the DUT is substituted for the calibrated light source and measured over the same measurement path. Sources calibrated at a national standards laboratory, and traceable to the national standard, are sometimes known as ‘standard lamps’, ‘standard reference lamps’ or ‘transfer standards’. Such lamps require carefully regulated power supplies and also require their voltage and current to be measured with low uncertainty. The equipment used to measure their voltage and current should also be traceable to national standards; otherwise the ‘transfer standard’ becomes meaningless.

Transfer standards may be calibrated for luminous intensity, colour temperature or spectral radiance or irradiance. A calibrated selective emitter, such as an LED source, may also be used as an alternative to spectral correction when the relative spectral responsivity of the photometer is not available.

Measurement by substitution is useful when the spectral transmittance of the measurement path is not linear; for instance, when measuring over a large distance, or when using adaptive optics such as a folding mirror or a collecting lens on the photometer. For scanning spectroradiometers, that can suffer considerable short-term calibration drift, it is recommended that a spectral irradiance standard reference lamp be used to calibrate the instrument before every measurement session.

* + 1. Calibration using Known Distance
    2. Relative Photometry of Optical Systems

For all types of AtoN lights, their luminous intensity and luminous intensity distribution (unit : cd) can be obtained by direct measurement, and this method is called absolute photometry.

However, in traditional AtoN lights, the light source can often be replaced, and the relative method can also be used when evaluating its luminous intensity. That is, when measuring the AtoN light , use the light source specified by the manufacturer to measure, and measure the total luminous flux of the light source included, and calculate the relative luminous intensity, the unit is cd/klm. The total luminous flux of the light source can be obtained by an integrating sphere photometer. When the light source in the AtoN light is attenuated or replaced with a light source of the same physical characteristics , the corresponding luminous intensity value can be quickly calculated through the relative luminous intensity.

With the application of LED light sources in navigation lights, more and more light sources are integrated in navigation lights and cannot be replaced. The scope of application of relative photometry is increasingly limited, and absolute photometry is more common .

* + 1. Measurement of Luminous Flux

When measuring the output of bare light sources such as incandescent lamps, the quantity of total luminous flux in lumens is usually obtained by placing the light source in an integrating sphere which collects the whole luminous output from the lamp. Such spheres need to be several times larger than the light source being measured and require careful calibration but the output is a useful measure of a lamp’s performance. The total luminous flux is the figure usually quoted by lamp manufacturers.

* + 1. Measurement of Modulated Light
       1. Talbot-Plateau Law

The Talbot-Plateau Law states that if a light source is flashed or pulsed at a rate above the critical flicker frequency or flicker fusion frequency, such that it appears as a continuous light, the luminance of the source will be equal to that of a steady light that has the same time-average luminance [4][29].

* + - 1. Measurement By Photometer

When using photometers, which typically have a slow response time, to measure the continuous intensity of a light flickering or pulsing above the flicker fusion frequency, the photometer output may need to be time-integrated to ensure that the Talbot-Plateau Law is obeyed.

Or use a fast photometer to capture the waveform, and then calculate to obtain the average value of light.

* + - 1. Measurement By Spectroradiometer

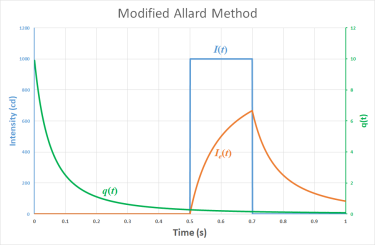
Mechanical scanning spectroradiometers are not suitable for measurements of modulated light. When using an array spectroradiometer, the entire modulation period should be taken for measurement.

* + 1. The convolution to determine flash duration

The method of directly using photometric measurement of flash to determine flash duration cannot take into account the human visual system's perception mode of light. In the case of LED lights that may have intensity spikes and pulse width modulation (PWM), the resulting flash duration may not be accurate.

Using MAM, the convolution, , of an AtoN flash profile and the Modified Allard visual impulse response function will be considered as the actual AtoN flash profile. The duration of 50% peak value of is the flash duration which takes into account the pulse response of the human visual system to the flash.

