CHARACTERISATION OF REDIRECTING DAYLIGHTING SYSTEMS BY GONIOPHOTOMETRIC MEASUREMENTS

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Abstract – The goniophotometric characterisation of materials plays an important role in photometry with different applications in metrology, daylighting system design, etc. At IEN this characterisation is carried out through a special goniophotometer that allows obtaining material characterisations (in reflection or transmission) for practically any orientation of the lighting and observing directions. The measurement procedure is here applied to characterise redirecting and diffusing daylighting products, which are utilised to improve illuminance and internal comfort in non-residential buildings. The goniophotometric characterisation is often necessary to simulate the illuminance distribution in office rooms equipped with these glazing units. After a short presentation of the IEN goniophotometer, this paper describes the measurement procedure. The system utilises a CCD (Charge Coupled Device) matrix: the availability on a single chip of a high number of independent and closely spaced small detectors permits the analysis of surface uniformity of materials and/or to resolve the angular behaviour in small steps. The matrix of pixels permits to apply a sophisticate geometrical model that considers the effects due to deformation and defocusing, typical in directional measurements. Furthermore the 2D (two-dimensional) Fourier transformation can be utilised to evaluate the effects of the inevitable not alignment between source, sample, detector and optical system lenses.

1. INTRODUCTION

At IEN the goniophotometric characterisation of materials in transmission and reflection is carried out through a special goniophotometer (Rossi and Soardo, 1991). The detector utilised is a CCD matrix: the availability of a high number of closely spaced small independent sensitive elements on a single chip permits the analysis of the surface uniformity of materials, a feature which is almost impossible to obtain with traditional detectors. So the utilisation of a digital detector can improve the metrological realisation of some photometric quantities (Rossi et al., 1997).

In the last years we have conduct our investigations towards diffusing glazing systems utilised to improve internal comfort in non residential buildings. The diffusing glazing units can avoid discomfort phenomena and permit to obtain a more uniform illuminance inside the room in spite of the solar direct radiation that generally causes many problems like uncomfortable visual conditions, photo-degradation, etc. Generally the optical characterisation of such samples presents some difficulties as a consequence of their large angle scattering properties. As example, in measurements carried out with integrating sphere, the transmitted or reflected beams striking the sample should not be entirely collected inside the sphere (Maccari et al., 1998). On the other side, integrating spheres with large sample ports cannot be always achieved for economical and technical reasons. The goniophotometric characterisation represents a solution for these problems. Furthermore it becomes necessary for redirecting systems: the main interesting properties request directional measurements in order to investigate the specimen behaviour for any orientation of the lighting and observing directions. This paper describes an accurate procedure to measure the luminance coefficient (CIE publication N. 17.4, 1987), in transmission or reflection, for practically any geometrical configurations. The measurement technique utilises a sophisticate geometrical approach since it considers a matrix detector that can be turned according to the sample orientation.

The measure analysis, now under test, considers:

• deformation and defocusing of the CCD image of the luminous spot that lights the sample;
• the theory of 2D Fourier transformation to overcome a possible not perfect alignment between the different parts of the measurement system during the rotation of the goniometer.

This measurement procedure is particularly important for redirecting glazing unit characterisation, when the transmitted light distribution strongly changes with sample orientation.

2. MATERIAL CHARACTERISATION BY IEN GONIOPHOTOMETER

2.1 The instruments

The IEN gonioreflectometer (Rossi and Soardo, 1991) consists essentially of a fixed source, a 4 m long optical bench supporting at one end a detector and rotating at its centre around the vertical axis of the instrument (figure...
On this same axis a set up is mounted, consisting of a cradle, on which the specimen is placed through a three axes positing system and a rotator. It is easy to verify that the specimen can be lighted and observed from any direction in the space, for reflection measurements (some dead angles due to the sample dimension exist in transmission directions). The cradle can also be lowered for permitting the measurement of the luminance of the lighting beam directly through the detector.

