Comparison of techniques for measuring luminous intensity distribution overall and across segments

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Summary

This paper is a survey of the currently available techniques for measuring luminous intensity distributions. The primary focus is on which measuring technique should be used for which subject: where there is an overlap, i.e. when several techniques could be used for the same subject or several subjects could be measured with the same technique, and where a distinction must be made. The common features and differences between the measuring techniques are treated, together with the advantages and disadvantages of their use for particular subjects.

1. Principles of lighting technology

The first chapter explains the quantities used in lighting technology which are of relevance to the paper, and, so as to avoid confusion, defines the terms used, together with their abbreviations. It also gives a general outline of the subject of photometry.

1.1. Terms and quantities in the lighting technology

In theory, the remarks which follow are also applicable to other types of radiation. It must, however, be said that there are restrictions which cannot be disregarded, some of them arising from the sensitivity of the detectors being used (cf. section 1.3, page 8). This paper is primarily about light. As light is the element of optical radiation which we as humans can recognise with our eyes, i.e. which we can see, the paper is largely concerned with the visible wavelengths (those between 360 and 830 nm), weighted for V(λ) and the luminous efficacy of radiation.

$$\Phi = \mathrm{K_m} \cdot \int_{360\ \mathrm{nm}}^{830\ \mathrm{nm}} \Phi_{\mathrm{e}\lambda} \cdot V(\lambda) \cdot \mathrm{d}\lambda \tag{1.1}$$

Φ - luminous flux
$\mathrm{K_m}$ - maximum luminous efficacy of radiation for photopic vision $\mathrm{K_m} = 683\ \mathrm{lmW^{-1}}$
$V(\lambda)$ - spectral luminous efficiency for photopic vision
λ - wavelength

Shining objects emit light with luminous intensity I. The integral of I over a solid angle is the relevant partial flux. If one integrates I over the whole sphere, the result is the total luminous flux from the object:

$$\Phi = \int_{\Omega_1} I(\gamma) \cdot \mathrm{d}\Omega_1 \tag{1.2}$$

I - luminous intensity
Ω_1 - solid angle

If the luminous flux Φ meets a surface, one speaks of the illuminance, E.

$$E = \frac{\mathrm{d}\Phi}{dA_2} \tag{1.3}$$

E - illuminance
A_2 - surface area illuminated
In combination with equation 1.2, this gives

$$E = \frac{I(\gamma) \cdot \mathrm{d}\Omega_1}{\mathrm{d}A_2} \tag{1.4}$$

The luminance, L is a (differential) quantity with spatial and directional dependence[FS09].

$$L(x, y, z, \vartheta, \varphi) = \frac{\mathrm{d}^2\Phi}{\mathrm{d}A_1 \cdot \cos(\vartheta, \varphi) \cdot \mathrm{d}\Omega_1} = \frac{\mathrm{d}I(\vartheta, \varphi)}{\mathrm{d}A_1 \cdot \cos(\vartheta, \varphi)} \tag{1.5}$$

L - luminance
A_1 - light-emitting area
$\cos(\gamma_1)$ - shielding angle

The greater the luminous intensity of a constant area, the greater the luminance. And, vice versa, the luminance will be the greater the smaller the area at constant luminous intensity.
As light sources are, in practice, elongated and not homogeneous, the luminance will vary with the exact origin and direction of the rays. To achieve a full description of the illuminating characteristics of the light source, the distribution of the luminance or radiance on the real or a sufficient virtual surface must be registered, and it must be measured as a field of rays on a virtual surface. The luminance or radiance must be known for each point of origin (on the surface of the light source, for example), and the direction in which the light is emitted - $\mathrm{L_e}(x, y, z, \vartheta, \varphi)$ In some instances, the wavelength, λ, will also be of interest. And, in rare cases, the direction will be given not in spherical coordinates but in Cartesian coordinates.
The figures for the field of rays are described as ray data/spatial ray models. If one integrates all the luminance L(x,y,z) from a particular direction (ϑ, φ), one obtains the luminous intensity for this direction and this is how the entire spatial luminous intensity distribution is found.

$$I(\vartheta, \varphi) = \int_{A_1} L(x, y, z, \vartheta, \varphi) \cdot \cos(\vartheta, \varphi) \cdot \mathrm{d}A_1 \tag{1.6}$$

By finding the integral of all the luminous intensity figures, one obtains the luminous flux for the light source (see Equation 1.2).The field of rays can be calculated back for the actual surface or for a virtual surface closely approximating to it and can then be termed the spatial ray model. Ray data are always relevant when different work is carried out depending on the origin of the light from a light source. An example of this appears with most luminaires. The ray data are necessary to the calculation of which optical elements, such as a reflector, added to a luminaire, will enable the lamp and its fixture to give the desired effect. Figure 1.1 helps to make this clear: from left to right, an LED, a depiction of its illumination characteristics in the form of the spatial ray model, and a simulation of the distribution of the luminous flux emitted in a prescribed direction by a directional headlamp reflector, using ray data [FS09].
On the other hand, if the need is to find the effect of the luminaire at some distance, it will usually be sufficient to measure the distribution of the luminous intensity. Unlike the ray data, the luminous intensity distribution contains no information about the extent of the origin of the light. The subject of the measurement is assumed to be a point source of light.

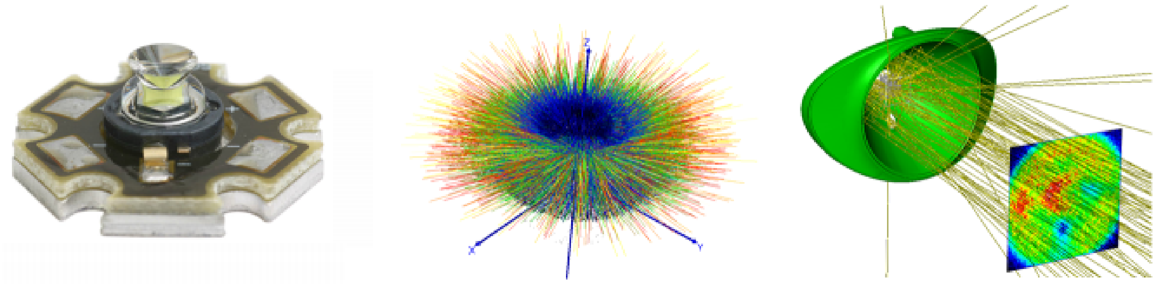

Figure 1.1.: High power LED with its spatial ray model and an example of simulation

The direction in which the light is emitted is given in polar spherical coordinates. The resulting formula is $I(\vartheta, \varphi)$. The distribution of the luminous intensity can be calculated on the one hand from the ray data by simply combining rays which are going in the same direction; and on the other hand it can be subjected to direct or indirect measurement by finding the luminous intensity for various directions (there are more details in chapter 2 page 13), though this methods will only be possible if the detector is far enough from the light source to be approximated to a point source.
If a real light source is simplified into a point source, there will always be a measurement error, which will decrease as the distance from the light source is increased. The distance at which the error becomes negligible is called the limiting photometric distance. This relationship between distance and error is dependent on the size of the light source, the complexity of the light distribution and the size of the tolerable error. For simple sources, such as an area which radiates light homogeneously, the relations are comparatively simple to calculate. The error will drop to below 1% if the distance measured is at least ten times greater than the maximum extent of the source (cf. [Hen94]). If the light distribution is more complex, as in the case of car headlamps, the assumption from the first will be that the limiting photometric distances are quite large. The distance over which to measure in such a case has been generally established as at least 10 m. 25 m is the figure required for measurements of legal relevance. As the surface area from which a headlamp beam exits is usually less than 25 cm, and in the case of projection modules even less than 10 cm, the quotient of distance over source size is > 100.

$$E = \frac{I(\gamma_1)}{r^2} \cos(\gamma_2) \Omega_0 \tag{1.7}$$

1.2. Notation and depiction of the LID

The term "luminous intensity distribution" has been defined already, in section 1.1. Its abbreviation is LID.
The luminous intensity distribution can be represented on a plane or spatially (3D). When representing it spatially, one speaks of the spatial luminous intensity distribution or 3D body. If a cross section is taken of this spatial model and laid flat, one has an luminous intensity distribution curve. It also possible to represent the spatial model or a part of it in the Cartesian manner within the $\vartheta - \varphi$-plane. Here, again, the term usually employed

is LID.

The term LID is used in most situations, regardless of which form of representation has been chosen. This paper, too, speaks of LID for luminous intensity distribution in general. Which form of representation is at the basis of the term is largely insignificant: it will either be clear from the context or explicitly noted.

1.2.1. A, B, and C planes

The A, B, and C planes are polar representations of cross-sections through the spatial luminous intensity distribution. The luminous intensity in these planes is usually standardised to the luminous flux from a lamp of 1000 lm = 1 klm. The section for each plane passes through the centre of the light source. If the light distribution is asymmetrical, several sections will be necessary to provide a clear description. These will then be turned towards each other round an axis passing through the centre of the light source. The direction of the axis of rotation will determine the name given to the section and the angle of rotation the index (cf. 1.2 - 1.3). If the axis of rotation is horizontal and perpendicular to the axis of the luminaire, one speaks of A planes; if the axis of rotation is the same as the axis of the luminaire, the plane is a B plane and if the angle of rotation follows the vertical line from the luminaire, the plane is a C plane.

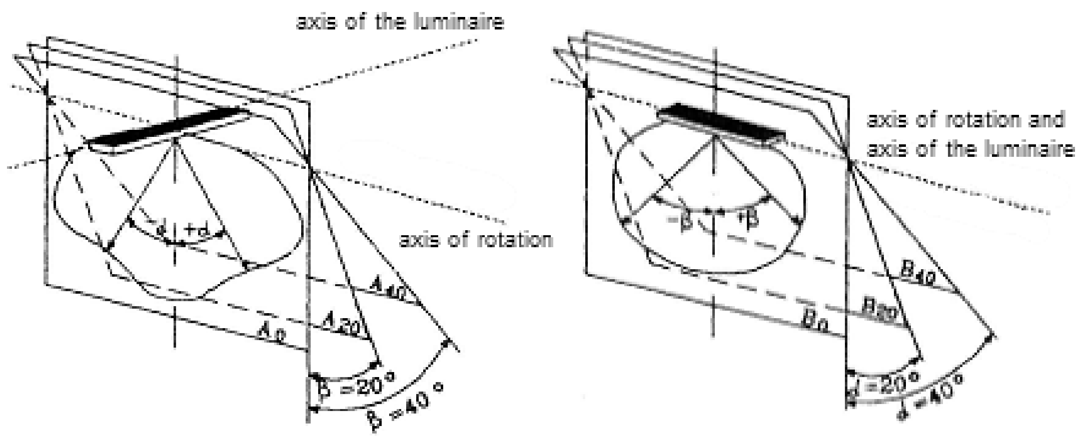

Figure 1.2.: A planes (left) and B planes (right) [www01]

If the light distribution is symmetrical around the axis of rotation, one single cross-section will give a clear description of the distribution. Many lamps and luminaires have light distribution which approximates to being symmetrical around the axis of rotation. In such cases, it is adequate to represent the light distribution as simply as this. The typical description is then whichever "0" plane (A_0 plane, B_0 plane, C_0 plane).

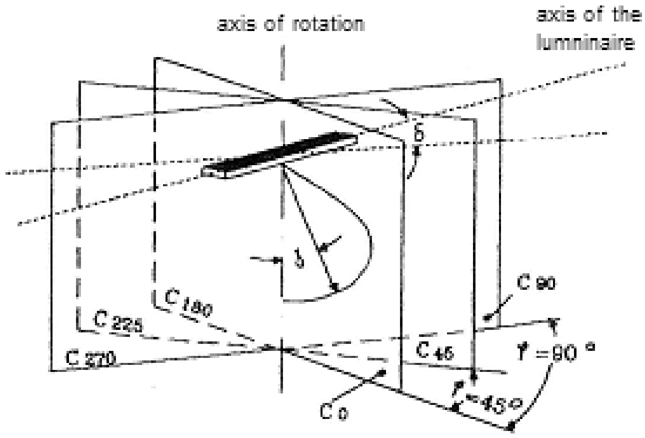

Figure 1.3.: C planes [www01]

Figure 1.4.: Halogen globe lamp with surround

The commonest description is the representation with C planes. Figure 1.5 will serve as an example of the measurement of a globe lamp[1] (to be seen in Figure 1.4) in the C plane. The same LID measurement is shown in Chapter 1.2.3 as a spatial representation (Fig. 1.7) and a projected representation (Fig. 1.6). As is clear from the illustration, the globe lamp was measured in the standing position. As a result, there is no symmetry of rotation to be seen in the representation of the LID in the C_0 plane. Thus, it does not give a full description of the LID.

[1]Halogen lamp with homogeneous light distribution for I($\vartheta = \pm15°$, $\varphi = \pm15°$) = 72cd ±1,5cd

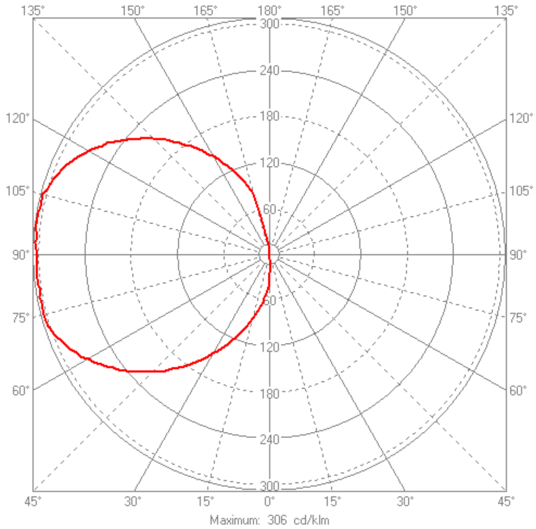

Figure 1.5.: Luminous intensity distribution curve of the halogen globe lamp

1.2.2. Representation in the theta-phi plane

One speaks of a representation of luminous intensity distribution in the ϑ-φ plane if the luminous intensity is graphically represented in a 3-dimensional Cartesian co-ordinate system with ϑ and φ axes. The illustration permits the use of shades of grey or pseudo-colours (see Figure 1.6). This form of representation is often used when it is only necessary to analyse a part of the luminous intensity distribution. An example of this is a highly directional light source or a situation where only the light for a particular solid angle will be relevant in later use. Figure 1.6 shows the luminous intensity distribution of the globe lamp in the ϑ-φ plane.

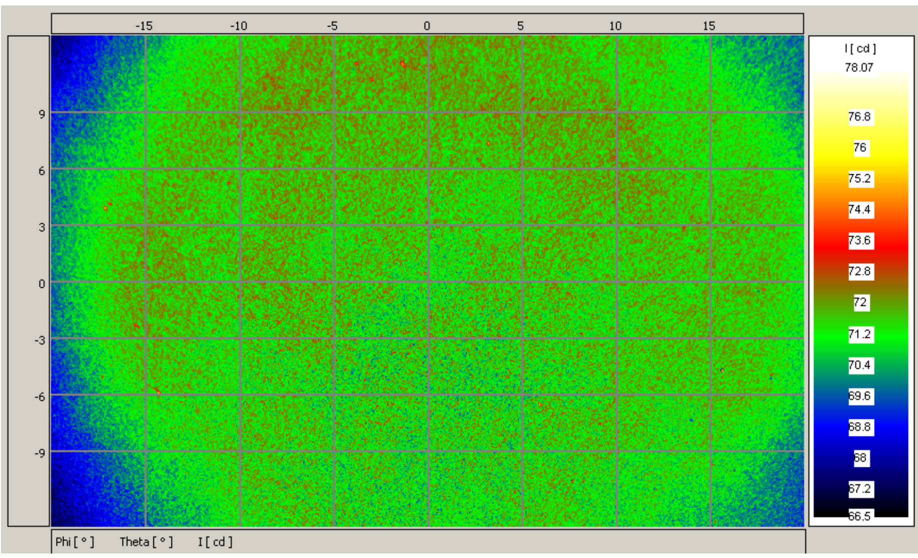

Figure 1.6.: Graphic of the halogen globe lamp in the ϑ-φ plane

1.2.3. 3D body of luminous intensity distribution

The body of luminous intensity distribution is the only way of representing the luminous intensity distribution in 3D. If it is represented by a suitable program, the body can be swung round so that one obtains an idea of how the luminous intensity is distributed spatially. The same body of luminous intensity distribution appears in Figure 1.7 seen from different angles. Unlike a representation using a single plane, the body is always a complete description of the luminous intensity distribution.

