17.4: Comprehensive Survey on Viewing Angle Measurement Devices: A Theoretical Study

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Abstract

Viewing angle properties are certainly among the most common characteristics measured on any type of displays and in particular on LCDs. Historically, goniometers have first been used for this task. In 1993 ELDIM has introduced Fourier optics instruments (conoscopes) that are now widely used by many display makers. More recently an imaging technique based on the use of a low reflectance hemisphere has been introduced. All these approaches have their inner advantages and drawbacks depending on the optical setup and the measurements constraints. We present a comparison of these three systems based on their theoretical specifications.

1. Introduction

Many applications such as FPD design and characterization or surface inspection (BRDF) require a complete angular characterization. As in any other technical fields, inspection devices are required to constantly improve their specifications in term of accuracy, resolution, flexibility and fastness. In this paper, our goal is to provide an accurate survey and comparison of the theoretically expectable specifications of the three main families of angular inspecting devices, in chronological order: the goniometer [1], the conoscope [2-3], and the hemisphere-based imager [4-5]. We'll pay a particular attention to the hemisphere-based imager since it is the youngest product on the market.

2. The various approaches

2.1. Goniometer

Historically, the goniometer was the first equipment used to perform angular measurements [1]. A lot of studies have been done and extended literature is available for comparison. For these reasons, the goniometer is still considered as the reference equipment. Various mechanical movements allow the scanning of the complete display viewing field with a directional detector (cf. figure 1). The main parameters which are controlling the performances of such a system are the angular aperture of the directional detector and its distance to the display surface. The main drawback of those systems is the "one after each other" nature of the measurements which results in very long measurement times if more than a few measurement directions are required.

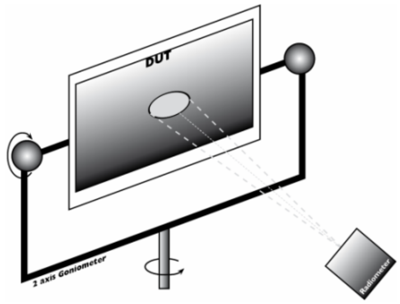

Figure 1. Schematic of a goniometric system.

2.2. Fourier optics or Conoscope

The Conoscope [1] principle is based on an optical Fourier transform (OFT): a specific optic is designed in order to convert angular field map into a planar one. This type of device is available on the market since its introduction by ELDIM in 1993 [2-3]. The principle is outlined in figure 2. A dedicated optics focuses every parallel light beam coming from an area of the display at a distinct position in the Fourier plane according to their angular coordinates. This plane is reimaged on a 2D detector and the full viewing field map can then be measured in one single step. Moreover, the use of a specific optical configuration allows controlling the spot size independently of the angular aperture with an iris located in a conjugate plane of the measurement spot. The collection efficiency is then similar to a goniometric system with a spot size that increases versus the incidence angle (cosine compensation). The main parameters which are controlling the performances are the spot size, the angular aperture, the detector size and the optical design.

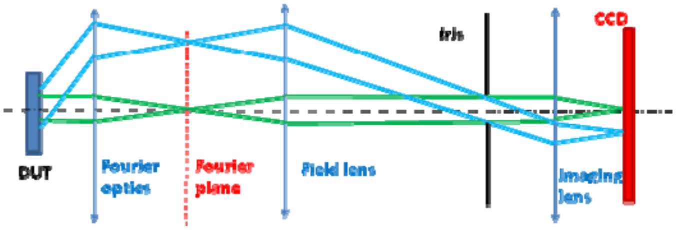

Figure 2. Principle of Fourier optics with cosine compensation

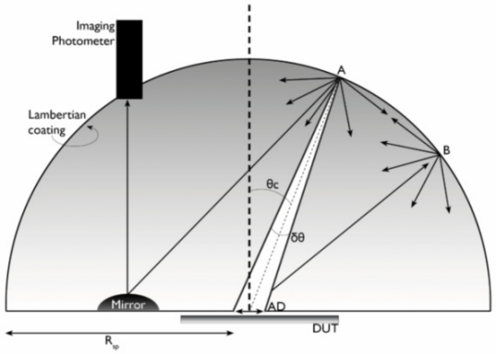

Figure 3. Principle of hemisphere based imager

2.3. Hemisphere based imager

The first hemisphere based imager called parousiameter has been developed by S. Wadman in 2000 [4] to measure optical scattering of surfaces. The main optical elements are a diffuse hemisphere, a curved secondary mirror and an imaging photometer or colorimeter (cf. figure 3) [5-6]. The hemisphere is attached to a flat non reflecting base plate containing a small aperture at its center. Light enters through this aperture and strikes the inner surface of the hemisphere. The convex mirror enables to image almost all the inner surface of the hemisphere and thus to

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monitor all the viewing directions in a single measurement. Important parameters are the sphere diameter, the aperture diameter and the reflection coefficient of the sphere wall.