When Modified Allard visual impulse response function is used to process asymmetrical flash waveforms such as triangular waves, the predicted results are different from those actually observed by observers in visual experiments [42], [43] . Couzin D. improved the MAM impulse response function model [ 44 ] , so that when it is used to deal with the complex waveforms, the theoretical calculation results are more consistent with the experiments.



1. Typical application of the MAM. The flash (blue) is convolved with the visual impulse response function (green) to produce the perceived flash (orange)

The results of studies using the aforementioned convolution method to calculate flash durations have shown that, in the vast majority of cases, the theoretical observed flash length is longer than that of the photometric flash length. Also, because of the filtering effect, any sharp spikes in the photometric data are smoothed out. The difference in the photometric flash length and the convolution flash length can vary significantly for complex flash shapes. For some flash shapes, the differences between the flash duration results obtained using the improved impulse function response model and the photometric method are less than those of the MAM method.

One should note that the results presented in this section are entirely theoretical and have not been tested through observation to understand the after-image effect that the convolution function predicts in its results (i.e. the falling edge of the convolution function gradually fades after the flash has ended, implying that light is “observed” after the flash has extinguished).

* 1. Colourimetry
     1. Measurement by Tristimulus Colourimeter

A tristimulus colorimeter is used to measure the color of a light source. The tristimulus colorimeter consists of three or four photodetectors, each with a filter that approximates one of the three colour functions , and . The three outputs are then arranged to give X, Y and Z values, or computed to give x, y chromaticity. Additionally, because the Y function is the same as V(λ), the Y output may be calibrated to give a luminous value (e.g. lux).



1. Schematic of a simple Tristimulus Colorimeter

Tristimulus colorimeters have the advantage that a relatively fast measurement can be made of colour. However, cheaper models may yield significant errors because the filters do not faithfully follow the colour functions. Such errors are more noticeable when measuring light sources with a narrow spectral distribution. Similar to photometric measurements, spectral mismatch correction can also be employed to reduce chromaticity measurement errors. Alternatively, errors can be minimized by calibrating the readings of the tristimulus colorimeter using light sources with known tristimulus values and the light source should have the similar spectral distribution with the DUT.

* + 1. Measurement by Spectroradiometer

After measuring the spectral power distribution of the light stimulus using a spectroradiometer, chromaticity parameters can be calculated using equations 15-17 (see Sections 4.22 and 4.23). When measuring chromaticity parameters, it is only necessary to obtain the relative spectral power distribution without requiring absolute values.

Spectral colorimetric methods do not involve spectral mismatch errors, but it's important to note that wavelength errors and stray light within the spectroradiometer can introduce measurement errors, thereby affecting the accuracy of chromaticity measurements.

* 1. Measurement Equipment Requirements
     1. Photometer

The spectral response of the photometric system should closely approximate the spectral luminous efficiency curve V(λ) for the CIE standard photometric observer in photopic vision (see Section 4.2).

The mismatch index [6] should be less than or equal to 6%, and , the linearity should be better than 1%.

The measurement sensitivity should be appropriate to respond to the expected signal without saturating. For example, if measuring a light with an expected intensity of 100 cd at a measurement distance of 10 m, the photometer will receive an illuminance of 1 lux. A photometer with a sensitivity of 0.01-2 lux might be selected.

Most photometers are calibrated using illuminant A, so when using a photometer to measure light with a spectral distribution different from that of illuminant A (such as colored lamps or discharge lamps), spectral mismatch correction is recommended (see APPENDIX 1 Section 3.2.3).

* + 1. Spectroradiometer

The spectroradiometer wavelength range should cover at least 380 nm to 780 nm, the bandwidth (FWHM) should not be greater than 5 nm, the wavelength accuracy should be better than ±0.5 nm, the spectroradiometer linearity in the visible light band should be higher than 1%.

* + 1. ColorImeter

Since the spectral response matching of a tristimulus value colorimeter is generally poor, it is only recommended to use this instrument to measure the relative change of color, and a spectroradiometer is recommended for higher accuracy color measurement.