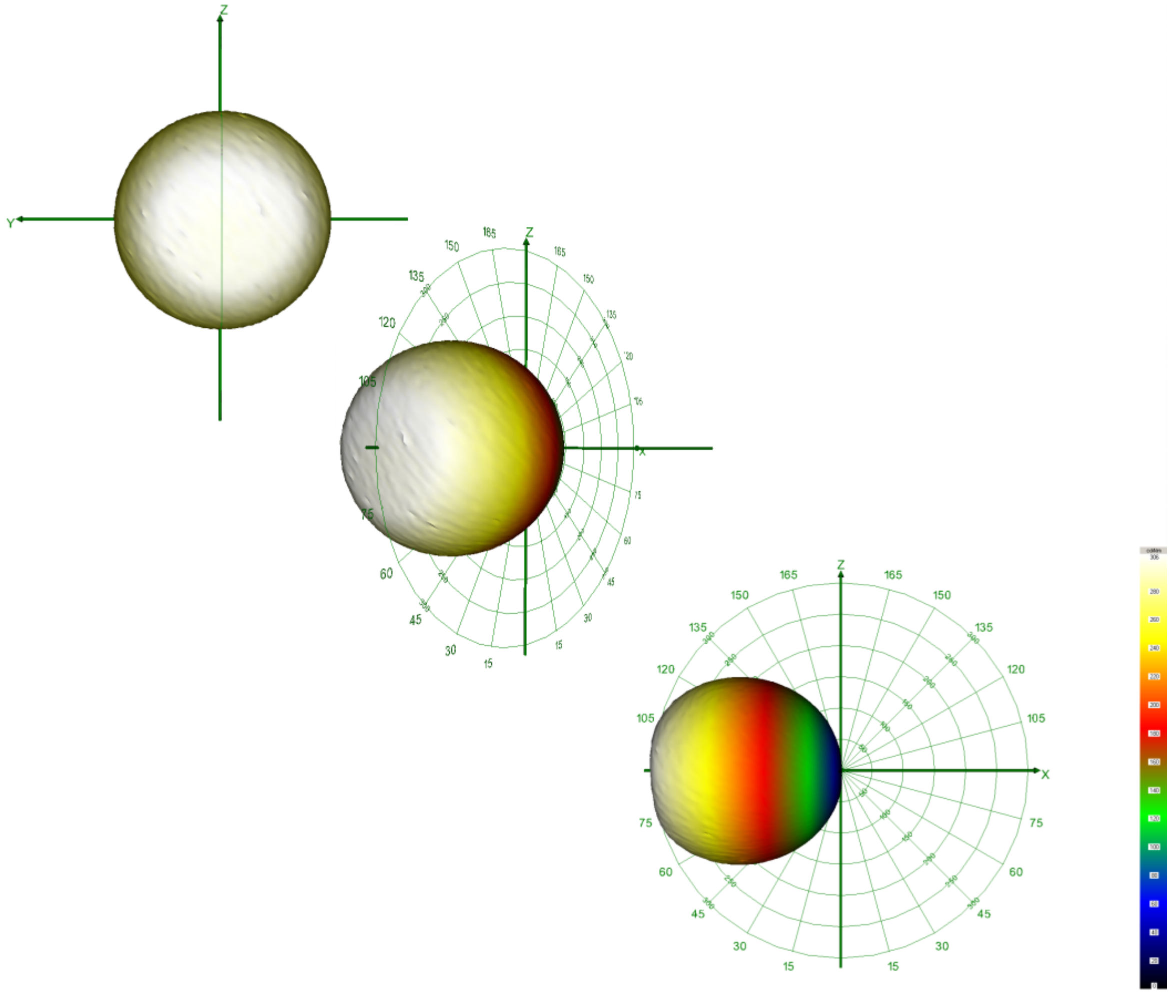

Figure 1.7.: Body of luminous intensity distribution of the halogen globe lamp

1.3. Photometry

A detector is necessary to the measurement of light, and it must either simulate the sensitivity of the human eye (see Figure 1.8) or register the entire spectrum in the visible range, resolving it spectrally, so that it can then be weighted for spectral luminous efficiency for photopic vision.

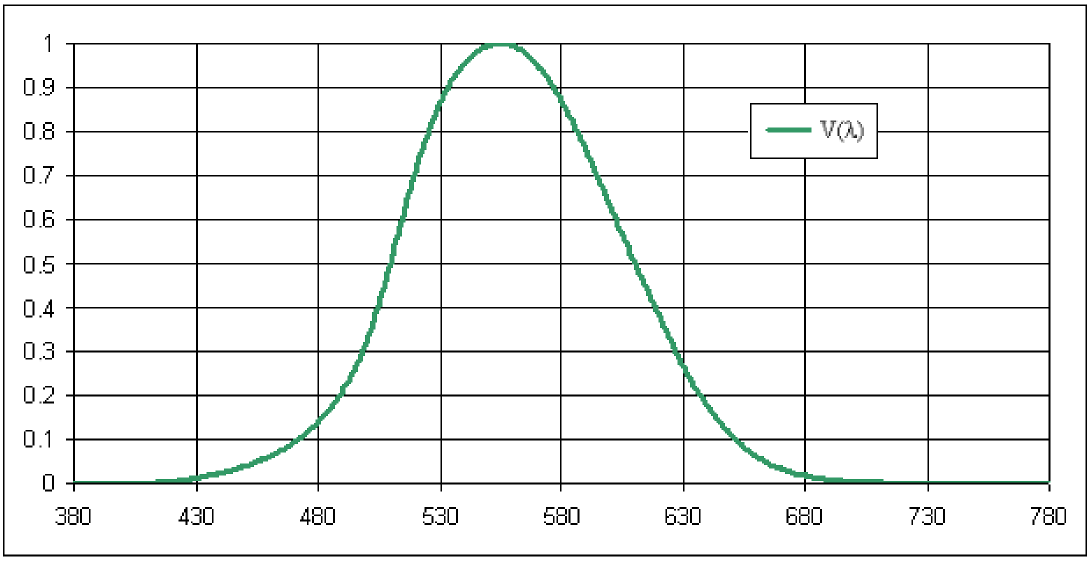

Figure 1.8.: The spectral luminous efficiency for photopic vision

The spectrum can be found with a spectroradiometer, for example. This instrument analyses the light or radiation by splitting it in a prism or grid into its spectral components. However, the spectrum does not play a major role in LID measurement. Only in the case of certain light sources, those in which the light has different colours depending on its place of origin and requires optical elements to be configured in the near field in such a way that the light is transmitted in its various colours, will the spectrum be of possible interest. In this case, less information will frequently suffice, for instance simply the colour coordinates. If tristimulus values for the light source are required, the spectral responsivity of the measurment system has to be matched to the standard colour observer (see Figure 1.9). Thereby the spectral responsivity of the Y channel is equivalent to the spectral luminous efficiency, $V(\lambda)$.

There are no detectors which directly recreate the spectral luminous efficiency of the human eye. Normally a detector is used which is sensitive to radiation across a wider range and this is fitted with additional filters to reduce incoming radiation and weight it as appropriate. It is possible to make a spectral adjustment with the assistance of full or partial filters. Both methods involve the use of several (glass) materials in order to achieve overall $V(\lambda)$ sensitivity. If a partial filter is used, only parts of the receiver are covered by each individual glass, which means that the radiation entering should be as homogeneous as possible. Adopting such parts permits very accurate adjustment to $V(\lambda)$: ($f_1' < 0.8\%$)[2].

[2]quality index for the deviation in the relative spectral luminous efficiency of $V(\lambda)$ (For details, see DIN

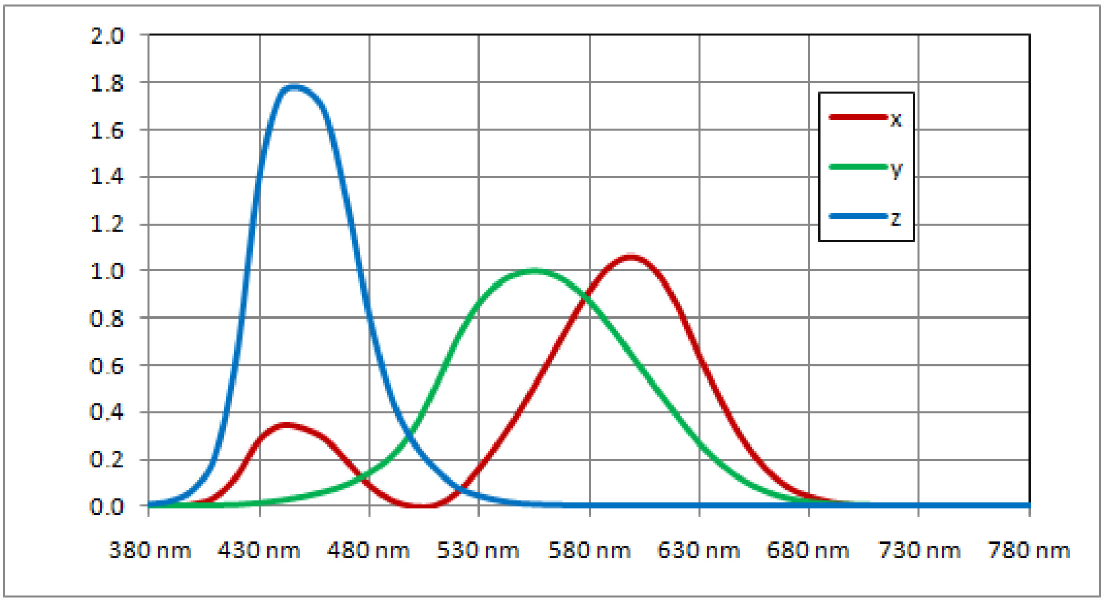

Figure 1.9.: CIE 1931 standard colorimetric system

However, what is obtained a single value without any spatial resolution. Partial filters are predominantly used in the photometer heads of angular photometers (see chapter 2). For colorimetry purposes the sensor heads may be fitted with 3 partial filters (for X, Y and Z).

Figure 1.10.: LMT Pocket Lux 2; manual lux meter [www02]

Like partial filters, full filters are also made up of several glasses but this time they are behind one another and equal over the full size. Unlike partial filters, however, they can be used not only in individual detectors (such as the manual lux meter, cf. Figure 1.10) but also in combination with a matrix detector (CCD or CMOS) in a camera capable of spatial

5032 part 6 and/or CIE Publication 69)

resolution. The CCD matrix, being a detector sensitive to radiation (for the sensitivity, see Figure 1.11), changes the elements of radiation falling on it into signal charges in accordance with its spectral sensitivity.

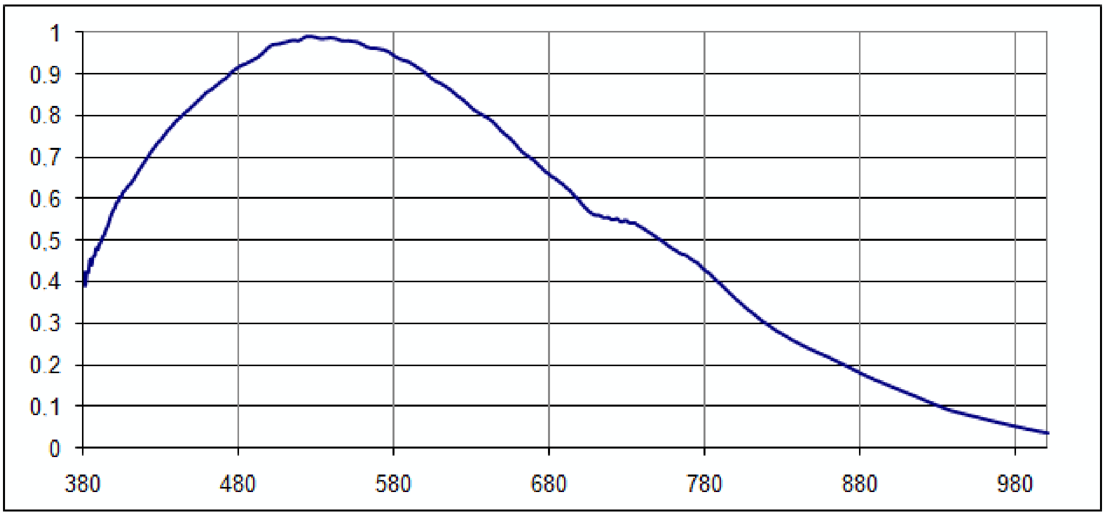

Figure 1.11.: relative spectral sensitivity of a CCD sensor

If the system is intended to carry out photometry, the spectral sensitivity of the overall system must be V(λ). For every camera a full filter is installed for this purpose which, out of the spectral sensitivity of its CCD matrix and the spectral transmission from the lens, will produce the standard sensitivity of the human eye (see Figure 1.12).

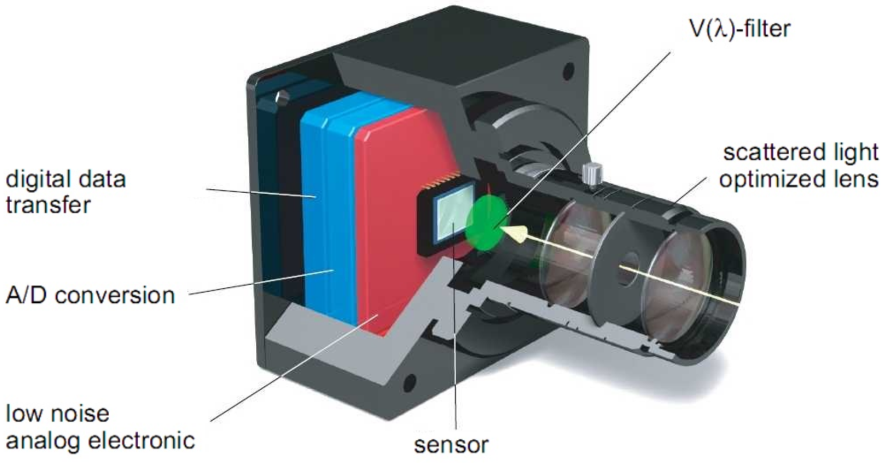

Figure 1.12.: Luminance measuring camera with V(λ)-filter [www03]

The spectral sensitivity of the CCD matrices must be measured in each case, because even samples from a single batch may vary considerably. On the CCD chip itself the issue of

spatial resolution is negligible, but the dependence of the spectral sensitivity on the angle of entry of the light rays (the field angle of the lenses used, measured on the image side) must be tested and if necessary taken into account for the design of the filter [FS09].
In principle, it is not possible to achieve as fine a V(λ) adjustment with full filters as with partial filters. The nominal value of f_1' is, at less than 4%, above that of a good partial filter.
If colour is being measured, several filters must be used as in the case of partial filtering. There is the possibility of using several detectors each with a different colour filter for a colour measurement camera (the multi-chip camera) or positioning the various colour filters behind one another in front of a detector (the filter wheel camera) and measuring in sequence. Figure 1.13 shows a filter wheel camera of this type made by TechnoTeam.

