

Report

NPL REPORT
DQL-OR 010

**A New Goniospectrophotometer
for Measuring Gonio-Apparent
Materials**

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NOT RESTRICTED

MARCH 2005



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A New Goniospectrophotometer for Measuring Gonio-Apparent Materials

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ABSTRACT

The measurement of appearance is an emotive topic that requires attention. There are many in industry who are aware that they need to make better measurements of parameters that correlate with the visual appearance of their products. Equally, there are many new materials that have exciting angular dependent characteristics, for example new interference-based, gonio-apparent pigments. This angle dependence implies that consideration should be given to measuring colour using geometries other than the conventional sphere-based or $45^\circ/0^\circ$ configurations. It also suggests that gloss might be usefully measured at angles other than the 20° , 60° and 85° conventionally used. An instrument is described in this report that measures the spectral radiance of a sample as a function of wavelength, the angle of illumination and the angle of viewing. The instrument is computer controlled and designed to be easily operable. The selection of defined angle regimes for specific applications is discussed.

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ISSN 1744-0610

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1. Introduction

The appearance of an object greatly influences a customer's appreciation of the quality of that object. We use our visual sense constantly to process the complex patterns of light around us into objects, space, location and movement, and with that information make judgements leading to a particular course of action. For example, how we perceive the visual 'appearance' of a product may cause us to buy it, reject it or even write and complain about it! We may choose a particular food because its appearance suggests freshness. Our choice of automobile may have been influenced because its glossy, sleek appearance made us think of quality and prestige.

Although at the moment, it is not possible to make a single measurement called 'appearance', and although this may never be the case, it is possible to design instruments to measure various components of appearance, Figure 1. It is reasonable to divide the characterisation of the optical properties of materials into at least four groups, colour, gloss, translucency and surface non-uniformity or texture[#]. These groups are perhaps not definitive but they represent useful categories for measurement, especially in view of the fact that measurement techniques already exist for some of them¹.

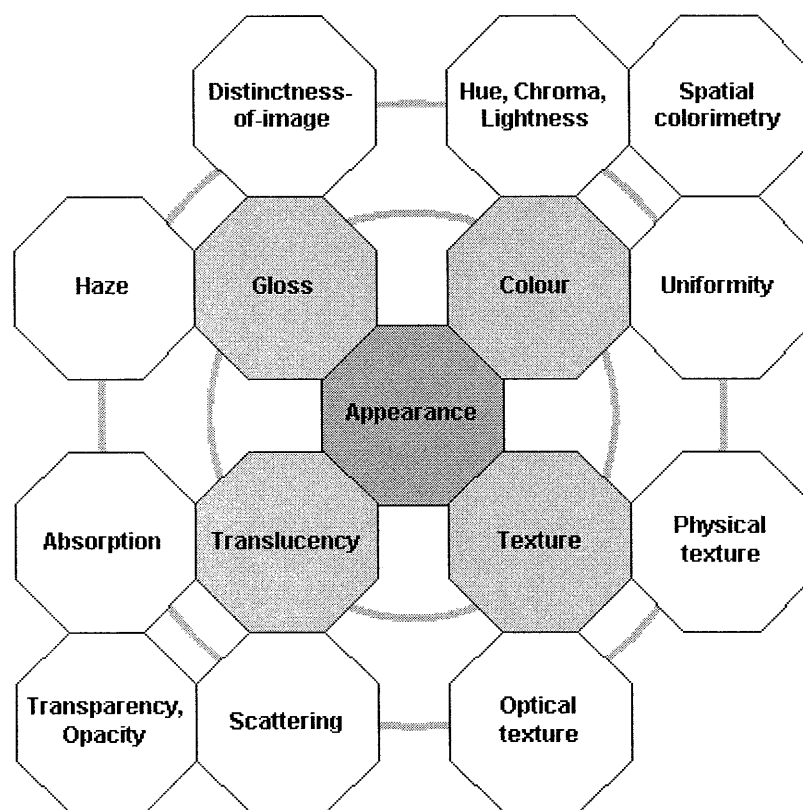


Figure 1. A framework showing how the measurement of appearance might be divided into four separate elements – gloss, colour, translucency and texture – some of which have established associated measures.

[#] The exact term for this aspect of appearance, and its definition, is still the subject of much discussion.

Colour measurement, colorimetry, is based on the measurement of spectral reflectance, and is an established science that is possible using commercial instrumentation available at reasonable cost^{2,3}. Two shortcomings have been identified. First, there are a number of modern materials where colour measurements made using a single pair of illumination/viewing angle is not sufficient to describe the perceived colorimetric effect. Thus, measurement at more illumination/viewing angle combinations is required. Second, the traditional, CIE recommended, colorimetric parameters, while providing correlates of visual percepts, are not able to predict the absolute appearance of a coloured sample because no recognition is given to the surround to the sample, the colour of the light source, and, most importantly, the absolute level of the illumination provided by that light source. As one of the 'fathers' of the CIE Standard Observer, W David Wright, has so aptly pointed out, "The definition of a colour C by the equation

$$C \equiv X(X) + Y(Y) + Z(Z)$$

expresses the fact that a certain mixture of three reference stimuli will produce the same colour sensation as C when both are seen under the same viewing conditions. Although this specification involves an observer and is therefore a subjective relationship, it does not in itself define the appearance of C ..."⁴.

Colour appearance models provide a viable approach to provide absolute measures of colour appearance and, while their derivation must be assumed to be on going, the model that is currently recommended for use by the CIE is robust enough to be used as an industrial tool^{5,6}.

It should be noted that traceable measurements are available in the field of colour measurement⁷. The extension of colour measurement to more angles of both illumination and viewing, however, requires further measurement to give traceability. It might also be useful if new artefacts became available to provide a traceable measurement chain specifically using some of the new special-effect pigments.

2. Gonio-apparent surfaces

When light passes from one medium to another its properties can change according to one or more of the following phenomena: reflection, transmission, absorption, scattering, interference, total internal reflection or refraction⁸. Thus, the surface of a painted, solid-colour, layer can be thought of as an interface between air and the colorant material.

A proportion of the incident light will be reflected from the front surface. This specular reflection gives rise to an appearance described in terms of the gloss, while the remainder of the light continues into the interior of the material where it undergoes absorption, scattering and reflection. Specifically the spectral absorption properties of the colorant, together with the reflection properties of the substrate layer, give rise to the appearance of a solid colour.

The predominant effect is the creation of variable lightness, colour and gloss with viewing angle via the addition of metallic, pearlescent and interference (organic) pigments. These pigments are used extensively in every imaginable application: they are incorporated in plastics, coated on substrates, used in printing inks, in cosmetics, and extensively in the automotive industry. A high percentage of domestic automobiles are now sold with special-effect finishes, but the measurement of these effects, from both a lightness, colour and an

appearance perspective, has no traceable basis and little demonstrated correlation with visual appearance. There is a very small number of instruments specifically available for the spectral measurement of these complex or 'gonio-apparent' surfaces as well as traditional colour measurement spectrophotometers: there is no internationally accepted measurement method however, and no traceability to national scales. Some of these instruments use a small number of additional viewing angles with a single angle of illumination⁹.