3. Main Characteristics of the 3 systems

3.1. Angular resolution

The angular resolution of a viewing direction measurement device is determined by the smallest angle between two punctual sources that can be discriminated. It is a critical feature in many applications and in particular for 3D displays measurement. Resolution can be limited at different steps in the measurement process: by the CCD definition (number of pixels), by the MTF of the optic, by geometrical concept, by mechanical steps. Unfortunately it is always the most limiting issue that prevails. Goniometers are limited by the angular aperture of the spectro-radiometer and by the mechanical accuracy of the goniometer. The resolution is constant in the entire angular aperture and typically equals 2°. It can be reduced to 0.5° by strongly collimating the spectro-radiometer but the spot size becomes small and/or the goniometer size has to be increased drastically. High resolution measurements are in addition extremely time-consuming because of the great number of measurements needed. OFT based imager resolution is limited by the optical resolution of the Fourier optics and the CCD definition. It does not strongly depend on the measurement spot size. Latest ELDIM systems devoted to 3D characterization are built with an optimized optical design and 16M pixels CDD. An angular resolution better than 0.03° (or 1.8') in a viewing field of ±50° incidence angle has been demonstrated experimentally [8-9]. The angular resolution of a hemisphere based imager is limited for geometrical reasons. It is strictly dependent on the hemisphere radius R_{sp} and the aperture size AD. A point A on the screen integrates the light rays inside a cone coming from the aperture hole (cf. figure 3). Half angle resolution δ (Expressed in radiant unit) is given by:

$$\delta = Tan(\frac{AD}{2R_{sp}}) \approx \frac{AD}{2R_{sp}}$$

Some calculation examples with a sphere radius of 275 mm and variable spot size are given in figure 4. The angular resolution is always very low even for very small aperture sizes and the light collection efficiency becomes dramatically low in these conditions. One solution could be to increase the sphere radius but very low angular resolution cannot be obtained. A **4.5 meter diameter sphere** would be needed to reach a 0.05° angular resolution with a measurement spot size of 4 mm. As we will see his gain would then be as low as 1.5 10^{-7}.

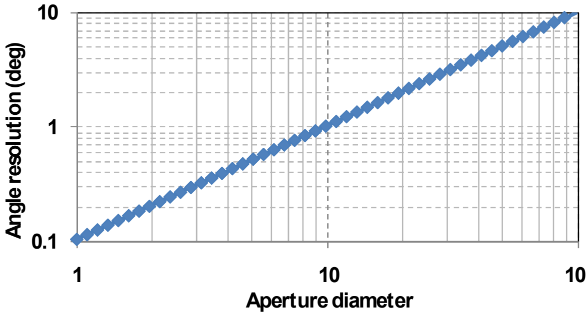

Figure 4. Theoretical angular resolution of a hemisphere based imager of radius 275 mm: aperture spot size is variable

3.2. Light collection efficiency

Since the measurement spot can be small and the angular resolution has to be as good as possible, light collection efficiency which controls the signal over noise ratio (SNR) is of primary importance for judging of the ability to measure low light signals. From that point of view, a major difference exists between goniometers and OFT based imagers on (?) one hand and hemisphere-based imagers on (?) the other hand. First of all, the well-known cosine decay of the luminous intensity with the angle is compensated by design in goniometers which are measuring a constant apparent surface and exhibits a constant collection efficiency in terms of solid angle. With the OFT based approach it is also possible to provide the same cosine compensation using a specific optical design (cf. figure 2). The spot size is controlled independently of the angular aperture and the effective spot size increases with the incidence angle in order to make the same cosine compensation that goniometers intrinsically provide. The hemisphere based imager principle does not allow such compensation for the loss in collection efficiency versus the incidence angle. The spot size is fixed by the aperture size (cf. Figure 3). This effect is most prominent at high angles as shown in figure 5. Without cosine compensation, measurements above 80° suffer from very bad collection efficiency.