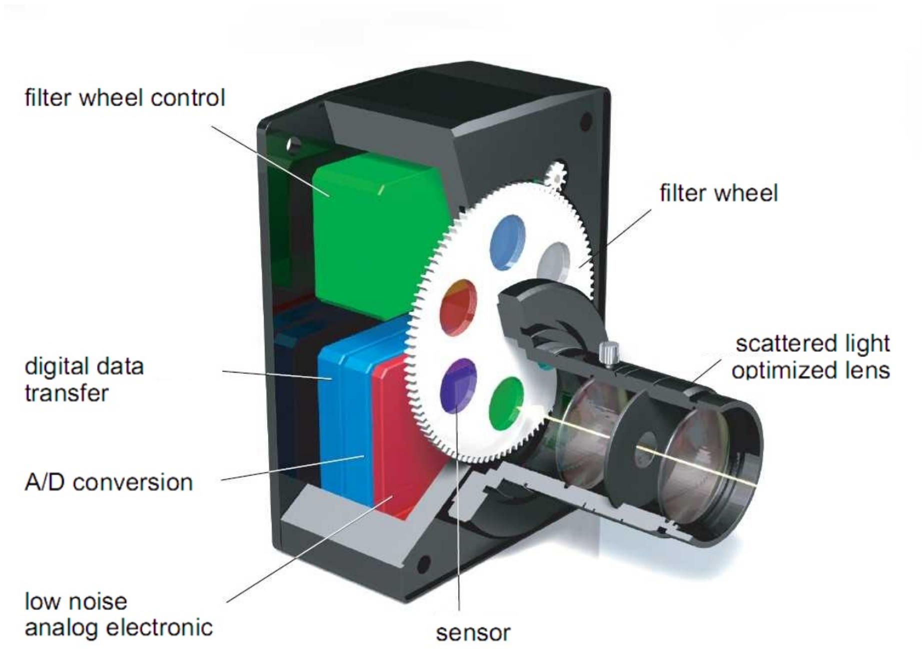

Figure 1.13.: Colorimetric camera with 4 full filters for colour [www03]

It is possible to use spectrally not matched measuring systems as an alternative to spectrally adjusted systems. However, they must be calibrated to the light source requiring measurement and are not suitable then for the photometry of other light sources. The accuracy will accordingly be less and as it is not possible to use them for any particular light source without a priori information, they will not be discussed further here.
Different detectors or at least different filters will be required for different ranges of radiation. As a CCD also possesses sensitivity outside the visible spectrum (see Figure 1.11), the detector can also be used for measuring radiation in that range. In the case of the TechnoTeam filter wheel camera, for instance, it is possible to integrate an IR filter into the filter wheel.

2. Measuring the LID

It is possible to measure the LID in the far field and in the near field. If one carries out the measurement outside the limiting photometric distance (cf. section 1.1), the term is far-field measurement and otherwise one is measuring the near field. The sections which follow provide an overview of the currently available measurement technology for the far and near fields.

2.1. Far Field

There are many and various measurement techniques for the LID measurment in the far field. They can basically be divided into two groups: direct (subsection 2.1.1) and indirect (subsection 2.1.2) LID measuring techniques.

2.1.1. Direct LID measurement

When LID is measured directly there will be at least one light-sensitive detector (or photometer head) at a defined distance from the light source being measured and it will be illuminated directly by the source. The sensor will measure the illuminance and from the known distance the luminous intensity can be calculated using the photometric law of distance (Equation 1.7) without further information. The relevant angle (ϑ, φ), will be obtained from the relative positions of the light source measured and the detector. To find the luminous intensity at another angle it is necessary to make the relevant change to the relative positions of the measured source and detector. This involves either moving the detector around the light source or turning the light source or redirecting the relevant bundles of rays to the detector. The light source is thus scanned sequentially. Photometric instruments which use this rotation of the detector or light source in order to obtain the light intensity sequentially are called goniometers. If the detector is a photometer, the whole apparatus is called an angular photometer or photogoniometer. It is possible to use colour measurement heads instead of detectors, to measure colour, or spectrometers, to measure the spectrum, or, indeed, other sensors. Normally the scanning takes place on the surface of a sphere with the distance between detector and light source measured remaining constant during the changes of relative position. In most pieces of equipment, the scanning grid can usually be variably set so that the resolution can be adapted to the requirements of the light source measured.

2.1.1.1. Luminaire turning device

When a luminaire turning device is used, the light source being measured is rotated round two axes which are perpendicular to each other and coupled together, i.e., one of the axes

is fixed in the space and the other is turned by it at the same time, thus changing its position. The position of the detector is fixed in the space at a defined distance from and perpendicular to the fixed rotating axis. It is necessary to distinguish which of the rotating axes is in a fixed relation to the space. Each of the rotating axes produces a different set of spherical coordinates. Though the different spherical co-ordinate systems are not identical to each other, but they can be transferred back and forth without confusion.
Depending on the measuring task or on the type of subject requiring measurement, the measuring distance and the position of the rotating axes in the space will vary from one luminaire turning device to another. A variant frequently met is that used in the measurement of headlamp beams as required by law. This will now be taken as an example of the basic construction and functioning of a luminaire turning device. There is a diagram of this type of goniometer in Figure 2.1 and a photograph of a sample made by Optronik in Figure 2.2.

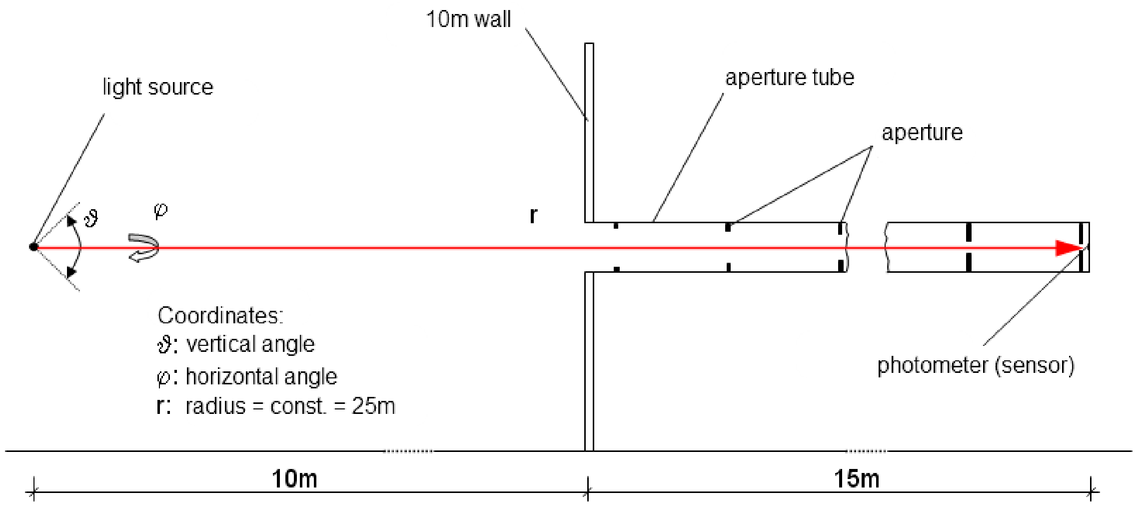

Figure 2.1.: Diagram of a goniometer system used for car headlights, side view

There are three axes of translation in this type of goniometer (left-right, up-down and back-forth) and two axes of rotation, coupled together. The horizontal axis of rotation is fixed in the space. The detector, or photometer head, is at a distance of 25 m. It usually has a diameter of 30 mm, producing angular resolution of approx. 0.07° at a measuring distance of 25 m. Before the measurement is carried out, the light centre[1] from the head lamp is aligned with the intersection of the two rotating axes (i.e. the pivotal point) and raised to the level of the detector 25 m away, with the help of the translational axes. There is a screen between the goniometer and the detector, 10 m in front of the goniometer, and it has a hole in the centre which is 30 cm in diameter and to which a tube 15 m long is connected. Among the purposes of the screen at 10 m is its use in helping to position the headlamps and to assist visual assessment of the light distribution. This type of goniometer

[1]Frequently, the centre of the lamp or a virtual point behind the light source is selected for this. However, as the measuring distance is so great in these cases, the errors arising from very slightly incorrect positioning are negligible.

Figure 2.2.: Optronik SMS10C luminaire turning device; front view [www04]

can usually be swung through $\pm 90°$ either horizontally or vertically, It will also function with great accuracy in most cases ($0.01°$ being the smallest interval available).
So that the detector measures only the specific bundle of light emitted by the headlamp below the angle which has been set, there are several apertures within the 15 m tube to shade against intrusive or stray light. The smallest value for illuminance that can be measured by this type of goniometer is approx. 0.001 lux, which equates to 0.625 cd at the 25 m measured distance. The reproducibility of the measurement is very high ([Sch05] Chapter 3.1). The construction is very effective from the photometric point of view, because of the apertures tube, but at the same time it takes up a huge amount of space.

2.1.1.2. Goniophotometer with mirror arrangement

The goniometer with mirror arrangement or also rotating mirror goniometer basically consists of a rotatable lamp holder, a rotating mirror and a photometer. The measurement procedure is to guide the lamp with constant orientation but on a radius round the rotating mirror, which directs the light towards the photometer head. The centre of the mirror is at the pivotal point. The spectral modification produced by the mirror is compensated for by a special adjustment of the photometer head to the spectral luminous efficiency curve of the human eye [www05]. The photometer is set up in a fixed position, but as with the lamp rotators, in a different position for each version. Scattered light is reduced by various apertures in the measuring space. Figure 2.3 shows the construction of a goniometer of this type and there is a photograph of an LMT version in Figure 2.4 (left).

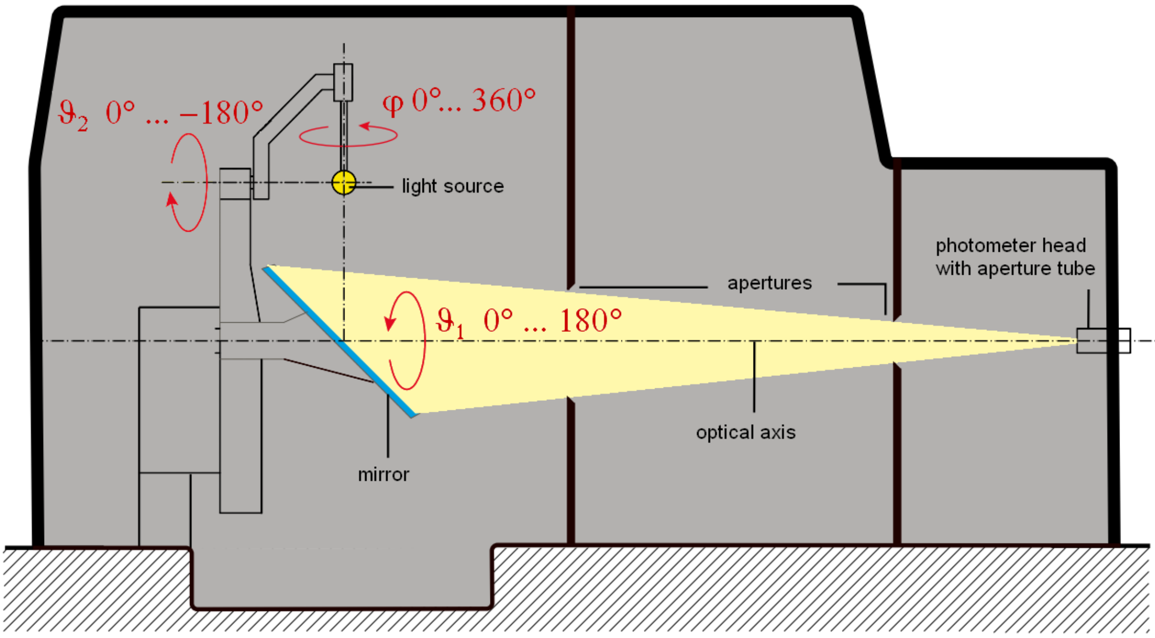

Figure 2.3.: Diagram of a goniometer with rotating mirror, side view [www05]

A rotating mirror goniometer usually has three axes of rotation. The first is a horizontal, theta axis (ϑ_1) which follows the optical axis and has the rotating mirror centrally upon it. This axis rotates the mirror and at the same time the arm on which the second theta axis (ϑ_2) is fixed by means of the lamp or luminaire arm. The second theta axis rotates in the opposite direction to the first, always through the same angle, in order to compensate for the tilting. The light source being measured is rotated solely on the phi axis (φ) on the horizontal.
There are, alternatively, rotating mirror goniometers in which it is not the light source which is moved on a circuit around the mirror but vice versa. An instrument of this type is shown in Figure 2.4 (upper right). In this case there is only one theta axis, positioned on the same level as the centre of the light source to be measured. The tilted mirror is turned around this axis and around itself. This photometric device is also known as a eccentric goniometer with rotating mirror. This type of construction makes it possible to increase the distance between the lamp and the mirror and at the same time to reduce the overall height of the construction, which, above all, will reduce zig-zag reflections between the lamp and the mirror ([Mar97]). The opening facing the photometer head is then either conical so that the light can be captured from the various spatial positions (in which case there is a rotatable scattered light aperture between the photometer and the goniometer,

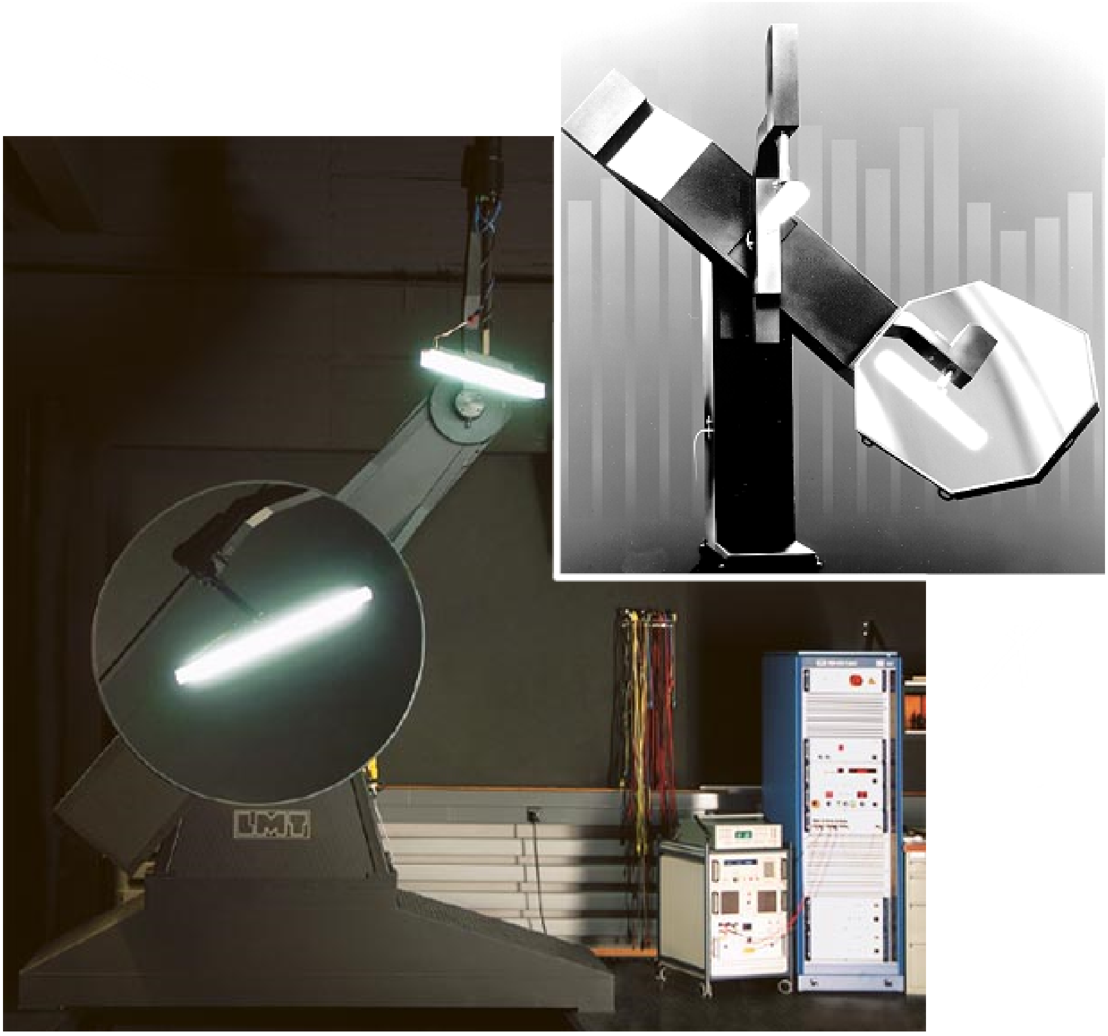

Figure 2.4.: goniometer with mirror arangement: left - LMT[[www05]; top - LightLab[www06]

which will cut off the segment being detected by the photometer to match the mirror position), or the detector and tube together are turned synchronously with the mirror and with the same radius.
The mirror goniometer is a borderline case between the groups of direct measurement techniques for LID, as the mirror, viewed as a medium, is actually in the path of the radiation. However, as the influence of the mirror on the spectrum is compensated for, and the light is directionally reflected and the illuminance can be measured directly, it is counted more as a direct than as an indirect technique.

