The Imaging Sphere™

The First Appearance Meter?

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Introduction

- Can an instrument truly measure appearance or is this just a tabloid headline used simply to grab your attention?
- This paper will review why we need to perform angular light and colour output measurements and how this impacts on the measurement of the optical properties of materials, on light sources and on displays
- Traditional measurement devices will be compared with the newly developed Imaging Sphere™ from Radiant Imaging
- Results from initial applications studies conducted using the Imaging Sphere™ will be presented

Presentation Outline

- Why do we need angular light intensity & colour measurements?
- Traditional instrumentation solutions
- New technology - the Imaging Sphere™
- Applications Survey

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Luminous Intensity

- Luminous intensity is the far-field photometrically-scaled radiation emitted by a source in a specific direction
- LI measurements quantitatively characterise light source output
- LI data is useful for optical design purposes

View Angle

- View angle measurements describe display appearance as a function of angle (luminance, colour and contrast ratio as a function of angle)
- View angle measurements may also include scattered light as a function of angle
- View angle data enables prediction of display appearance at various view angles

Scatter Analysis

- BRDF (bidirectional reflectance distribution function) describes light scatter by a surface under specific illumination conditions
- BTDF (bidirectional transmittance distribution function) describes light scattered as light passes through a material
- Enables us to determine how surface characteristics will affect overall surface appearance under various illumination conditions

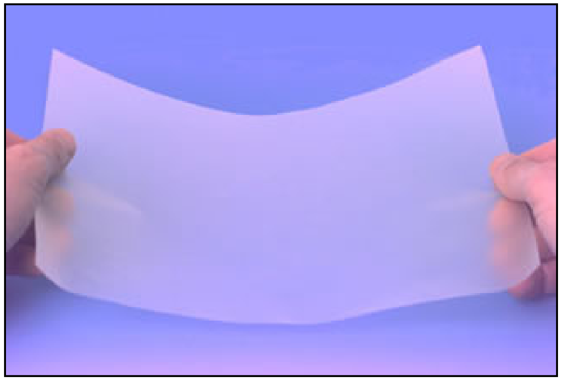
What is Appearance?

- The appearance of a material is not just a function of its colour; as important is the variation of reflectance with angle
- Knowing both sets of data allows us to quantify the appearance of an object for different illumination and viewing conditions

Specular Reflectance

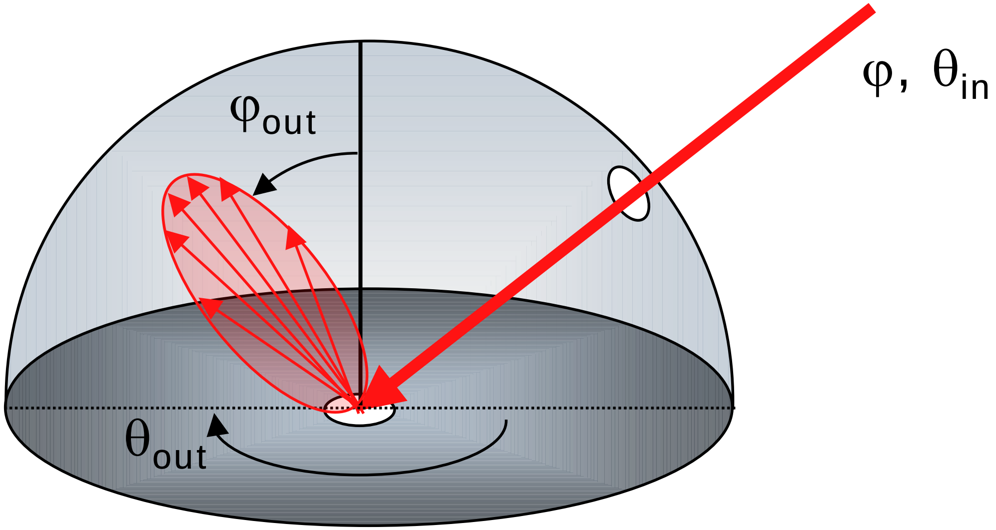
Combination

Diffuse Reflectance



Scatterometry

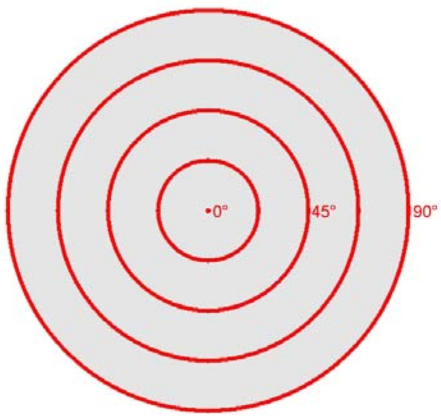
- The intensity and angular distribution of the light scattered from a surface tells us about its surface profile
- Scatter parameters are TIS & BRDF



BRDF

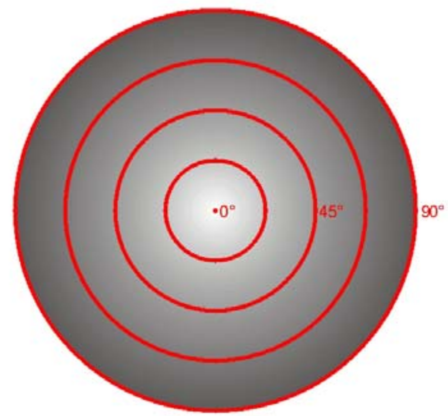
- BRDF is the ratio of directional reflected radiance to the incident irradiance. Units are inverse steradians (sr^{-1})
- BRDF of a perfect Lambertian surface is $1/\pi$ at all points
- Cosine corrected BRDF (CCBRDF) is BRDF x $\cos(\theta)$

Radar Plot of BRDF of Lambertian Surface



$\frac{1}{\pi}$ at all points

Cosine Corrected BRDF of Lambertian Surface



$\frac{1}{\pi} \times \cos(\theta)$

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Traditional Solutions

Luminous Intensity

- Goniophotometer/gonio-spectroradiometer

View Angle

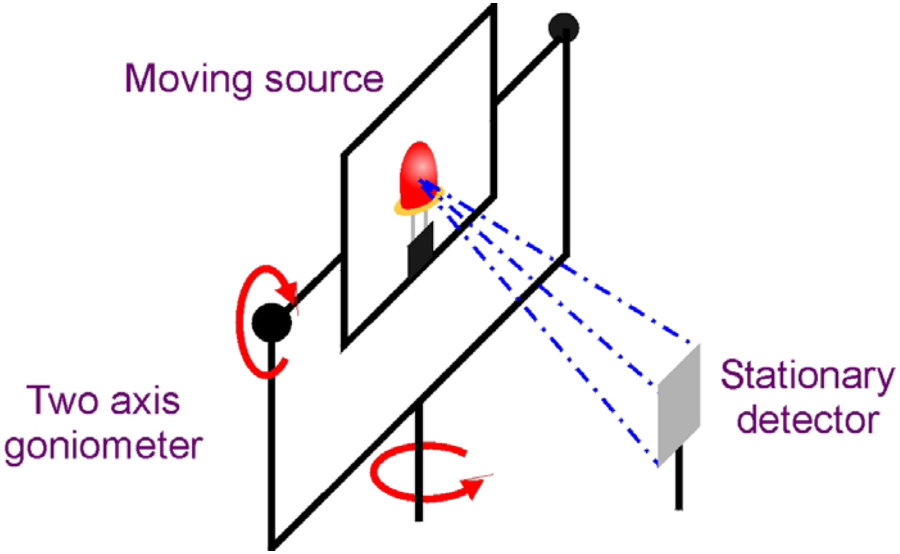
- Goniophotometer/gonio-spectroradiometer
- Conoscope
- Imaging goniometer (e.g. Radiant Imaging flat panel measurement system)

Scatter

- Gloss meter
- Gonioreflectometer (scatterometer)

Luminous Intensity - Goniophotometer

- Dual-axis goniometer used to rotate source relative to a fixed detector
- Uses a spot photometer for luminance or intensity measurements or a spot colorimeter or spectroradiometer for luminance and colour measurements

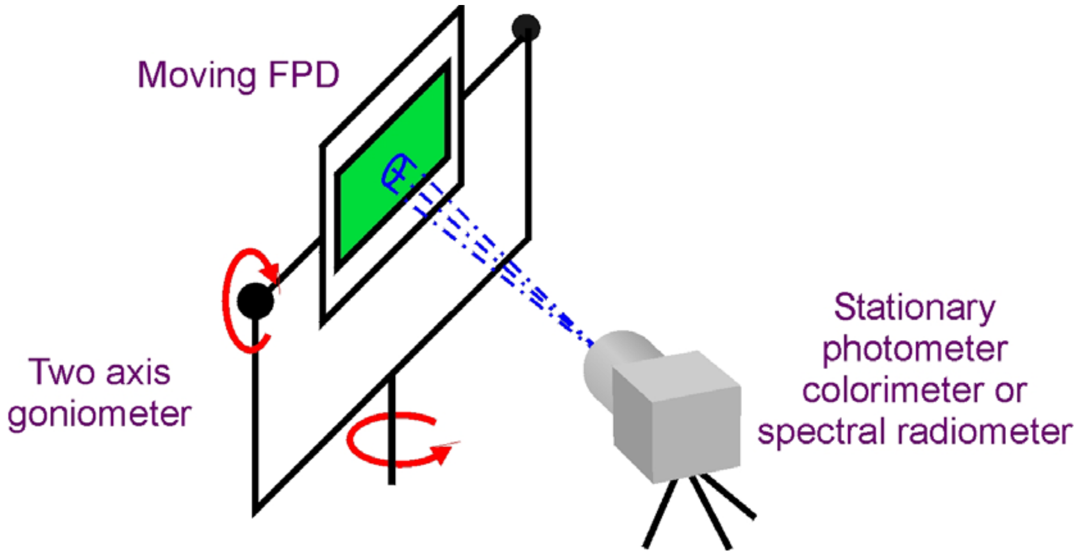


Luminous Intensity - Goniophotometer

- Used for LED measurements
- Advantages
  - Colour accuracy (if spectroradiometer)
- Disadvantages
  - Speed
  - Cost

View Angle - Goniophotometer

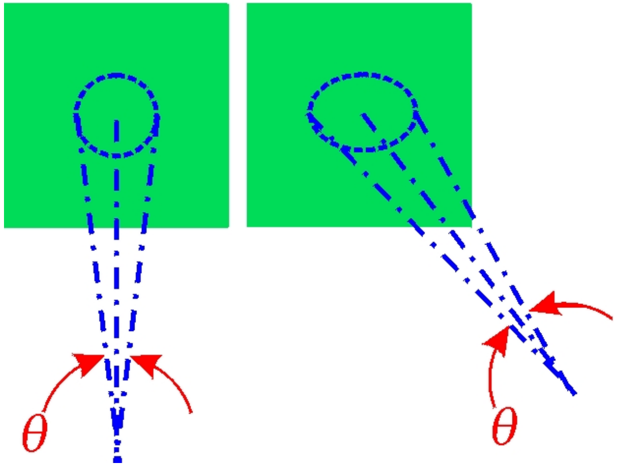
- Dual-axis goniometer used to rotate FPD relative to the detector
- Uses a spot photometer for luminance or intensity measurements or a spot colorimeter or spectroradiometer for luminance and colour measurements



View Angle – Gonio-spectroradiometer

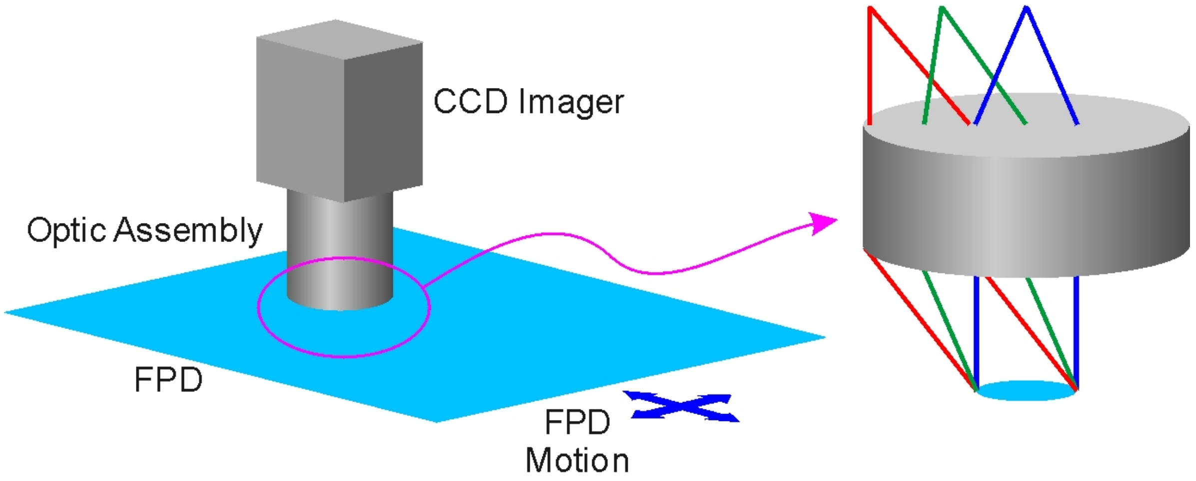
- Used for FPD measurements
- Advantages
  - Colour accuracy (if spectroradiometer)
  - Less sensitive to stray light
- Disadvantages
  - Cost
  - Inconsistent measurement spot size
  - Speed
  - Moving parts

Measurement spot size changes with angle of view



View Angle - Conoscope

- Utilises exotic (Fourier) optics that map an emitting spot to a CCD so that each pixel corresponds to a different emission angle

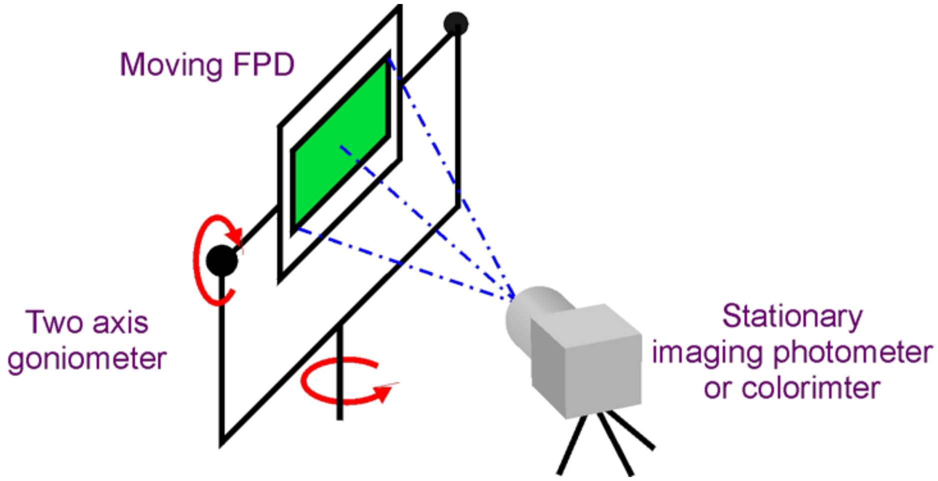


View Angle - Conoscope

- Measures FPD luminance and colour vs. angle
- Advantages
  - Speed
  - Consistent measurement spot size across all view angles
  - Good angular resolution
- Disadvantages
  - Expensive
  - Inaccuracy due to stray light
  - Limited measurement spot size (~2 mm) or larger spot (~ 7mm) with reduced field of view

View Angle - Imaging Goniophotometer

- Dual-axis goniometer used to rotate the source relative to an imaging photometer or colorimeter – all positions for one angle at a time
- Imaging capabilities provide precise spatial measurements of luminance and colour



View Angle - Imaging Goniophotometer

- Measures FPDs and FPD components
- Advantages
  - Measures entire display surface, not just a few spots
  - Provides uniformity as a function of view angle
  - Provides view angle performance for any number of separate locations
  - Selectable spot size
  - Spot size constant with measurement angle
  - Gives “infinity” type view perspective
- Disadvantages
  - Speed (all locations but only one angle at a time)

