The Imaging Sphere – the First Appearance Meter?

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Abstract

The Imaging Sphere™ is a unique tool that can be used to measure the angular luminous intensity and colour variation of light sources, the view angle performance of displays, and the light scatter from surfaces (bi-directional reflectance distribution function or BRDF). Combining a CCD imaging photometer with a hemispherical reflecting chamber, the Imaging Sphere is based on novel technology jointly developed by Radiant Imaging and Royal Philips Electronics. For light source and display characterisation, the Imaging Sphere functions as a far-field goniophotometer, except there are no moving parts, the measurements take just a few seconds and the source is characterised in all directions in a single measurement. For surface appearance testing, the Imaging Sphere functions as a BRDF instrument, capturing the full 2π hemispherical reflected intensity distribution for a given angle of illumination in a matter of seconds. In addition, the Imaging Sphere costs a fraction of the price of traditional goniometer and BRDF systems, allowing its use in routine production testing as well as R&D.

1. Introduction

The newly developed Imaging Sphere™ from Radiant Imaging, Inc. is a novel instrument which allows for the quantification of the magnitude and colour of the light output emitted or reflected from a device under test and how they vary with viewing angle (or with viewing and illumination angles for non-emitting samples). By providing data on the variation of colour, intensity and reflectance as a function of viewing and illumination angles, the Imaging Sphere provides much more information to better describe the appearance of a light source, display or material.

This paper will review the need for angular light, colour and reflectance measurements on light sources, displays and materials. Traditional measurement devices will be compared with the Imaging Sphere and results from initial application studies conducted using the Imaging Sphere will be presented.

2. The Need for Angular Light Intensity and Colour Measurements

The "appearance" of an object does not depend solely upon its spectral reflectance but also upon the directionality of the light upon reflection from the material. Few materials exhibit the ideals of specular (i.e. mirror-like) or diffuse reflectance; in reality, most samples exhibit some combination of diffuse and specular reflectance. Moreover, the spectral distribution of the light upon reflection may vary with both viewing and illumination angles. Examples of difficult to measure coatings and finishes include metallic effect finishes, so-called "colour flip" (or gonio-apparent) special-effect decorative paints and holographic foils. Colour flip pigments are multi-layer paints which cause the object to change colour dramatically when viewed (or illuminated) from different angles leading to a very complex analysis if one were to try to quantify the appearance of the material.

The luminous intensity (photometric power per unit solid angle) from a light source such as a light emitting diode (LED) will vary with angle. In addition, the colour of light emitted from certain types of white LED also varies with angle (for those LEDs that produce white light as a result of propagating the output from an ultraviolet or blue LED through a phosphorescent coating). The photometric modelling of LED-based light sources or luminaires generally (and incorrectly) assumes that the LED performs as an isotropic, point source. Thus, computer-aided design models of LED-based lighting rarely give an accurate prediction of the illumination performance of the final product due to the light from the LED being more concentrated in particular directions. Standards such as CIE 127 attempt to apply a universal frame of reference to LED measurements by specifying that the luminous intensity of an LED should be reported in the direction defined by the LED package's mechanical axis, but that simply serves to avoid the issue that the direction of peak intensity will probably be aligned along a different axis altogether. LED manufacturers also generally specify the view angle for their device, but this is a single number which defines the range of angles (in a single plane) over which the intensity from the LED falls to half that at its peak. Such scant information is wholly insufficient for LED system designers to know how the LED will perform in the intended application.

The visibility of LCD displays varies greatly with the direction from which one views the flat panel. For display manufacturers, three of the most important parameters to test are the luminance (often called the brightness or photometric intensity per unit area), colour and contrast ratio as a function of angle. In addition, the readability of a display will be greatly impacted by the ambient light to which it is exposed. The reader will be familiar with the problems of glare caused by specular and near-specular reflections from the surface of a display which can almost completely mask the image being viewed. Fully characterising a flat panel display requires not only a spatial (i.e. on-axis) measurement of luminance and colour uniformity but also how the display performs at off-axis angles.