Figure 1 – IEN goniophotometer.

The source utilised is a tungsten halogen lamp realising the CIE illuminant A (colour temperature of 2856 K - CIE publication N. 17.4, 1987). To stabilise the source there are two quantities continuously under test: its colour temperature and luminance. Moreover there is the possibility to automatically control the power supply circuit of the lamp by the output signal of a silicon detector head, illuminated by the source light linked with a fiber optic. Between the fiber output and the silicon detector, a turret can rotate four different filters:

- one black that obstructs the signal to avoid detector fatiguing;
- one reproduces the $V(\lambda)$ colour matching function of CIE, to measure the source luminance;
- one blue, centred on 430 nm and one red, centred on 990 nm (for both the full width half maximum is 10 nm), to control the source colour temperature.

The red to blue ratio evaluation is a traditional method for fast measurement of colour temperature of incandescent sources: with only two measures it is possible to control the colour temperature, in our case with an accuracy of 4 K. Using the $V(\lambda)$ filter, the source luminance is stabilised better than 0.2%. (Rossi and Sarotto, 2000).

The detector utilised is a CCD matrix composed by 512 x 512 square pixels, with a side of 27 µm: the size of the whole matrix being 13.8x13.8 mm$^2$. Like any other light detectors, a CCD can measure luminance when used with a lens or illuminance if alone (Rossi et al. 1997). In the first case the availability of a great number of pixels on a single chip permits a great directional resolution of the incoming light and it could be employed in the analysis of surface of materials. Furthermore there are other metrological characteristics (i.e. linearity) that make the CCD preferable if compared with the traditional detectors used in photometry and permit to improve the measuring uncertainties.

2.2 The measured physical quantity

A full photometric characterisation of materials requires the measurement of the spatial distribution of reflected or transmitted light when the specimen is lighted from any directions. For this reason a complete set of spatial measures is required in the CIE publications: a four-dimensional matrix depending on the illumination and observation angles shall be defined. The characterisation is usually carried out through the measurement of the luminance coefficient, which is definite as:

$$BRDF, BTDF(\epsilon_1, \phi_1; \epsilon_2, \phi_2) = \frac{dL_2(\epsilon_1, \phi_1)}{dL_1(\epsilon_1, \phi_1) \cos \epsilon_1 \ d\omega_1}$$ (1)

where:

- BRDF (Bi-directional Reflectance Distribution Function), BTDF (Bi-directional Transmittance Distribution Function) are the luminance coefficients measured in reflection or transmission conditions;
- $E_1$ is the incident beam illuminance on the sample;
- $L_1$ is the incident luminance;
- $d\omega_1$ is the incident beam solid angle;
- $L_2$ is the reflected or transmitted luminance;
- the angles $(\epsilon_1, \phi_1; \epsilon_2, \phi_2)$ are self evident in figure 2 where the reflection geometry is represented;
- $(xsn, ysn, zsn)$ are the axes for the sample reference system with zsn axis along the sample normal.

As equation (1) suggests, the luminance coefficient measuring procedure is of relative type when the luminances $L_2$ and $L_1$ are measured through the same detector. Therefore its measurement uncertainty is in principle low because no detector calibration is required. At the same time, the linearity requirements of the detector can be greater then four orders of magnitude: the typical ratio of the two luminances in equation (1). This requirement can be reduced using different exposure
times: of course a very good and stable shutter is necessary (Rossi et al., 1996). The solution adopted here consists in utilising a calibrated filter that reduce the signal level in \( L_1 \) measurement, even if it produces a limited uncertainty grown of the luminance coefficient values.

2.3 The image optical system

In photometric measurements of materials the possibilities to light a sample are generally two: with a collimated beam or with an image optical system that produces on the sample the source image. We have chosen the second possibility projecting the image of a PTFE (polytetrafluoroethylene) sheet on the sample. For normal incidence, the projected spot is circular and has a nominal diameter of 13 mm. The focused spot on the CCD matrix has theoretically the same dimension since the magnification ratio of the second part of the optical system is 1.