Scatter - Gloss Meter/Multi-Angle Colorimeter

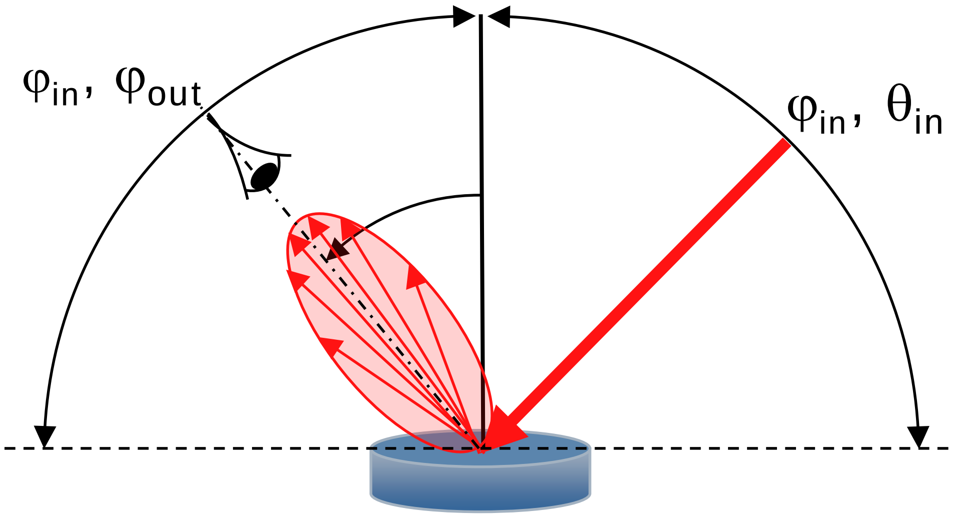
- Simple gloss meter
  - Measures specular reflectance for a single illumination and collection geometry (e.g. 0/45°)
- Multi-angle Colorimeter
  - Measures reflected colour in several directions (e.g. 15°, 25°, 45°, 75°, 110°) for a single illumination direction (e.g. 45°)

Scatter - Gloss Meter/Multi-Angle Colorimeter

- Measures paints, plastics, metals, skin (etc)
- Advantages
  - Inexpensive
  - Simple
  - Fast
- Disadvantages
  - Only one illumination direction
  - Only measures reflectance in a single direction or limited number of directions, and only in the same plane as the illumination
  - Cannot provide meaningful characterisation of appearance for all illumination or viewing conditions

Scatter - Gonioreflectometer

- Variously known as a scatterometer or a gonioreflectometer
- Measures the in-plane BRDF (BTDF) of a sample
- Photodetector normally rotates about the sample



Scatter - Gonioreflectometer

- Measures paints, plastics, metals, skin (etc)
- Advantages
  - Accuracy
  - Resolution
- Disadvantages
  - Speed – **very, very slow**; must measure reflected radiance sequentially at one angle of elevation and at one azimuth angle for each angle of illumination
  - Cost
  - Complexity

Instrumentation Summary

- There has not been an instrument for either luminous intensity, colour, view angle or BRDF measurements that offers speed, angular resolution and low cost – until now

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In the Beginning

- 1996: technology developed and patented by Philips Applied Technologies (Eindhoven, The Netherlands)
- Philips called this the *Parousiameter* (after the Greek word for “appearance”)
- Originally developed to address the mismatch of appearance of the cabinet, front piece, stand and VCR recorder of Philips “Matchline” TV sets

Image © Philips

Genesis of the Parousiameter

- These used plastic parts with metallic finishes
- Made at different factories worldwide
- Parts met the specified colour point and gloss level but didn't match
- Parousiameter showed that this 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

Imaging Sphere™ Latest Developments

- Philips sought a partner to commercialise its invention
- Radiant Imaging was chosen for its expertise and leadership in CCD-based light and colour instrumentation
- Radiant Imaging and Philips sign a cross-licence agreement in February 2005
- April 2005: Radiant receives its first order for an Imaging Sphere™
- October 2005: First commercial Imaging Sphere™ delivered
- June 2006: series production begins
- July 2006: first deliveries of production-specification units begins

An Imaging Sphere™ Comprises

- A 508mm (20”) diameter dome with an approx. 20% diffuse reflectance interior coating
- Radiant Imaging ProMetric™ CCD camera with either:
  - Radiometric response (350-1100nm)
  - CIE photopic response V(λ)
  - CIE tristimulus response (XYZ)
- Imaging Sphere™ software (& PC)
- Probe beam(s) - for passive devices

What Does an Imaging Sphere™ Look Like?

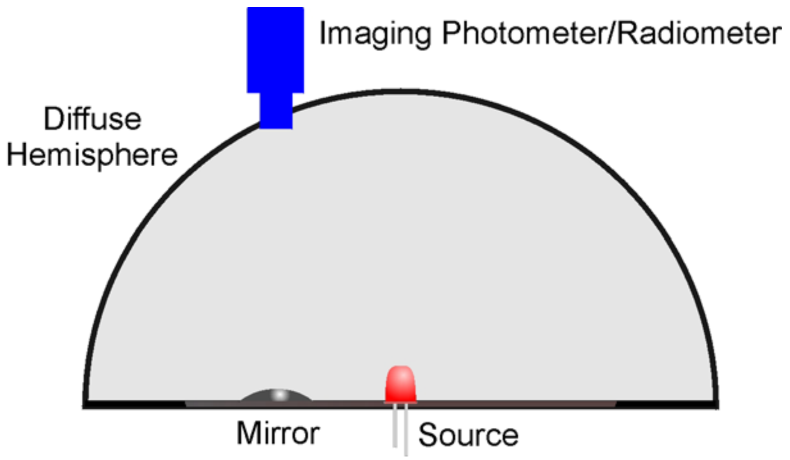
The original Philips "Parousiameter" with its inventor, Sipke Wadman

Image © Philips

The Production Imaging Sphere™

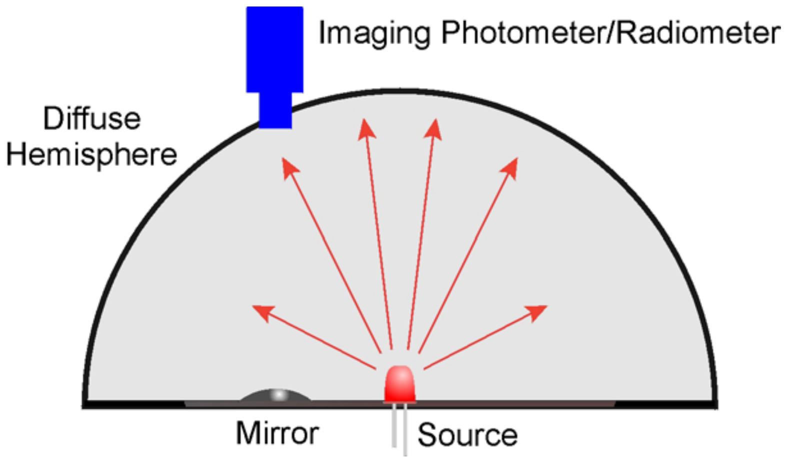
Imaging Sphere Operation

- Hemisphere coated with a diffuse, ~ 20% reflectance coating
- Imaging photometer/radiometer/colorimeter with optics that enable entire inner surface of hemisphere to be viewed



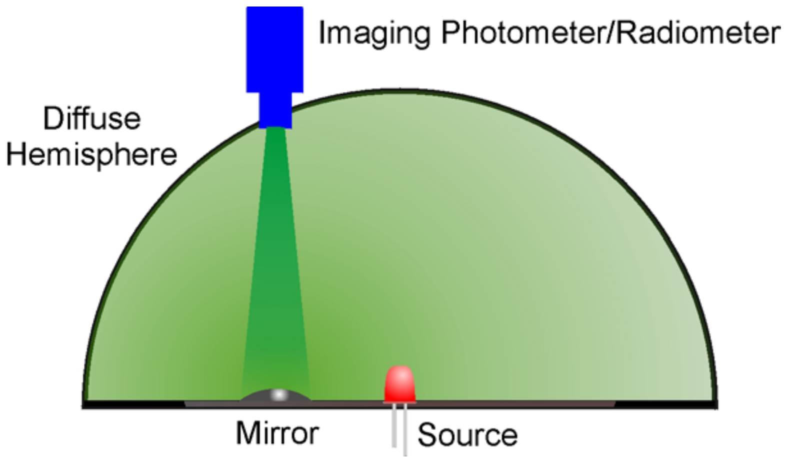
Imaging Sphere™ Operation

- Device Under Test (DUT) is placed at geometric center of sphere – can be emissive or passive
- Light emitted, reflected from or transmitted through the DUT strikes the inner surface of the sphere
- Sphere coating produces diffuse reflection with minimal multiple reflections



Imaging Sphere™ Operation

- The imaging photometer/radiometer/colorimeter captures an image of the entire inner surface of the sphere (2π steradians) in an instant
- Convex mirror placed to one side of DUT acts as a fisheye lens to enable this

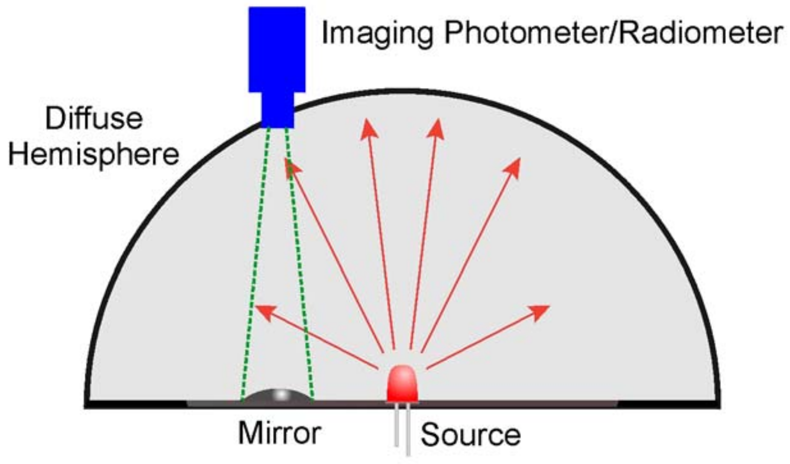


The Three Configurations

- Far-field (luminous intensity) for emissive devices (e.g. LEDs)
- Near-field (luminance) for emissive devices (e.g. LCDs)
- Far-field intensity for passive devices
- All three versions can be equipped for radiometric, photometric or colorimetric measurements (or any combination thereof)

IS-LI (Luminous Intensity)

- LED luminous intensity distribution
- Small light source luminous intensity
- Production-line testing of LEDs



Emissive Sources

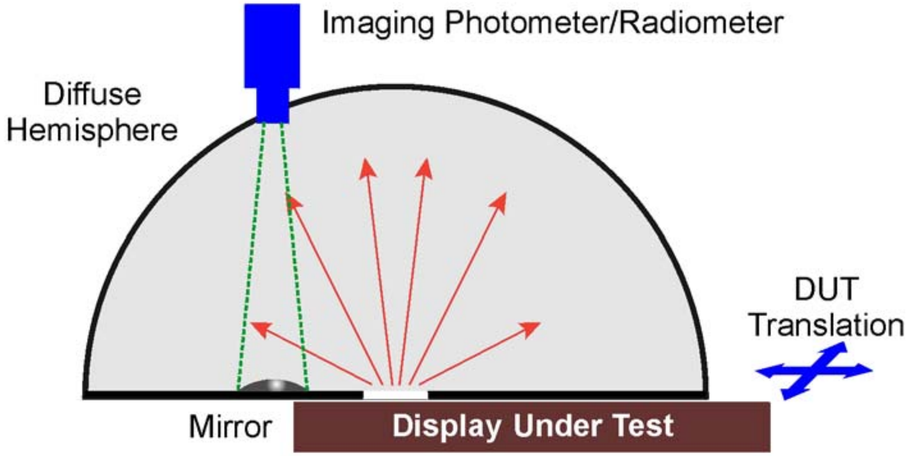
IS-LI (Luminous Intensity)

Benefits

- Speed
- Angular resolution
- Cost
- Reliability (no moving parts!)

IS-VA (View Angle)

- LCD, PDP, OLED, Backlights, etc.
- Brightness vs. Angle
- Colour vs. Angle
- Contrast Ratio vs. Angle



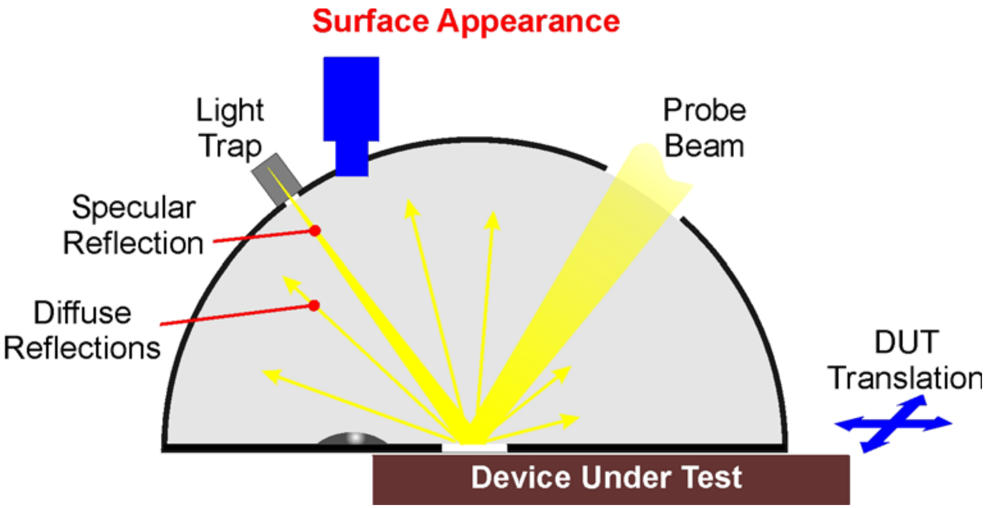
IS-VA (View Angle)

Benefits

- Rapid
- Economical
- Angular resolution
- Large spot size possible (up to 40mm)
- Not sensitive to stray light
- Consistent spot size over all angles

IS-SA (Scatter Analysis)

- Uses a probe beam to illuminate the material at various incident angles
- Analyse scattered light from the surface
- Can be used in both transmission and reflection



IS-SA Alternative Illumination Schemes

Single Lamp, Variable Angle*

Multiple Lamps, Fixed Angles

* Single lamp, variable angle scheme has been chosen as standard configuration for production sphere

IS-SA (Scatter Analysis)

Benefits

- Speed
- Cost
- Can be used in ambient light conditions
- Characterisation of reflectance for all viewing and illumination directions

Modularity

- All three IS embodiments use the same basic hardware
- This enables a single instrument, along with various hardware and software modules, to be used for multiple measurement types
- This offers the ultimate in cost effectiveness

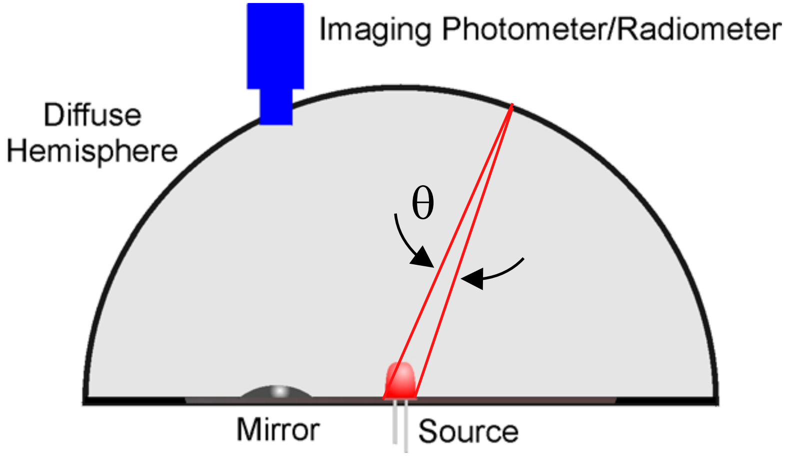
Performance Parameters

- Angular range:
  - Azimuth: 0 -360°
  - Inclination: 0 - 85°
- IS-LI (luminous intensity): 0.1 – 10^7 cd
- IS-VA (luminance): 1.0 – 4.0 x 10^7 cdm^{-2}
  - Aperture (max. DUT) size: 40mm (on 508 mm dome)
- IS-SA (min. reflectance): 1.0%
  - Measurement spot size: 2-10 mm
- Dynamic range: 10-14 bits (1,024 – 16,384 grey scale levels)
- Min. measurement time for 512 x 512 pixel ProMetric CCD:
  - 1 sec (photopic)
  - 5 sec (colour)