3. Traditional Measurement Solutions

Traditionally, the direction-dependent variation of light intensity and colour emitted by a source, or reflected from a material have been determined using a goniometer (sometimes referred to as a goniophotometer – Figure 1). A goniometer typically comprises a moving platform which rotates a sample about one or two axes (azimuth and inclination) and a photodetector which views the sample in a fixed direction. Measurements are performed incrementally, one angle at a time over the complete hemisphere (2π steradians) or in a single plane. The platform is often motorized so that the measurements can be automated; depending upon the angular range and resolution required, goniometric measurements can take a long time to perform, sometimes several hours. The photodetector will be photometrically filtered for luminance or luminous intensity measurements, or comprise a tristimulus response photodetector for colorimetric measurements. Alternatively, a spectroradiometer can be used for spectral analysis, from which the photometric and colorimetric parameters are calculated. The photodetector will be positioned at a defined distance away from the light source in order that the correct geometric conditions for luminance or luminous intensity measurements are met.

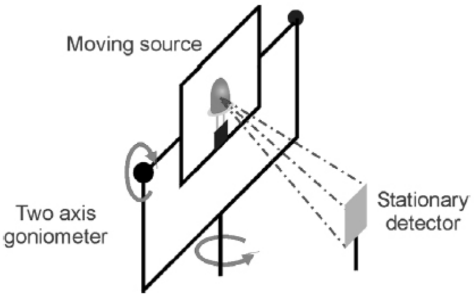


Figure 1: Goniometer for LED Angular Luminous Intensity Measurements

For intensity, measurements are performed in the "far-field", whereas luminance measurements are made in the "near-field". The far-field is defined as the region within which the source behaves as if it were a point source and as such, the inverse squared law applies. A star is a large object, but when viewed from Earth, has no physical extent and behaves as a point source. For many traditional lamps, the far-field is defined loosely as being between 5 and 10 times the source radius away from the lamp. For LEDs, the analysis is more complex and readers are referred to CIE 127 for the definition of how to perform average intensity measurements, which are – in effect – near-field intensity measurements performed under defined geometric conditions. Conversely, luminance measurements are made in the near-field, with the source and receiver physically close. In the near-field, the source has a physical extent and measurements are made of source intensity per unit area, which is the luminance.

3.1 LED Measurements

In the production of encapsulated LEDs or LED-based optical assemblies, an important step is the alignment of the optics to the LED die. Typically, this is performed by means of a goniometric measurement. A dual-axis goniometer provides all the data necessary for this task, but the measurement speed is quite slow. A 2D goniometric analyser only samples the intensity distribution in one plane. This makes the quality of the results highly dependent upon the placement of the LED in the device, which cannot be accurately controlled. Furthermore, most commercially available 2D goniometric analysers are not configured to handle larger sources, such as multi-die chip-on-boards, or systems with large optical components. Motorized goniometer systems tend to be slow, complex and relatively expensive devices.

These limitations severely limit the amount and quality of data which LED manufacturers can realistically make available to integrators of their devices. As a rule, LEDs are supplied with a view angle specification and a typical plot of the intensity versus angle for a single plane. Such scant performance information makes the job of designing optical systems around an LED much more complicated and very much a "hit and miss" affair. Moreover, it would be impractical for an LED manufacturer to sample and bin devices according to their directionality (as is common practice in the industry for LED intensity and colour) due to the time involved in individually testing devices as they come off the production line. It should be noted however that the colorimetric accuracy of goniometric measurements can be very high provided that a spectroradiometer is used as the detector. Conversely, the colorimetric accuracy of filter photometers or colorimeters can be quite poor unless the detector is calibrated against a source possessing a similar spectral power distribution to the samples it is intended to measure.

3.2 Flat Panel LCD Display Measurements

The method applied to testing LEDs is also used to measure the angular output of flat panel displays and LED arrays and clusters. A goniometric stage is used to position and rotate the sample with respect to a fixed detector which views a defined area on the display (Figure 2).

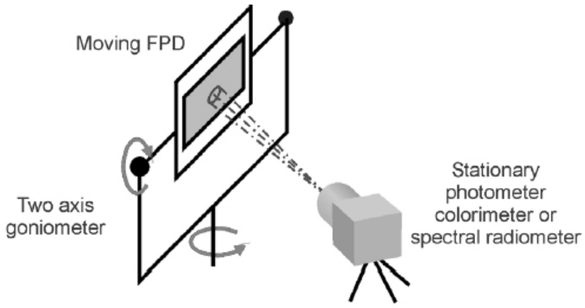


Figure 2: Goniometer for Flat Panel Display Measurements

The luminance variation from a display is measured in the near-field, hence the detector will be positioned relatively close to the source. Goniometers for display testing will, by necessity, be much larger than for discrete LED emitters, and their slow speed and high cost limits their use to off-line QA sampling and developmental use in the display industry. A further drawback of classical goniometers for display view angle testing is the measurement spot size varies as the angle of the display is changed, leading to an inconsistent sampling position. On the other hand, if used with a spectroradiometer detector, the colorimetric accuracy of a goniometer can be very high and less susceptible to errors arising from stray light.