The diffusing behaviour of the PTFE in transmission guarantees good uniformity of the luminous spot projected on the sample. However the use of CCD system permits to control the uniformity of the incident lighting beam and to get a correspondence between the array pixels and different zones of the measured sample.

In \( L_1 \) measurement (upper part of figure 3), the sample cradle rotator is lowered but the CCD is anyway focused on an imaginary sample plane. This plane is normal to incidence direction, parallel to PTFE sheet and it passes through the sample central point (centre of the goniophotometer cradle rotator that remains fixed for each geometrical configuration \((\varepsilon_1, \phi_1; \varepsilon_2, \phi_2)\)). So we can imagine the source and the imaginary sample plane also divided in pixels (figure 3): in \( L_1 \) measurement each source pixel has a single pixel as image on the imaginary sample plane and consequently on the CCD matrix.

Otherwise, in the reflected or transmitted luminance measurement, the direct correspondence between source and sample pixels is generally not satisfied because the image is deformed and defocused (lower part of figure 3: \( L_2 \) measurement). However the geometry of the problem can be analysed (as shown in §3) in order to restore the correspondence between lighting areas of the source and their projection on sample plane.

2.4 The full oriented CCD matrix

As shown in figure 3, in the \( L_2 \) measurement the image of an ideal source single pixel generally keeps different ideal pixels on sample plane. In other words, if the incidence is not normal, the source image on the sample is deformed and defocused.

For simplicity only the first part of the optical system is represented in figure 3, avoiding to represent the other part (sample plane, CCD lens, CCD matrix) that composes the entire system. But in the deformation and defocusing analysis, we can consider only the first part of the optical system, since images on the CCD matrix should be on focus for any angular position of the sample with reference to the observation axis. In principle (Born and Wolf, 1964), this can be obtained if the planes containing the sample and the CCD matrix are maintained symmetrical with reference to the plane of the lens throughout the whole measurement procedure, as shown schematically in figure 4 (Scheimpflug condition). A full orientation system for the CCD matrix synchronised with the cradle-rotator set-up for the sample is required. Mechanical constraints do not permit to satisfy this requirement for all the measuring conditions.

3. ANALYSIS OF DEFORMATION AND DEFOCUSING EFFECTS

In the case of ideal lenses, perfect alignment and satisfying the Scheimpflug condition, the deformation and defocusing for the spots on sample plane and on CCD the matrix are the same. Reducing the deformation and defocusing analysis to the first part of the optical system, it is however necessary to evaluate:
• the CCD matrix orientation for each measurement geometry in order to obtain images always focused (Rossi and Sarotto, 2000);
• the deformation and defocusing of the PTFE sheet image projected on the sample plane.

To evaluate the deformation we have to consider only rays passing through the nodal point P1n of lens \( f_1 \) (figures 3 and 5). So the image of an ideal source pixel is a quadrilateral formed by the intersections of lines starting from the ideal pixel edge, passing through the nodal point P1n, and the sample plane. In figure 5 these intersections are represented by points \( P_{A,B,C,D} \), images on the sample of the four object points \( P_{oA,B,C,D} \) (vertices of PTFE sheet pixel). Furthermore there are indicated the ideal vertex images \( P_{idA,B,C,D} \) obtained by the intersection of rays starting from source pixel edges \( P_{oA,B,C,D} \) passing through nodal point P1n and rays passing trough the focal point Pf1. The focused image of the PTFE is on the plane \( y_s-z_s \) that corresponds to a normal incident geometrical configuration (figure 5).

![Image of Figure 5](image5.png)

**Figure 5 - Pixel source deformation and its ideal image.**

As shown in figure 6 the source pixel image on sample plane (obtained by rays passing through P1n) is generally a quadrilateral of vertices \( P_{sA,B,C,D} \) and \( P_{idA,B,C,D} \). The vertex co-ordinates have been calculated (Rossi and Sarotto, 2000) as function of the pixel position on PTFE and of the angles set up on sample cradle rotator.