All performance specifications are subject to change without notice

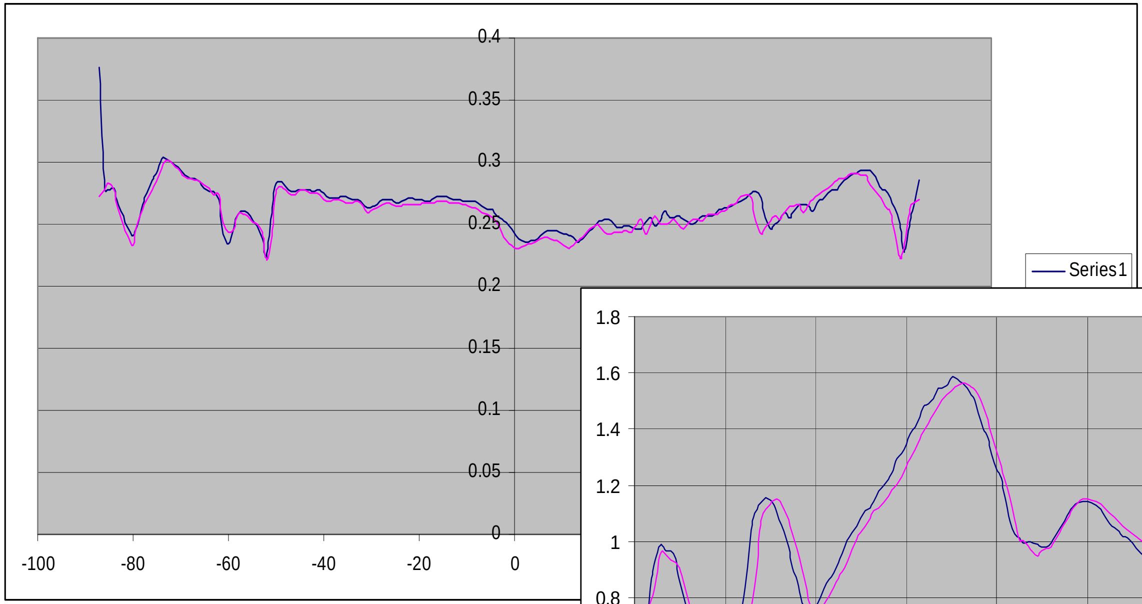
Angular Resolution

- The two limiting factors are:
  - CCD pixel resolution – with 512 x 512 pixels (on a full frame CCD), field of view of each pixel is 0.35°
  - Size of DUT:
    - With a 4mm aperture, the angular uncertainty θ is calculated per arc tan (4/508) = ± 0.45°
    - 10mm aperture: ± 1.13°
    - 40mm aperture: ± 4.50°

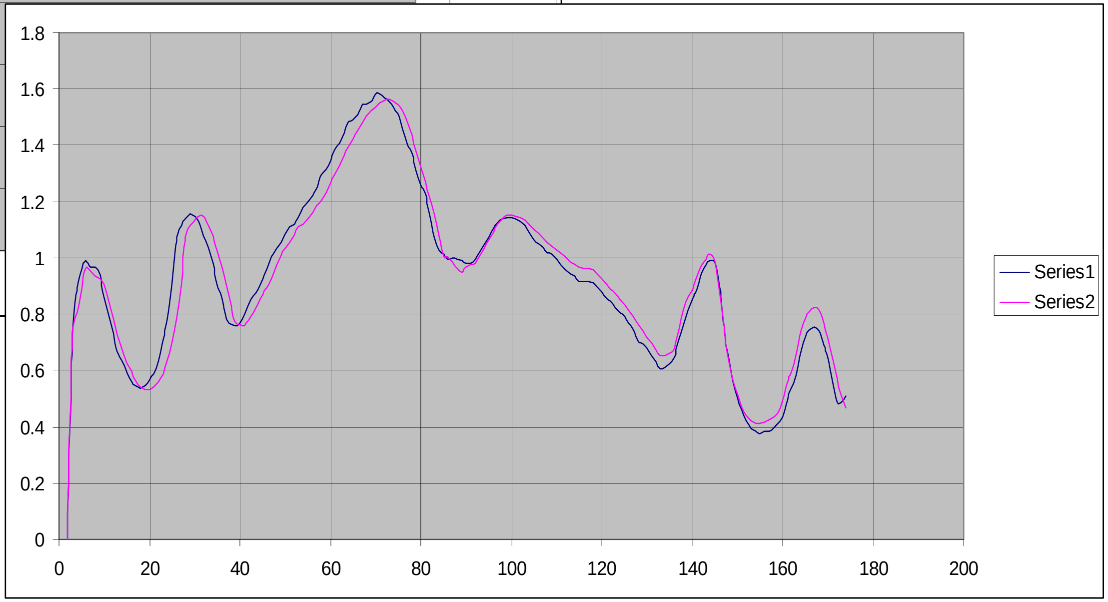


Validation Data

Colour (Cx)



Luminance

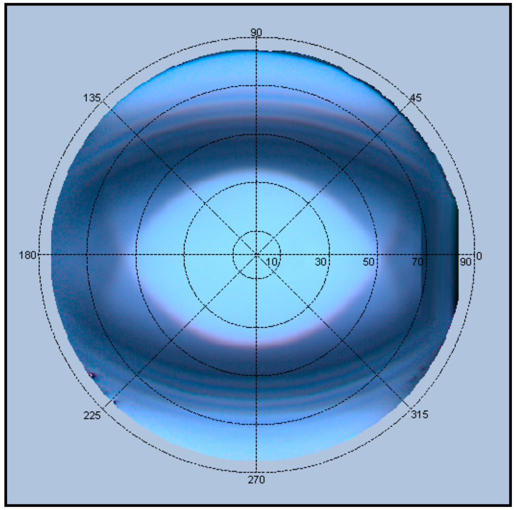


White LED, Imaging Sphere™ versus goniometer

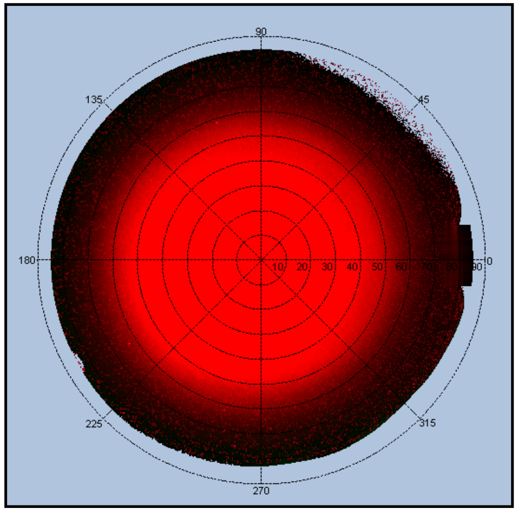
Software

- Imaging Sphere™ software enables instrument calibration, data acquisition, and a diverse range of data analysis capabilities

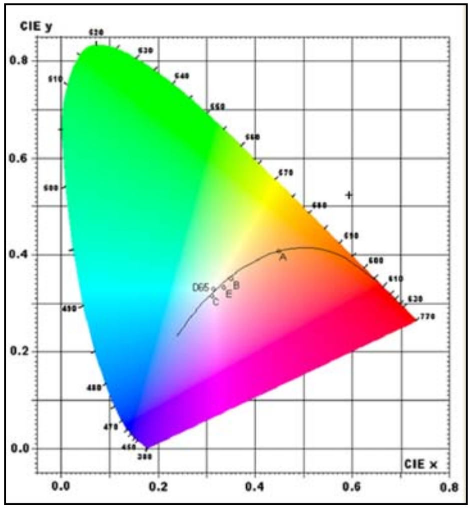
True Color



Luminous Intensity



CIE Coordinates



Software

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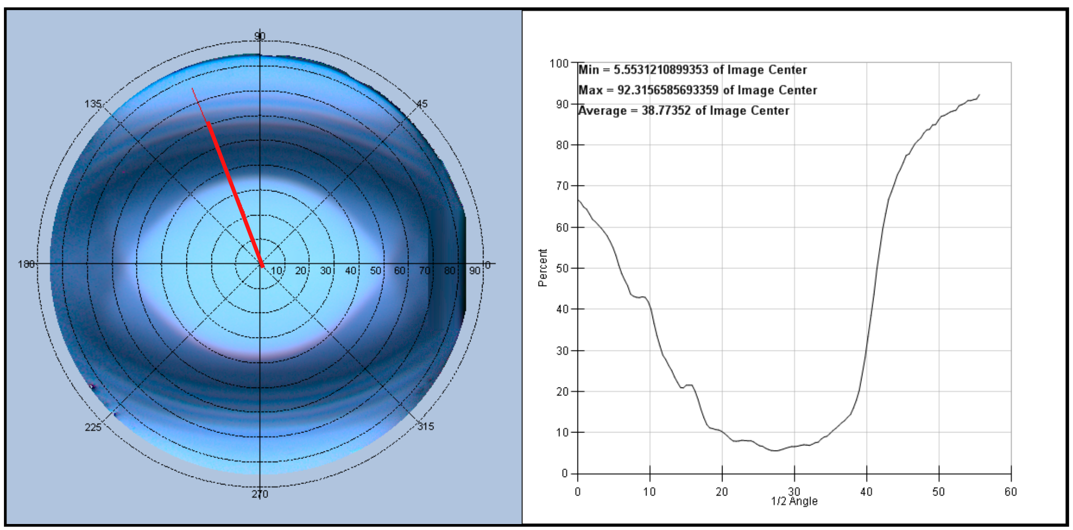
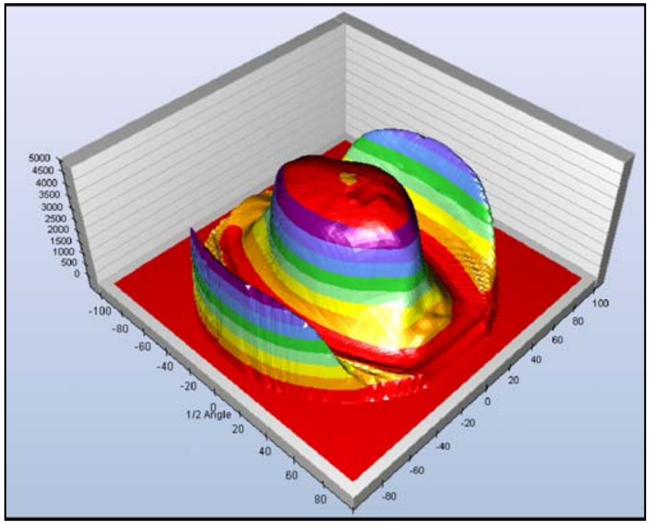
Cross Sections



3D Plots



Software

- Imaging Sphere™ software enables instrument calibration, data acquisition, and a diverse range of data analysis capabilities
  - True Colour
  - Luminous Intensity, Luminance
  - CIE Coordinates (x, y; u’, v’; L*a*b*)
  - Tristimulus values (XYZ)
  - Correlated Colour Temperature (CCT)
  - View angle
  - BRDF and CCBRDF

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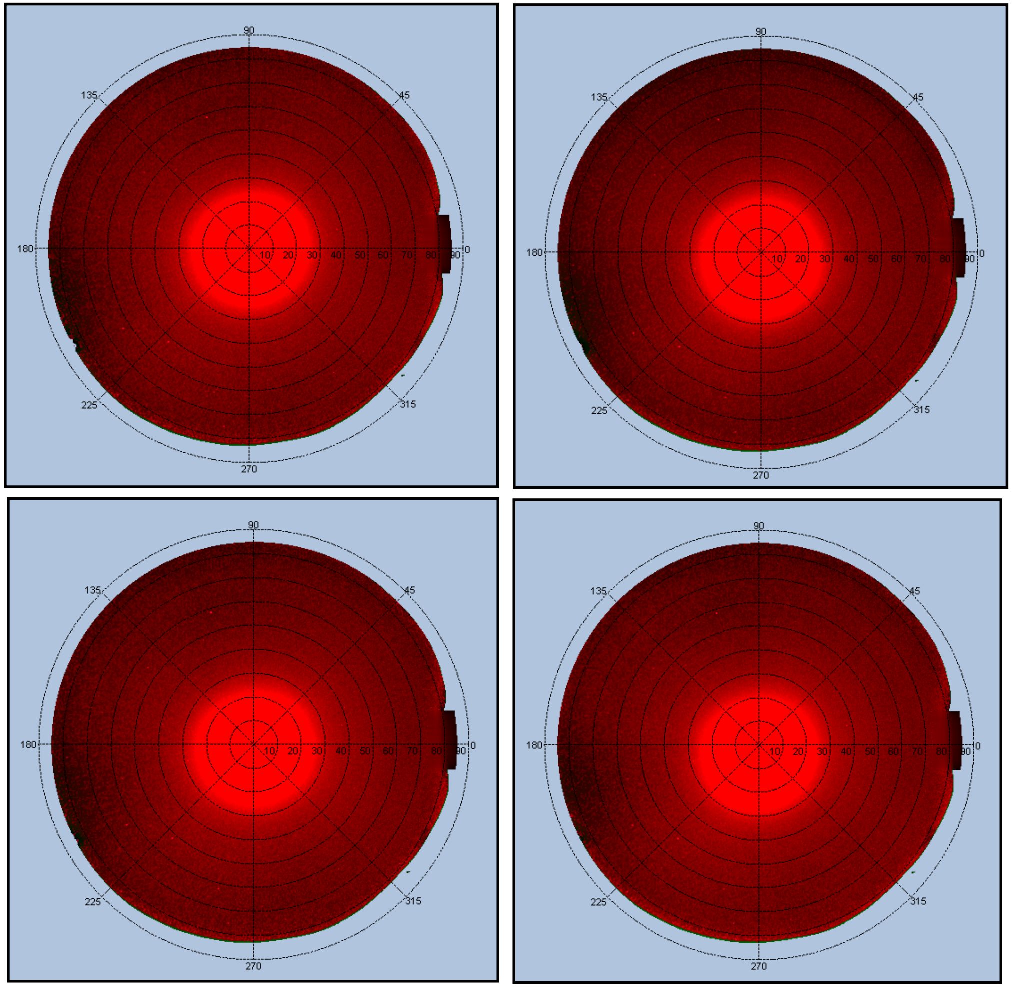
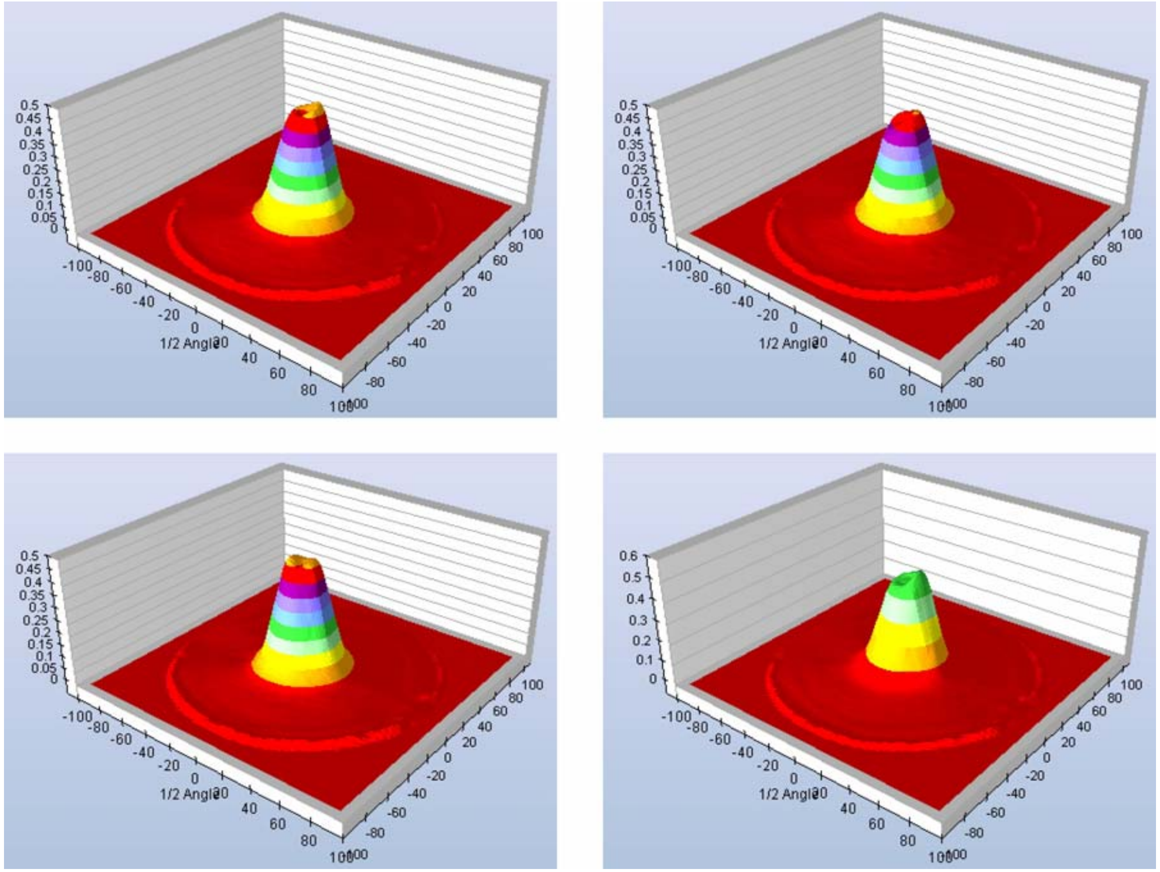
LEDs