An alternative method for testing display angular luminance and colour exists in the form of the Conoscope (Figure 3). This is an instrument which combines a high resolution CCD camera with Fourier optics which maps an emitting spot on the display onto the CCD detector. Each pixel on the CCD corresponds to a specific emission angle from the measured spot on the display. The Conoscope is a well established technique but its utility is restricted by its high cost, susceptibility to stray light and limited measurement spot size (which makes it sensitive to the display's pixel size). The Conoscope is however very fast, gives a consistent measurement area for all angles and offers good angular resolution.

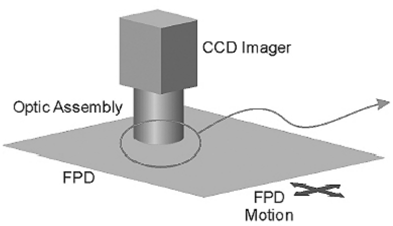


Figure 3: Conoscopic Method for Display Testing

A more recent refinement on the goniometer theme has been to replace the spot detector with a CCD-based imaging photometer, as implemented in the Radiant Imaging FPMS Flat Panel Measurement System. The CCD imaging photometer employs a 2D detector array with a spectral response scaled to match the CIE V(λ) or tristimulus functions to image the whole area of the display in one measurement. Conceptually, the imaging goniometer provides measurements of the display luminance and colour for all positions, one angle at a time. From this data, the uniformity as a function of view angle can be easily computed, as can the view angle performance for any location on the display. Further advantages include a selectable measurement spot size, a measurement area that remains constant for all view angles and the ability to provide measurement data from an infinity perspective (all measurement locations measured at normal incidence).

3.3 Measurement of Surface "Appearance"

Colorimeters are instruments which are commonly used to measure the colour or spectral reflectance of materials. A variety of standardised measurement geometries are employed in such instruments, including directional illumination (e.g. 8°) with diffuse (hemispheric) collection using an integrating sphere or directional illumination (e.g. 0°) with directional collection (e.g. axial or annular 45°). Whilst such instruments provide measurements which conform with internationally accepted conventions, they suffer from severe limitations when used to measure the colour of materials whose spectral reflectance varies greatly with viewing or illumination angles, such as certain metallic finishes and special effect paints. To fully quantify the appearance of such materials, it would be necessary to measure the reflected colour at all angles of illumination and viewing. Certain manufacturers have attempted to address this problem with so-called "multi-angle" colorimeters. These measure the reflected colour in several directions (e.g. 15, 25, 45, 75 & 110°) for a single illumination direction (e.g. 15°). Such instruments can only be a partial solution to the complex problem of measuring exotic paints and finishes however.

Single or multi-angle colorimeters are simple, inexpensive and fast tools but can only report colour for a fixed angle of illumination and a single or limited number of viewing directions in one plane. As such, they cannot provide a meaningful measurement of appearance for complex materials.

A much more sophisticated (and expensive) device is the scatterometer. This is a generic name for the type of instrument which measures angular reflectance (Figure 4). A scatterometer is normally configured to measure the BRDF (bi-directional reflectance distribution function) of a surface, the ratio of incident irradiance to reflected radiance for defined angles of illumination and viewing. The light source is usually a laser, and BRDF data is given at specific wavelengths. A scatterometer is a very powerful device, providing high resolution and accuracy. However, measurements are very slow (reflected radiance is measured sequentially at one angle of elevation and at one azimuth angle for each angle of illumination), and scatterometers are very costly and complicated to use.

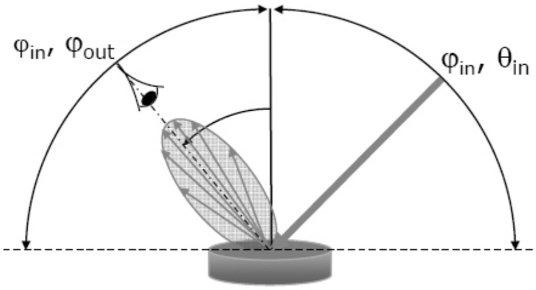


Figure 4: Scatterometer for BRDF Measurements

4. New Technology – the Imaging Sphere

There has not been an instrument for luminous intensity, colour, view angle or BRDF measurements that offers speed, angular resolution and low cost – until now. The Imaging Sphere™ from Radiant Imaging provides a unique and innovative solution to the problem of obtaining meaningful angular light distribution data for both research and development and on-line production QA testing.

