

Study of Improved Methods for Absolute Colorimetry

Fourth Report

Investigation of Colorimetric Errors

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INTRODUCTION

This report covers the second workpackage in the study of Improved Methods for Absolute Colorimetry.

The first workpackage determined the needs, particularly within industry, for absolute colour measurements, assessed how adequately the needs are currently being met and formulated well supported recommendations to direct the future implementation of improved methods where gaps were identified.

The technical studies which form Workpackages 2 and 3 aim to identify why in many cases, the levels of accuracy obtainable in principle through calibration services and artefacts are not achieved in practice. The intercomparison of colour measurements carried out by 24 members of the NPL Spectrophotometry and Colorimetry Club (1) showed considerable variations in the accuracy achieved in industry.

The objectives of the technically based studies were:

- to identify how current industrial practice can be improved;
- to identify and quantify the sources of measurement errors in industry;
- to further identify and quantify the least understood sources of error in national measurement instruments.

This report summarises an investigation into the causes of colorimetric errors, many of which are not understood even for national reference instruments. Also included is a summary of the present understanding of all known sources of colorimetric errors.

1. BACKGROUND TO TECHNICALLY BASED STUDIES

A recent intercomparison of surface colour measurements between four European countries led by NPL gave spreads of differences in measured values of greater than 0.5 CIELAB units for about half the measurements. Maximum spreads were up to 2.2 CIELAB units, which was considered unsatisfactory by all the participants as the human eye can distinguish between colours which differ by 0.5 CIELAB units. An appropriate long term objective for national laboratories is for 95% of measurements to agree to within 0.2 CIELAB units.

The intercomparison of surface colour measurements between 24 companies, organised as a working group of the NPL Spectrophotometry and Colorimetry Club (1), gave a roughly similar level of agreement as the international intercomparison above for those companies using the best available commercial equipment and having traceability to NPL. Companies with lower quality equipment and companies not having traceability to NPL showed much larger divergences. An appropriate long term objective for industrial laboratories would be 95% of measurements to agree to within 0.5 CIELAB units.

2. WORKING PROGRAMME

The accuracy of surface colour is limited by many factors as summarised here.

- i. Differences in national scales of diffuse reflectance.
- ii. Lack of traceability to national standards.
- iii. Errors associated with transfer standards
 - iii a Thermochromism
 - iii b Translucency
 - iii c Temporal instability of colour standards.
- iv. The effect of field size on measured and perceived colour difference.
- v. Differences in instrument geometries within the specified limits.
- vi. Measuring head errors
 - vi a Non uniformity of integrating spheres
 - vi b Time dependent changes of integrating spheres
 - vi c Gloss trap errors
 - vi d Specular beam errors
 - vi e polarization errors in 0/45 instruments
- vii. Errors in the instrument photometric scale.
- viii. Wavelength errors.
- ix. Errors due to finite bandwidth.
- x. Differences in colour data due to different methods of calculation from spectral data.

Item i is covered by the project on Diffuse Reflectance Scales in the present NMSPU programme. Item ii requires education, which is included in the Technology Transfer project within the current NMSPU programme. Items iii a and iii b were investigated in the preceding NMSPU programme. Items iii c, iv, v, vi a, and vi b are the subject of Workpackage 2, the results of which are presented in this report. Items vi c, vi d, vii, viii, ix and x are addressed in Workpackage 3 of this project.

The investigations in Workpackage 2 are addressed in the following order.

1. The effect of visual field size on measured and perceived colour differences.
2. The effect of differences in instrument geometry within the specified limits.
3. Non uniformity and time dependent changes of integrating spheres.
4. Temporal instability of colour standards.

2.1 DIFFERENCES IN FIELD SIZE

The CIE has recommended different versions of the system for colorimetry for 2° and 10° visual field size diameters. The corresponding numerical tables which represent the colour matching properties of the eye are known as the 2° and 10° Standard Observers. The differences between the two are due to differences in the concentrations of the four different types of visual receptor in the eye. Colour measuring instruments fall into two broad classes, spectrophotometers and colorimeters. Spectrophotometers realise the Standard Observers as tables of numerical data in the computer. They can give colour data corresponding to both Standard Observers. However, colorimeters simulate the Standard Observers through the design of optical filter and detector combinations. Usually they simulate either the 2° observer or the 10° observer but not both. The experiments carried out in this study compared the results of measured and perceived colour differences for field sizes of 2° and 10°.

2.2 DIFFERENCES IN INSTRUMENT GEOMETRY

The CIE has recommended geometrical tolerance limits for angles of incident and observed beams of light. Colour measuring instruments should ideally be within these tolerance limits. The results of a preliminary study of the variation of measured reflectances of surface colour standards with different geometric parameters, within the specified tolerance limits, are presented.

2.3 NON UNIFORMITY AND TIME DEPENDENT CHANGES IN INTEGRATING SPHERES

Many instruments for the measurement of surface colour use an integrating sphere to irradiate the sample diffusely or to collect the diffusely reflected light. An integrating sphere has a highly reflective coating on the inside wall. The sample is usually mounted against a port in the sphere wall. The spheres are never completely uniform because of non uniformity in the reflectance of the sphere coating or because of ports in the sphere wall. In the study reported here a laser was used to determine the variation of the collection efficiency with angle of incidence of three integrating spheres, each with a different coating. Changes in the reflectances of the coatings were investigated for removable plugs measured on a spectrophotometer.

2.4 STABILITY OF SURFACE COLOUR STANDARDS

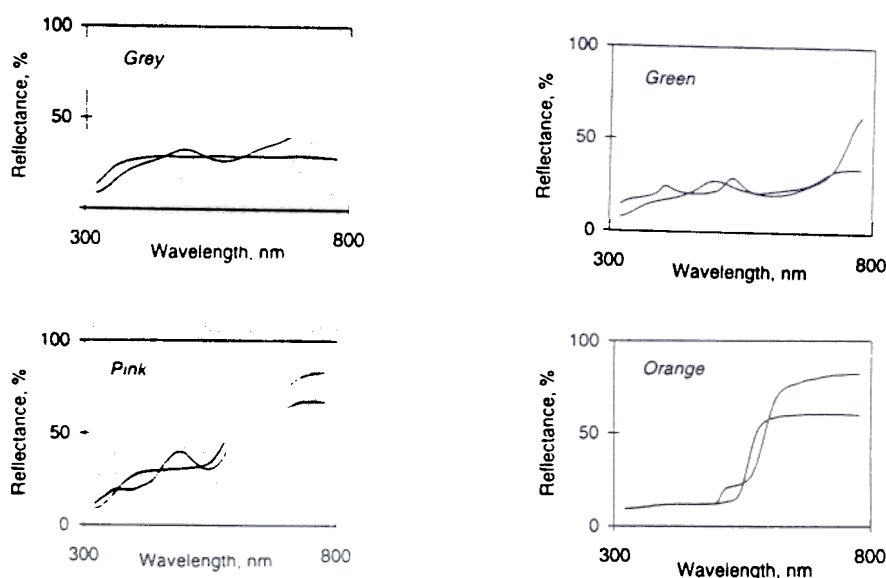
Surface colour standards are used not only for calibrating colour measuring instruments but also for testing their stability. However, their ability to do this is limited by lack of knowledge of the standards themselves. This report gives results of attempts to measure the stability of surface colour standards using two very different instruments, a high quality commercial spectrophotometer and the NPL Reference Reflectometer. Consideration is given to the design of an instrument built specifically for this task.

3. THE EFFECT OF VISUAL FIELD SIZE ON MEASURED AND PERCEIVED COLOUR DIFFERENCES

3.1 METAMERIC COLOUR STANDARDS

The National Physical Laboratory and Ceram Research Ltd have developed 5 pairs of metameric ceramic tile colour standards (grey, green, pink, orange and yellow) to extend the range of colour standards available to industry (2). Each pair of tiles was designed to be an instrumental colorimetric match in terms of CIELAB ΔE units under Standard Illuminant D65 (standardised daylight) for the CIE 10° Standard Observer and to be a mismatch under Standard Illuminant A (tungsten light) for the same observer. The 10° Standard Observer was chosen in the design criteria for the metameric tiles due to its wide industrial use, in particular by the textile industry. The tiles may be used as a tool for evaluating the performance of filter-based colorimeters and for visually assessing the match of simulated daylight sources to illuminant D65.

Spectrophotometric measurement of the colour standards showed that the colorimetric match/mismatch under the two illuminants did not hold for the CIE 2° Standard Observer. In this case the colorimetric values showed a mismatch for both illuminants. Experiments were conducted to compare the instrumentally measured colour difference values on the pairs of tiles, for the 2° and 10° observers and for illuminants D65 and A, to visual assessments of the colour differences graded against a grey scale difference.



Figures 3.1a-3.1d: Spectral reflectance curves for pairs of metameric ceramic colour standards

The spectral reflectance curves for each pair of metameric tiles exhibit at least 3 cross-over points (figures 3.1a-3.1e). This ensures that similar colorimetric values will be produced when the curves are combined with the spectral power distribution of a particular illuminant and integrated over the broadband CIE colour matching functions representing one of the Standard Observers. The 2° Standard Observer and the 10° Standard Observer, represent the different distributions of

receptors present in the retina. The 2° observer represents the small area containing and surrounding the fovea and is dominated by cone receptors, whereas the 10° observer contains both the foveal area and much of the periphery of the retina where the number of short wave cones is greater and the low light level receptors, the rods, are also present. The two sets of colour matching functions for the Standard Observers differ predominantly at the lower wavelengths (figure 3.2). The CIE has recommended the use of the 2° observer for visual fields below 4° in diameter and the 10° observer for larger fields (2).

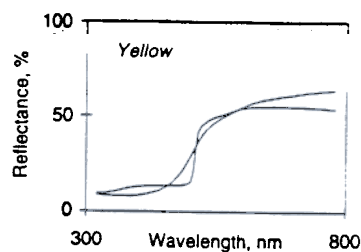


Figure 3.1e: Spectral reflectance curves for a pair of metameric ceramic colour standards

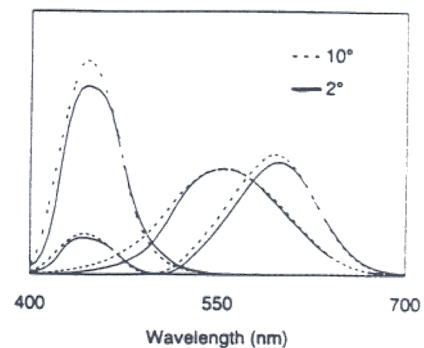


Figure 3.2: CIE colour matching functions for the 2° and 10° Standard Observers

3.2 EXPERIMENTAL PROCEDURE

Experiments were conducted to determine the correlation between the instrumental colour difference (in CIELAB ΔE units) and the visual assessment of colour difference for 10° and 2° field sizes under illuminants D65 and A and for a measurement and viewing geometry of 0/45.

A set of metameric colour standard pairs was measured for radiance factor on a Lambda 19 scanning spectrophotometer in the 0/45 CIE specified measurement geometry. The tiles were cut in half and each half was measured. Only one half of each tile was used in the subsequent visual experiments. The grey and green colour difference pairs (which form part of the traditional set of 12 BCRA-NPL Ceramic Colour Standards) were also added to the test set. These pairs are not metamers and therefore do not significantly change colour difference with change of illuminant. CIELAB L^* , a^* , b^* and ΔE values were calculated for the four combinations of the CIE Standard Observers and Illuminants mentioned above. The values for ΔE are shown in Table 3.1. These confirm the illuminant D65 colour match and illuminant A mismatch for the 10° observer. The colour match is not perfect and ranges from ΔE value of 0.2 to a value of 1.2. An average human observer is usually able to detect colour differences of the order of 0.5 ΔE or greater. In all cases in Table 3.1, for the 10° observer, the ΔE values are greater (in a range from 3.5 to 9 times greater) for illuminant A. For the 2° observer the calculated ΔE values are greater than 1.0 ΔE for all the pairs of tiles for both illuminants. The calculated colour differences are smaller for illuminant D65 than A but at a level that should not be acceptable as a visual match.

Table 3.1: Normal colour differences in CIELABΔE units for the metameric pairs of ceramic tiles under two different CIE Standard Illuminants and for the two CIE Standard Observers.