- True color view shows little difference between units



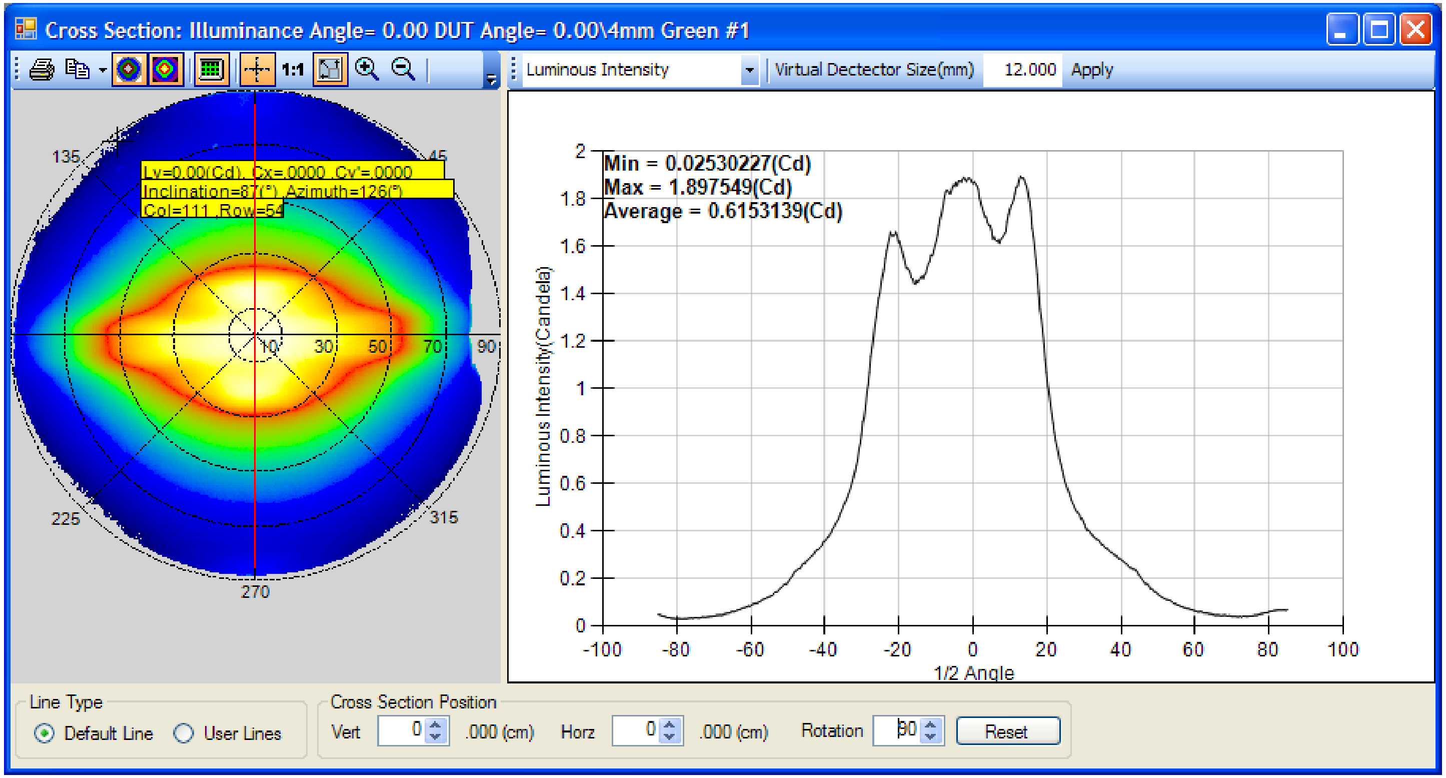
LEDs

- A 3D plot of luminous intensity displays the subtle differences



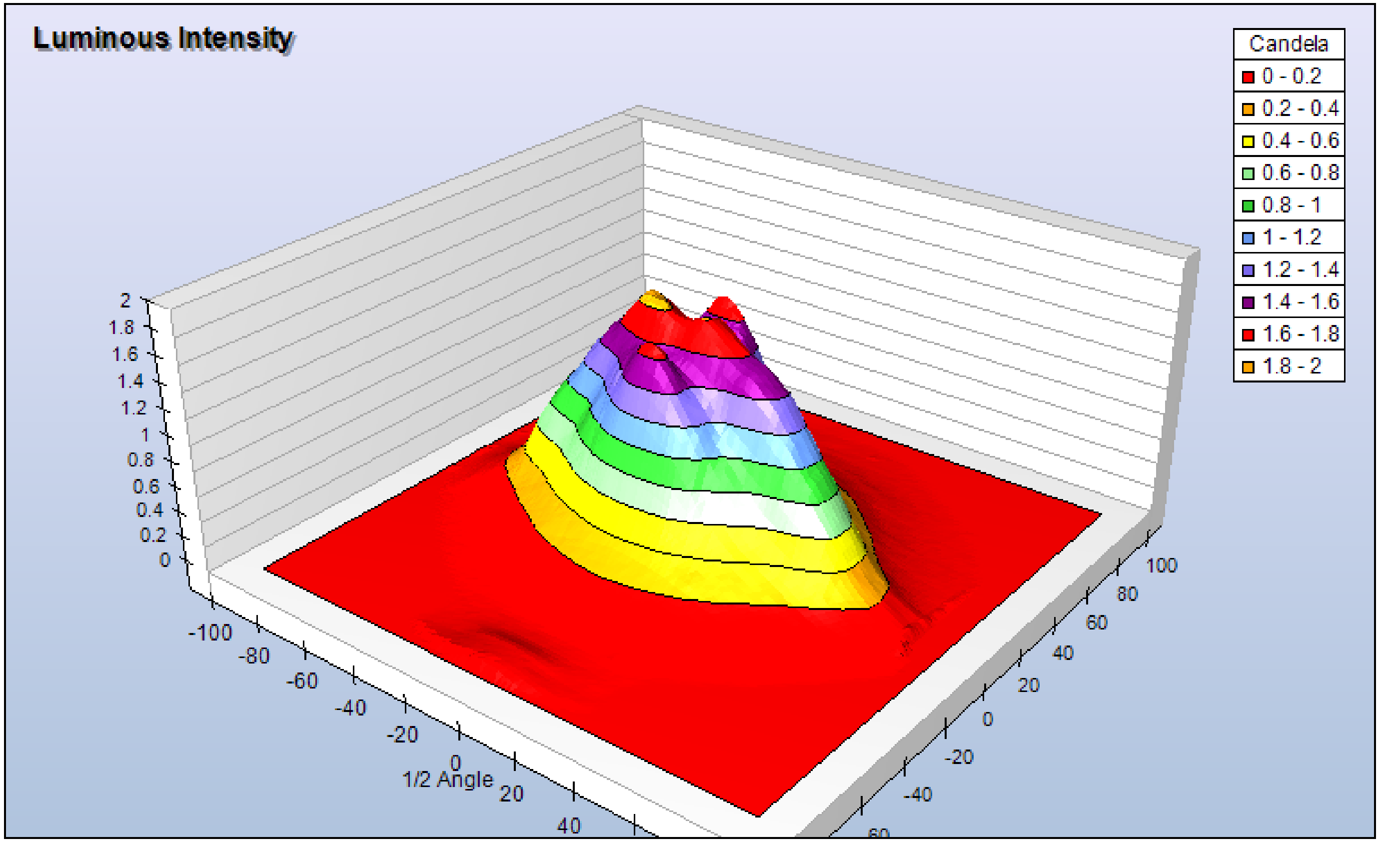
LEDs

- The Imaging Sphere™ can be used to make quantitative LED measurements in production



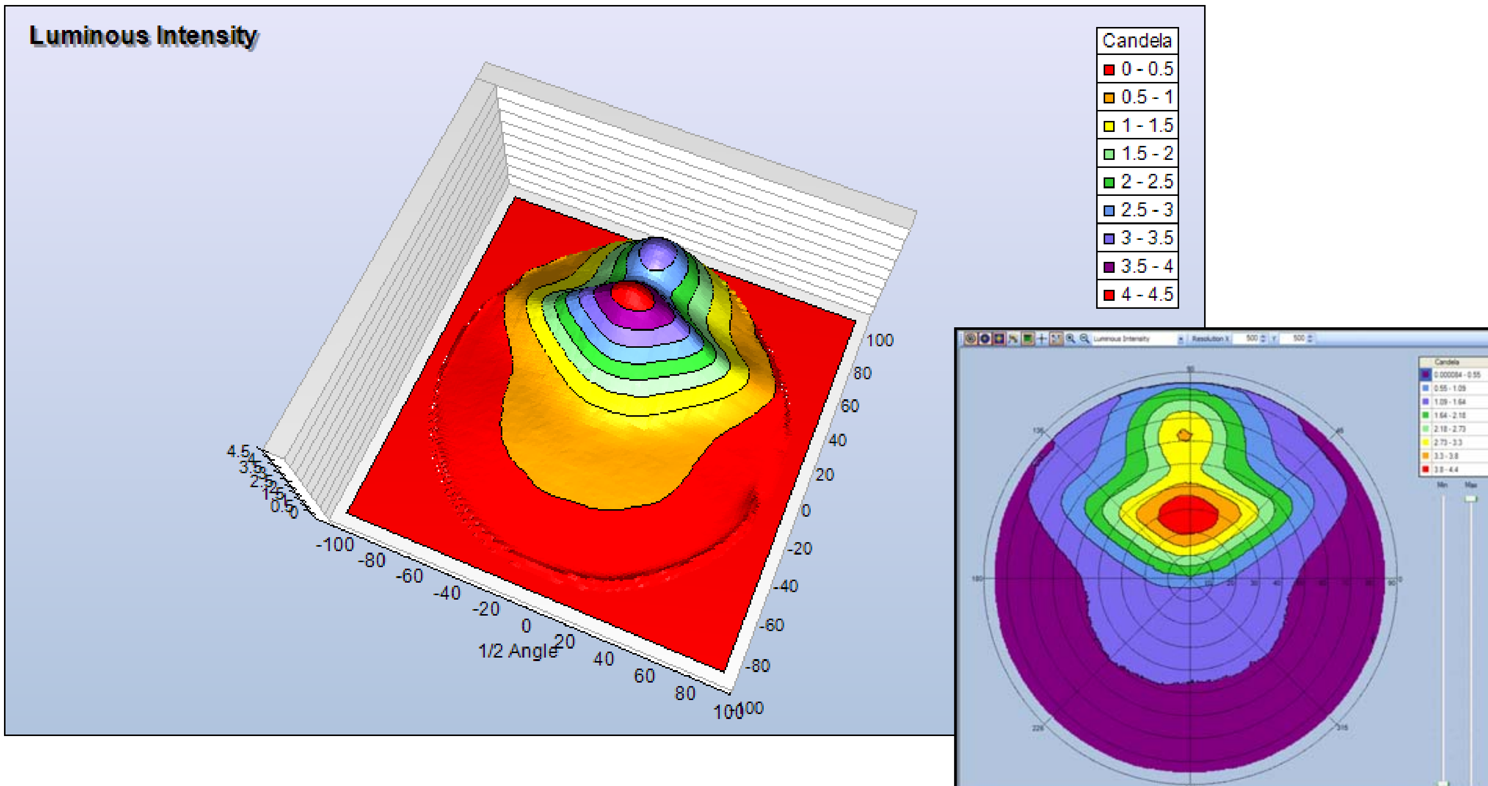
LEDs

- This is the same LED rendered in 3D



LEDs

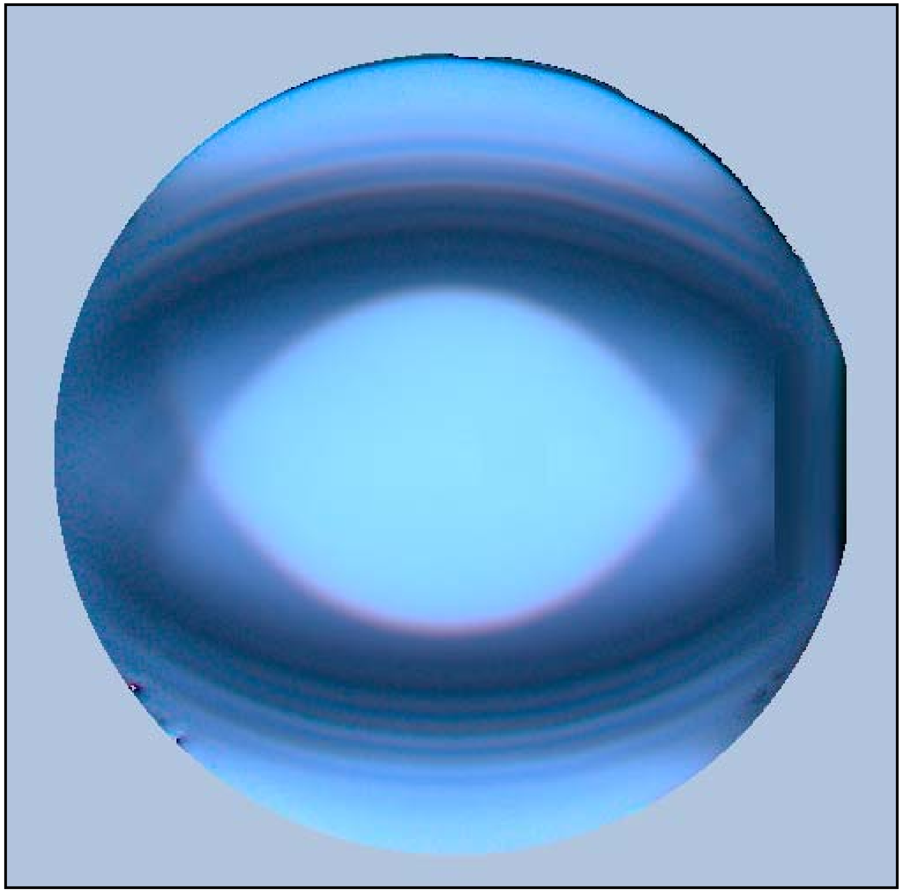
- This is an LED rendered in 3D and as an isometric plot – it is clearly defective



Brightness Enhancing Films

- Performance of FPD brightness enhancing films can be tested using the Imaging Sphere™
- Measurements are performed with a diffuse backlight illuminator
- Detailed output structure can be visualised