* 1. Measurement in the Field
     1. OUTDOOR PHOTOMETRY
        1. overview

Because some AtoN lights are projection systems, with minimum photometric distances in excess of 100 metres, all or part of the light range path may be situated outdoors. In these cases, outdoor telephotometry can be used. Advantages are that a large building is not required and stray light bouncing off walls will not distort the measurement result. A further advantage is that this method allows for photometric measurements of lighthouses ‘in situ’. Disadvantages of outdoor telephotometry are that ambient light levels, such as daylight, may be high and/or variable and that the state of the weather may affect the light path. The timing of the measurement may therefore be important, and measurements may be limited to periods of fine weather or at night.

A further problem with long distance photometric measurements is that the photometer may not be sensitive enough to measure illuminance from a light source several hundred metres away. One solution to this is to use a sensitive photometer receptor (e.g. photomultiplier); another is to use optical magnification (e.g. telephoto lens or telescope) in front of the receptor. At extreme distance both options may be required.

Outdoor measurements may be divided into two types:

* Those carried out on an outdoor light range, where the DUT is mounted on a goniometer table and its intensity is measured against angular displacement.
* Those of a lighthouse ‘in situ’ where no goniometer is used, the character of the light is measured against time and shallow prisms are used to obtain a plot of the vertical beam profile.

Just as for standard laboratory photometry, the path length used in outdoor telephotometry should be greater than the crossover distance of the DUT. A flat folding mirror may be used to double the path length of the light range. The photometer should be shielded from stray light emitted by the DUT when folding the light path.

* + - 1. additional equipments required for outdoor telephotometry
         1. Telephotometer

The low values of illuminance that may be incurred when using an outdoor light range may result in the need to couple the photometer to a collecting telescope. The telescope should be capable of collecting light from the DUT and any reference source that might be used. It should also incorporate an iris so that the acceptance angle may be adjusted to exclude unwanted background light. The use of a telescope, or any such device in the optical measurement path, may alter the spectral correction factor, SCF.

* + - * 1. Reference Light

To overcome uncertainties caused by varying atmospheric transmissivity over a longer measurement path, a reference light should be used. This is a light source of known intensity, preferably one calibrated to national standards, with a controlled supply voltage and current.

In practice two measurements are made, one of the DUT and one of the reference light, which is placed in the same (or equivalent) physical position as the DUT. The two readings are then compared. This method does not rely on accurate measurements of distance nor does it require the photometer to be calibrated in absolute units. However, the photometer output should be directly proportional to the illuminance input. Any non-linearity should be accounted for in the uncertainty budget. The measurement path from the reference light to the receptor should, as far as possible, be the same as that from the DUT to the receptor.

* + - 1. calibration procedures

The use of a reference light as the comparator eliminates the need for absolute calibration of the light measurement system. However, calibration is required of the reference light itself, and the test equipment. The uncertainty in measurements due to the geometric relationships between the reference light, the DUT, and the photometer should also be evaluated and quantified.

* + - 1. atmospheric conditions and ambient light

One of the greatest uncertainties in outdoor photometry is that caused by changing atmospheric conditions during measurements. Those contributing most to the uncertainty figure are changing visibility and scintillation.

A sizable error may result when visibility varies between the time of measurement of the DUT and the time of measurement of the reference light. If visibility is varying considerably, due to fog or rain, measurements should not be undertaken.

Variation of received light due to scintillation can increase the uncertainty of the resulting intensity figure in the same way as noise. This variation can be reduced by increasing the response time of the photometer or by using some averaging of the photometer output. However, care should be exercised when measuring flashing lights. Increasing the response time of the photometer may cause distortion of the measured flash profile. The response time used should be less than one tenth of the expected flash duration. Several measurements should be made and an average of each flash profile can then be calculated.

Variation in ambient light, for instance when the measurement is being undertaken in daylight, can produce an error similar to a zeroing error. Care should be taken to ensure that readings taken from the photometer under ambient light conditions, i.e. with the DUT and reference light switched off, do not vary significantly.