	Grey	Green	Pink	Orange	Yellow
D65/10°	0.5	0.4	1.2	1.0	0.9
A/10°	3.1	3.3	4.3	4.2	3.1
D65/2°	1.6	2.7	2.2	1.0	2.2
A/2°	4.6	5.2	6.8	6.2	5.2

The visual experiments were carried out in an industrial viewing cabinet fitted with several commercial light sources. The geometry was such that the illumination fell onto the test pairs at approximately 0° and they were viewed at 45° (figure 3.3). The cabinet, as purchased, was lined with grey plastic (Munsell N7). The 2° and 10° bipartite circular viewing fields were created with masks resting on top of a pair samples such that one sample showed through each half of the field (figure 3.4). The masks were made from card that had been coated with a grey paint that did not change colour with change of illuminant. The perceived visual colour difference of the pairs of samples was assessed by an observer against a bipartite grey scale of a fixed 4° size situated between the observer and the samples (figure 3.4). One half of the scale was fixed at Munsell N6.75 while the other half was adjusted by the observer until the grey colour difference was judged to be equivalent to the perceived colour difference present in the pair of samples. The grey scales were made from glossy Munsell chips with a step size of 2.5 ΔE.

The definition of CIE illuminant A is based on a real tungsten source; therefore it was relatively simple to replicate in a viewing cabinet. Conversely, illuminant D65 could only be approximated by an artificial daylight source (a Macbeth 6500 fluorescent tube) which was not a good match to the defined illuminant (figures 3.5a and 3.5b). Because of these differences the instrumental ΔE values were calculated for the actual sources used in the experiment (see Table 3.2).

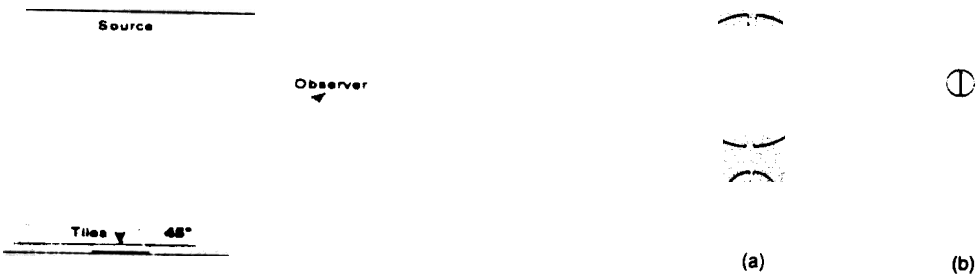


Figure 3.3: Side view of experimental set-up showing 0°/45° viewing condition

Figure 3.4: Plan view of sample (above) and grey scale viewing fields (below) for (a) 10° case and (b) 2° case

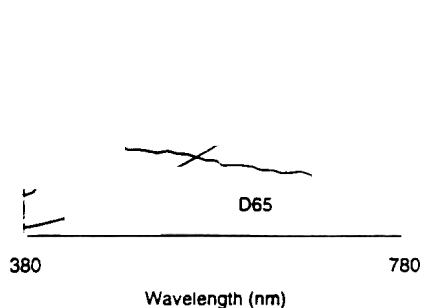


Figure 3.5a: Relative spectral power distributions of CIE illuminants

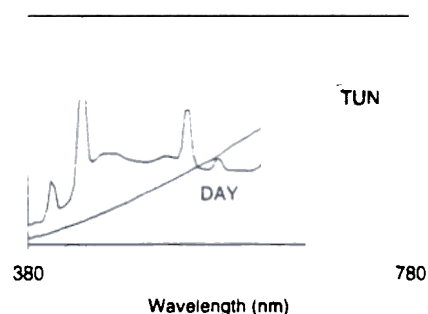


Figure 3.5b: Measured spectral power distributions of sources used in experiments

3.3 RESULTS

The results reported in Table 3.2 show the visual assessments of one observer on 3 pairs of the metameric tiles under the two light sources for both the 2° and 10° viewing conditions. 5 assessments were made per pair per condition, and the mean and standard deviation are quoted in the table. The values quoted for the visual assessment are in terms of the measured CIELAB ΔE for the grey scale difference selected by the observer. The calculated values for ΔE are also shown for each pair of tiles for both the CIE Standard Illuminants D65 and A as well as for the actual sources used, a daylight fluorescent tube (Day) and a tungsten lamp (Tun).

Table 3.2 shows, as expected, that the calculated ΔE values for the pairs of samples for the tungsten source used and illuminant A only differed slightly (from 0 - 0.2 ΔE), whereas the differences between the daylight source and illuminant D65 were larger (0.2 - 0.4 ΔE). Although the real daylight source caused the calculated ΔE values to increase (in all but one case) the values still, according to the calculated colour differences, predicted a closer match for the samples under the daylight source than under the tungsten source. A similar assessment of the grey scale colour values under the real sources used in the experiment revealed no significant differences from the colour values under the CIE Standard Illuminants. This was due to the spectrally flat nature of the reflectance curves of the Munsell chips.

Table 3.2: Calculated and perceived values of colour difference for the metamer pairs of tiles. Values are in CIELAB units ΔE .

Conditions	Grey		Orange		Yellow	
	calc	visual	calc	visual	calc	visual
D65/10°	0.5		1.0		0.9	
Day/10°	0.7	2.1 ± 1.0	1.4	0.4 ± 1.0	1.3	1.9 ± 1.0
A/10°	3.1		4.2		3.1	
Tun/10°	3.1	5.8 ± 1.3	4.3	2.5 ± 0	3.3	2.3 ± 0.5
10° day/tun difference	2.4	3.7	2.9	2.1	2.0	0.4
D65/2°	1.6		1.0		2.2	
Day/2°	2.0	2.5 ± 0	1.3	0.4 ± 1.0	2.0	1.5 ± 0.9
A/2°	4.6		6.2		5.2	
Tun/2°	4.6	3.5 ± 1.2	6.2	1.3 ± 1.1	5.3	1.7 ± 0.6
2° day/tun difference	2.6	1.0	4.9	0.9	3.3	0.2

The visual results of colour difference for the 10° field size do not closely agree with the calculated values, but they do demonstrate a basic trend of a closer visual match for the daylight source than for the tungsten source for the grey and orange pairs of tiles. For the yellow pair, once the standard deviation is taken into account, the results show no distinct difference between the two sources for the 10° case. The visual results for the 2° case also show no marked agreement with the calculated values. For two of the three pairs of samples show a smaller colour difference (and therefore, a better colour match) for the daylight source than predicted from the calculated values. In fact while the mean visual colour difference values show a trend of a smaller difference for the daylight source than for the tungsten source, the standard deviation of the mean value is such that the results for the two sources overlap considerably. The calculated values for the 2° observer actually predict the differences in ΔE between the sources to be much greater than for the 10° observer for the three pairs of samples used. The visual results are the reverse of this and are consistent with observer comments that in the 2° case the colour differences were not greatly apparent and the task was perceived as more difficult than for the 10° case.

3.4 DISCUSSION

For the 10° field size the visually assessed colour differences agree with the calculated CIELAB ΔE values in so far as there is a general trend of a smaller colour difference for the daylight source than for the tungsten source. There is not a similar agreement for the 2° case. Observer comments that the colour difference was not greatly apparent for the 2° field for either source would suggest that the results are a measure of a real effect. The standard deviations on the visual results are large and it is not clear whether this is due to coarseness of the grey scale used or actual variability in the observer's ability to assess the visual colour difference to a grey scale difference. The step size in the grey scale used (a standard Munsell grey scale) was 2.5 ΔE . The scale was used in two ways - as an ascending scale with the darkest chip at one end and the lightest at the other and as a randomly distributed scale. The results with the different scales did not vary significantly. The ascending scale had the added advantage of allowing the observer to select a half-way position between any two points on the scale resulting in an effective step size of 1.25 ΔE . In addition, the observer found the ascending scale easier and quicker to use. The visual results above have been compared to the calculated colour difference values for the 0/45 geometry and the experimental set-up was designed to match this condition as far as possible. In reality the samples were illuminated with diffuse light reflected from the walls of the light cabinet as well as direct illumination from the source. It may also be necessary to compare the visual results to those calculated for the 0/d (specular excluded) measurement geometry.

Further experiments are required to extend the number of pairs of samples assessed and results from more than one observer are required. A source of a finer grey scale is being sought. At present, the uncertainties are in the region of 1 CIELAB unit. The finer grey scale might reduce this to 0.5 CIELAB units or less. This will either enable the colour differences to be assessed to a higher degree of precision or establish the level to which observers are able to repeatably assess the colour difference.

4. THE EFFECT OF DIFFERENCES IN GEOMETRY WITHIN THE SPECIFIED LIMITS

4.1 GEOMETRIC TOLERANCES

The CIE (3) recommends that colorimetric specifications of diffusely reflecting samples be measured with defined illumination and viewing conditions. The tolerances on these geometric definitions were last adjusted in 1986 on the basis of goniophotometric measurements made by Clarke (4, 5) at NPL. These are:

For normal/diffuse reflectance, the sample is illuminated by a beam whose axis is at an angle not exceeding 10° from the normal to the sample. The reflected flux is collected by means of an integrating sphere. The angle between the axis and any ray of the illuminating beam should not exceed 5° .

For 0/45 radiance factor, the sample is illuminated by a beam whose effective axis is at an angle not exceeding 10° from the normal to the sample. The sample is viewed at an angle of $45^\circ \pm 2^\circ$ from the normal. The angle between the axis and any ray of the illuminating beam, should not exceed 8° . The same restriction should be observed in the viewing beam.

These tolerances are shown in Figures 4.1 and 4.2.

In the following investigations, the NPL Reference Reflectometer was used to examine the angular distribution of reflectance for certain glossy and matt ceramic colour standards and to evaluate the variation of chromaticity and luminance factor within the defined tolerance limits.

4.2 EQUIPMENT

For this work, the NPL Reference Reflectometer (6) was used to enable full control of incident and reflected beams as shown in Figure 4.3. Optics originally designed for gloss work provided a relatively high detector flux but suffered some chromatic aberration. The effect of this was removed in the normalisation process. Illumination was provided by a tungsten ribbon lamp filtered by narrow bandpass filters of about 16 nm bandwidth centred at 407, 568 and 700 nm. A patch approximately 9 mm in diameter was illuminated at the centre of each sample. A rectangular aperture placed before the silicon detector provided detection angles of 4.4° in the measurement plane and 11.7° perpendicular to the measurement plane.