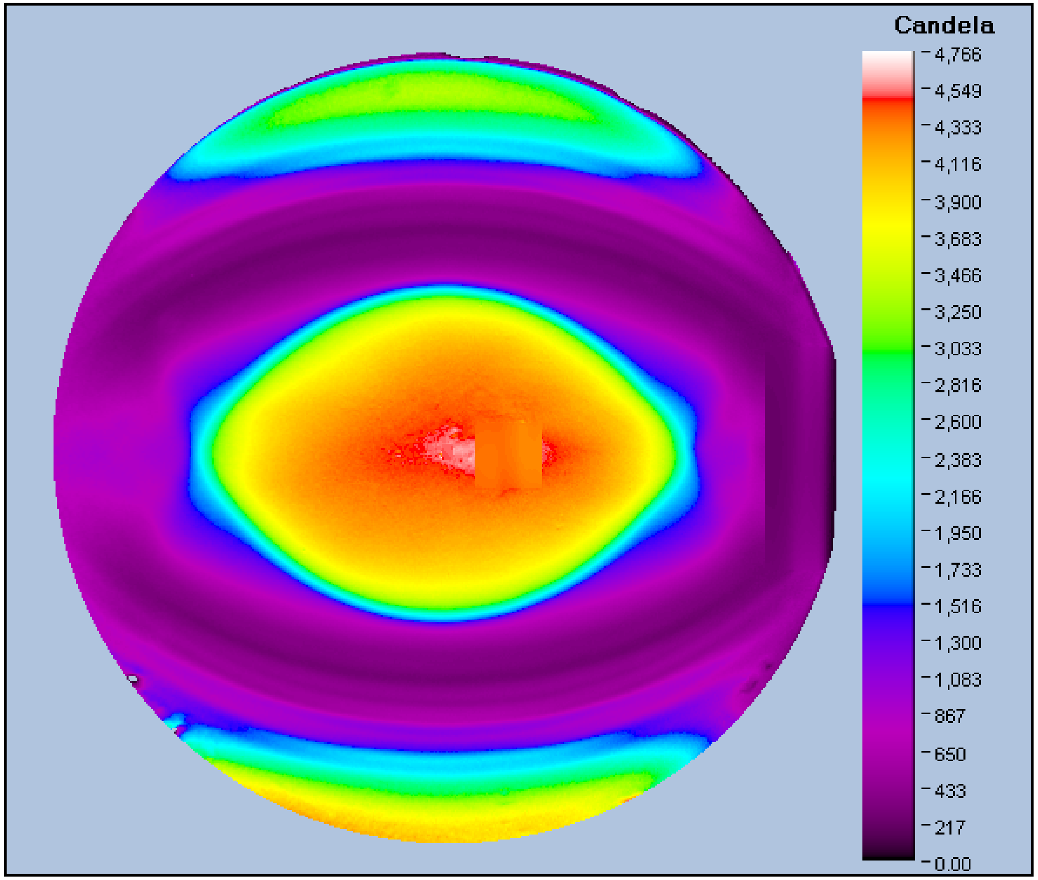
True Colour



Brightness Enhancing Films

- This can be enhanced in a false colour plot of the luminous intensity

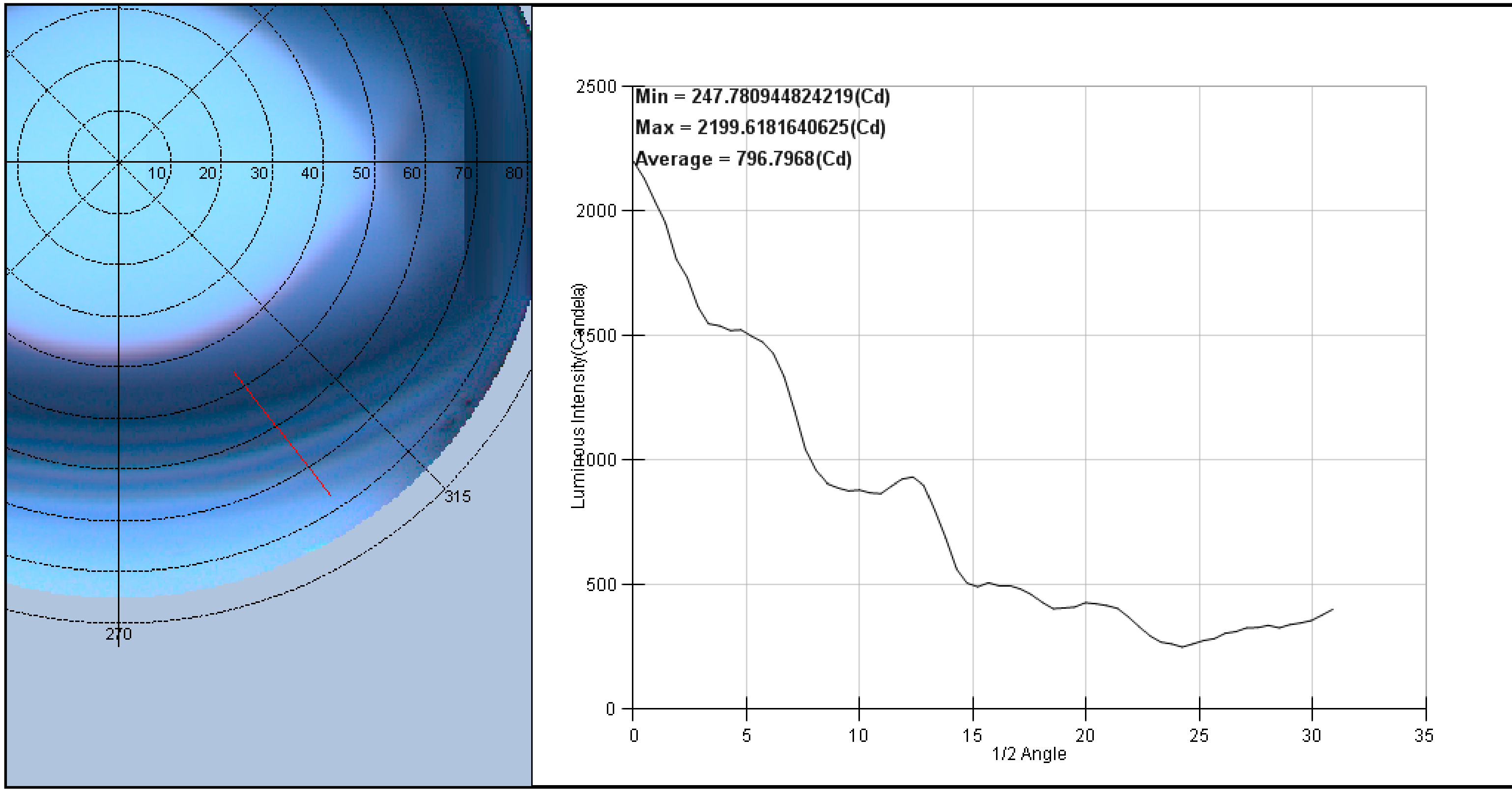
Luminous Intensity



Brightness Enhancing Films

- Quantitative performance measurements can be obtained

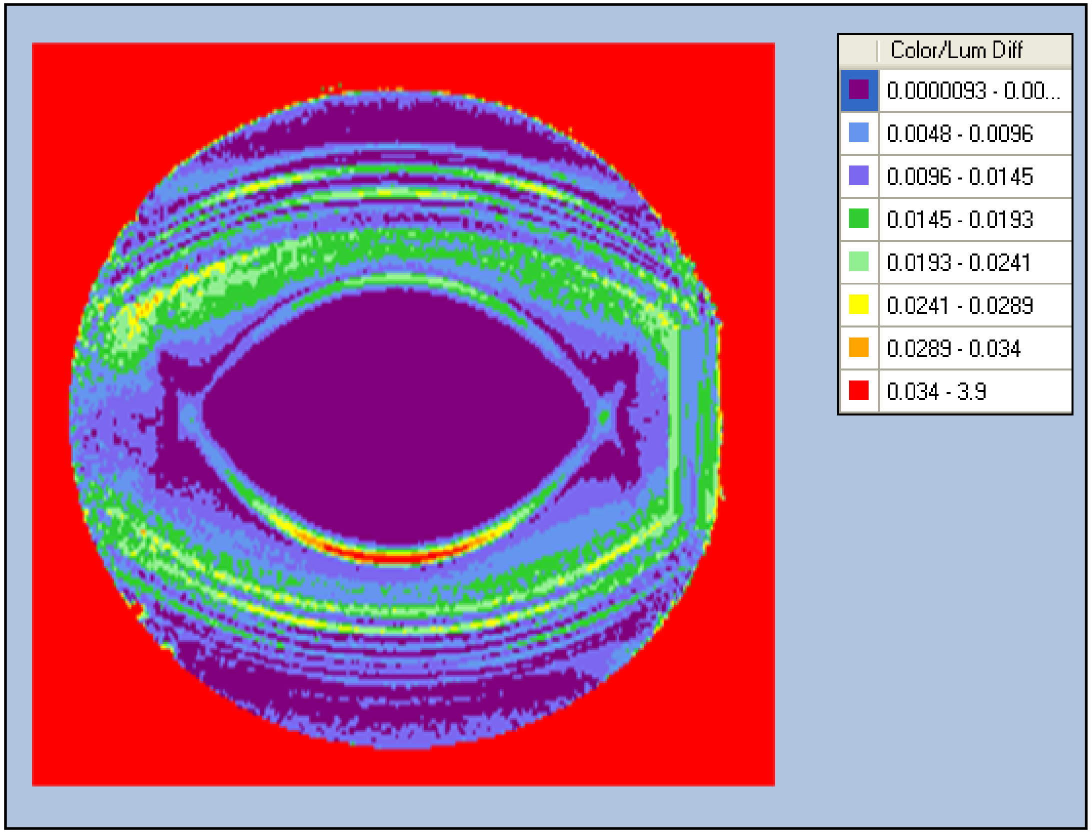
True Colour



Brightness Enhancing Films

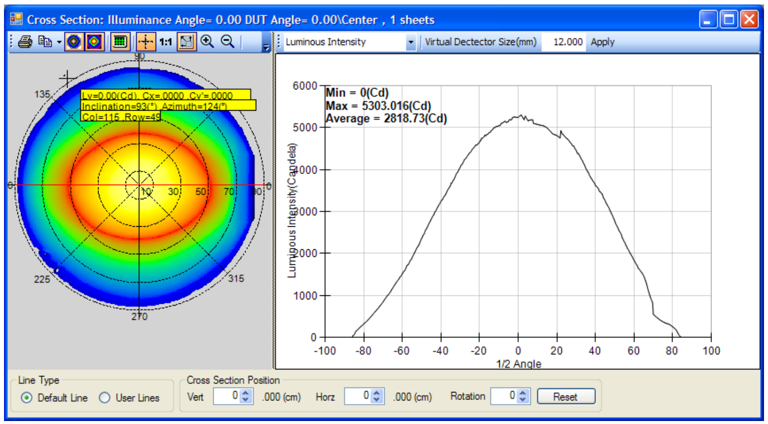
- Colour/luminance difference can be plotted

Colour/Luminance Difference

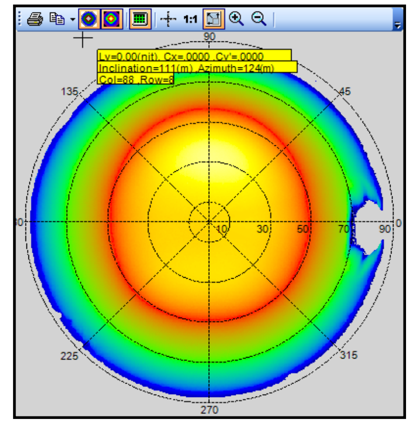


BEF – Quantifying the Difference

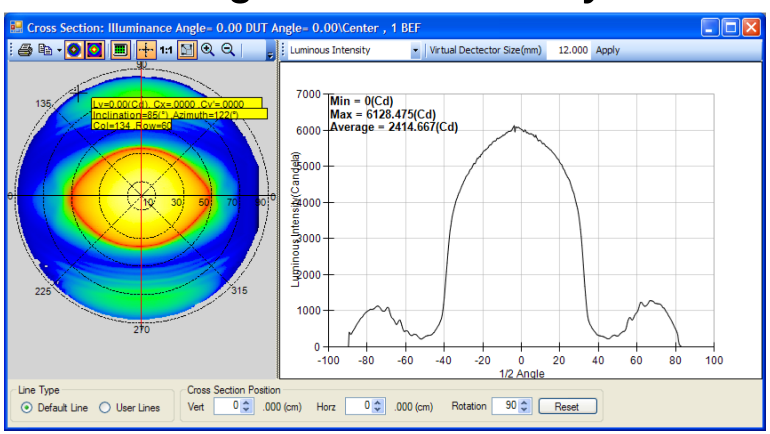
Backlight – 1 BEF Layer



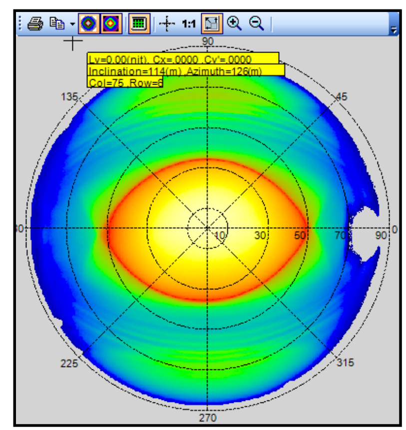
No BEF



Backlight – 2 BEF Layers



2 BEF Layers

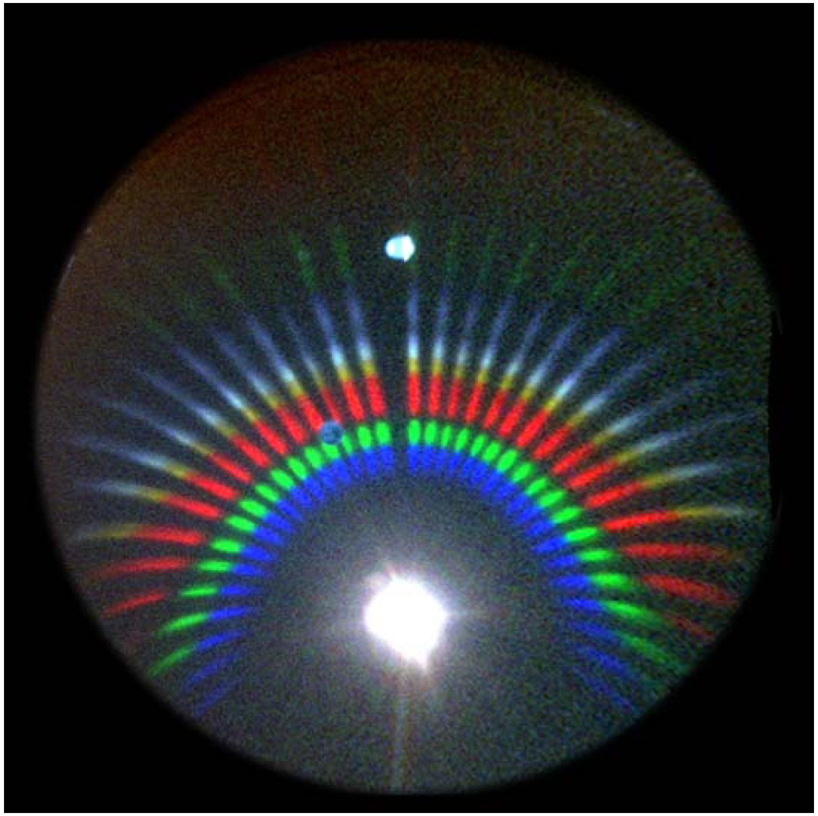


Surface Analysis

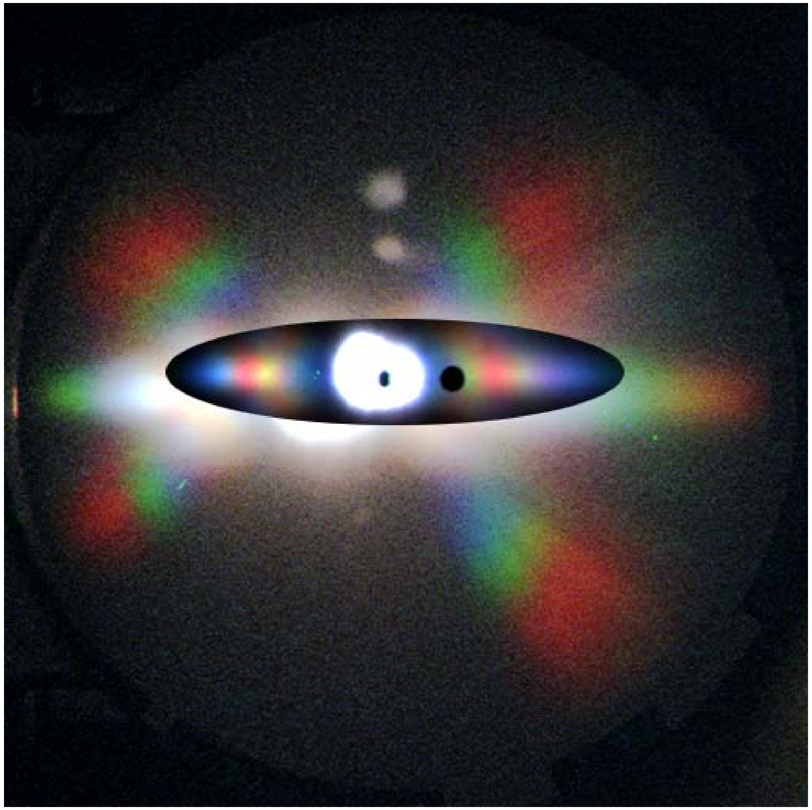
- The ability to measure BRDF enables quantitative analysis of surface appearance under a variety of illumination conditions.
- This can be utilised with plastics, metals, glass, painted surfaces and even human skin (etc)