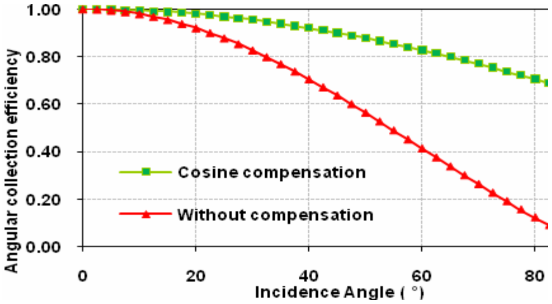

Figure 5. Angular light collection with and without cosine compensation

Furthermore, with goniometer and OFT based imager, all the light emitted in a small angular cone around the angle under interest is collected by the equipment and measured by the sensor (For OFT based imager the optical transmission of the optics must be taken into account but is always high). In the hemisphere-based imager, the light flux Φ_1 coming from an object of luminance L and collected from a fixed spot size at the incidence angle θ and striking the hemisphere is given by equation (1):

$$\Phi_1 = 2\pi(1-\cos\delta)L\cos\theta \approx \pi L\delta^2\cos\theta \quad (1)$$

It is (?) then reflected and spread in 2π steradian according to the lambertian diffusion behavior of the internal coating. Only a very small fraction is further collected by the imaging system (Curved mirror + camera). The gain ratio G between the DUT luminance L_0 and the wall inner surface luminance L_s is then given by:

$$G = \frac{L_S}{L_0} = \rho.\delta^2.\cos\theta = \rho.\left[\frac{AD}{2R_{sp}}\right]^2.\cos\theta$$

where ρ is the reflection coefficient of the sphere coating. It is striking to see that collection efficiency will decrease as the square of the resolution. A compromise must be made from the ground when setting the device size. Increasing resolution by a factor of 10 will decrease the efficiency by a factor of 100.

Hereafter we have reported the flux collection efficiency versus the incidence angle for a goniometer assuming a transmission efficiency of 90%, a conoscope with cosine compensation assuming a transmission efficiency of 50% and hemisphere-based imager of radius 27.5 cm, reflection coefficient ρ of 20% and measurement spot size of 2 cm (cf. figure 6). The difference of collection efficiency between the three systems is obvious. A first conclusion is that it is nearly impossible to measure low light levels using hemisphere-based imager. On axis loss ratio will be close to 10^{-4}. Measuring a 100Cd/m² sample with the above described hemisphere-based setup yields to the measurement of a 10^{-2}Cd/m² inner wall luminance. Moreover, the SNR situation is even worse when taking into account parasitic light as we will see below (see 3.3).

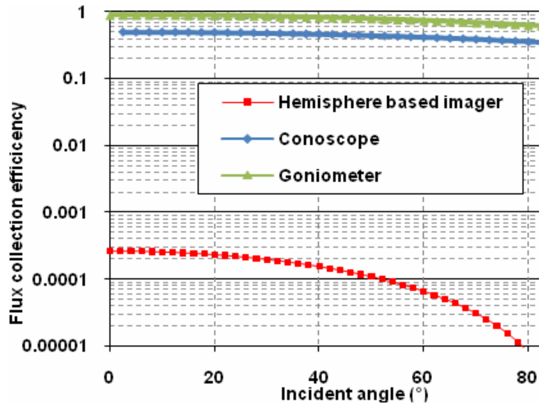

Figure 6. Light collection efficiency versus incidence angle: for goniometer assuming 90% optics transmission, for conoscope assuming 50% optics transmission and hemisphere based imager (R_{sp}=27.5cm, ρ= 20% and AD =2cm).