* + - 1. recording environmental conditions

A record should be made at the time of the measurement of the following environmental conditions:

* General weather.
* Visibility.
* Temperature.
* Relative humidity.

Visibility meters placed in the optical measurement path can be useful indicators during the hours of darkness.

* + - 1. aligning the telephotometer

Using a viewing sight, or similar apparatus, look into the optical path of the telescope and adjust the telescope alignment and focus until the DUT can be seen clearly in the centre of the eyepiece. The output aperture should then be adjusted so that only the DUT is visible.

The DUT should then be turned on and allowed to come to full brightness. When viewed once more through the eyepiece care should be taken to avoid excessive glare to the eye. A filter may be inserted at the eyepiece to facilitate comfortable viewing. The goniometer table should then be turned through the desired angles of measurement to ensure that there is no obscuration of the light emitting surfaces by components in the optical path. When the image is satisfactory in all positions, the optical path output from the telescope should be directed to the photometer receptor.

* + - 1. measurement procedures for outdoor telephotometry
* Ensure the photometer is switched on and warmed up. The received light from the DUT falling upon the receptor should be measurable on the photometer readout. The gain of the photometer may need adjusting until a satisfactory reading is obtained. To ensure that the reading obtained is caused by received light, the light path can be interrupted and the effect on the reading observed.
* The DUT should then be extinguished and the photometer reading observed. If the reading is not zero, due to ambient light, a zero offset may be used to reduce the photometer readout in ambient light conditions. Care should be taken however, when ambient conditions are variable, not to allow the reading to go below zero unless the recording system is suitable.
* Complete measurements of the angular and time dependency of the luminous intensity of the DUT, as outlined in Chapter 4.
* Following measurement of the DUT, mount the reference light on the goniometer table, and ensure that it is in the same position relative to the photometer as was the DUT. Allow the output of the reference light to stabilise, in compliance with the reference lamp calibration data. Take at least two measurements of the luminous intensity of the reference light as soon after the measurement of the DUT as is possible.
* The reference light should then be powered down (or baffled, depending on the calibration conditions) and further photometer readings of the ambient light (or ambient plus stray light) recorded. The resultant average value of the reference light minus ambient light (or ambient plus stray light) and associated uncertainties should be calculated and recorded.

A minimum of three complete measurements should be carried to obtain average and uncertainty values.

* + - 1. additional equipment for ‘in situ’ measurement
         1. Prisms and Prism Frame

For in situ measurements of large optical systems, a lighthouse lantern for example, it may not be feasible to mount the DUT on a goniometer table; nor may it be feasible to tilt the DUT. In these cases, the vertical beam profile may be measured by placing prismatic sheets on the focal plane of the DUT, to ‘tilt’ the beam by refraction. Two sets of such prisms, each providing 0.5° and 1.5° deviation, enable measurements to be taken over ±2° in 0.5° steps; a total of nine points on the vertical beam plot. A further step at ±3° is possible by the provision of a second set of 1.5° prisms; for a total of 11 points. The relative spectral transmissivity of the prisms, singly and in combination, should be determined and recorded (see Figure 29).

* + - * 1. Reference Projector

For long-range measurements of high intensity beacons, a calibrated, high-intensity reference projector should be used as the reference light. The reference projector should be of comparable intensity, within two orders of magnitude, to the DUT.



1. The use of Prisms to Divert a Beam through a Vertical Angle
   * + 1. additional procedures for ‘in situ’ measurement

In situ measurements are generally conducted on existing lighthouse optics. Because measurement sites using telephotometry should be situated on land, it should be remembered that in situ measurements are usually only feasible in one or two directions within the zone of utilisation of the light. During the measurements, the operational availability of the lighthouse may be affected. Appropriate navigational warnings should be raised.

* + - * 1. Choice of Measurement Site

The first requirement when carrying out a field light measurement is to find a suitable measurement site. This should be a site where stable mounting of the photometric equipment is possible, preferably away from any adverse conditions of weather or unwanted interference from extraneous light sources. The whole of the optic to be measured should be clearly visible from the measurement site.