That measurement techniques are not well defined has implications where colour matching needs to be carried out when, for example, a car requires re-spraying after an accident. Traditional solid colours are relatively easy to colour-match using established spectrophotometric measuring techniques and the CIE system of colour measurement. Gonio-apparent pigments however, require considerably more expertise to match because of their inherent complexity¹⁰.

3. Materials

The use of metallized paint films, that is paint films containing flake aluminium or another finely divided metal as a colorant, has become popular in recent years - approximately 17% of cars sold in the UK are now finished in metallic silver! Much of the appeal of these coatings comes from the change in their appearance with change in conditions of illumination and viewing. For example, there may be a decrease in lightness, and frequently an accompanying change in chromaticity due to the admixture of a colorant, when viewing is altered from near normal to grazing angles. This effect is commonly referred to as *flop*, the colour observed near the normal being the *face colour*, and that seen at grazing angles, the *flop colour*¹¹.

These changes in appearance are simple manifestations of the complex phenomenon of the scattering, absorption and reflection of light by metallized paint films. Aluminium pigments are present in the form of lamellar flakes of aluminium metal and hence are essentially two-dimensional. Typical flake thicknesses are of the order of 0.1 – 1.0 μm while the length and breadth can be between 5 and 50 μm ¹². Most automobiles for example, are now coated with a two-coat system. This consists of a 12 to 15 μm thick dry film, highly pigmented, base coat and an overlaying transparent lacquer of approximately 40 μm dry thickness. As the base coat dries after spraying its volume shrinks to about 10% of the coated volume which has the effect of causing the aluminium flakes to become orientated parallel with the coated surface.

The characteristic feature of pearlescent pigments is their lustrous and brilliant appearance that is due to the interaction of visible light with a metal-oxide coating on a mica substrate¹³. Its colour occurs through interference between the beams reflected from the top and the bottom of thin metal-oxide coatings rather than by direct absorption of light at specific wavelengths. Different thicknesses of metal-oxide coating cause different wavelengths to constructively interfere to produce different reflection colours. When, for example, mica platelets are coated with a smooth, thin layer of titanium dioxide, a lustrous, highly reflecting pigment is obtained that reflects light across the visible spectrum¹⁴. If the thickness of the titanium dioxide layer is increased, interference between the visible light takes place, and different colours are produced¹⁵, Figure 2. Three colours can usually be observed, depending on the colorants, the interference pigment and the background^{16, 17}. On a transparent substrate, one colour is seen at the specular angle, another at the diffuse angles and a third by transmission.

An example of the extension of the above pearlescent pigment technology is that known as ChromaFlair^{®18}. This pigment is produced by a patented process and is manufactured by the deposition of five ultra-thin layered structures on to a carrier film via precise vacuum deposition. The flake materials are colourless and the coloured effects are created by controlling the thickness of the coating to produce interference between the light reflected from the various layers. Eight pigments are available, each with a unique two-colour combination.

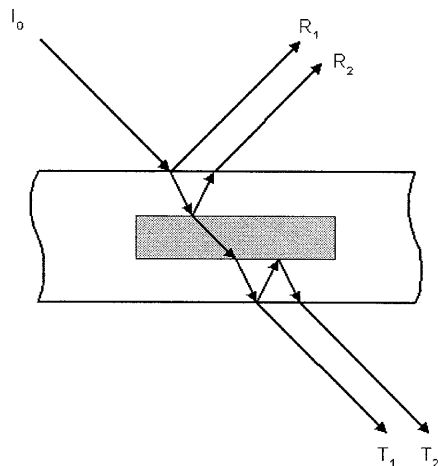


Figure 2. Incident light, I_0 , is split at a thin layer. Reflection occurs on both sides of the layer and the individual components R_1 , R_2 , interfere. In a similar manner, interference occurs in the transmitted beam between T_1 and T_2 .

The above introduction has dealt with what are coming to be termed *gonio-apparent* or *complex* surfaces produced by coating a 'complex' pigment onto a base. Many surfaces can be designated as complex, and hence lead to associated measurement problems, but are themselves natural, i.e., uncoated. Examples include metals, for example, brushed aluminium which exhibits a marked directional effect according to the direction of the brushing; textiles, which can exhibit a directional effect according to the direction of the weave; plastics with a moulded stipple, used for example over car dashboards to minimise glare but required to colour-match the rest of the trim of the car. These examples all have surfaces that are not flat, exhibit directional properties, and thus require careful consideration as to the method of colour and 'appearance' measurement.

4. The NPL Goniospectrophotometer

It should be clear from the above introduction that there is a requirement to measure the spectral reflectance of many modern gonio-apparent surfaces using more combinations of illuminating and viewing angle than the traditional sphere-based, or $45^\circ/0^\circ$ (or $0^\circ/45^\circ$) geometries. This requires the construction of a gonio-spectrophotometer – a spectrophotometer with the facility to vary the angle of illumination and the angle of viewing over a defined range – and this paper describes such an instrument.

Due note was taken of those instruments that are commercially available and a specification put together that embraced the best features of each while adding some capabilities that would make the instrument both adaptable and easy to use.

4.1 Initial Requirements

The instrument was designed to make measurements using an illumination angle in the range $\pm 75^\circ$, a viewing angle of $\pm 75^\circ$, and with a minimum resolution of 1° . It had been hoped that this range might be at least $\pm 80^\circ$ but the size of the light beam required precluded this.

The detector was to be a commercially available telespectoradiometer. The whole instrument was constructed to work in a lit room and under computer control. Facilities were to be provided to enable the sample to be moved between measurements to enable vertical shift, lateral shift, and rotation. The instrument was to be uniplanar. By this is meant that the illumination beam, the viewing path and their associated scanning directions would all be in the same horizontal plane. It can be argued that, to measure the total gonio effect of a surface, sample measurements need to be made over a complete hemisphere, with illumination coming from a number of points on that hemisphere. This represents a very complex instrument, and an associated large volume of data to be both visualised and assimilated. It was felt that, by assuming a degree of isotropy in the surface to be measured, and allowing for rotation of the sample, a uniplanar instrument would suffice.

A number of other criteria needed to be met:

- The range of occlusion angles, the angles where the illumination beam occludes the measuring head, should be kept to a minimum.
- The instrument should use no fibre optics thus removing potential problems due to the fibres moving (bending) while scanning a sample.
- The level of illumination should be such that a gloss black BCRA-NPL Ceramic Colour Standard tile could adequately be measured, at glancing angles of illumination and viewing, without resorting to an excessively long detector integration time for the measurement.
- The temperature and humidity of the sample should be monitored as closely as possible during the measurement cycle and the amount of heat generated by the instrument should be such as to not cause wide variation in the sample temperature during the cycle.
- The minimum wavelength range to be covered should be 380 nm to 780 nm in steps of 5 nm.
- The accuracy using a geometry of $45^\circ/0^\circ$ should be at least ± 0.002 in x, y chromaticity, ± 0.05 in Y tristimulus value using a gloss white BCRA-NPL Ceramic Colour Standard tile.
- The repeatability using a geometry of $45^\circ/0^\circ$ should be at least ± 0.0005 in x, y chromaticity for the gloss white BCRA-NPL Ceramic Colour Standard tile.
- The angular accuracy should be better than ± 0.1 degrees.
- The instrument should be no bigger than 2 m x 2 m x 2 m.
- The instrument should weigh less than 4,000 kg.