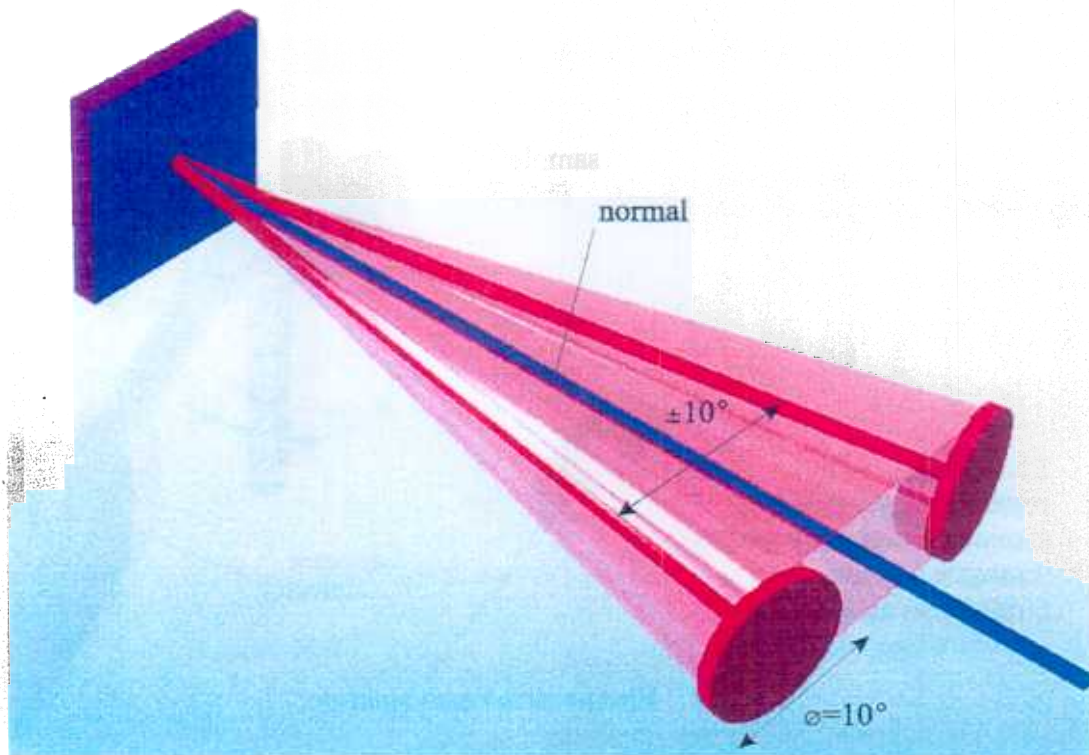


Figure 4.1 CIE geometric tolerances for illumination in normal/diffuse geometry

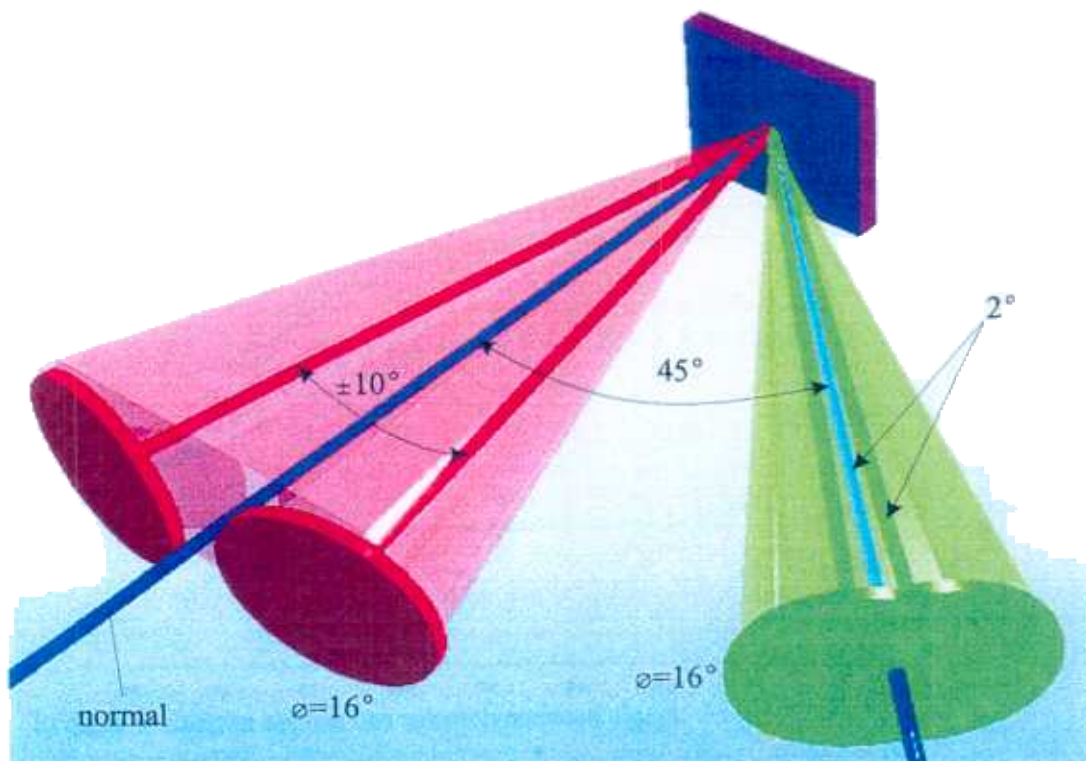
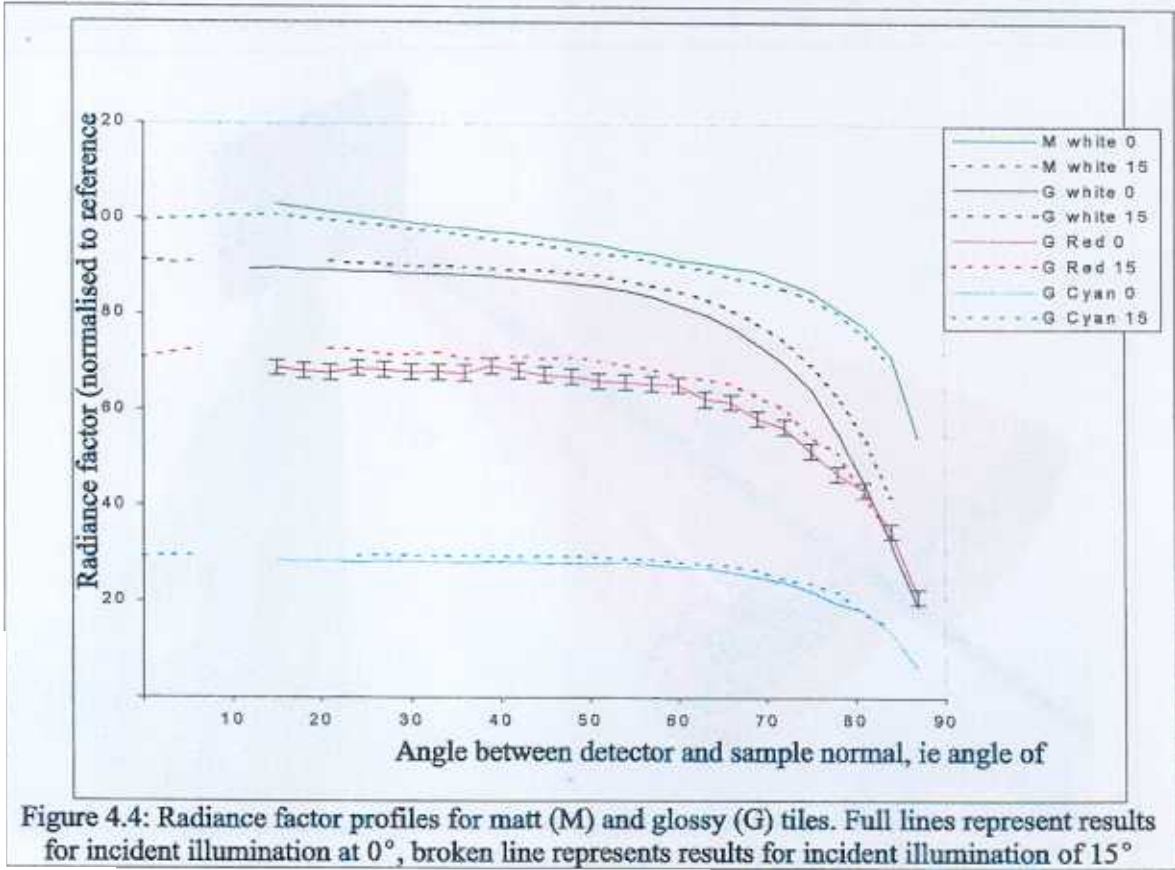
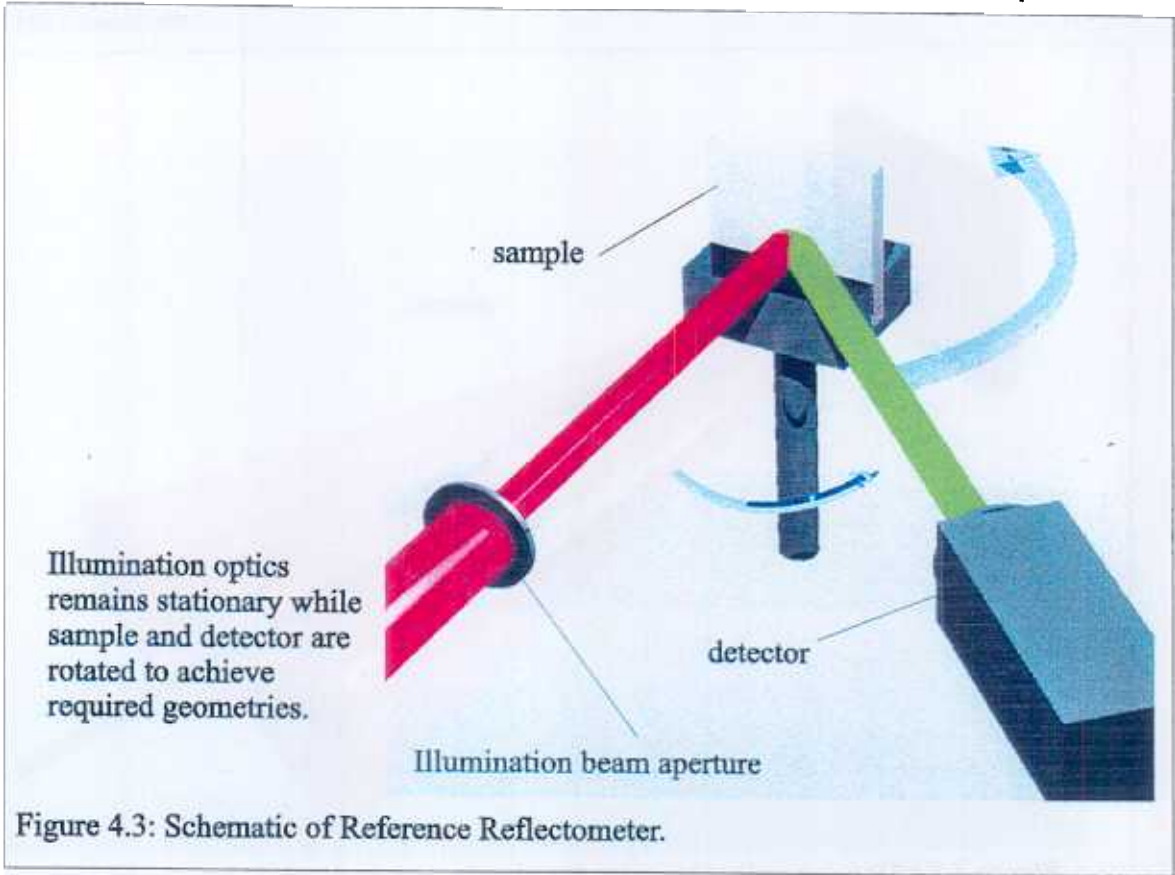


Figure 4.2 CIE geometric tolerances in the 0/45 geometry for illumination (red) and collection (green)



4.3 MEASUREMENTS

The schedule of measurements is shown in Table 4.1. The symbol 't' is used where the range of angles of reflectance was sufficiently large to cover the normal/diffuse geometry. The notation 5/t indicates illumination at 5° and detection at 3° intervals between -90° and +90°. The range of angles used for the 0/45 geometry was: for illuminator: -10°; -5°; 0°; 5°; 10° and for detector: 35°; 45°; 55° on both sides of the sample normal. All angles are quoted from the normal to the sample.

Radiance factors were evaluated by dividing measured fluxes by a geometric cosine factor. Values were then normalised using 0/45 spectral radiance factor standards.

Table 4.1: schedule of measurements.

Tile	Geometry
Glossy white	-8/t, 0/t, 5/t, 8/t, 12/t, 15/t, 0/45
Matt white	0/t, 5/t, 8/t, 12/t, 15/t, 0/45
Glossy Red	0/t, 15/t, 0/45
Glossy Cyan	0/t, 15/t, 0/45
Glossy Yellow	0/45
Glossy Green	0/45

4.4 INTERPRETATION OF RESULTS.

Polarisation

In accordance with Clarke (4, 5), radiance factors showed a small dependency on the state of the incident polarisation. The detector used was demonstrated to be free from polarisation bias. (Polarisers were not placed in the reflected beam but it can be assumed from the work of Clarke that different results would be given for s and p planes of polarisation of the reflected beam.) Results quoted in this report are all for p polarised incident illumination.

Investigation of wavelength dependence on angular values of reflected flux

For non-neutral tiles such as red and cyan, chromaticities are usually quoted as being different for normal/diffuse and 0/45 geometries. However, in this investigation, within the limits of measurement uncertainty, the radiance factor angular profiles shown as the curves in figure 4.4 are similar for additional wavelengths. This was an unexpected result and requires further investigation.

Total reflectance

The radiance factor profiles for four tiles measured in 0/t and 15/t geometries are shown in figure 4.4. The data are given in Table 4.2. There appears to be a difference between values for the two geometries. However this difference is, at present, within the range of uncertainties. Further work needs to be done at higher resolution to resolve this point.