In figure 6 it is also schematised the defocusing of a single point PoA: an ellipse passing through 4 points \( (P_{ssupA}, P_{sinA}, P_{sdxA}, P_{ssxA}) \) that surround the image point PoA. These four points are obtained considering rays starting from PoA and passing through the vertical and horizontal lens extremes.

Considering ideal lenses and the system (source, lenses, sample and CCD) perfectly aligned, we can argue which CCD and sample pixels are lighted by a single PTFE sheet pixel during \( L_1 \) or \( L_2 \) measurement. An example of calculation is reported in figure 7: deformation \( (ds_{ABn}: \) continuous lines) and defocusing \( (dssupinfAn: \) dash lines) are represented in number of pixels as a function of:

- the polar angle \( \alpha \) imposed by the sample cradle-rotator;
- a fixed position for the PTFE point PoA(\( y_oA, z_oA \));
- a fixed azimuth direction \( \beta = 0 \) imposed by the sample cradle-rotator.

In this particular case \( \beta = 0 \), therefore \( \alpha = \varepsilon_1 \) i.e. the polar incident angle.

![Image of Figure 7](image7.png)

**Figure 7 - Deformation \( (ds_{ABn}: \) continuous lines) and defocusing \( (dssupinfAn: \) dash lines) versus polar angle \( \alpha \), for a fixed geometrical configuration with: azimuth plane \( \beta = 0 \), pixel position on the PTFE sheet PoA(0, 0.3 mm).**

One of the investigated samples measured in transmission is a clear diffusing laminated-glazed made by two glass sheets of the same thickness (3 mm) and a diffusing PVB (PolyVinylButyral) material, 0.38 mm thick. The goniophotometric measurements demonstrated that the transmittance and reflectance properties of this pane were the same on both sides and independent of the orientation of the pane.

An example of acquisition, done in the normal direction of transmission with a polar incidence of 10°, is reported in figure 8. To highlight the form of the luminous spot projected on the sample (lightly elliptic), the area lighted directly by the incident beam is represented as white in figure 8. The luminance values outside this area are different from zero and are due to the multiple reflections between the layers that compose the laminated pane. The
form of this luminous area is approximately a ring. In other words observing the lighted sample, a luminous area greater than the zone intercepted by the beam is clearly visible. In this case a CCD lens of focal 50 mm and a magnification ratio lower than 1 was utilised otherwise, using the optical system previously described, only the region lighted by the beam will be detected. The deformation and defocusing analysis permit us to distinguish between:

- an area interested by the incident beam calculated applying the deformation analysis;
- an area interested by the defocusing;
- a lighted area due to multiple reflections inside the pane.

![Image of a lighted laminated-glazed pane.](image)

It is to be outlined that integrating sphere measurements consider the flux transmitted by the ring surrounding the area of the sample hit by the incident beam only if the port sphere is sufficiently greater than beam diameter: a feature that is not always possible to realise (Maccari et al., 2000). Furthermore usual luminancemeter used for directional measurements refer to sample areas lower than the zone hit by incident beam: so also in this case the luminous ring is not detected. Otherwise this effect is clearly shown by the CCD acquisition.

4. ILLUMINANCE EVALUATION ON SAMPLE PLANE AND CCD MATRIX

To correlate the light emitted by a single PTFE sheet pixel to the light measured by several CCD pixels, the illumination level on the sample shall be evaluate.

The radiation emitted by a single PTFE sheet pixel and collected by lens $f_1$ (figures 3 and 5) lights the sample (and then the CCD) over an area determined by deformation and defocusing. The CCD measures the illumination distribution on its matrix plane. The distribution form depends on sample plane orientation; its value depends on the light flux collected by the image optical system (solid angles taken by incident beam and subtended by the detector).