Calculations of the crossover distance of the optic being measured should be made to establish the minimum photometric distance. Once this minimum is established, a measurement site should be sought which is beyond the minimum photometric distance, and within plus or minus one degree of a line between the optic centre and the horizon. This vertical tolerance of two degrees is approximate and depends on the vertical beam profile of the light to be measured. The closer the measurement site is to the nominal beam centre, the less the measurement uncertainty.

* + - * 1. Setting Up the Photometer

The iris of the photometer should be set to accept light from the optic being measured and the reference light. The field outside that of interest should be stopped. Daytime is the best time to set up the equipment because the field of view can be easily seen and any potential obstructions accounted for.

* + - * 1. Setting UP the Lighthouse Optic

The lighthouse optic to be measured should be inspected and cleaned. The optic type and dimensions plus any manufacturer’s details should be noted, as should any faults or defects in its operation.

The optic should be outfitted with lamps that conform to design dimensions, rated power consumption, and rated lumen output. The light source should be positioned in the optic in accordance with the procedures established by the optic manufacturer and the Lighthouse Authority.

If the optic is a rotating type, with several light emitting axes, each one should be identified and numbered if not already done so by the manufacturer. This may be done by identifying a unique mark on the rotating part of the DUT (e.g. datum mark or optic door hinge) and numbering each beam or axis from there in the direction opposite to the direction of rotation.

* + - * 1. Setting Up the Prism Frame and Prisms

Install the prism frame between the optic and the measurement site so as to include the maximum area of the lens (or lenses) as possible. Any remaining area of the emitting surface(s) should be screened to prevent light from the optic going past the outside of the frame in the direction of the measurement site (see Figure 29). It should be noted that any blanked area would increase uncertainty of beam profile measurement as upper and lower reflectors/refractors may affect the beam shape.

* + - * 1. Setting Up the Reference Projector

A reference projector should be installed on the outside of the lantern, e.g. on the gallery handrail, as close as possible to the optic and directed towards the measurement site. The path between the reference projector and the measurement site should be free from obstructions.

* + - * 1. Carrying On the Measurement

Measurements may commence as soon as conditions allow. Bear in mind that zero conditions are those of ambient light, if the ambient light level is varying significantly, e.g. because of clouds passing in front of the sun, measurement uncertainties will be increased. Most field light measurements will need to be carried out at night and in good weather.

On commencement, the reference projector should first be aligned so that its beam centre is directed towards the measurement site. The amount of variation in the reference light reading will give a good indication of the suitability of conditions.

Measurements with different prisms should then be carried out to ascertain the vertical beam profile. Each set of prisms is inserted and the flash profile(s) from the optic recorded. Each measurement set should contain a sample of reference light and ambient light. The range setting on the telephotometer should be recorded.

When all relevant prism positions have been recorded, the prisms, prism frame and screening should be removed. Flashes from the unobstructed optic should then be recorded along with reference light, ambient light and photometer settings. At least three recordings of each flash profile should be taken.

A minimum of three complete measurements should be carried out for each complete character to obtain average and uncertainty values. Dominant measurement uncertainties are likely to be due to variation in light path conditions and reference light alignment. Extreme measurement distance requires a large number of repeated measurements to reduce uncertainty.

* + 1. Measurement of character of AtoN light based on spectral analysis

Characters of AtoN lights are usually required to be measured in AtoN inspection and technical measurement of the new AtoN light employed in the field. In these cases, a detector based on spectral analysis technology can be used.

* + - 1. key problems and technical strategy
         1. Remote Collection of AtoN Light

The working environment of AtoN lights is complex, especially for the large optical systems mounted on lighthouse, an appropriate selection of the location for the detector is limited, which requires the detector has the ability of collect the AtoN light remotely.

An optical telescope can be used for remote collection of AtoN light. In the design and selection of a telescope, high resolution, small aberration, strong light collection ability and portability are required.

* + - * 1. Stable Acquisition of AtoN Light

In situ light measurement is usually carried out by boat. The buoy light sways and fluctuates irregularly under the influence of ocean wind and waves, and the ship also inevitably sways and drifts, so it is difficult to have a stable acquisition of AtoN light.