4.2 Building the Instrument

The instrument was built using funds obtained from the Intersect Faraday Partnership. This initiative, co-funded by the DTI and EPSRC, is an extensive network of academic and industry partners in the field of sensors, measurement and data analysis. It assists the sensors and measurements sectors in developing research and development for commercial exploitation. The Partnership is co-managed by NPL and Sira, hub partners who have successfully bid for approximately 40 projects since 1998, achieving a total funding about £20M. The bid for funding required that a consortium of companies, as well as the lead company, the National Physical Laboratory, be assembled to demonstrate the strength of the

likely application of the measurements made using the instrument. One of the companies should ideally be an SME (Small- or Medium-sized Enterprise). The supporting consortium for the grant bid comprised, in addition to the National Physical Laboratory: The Tintometer Limited, Alcan International Limited, Unilever Research (Port Sunlight), Mars UK Limited and Reckitt Benckiser Limited. The bid for funding was successful and the SME, The Tintometer Limited, was subsequently contracted to actually specify, design and build the instrument, in collaboration with NPL.

4.3 Optical Design

The illumination beam is provided by a LOT Oriel 10-250 W Research stabilised tungsten halogen light source with associated rear reflector, and condenser lenses in a focussing barrel. The unit is currently operating with a 100 W lamp. The light is passed through a water filter to remove unwanted NIR radiation (excess heat) and then focussed on to a pinhole. Condensers are used to provide a parallel beam of light on to the sample via a periscope. A LOT Oriel Light Intensity Control System is used to control the lamp unit via a feedback loop. This unit is designed to control the lamp output to better than 0.1% over an extended period of time.

There is provision for placing neutral or coloured filters in the light beam at the output of the water filter. There is also provision for placing a polarising filter in the beam after the final condenser. All of the components are mounted on an optical bench and so a degree of flexibility is incorporated allowing other components or designs to be easily facilitated.

The main size of the optical design was set by the acceptance angle of the detector, a Minolta CS-1000 telespectroradiometer. Because this is an imaging device, essentially a telescope imaging light onto a monochromator/sensor combination, it has a lens with a near focus closer than which it is not possible to focus on to the sample. This distance is 450 mm and this sets the position of the spectroradiometer on its scanning arm, Figure 3 below.

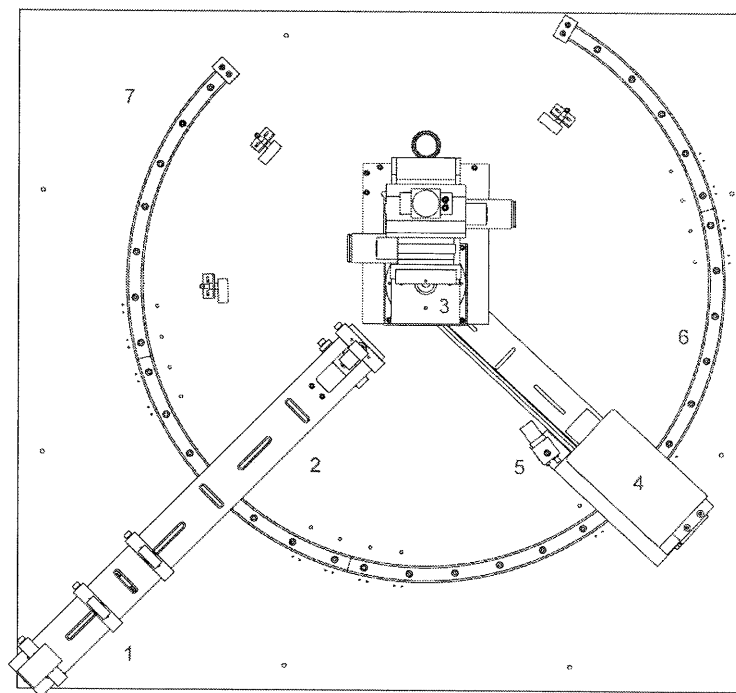


Figure 3(a). Plan.

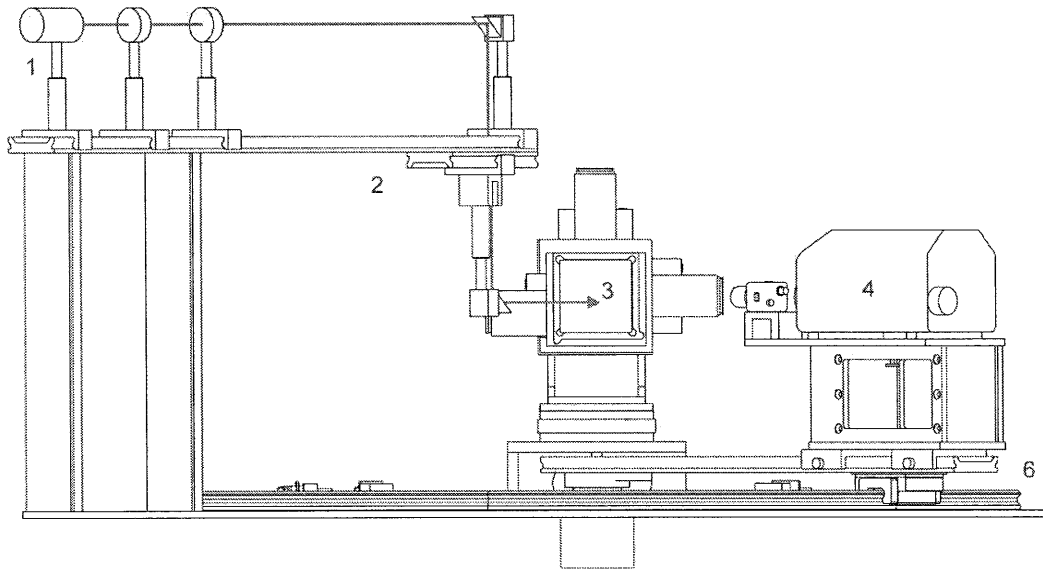


Figure 3(b). Elevation.