4.1 The Philips Parousiameter

The genesis for the Imaging Sphere began in 1996. Philips was in the process of developing its "Matchline" series of television sets and companion video recorders. These featured plastic cabinets with metallic-effect finishes. The cabinets for the TV, VCR and stand all came from different factories. Colorimetrically, all the parts met the colour matching specification, and the parts also matched in terms of their gloss levels, however upon visual inspection, the parts clearly had different finishes. Existing colorimetric and gloss measurements were simply unable to detect these differences, so Philips decided to develop a new method for evaluating the visual "appearance" of the plastic parts. Philips Applied Research in Eindhoven, The Netherlands was entrusted with this project and the result was the Parousiameter, a name chosen after the Greek word for appearance. The original

Philips Parousiameter is shown below (Figure 5) together with its inventor, Sipke Wadman.

Figure 5: The Original Philips Parousiameter with its Inventor, Sipke Wadman

The Parousiameter showed that the differences in appearance of the Matchline parts was due to the directionality of the anisotropy of the reflections when viewing in the direction of the short axis on one part and the long axis on the adjacent part. This caused a brightness difference in one direction of view, that could flip over in another viewing direction.

With data obtained from its new instrument, Philips was better able to control the production of the metallic effect finishes applied to its Matchline products such that all the parts looked the same under a variety of lighting conditions. Philips realised that it had developed a powerful new technique for assessing the colour and appearance of materials and applied for and was granted protection for its intellectual property. Since then, Philips sought a partner company to help commercialise its invention and in February 2005, signed a cross-licence agreement with the Seattle-based light measurement specialists, Radiant Imaging, Inc. Radiant Imaging was chosen as Philips' partner based on its experience and leadership in CCD-based light and colour measurement instrumentation.

4.2 Commercialising the Parousiameter – the Radiant Imaging Imaging Sphere™

The main optical elements of the Imaging Sphere are a diffuse, low reflective hemisphere, a curved secondary mirror and a CCD-based photometer or colorimeter (Figure 6). The camera software automatically applies corrections for image offset, stray light and flat-field distortion so that the displayed image is a true representation of the light source's angular intensity and colour distribution.

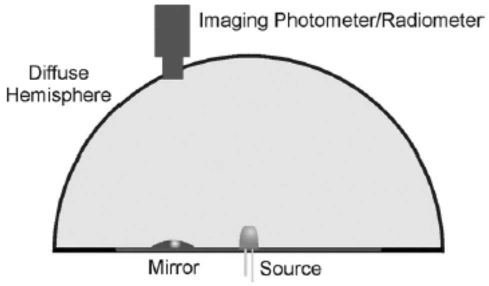


Figure 6: Basic Elements of the Imaging Sphere

The hemisphere is attached to a flat, non-reflecting baseplate containing a small aperture at its centre. Light enters the light-tight device through the aperture in the baseplate (Figure 7), strikes the inner surface of the coated hemisphere, and is then reflected by a convex mirror (Figure 8) as an image of this illumination pattern onto the CCD camera (a Radiant Imaging ProMetric™ Imaging Photometer or Colorimeter). The convex mirror enables the camera to image almost the entire inner surface of the hemisphere at once. The image thus contains all the information necessary to reconstruct the entire angular intensity profile of the illumination at a resolution determined by the camera's image sensor. Almost 2π steradians of data can be recorded in a single measurement. For automated display testing, the imaging sphere or the device under test is mounted for rapid relative motion (X,Y stepped translation) so that the sphere or device under test can be repositioned to sample the angular profile from multiple test points on the display, according to the specific test protocols required.