The core of stably obtaining light is to effectively deal with swaying. Placing the telescope on a hydraulic pan/tilt, whose direction can be smoothly adjusted manually, can counteract the effect of swing, track and collect signals accurately to some extent.

In addition, it is not easy to timely and accurately collect the AtoN light signal through the telescope to directly observe the image of the AtoN light. For this reason, beam splitting technology can be used to obtain a small part of the light signal collected by the telescope. Then an electronic eyepiece can be used to directly watch the image of AtoN light through the display screen of the laptop, which is convenient for the inspection personnel to observe, and adjust the observation angle in time to accurately collect and obtain the light signal of the AtoN.

* + - * 1. Elimination of the Interference of the Background Light

In the daytime, sunlight and various reflective lights are strong. At night, various lights create chaotic background interference for AtoN lights. Moreover, the changes in this interference lack a definite pattern. To accurately detect AtoN light signals, certain technical means must be employed to eliminate background interference.

Spectral analysis technology is used to perform spectral analysis on the obtained optical signal, and the spectrum of the AtoN light is accurately extracted based on its specific wavelength. Generally, a spectrometer can be used for spectral analysis.

A software is then developed with a mathematical model to fit the changing trend of the background light data, and a certain threshold can be set to accurately distinguish the AtoN light signal from the background signal . The recognition of the light character can be solved by the background extraction algorithm, but for some environments with strong background light interference, the character may not be accurately identified. In order to improve the adaptability of this algorithm, the method of processing data using a part of the signals can be employed to identify the character, which involves selecting AtoN light signals within a certain range where background light interference is minimal.

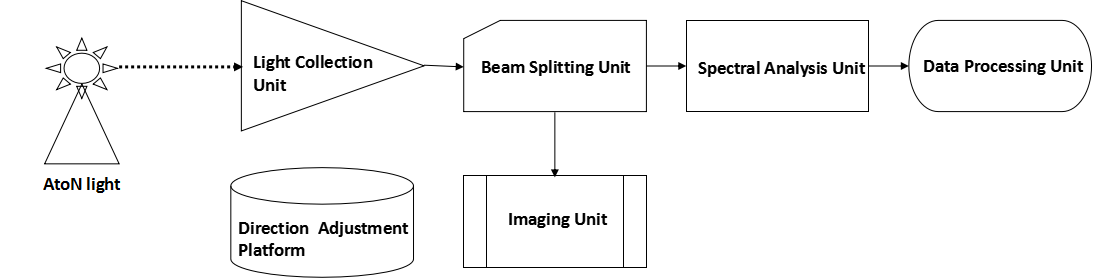
* + - * 1. Identification of the Rhythm and Period of the AtoN Light

AtoN lights exhibit a wide variety of rhythmic patterns. They follow specific rules, but there is no uniformity between different rhythms. Rapidly identifying flash duration and the rhythm of light from continuous and irregular flashing signals, and determining their compliance, poses considerable technical difficulty.

For irregular flashing rhythms and periods, establish a database of light characteristics and thoroughly analyze their compositional traits. Summarize the temporal characteristics of light, including the uniqueness of a few specific light patterns as well as features common to all light patterns. For instance, light patterns with a visible duration greater than 7 seconds can be matched with unique light characteristics. The longest duration of darkness within each light pattern is always at the end. Finally, employ specific algorithms in software processing to recognize light rhythms and periods. In general, the algorithmic processing sequence involves: firstly, determining the flashing duration; secondly, identifying the flashing rhythm; and lastly, determining the type of light pattern.

* + - 1. detecting system

The intelligent detection system for the character of AtoN lights based on spectral analysis technology can be illustrated in Figure 30.