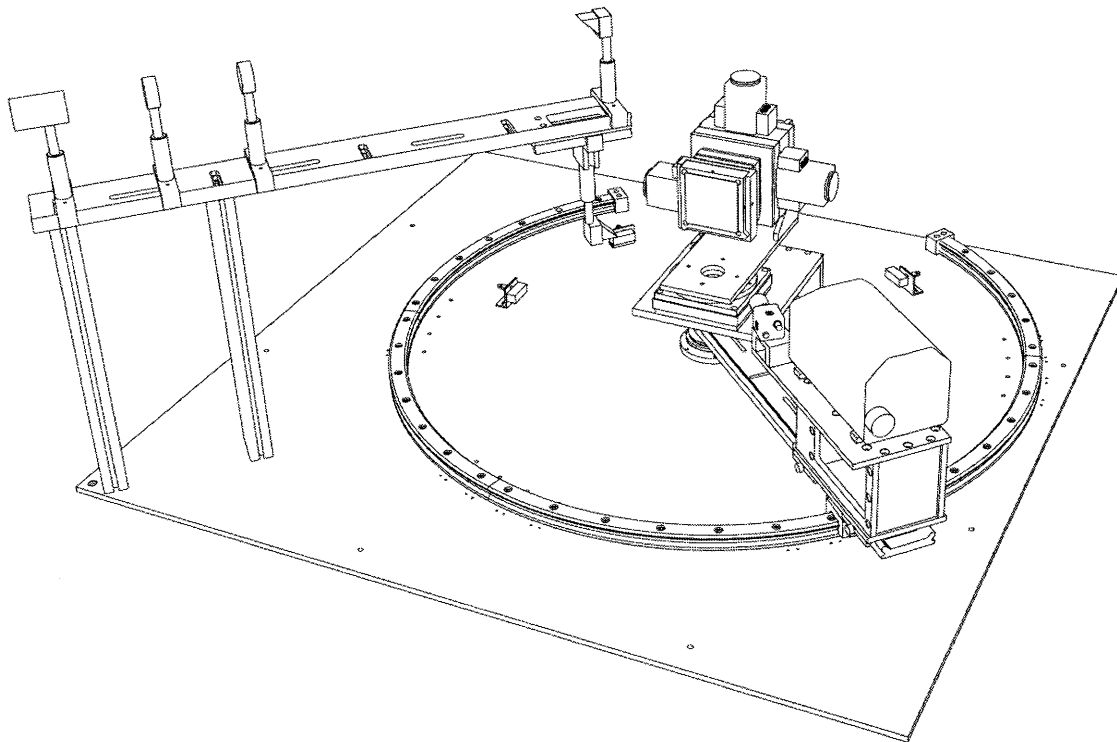


Figure 3(c). View.

Figure 3. Schematic (a) elevation, (b) plan and (c) view of the GASP instrument. 1. Light source. 2. Optical bench. 3. Sample holder on translating and rotating stages. 4. Detector – spectroradiometer. 5. Camera. 6. Support rail. 7. Bench top.

The acceptance angle of the instrument is 1° (half angle 0.5°) which has implications on the required size of the illuminating spot of light on the sample. When the sample is illuminated normal to its surface then this spot can be 8 mm in diameter to fill the acceptance angle. When viewed by the detector from a glancing angle (e.g. 75°) however, this illumination spot must be at least 31 mm wide to fill the acceptance angle. This is because the illumination spot is no longer circular but appears, to the instrument, as a vertical ellipse. In order that this ellipse has a width of 8 mm then it must be approximately 31 mm high, which corresponds to a circular illumination spot with a diameter of 31 mm when viewed normal to the sample surface. Thus, the size of the illumination beam was set to be a minimum of 32 mm diameter.

In order that the range of the occlusion angles is minimised, the light from the source is imaged onto the sample via a periscope, Figure 3, and it is the final mirror of the periscope that sets the range of the angles where the detector cannot see the sample. There is some scope for changing this mirror but, at present it is 40 mm wide giving a range of occlusion angles from 39° to 51° inclusive. Further investigation might lead to an alternative reflecting device to reduce this range of occlusion angles.

4.4 Detector

A Minolta CS-1000 telespectoradiometer is used as the detector. The main reason for this choice was to provide an off-the-shelf detector with associated control software that had a defined traceability path. A number of other options were considered but all rejected on the grounds of physical size. It was a requirement that the detector be as small as possible so that it would not interfere with the digital camera system that was to be mounted adjacent to it. The instrument has a wavelength range of 380 nm to 780 nm, a spectral bandwidth of 5 nm and provides data interpolated to 1 nm interval. It has a measurement capability of 6 log units (0.01 to $80,000 \text{ cd/m}^2$) with associated integration times of 40 msec to 60 sec. Also important was its weight at 4.7 kg: it is precision mounted on a radius arm and rotated by a suitable drive motor and the lower the weight, the less the torque needed to start this motion. The actual stage used has a harmonic drive motor and is capable of being set to a repeatability of better than 0.001° ($400,000$ pulses in 360°) which is well within the value required by the specification. The weight of the detector and the arm on which it is mounted is supported on a rail with a nylon friction bearing to minimise the effect of the downward force. The detector can be scanned over an arc of 270° . This enables measurements to be made on samples illuminated over the range 0° to 75° and with viewing over a similar range. It also enables 'straight through' measurements to be made of the instrument light source and transmitting samples. The mounting of the detector on its radius arm is such that its position from the centre of rotation is kept constant.

4.5 Specular Reflection

Many samples exhibit a degree of specular reflection at the angle opposite to the illumination angle – the specular angle. For example, if the illumination angle is at -45° with respect to the normal to the surface of the sample, then the specular angle is at $+45^\circ$, that is on the opposite side of the sample normal, Figure 4a. For samples with a high gloss finish, the amount of radiant power at this angle is very high and causes the spectroradiometer to saturate. As the instrument is presently constructed, no adjustment can be made to accommodate this, for example, by automatically inserting a suitable neutral filter. Thus, with the present instrument configuration, the angles specified for measurement do not include

those close to the angle that exhibits specular reflection. For example, for illumination at -45° , measurements are not made in the range of angles from $+40^\circ$ to $+50^\circ$ ($45^\circ \pm 5^\circ$).

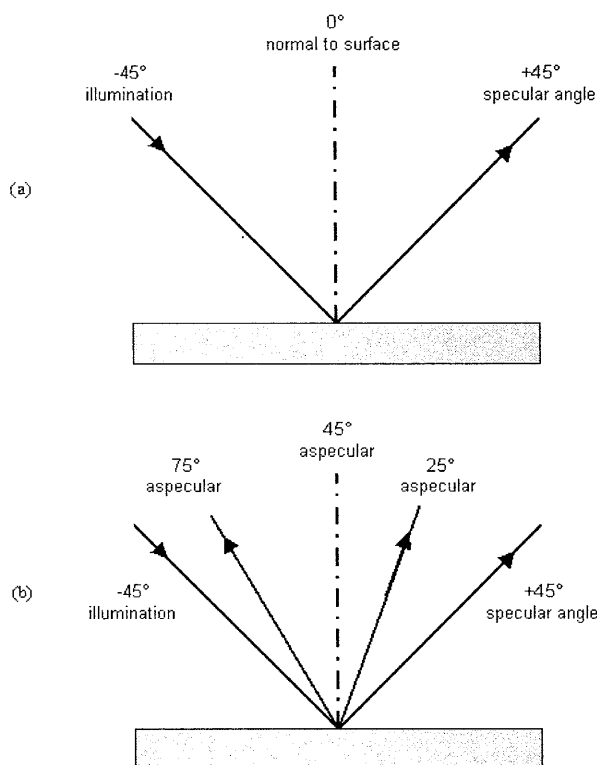


Figure 4. (a). Illumination incident at -45° with specular reflection at $+45^\circ$ - angles measured with respect to the sample normal. (b). Viewing angles measured with respect to the specular angle.

4.6 Angle Conventions

In a uniplanar goniospectrophotometer, the axes of the illumination beam, the viewing detector and the normal to the reference plane are all in the same plane. The reference plane is fixed and the illumination and detector rotate about a common line perpendicular to the normal to the reference plane. The reference plane is the front surface of the sample or object being measured.