	M white 568 nm		G White 568 nm		G Red 700 nm		G Cyan 407 nm	
Angle	0	15	0	15	0	15	0	15
0		99.6		91.2		70.9		29.4
3		99.9		90.7		71.9		29.5
6		100.2		90.9		72.8		29.6
9		100.5						
12		100.6	89.3					
15	103.0	100.8	89.5		68.7		28.4	
18	102.2	100.1	89.2		68.2		28.4	
21	101.4	99.7	89.2	90.9	67.7	72.8	28.3	
24	100.8	99.1	88.8	90.5	68.7	72.5	28.2	29.5
27	99.9	98.5	88.7	90.3	68.4	71.6	28.2	29.6
30	99.2	97.8	88.6	89.9	67.9	71.5	28.3	29.5
33	98.5	97.3	88.3	90.0	67.9	72.1	28.2	29.3
36	98.0	96.5	88.2	89.9	67.8	70.7	28.0	29.4
39	97.4	95.7	87.9	89.6	69.2	70.9	28.3	29.3
42	96.9	95.0	87.5	89.2	68.2	71.3	28.1	29.4
45	95.9	94.5	87.1	89.2	67.4	70.7	27.9	29.2
48	95.3	93.5	86.6	88.5	67.1	71.1	27.8	29.3
51	94.6	92.6	85.8	88.0	66.2	70.4	27.9	29.2
54	93.4	92.3	84.9	87.0	65.9	69.3	28.1	28.9
57	92.8	91.1	83.7	86.0	65.5	68.7	27.6	28.6
60	91.5	90.4	81.9	84.9	65.3	67.1	27.1	28.2
63	90.8	89.5	80.1	83.3	62.3	66.5	27.0	27.7
66	89.9	87.9	77.5	81.1	61.8	65.6	26.1	27.3
69	89.2	86.7	73.7	78.3	58.3	63.1	25.1	26.5
72	87.0	85.5	69.7	74.5	56.5	60.5	24.1	24.7
75	85.1	83.6	64.5	69.5	51.5	54.7	22.4	23.8
78	81.5	80.5	55.5	63.1	46.7	51.3	19.7	21.9
81	77.8	76.0	45.1	54.5	43.3	42.3	18.1	17.6
84	71.6	69.8	32.0	41.8	34.7	33.7	13.5	14.5
87	54.4		18.8		21.0		6.2	

Table 4.2: Radiance factor profiles for four ceramic tiles. (These are plotted in figure 4.4). Data are omitted where (1) the detector obscures the incident beam, or (2) the specular component intrudes on the diffusely reflected component. The first column is the angle of measured flux. The uncertainties are approximately 1%. The wavelengths reproduced here were selected for maximum signal to noise ratio for each tile.

0/45 radiance factor

Samples were measured over the CIE tolerance ranges and radiance factor obtained. The results at the extremes of the tolerance ranges are summarised in Table 4.3.

Table 4.3: Variation in reading over 0/45 geometric tolerances. All values are in units of flux normalised to certified values of radiance factor at 0/45.

Sample	Wavelength	Radiance factor					
		0/45	0/35	0/55	10/35	10/45	10/55
Glossy white	568 nm	88.4	87.8	89.0	87.5	88.3	88.9
Matt white	568 nm	90.0	91.3	88.7	91.2	90.2	88.6
Red	700 nm	67.8	67.2	68.2	66.4	67.9	68.7
Cyan	409 nm	12.1	11.9	12.2	11.9	12.1	12.3
Yellow	568 nm	72.9	72.0	73.4	71.8	72.7	73.3
Green	568 nm	16.4	16.1	16.7	16.1	16.5	16.8

Uncertainty

Systematic uncertainty in spectral radiance factor for these measurements is in the range of 1-2%. The random uncertainty in spectral radiance factor rises from $\pm 0.2\%$ below 60° to $\pm 0.7\%$ at higher angles. The uncertainty in angle is $\pm 0.01^\circ$. The reported uncertainties are based on a standard uncertainty multiplied by a coverage factor $k=2$, providing a level of confidence of approximately 95%.

4.5 DISCUSSION

Preliminary results are given for the variation of spectral radiance factor with angle using the Reference Reflectometer. Although there are indications that there are differences in reflectance for angles of incidence of 0° and 15° , it is not possible at this stage to say whether or not the current CIE geometric tolerances for colorimetry are optimum for current industrial practice. A difference of 1.5% in reflectance between the different geometries would correspond to an error of about 0.5 CIELAB units. In order to achieve definitive results the uncertainties of measurement need to be reduced by making modifications to the incident and detector beam optics. The range of measurements also needs to be extended to include industrial materials such as textiles and painted samples, measured against white reflectance standards.

A surprising result is that the angular variation of radiance factor is independent of wavelength. This requires further investigation. It is not yet clear whether the result is genuine due to the limitation of the currently available accuracy. However, it is possible to realise absolute spectral diffuse reflectance and absolute spectral 0/45 radiance factor with the same instrument. This means that the differences in results for the normal/diffuse geometry and the 0/45 geometry have the potential to be realised with greater accuracy on this instrument than was previously the case when normal/diffuse values and 0/45 values were obtained from different instruments traceable to different scales.

5. NON UNIFORMITY AND TIME DEPENDENT CHANGES OF INTEGRATING SPHERES

5.1 INTEGRATING SPHERES

Integrating spheres are employed in spectrophotometric systems to achieve diffuse illumination of a sample or diffuse collection of light reflected from a sample. They form an essential part of CIE specified geometries for colour measurement. An ideal integrating sphere would be coated uniformly with a 100% diffuse reflecting material with a perfectly Lambertian reflectance profile. It would therefore diffuse all rays of light equally and absorb no radiation, enabling the maximum throughput without any bias due to non-uniform sources, samples or detectors. In practice the sphere coatings used are neither perfect Lambertian diffusers or 100% reflecting. An area of concern is the non-uniformity of the coatings within the sphere and their stability or ageing with time. These latter two issues were investigated within the current project.

The uniformity and ageing of commercial integrating spheres was investigated with a rotating diode laser device that had been previously constructed to investigate the uniformity of the integrating sphere on the National Reference Spectrophotometer (6, 7). Results obtained with this device in the past had indicated a deterioration in the uniformity of the sphere coating with usage. In the current project a more controlled pilot study of integrating sphere uniformity and ageing was conducted.

5.2 EXPERIMENTAL PROCEDURE

Three commercially coated integrating spheres were purchased from Labsphere with the same simple geometrical design but different coatings. The coatings are known by their trademark names of 'Spectrafect' (SF), 'Duralect' (DF) and 'Spectralon' (SN). Spectralect is a barium sulphate based coating, Duralect is of unknown composition and Spectralon is a polymer based solid material of high diffuse reflectance often used for white reflectance standards. As the latter is a solid material the sphere was machined directly from the material and housed in an aluminium box. The former were aluminium spheres coated with the white materials. The spheres were all fabricated in two halves which were then joined together. Each had three openings or 'ports' of 20 mm diameter - two directly opposite each other and one at 90° to them - and they contained no screening baffles (figures 5.1a and 5.1b).

The laser device consisted of a diode laser of wavelength 670 nm mounted on two rotating gimbals allowing (manual) movement about two axes. It was positioned above each sphere in turn (figure 5.2a) and aimed into the sphere through the centre of the top port. The rotation of the laser allowed the beam to be aimed at various points on the sphere surface. With both angular positions at zero the beam fell at the base of the sphere. The 'pitch' angle allowed adjustment of the vertical height of the beam within the sphere, while the 'roll' angle allowed the beam to sweep out a horizontal circle at a fixed height (figure 5.2b). Points above a certain height within the sphere could not be reached with the laser beam as the pitch angle was such that the beam was occluded before it could enter the sphere.

A silicon photodiode cell was positioned against one of the other ports forming part of the

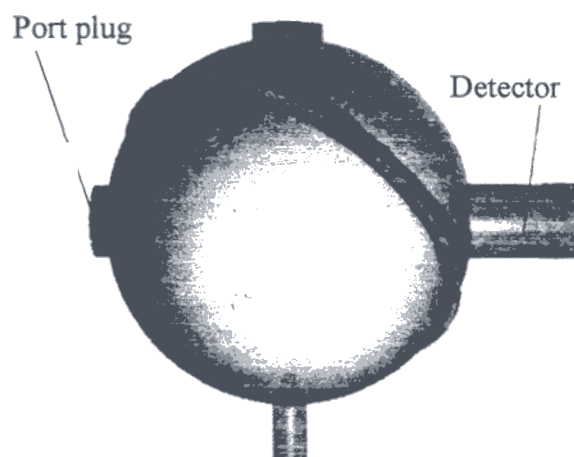


Figure 5.1a: Side view of spheres SF and DF

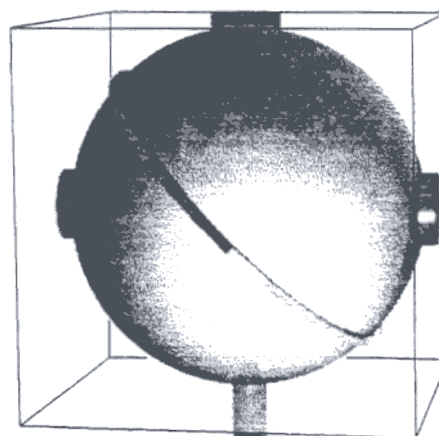


Figure 5.1b: Side view of sphere SN

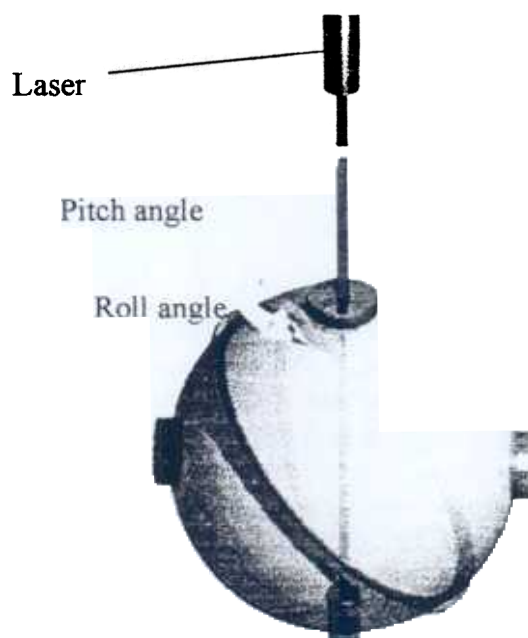


Figure 5.2a: View of sphere showing axes of rotation of laser beam

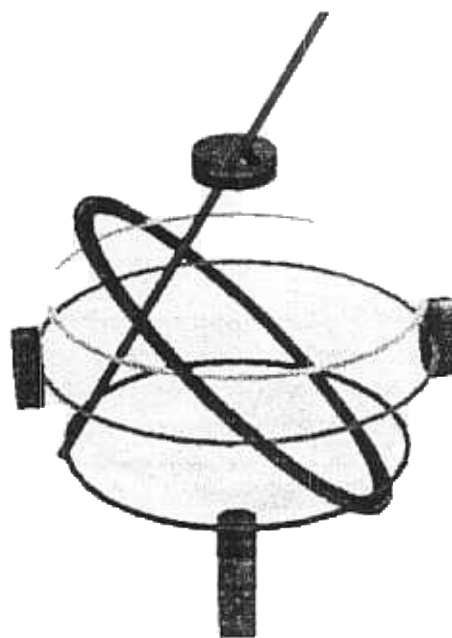


Figure 5.2b: Three scan positions of laser beam within sphere

sphere wall and measured the amount of radiation falling onto that area. A 'plug' made of the same material as each sphere was placed at the third port. To ensure that fluctuations in the laser output did not affect the results, the laser device also contained a small silicon cell detector to monitor the radiation from the laser. This was achieved by folding the laser beam with a partially reflecting mirror before it entered the sphere. The light transmitted by the mirror fell onto the small silicon cell. Both detectors were connected to amplifiers and digital voltmeters which, in turn, were connected to a PC via an IEEE board.

For each position of the laser beam on the sphere wall a computer program took 20 alternate readings from both detectors and then calculated the ratio of the two signals. Measurements at each laser position took approximately 5 seconds and the mean values and standard deviations of the 20 readings were recorded with both of the detectors and the ratio. For a fixed pitch angle a horizontal 360° scan of the sphere was carried out at 10° intervals. The scan was then immediately repeated in the opposite direction to check the consistency of the results. At the beginning and end of each pair of scans the zero position (i.e. with both pitch and roll angles set to zero) was measured several times. This provided information on the overall repeatability of the experimental set up. Scans were made at three different pitch angles/heights within each sphere; approximately 20 mm below the ports, across the ports and just above the ports (figure 5.2b).

Initial investigations revealed that the measurement set up was sensitive to temperature, so all measurements were taken within a temperature range of 24.8 °C to 25.5 °C. For any pair of scans the temperature range was usually less than 0.2 °C.