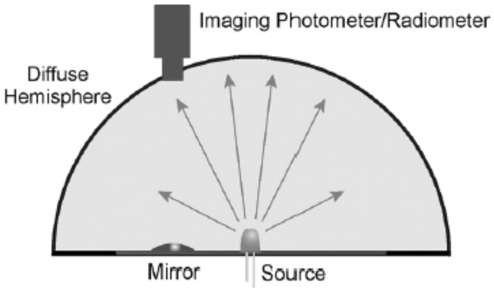


Figure 7: Light Enters the Imaging Sphere and Creates an Illumination Pattern on the Inside of the Dome

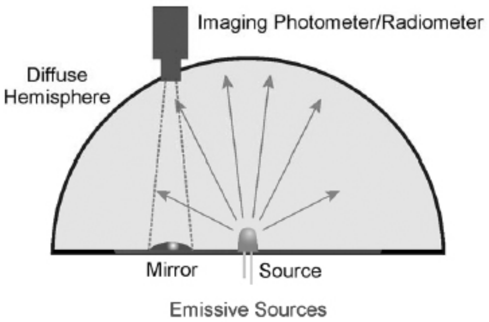


Figure 8: The CCD Camera Images the Illumination Pattern from the Convex Mirror

Those readers familiar with the operation of integrating spheres may question the Imaging Sphere's ability to retain image quality and hence angular data integrity due to the multiple, diffuse reflections that occur within the dome. An integrating sphere is a hollow sphere which serves to spatially integrate (i.e. average) the spatial light distribution from a light source propagated into it. Integrating spheres are typically coated with a high reflectance (>90%) diffuse coating which causes multiple reflections to occur within the sphere. The multiple reflections lead to a uniform radiance distribution within the sphere, which can then be sampled by a photodetector mounted on the sphere wall. Thus, an integrating sphere can measure the beam flux from all manner of extended area and divergent optical sources.

One of the keys to the successful operation of the Imaging Sphere is a novel coating on the inner surface of the hemisphere. This is a grey (18-20%) diffuse reflectance coating designed to deliver only scattered reflections. The baseplate is coated black to approach zero reflectivity. As a result, the CCD camera sees an intense image of the first-order illumination pattern with a very weak, uniform background created by second strikes and beyond. This background level depends upon the total light flux and is typically below 1% of the peak image intensity. The Imaging Sphere samples the background light level and this is then subtracted out from the measured source image in the camera software.

The angular resolution of the Imaging Sphere is defined by two parameters. The ProMetric CCD cameras used on the Imaging Sphere are available with a range of pixel resolutions, but the camera chosen for most applications has a full frame CCD sensor with 512 x 512 pixels. Over the complete hemisphere, each pixel sees a view of 0.35°. However, the size of the sample must also be considered. Light from two locations on the same source can impinge upon the same spot on the wall of the dome (Figure 9). With a 7mm sample aperture, the angular uncertainty θ is calculated from arc tan (4/254) = ± 0.79°.

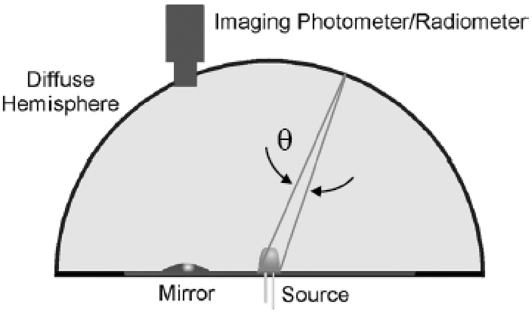


Figure 9: Limiting Resolution of the Imaging Sphere

4.3 The Three Imaging Sphere Configurations

The configuration outlined above (referred to as the model IS-LI Imaging Sphere) applies to the measurement of angular luminous intensity and colour from point light sources such as LEDs and small, planar LED clusters or arrays. Compared with traditional goniometric testing, the Imaging Sphere is much faster (measurements of the full hemispherical intensity and colour distribution take a few seconds compared with many minutes if not hours for goniometric testing) and provides data in all planes, not just one. The imaging sphere has no moving parts to go wrong, has a high angular resolution and is significantly less expensive than traditional instrumentation. Combined, these attributes allow the Imaging Sphere to be employed not just in R&D, but also on the production line for quality assurance and device selection and binning. LED manufacturers who adopt on-line testing of the angular variation and direction of peak intensity of their devices will be rewarded with a significant competitive edge in the market place.