It should be noted that some instrument manufacturers denote the angles at which measurements are made as aspecular angles. These are angles measured with respect to the specular angle, the angle opposite to the illumination angle, Figure 4a. Thus, viewing at an aspecular angle of 45° corresponds to a viewing angle of 0° with respect to the normal to the surface of the sample; likewise an aspecular angle of $+25^\circ$ corresponds to an angle of $+20^\circ$ to the normal to the surface of the sample, Figure 4b. In this paper, all angles are denoted with respect to the normal to the sample surface. Thus, illumination is at -45° and viewing angles range from -75° to $+75^\circ$. There is still discussion as to how best to designate the angles associated with gonio measurements because there is, as yet, no accepted convention.

4.7 Sample Holder

The sample is held in a holder that was designed to take NPL Ceramic Colour Standards that are 105 mm square. This holder is attached to an assembly of four Linos stepper motor controlled translation stages that provide lateral (± 100 mm), vertical (± 100 mm) and rotational (360°) movement of the actual sample, and rotation of these three stages as one unit to change the angle of illumination. Each stage is separately controlled via a Linos motor control box.

The instrument is not restricted to measuring Ceramic Colour Standards. It is important that the centre of rotation of the measurement arm be at the front surface of the sample and the thickness of the sample is allowed for by the method of mounting the tile, or any other sample, in its holder. The adjustment is manual such that the front surface of the sample is aligned with the surrounding front face of the holder.

4.8 Digital Cameras

The instrument is fitted with two digital cameras whose output images can be displayed as part of the window on the control computer. The first camera is a monochrome device and is fitted into the eyepiece of the spectroradiometer. It is designed to aid alignment of the sample before the measurement is made. The view is of the sample except for the measurement aperture which appears as a black dot in the middle of the image. While the actual measurement is being made, a shutter inside the spectroradiometer blanks off the eyepiece to prevent light entering and thus this image is not available. The second camera is currently a low-resolution colour device and is mounted on the same stage as the spectroradiometer at an angle of 10° to the left side. If a software flag is set for a particular measurement then, after the measurement by the radiometer has been completed, the stage moves by 10° and an image is recorded of the sample measurement area. Thus, images can be associated with as many measurements as required.

4.9 Instrument Construction

The instrument was first drawn in AutoCAD to enable the feasibility of the design to be demonstrated. A computer-generated video enabled the scanning motion to be evaluated to ensure that the range of angles was achievable and that there would be no collisions during the course of a scan.

The instrument is constructed on a well-supported, solid metal base such that the main components are at a convenient height off the floor. The whole structure is encased in metal cladding, with suitable sliding access doors, such that it can be operated in a room with low-level illumination.

4.10 Software

The control software is written in Microsoft Visual Basic[®]. The structure is such that the instrument can be operated with the minimum training and the maximum flexibility. The key to controlling the instrument is an 'Angle Table' that is set up in Microsoft Excel[®] and saved as a comma delimited (.csv) text file. This table is read by the control software and establishes the angles and positions to which all of the four sample translation stages are to be set, the range of angles for setting the arm on which the spectroradiometer is mounted, and whether an image is to be recorded. The first process is for each stage to be initialised so that they each establish their own 'zero' positions. After this process is completed the instrument sets each stage to the required position, initiates a measurement from the spectroradiometer, places the spectral data into a column in a worksheet of a Microsoft Excel spreadsheet, and

moves to the next set of positions to repeat the process. Additional measurements are placed in adjacent columns of the same Excel worksheet. Also recorded are the CIE colorimetry associated with the spectral radiance data, the colour temperature associated with the measurement, and the temperature and relative humidity from sensors close to the sample surface. A typical set of measurements that includes the initialisation process, the setting of one illumination angle and measurements over the range -75° to $+75^\circ \times 5^\circ$ takes approximately 30 minutes but is dependant on the actual values of the spectral radiance of the sample; a darker sample requires longer spectroradiometer integration times and hence a longer total measurement time.

4.11 Calibration

In its basic state, the spectroradiometer measures the spectral radiance, L , of the light coming from the sample in watts per metre per steradian and, with suitable calibration, a traceability path could be established for this measurement. The requirement however, is the spectral reflectance factor, R , of the sample.

The spectral reflectance factor of the sample, $R_{Sample}(\theta_i, \theta_r, \lambda)$ can be given by:

$$R_{Sample}(\theta_i, \theta_r, \lambda) = \frac{L_{Sample}(\theta_i, \theta_r, \lambda)}{L_{PRD}(\theta_i, \theta_r, \lambda)} \quad (1)$$

where $L_{Sample}(\theta_i, \theta_r, \lambda)$ is the spectral radiance of the sample and $L_{PRD}(\theta_i, \theta_r, \lambda)$ is the spectral radiance of the perfect reflecting diffuser, identically illuminated, θ_i is the angle of illumination, θ_r is the angle of viewing, and λ the wavelength.

However, the spectral reflectance factor of a reference standard, $R_{Reference}(\theta_i, \theta_r, \lambda)$ is given by:

$$R_{Reference}(\theta_i, \theta_r, \lambda) = \frac{L_{Reference}(\theta_i, \theta_r, \lambda)}{L_{PRD}(\theta_i, \theta_r, \lambda)} \quad (2)$$

where $L_{Reference}(\theta_i, \theta_r, \lambda)$ is the spectral radiance of the reference standard.

By substitution for $L_{PRD}(\theta_i, \theta_r, \lambda)$ in Equation 1:

$$R_{Sample}(\theta_i, \theta_r, \lambda) = \frac{L_{Sample}(\theta_i, \theta_r, \lambda)}{L_{Reference}(\theta_i, \theta_r, \lambda)} R_{Reference}(\theta_i, \theta_r, \lambda) \quad (3)$$

Thus, the spectral reflectance factor of the sample, Equation 3, can be found for any angle of illumination, angle of viewing and wavelength assuming knowledge of the spectral reflectance of a reference standard at that same angle of illumination, angle of viewing and wavelength.

The reference standard chosen is a white matt BCRA-NPL Ceramic Colour Standard tile and this has been calibrated for a number of illuminating/viewing angle combinations, as a function of wavelength, on the NPL Reference Reflectometer which provides an absolute measurement of reflectance¹⁹. Thus, the goniospectrophotometer can be used to measure

spectral reflectance factor, as a function of wavelength, in a manner that is traceable to the reflectance scale on a national reference instrument.

It should be noted that NIST has available a Russian Opal reference standard (No. 2017)²⁰ with spectral reflectance measured at an illumination angle of 45° and viewing angles of 30°, 20°, 0°, -30° and -65°, corresponding to aspecular angles of 15°, 25°, 45°, 75° and 110°, respectively[#]. This artefact has not been used for calibrating the GASP instrument, but will be used in the future for verifying the measurement data once the instrument is suitable calibrated.

5. Example Measurements

As an example of the capability of the instrument, a Red/Gold ChromaFlair sample was measured using a -45° illumination angle and a range of viewing angles from -75° to +75° in steps of 5°. The ChromaFlair pigments exhibit a change in colour with change in both illuminating and viewing angles and these measurements yield a set of 29 spectral reflectance factor data. This amount of data is difficult to interpret although the movement of the peak reflectance factor as a function of angle is obvious and to be expected for these pigments. Calculating the CIELAB coordinates associated with the spectral data enables a number of plots to be made which make it easier to interpret the data, Figure 5. All colorimetry is calculated using the CIE Standard Illuminant D65 and the CIE 1931 2° Standard Observer².