The first measurements were made on the spheres in July/August 1997 to assess their degree of uniformity. In October 1997 the spheres were remeasured to determine if any changes to the level of uniformity had occurred within the elapsed time of 3 months. During this time the spheres were stored, along with the relevant port plug, in sealed plastic bags in a temperature controlled environment.

5.3 RESULTS

The results must be interpreted with respect to the measurement uncertainties which define the minimum non-uniformity that can be determined. An assessment of maximum uncertainty (based on the repeatability of measurement at the zero position for a series of scans on each sphere) demonstrated an uncertainty of 0.025 on the ratio value for spheres SF and DF and 0.05 on ratio values for sphere SN for a fixed sphere/detector position. The absolute level of the ratio value is dependent on the exact positioning of the sphere with respect to the laser and the silicon cell detector. Therefore only relative differences in uniformity are measurable and it is for these relative differences that the uncertainties above are quoted. For the same reason only the relative differences can be compared between the first and the later measurements. Great care was taken to re-position the sphere with respect to the laser beam to ensure that the same part of the sphere was remeasured in the later scans. However, the actual level of the ratio is too dependent on position of the detector relative to the sphere wall to be repeatable. Differences in the ratio value due to re-positioning the sphere with respect to the detector can be as large as 0.2, but the level of the ratio value is fixed once the sphere and detector positions are fixed. Therefore only the shapes of the uniformity plots between the two scans can be compared, and no information

on changes in the overall level of the reflectance of the sphere coatings can be determined unless the ratio values changed by an amount significantly greater than 0.2.

Figures 5.3-5.5 show the results for sphere SF for the three scans at different heights within the sphere. The outer plot of each chart represents the results from the first scan and the inner one the results from the second later scan. The sharp dips in figure 5.3 at approx. 180° and 310° are where the laser beam hit the join between the two halves of the sphere. The joins also show up as sharp dips on figure 5.4 (at approximately 160° and 330°) and figure 5.5 (at 150° and 340°) but at different positions due to the relationship of the sphere join to the scan positions (see figures 5.1 and 5.2). The plug port was situated at 10° - 30° on the scan across the ports, and figure 5.4 shows the edge of the port at 10° where the ratio value drops as the laser beam hit the edge of the port. Directly opposite at 180° to 220° the high readings represent where the laser beam fell directly onto the detector. All three figures show that one half of the sphere - the half containing the plug port - had a higher reflectance than the other half. Looking into the sphere by eye also demonstrated that the two halves were visibly different. The half which has lower reflectance had a more granular surface. There is no significant difference between the shape of the two plots for the July and the October measurements.

Figures 5.6-5.8 show the results for sphere DF. Despite being visible to the eye the joins of the sphere are not visible on the plots. By looking into the sphere it was determined that they fell at approx. 165° and 320° on figure 5.6, at 150° and 330° on figure 5.7, and at 140° and 340° on figure 5.8. Figure 5.6 shows that both halves of the sphere had a profile of non-uniformity with the ratio values decreasing by 0.1 to 0.15 away from the joins. All three figures show a small decrease in reflectance in the half of the sphere containing the detector port. Figure 5.7 - the scan across the ports - shows the laser beam falling onto the detector and the port plug. The port plug, at 10° - 30°, appeared to have a slightly higher reflectance than the surrounding sphere. The coating on sphere DF was visibly more granular in structure than sphere SF. Again the plots do not differ significantly between the July and October scans.

There are only two plots, figures 5.9-5.10, for sphere SN due to the method in which the sphere was manufactured. The sphere was machined from two blocks of Spectralon and the whole sphere housed in a square box. This design meant that the laser device could not be placed as close to the sphere as for SF and DF, and that the maximum height that the laser could scan inside the sphere was lower. Two scans were carried out; one below the ports and one across the ports. Both scans show a slightly lower reflectance for the half containing the detector port. Figure 5.9 shows a higher degree of non-uniformity than figure 5.10, particularly around 80° - 240°. It may be that the area just below the detector port (at 150° - 190°) was damaged during machining. Again there is little difference in the shape of the plots for the two measurements.

Although the absolute level of the ratio value is highly dependent on the measurement set-up, and cannot be repeated to better than 0.2, its value differs between the three spheres quite considerably. It is of the order of 7.4 for sphere SF, 3.2 for sphere DF and 8.7 for sphere SN. This hierarchy is representative of the reflectances of the various coatings as quoted by the manufacturer and measured by NPL on the corresponding port plugs (figures 5.11-5.13). The ratio value measured is therefore representative of the throughput of each sphere. The port plugs were stored with each sphere and their reflectances were measured in both July/August and October showing a small decrease over time, with SF being the worst