1. Diagram of Detecting System

The entire system is mainly composed of a light collection unit, a direction adjustment platform, a beam splitting unit, an imaging unit, a spectral analysis unit, and a data processing unit. The AtoN light is collected by the light collection unit, and a small portion is directed to the observation unit through the beam splitting unit, while the majority of the light is transmitted to the spectral analysis unit for spectral analysis. The spectral analysis unit decomposes the detected light signals according to their wavelengths and performs photoelectric conversion on the light signals of all wavelengths. The data processing unit analyzes and computes the electrical signals from the spectral analysis unit, detecting the color, flashing rhythm, and period of the light signals. Inspection personnel observe the detection process through the imaging unit, controlling the light collection unit to acquire the light signals in the best way possible to ensure accurate detection. The direction adjustment platform can be freely adjusted in three dimensions. When detecting moving targets, the platform needs to be adjusted manually to track the AtoN light signals.

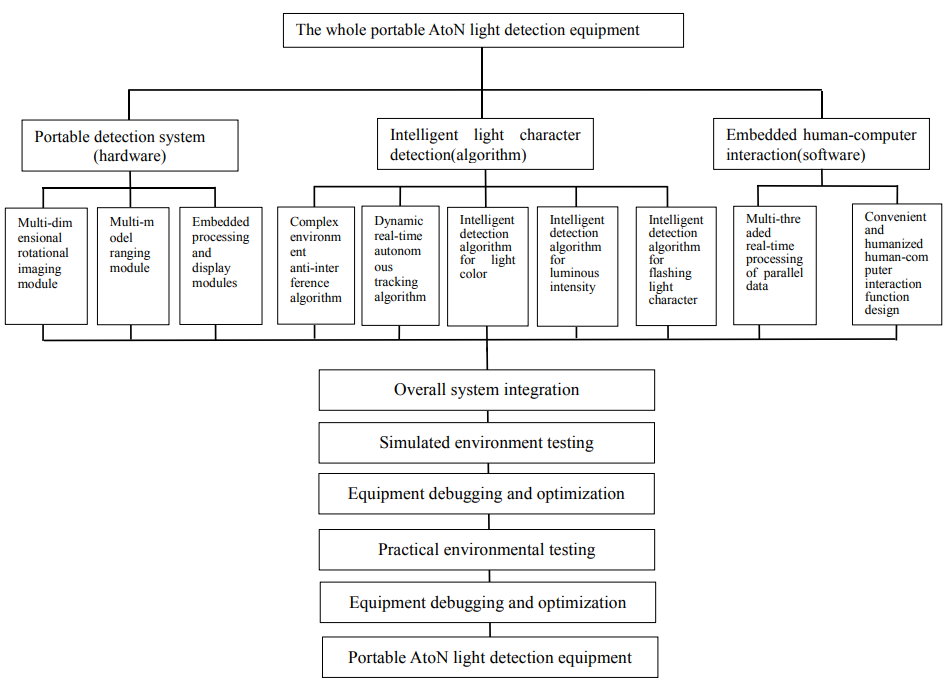
It is worth noting that when using this detector to conduct in situ measurement, only the flashing period and rhythm can be measured. However, the colour measurement still needs to be in a dark room. In addition, when measuring the floation AtoN lights, the AtoN lights would fluctuate irregularly and the detecting ship would swing and drift inevitably. To ensure the detector’s telescope can capture the signal continuously, the detectors have to track the target manually, which requires for certain techniques and experiences. Another detector based on image processing technology introduced in APPENDIX 1 Section 6.3 can realize automatic tracking of the fluctuating AtoN lights.

* + 1. Measurement of AtoN light based on image processing technology
       1. overview

Unlike the detector based on spectral analysis, this detector is based on image processing technology and deep learning technology. It is designed with a multi-dimensional rotating imaging module that includes a camera, a filtering module, and a 3D PTZ. It uses a multi-modal ranging module with laser ranging and GPS positioning modules, combined with real-time automatic identification, tracking, and detection algorithms for AtoN lights, to achieve measurement of the flashing rhythm, period, color, and luminous intensity of various AtoN lights in the marine on-site environment.

* + - 1. technology roadmap

The technical roadmap for the research of the detector is shown in Figure 31.