Figure 5a shows a graph of the spectral reflectance factor data plotted as a function of wavelength, for a sub-sample of the complete set, to illustrate the point that the wavelength at which the maximum reflectance occurs changes with viewing angle. These changes are further illustrated in Figure 5b where the wavelength associated with the maximum reflectance value is plotted as a function of viewing angle. Specifically it can be seen that the peak wavelength moves from the red to the yellow part of the spectrum with increasing viewing angle. In addition, it can be seen that there is little variation with angle for values less than -20° – all measurements would be visualised as red in this range. This is because the ChromaFlair sample reflects very little back-scattered light, thus the values of spectral reflectance factor are very low in this part of the range and the sample looks not red but neutral.

Figure 5c shows the CIELAB a^* vs b^* plot showing the path that the sample maps out with changing viewing angle. The sample starts with low reflectance and so appears almost neutral. As the reflectance increases the values of a^* and b^* increase, hence the associated value of chroma, C_{ab}^* , increases and the sample appears to gradually increase in chroma. Near to the point of specular reflectance – where data points are not obtained – the chroma reaches a maximum and then, at angles beyond the specular, the chroma decreases and the hue of the sample moves towards the yellow. This is shown by the value of a^* decreasing towards zero while the value of b^* remains relatively high. The change in hue is accompanied by a change in CIELAB lightness, L^* , shown in Figure 5d which is a graph of CIELAB lightness, L^* , plotted as a function of chroma, C_{ab}^* and adds the third lightness dimension to the a^* , b^* diagram shown in Figure 5c. It can be seen that, as the viewing angle increases, the value of C_{ab}^* increases as described above. After the specular angle, the chroma decreases, as does the lightness.

[#] See the discussion section of this report for further information on the choice of measurement angles.

Figure 5e is a traditional x, y chromaticity diagram showing the path represented by the sample as a function of viewing angle. Also shown is the position of the illuminant, D65.

Figure 5f is a graph showing the change in lightness, L^* , as a function of viewing angle. As described above, the lightness increases towards the specular angle. At this angle, the lightness will be a maximum and it then falls for angles on the other side of the specular angle. Figure 5g shows the increases and decreases in chroma, C_{ab}^* , with changing viewing angle, and Figure 5h shows the change in the hue angle, h_{ab} , and hence perceived hue, with changing viewing angle.

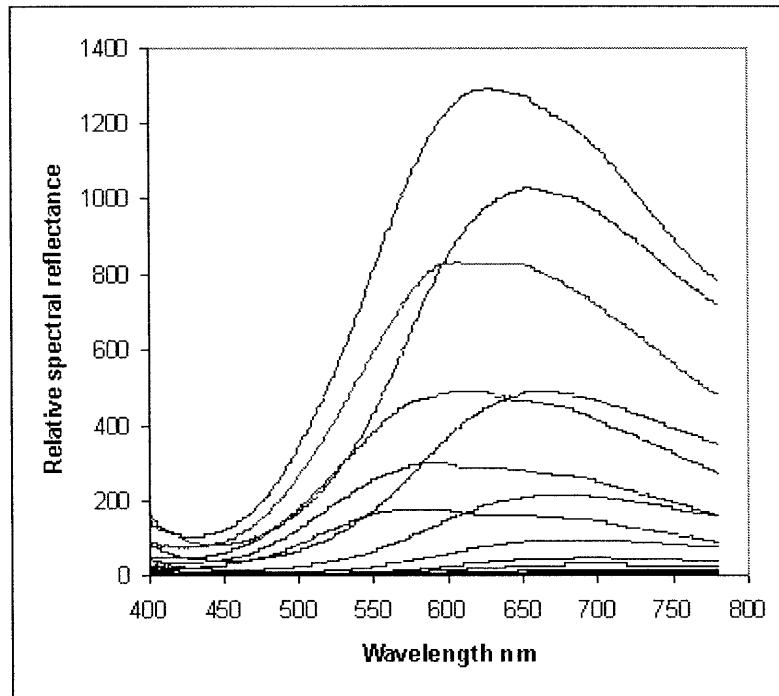


Figure 5a. Spectral reflectance factor as a function of wavelength and viewing angle.

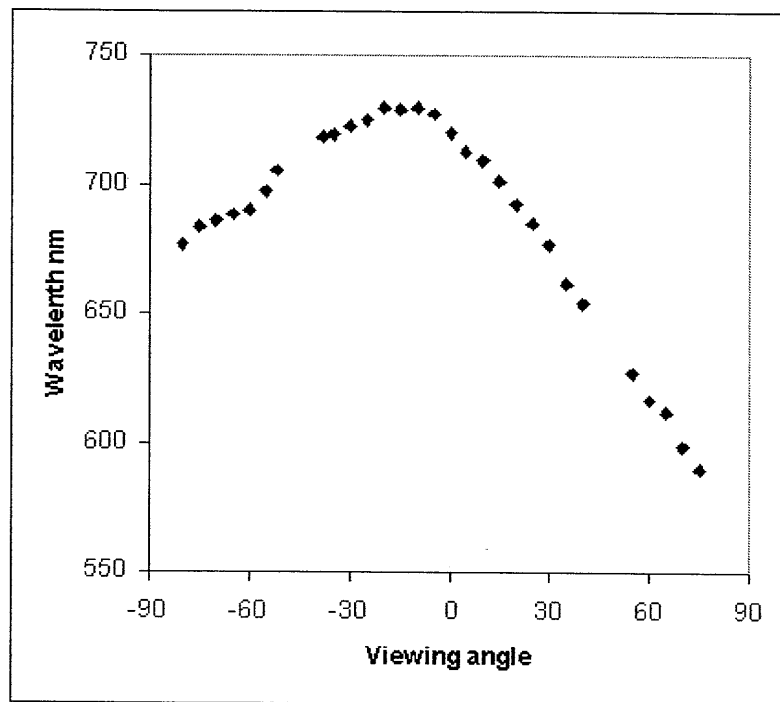


Figure 5b. The wavelength corresponding to the peak of the spectral reflectance factor, plotted as a function of viewing angle.