Surface Analysis

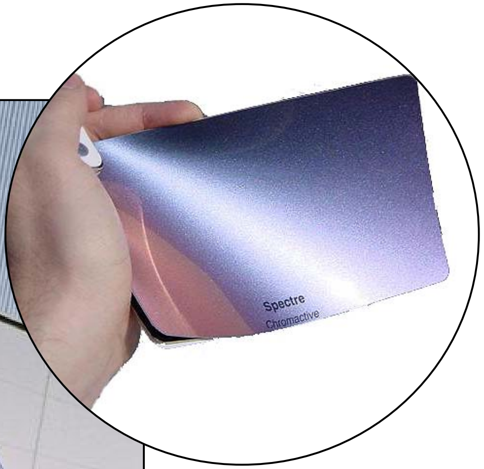
Decorative Foil



Hologram on €10 Bank Note



Special Effect Finishes



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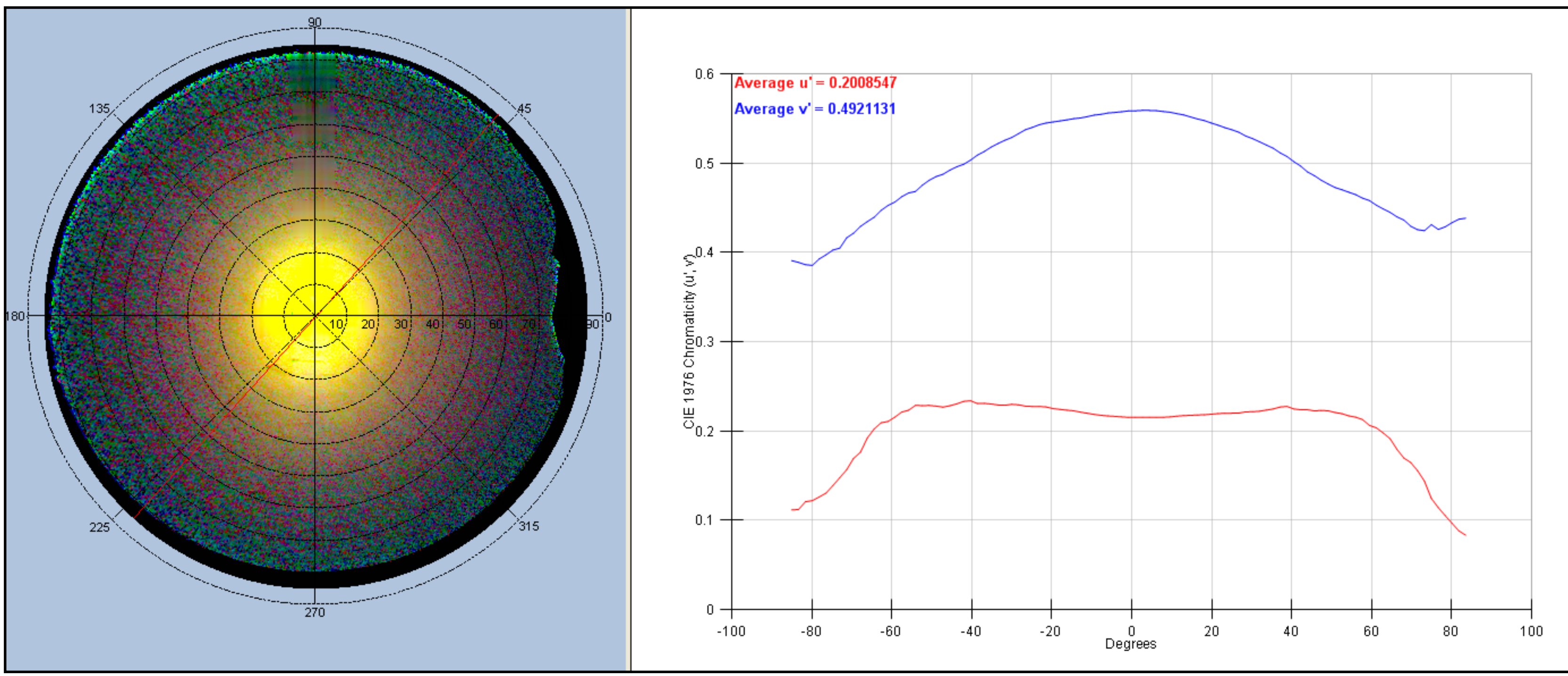
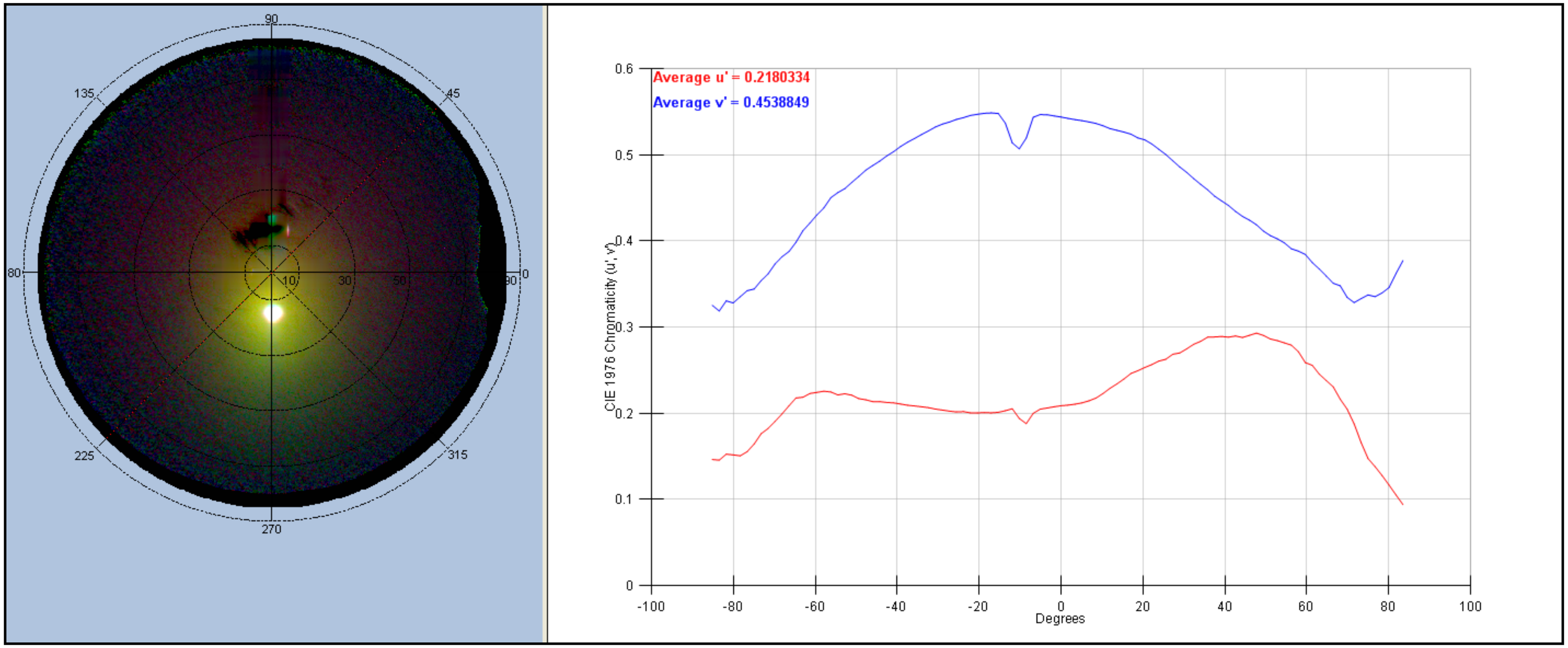
Helicone Paint 0° Illumination

Cross Sectional Plot at 45° Azimuth Angle (u’,v’)



Helicone Paint 15° Illumination

Cross Sectional Plot at 45° Azimuth Angle (u’,v’)



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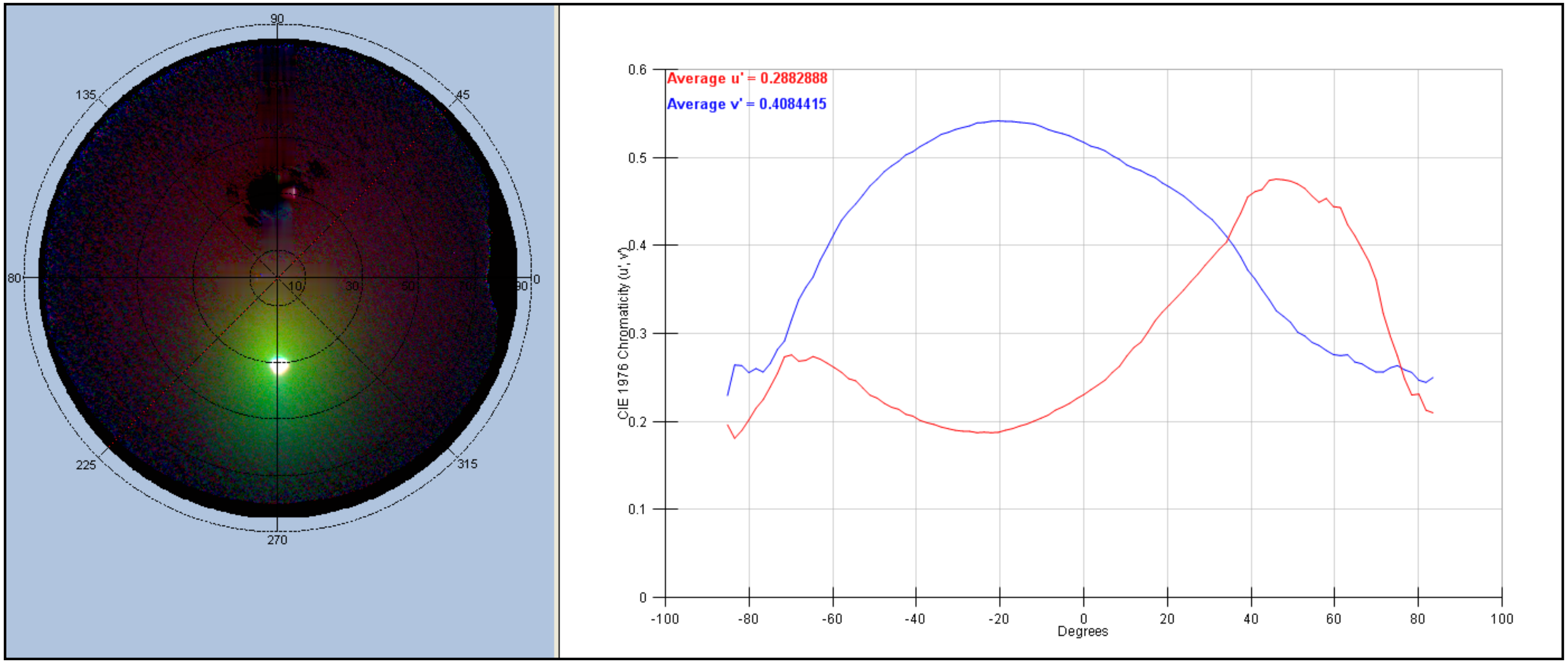
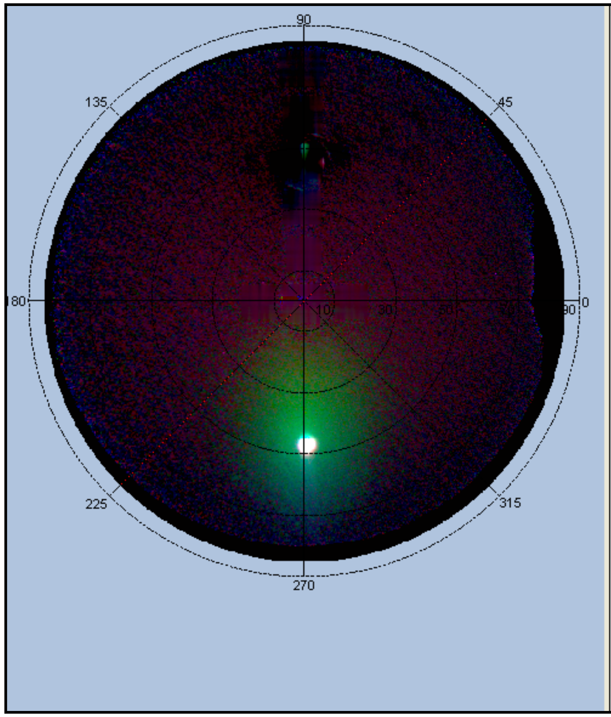
Helicone Paint 30° Illumination

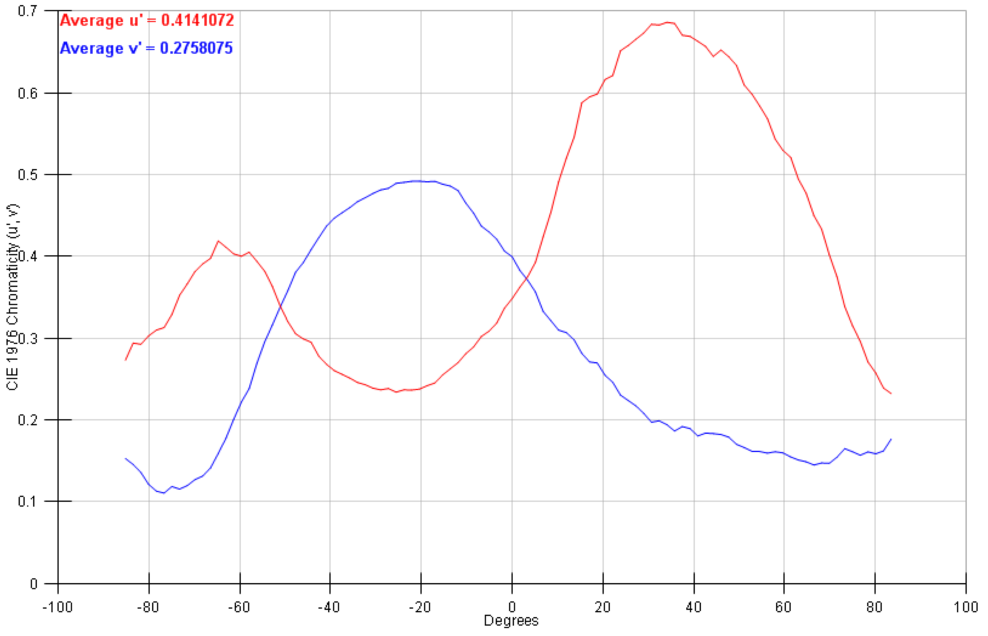
Cross Sectional Plot at 45° Azimuth Angle (u’,v’)



Helicone Paint 45° Illumination

Cross Sectional Plot at 45° Azimuth Angle (u’,v’)





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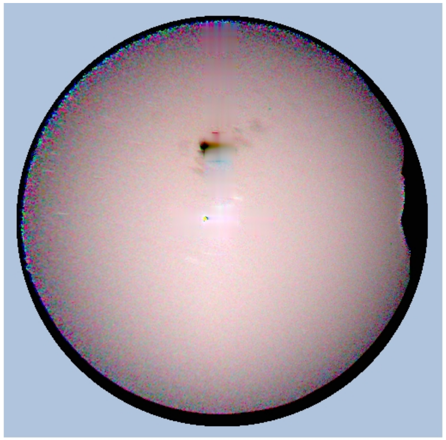
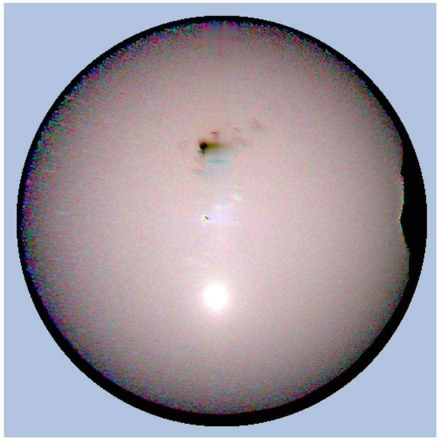
Paper