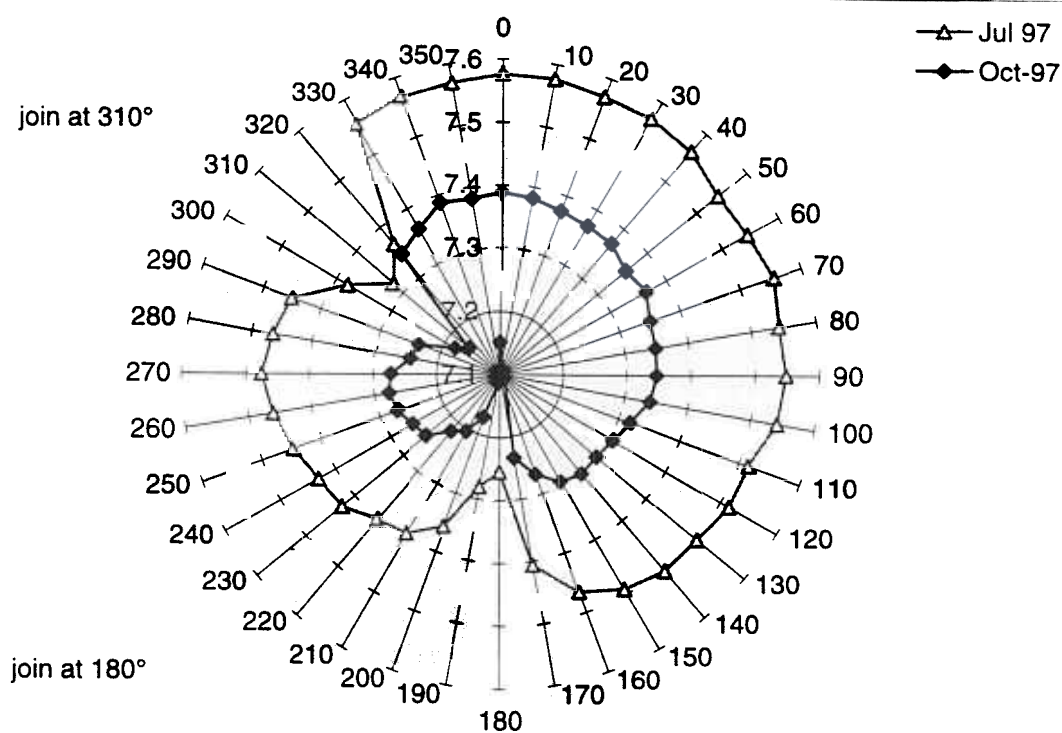


Fig 5.3: Sphere SF - Uniformity below port

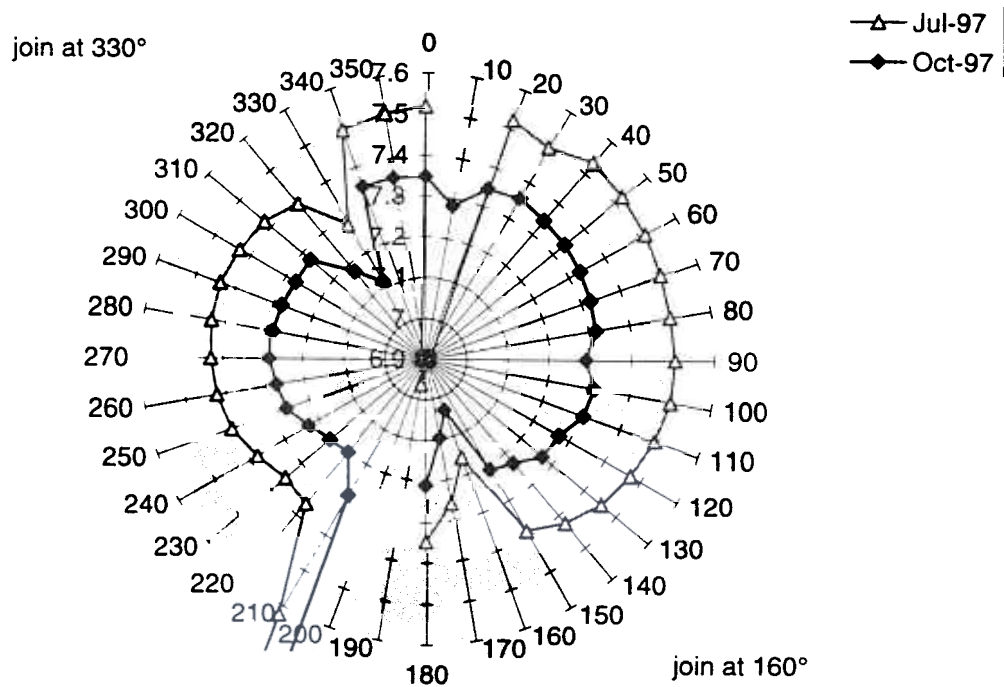


Fig 5.4: Sphere SF - Uniformity across ports

join at 340°

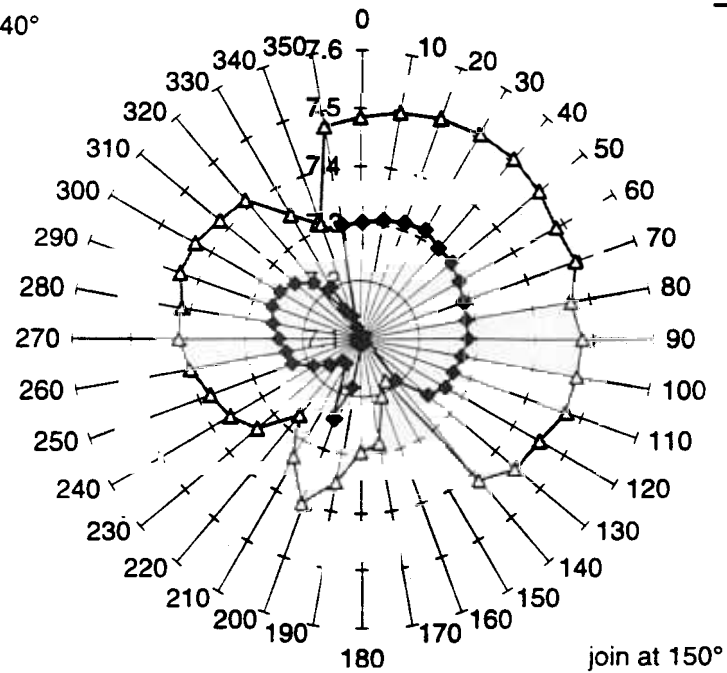


Fig 5.5: Sphere SF - Uniformity above ports

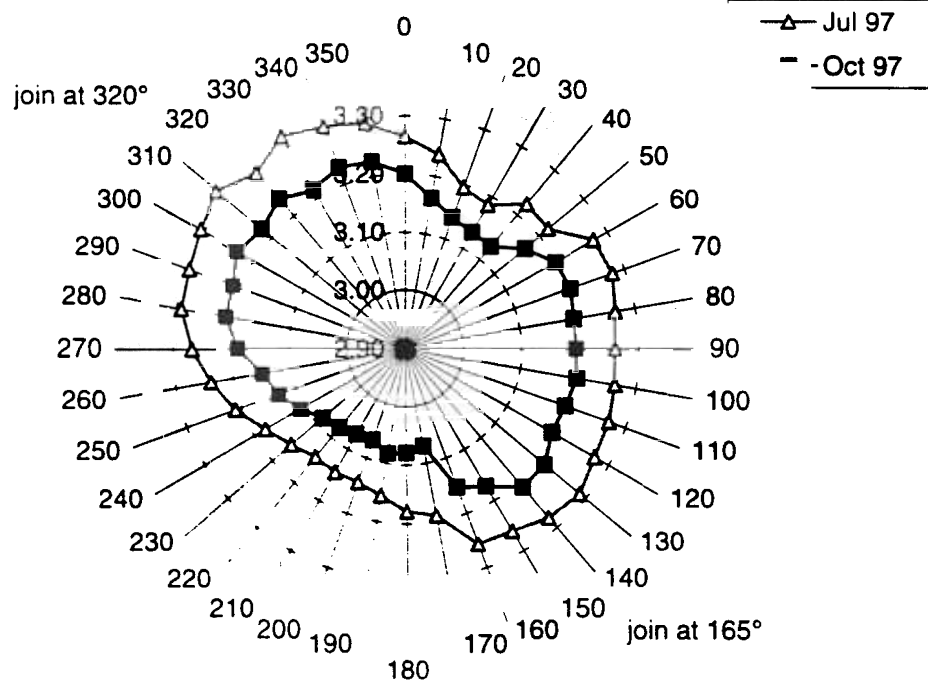
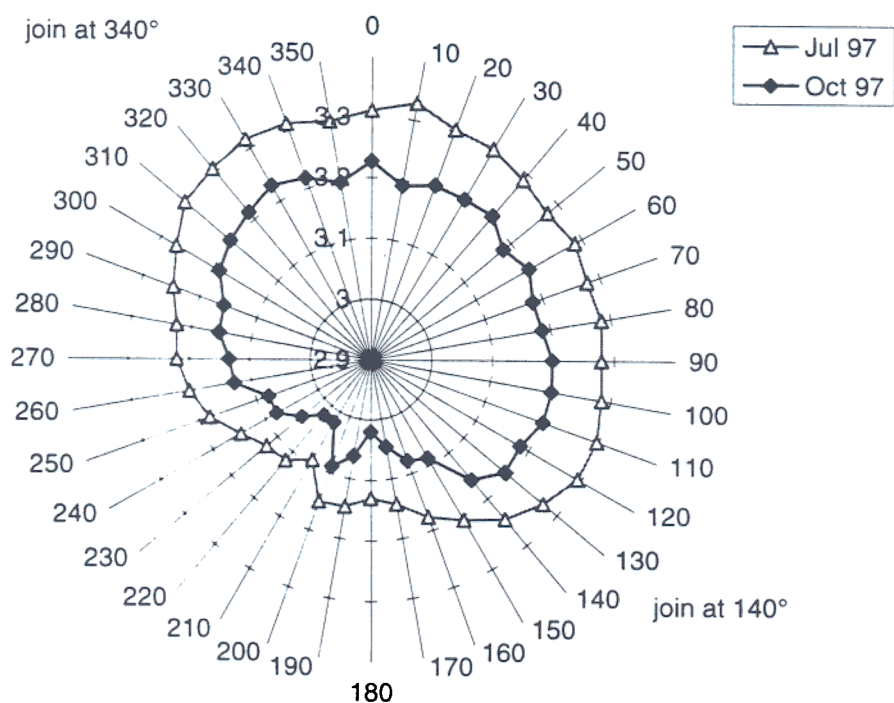
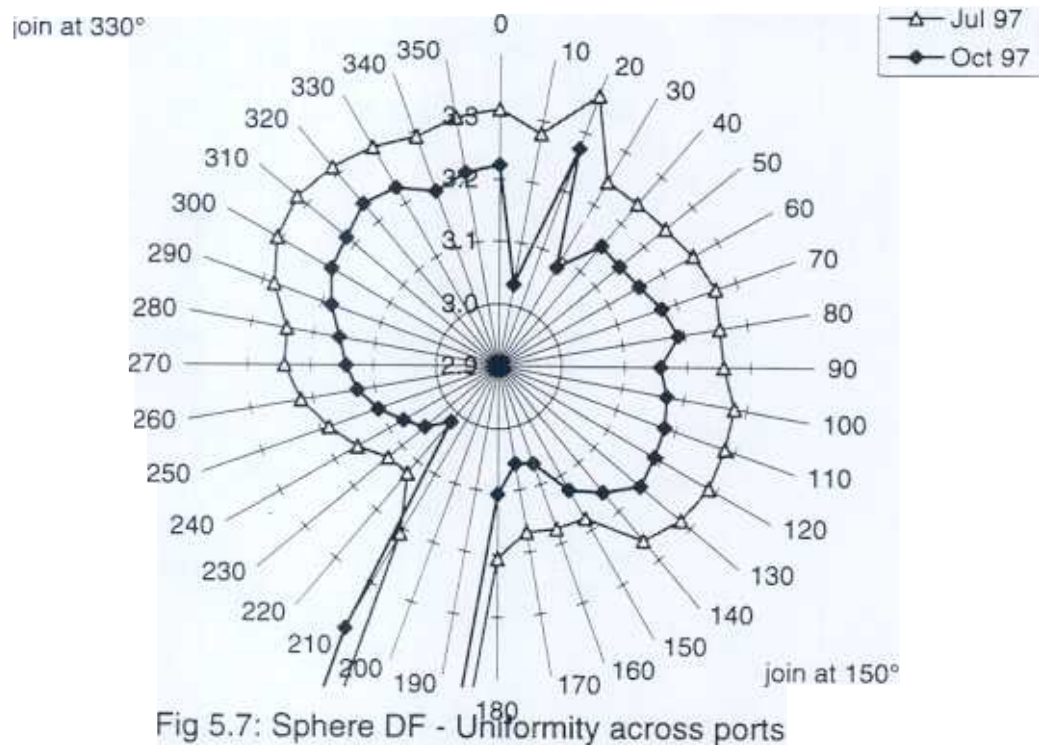
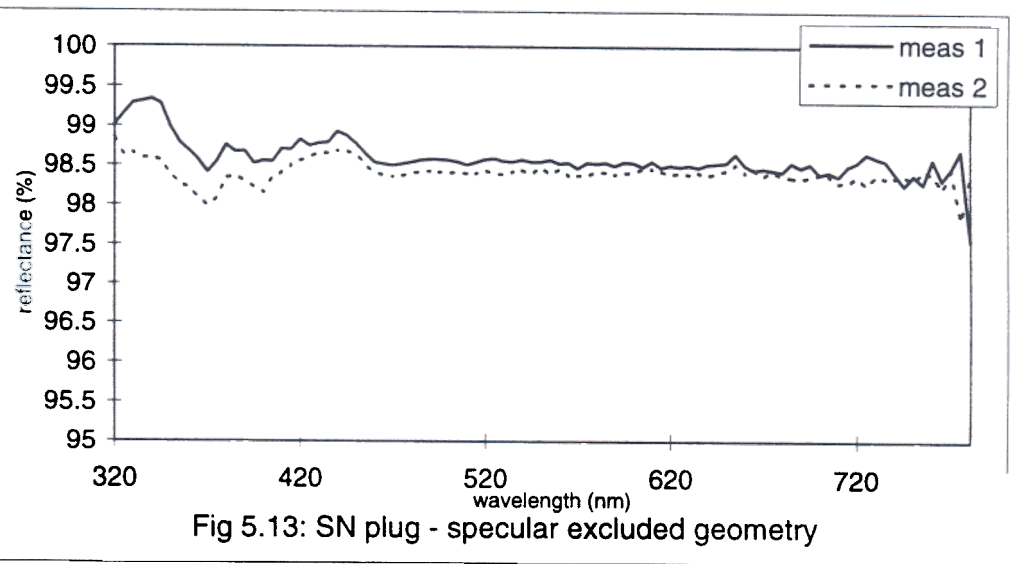
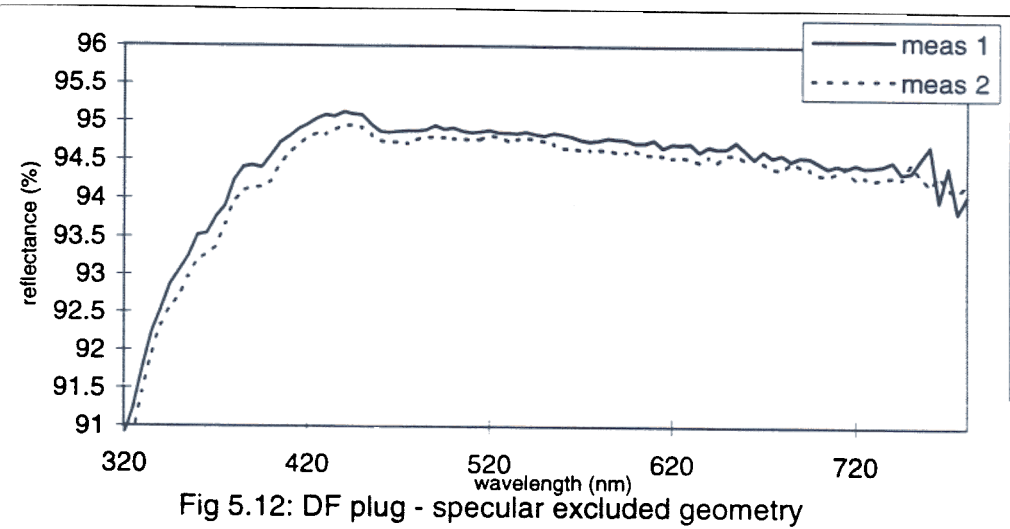
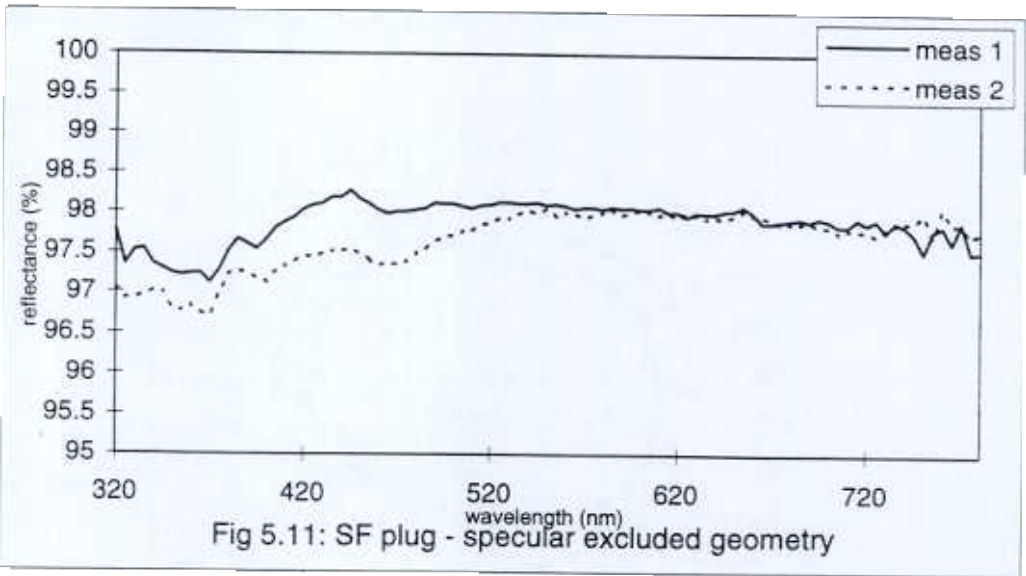


Fig 5.6: Sphere DF - Uniformity below ports





affected. Plugs SF and DF are painted samples and suffered some surface damage when mounted onto the sphere ports, whereas plug SN was not visibly damaged.

5.4 DISCUSSION

Spheres SF and SN were uniform to within 2% and sphere DF to within 6%. The major differences were between the two halves of the sphere in all cases. Sphere DF had the least uniform individual halves as well as the lowest throughput. Non uniformity of about 2% could lead to errors of a few tenths of a CIELAB unit when a matt sample is measured against a glossy standard.

Non-uniformity in the ratio values may be attributed to two factors: (i) differences in the reflection of the sphere coating at the point where the laser beam first hit the sphere wall and encountered its first reflection within the sphere and (ii) non-uniformity of collection due to the geometry of the ports within the sphere. As all three spheres were of the same design and were used in the same geometrical set-up, any geometrical effect would be present in the results for each sphere. The experimental set-up was also symmetrical in arrangement with respect to the ports so any effects would be replicated for each half (i.e. 180° scan) of the sphere with the ports defining a plane of symmetry. This division of the sphere into halves is geometrical and is distinct from the physical split where the two manufactured pieces are joined together. The results for the ratio value demonstrate variability in line with the position of the physical halves of the sphere rather than the geometrical halves. For spheres SF and SN geometrical effects may be the cause of the small decrease of the ratio value with height of scan within the spheres.