2.1.1.3. Others

In order to be able to avoid moving the light source at all or to move it only within the plane of gravitation, as is the case with the mirror goniometer, there are a number of devices which manage without an additional medium, the mirror, in that they move the

detector around the subject of measurement. These techniques are only applicable to small light sources with a short limiting photometric distance, as the equipment would otherwise be too large, too impractical and too expensive.
The compact goniometer shown in Figure 2.5 rotates the light source solely around its vertical axis. The detector travels on a circuit with axis of rotation perpendicular to the vertical axis of rotation of the light source, around the object. A goniometer like this can be used to establish the LID of smaller light sources. Larger such subjects, as in the illustration, do not permit of observation of the limiting photometric distance and so using this instrument it is only possible to establish an integral value such as the total flux.

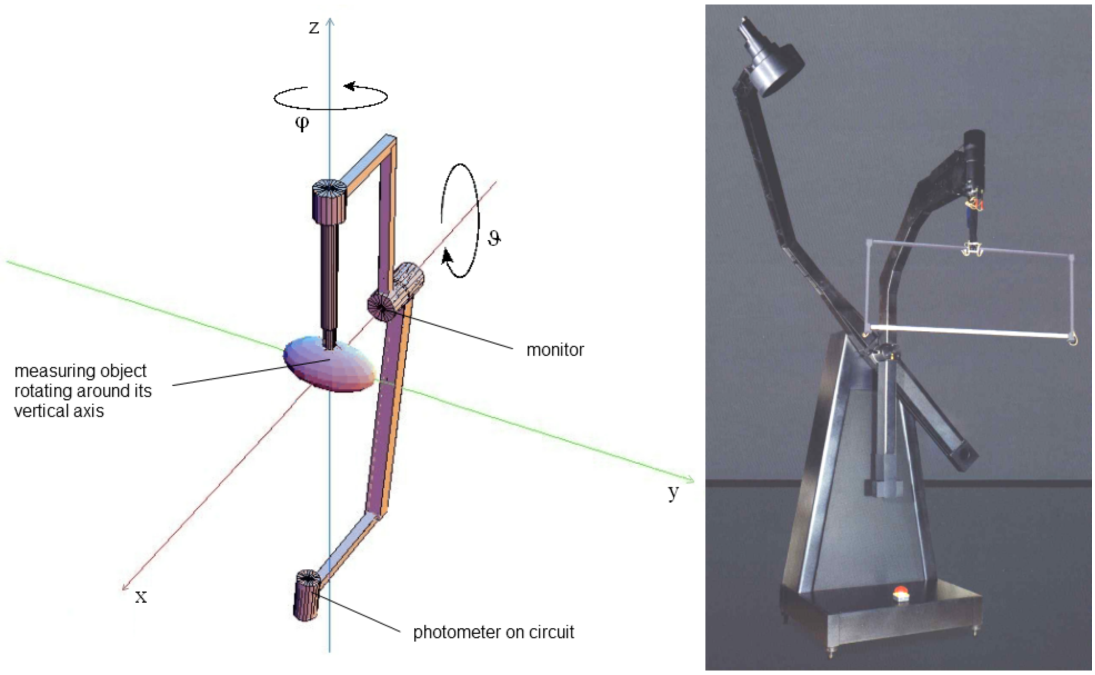

Figure 2.5.: LMT GO-FI 2000, left - diagram, right - front view [Lin08]

To bring the subject into a chosen burning position, and to measure the LID while stationary at that position, a goniometer with more degrees of freedom is required. Examples of these are the PTB[2] cardan and robot arm goniometers and the near-field goniometer (cf. section 2.2),which can, of course, also be used as a far-field goniometer for smaller measured subjects.
The cardan goniometer (Figure 2.6) has an external frame (known as an alpha frame) within which the light source can be positioned at various burning positions. The two internal frames (the theta and phi frames) travel on a spiral track around the light source in order to carry out the measurement. The angle speed of the frames is variable but remains fixed during the measuring process. The frames are suspended on a cardan shaft and possess a radius of approximately 2.5 metres. A variety of detectors can be used, photometer, colour detector or spectro-radiometer [Lin08].
The PTB robot arm goniometer has three robot arms (compare the illustrations A.1 and

[2]PTB - Physikalisch-Technische Bundesanstalt (the German national metrology institute)

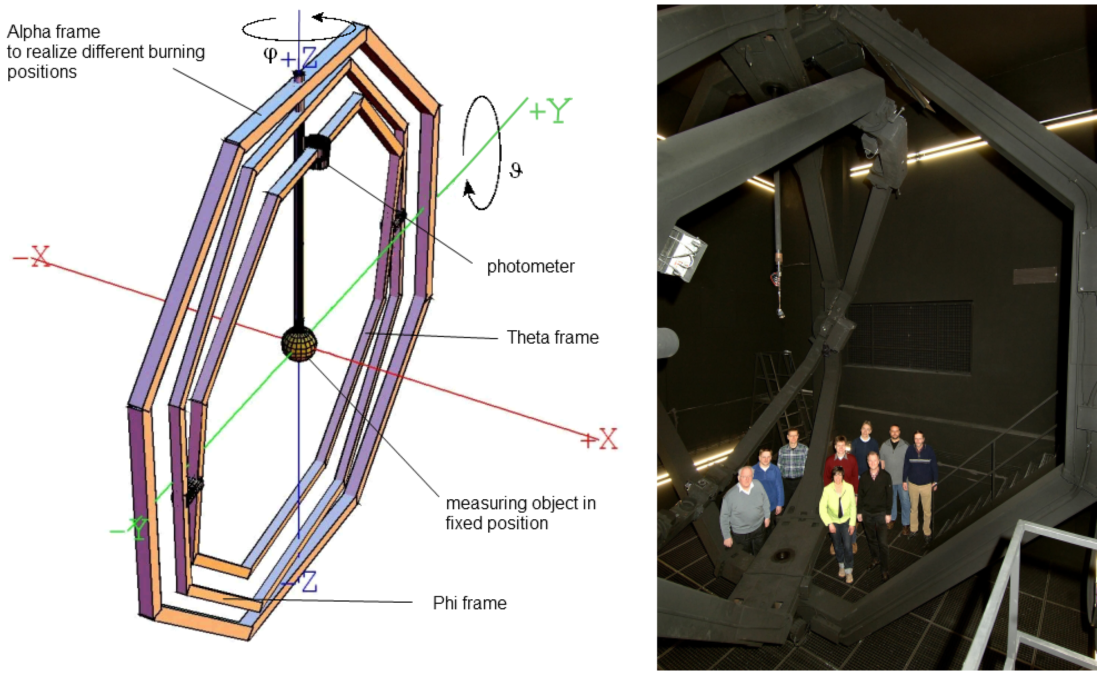

Figure 2.6.: Kardangoniometer: links - Schema; rechts - Ansicht[Lin08]

A.2 in the appendix). One arm is used freely to position the light source. It will bring the subject into any burning position and fix it there. Both the other robot arms have four joints and each of them can be extended over half of the space with a diameter of between 0.5 and 6 metres. The procedure is a dynamic measurement along a track, as a stop-start method would be far too slow. The calculation necessary from the movement of the joints can be at times very complex (compare the illustration A.3 in the appendix). There is no general procedure available to achieve the solution. Sometimes the method is used is analytic, sometimes a numeric approximation. The detectors used can here again be photometers, colour detectors or the sort of detector that will register spectral or radiometric data. [Rie03] [Lin08]

2.1.2. Indirect LID measurement

When the LID is measured indirectly, the illuminance is not measured directly but an intermediary is placed in the path of the radiation beyond the limiting photometric distance. The materials used for this are usually those with lambertian qualities (i.e. diffuse and scattering) and which are spectrally neutral. The intermediary is then subjected to spatial resolution and captured using a luminance measuring camera (LMK[3]) or a colour measurement camera (LMK-Color). This method involves the use of either diffusely reflective surfaces or light scattering discs (cf. chapter 4), depending on the measuring task and the construction which is possible in the circumstances. In the first case, the camera will view the intermediary from a position within the same half space as that from which it is illuminated. In the second case, the camera is usually positioned opposite the light source

[3] german brand name, LMK - Leuchtdichtemesskamera

behind the light scattering disc on the optical axis. Depending on which solid angle area is projected onto the intermediary and captured by the camera, the size of the partial LID will vary. If the size of the segment is not adequate to the application, it is possible to swing the light and capture different sections of the LID. Although it would be possible to capture the whole polar sphere by this rotation, the equipment found in practice is usually fixed or in a few cases permits the light source to be moved several times through fixed angles.

2.1.2.1. Digital image processing measuring station

If light is allowed to radiate from the measured light source onto an intermediary beyond the limiting photometric distance, the flux reaching the intermediary produces illuminance. From this results a luminance, which can be spatial resolved and measured. Then from the image of the luminance and with knowledge of the geometrical relations (the position of the light source, the intermediary and the camera), the corresponding image of the illuminance and the LID can be calculated. Because the calculation of the LID is achieved via an additional intermediary and is derived from pixel coordinates based on luminance measured, the method is defined as indirect measurement of LID. Additional information and steps in calculation are necessary to conclude from the luminance in the camera coordinates system the luminous intensity which is dependent on the angle. Figure 2.7 makes the measuring principle clear, taking a headlamp measurement as the example. Here the typical photometric distances are 10 metres and more. In other applications, as, for example, LED measurements, considerably shorter photometric distances are adequate.

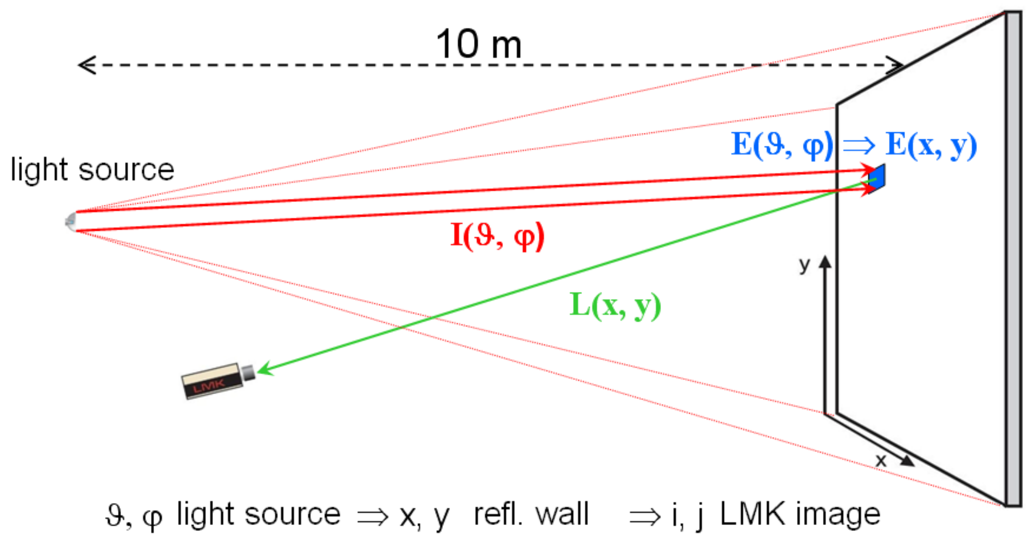

Figure 2.7.: Principle of indirect LID measurement

If the reflection is only diffuse, the intensity of illumination will not be a function of the direction of the beam

$$L(x, y, \vartheta, \varphi) = L(x, y) \neq f(\vartheta, \varphi) \quad (2.1)$$

but will be constant for different sets of measuring equipment and directly proportional to the exitance intensity E(x, y)) with a conversion factor of k:

$$\mathrm{E}(x, y) = \mathrm{L}(x, y) \cdot \mathrm{k} = \mathrm{L}(x, y) \cdot \frac{\pi \cdot \Omega_0}{\rho} \quad (2.2)$$

ρ - reflectance

2.1.2.2. Compact measuring station

The compact measuring station (CMS) is based on the same principles as the digital image processing measuring station. In addition a optical imaging system reduces the photometric distance by imaging the light distribution into the focal plane. Any rays emitted in parallel by the light source are imaged on one point by the imaging system. Rays emitted in parallel at a different angle will be imaged on another point within the focal plane. The imaging system must be set so large that absolutely all relevant bundles of rays strike the lens fully and are imaged onto the focal plane. If the focal plane is then registered with its spatial resolution, and if the geometrical and photometric relations between the light source (in spherical coordinates) and the focal plane (in camera coordinates) are known, the luminous intensity can be calculated from the image of the luminance. To assist with light scattering, reflective walls or diffusion screens are used in this case also. Figure 2.8 shows the measurement principle of the CMS.

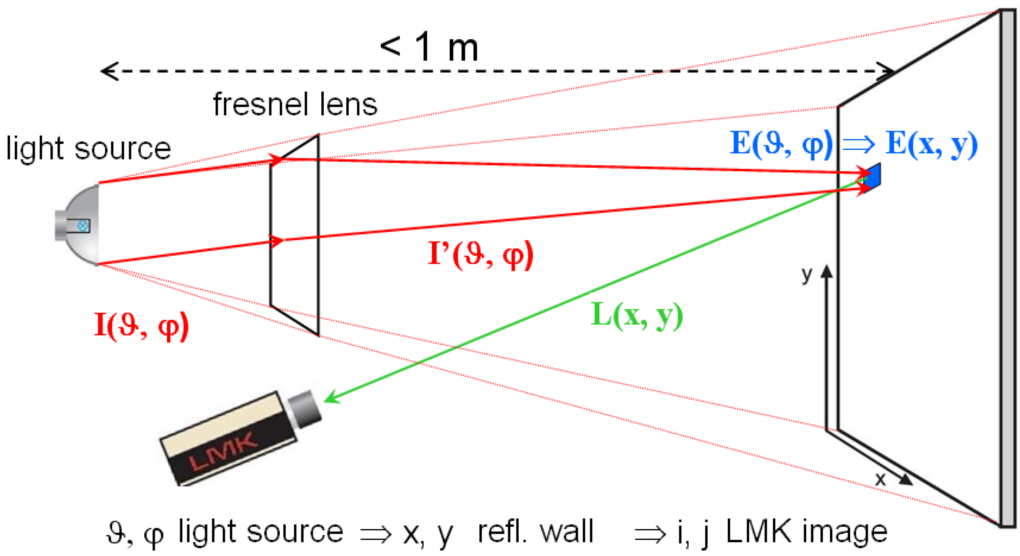

Figure 2.8.: Principle of indirect LID measurement using the CMS

If the photometric distance at, for example, a digital image processing measuring station for a car headlamp is 10 m, a CMS will enable that distance to be reduced to 40 cm. Depending on the light source being measured, and the optical imaging system this permits, the photometric distance may be shortened even further. The space required as a result is then very compact.