Nevertheless our measure analysis is limited to CCD pixels, in a preliminary evaluation step we need to determinate the hypothetical (because can exceed sample or CCD dimension) area lighted by the flux generated by each source pixel. The illuminance level on deformed zones is surely greater than that on defocusing zones: so the two regions shall be distinguished. The optical system aberrations shall be considered too.

To simplify the problem and to reduce the computation time, we strongly approximate the illuminance distribution generated by each single source pixel considering only two signal levels respectively for the defocusing and deformed lighted areas (Rossi and Sarotto, 2000).

The signal level of each CCD matrix pixel is then obtained by:

- starting from the luminance of each pixel source (measured in source calibration);
- determining the deformed and defocused pixel image and its two signal levels;
- applying equation (1) to represent sample behaviour in reflection or transmission.

5. THE 2D FOURIER TRANSFORM FOR IMAGE ANALYSIS

5.1 The two dimensional discrete Fourier Transform

The Fourier transform theory for one-dimensional signal processing can be extended to two dimensions for the analysis, manipulation and enhancement of images of all types. An image is represented by a two-dimensional array of numbers. In visible light images, the array of numbers corresponds to object luminance levels or image illuminance levels.

The 2D discrete Fourier transform (DFT) is written as:

$$F(u, v) = \frac{1}{M \cdot N} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} f(m, n) \cdot \exp \left[ -j2\pi \left( \frac{m \cdot u}{M} + \frac{n \cdot v}{N} \right) \right]$$

while the inverse DFT is:

$$f(m, n) = \sum_{u=0}^{M-1} \sum_{v=0}^{N-1} F(u, v) \cdot \exp \left[ j2\pi \left( \frac{m \cdot u}{M} + \frac{n \cdot v}{N} \right) \right]$$

In equations (2.a) and (2.b) the integers $m, n$ determine the pixel position on CCD, while $u, v$ represent the spatial frequencies. Both equations can be easily calculated by a computer program: to speed up the calculation time the FFT algorithm is utilised (Rossi and Sarotto, 2000).

On the contrary of deformation and defocusing analysis, the Fourier transform theory is applied on the whole image of the source and not on a single pixel. It is utilised to check the alignment between source, sample, detector
and the optical system lenses. This control is different in the case of L₁ or L₂ measurement since image on the CCD in L₁ measurement is a circle always focused, while in L₂ measurement the luminous spot projected on sample plane becomes a defocused ellipse. In both cases the PTFE sheet image projected on the material is sampled by the discrete grid of CCD pixels and is quantized by 14 bit for each pixel.

5.2 Modelling imaging system

Our imaging systems can be considered as a two-dimensional linear system. If \( x(m, n) \) represents the pixel luminance distribution on PTFE sheet, and \( y(m, n) \) represents the pixel illuminance distribution on CCD matrix, we can write:

\[
y(m, n) = H[x(m, n)]
\]

(3)

where “H” is the function that represents the imaging system. When the input is the two-dimensional Kronecker delta function at location \( (m', n') \), the output at location \( (m, n) \) is defined as:

\[
h(m, n; m', n') = H[δ(m-m', n-n')]
\]

(4)

and it is called the impulse response of the system or point spread function (PSF). In our case, it represents the image of a single source pixel of the PTFE sheet \( (m', n') \) projected on sample and then on CCD plane. The output of any linear system can be obtained from its impulse response and the input by applying the superposition rule:

\[
y(m, n) = H[x(m, n)] = ∑_{m}∑_{n} x(m', n') · h(m, n; m', n')
\]

(5)

since:

\[
x(m, n) = ∑_{m}∑_{n} x(m', n') · δ(m - m', n - n')
\]

(6)

Generally a system is called “spatially invariant” or “shift invariant” if a translation of the input causes only a translation of the output. Defining the impulse response in the origin:

\[
H[δ(m, n)] = h(m, n; 0, 0) = h(m, n)
\]

(7)

it must be true for shift invariant systems that:

\[
h(m, n; m', n') = H[δ(m-m', n-n')] = h(m-m', n-n'; 0, 0)
\]

(8)

that means the shape of impulse response does not change as the impulse moves on the input plane. For shift invariant systems, the output becomes:

\[
y(m, n) = x(m, n) ⊗ h(m, n) = ∑_{m'}∑_{n'} x(m', n') · h(m-m', n-n')
\]

(9)

which is called convolution of the input with the impulse response. The last equation means that impulse response is a function of the two displacement variables only.