3.3. Parasitic light

Goniometers do not suffer from particular parasitic light but from ambient light. Good SNR can be obtained by using the device in a dark room. OFT based imagers, as all other optical systems, suffer from internal parasitic light controlled by the optical design and the quality of the lenses (and in particular of the antireflective coatings ARCs on optics). To reach very high angular apertures, the first Fourier lenses have always very small curvature radius and are always challenging for ARC. ELDIM has developed its own coating facilities using triple planetary electron beam evaporation system. Parasitic light is reduced down to 10^{-4} at 1° on the latest systems [9]. On the contrary in the hemisphere-based imager, a large part of the sample illuminance participates to an intense parasitic signal because of the secondary reflections on the hemisphere coating that acts as a "background" luminance. This background signal approaches a DC component [6] if a perfect lambertian diffuse coating is assumed and in the absence of any aperture in the sphere and any reflection on the display under test. The flux reflected on the sphere surface can be calculated using the following formula:

$$\Phi_S = \sum_{k=1}^{\infty} \rho^k (1-f)^k \Phi_0 = \frac{\rho(1-f)}{1-\rho(1-f)} \Phi_0$$

Φ_0 is the incoming flux, f is the ratio of the reflecting surface compared to a perfect sphere that we can approximate to ½. We assume also that the base of the hemisphere is perfectly non-reflective (which is not true especially at grazing angle). The background signal can then be estimated as the total reflected flux Φ_s minus the first reflection:

$$\Phi_B = \Phi_S - \rho(1-f)\Phi_0 = \frac{\rho^2(1-f)^2}{1-\rho(1-f)} \Phi_0$$

Aside that this parasitic pseudo-DC signal needs to be correctly handled and removed at best, it degrades significantly the signal over noise ratio. It is easy to estimate the amplitude of this DC component with respect to the real component in the case of a emitter in cosines of the incident angle $L(\theta) = L_0 . \cos^n \theta$. n=0 corresponds to the case of Lambertian emitter and n=2 corresponds to a standard LCD emission shape. The incoming flux is given by:

$$\Phi_0 = \int_0^{\frac{\pi}{2}} \phi(\theta) 2\pi . R_{sp}^2 \sin\theta . d\theta = \frac{2\pi^2 R_{sp}^2 L_0 \delta^2}{n+2}$$

The parasitic flux produces a luminance given by:

$$L_B = \frac{\Phi_B}{(1-f)4\pi^2 R_{sp}^2} = \frac{\Phi_0}{4\pi^2 R_{sp}^2} . \frac{(1-f)\rho^2}{1-\rho(1-f)} = \frac{L_0 \delta^2}{2(n+2)} . \frac{\rho^2}{2-\rho}$$

With f=1/2. So the ratio of the parasitic signal over the real signal is given by:

$$\frac{L_B}{L_S} = \frac{\frac{L_0 \delta^2}{2(n+2)} . \frac{\rho^2}{2-\rho}}{\rho \delta^2 L_0 \cos^{n+1} \theta} = \frac{\rho}{2(n+2)(2-\rho)\cos^{n+1}\theta}$$

Some values of this ratio obtained for reflection factors from 0.2 and 0.9 are given in figure 7. It explains the choice of a low reflection coefficient inside the sphere in spite of the poor collection efficiency but even in these conditions a minimum of 3% of the light is parasitic at normal incidence and much more at higher angles. For the case of a LCD, 10% of the light is parasitic at 60° of incidence. Combined to a strong angular dependence of the equipment transfer function and a poor ability to measure small signals, this drawback limits its applicability to bright and low contrast sources.

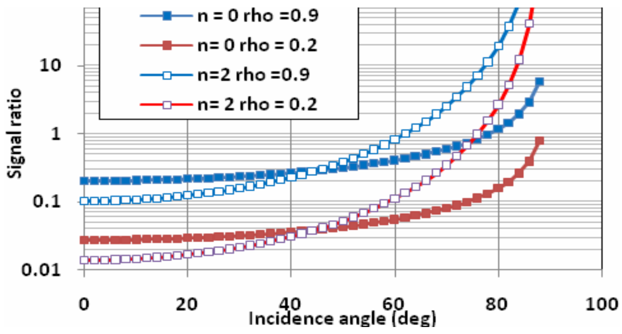

Figure 7. Ratio between parasitic signal and real signal for two types of sources and two internal reflection coefficients.

3.4. Working distance & shadow effect

For goniometers the working distance is always large but the measurement area needs to be exactly at the center of the rotation movement and perfectly oriented.

The OFT based imager has an optimal working distance in the range of 1 to 4mm depending on the angular aperture of the system. This working distance is not critical since the system is collecting "plane waves" at each angular direction. Exact focusing is not required and the system can easily work at larger distances (cf. figure 8). The impact on the measurement is only that measurement spot centers are not perfectly aligned when varying the incidence angle. This behavior can be related to misalignment of goniometer axis.