Storage in clean conditions caused no observable deterioration to the sphere uniformity over the three month time interval. As mentioned above, the ratio value cannot reliably be repeated with repositioning of the sphere with respect to the detector and no judgement can be made about changes to the reflectance of the coatings in this experiment. However, as figures 5.11-5.13 show, the plug ports did decrease slightly over the three month time period. The decrease in reflectance may have been caused by the damage to the surface but, conversely, the actual measurement area may not have been affected as the damage was restricted to a ring of the same diameter as the sphere port. Further measurements of the reflectance of different areas of the plugs should confirm which is the case. The plugs were made of the same material as the spheres and were stored with the spheres during that time and it is noteworthy that, despite the repositioning difficulties, all of the later ratio values are less than the earlier values. This may or may not be a real effect. Additional further work needs to be carried out to determine the effect of normal usage on the uniformity and reflectance of the coatings.

6. TEMPORAL INSTABILITY OF COLOUR STANDARDS.

6.1 REQUIREMENTS

BCRA-NPL Ceramic Colour Standards are used not only for calibrating colour measuring instruments, but also for determining the short and long term stability of these instruments (8, 9). However, studies of long term instrument stability are limited by a lack of knowledge of the long term stability of the colour standards themselves. It is often difficult to distinguish changes in measured values of the reflectance of the standards, due to changes in the instrument, from actual changes in the reflectance of the standards themselves. Small but measurable changes in the reflectance of some of the deep blue tiles have been observed at NPL. These changes amount to about 0.3% reflectance over a period of 5 years. They are associated with a slight crazing in the glaze which can be seen under a microscope. The effect has not been observed for the other tiles in the set. The determination of changes in reflectance of these standards requires an instrument capable of measuring changes in reflectance as small as 0.03% or less. It must also be possible to measure these changes directly and not relative to a white reflectance standard because of the need to distinguish changes in the tile from changes in the white standard. It should be stressed that an appropriate instrument does not need to be able to measure absolute values of reflectance to an uncertainty of 0.03%, only changes in absolute values of reflectance to within this uncertainty. This study gives the results of attempts to measure temporal changes in the BCRA-NPL colour standards on two very different instruments, neither of which proved ideal for the task. However, conclusions are reached as to the type of instrument that could be used successfully. It would need to be a dedicated instrument not used for other tasks.

6.2 EQUIPMENT

A commercial diode array spectrophotometer with an integrating sphere geometry and the Reference Reflectometer fitted with optics designed for gloss measurement were used. Both instruments were left for an hour to warm up prior to measurements. The samples were a set of twelve glossy ceramic colour standards, plus glossy black and white tiles. All the samples were measured on the commercial instrument. Seven tiles were measured on the Reference Reflectometer.

6.3 MEASUREMENTS

All tiles were cleaned with distilled water, left to dry for one day, then measured in the normal/diffuse specular excluded geometry on the spectrophotometer. A second set of measurements was made on the following day. A final set of measurements was made nine months later.

The tiles were measured on the Reference Reflectometer in the 0/45 geometry. Values of spectral reflectance factor were obtained with both s and p polarised light incident normal to the sample, and with the detector at 45° on either side of the sample normal. The mean of the four spectral reflectance factor values was converted to spectral radiance factor using an empirical normalisation factor based on data for a reference white standard. A repeat measurement of the tiles was made after six months.

The tiles were only cleaned once - at the very start of the project. In all cases the tiles were left to stabilise to room temperature for 24 hours prior to measurement.

6.4. RESULTS.

Spectrophotometer

Table 6.1 gives changes in spectral normal/diffuse percentage reflectance for the tiles over nine months as measured on the spectrophotometer. Results are presented in graphical form in Figure 6.1 The greatest contribution to changes on the slopes of non-neutral tiles such as the red and orange are probably due to thermochromism in the tile as the room temperature was 24.5 °C for the first session, and 23 °C for the second. The reflectance values have not been corrected for temperature.

Spectrophotometer Uncertainties

An assessment of type (A) uncertainty reveals a good repeatability of >0.01% for a white tile. Full estimation of type (B) uncertainty is not possible since it is not possible to distinguish between drift in instrument and change in the standards which would be used for such an evaluation.

Table 6.1: Changes in values of normal/diffuse reflectance over 9 months as measured by a spectrophotometer.

wl /nm	White	Black	Pale Grey	Mid Grey	Diff Grey	Deep Grey	Pink	Red	Orange	Yellow	Green	Diff Green	Cyan	Deep Blue
360	0.06	0.05	0.07	0.07	0.08	0.03	0.03	0.06	0.00	0.01	0.01	-0.01	0.01	0.04
370	0.05	-0.01	0.00	0.06	0.06	0.01	0.02	0.05	0.01	0.00	0.00	0.01	0.01	0.04
380	0.04	0.01	0.01	0.02	0.06	0.02	0.03	0.05	0.04	0.01	0.02	-0.01	0.03	0.02
390	0.09	0.01	0.09	0.05	0.06	0.00	0.03	0.06	0.03	-0.01	0.02	0.02	0.05	0.07
400	0.09	-0.01	0.05	0.04	0.03	-0.02	0.03	0.05	0.03	-0.02	0.01	0.00	0.02	0.04
410	0.09	0.01	0.04	0.03	0.05	0.00	0.02	0.08	0.03	0.00	0.02	0.02	0.06	0.07
420	0.10	0.01	0.07	0.05	0.05	0.00	0.02	0.05	0.02	0.01	0.01	0.00	0.06	0.06
430	0.10	0.00	0.07	0.05	0.04	-0.01	0.02	0.06	0.04	0.01	0.00	0.01	0.06	0.05
440	0.10	0.00	0.05	0.04	0.05	0.00	0.01	0.05	0.02	0.00	0.01	0.01	0.05	0.04
450	0.09	0.00	0.05	0.04	0.05	-0.01	0.00	0.05	0.02	0.00	0.01	0.00	0.05	0.04
460	0.09	0.01	0.05	0.04	0.05	0.00	0.00	0.05	0.02	0.00	0.02	0.02	0.06	0.03
470	0.10	0.00	0.04	0.04	0.05	-0.01	0.00	0.05	0.02	0.00	0.04	0.03	0.06	0.02
480	0.08	0.00	0.05	0.04	0.05	-0.01	0.00	0.05	0.03	-0.02	0.07	0.06	0.10	0.02
490	0.09	0.01	0.03	0.03	0.05	-0.01	-0.01	0.05	0.03	-0.01	0.11	0.10	0.11	0.02
500	0.09	0.00	0.03	0.03	0.05	-0.01	-0.01	0.05	0.04	-0.02	0.14	0.13	0.13	0.01
	0.09	0.00	0.03	0.04	0.05	0.00	-0.01	0.04	0.05	-0.01	0.14	0.12	0.13	0.01
	0.09	0.01	0.05	0.04	0.05	-0.01	-0.01	0.05	0.05	-0.03	0.13	0.10	0.13	0.01
	0.09	0.00	0.04	0.04	0.05	0.00	-0.01	0.05	0.09	-0.05	0.09	0.05	0.11	0.01

wl /nm	White	Black	Pale Grey	Mid Grey	Diff Grey	Deep Grey	Pink	Red	Orange	Yellow	Green	Diff Green	Cyan	Deep Blue
540	0.09	0.00	0.04	0.03	0.05	-0.01	0.00	0.05	0.24	-0.08	0.07	0.04	0.09	0.02
550	0.09	0.00	0.02	0.03	0.04	0.00	0.01	0.05	0.54	-0.10	0.05	0.01	0.06	0.02
560	0.08	0.00	0.03	0.05	0.05	0.00	0.01	0.05	0.73	-0.10	0.04	0.01	0.05	0.02
570	0.07	0.00	0.02	0.04	0.04	0.00	0.01	0.05	0.64	-0.11	0.03	0.00	0.03	0.01
580	0.08	0.00	0.04	0.04	0.05	-0.01	0.04	0.13	0.50	-0.11	0.02	0.00	0.03	0.01
590	0.07	0.00	0.04	0.05	0.05	-0.01	0.06	0.28	0.36	-0.12	0.01	-0.01	0.02	0.01
600	0.07	0.01	0.05	0.05	0.06	-0.01	0.09	0.44	0.29	-0.09	0.00	0.00	0.03	0.02
610	0.07	0.01	0.04	0.04	0.04	-0.01	0.12	0.52	0.25	-0.09	0.00	-0.02	0.02	0.01
620	0.07	0.00	0.04	0.05	0.05	-0.01	0.16	0.45	0.22	-0.08	0.00	-0.02	0.00	0.01
630	0.06	-0.01	0.05	0.04	0.04	-0.02	0.18	0.29	0.20	-0.08	-0.02	-0.03	0.01	0.01
640	0.06	0.01	0.04	0.04	0.05	0.00	0.20	0.17	0.19	-0.08	0.00	-0.02	0.02	0.01
650	0.06	0.01	0.04	0.04	0.04	-0.01	0.22	0.17	0.17	-0.09	0.00	-0.02	0.01	0.01
660	0.04	0.00	0.04	0.04	0.04	-0.02	0.21	0.17	0.17	-0.07	-0.02	-0.03	0.01	0.01
670	0.02	0.01	0.04	0.04	0.05	-0.01	0.21	0.18	0.14	-0.08	-0.01	-0.02	0.01	0.02
680	0.04	0.01	0.04	0.05	0.04	0.00	0.21	0.19	0.16	-0.08	-0.01	-0.03	0.02	0.03
690	0.05	0.02	0.05	0.05	0.05	0.01	0.19	0.19	0.14	-0.07	-0.01	-0.03	0.02	0.04
700	0.07	0.01	0.07	0.05	0.05	0.02	0.17	0.19	0.16	-0.06	-0.01	-0.02	0.03	0.08
710	0.05	0.02	0.06	0.05	0.03	0.03	0.16	0.20	0.15	-0.07	0.00	-0.01	0.04	0.15
720	0.06	0.00	0.04	0.05	0.05	0.04	0.13	0.17	0.15	-0.06	0.01	-0.02	0.04	0.23
730	0.04	0.02	0.05	0.06	0.04	0.03	0.11	0.14	0.14	-0.06	0.01	-0.02	0.05	0.30
740	0.04	0.01	0.04	0.05	0.04	0.05	0.09	0.14	0.12	-0.06	0.01	0.00	0.05	0.31
750	0.03	0.01	0.03	0.05	0.04	0.05	0.07	0.14	0.12	-0.05	0.01	-0.01	0.05	0.26

Reference Reflectometer

The differences in measured values of spectral 0/45 radiance factor over six months using the Reference Reflectometer are given in Table 6.2. Results are presented in graphical form in Figure 6.2. The greatest changes occur in the non-neutral tiles, and at 700nm.

Reference Reflectometer Uncertainties

Systematic uncertainty in spectral radiance factor for these measurements is in the range of 1-2%. The uncertainty in angle is $\pm 0.01^\circ$. The random uncertainty in spectral radiance factor rises from $\pm 0.2\%$ below 60° to $\pm 0.7\%$ at higher angles. The reported uncertainties are based on a standard uncertainty multiplied by a coverage factor $k=2$, providing a level of confidence of approximately 95%.