Goniophotometric system is:

- Spatially invariant in L₁ measurement: the shape and dimension of source pixel image on CCD does not change varying the input pixel position.
- Spatially varying in L₂ measurement in the first part of the optical system (PTFE sheet – lens \( f_1 \) – sample) since a translation of the input pixel does not cause a simply translation of the output: the shape of PSF changes as the impulse moves on the input plane.
- Spatially invariant in L₂ measurement in the second part of the optical system: the Scheimpflug condition (imposed on sample, CCD and its lens planes) guarantees that the shape and dimension of sample pixel image on CCD does not change varying the sample pixel position.

The image detected by the CCD is a reconstruction of real image (in L₁ or L₂ measurements) by sampling (on a discrete grid of pixels) and quantization (using 14 bits). The reconstructed image is given by the interpolation formula:

\[
\sum_{m,n} f(m \cdot Δy, n \cdot Δz) \left( \frac{y - y_s}{Δy} \right) \left( \frac{z - z_s}{Δz} \right)
\]

(10)

The CCD pixel dimensions fix the bandwidth (spatial frequency) or Nyquist rate of the measurement system:

\[
u_y = v_z = 1 / (2 \cdot Δy) = 1 / (2 \cdot Δz) = 1 / 54 \, μm^{-1}
\]

(11)

The measured sampled image is obtained by a flat top sampling on the CCD pixels: the system does not register illuminance variations over a distance less than 27 μm. The cost of attenuate higher spatial frequencies is however inevitable since the finite aperture of optical system causes resolution decrease too (Jain, 1989).

5.3 Application of Fourier theory in L₁ measurement

In L₁ measurement the Fourier theory is utilised to find the best alignment between source, detector and their lenses. As representative of ideal image on the sample we consider a circle of diameter \( Φ_s = 13 \, mm \) with a unitary luminance value, projected on the ideal sample plane \( ycs'zcs' \) (figure 5) normal to incident direction and centred in \( (ycs', zcs') \):

\[
g(ycs', zcs') = \begin{cases} 1 & \text{if } (ycs' - ycs')^2 + (zcs' - zcs')^2 \leq (Φ_s/2)^2 \\ 0 & \text{otherwise} \end{cases}
\]

(12)

The circle is generally centred in \( (ycs', zcs') \) instead of origin \( (0,0) \) to consider eventual not perfect alignments. The ideal signal (equation 12) varies over an infinitesimal distance. The CCD output (ideal sampled signal - \( f_{IS} \)) obtained by simulated the flat top sampling on finite dimension pixels can never exactly reproduce it.

Figure 9 shows the measured profile of a CCD matrix
column interested by the incident beam: the $L_1$ luminance is almost uniform in the zone interested by the beam.

![Source luminance](image1)

Figure 9 – Signal levels on a CCD pixel column by $L_1$ measurement.

To determinate the real centre co-ordinates ($y_{cs'}$, $z_{cs'}$) of the PTFE image, we have to maximise the spatial correlation between the ideal sampled signal ($f_{IS}$) and the measured sampled signal ($f_{MS}$):

$$f_{MS}(m,n)@f_{IS}(m,n) = \sum_{m',n'} f_{MS}(m',n') \cdot f_{IS}(m+m',n+n')$$

(13)

Using the properties of Fourier transform the spatial correlation is reduced to a product of Fourier transforms:

$$F(f_{MS}(m,n)@f_{IS}(m,n)) = F_{MS}(-m,-n) \cdot F_{IS}(m,n)$$

(14)

Imposing co-ordinate ($y_{cs'}$, $z_{cs'}$) to change discretely on centre of adjacent pixels, the centre of measured signal coincides with co-ordinates that maximise the correlation product (equation 13).