As optical imaging systems deviate in reality from the theoretically ideal features, there are certain limits to the light sources which can be measured. The size of the light source will play a significant role because there are limits to the size of the imaging system which is both reasonable in price and high in quality. Fresnel lenses will therefore often be used as the imaging system. These can be obtained to an adequate size as standard (60 cm or more) but do bring a risk of error from the edge interference which is a condition of their principle. It is possible to use achromatic lenses or lenses with a larger aperture as an alternative. Their opening is considerably smaller than that of the Fresnel lenses (smaller than 10 cm), but they have been chromatically corrected so that colour measurement is possible and as they have no edge interference they do not have the associated error.
Depending on what they are used for, the CMS can have a casing and addtional apertures/diaphragms to reduce interference from ambient or scattered light. Figure 2.9 demonstrates a CMS for the measurement of small spotlights. The CMS uses an achromatic lens which can register the LID for light sources with a flux exit of up to 70 mm and an angle of ±20° on the horizontal and ±13° in the vertical plane. The apertures, reflective screen and camera are all contained within the measuring chamber.

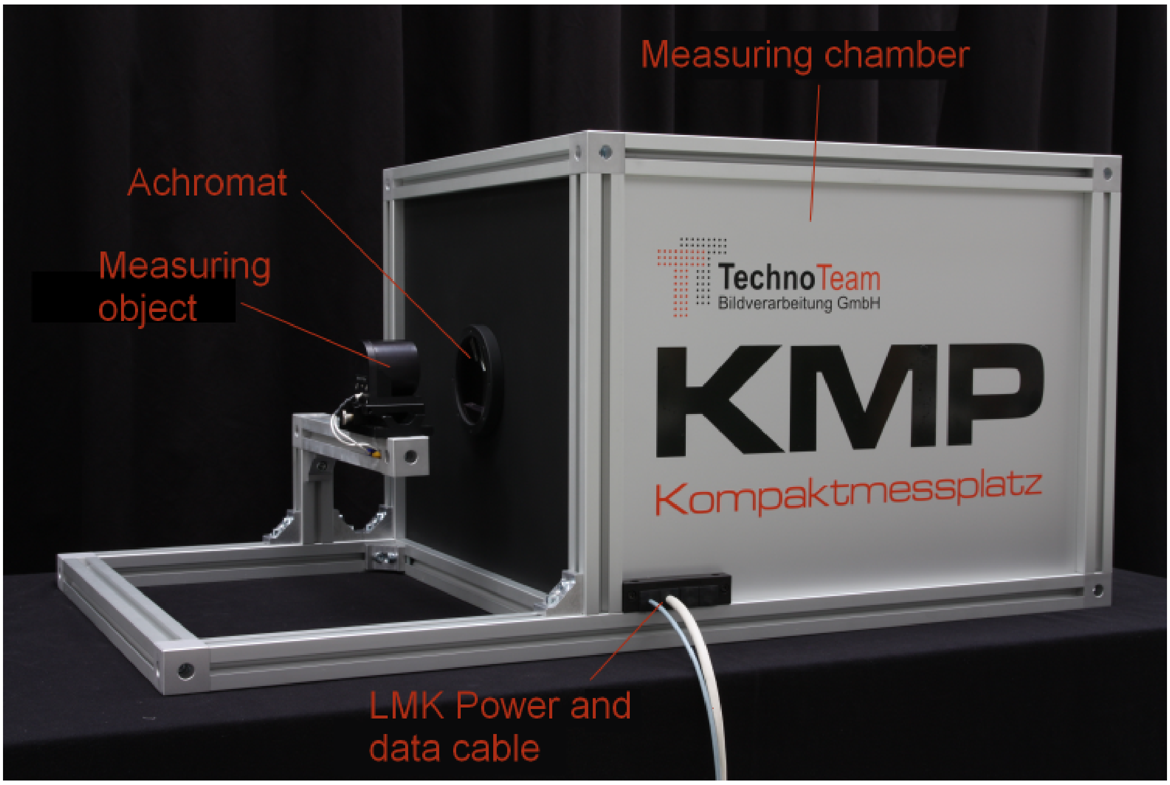

Figure 2.9.: TechnoTeam CMS[4][www07]

It is also possible for a CMP to include a second chamber as an option. This can be called a sample or subject chamber and is where the holder and the spotlight to be measured are positioned. It is also possible to build the LMK video-photometer into this space. Then the imaging system will be between the two chambers.

[4] German KMP - Kompaktmessplatz

2.1.2.3. Imaging Sphere

Different variations on the theme of these two measurement systems of indirect LID measurement are imaginable. For example, one can use a curved rather than a flat reflective surface area. Spatially resolved information at the right degree of accuracy (in contrast to integrated data) can, however, only be obtained with difficulty. Section A.2 of the Appendix describes the disadvantages of curved reflective surfaces in detail.
The Imaging Sphere (see Figure 2.10) is an example of a construction with a curved reflecting surface for use in LID measurement. The light source is positioned centrally beneath a hemisphere of approx 550 mm diameter (or in a differnt model about 10 mm); a camera behind an opening in the hemisphere measures the luminous intensity distribution on the hemisphere via a convex mirror. This technique facilitates measurement of the partial LID of smaller objects such as LEDs. It is also possible to use it to measure segments of displays or the reflective properties of materials. Figure 2.10 demonstrates the construction required for measuring an LED.

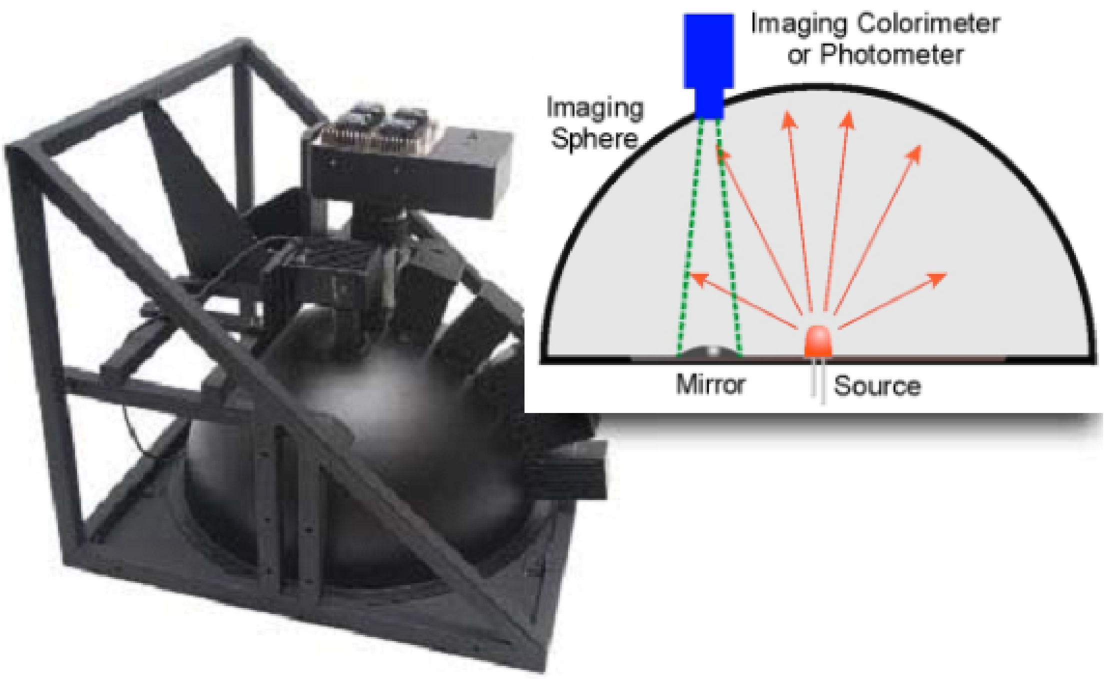

Figure 2.10.: Radiant Imaging´s Imaging Sphere (left) and diagram of an LED measurement (top) [www08] [www09]

2.2. Near field

In the near field, it is possible to use a near-field goniophotometer or a Fourier lens to measure the LID. Both systems work with a spatially resolved detector (for example, a CCD) and can register the origin as well as the direction of the rays.

2.2.1. Near-field goniophotometer

The near-field goniophotometer has a luminance camera which is moved around the light source. The movement can be carried out in relation to the subject being measured and proceeds along a fictitious, closed pod surface which can be created by rotation around at least two axes perpendicular to each other. The luminance measuring camera is directed at the centre of the apparatus, the point of intersection of the two rotating axes. If the distance from this point of intersection is maintained as a constant, the pod is a sphere. It usually has a radius much smaller than the limiting photometric distance. The luminance camera is used to capture luminance in a sufficent number of directions (i.e. points on the virtual spherical surface). [FS09]
If all the figures for luminance in the same direction (ϑ, φ) are integrated, the result is the luminous intensity for this direction (as described already in chapter 1), and thus the LID. Figure 2.11 makes the principle clear using "‘red"’ rays for direction 1 and "‘green"’ rays for direction 2.

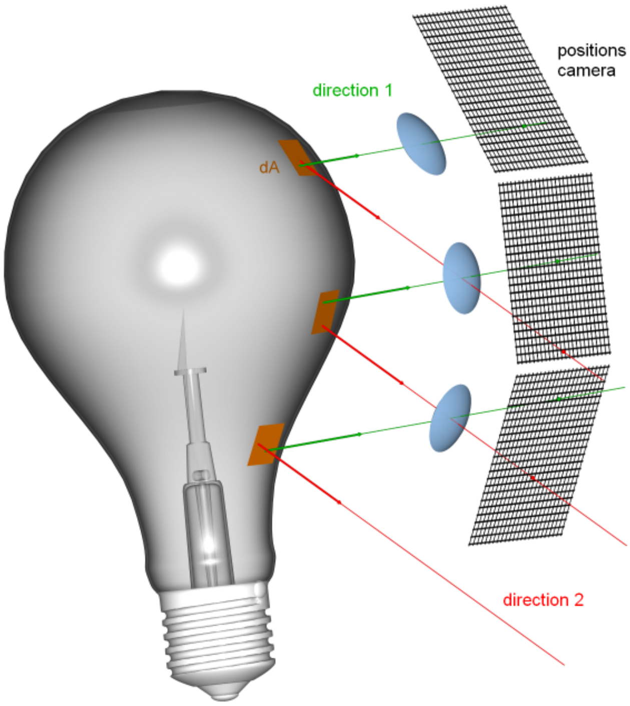

Figure 2.11.: Principle of LID calculation from partial flux elements [www03]

There are various sizes of near-field goniophotometers, depending on the subject requiring measurement and the laboratory space available. The decisive factor is whether the light source fits into the virtual pod described by the camera and can be captured with an appropriate lens so as to fill the picture as well as possible. TechnoTeam has three basic goniometer models in the RIGO801 series available for light sources with dimensions between 6 x 6 x 6 mm^3 and 2000 x 2000 x 2000 mm^3, which can all be scaled to the actual requirements (see Table 2.1).

Application	max. size of subject	Space requirements LxWxH
LED, smal lamps	Sphere of D = 6 mm bis 50 mm	0,6 x 0,6 x 0,8 m^3
Lamps, small luminaires	Sphere of D = 20 mm bis 300 mm	1,3 x 1,3 x 1,9 m^3
Luminaires	Sphere of D < 2000 mm	< 4 x 4 x 4,9 m^3

Table 2.1.: Goniometer model, TechnoTeam RIGO801 series

The smallest of the RIGO near-field goniophotometers is the LED goniometer with a total height of about 70 cm (see Fig. 2.12). This moves the detectors on a circuit around the light source. The angle of rotation in this instance is the horizontal ϑ axis. The rotation in the φ direction is achieved by turning the light source around its vertical axis. This means that the LED goniometer is the only one in the RIGO series which does not leave the light source in a position of absolute rest during measurement. However, the LED goniometer is preferable for LED photometry where rotation in the gravitational plane has no effect on the characteristics of the flux from the light source. The detectors used in the LED goniometer are usually an LMK and a photoelement. It is possible to install different detectors such as a spectrometer or a colorimetry camera. In the φ direction, the angle that can be covered is from 0° to 360°. Because of the holder for the light source, the ϑ angles that can be covered are from -140° to +140° [www03]. The two large goniometers are shown in Figure 2.13. In both cases, the detectors are moved on a spherical surface around the light source being measured. Likewise, the detectors that can be used are a LMK and a photometer at the minimum, as with the LED goniometer. But there are others or additional ones (spectrometers etc) which can be used.

Figure 2.12.: TechnoTeam LED goniometer [www03]

The goniometer for luminaires has an external carrier arm a little higher than two metres. The theta and phi frames are suspended in this. This system, as with the cardan goniometer (cf. subsubsection 2.1.1.3) makes it possible to measure the light source in different burning positions (α). When this is taking place, it is possible to register slightly more than a full circle in the φ direction and slightly less in the ϑ direction (because of the lamp holder).

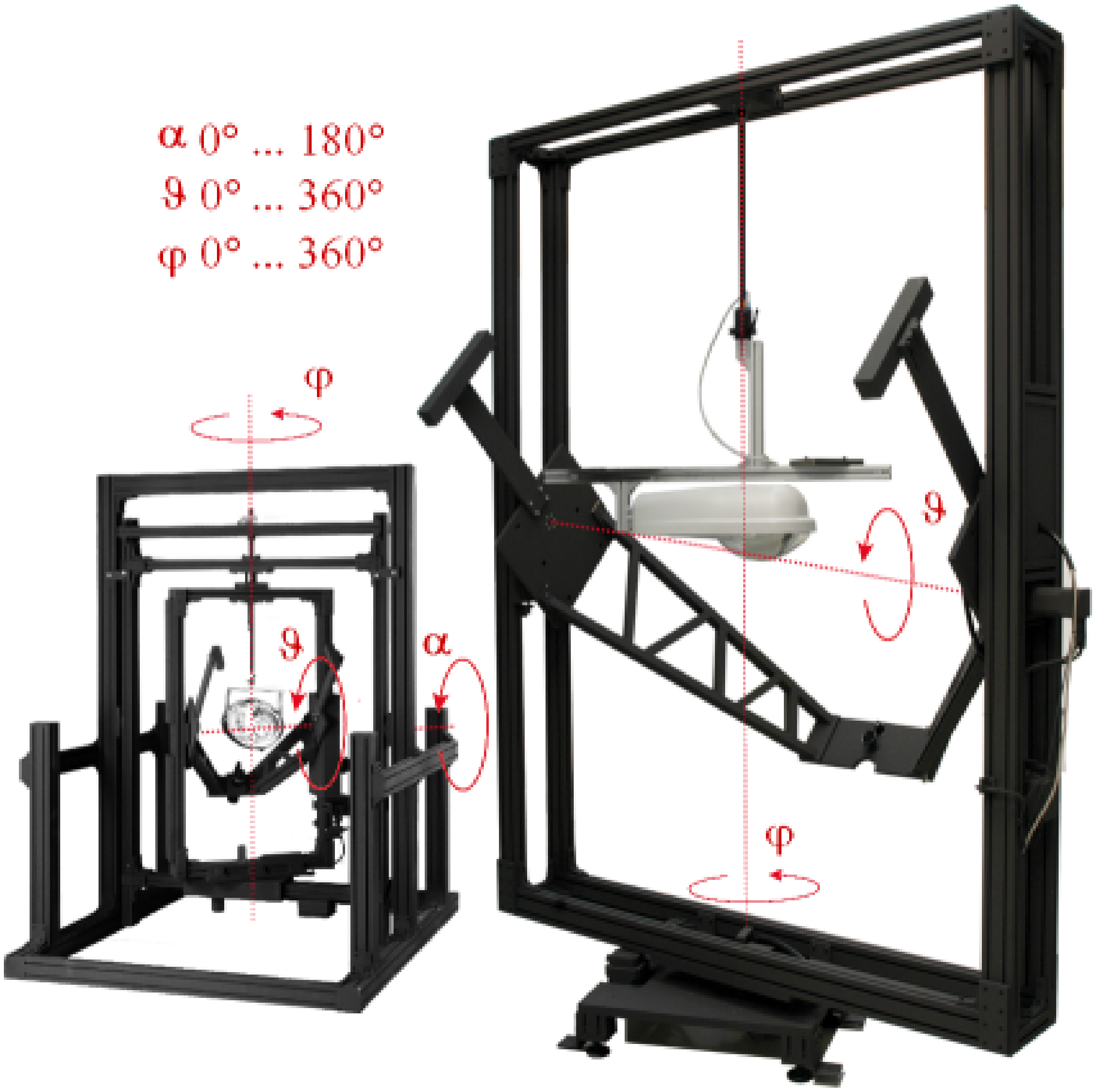

Figure 2.13.: Near-field goniometers from TechnoTeam; left: lamp goniometer; right: luminaire goniometer [www03]

The luminaire goniophotometer is the largest in the RIGO series, having a height of up to 5 metres. The light source being measured can be fixed in it on the suspension bracket attached vertically. This can be installed either at the top or low down, i.e. the luminaires can be measured in a hanging or standing position. The area that can be registered (ϑ, φ) is similar to that for the lamp goniometer.
Das Leuchtengoniometer ist mit einer Höhe von bis zu 5 m das größte aus der RIGO-Serie.