Two further versions of the Imaging Sphere have been developed for the testing of displays (model IS-VA) and for scatterometry and surface appearance testing (model IS-SA). In display testing, the Imaging Sphere measures the luminance and colour variation at one point on the display at a time. The measurement spot is selectable up to 40mm diameter. To test the luminance, colour and contrast variation over the whole display, the device under test must be translated and the required locations on the display measured sequentially (Figure 10). It is instructive to compare the approach taken with the Radiant Imaging Imaging Goniometer (all locations on the display, one angle at a time) with that of the Imaging Sphere (all angles, one location at a time). The Imaging Sphere can be used to test a variety of display technologies, including OLED, LCD, PDP, LED and LED backlight. Compared with goniometric and Conoscopic techniques for display testing, the Imaging Sphere is significantly faster and less expensive, possesses a high angular resolution, is insensitive to pixel dimensions and stray light and measures with a constant spot size at all angles.

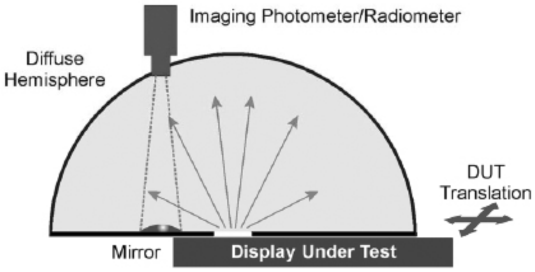


Figure 10: Imaging Sphere Configuration for Display Testing

As a scatterometer for surface appearance testing, the IS-SA version of the Imaging Sphere can be equipped with a probe beam to illuminate the sample at either a variety of fixed angles of illumination, or at any angle if equipped with an adjustable illuminator (Figure 11). Both illumination configurations have been evaluated for the Imaging Sphere, but that chosen for the production version uses a single, variable angle, white light illuminator (Figure 12) over that which uses fixed illumination directions (Figure 13).

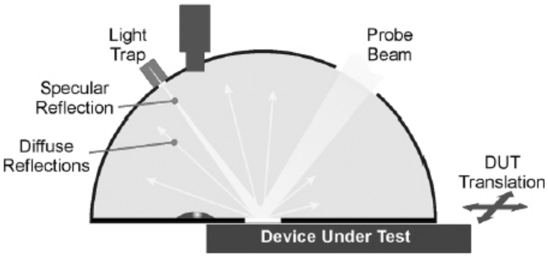


Figure 11: Imaging Sphere Configuration for Appearance and BRDF Testing

The reflected radiation pattern imaged onto the CCD camera from the dome will be characteristic of the sample under test. If the sample is glossy, there will be a distinct specular reflection whereas matte materials will create a uniform light distribution within the dome. The Imaging Sphere software will analyse the light distribution and compute the BRDF of the material.

Figure 12: The Imaging Sphere IS-SA for Surface Scatter Testing with Adjustable Illumination Direction

Figure 13: The Imaging Sphere IS-SA with Prototype Fixed Illumination Positions

Geometrically, the Imaging Sphere holds a major advantage over conventional goniometric scatterometers in that the reflected radiation distribution is measured simultaneously at all azimuth and elevation angles for each direction of illumination (Figure 14). Traditional goniometric scatterometers are limited to measuring the reflected light in one direction at a time for each angle of illumination. Characterising the complete hemispheric scatter distribution for every angle of illumination with a traditional instrument would clearly be a prohibitively time consuming task.

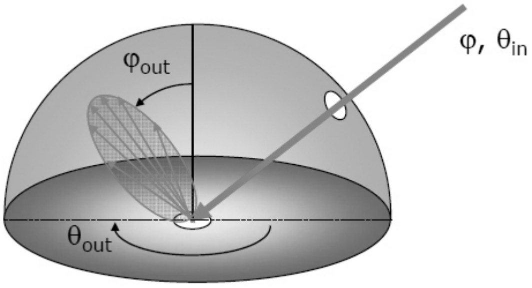


Figure 14: Imaging Sphere Performs Out of Plane Scatter Analysis in Real Time

The speed, ease of use, relatively low cost and ability to perform measurements in ambient light conditions are further advantages of the IS-SA over conventional technologies. All three versions of the Imaging Sphere employ the same basic hardware which enables the user to configure a single instrument for luminous intensity, view angle and scatter measurements if he or she so wishes.

Validation testing of the Imaging Sphere has been performed by comparing the variation of colour and luminance from a flat panel LCD display on the IS-VA with a traditional goniometer. These results are shown below (Figure 15).