As example the one-dimensional Fourier transform of CCD pixel column signal of figure 9 is reported in figure 10. In this case, we can approximately neglect spatial frequencies greater than 0.010 $\mu$m$^{-1}$: this value corresponds to a spatial variation of 3-4 pixels.

![FFT of a CCD pixel column](image2)

Figure 10 – FFT of a CCD pixel column.

In order to maximise equation (13), some problems can arise. If the dimension of measured signal is different from the ideal image dimension, there are several co-ordinates ($y_{cs'}$, $z_{cs'}$) that maximise the spatial correlation. This problem can be solved choosing between co-ordinates ($y_{cs'}$, $z_{cs'}$) which make the differences between bounds of measured and ideal signals as close as possible in each direction (figure 11).

![Determinination of centre if ideal and real image dimensions are different](image3)

Figure 11 - Determination of centre if ideal and real image dimensions are different.

5.4 Procedure utilised for $L_2$ measurement

For $L_2$ measurement configuration, using the sample reference system ($x_{sn}$, $y_{sn}$, $z_{sn}$) of figure 2, the equation of the deformed image is theoretically an ellipse centred in the origin (0,0):

$$A \cdot x_{sn}^2 + B \cdot x_{sn} \cdot y_{sn} + C \cdot y_{sn}^2 + F \cdot x_{sn} + G \cdot y_{sn} + H = 0$$

(15)

Its parameter values are generally functions of angles set up on sample cradle rotator and of the geometrical distances involved (Rossi and Sarotto, 2000).

As in $L_1$ measurement, to take in account eventual not perfect alignments, we consider as ideal image an ellipse not centred in (0,0) but shifted in ($x_{sn'}$, $y_{sn'}$). Then the alignment between sample and CCD cradle rotators is checked looking for the maximum of the spatial correlation of ideal and measured signals. Again some problems can arise if the dimension of ideal and measured images are different: these problems can be solved in similar way as done for $L_1$ measurement, taking into account that measured signal is deformed and defocused, while ideal signal is only deformed. However this aspect should not generate problems because the signal level in the defocused zone (on the edge of the image) is lower than signal level in the central zone, where there are both contributes (deformed and defocused).

To conclude we observe that the alignment check in $L_2$ measurement can be done only for angle values lower than 20°: for greater values the projection of luminous spot on the CCD exceeds the matrix dimension. However, if the system is aligned for angles lower than 20°, we can reasonably retain that it maintains with acceptable accuracy this property for the other geometrical configurations.
6 SOME APPLICATIONS OF GONIOPHOTOMETRIC CHARACTERISATION

The reflection and transmission properties of materials can be utilised in different application fields. Two goniophotometric characterisations and their applications are here analysed:

1. Diffusing daylighting system to improve internal comfort in non residential buildings;
2. Redirecting daylighting system to exploit the solar radiation in different seasons.

6.1 Characterisation of diffusing daylighting systems

Diffusing glazing systems, able to diffuse daylight in all directions, permit to obtain a more uniform illuminance inside the room, in spite of the variability of the direct and diffuse components of the solar radiation. On the other side, the optical characterisation of such samples presents some difficulties as a consequence of their large angle scattering properties. As a matter of fact, to perform accurate transmittance (reflectance) measurements with integrating spheres is necessary that all the transmitted (reflected) beams, striking the sample, are collected inside the sphere. Consequently, large integrating spheres with large sample ports must be used. Nevertheless, for lambertian and/or remarkably thick samples, some of the transmitted (reflected) radiation is lost, introducing a systematic error: the higher is the port diameter, the lower will be the error (Maccari et al., 2000).