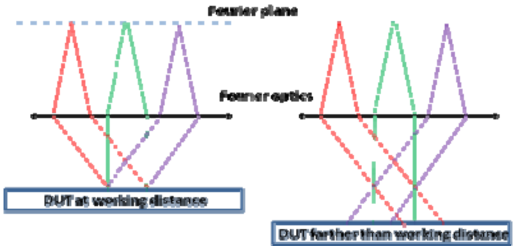

Figure 8. Effect of working distance in OFT based imager

In the hemisphere based imager, the measurement spot being defined by the entrance hole, the ideal working distance is zero or even negative (Because of the non zero thickness of the sphere inner wall). For LED or small source that can be put inside the sphere, there is not disadvantage. On the contrary, this is a serious drawback for display measurement. Indeed the poor light collection efficiency is another time reduced by the shadow effect due to the thickness of the sphere inner wall as schematized in figure 9.

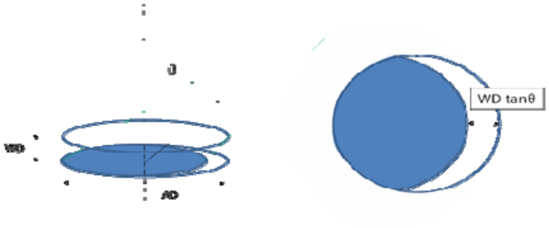

Figure 9. Shadow effect in hemisphere based imager

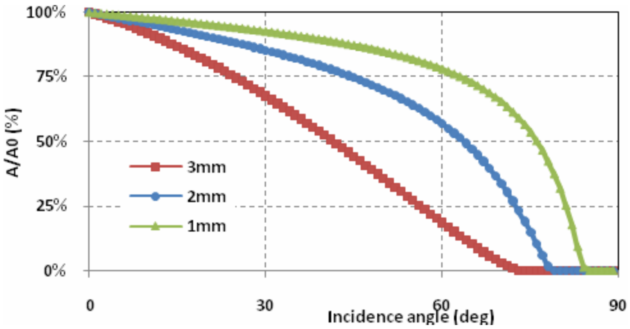

Figure 10. Shadow effect in hemisphere based imager as a function of incident angle and drawn for three different WD.

If WD is the thickness of the sphere inner wall and AD the aperture diameter, the effective area contributing to the internal lighting of the sphere is given by:

$$A(\theta)=\frac{AD^2}{2}\left[\cos^{-1}\left(\frac{WD.\tan(\theta)}{AD}\right)-\frac{WD.\tan(\theta)}{AD}.\sqrt{1-\left(\frac{WD.\tan(\theta)}{AD}\right)^2}\right]$$

The surface ratio A/A0 can then be calculated versus the incidence angle θ and WD. It is reported in figure 10 for three values of the wall thickness. It is clear that even for very small thickness the amount of light entering the sphere is drastically reduced at high angle. This shadow effect is of course combined to the lack of light collection efficiency reported in fig. 5-6 and makes this instrument impracticable for high angles.

4. Conclusions

We have compared some theoretical characteristics of the different technical solutions to measure viewing direction related parameters of displays. From this study it clearly appears that hemisphere-based imager suffer from very poor light collection efficiency, tradeoffs between angular resolution and efficiency and important parasitic light. This instrument appears more suitable to measure small and intense light sources that can be introduced directly inside the sphere. In addition, polarization analysis and visualization of the spot position is not possible.

Goniometers do not suffer from collection problems or parasitic light by design. The main drawback has always been the measurement time that becomes prohibitive for a high angular resolution on an extended (θ,φ) range as required with 3D displays for example. Attempts to overcome this major problem using up to 10 spectro-radiometers simultaneously are not cost effective for a time saving that is relative.

Best technical solution for viewing angle measurements is clearly the Fourier optics approach. There is no strong theoretical limitation, neither for light collection efficiency nor for angular resolution. The ELDIM optical design that includes cosine compensation allows measurements up 88° and even 89° incidence angle (Equipments from ELDIM are working up to 88° for more than 4 years). The practical quality of a Fourier optics instrument is driven by the optical design of the system but also by the quality of the manufacturing (in particular of the optics). New VCMaster3D system dedicated to 3D displays has shown angular resolution of 0.03° up to 50° incidence [8-9].

5. References

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