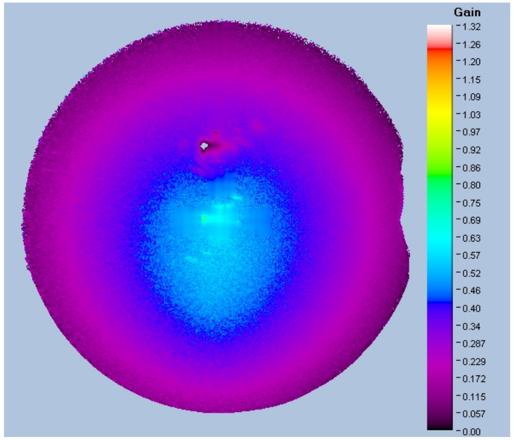
Plain Paper | Glossy Paper

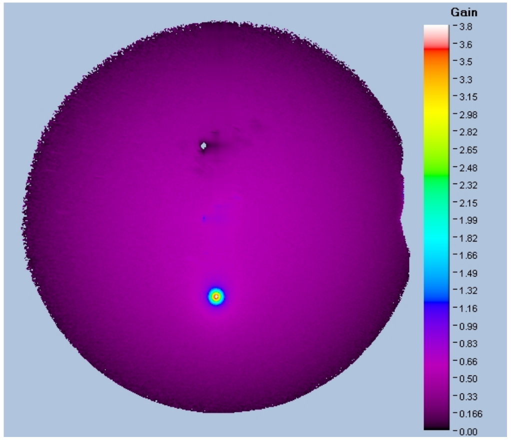
True Colour





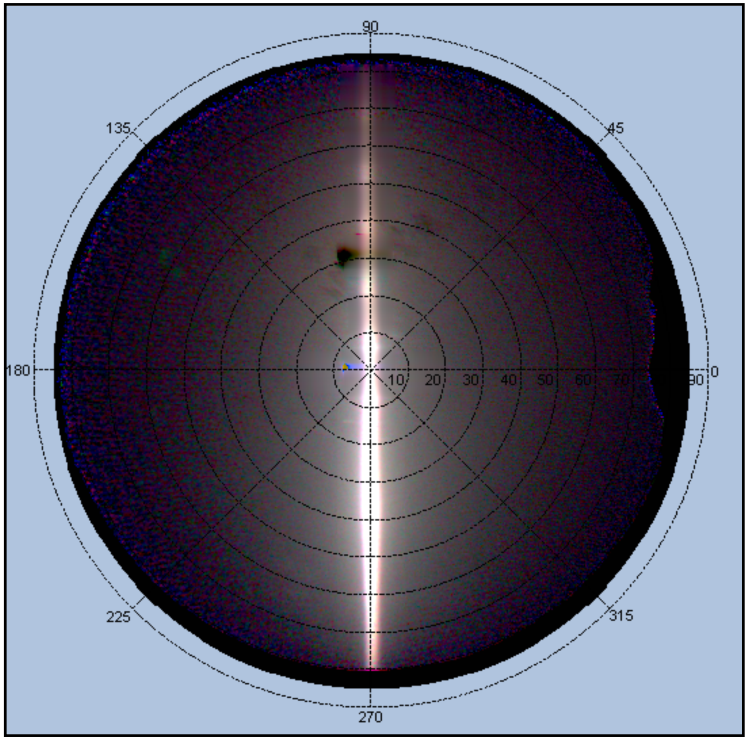
CCBRDF



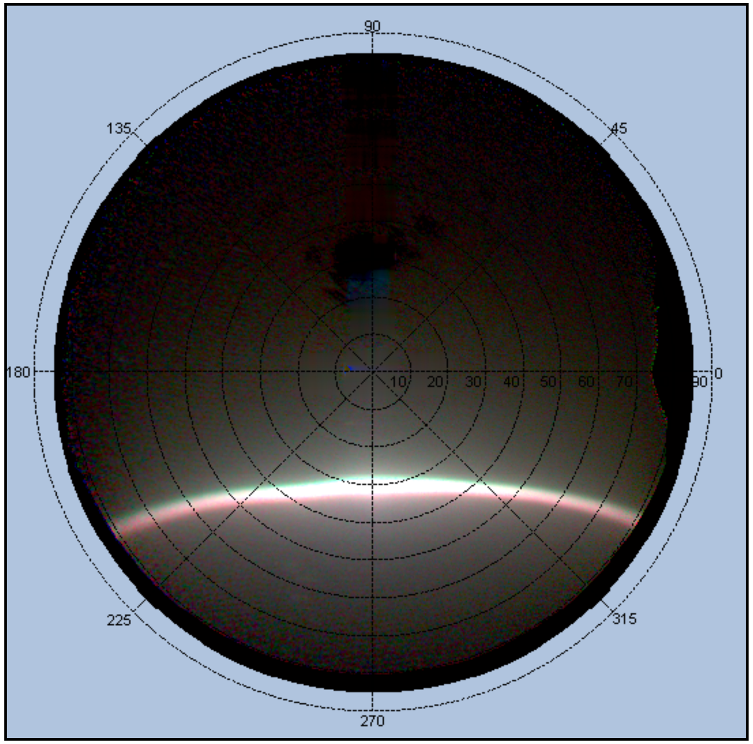


Metallic Surfaces

Un-brushed Aluminum
Parallel Orientation
CCBRDF

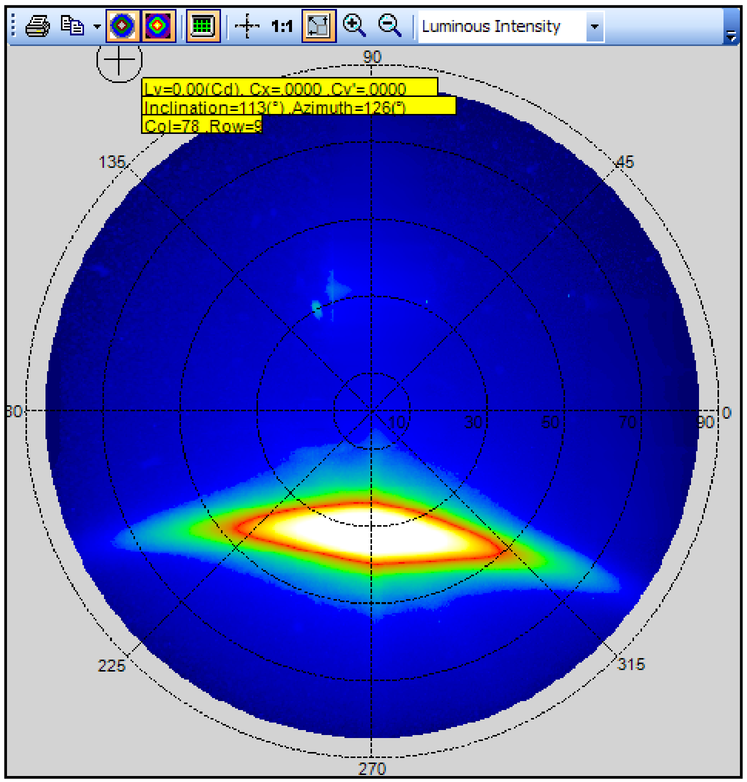


Un-brushed Aluminum
Perpendicular Orientation
CCBRDF

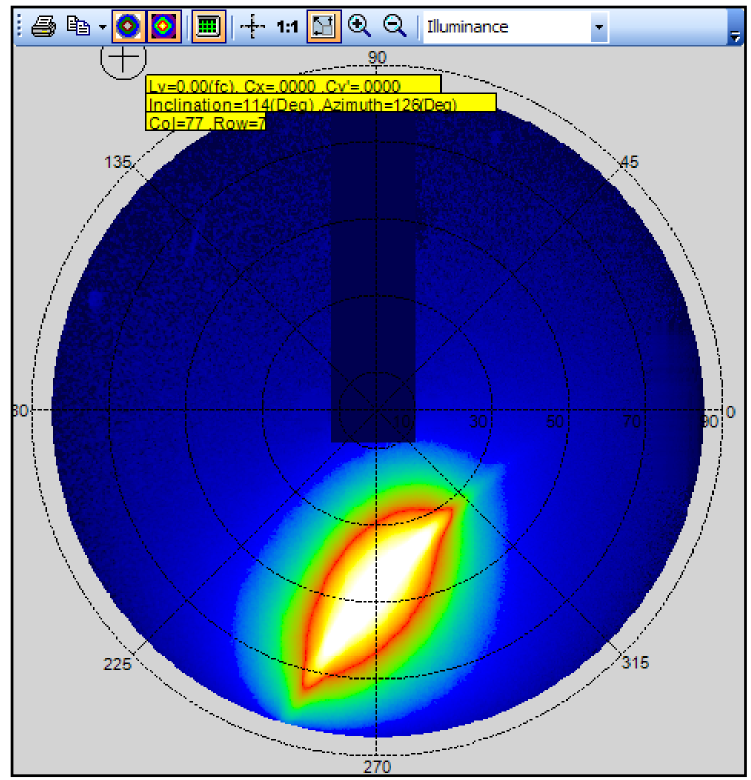


Metallic Surfaces

Brushed Aluminum
Parallel Orientation
False Colour

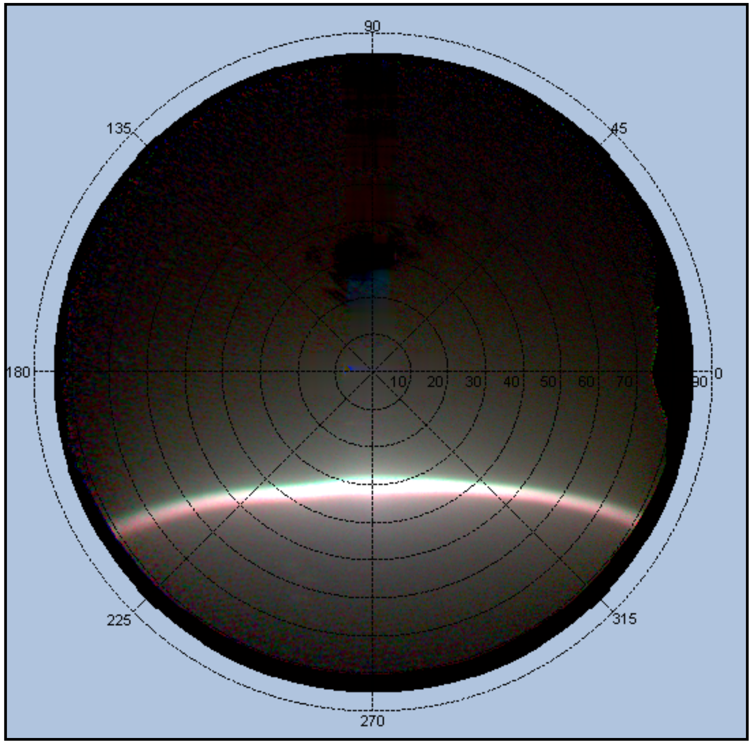


Brushed Aluminum
Offset Orientation
False Colour

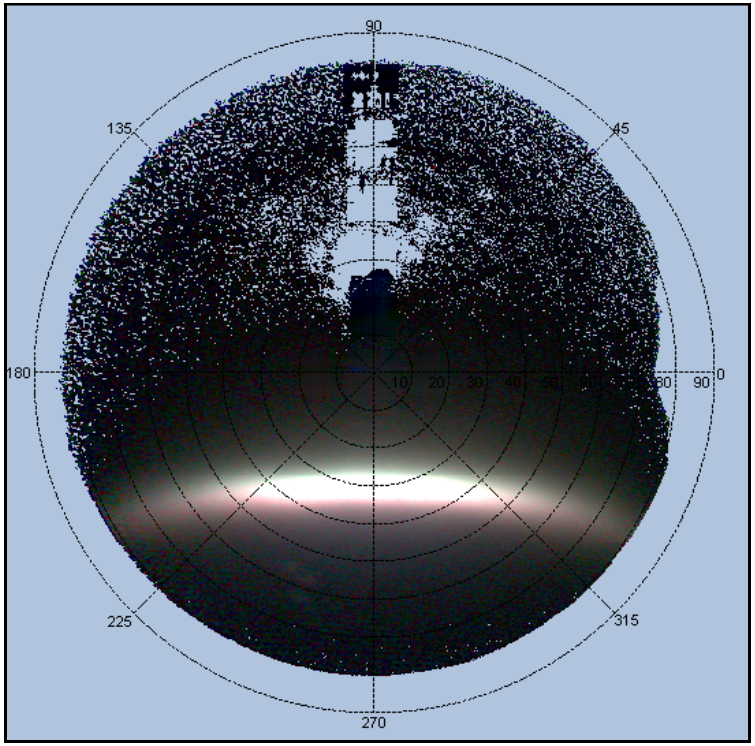


Metallic Surfaces

Un-brushed Aluminum
Perpendicular Orientation
CCBRDF

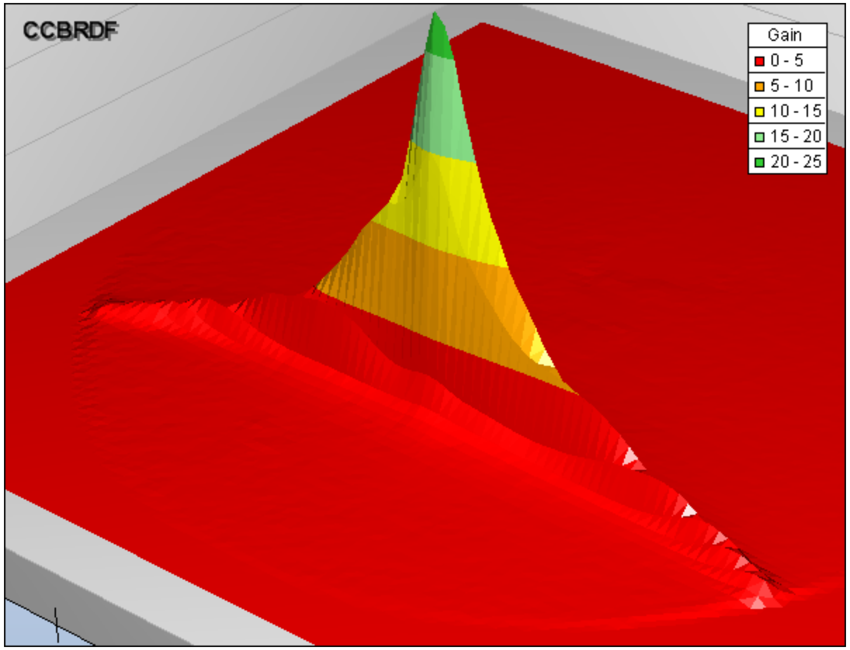


Brushed Aluminum
Perpendicular Orientation
CCBRDF

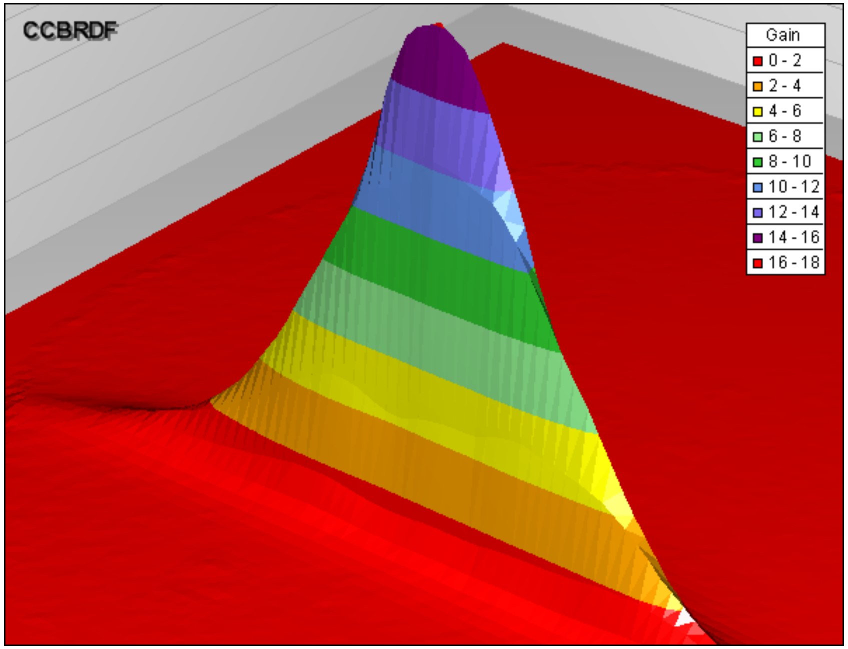


Metallic Surfaces

Un-brushed Aluminum
CCBRDF



Brushed Aluminum
CCBRDF



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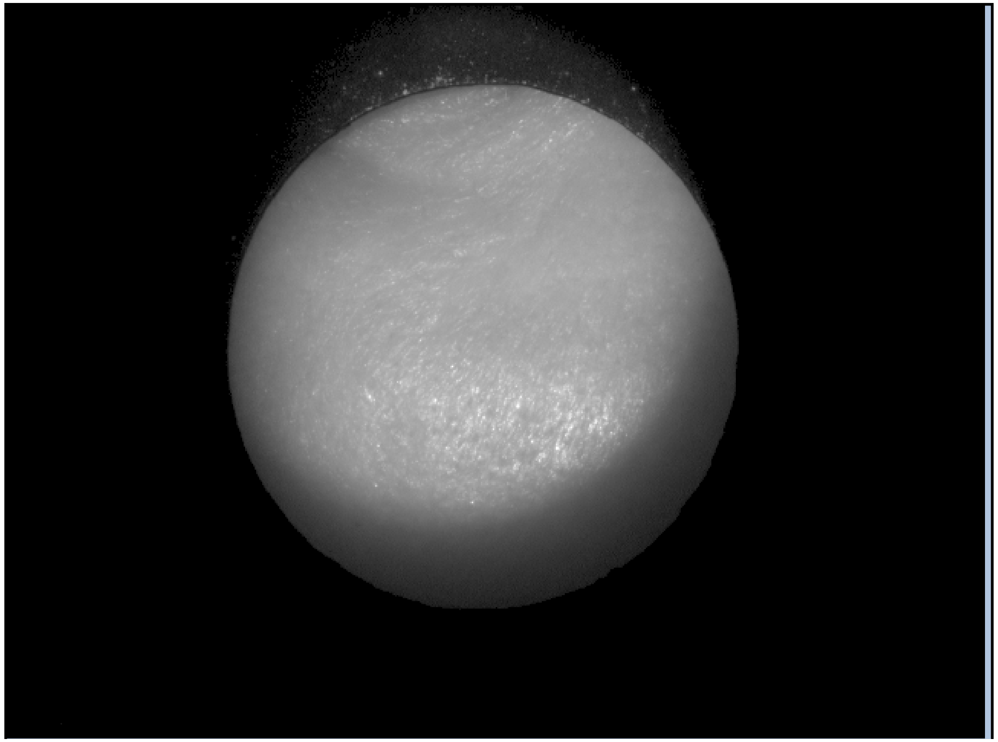
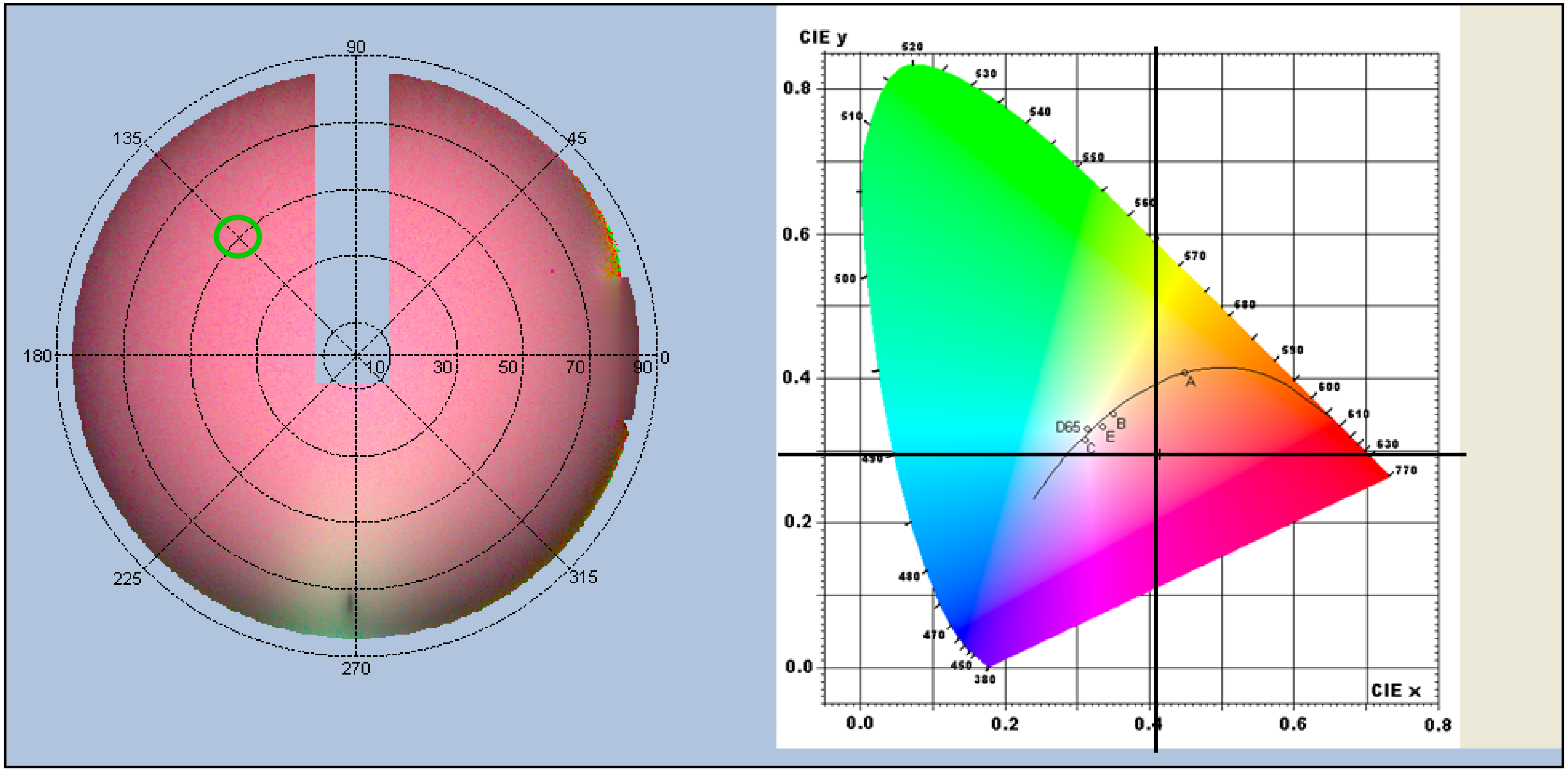
Skin

Caucasian Male Cheek



Skin

Caucasian Male Cheek