Hier können die Messobjekte in der senkrecht angebrachten Aufhängung fixiert werden. Diese lässt sich wahlweise unten oder oben anbringen, d.h. die Leuchten können hängend oder stehend positioniert werden. Der Erfassungsbereich (ϑ, φ) ist äquivalent zu dem des Lampengoniometers.
If one measures a small subject in a near-field goniometer and its photoelement already contains the limiting photometric distance, it is also possible to measure the LID directly with the photometer without first obtaining the ray data.

2.2.2. Near-field Fourier lens

With the assistance of a Fourier lens, the directions of rays can be converted into localised data in a single plane (the focal plane), as is also the principle of the CMS. If a conoscope is used as the lens, angles of approx ±88° can be imaged. An iris-type filter can additionally be used to set the size of the focal plane, so that the size of the area measured can be varied [CIE]. With an additional relay lens for the exiting light, the plane can be imaged with spatially resolved information on direction at a detector such as a CCD camera. The principle is made clear in Figure 2.14.

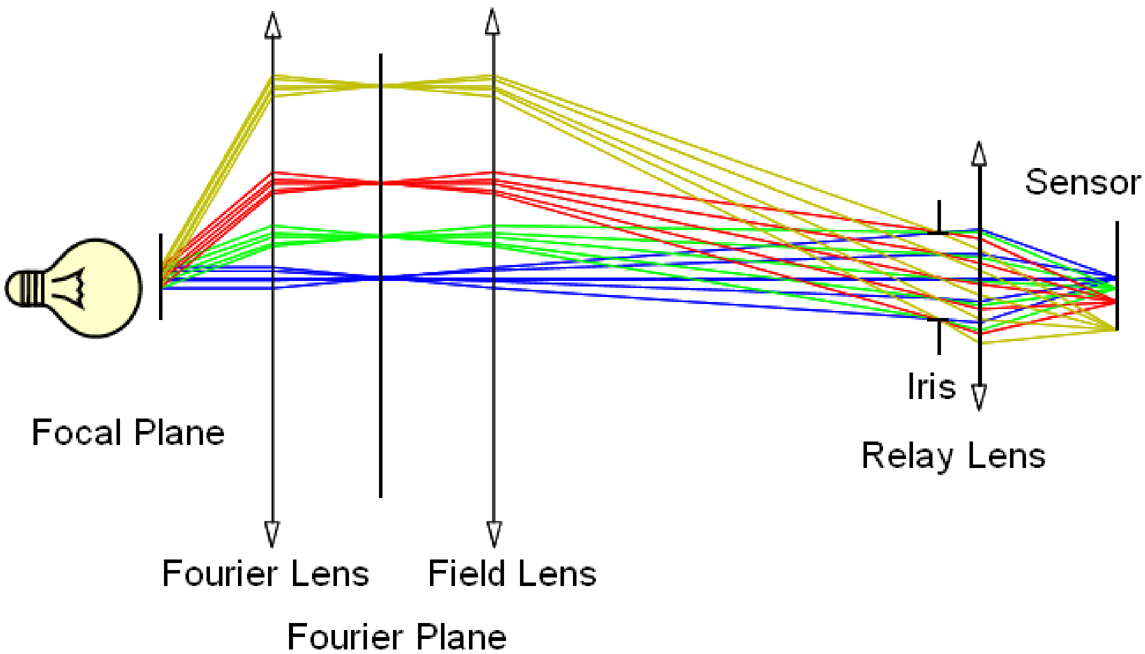

Figure 2.14.: Principle of near-field measurement using Fourier lens [CIE]

All rays crossing the area measured in the focal plane and having an angle less than the maximum that can be measured (±88°) will be registered by the system. If the light source is tiny, with an angle of emission which is similarly small, as in the case of an LED, a single measurement suffices to obtain the LID. If the patch measured is selected with small enough dimensions, the light source can be scanned in front of the Fourier lens using a translatory movement (x, y). The sum of all the measurements will then give the LID and all the individual images taken together will produce the radiation data for the light source. A similar method can be used to measure the LID of larger light sources.

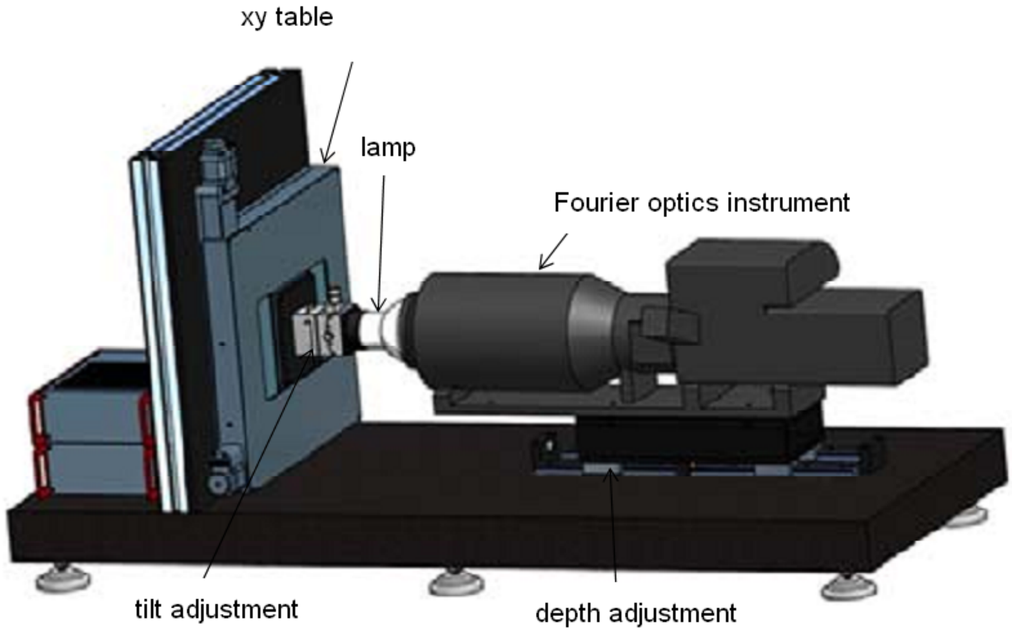

Figure 2.15.: Measuring station with Fourier lens for subjects up to 150 mm [CIE]

As also in the case of indirect LID measurement techniques and the imaging sphere, near-field Fourier lens methods do not permit a full sphere measurement. In contrast to the near-field angular photometers in which the angular resolution is limited by the steps in the motor, near-field measurement with the Fourier lens has the angular resolution limited by the size of the detector and the angular field which can be registered. If a standard CCD with about 1.3 megapixels is used, the angular resolution will be 0.18° if ±88° is the range that can be captured. If the CCD camera has 11 megapixels, it will be 0.06°.

3. Comparison of the measuring techniques

The previous chapter has presented a number of techniques for the determination of the LID of a light source. The present one will go on to show the advatages and disadvantages of the individual methods, so as to assist in the appropriate choice of technique for the measuring task in hand. In section 3.2 at the end of the Chapter, there is a table of the features of the various measuring techniques.
In this question of which measuring technique, the vital issue is, "'What is the information needed?"' - the different methods will provide different data. If radiation data are required, near-field measurement is an unavoidable necessity. If the full body of luminous intensity has to be measured as well, or a very finely resolved angle, the only instrument to consider is the near-field goniophotometer. For small light sources, a limited range of angles and lower contrast, near-field measurement with a Fourier lens is practicable. If only the LIDs are required, there is the choice of a variety of techniques for many of the measuring tasks. The most frequent criteria on which to base the selection include the size and the limiting photometric distance of the light source, the accuracy required, the angular resolution (scanning grid) and the total measurable range (relevant solid angle), the rate of measurement through-put, the space required by the equipment or measuring set-up, and, frequently, others such as the type of light source, the contrast in the LID - or, quite simply, what the measuring system can cost.

3.1. Overview of the criteria

If one is wishing to take measurements for a light source, the features of the light source should at least be known. They will of themselves restrict the choice of measurement method available for use. One vital issue is whether the light source will be moved during the measurement procedure. Certain subjects for measurement will react very sensitively to a spatial change of position (for example, fluorescent lamps, T5). If the change in position will result in an alteration to the characteristics of the beam or flux which is of similar magnitude to the degree of accuracy required, it is essential to avoid moving the light source during the course of measurement. In this case, the only LID measurement techniques that may be considered are those which leave the subject at rest.

3.1.1. Size and limiting photometric distance of the light source

As has already been said in section 1.1, the limiting photometric distance for subjects with homogenous beam or flux characteristics is shorter than for more complex light sources.

If the beam or flux characteristics remain similar, the limiting photometric distance will increase with the size of the subject. It is possible either to calculate the limiting distance (on the basis of radiation data, for instance) or to find it by experiment. If the far field is being measured, the only remaining concern is that the detector is at least within the required distance (cf. Table 3.1, "Measuring Distance"). Here, the size of the subject is only of importance because it affects the limiting photometric distance. Theoretically, therefore, the subjects can be of any size but are limited by practical considerations such as the size and cost of the necessary equipment. For near-field measurement, on the other hand, the limiting photometric distance is of no importance (cf. section 2.2).
The same is true in the case of the CMS, which can theoretically measure in the infinite range because of its optical imaging system. But the CMS is very much affected by the size of the subject requiring measurement, although there may be a variety of imaging lenses that could be used, depending on the relevant details, such as colorimetry or luminous intensity. The lens features will then limit the maximum extent of the area from which light is emitted.

3.1.2. Relevant solid angle

There is no measuring technique which allows a complete sphere to be scanned by means of the equipment so that the light in the whole space can be registered, because there will always be a tiny solid angle blocked by the point from which the light source is suspended. However, as light sources themselves are also usually equipped with pedestals, holders, electricity cables and so on and thus cannot in any case illuminate the entire space, this detail is rarely of any significance.
The relevant solid angle can also be restricted by either the fact that the subject is directed only at a small part of the space or the fact that there is only a section of the emitted light which is of interest. The first fact applies to directional light sources as in the case of halogen spotlights, the second to subjects of which only a certain range of the light distribution is going to be used in the later application. This is true of car headlamps, for example: in certain measuring situations it is only the range of light distribution which will later illuminate the road which requires consideration.
Both cases, of course, need only have the light which is of interest measured, and this can reduce the time needed for the scanning technique and is,indeed, what makes measurement with a technique that restricts the measured area possible at all.

3.1.3. Light source

The type of light source is rarely a factor in the choice. The detector must simply have a layout appropriate to the measurement. Here the CMS is to a small extent an exception. It is affected by the complex relation between beam characteristics, optical imaging system (lens) and type of light distribution, as already described in subsubsection 2.1.2.2, and for this reason it may also be that the type of light source has an effect on the choice of the best optical imaging system. A further factor is the power of the light source. It is not a direct problem for the measurement method. Above a certain power level, however, there may be a heating problem in the case of compact measuring systems in particular, such as the CMS, the imaging sphere and Fourier near-field method. It is thus, for instance, not possible to measure 2 kilowatt headlamps in a CMS. The exact limit will depend on the actual construction of the measurement system and the concentration of the heat. By using suitable auxiliary systems such as passive or active cooling, a certain amount of heat can be transported away and the limit raised.

3.1.4. Relevant contrast

All the measuring procedures presented can analyse homogenous luminous intensity distribution without difficulty. However, if distribution which is rich in contrast requires measuring, there are various factors at play. Today's detectors will provide the necessary dynamics for high contrast in principle. Single detectors will achieve this using several measurement ranges each with a resolution of several bits, and spatial resolved sensors will use different integration times or illumination periods. In addition, neutral grey filters can be used to displace the area of intensity.

Measuring procedures which use a rapid succession of measurements (scanning techniques, for instance) do not usually permit a change of measurement range in the course of a measurement procedure. This limits the dynamic range to the resolution of the measurement range, but this is adequate to most applications.

A further problem is constituted by scattered light in the space. The higher the relevant contrast, the more closely attention must be paid to preventing any light from the bright areas being measured at the same time as the dark areas of the LID because of (zig-zag) reflection. The far-field goniometers usually solve the problem with filter tubes. The most efficient example of this is the goniometer used for headlamps (cf. subsubsection 2.1.1.1). If there is little or no limit to the solid angle range that can be measured as in the case of more compact goniometers, care must be taken that the environment is made black enough to have the effect of weakening rays of light from bright areas before they are reflected towards the detector.

For the indirect measuring techniques, the scattered light in the space can be reduced to a negligible level by suitable apertures/filters and blackout. This is not possible in the case of the Imaging Sphere because of the problems with curved reflecting surfaces. There will residual scattered light which can only be calculated out of the image by means of correction algorithms which are based on exact knowledge of the scattered light relations.

In addition to the scattered light in the space, techniques with spatial resolution also have the problem of scattered light inside the receiving system (the lens, the CCD detector, the filter), which will also reduce the contrast. Depending on the lens, contrasts greater than 1:100 will not be measurable without suitable correction algorithms. Depending on the correction method, the measurable contrasts can be increased by a factor of 10.

Apart from the contrast which is present in any case, the actual gradient between the dark and bright area will have an effect on the contrast which is measurable in practice. The scattered light in position-sensitive systems, for example, is not one simple offset but has different local effects. Bright areas scatter more light into their direct environment than into that which is further away. This means that dark areas situated very close to bright areas are will be brightened more by scattered light than those at a greater distance. In certain correction procedures this is catered for.

Even despite correction, position-sensitive measurements are capable of the least degree of measurable contrast in comparising individual detectors. At contrasts of 1:1000 there will frequently be measurement uncertainty of two-figure percentages despite correction, which limits the use of these methods for such areas.
If dark and bright areas are very close together and the gradient in the LID will be very steep, also single detectors may well reach their limit even if there is good shading. As the photometer heads are usually very large (cf. subsubsection 2.1.1.1 Luminaire turning device), they will have the effect of a box filter on the signal being measured and this cannot be corrected even by smaller step intervals or better shading.

3.1.5. Reproducibility and accuracy

The reproducibility (or precision on repetition, or comparative precision) of the measurement techniques here presented is sufficient in general for all photometric tasks. The same cannot be said for the deviation and the uncertainty of measurement. There are measurement subjects (basically those with high contrast) for which in the present state of the art of photometry neither indirect nor near-field methods are appropriate. The measurement deviations cannot, however, be lumped together because these values are very much dependent on the subject being measured and on the detailed measuring tasks (cf. chapter 4 Examples of use). In the case of far-field goniometers this dependence is of much less significance.

3.1.6. Angular resolution of the LID

In indirect measurement methods and Fourier near-field measurements, the resolution is obtained from the number of degrees per pixel. This resolution may be more or less equidistant, depending on how the image is produced (the perspective, the lens type, plane surface or curved surface, etc.). A minimum resolution will be obtained based on the angle measured and the number of pixels. The larger the angle measured, the less fine the resolution. If the number of pixels in the detector is increased, the resolution will be increased. A wide variety of resolution figures is therefore imaginable. Using a 1.5 megapixel camera to measure an angle of $\pm 15°$ will, for example, produce a resolution of approximately $0.02°$ per pixel, which is quite common (cf. chapter 4 Examples of use).
The angular resolution for goniophotometers is basically obtained from the smallest possible step size, which is frequently $0.01°$. This is mainly nothing more than a theoretical value, however, as this step size is also subject to uncertainty (e.g. hysteresis), and as the size of the detector head (cf. subsection 3.1.4) will likewise affect the actual angular resolution.