1. Diagram of Detecting System

The detector mainly includes three modules: hardware module, intelligent detection algorithm, and human-computer interaction software. Portable detection hardware system is composed of multi-dimensional rotation imaging sub-module, multi-modal ranging sub-module, and embedded processing display sub-module.The intelligent light character detection algorithm integrates complex environment anti-interference algorithms and dynamic real-time autonomous tracking algorithms for data pre-processing. It conducts intelligent algorithm detection of color, light intensity, rhythm, and cycle, and ultimately performs concurrent multi-line real-time processing of data in the human-computer interaction software module, providing users with a convenient and user-friendly interactive operation interface.

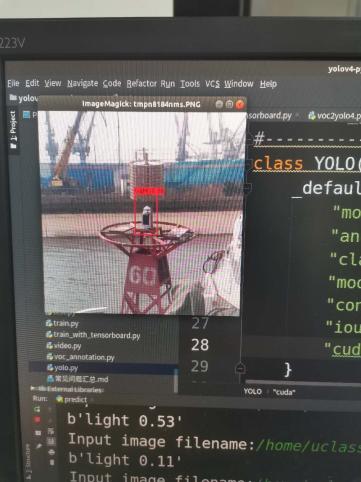
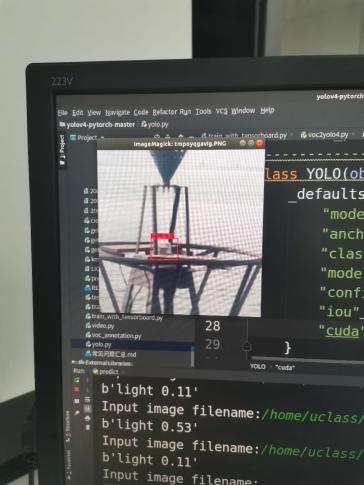
* + - 1. technical characteristics
         1. Remote Acquisition of AtoN Light Signals Using Photoelectronic Imaging Technology

On-site measurement of AtoN lights generally requires remote telemetry. If traditional detection equipment such as photometers and spectrometers are used, it is necessary to align the detector with the AtoN light accurately. However, in the case of remote telemetry, it is difficult to adjust the direction of the detector manually to maintain precise alignment between the two. Due to its large field of view, the detector based on photoelectric images can easily capture the measured AtoN light. Therefore, this detector adopts photoelectronic imaging technology to achieve the acquisition of AtoN light signals.

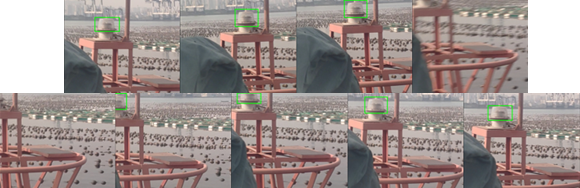


1. Diagram of the multidimensional rotational imaging module of the detector
   * + - 1. Automatic Recognition and Long-term Tracking of AtoN Lights Based on Deep Learning Algorithms

When using photoelectric imaging technology to obtain AtoN light images, in order to make the images clear, the imaging system needs to be zoomed in, but its field of view will also be narrow. In addition, the actual situation of the floating buoy swaying and the tester waggling with the ship will make the AtoN light run out of the imaging system’s field of view. Therefore, based on imaging, a single object detection, recognition, and long-term automatic tracking algorithms based on deep learning are designed to achieve real-time automatic recognition and tracking of AtoN lights, in order to achieve stable acquisition of AtoN light images.



1. Real time detection of AtoN lights by the detector



1. Real time tracking of AtoN lights by the detector



1. Comparison of tracking before and after introducing a correction algorithm, left figure is tracking loss before adding correction, right figure is after adding correction
   * + - 1. Integrated Detection of Parameters of AtoN Lights by Image Processing Technology

Unlike traditional detection methods, in order to achieve simultaneous on-site detection of the character, color, and luminous intensity of AtoN lights by the same equipment, this method uses image processing technology to crop and balance the location information in the tracked AtoN light image, analyze the grayscale value distribution curve of the light source , and identify the flashing rhythm, cycle, and color information of AtoN lights. By collecting and fitting a large amount of grayscale and light intensity data for different colors and types of AtoN lights in the early stage, a grayscale illuminance data model is established. Combined with distance information, the luminous intensity of AtoN light can be calculated.