For design purposes the detailed knowledge of the spatial scattering light distribution of a specimen is often necessary, but generally too complex to manage: in this case a reduced set of parameters is preferred. We have identified a suitable model of the glazing unit to find out the more appropriate analytical function for the goniophotometer result point fitting. In the case of normal incidence, the luminance coefficient of equation (1) can be expressed as a sum of two or more cosine terms with different $n_j$ scattering indexes (not necessarily integer) and $k_j$ scaling factors:

$$\text{BTDF, BRDF}(\varphi_2) = \sum_{j=1}^{M} k_j \cdot \cos^{n_j}(\varphi_2)$$

where:
- $\varphi_2$ is the reflection / transmission polar angle;
- the values of $k_j$ and $n_j$ depend on the prevailing diffusing (lambertian: $n_j = 0$) or regular ($n_j \to \infty$) behaviour of the glazing unit;
- each one of the $M$ terms in the above sum represents a different scattering comportment.

As example, in figure 12 the luminance coefficient in transmission and its fit are reported for a typical diffusing glazing. With only four parameters, equation (16) fits the measured function with accuracy sufficient for nowadays requirements and simulation algorithms.

Figure 12 - Goniophotometric characterisation of a diffusing glazing in transmission: measured and fitted values.

6.1 Characterisation of redirecting daylighting systems

Transparent glazing systems are used in architecture when a perfect view through is need. In order to prevent glare effects, a reduced level of natural light intake is obtained by using tinted or coated glass or, alternatively, redirecting glazing systems. These systems are usually implemented to exploit the solar radiation in different seasons in order:

- to collect the maximum of light in winter;
- to reduce the light in summer to avoid effects like overheating, photo-degradation, etc...

If compared with diffusing glazing units, the optical characterisation of such samples presents some more difficulties. The utilisation of a digital detector becomes very useful to stabilise how the transmitted light is scattered. In figures 13 and 14 two images of one of such samples obtained by the CCD detector are reported.

Figure 13 - Redirecting glazing systems measured for $\varphi_1 = \varphi_2 = 45^\circ$, $\Phi_2 = \Phi_1 \pm \pi$. 
Both acquisitions refer to a regular transmittance measurement. In the first case (figure 13) the measurement geometry is: $\varepsilon_1 = \varepsilon_2 = 45^\circ$; in the second (figure 14): $\varepsilon_1 = \varepsilon_2 = 5^\circ$. In both cases the incident beam diameter is the same and $\varphi_2 = \varphi_1 \pm \pi$, so $\varphi_2$ is the azimuth plane containing the regular transmittance component. To highlight the different behaviour of the specimen the luminance scale of the two graphs is different. The two digital acquisitions (particularly the first) show the internal structure composed by glass deflecting prisms supported by a plastic grid. These deflecting prisms obstruct the light incoming when the incident polar direction is near the normal (figure 14) and increase the transmitted flux if the polar incident angle increases. If glazing systems like this one are mounted on a mansard roof window, the solar radiation will exploit in order to maximise daylight in winter and avoid overheating in summer.

7. CONCLUSIONS

Goniophotometric measurements are important to correctly characterise unconventional glazing units when the main application parameter is their redistribution of incident daylight in the internal environment.

From the metrological point of view the measurement of the transmitted or reflected light is a difficult task particularly when redirecting daylighting systems are considered. The use of CCD digital detectors and sophisticated measurement algorithms and procedures greatly simplify this problem.

For the characterisation of diffusing and redirecting glazing units, the IEN goniophotometer main features are:

- source luminance stability and colour temperature absolute values controlled by the fiber optic feedback with an accuracy of 0.2% and 4 K respectively (described in §2);
- angular alignment precision during movements: guaranteed lower than 0.1°;
- deformation and defocusing of the luminous spot on the sample and on the CCD: influence considered as described in §3 starting from the geometry of the problem;
- alignment between source, detector and sample: checked and corrected by the 2D Fourier analysis shown in §5.

REFERENCES