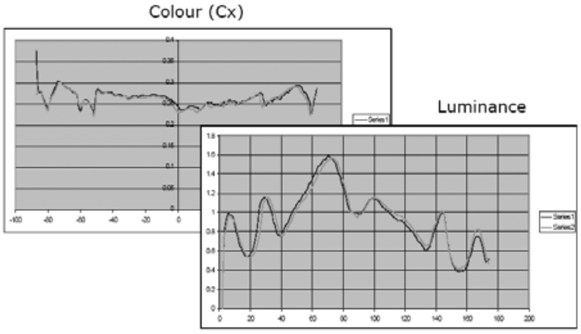
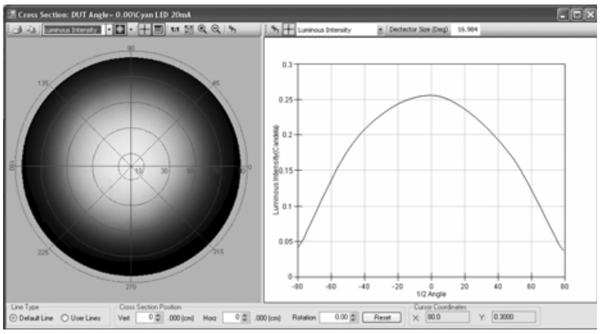


Figure 15: Inter-Comparison of IS-VA and Traditional Goniometer

The Imaging Sphere software provides for instrument calibration and recalibration, data acquisition, and a diverse range of data analysis functions. Measurement results are presented graphically and numerically. The parameters reported include luminous intensity, luminance, CIE colour coordinates (xy, u'v' & L*a*b*), tristimulus values (XYZ), correlated colour temperature (CCT), view angle, BRDF and cosine-corrected BRDF (CCBRDF).

5. Application Overview

To illustrate the utility of the imaging sphere in each of its three areas of application, results are presented below from an LED, a flat panel display and from a gonio-apparent, special-effect paint sample. A single LED emitter was placed at the input port on the Imaging Sphere (model IS-LI) and the complete hemispheric luminous intensity and colour variation recorded. A screen grab of the measurement results in shown below (Figure 16). The isometric plot shown on the left displays regions of constant intensity in the same colour, whilst the cross sectional Cartesian plot shown to the right is the luminous intensity sampled through a user-defined axis in the isometric plot. Of course, the value of the Imaging Sphere is that it records the spatial light distribution in all axes at the same time, and this data can be displayed in a 3D plot which greatly simplifies the visualisation of the output of the LED (Figure 17). It should be noted that this measurement took about 5 seconds to perform. By comparison, a traditional goniometric measurement might take about 30 seconds to perform, but this measurement is limited to one plane only; to sample the LED at every 5° of azimuth would take the operator over an hour.


Cross Section: DUT Angle= 0.00\Cyan LED 20mA

Detector Size (Deg) 16.904

Cursor Coordinates X: 80.0 Y: 0.3000

Figure 16: Angular Intensity Profile of an LED

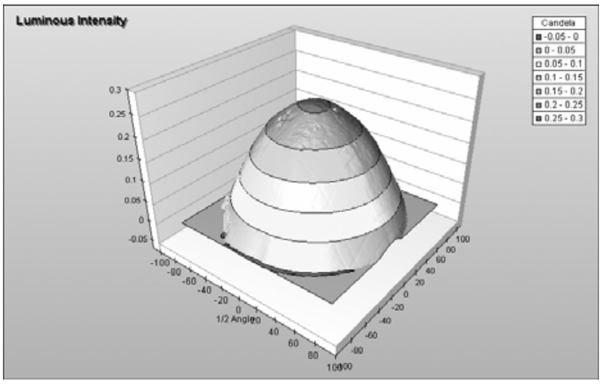
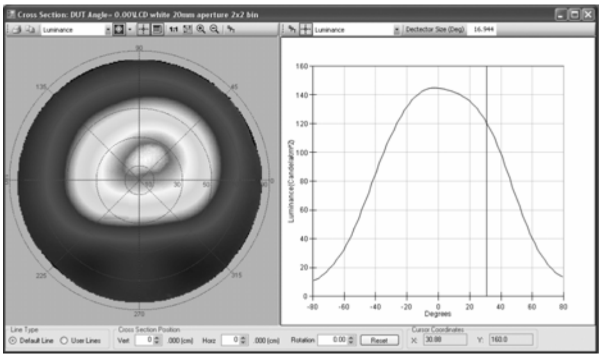


Figure 17: 3D Plot of the Angular Luminous Intensity of an LED

An LCD flat panel display was tested with the Imaging Sphere (model IS-VA). A single location on the display was selected for simplicity. The variation of luminance with angle (view angle performance) is shown with the LCD set to display uniform white (Figure 18). The next figure shows the luminance of the FPD when it is set to display black. This plot demonstrates the sensitivity of the IS-VA system, and also underscores the value of its ability to determine an entire output distribution at one time. Specifically, this single measurement, which took only seconds to make, clearly enables visualization of the leakage pattern from the LCD in both qualitative and quantitative terms.