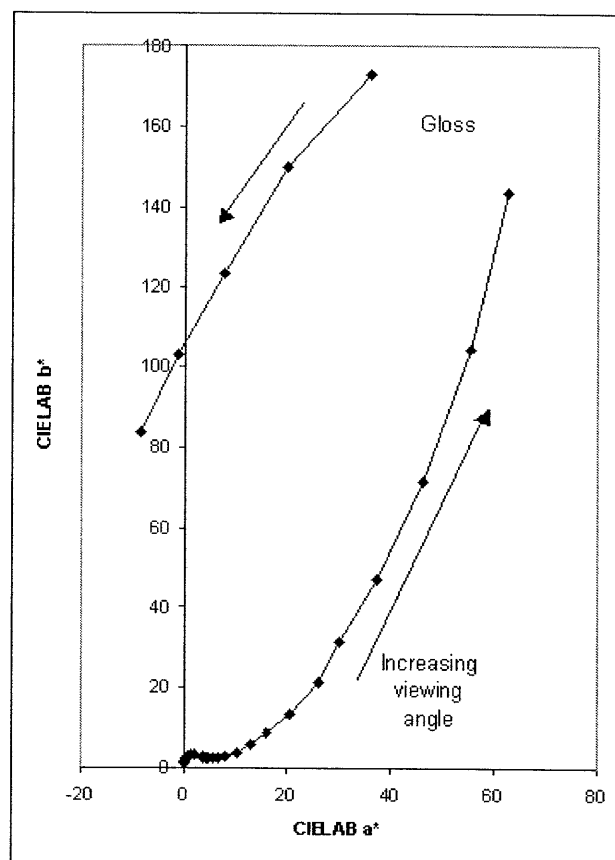


Figure 5c. CIELAB a^* vs b^* .

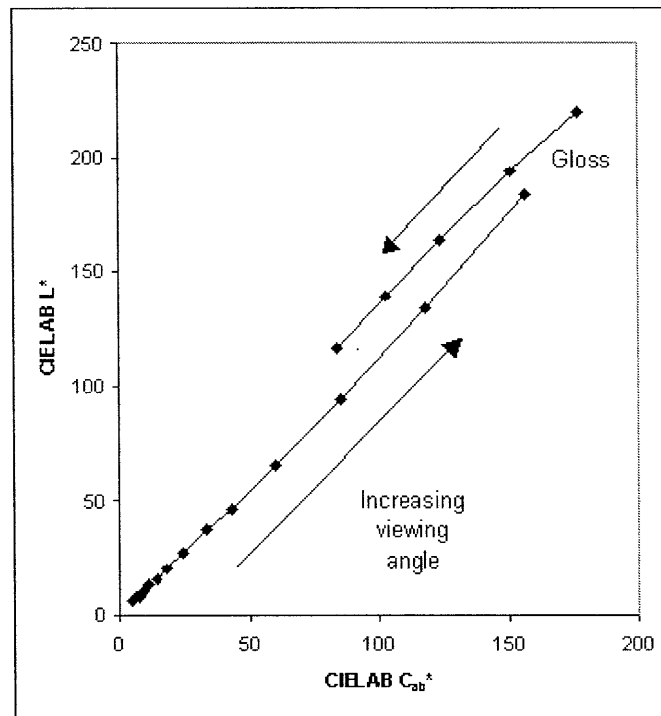


Figure 5d. CIELAB L* vs C_{ab}*.

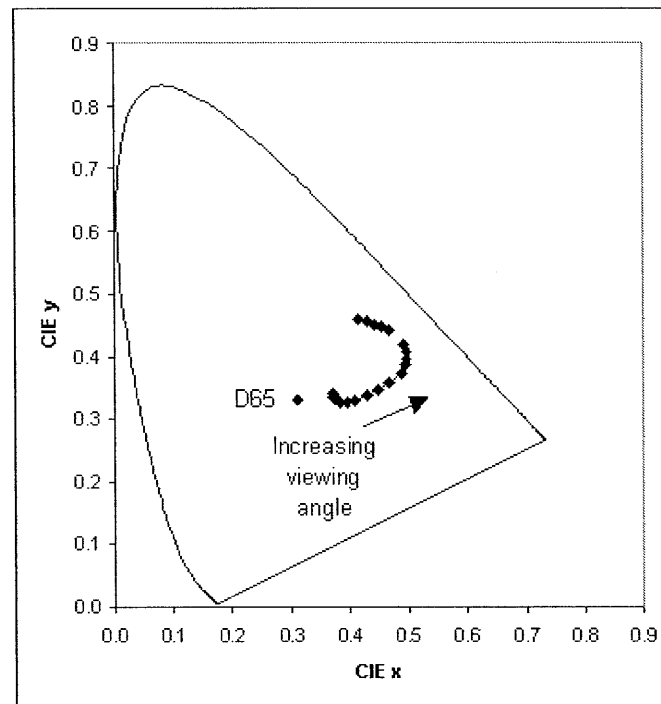


Figure 5e. CIE chromaticity x vs y y – CIE Standard Illuminant D65, CIE 1931 2° Standard Observer.

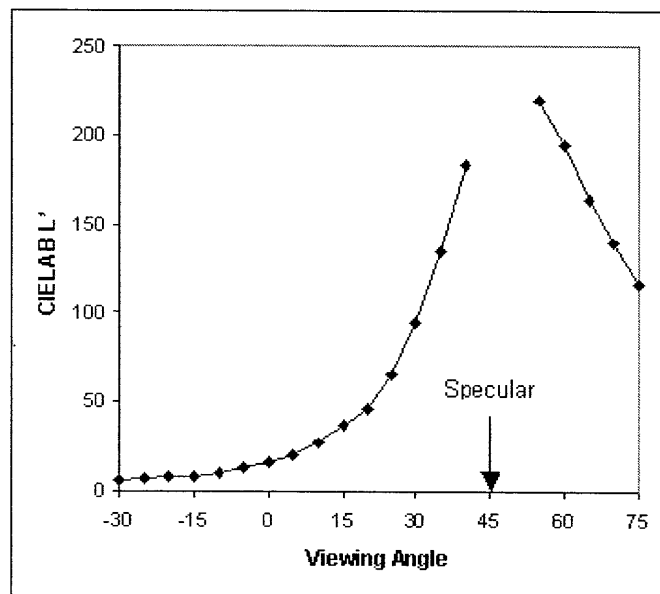


Figure 5f. CIELAB lightness, L^* vs viewing angle.

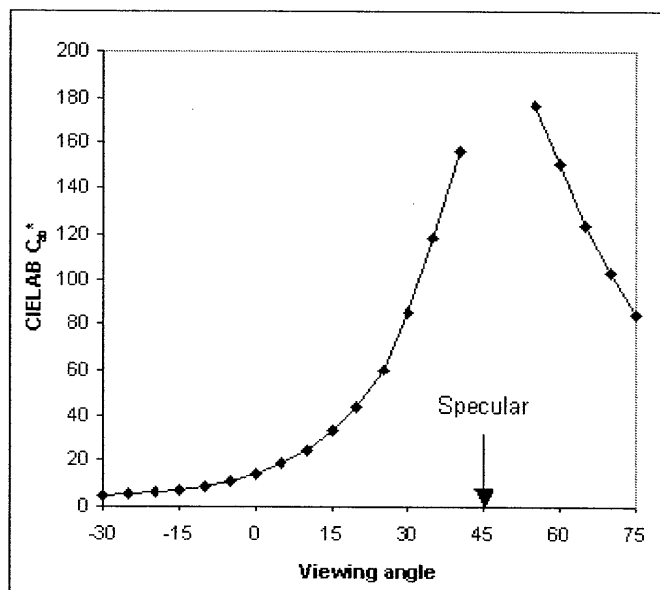


Figure 5g. CIELAB chroma, C_{ab}^* vs viewing angle.