3.1.7. Time taken by measurements

The LID can be measured sequentially using angular photometers. Depending on the size of the solid angle being scanned and the resolution, the measurements may take quite long periods, from several minutes even to hours. In the case of Fourier near-field measurement, the situation is similar, depending on the size of the subject, as larger subjects have to be scanned for the appropriate longer time in this case also. This is where the main advantage of indirect measurement lies, for such methods are capable of measuring the partial LID of both large and small subjects in even fractions of a second.

3.1.8. Space requirements

How much space is required can be directly derived from the photometric distances and equipment dimensions, which means that the rotating mirror goniometer needs most space of all. Then in order of size come the other far-field goniometers, the luminaire turning device, the robot goniometer, the cardan goniometer and the compact goniometer. At the other end of the scale are the near-field devices and the indirect techniques. In Table 3.1, the equipment are numbered according to their space requirements. The least amount of space is required by number 1 and the most by number 7.

The CMS method is probably the only one of the LID measurement techniques here presented that can be incorporated into a production line because of its compact size. The other indirect methods can be used to accompany production because the measurement takes so little time, but the direct methods can only be adopted as laboratory techniques.

3.1.9. Price

Cost is involved both in purchase or construction and maintenance of the equipment and in the space required for its use. Large items of measuring equipment which also require a large amount of space because of the photometric distance are also usually the most expensive. Here is a rough estimate of the equipment costs without naming specific figures. Simply from the view of the equipment itself, without counting the space required, the indirect measuring equipment is usually smallest and, at 5-figure prices in euros, the least costly. The near-field measuring equipment occupies the middle range. Here the prices are from the 5-figure to the 6-figure range of euros. The larger than more expensive is also true for near-field goniophotometers. A Fourier near-field set-up will be more expensive despite the compact dimensions because of the costly special lens and, probably the high detector resolution. Here the price is also likely to be at the 6-figure level. The far-field goniometers are the most expensive and are all in the 6-figure range. As the cardan and robot goniometers are individual or custom productions, they will be most costly of all, followed closly by the rotating goniometer, the luminaire turning device and the compact goniophotometer. In Table 3.1, the equipment are numbered according to their cost. In this case, the cheapest is 1 and the dearest is 7.

Because space also costs money, it is customary to place several pieces of equipment in the same room. For example, in many laboratorys, digital image processing measurement set-ups will be installed into existing goniometer measuring ranges. The 10 m screen in front of the goniometer will in this case also act as reflecting screen for the digital image processing measuring equipment.

3.2. Tabularly comparison of the measuring techniques

Table 3.1 gives an overview of the features of the various measuring techniques listed in section 3.1.

	far field							near field			
	direct				indirect						
	Luminaire turning device	Goniophotometer with mirror arrangement	Compact-goniophotometer	Kardan-/Robot-goniophotometer	Image processing measurement	Compact measurement setup	Imaging sphere	LED-goniophotometer	Lamp-goniophotometer	Luminaire-goniophotometer	Fourier lens
fix burning position	no	partial	partial	yes	yes	yes	yes	partly	yes	yes	partial
max. size of object	1m	2m	20cm	30cm	1m	20cm	5cm	5cm	30cm	2m	1m
typical measuring distance	10-30m	40m	2m	3m	any; 10m	any; 0.5m	0.5m	any; 10cm	any; 27cm	any; 2m	any
solid angle	sphere				ϑ±45°,φ±45°		±85°	sphere			±88°
power	any		attend power		any	attend power					
meas. contrast	>1:20.000		<1:20.000		<1:1000		<1:200	<1:500			<1:200
angle resolution	>0.04° dependent on size of sensor and measuring distance; 0.01° step size				0.01° depending on size of sensor and solid angle		0.5° depending on size of sensor	0.1° depending on size of sensor			0.2° depending on size of sensor
measuring time	minutes-hours				seconds			minutes-hours			sec.-hours
size[1]	6	7	4	5	6-1	2-1	2	1	3	4	1
price[2]	5-6	5-7	5	-	1	2	3	3	4	5	4

[1] numeration according to size; starting with 1 as smallest

[2] numeration according to estimated costs; starting with 1 as least expensive

Table 3.1.: Comparison of the measuring techniques

4. Examples of use

Now that the way the various measurement methods work has been largely described, and the common and distinguishing features presented, here, by way of conclusion, are some examples of light sources and the type of measurement that could applied in each case.

4.1. Photometry of luminaires

Luminaires come in a great variety of sizes. On one hand, they represent the largest light sources providing artificial light. On the other, there are luminaires which are smaller than many a lamp. To measure the LID of large luminaires such as street lamps, ceiling lights, etc., the instruments used can be luminaire turning devices, rotating mirror goniometers and near-field goniometers (for luminaires). Figure 4.1 shows a typical ceiling light installed into a near-field goniometer (cf. Figure 2.13, right).

Figure 4.1.: Ceiling light (for office lighting, for example) in near-field goniometer

The three procedures (luminaire turning device, rotating mirror and near-field goniometer) are all equally suitable for measuring the LID of such a light. The choice will largely be determined in this case by the burning position, the price and the space requirements. Figure 4.2 shows the result of the measurement using the near-field goniometer.

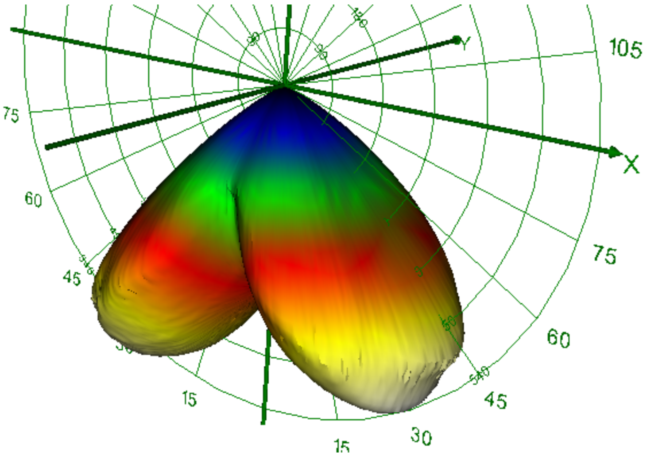

Figure 4.2.: LID of the ceiling light from Figure 4.1

4.2. Measuring the LID of lamps

Lamps also come in very varied sizes. The large ones, such as fluorescent lamps have to be measured like luminaires. The smaller ones, such as ordinary lightbulbs, halogen bulbs, high pressure discharging lamps etc. can be evaluated in the near-field goniometer (for either luminaires or lamps), the compact, the cardan or the robot arm goniometer (see Figure 4.3 for an example and the actual measurement).

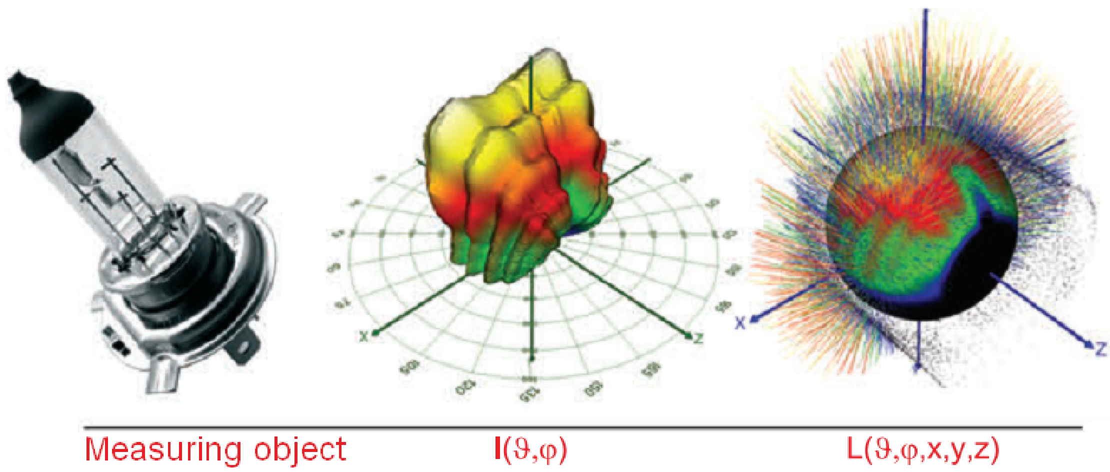

Figure 4.3.: Halogen bulb, LID and ray data

If the lamps emit directed light, as in the case of cold light reflector lamps, it is also possible to use a digital image processing measuring station or the CMS. The speed advantages of the last two mean that they can even be used during the production process.

Figure 4.4.: Automatic adjuster for adjusting cold light reflector lamps

For example, there are thus automatic adjusters available for cold light reflector lamps, to position the lamp in the reflector so that a certain half-value angle is achieved at the same time as (usually) maximum luminous intensity at the centre. The measuring technology has to calculate and evaluate various LIDs for the purpose within a few seconds. The adjuster is then controlled on the basis of the data obtained.

Figure 4.5.: CMS measuring equipment for adjustment of cold light reflector lamps

The same method is available as a manual version for use in laboratories or in development (see Figure 4.5) to find the best positions without depending on adjustment algorithms for instance, or to test new products. The LID measured in this manner is shown in Figure 4.6

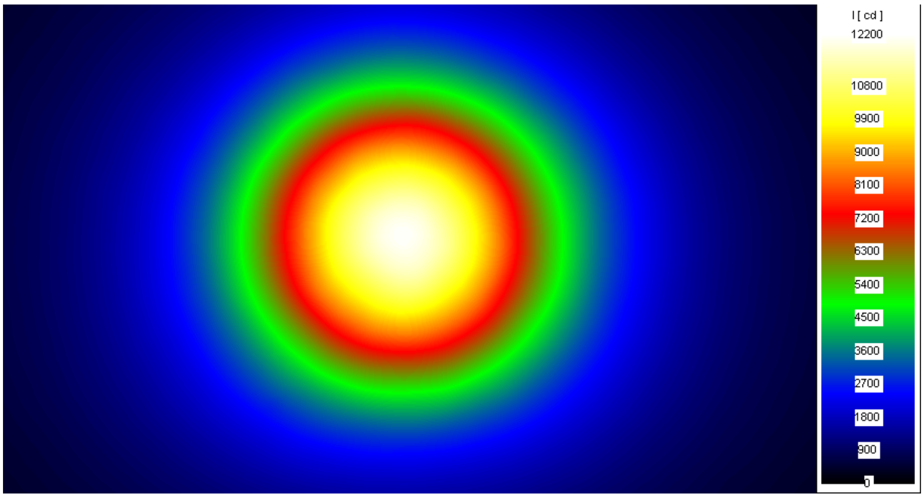

Figure 4.6.: LID; measured in the CMS system from Figure 4.5

4.3. Measurement of headlamps

Headlamps emit light which is (strongly) directed, in contrast to most luminaires and lamps. Depending on the type of headlamp, almost all the methods which have been presented here are suitable for headlamps, with the exception of the LED measuring systems (the LED goniometer and the Imaging Sphere). The choice of method is, nonetheless, not arbitrary. Headlamps come in a very varied range. The CMS ceases to be appropriate, for instance, when the headlamps are particularly large or powerful. Because it is so compactly constructed, overheating can take place. Also the imaging lens will set a limit on the size of the light source (cf. chapter 2 and 3). On the other hand, if the headlamp contains a lot of contrast as is the case with low beam headlights for cars, there maybe problems with the use of near-field goniometers.

Figure 4.7.: projection headlamp for cars

A projection headlamp[1] for cars is shown in Figure 4.7. This is subjected to measurement for legal purposes on a luminaire turning device with a limiting photometric distance of 25 m, because high accuracy is required the dark area of the light distribution. If measurements without legal implications are required during development or to accompany production, headlamps like this can also be measured on image processing measuring systems or compact measuring stations. These will, of course, involve rather larger measurement uncertainty in the dark areas. However, the measurement will be many times faster. Figure 4.8 demonstrates the site view of an image processing measuring room of this kind.

The LID of the headlamp can be seen in Figure 4.9. To enable the dark area (the upper half) to be shown more clearly, the representation is 4 times logarithmical. It can clearly be seen that the contrast between the upper and lower areas is more than 1:1000.

[1] low beam headlamp comprising an ellipsoid reflector with halogen lamp at the first focal point and a lens in the second focal point; area of exiting light approx. 70 mm.

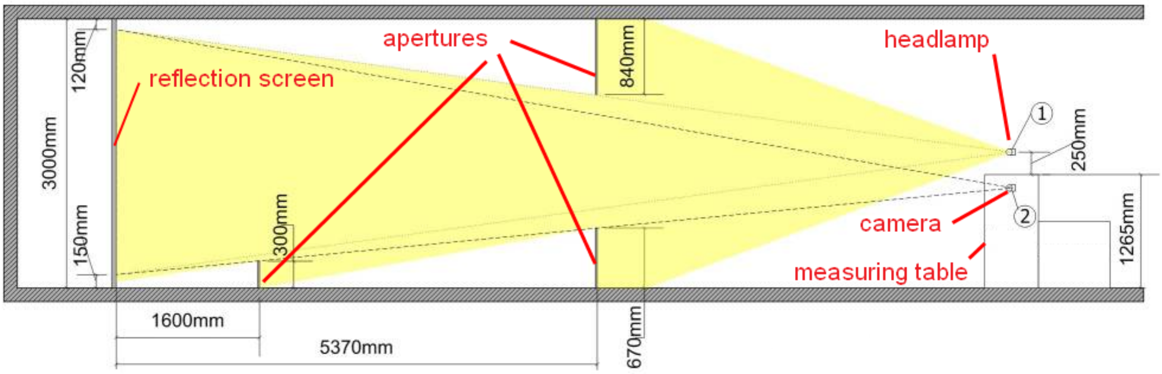

Figure 4.8.: DIP measuring station; for complete horizontal section see Figure A.4

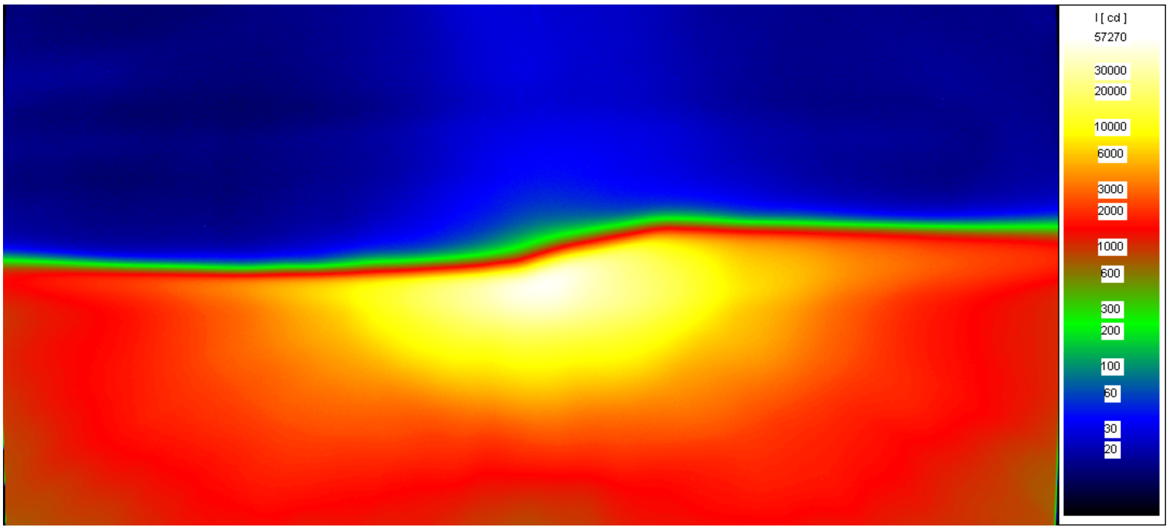

Figure 4.9.: Lid of the car projection headlamp; 4 times log.