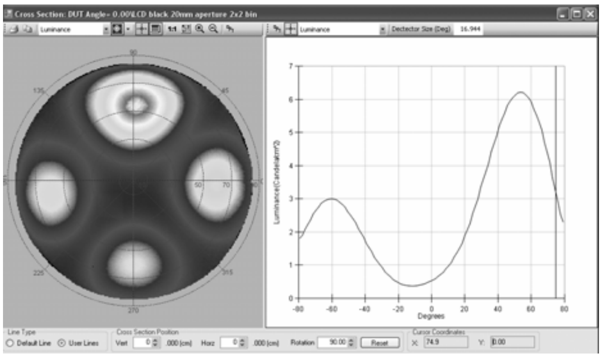

Cross Section: DUT Angle= 0.00\LCD white 20mm aperture 2x2 bin

Detector Size (Deg) 16.944

Rotation 0.00

Cursor Coordinates X: 30.00 Y: 160.0

Figure 18: View Angle Plot of LCD monitor set to display uniform white


Cross Section: DUT Angle= 0.00\LCD black 20mm aperture 2x2 bin

Detector Size (Deg) 16.944

Rotation 90.00

Cursor Coordinates X: 74.9 Y: 0.00

Figure 19: View Angle Plot of LCD monitor set to display uniform black

A sample of Helicone paint (a gonio-apparent, colour flip finish) was tested using the Imaging Sphere (model IS-SA). The probe beam was brought into the dome at an azimuth angle of 45° and at a number of elevation angles. The variation of the CIE u' and v' chromaticity coordinates at a viewing azimuth of 45° is shown below (Figure 20). With the illumination at normal incidence, the paint sample exhibits a consistent yellow colour (mean chromaticity of u' 0.20 and v' 0.49). When the illumination angle is increased to 45° (Figure 21), the colour of the paint flips over to a distinct green hue at high view angles. From the data obtained in a matter of a minute or so using the Imaging Sphere, it is possible to determine the colour shift for the gonio-apparent paint for any viewing direction and for the particular illumination conditions recorded.

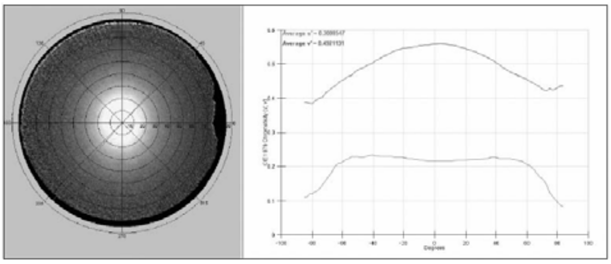


Figure 20: Angular Colour Variation of Helicone Special-Effect Paint Illuminated at Normal Incidence

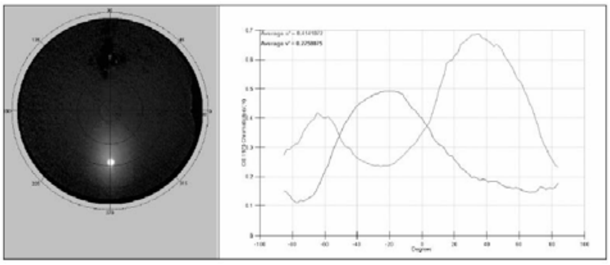


Figure 21: Dramatic Colour Shift of Helicone Paint Illuminated at 45 Degrees is Revealed by the Imaging Sphere

6. Summary

The Imaging Sphere from Radiant Imaging represents a powerful, enabling technology that provides access to angular light and colour distribution data from all manner of light sources (in particular LEDs and small arrays), displays and from materials and coatings. Its reduced measurement times, lower capital cost, simple operation and robust construction make the Imaging Sphere a viable proposition for both laboratory research and development as well as in production line testing, an application that until now has not been possible due to the slow speed of traditional goniometric techniques. Statistical process control and the selection and binning of LEDs and other sources and materials by view angle and direction of peak intensity is now made possible using the Imaging Sphere.

7. References

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