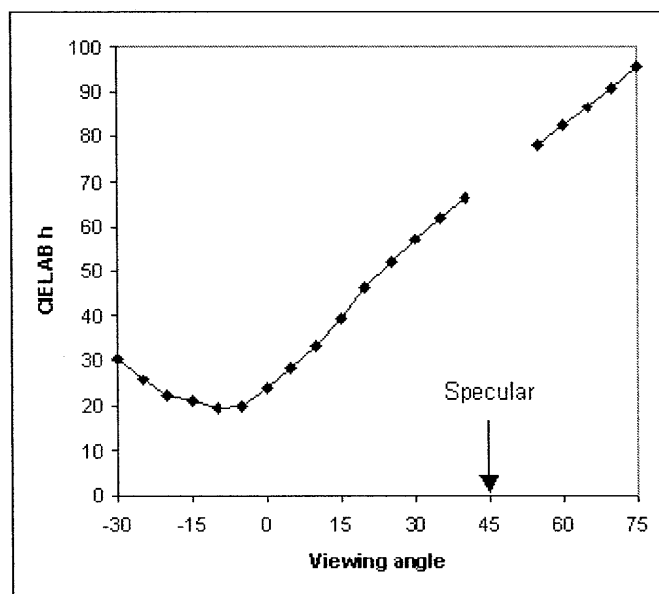


Figure 5h. CIELAB hue angle, h_{ab} vs viewing angle.

Figure 5. Data obtained by measuring a Red/Gold ChromaFlair[®] sample and deriving the spectral reflectance factor as a function of wavelength for viewing angles in the range -70° to $+70^\circ \times 5^\circ$ with illumination at -45° .

6. Discussion

As part of the present optical programme, it is planned that an uncertainty budget will be assembled for spectral and colorimetric measurements. Following this, a procedure will be written to enable the instrument to operate within the UKAS framework and perform customer work. At present, the instrument is only calibrated for illumination at an angle of -45° and calibration using other angles of illumination will be added as required.

6.2 Measurement Angles

The choice of angles of illumination and viewing for specific applications remain undecided. There is a desire amongst pigment manufacturers to not to have to make multiple spectrophotometric scans of their samples, but select a set of angle combinations that give them enough information to control their processes. There is a move by the makers of interference pigments to make measurements using three angles of illumination although no suggested scheme has found universal agreement. One present, commercially available, multi-angle spectrophotometer uses the scheme shown in Table 1.

This scheme is based on early work by Alman²¹ who, in work using metallic pigments, recommended the use of three angles of viewing, corresponding to the specular, face and flop directions. The selection of these angles had previously been patented by Du Pont²². This scheme, in turn was used as a basis for the angles recommended by DIN Standard 6175-2 which is concerned with the measurement of colour tolerances for the automobile industry²³.

Table 1. Angle scheme for a commercially available spectrophotometer.
(The original Alman/Du Pont angles are shown in bold.)

Angle of illumination	Angle of viewing – aspecular	Angle of viewing - geometric
-45°	15°	30°
-45°	25°	20°
-45°	45°	0°
-45°	75°	-30°
-45°	110°	-65°

A second scheme, suggested by the Merck, another manufacturer of special-effect pigments, uses illumination at $-45^\circ \pm 20^\circ$, with detection at 15° either side of the corresponding specular angle. The angles for this scheme are shown in Table 2.

Table 2. Angle scheme suggested by the Merck,
a manufacturer of special effects pigments.

Angle of illumination	Angle of viewing – aspecular	Angle of viewing - geometric
-25°	15°	10°
-25°	-15°	40°
-45°	15°	30°
-45°	-15°	60°
-65°	15°	50°
-65°	-15°	80°

A third scheme, suggested by the Flex Products, the manufacturers of ChromaFlair pigments, is to use illumination at $-30^\circ \pm 15^\circ$, with detection at the five aspecular angles designated in Table 1 but now applied to all three illumination angles. The angles for this scheme are shown in Table 3.

Table 3. Angle scheme suggested by the manufacturers of ChromaFlair pigments.

Angle of illumination	Angle of viewing – aspecular	Angle of viewing - geometric
-15°	15°	0°
-15°	25°	-10°
-15°	45°	-30°
-15°	75°	-60°
-15°	110°	#

-35°	15°	-20°
-35°	25°	-5°
-35°	45°	10°
-35°	75°	40°
-35°	110°	75°

-45°	15°	30°
-45°	25°	20°
-45°	45°	0°
-45°	75°	-30°
-45°	110°	-65°

angle not attainable

Yet another scheme is that proposed by Werner and presented at the meeting of ASTM Sub-Committee E12.12 *Metallic and Pearlescent Colors* in January 2005²⁴. This scheme uses two sets of angles to trace out two lines in colour space. Werner claims that the first describes the change in colour with angle of viewing, and the second the interference effect, the change in colour due to change in the angle of illumination. In the latter case, the angle of illumination is changed while the specular angle is kept constant, Table 4.

Table 4. Angle scheme suggested by Werner²¹.

Angle of illumination	Angle of viewing – aspecular	Angle of viewing - geometric	Werner designation – protractor
-45°	65°	20°	45°/70°
-45°	60°	15°	45°/75°
-45°	55°	10°	45°/80°
-45°	50°	5°	45°/85°
-45°	45°	0°	45°/90°
-45°	40°	-5°	45°/95°
-45°	35°	-10°	45°/100°
-45°	30°	-15°	45°/105°
-45°	25°	-20°	45°/110°
-45°	20°	-25°	45°/115°
-45°	15°	-30°	45°/120°

-65°	15°	50°	25°/140°
-60°	15°	45°	30°/135°
-55°	15°	40°	35°/130°
-50°	15°	35°	40°/125°
-45°	15°	30°	45°/120°
-40°	15°	25°	50°/115°
-35°	15°	20°	55°/110°
-30°	15°	15°	60°/105°
-25°	15°	10°	65°/100°
-20°	15°	5°	70°/95°

It should be noted that Werner, in his paper, quotes all angles with respect to the surface of the sample, the so-called ‘protractor method’, as shown in the fourth column of Table 4.

7. Summary

An instrument has been described that measures the spectral radiance of a sample as a function of wavelength, the angle of illumination and the angle of viewing. By also measuring the spectral radiance of a suitably calibrated white tile, the sample spectral reflectance factor can be calculated. The instrument is computer controlled and designed to be easily operable. The calibration of the instrument is via a matt white BCRA-NPL Ceramic Colour Standard and is traceable to a reflectance scale derived using the NPL Reference Reflectometer. By way of an example, the spectral data obtained using the instrument, and subsequently calculated colorimetric data, are plotted in various combinations and interpreted in terms of their visual correlation. Several angle schemes are described which different manufacturing groups, and instrument manufacturers, have found useful for describing specific product types.

8. Acknowledgements

The authors acknowledge the funding obtained as part of the Intersect Faraday Partnership and thank their colleagues at The Tintometer Limited and the National Physical Laboratory for occasional constructive discussion. They especially acknowledge the contribution made by David White, of The Tintometer Limited, who managed the project, and Steve Neville, also of The Tintometer Limited, who made the CAD drawings for the evaluation and design of the instrument, and carried out much of the actual construction work.

A shorter version of this Report has been accepted for publication in Coloration Technology, the Journal of the Society of Dyers and Colourists, in 2005.

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