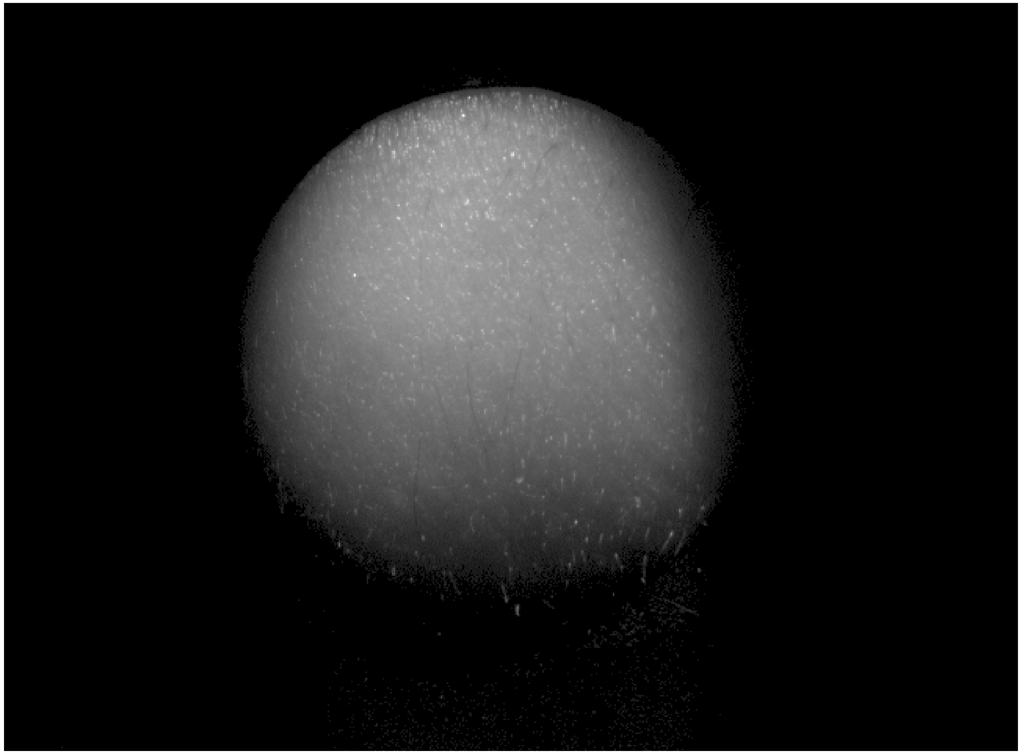


RADIANT IMAGING

SEE THE DIFFERENCE™

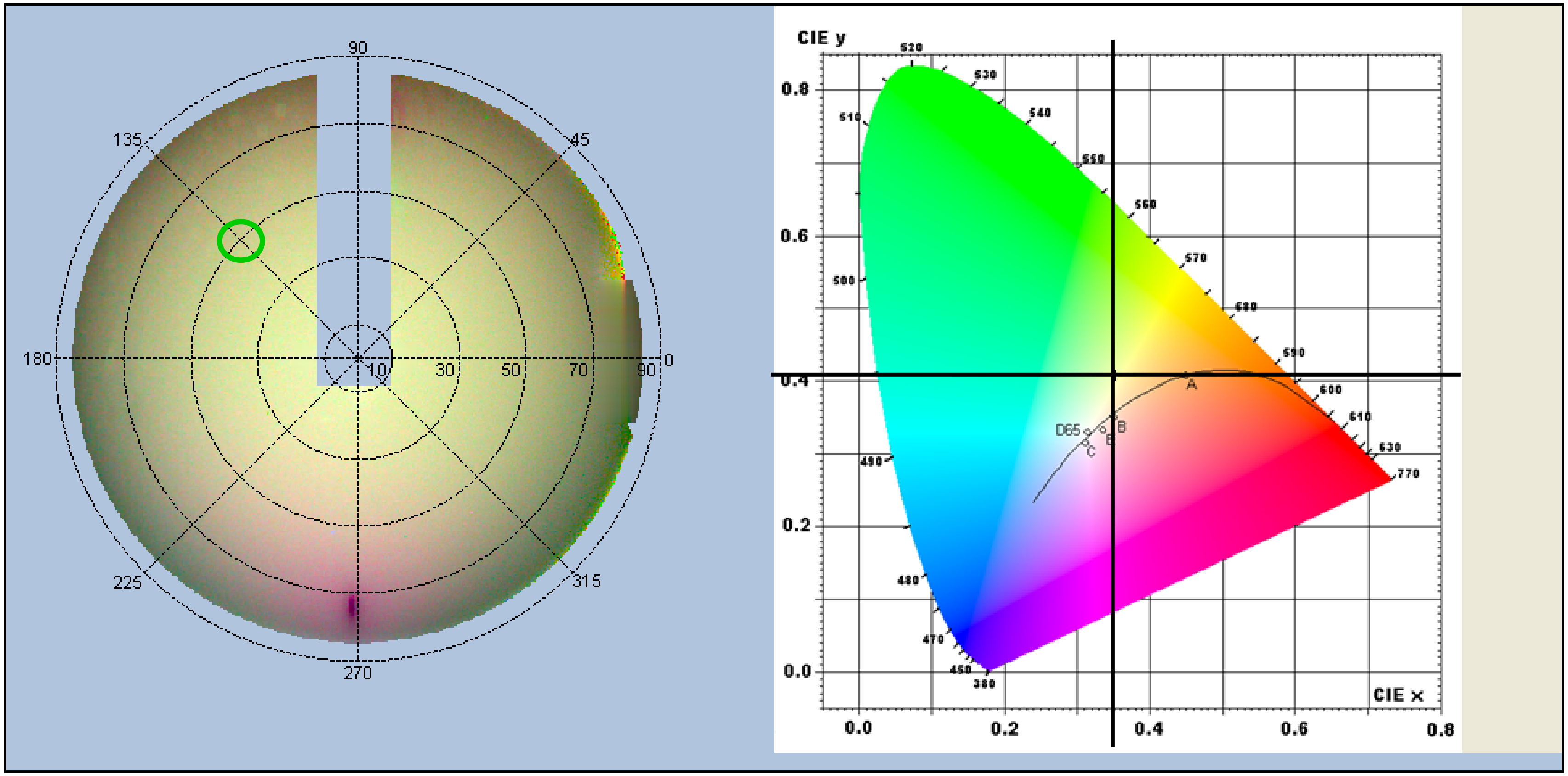
Skin

Asian Male Cheek



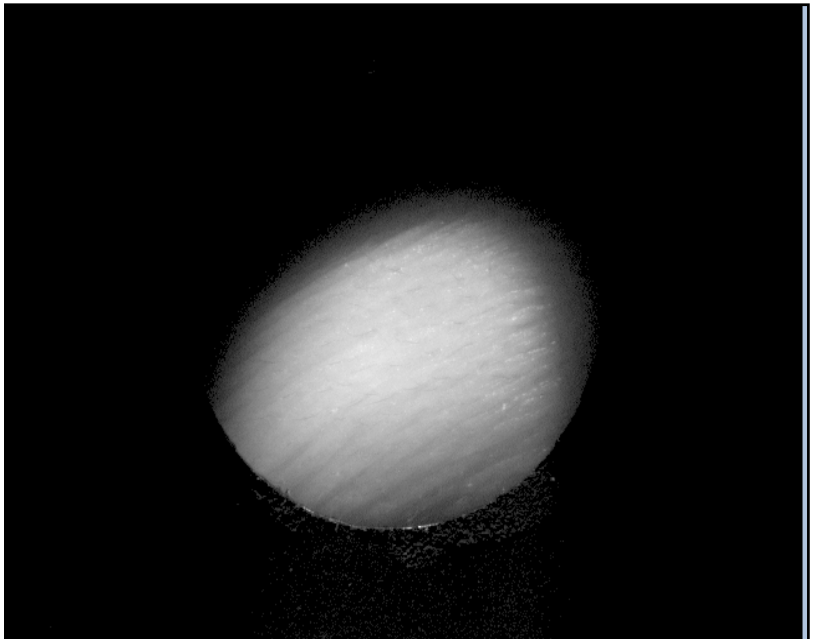
Skin

Asian Male Cheek

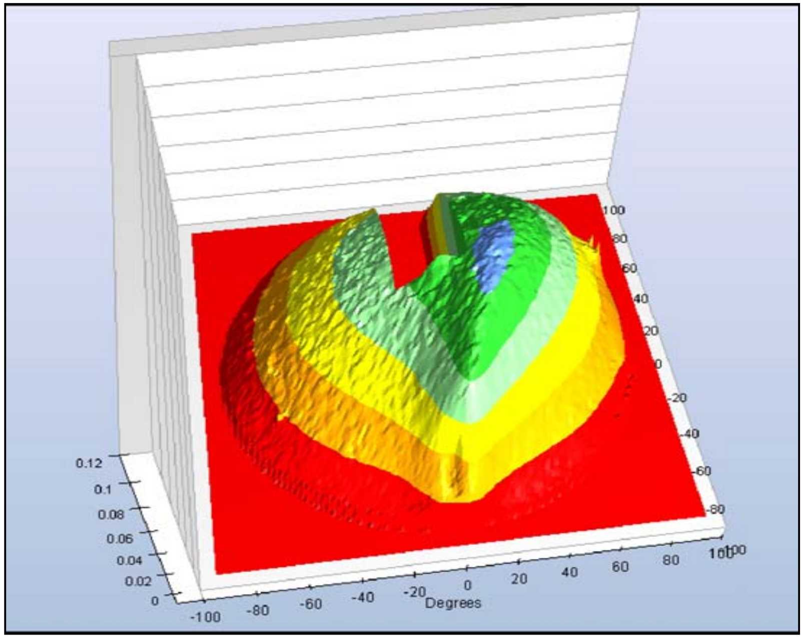


Skin

True Colour - Forehead



CCBRDF - Forehead



Summary

- The Imaging Sphere™ enables **fast** measurement of luminous intensity, view angle performance and scatter
- It can be used to quantify **appearance**
- The same basic set of hardware can perform all the measurements providing maximum **flexibility**
- The Imaging Sphere™ is a **cost effective** tool for both R&D, process development and statistical process control

References

- R. Rykowski, D. Kreysar & S. Wadman, ***"The Use of an Imaging Sphere for High-Throughput Measurements of Display Performance – Technical Challenges and Mathematical Solutions",*** SID 06 Digest, pp. 101-104
- R. Rykowski, K. Chittim & S. Wadman, ***"Imaging Sphere",*** Photonics Spectra, September 2005, pp. 64-68
- S. Wadman & S. Baumer, ***"Characterisation of Appearance by a Parousiameter",*** Annual Proceedings SPIE, Vol. 48, August 2003