4.4. LED photometry

Geometrically, LEDs are the smallest artificial light sources. Certain of the SMD LEDs are barely visible to the naked eye. The larger type of LED includes those known as high-power LEDs. One such is shown in Figure 4.10.

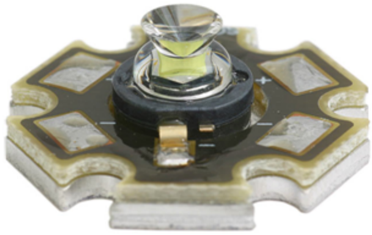

Figure 4.10.: High-Power LED

It is possible to measure the LID of individual LEDs with the LED goniometer, the Fourier method, the Imaging Sphere, the DIP measuring range and also in some cases the lamp or luminaire goniometers. The LID of the LED shown in Figure 4.10 is to be seen in Figure 4.11.

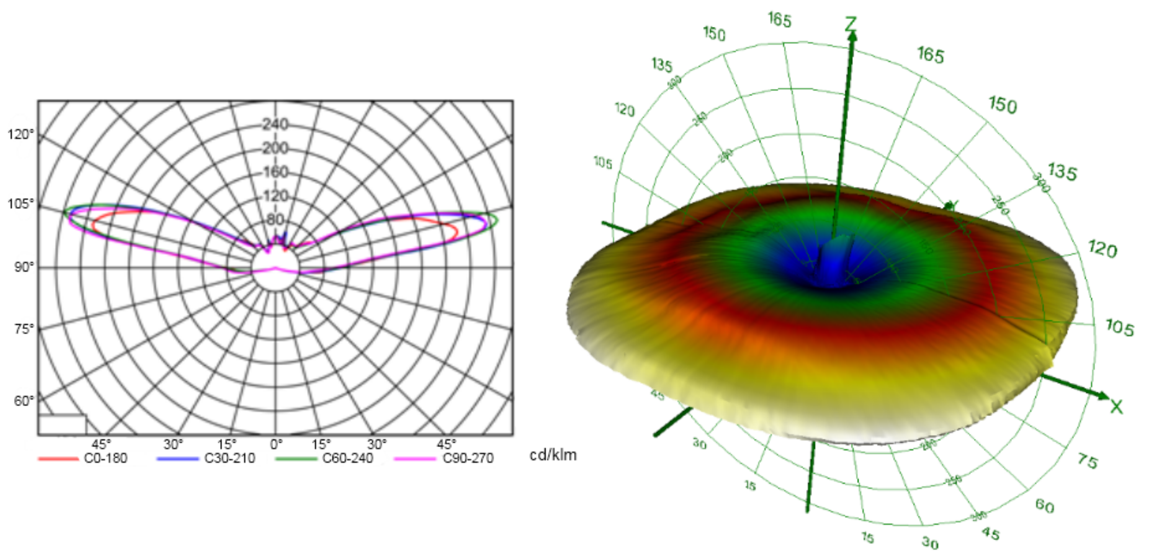

Figure 4.11.: LID of the high-power LED; left - plane representation, right - 3D

LEDs are very flexible light source and frequently installed as arrays. They may be very large and must then be measured using the larger type of equipment.

A. Anhang

A.1. Robot arm goniometer

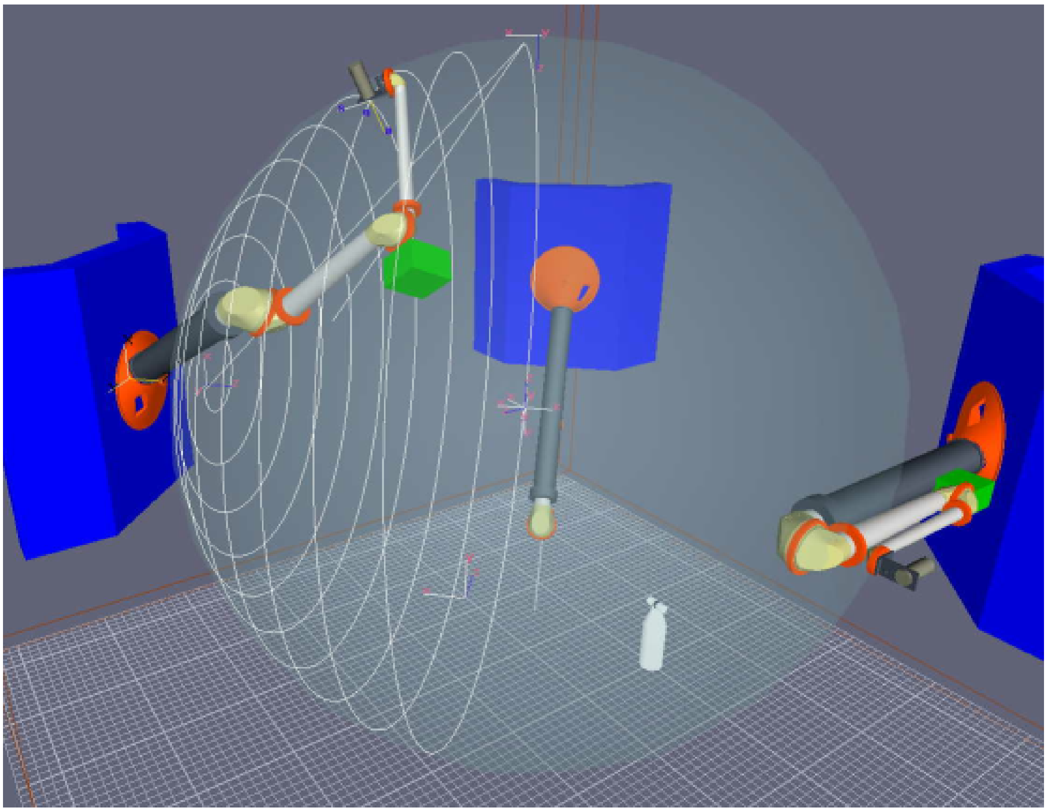

Figure A.1.: Diagram of the PTB robot arm goniometer [Lin08]

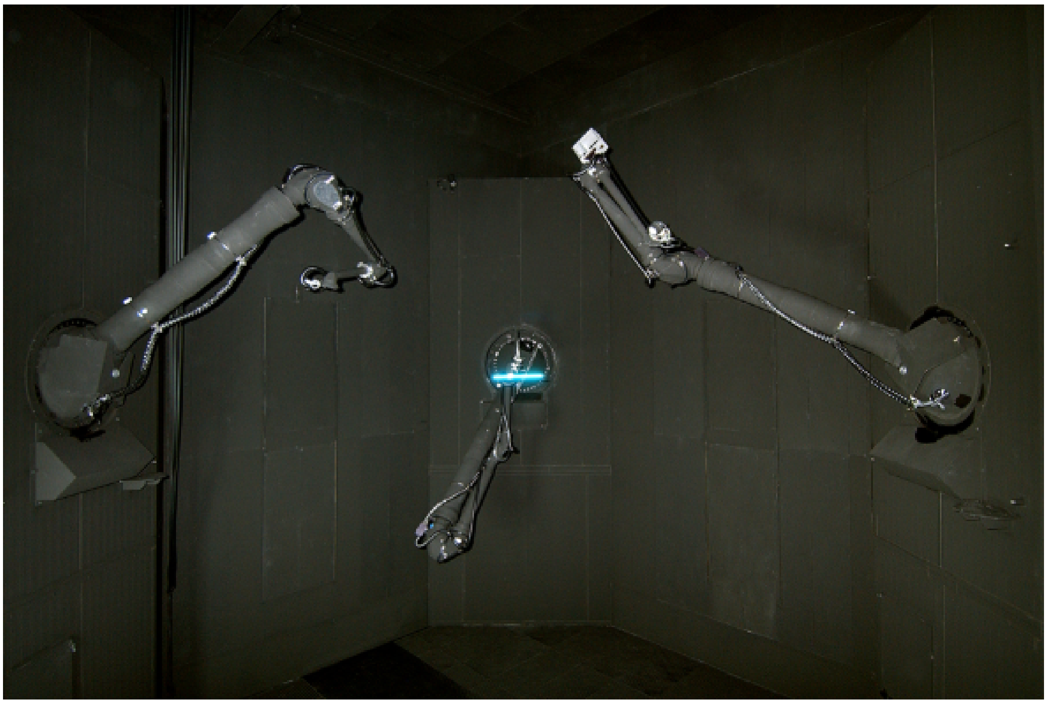

Figure A.2.: View of the PTB robot arm goniometer [Lin08]

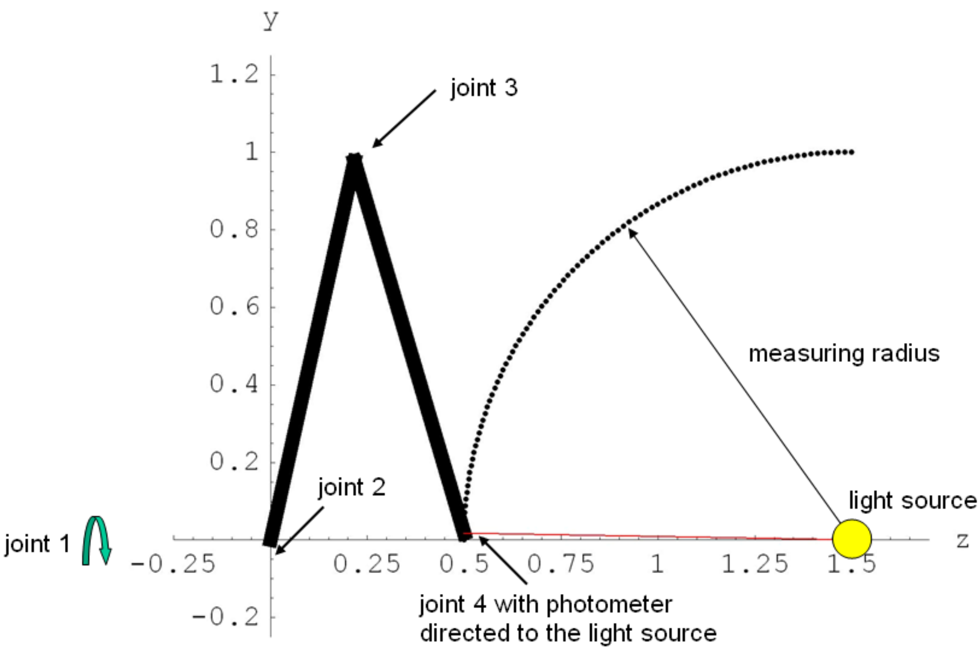

Figure A.3.: How the robot arm functions in principle [Lin08]

A.2. Measuring on curved surfaces

The main problem with measuring on curved surfaces is that of zig-zag reflections. As the screen is a diffuse reflector of light, each element of the surface reflects incident light back into the whole hemispherical space in front of it. The reflective surfaces are usully white (ρ 0.9, for example). This means that 90% of the flux beamed onto the screen will be reflected back into the room and thus onto all other surfaces, such as the walls, ceiling and floor. If the screen is plane, the only way for light to return to the screen via these other surfaces is by zig-zag reflection. If the other surfaces are dark enough (Rho approx. 0.1), the zig-zag reflected light will be reduced to a negligible amount. However, if the screen is spherical, it can reflect light back onto itself. The errors thus arising will be especially great if larger solid angles require to be covered or the distribution of low beam headlamps to be measured, as in that case one half of the screen will be many times brighter than the other. In the active area of a low beam headlamp distribution there is about 98% of the entire flux, and the other 2% is in the passive area. To give an example -as a worst case estimate - In a measuring space 6 m wide, 3 m high and 10 m long, 0.3% of the exiting luminous flux will be reflected into the passive area (2%) if the screen is plane. This is equivalent to an offset of 15% in relation to the passive value actually measured, which can be reduced further by suitable filter arrays. If the screen were spherical, the share of light reflected into the passive area would be more than 3%. This is equivalent to an offset of more than 150%. Furthermore, there is no possibility of avoiding this direct reflection with the aid of filters/apertures.
Even flat screens are difficult to build to suitably large sizes. To create a spherical screen with comparable size and tolerance would be many times more difficult and therefore, also, very costly.

A.3. DIP Measuring Station

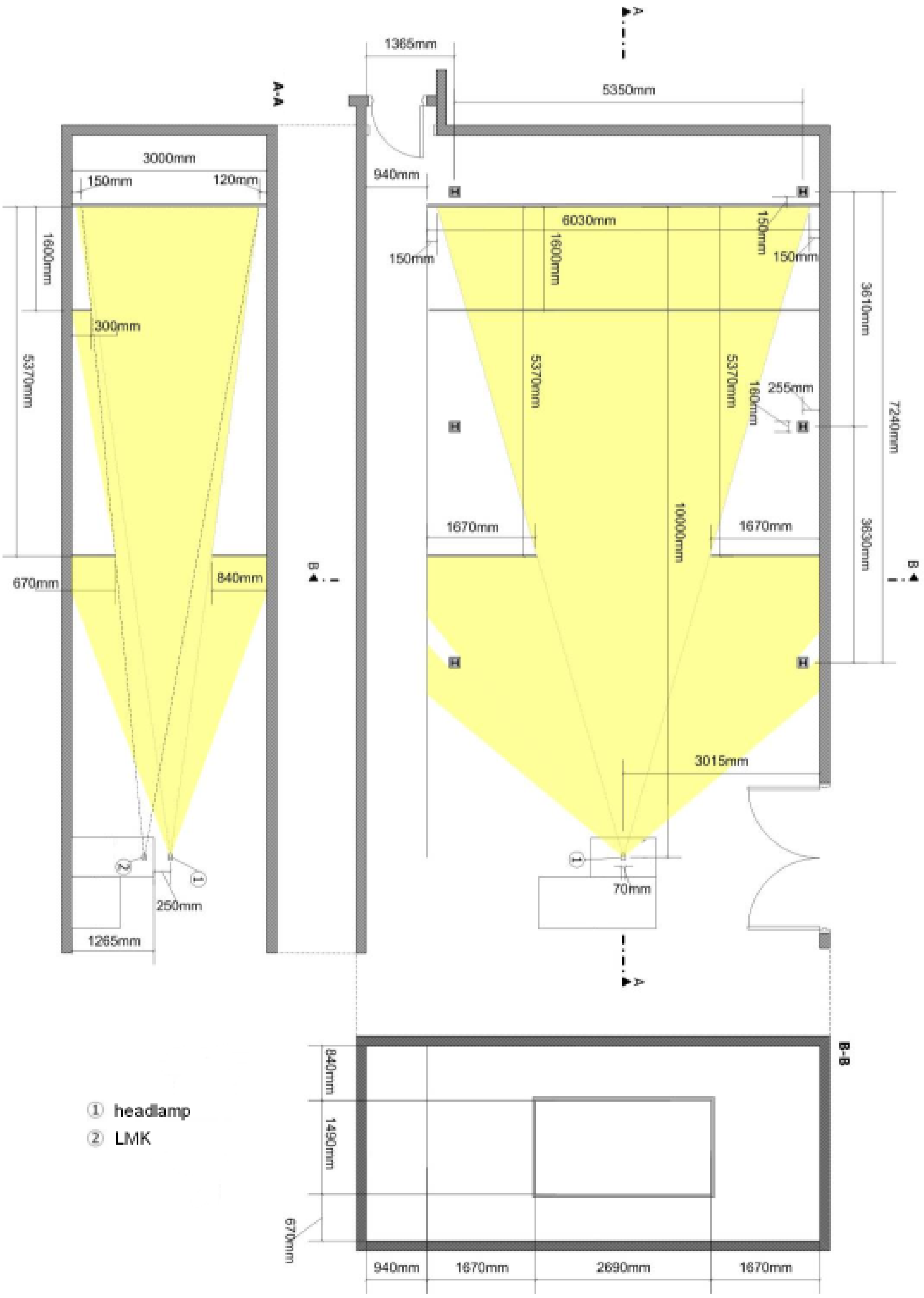

Figure A.4.: Horizontal and vertical section of a DIP measuring station

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