Table 6.2: Changes in measured values of 0/45 radiance factor over six months using the Reference Reflectometer.

wl /nm	white	black	mid grey	red	yellow	cyan	deep blue
409	-0.14	-0.06	0.04	0.21	0.08	0.09	-0.08
501	-0.23	0.00	-0.22	0.36	0.15	-0.05	0.05
568	-	-	0.04	0.15	-	0.05	-
600	-0.43	-0.04	0.09	0.41	-0.17	-0.03	0.07
700	-0.11	0.31	0.27	-0.55	-0.13	-1.13	0.62

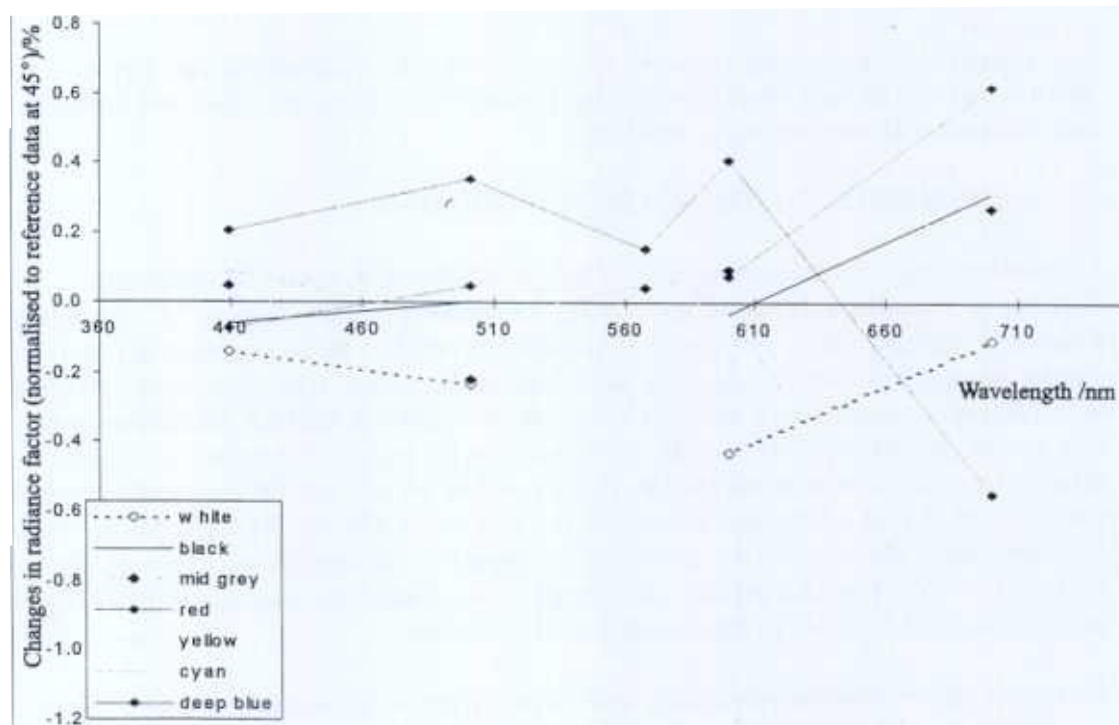
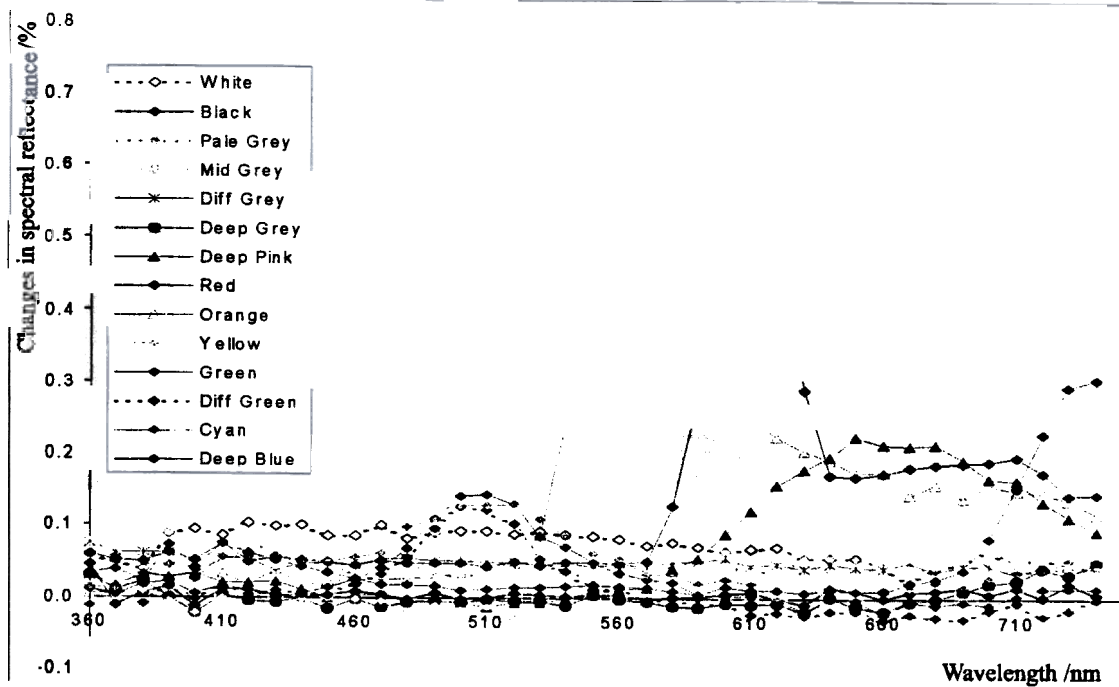


Figure 6.2: Changes in results of White, Black and CCS tiles measured on Reference Reflectometer over 6 months. 0/45 geometry.

6.5 DISCUSSION

The results from the spectrophotometer show changes in measured reflectance values of up to 0.73%. However, it cannot be inferred that any of the observed changes are definitely due to changes in the tiles themselves. The biggest changes are almost certainly due to thermochromism, the change of colour with temperature. Other changes in measured values could be due to instrument changes such as ageing of the integrating sphere, ageing of the lamps and movement of the spectrum relative to the diode array detector, or possibly environmental effects such as sensitivity to humidity changes, a subject that has yet to be investigated. It has been shown that the effects of thermochromism can be corrected for when the relevant coefficients are known (8, 9, 10), but this still leaves all the results of other potential sources of change to be distinguished from any actual changes in reflectance of the tiles themselves.

The results from the Reference Reflectometer show changes of up to 1.3%. If this were a real effect, it would correspond to errors in the region of 0.5 CIELAB units. However, again it cannot be inferred that any of the observed changes are definitely due to changes in the colour standards themselves. The main difficulty with this instrument is that it is used for several different tasks such as realisation of scales of spectral diffuse reflectance, measurement of gloss, and measurement of turbidity. These require changes to the incident and reflected optical beams, and also to the method of wavelength selection. This is far removed from the ideal for measurements of stability where there should be the minimum number of changes between measurements. It is never possible to reproduce exactly the settings of components once they have been moved.

The results of the measurements demonstrate the limitations of currently available instruments. It has not been possible to demonstrate changes in the reflectance of the tiles with instrumentation currently available.

6.6 THE NEED FOR A DEDICATED INSTRUMENT

A dedicated instrument is needed to measure changes in the reflectance of the BCRA-NPL Ceramic Colour Standards. This would incorporate some aspects of the design of the Reference Reflectometer. However, it would not need to be as complex an instrument as it would be used for only one task and would be much less expensive to develop. The measurements would only need to be made at a limited number of wavelengths, perhaps five or six. Measurements would only need to be made at a small number of angles of reflectance and at normal incidence. Rotary tables would not be essential. The light source would probably be a tungsten lamp and the detector a silicon cell. Relocation of the detector and samples is likely to be the most critical aspect of the design but it should be possible to achieve this with good kinematic mountings. If necessary, an optical alignment system could be incorporated in order to check and adjust relocation.

An investigation into the possibility of changes in reflectance with humidity is also required.

7. SOURCES OF COLORIMETRIC ERRORS

A list of sources of error in colour measuring instruments was given in Section 2. A summary of the current understanding of these is given here.

7.1 DIFFERENCES IN NATIONAL SCALES OF DIFFUSE REFLECTANCE AND RADIANCE FACTOR

Some years ago the national scales of diffuse reflectance of the USA, Canada and Germany agreed to within $\pm 0.1\%$ (11). About four years ago questions were raised, particularly from the paper industry, as to whether this level of agreement was still maintained. Subsequent investigations showed that the scales of Canada and Germany had diverged due to changes in the uniformity of integrating sphere coatings and other factors relating to wavelength selection. Following adjustments to the instrumentation realising the national scales of diffuse reflectance, the agreement between the scales of Canada and Germany has been restored.

Diffuse reflectance is the ratio of the diffusely reflected light to the incident light. Reflected radiance factor is the ratio of the light reflected by a sample in a given direction to that reflected by a perfect diffuser in the same direction for the same conditions of illumination and viewing. There has not, as yet, been a published international intercomparison of reflected radiance factor.

NPL has not yet realised scales of absolute diffuse reflectance and radiance factor although this will be done in the near future. Until now the scales used by NPL have been received from other national standards laboratories. After realising UK scales of diffuse reflectance and radiance factor, NPL intends to use international mean scales rather than UK national scales, for traceable calibrations, as this is likely to lead to greater international uniformity and stability of scales of measurement, especially for surface colour.

7.2 LACK OF TRACEABILITY TO NATIONAL STANDARDS

Part 1 of this study showed that half the colour measurements in UK industry are not traceable to national standards (12). NPL has anecdotal evidence that some companies who believe they have traceability are using uncalibrated standards and therefore do not have traceability. Part 1 indicated the need for improved education on traceability and accuracy of colour measurement.

7.3 ERRORS ASSOCIATED WITH TRANSFER STANDARDS

Thermochromism

All chromatically coloured materials change colour with temperature. Although the changes are usually fairly small they can be of significance in industries where the supplier and purchaser are in different climatic zones with very different temperatures in the workplace. For the most saturated colours, orange, red and yellow, the coefficients of thermochromism are usually in the region of 0.1 CIELAB units per $^{\circ}\text{C}$ (10, 13). Differences in working temperatures of 10°C between supplier and purchaser can occur, with consequential

differences of colour of 1 CIELAB unit. There have been requests for standards of lower thermochromism. Anomalous samples suggest that a lower figure of 0.03 CIELAB units per °C may be feasible but with some loss of saturation of the colours (13). However, improved standards will not eliminate the problem of thermochromism as manufactured goods still have the original coefficients of thermochromism.

Translucency

Diffusion of reflected light can occur at the surface or inside the body of the material. For samples with glossy surfaces almost all the diffusion is within the body of the material. Translucency is the diffusion of light within the material. Translucency can affect the measured reflectance value in two ways. Firstly light can penetrate through the material so that the measured reflectance depends upon the backing material, if any. For such samples it is usual to define the backing material as a white or a black material. Secondly light can spread laterally inside the material so that not all the reflected light enters the sample port of the instrument. Materials which present problems include some used for white reflectance standards (2). The problem can, in principle, be solved by designing the instrument to have a sufficiently large gap between the edge of the sample port and the area of the sample from which light is collected. However, this does lead to a loss of signal. Some measuring heads give significant measurement errors due to translucency when used with some materials. The problem is particularly acute where the area of sample from which light is collected is small. There is no recommended method for measuring and quantifying translucency and research is needed to establish one.

Temporal instability of colour standards

Almost all measurements of diffuse reflectance are made relative to white reference standards. The latter should be traceable to an absolute measurement of diffuse reflectance (which constitute the small minority of measurements of diffuse reflectance). Although changes are noted in the results of measurements of diffuse reflectance, they are almost always followed by an argument (usually unresolved) as to whether the observed change was due to a real change in the diffuse reflectance of the standards (white or coloured) or is an error in the measurement due to a change in the instrument. Temporal changes in light sources, integrating sphere coatings and wavelength scale errors can all lead to errors in the measurement of diffuse reflectance and surface colour (8, 9).

The measurements of the temporal stability of surface colour standards and diffuse reflectance standards suggest a need for the development of new types of instrument which eliminate as many as possible of the sources of instrument drift and allows direct quantification of the remaining sources of drift.

7.4 THE EFFECT OF FIELD SIZE ON MEASURED AND PERCEIVED COLOUR DIFFERENCE

The CIE has recommended separate Standard Observers for 2° and 10° fields of view (3). According to the CIE system of colorimetry, pairs of coloured samples which are a metameric match for the 10° field of view will not be a match for the 2° field of view. Experimental work detailed in this report indicates some agreement between visual results and CIE values for the 10° condition but not the 2° condition. However, full consideration of

the selection of observer has been taken into account in the writing of specification standards for measurement of colour in particular situations. The use of the 2° observer should be discouraged for uniform coloured materials and the 10° observer specified. This is another example where better education is needed.

7.5 DIFFERENCES IN INSTRUMENT GEOMETRIES WITHIN THE SPECIFIED LIMITS

The CIE recommendations included specifications of geometrical tolerances (3). These were last revised in 1986. Some have suggested there is a need for tightening these tolerances or for bringing them more closely into line with current practice. An example of the former is the generous tolerance for angular ranges associated with the 0°/45° and 45°/0° geometries. An example of the latter is the use of an 8° angle of reflectance for the diffuse/normal geometry. (The tolerances allow a departure of 10° from normal. However, if 8° is widely used better inter-instrument agreement might be achieved if $8^\circ \pm$ (say) 2° was specified instead of $0^\circ \pm 10^\circ$. The situation requires practical investigation using gonireflectometry. This report includes a limited study using white reflectance standards which showed that within the limits of uncertainty, there is no difference between measurements made using illumination normal to the sample surface, and illumination at 15° to the normal. More studies using a wider range of samples and standard materials are required.

7.6 MEASURING HEAD ERRORS

Non uniformity of integrating spheres

The assumption is often made that all rays of light entering an integrating sphere are collected with the same efficiency. In fact studies at NPL including those reported in this document, using a laser probe, demonstrate variation in efficiency of collection with angle of reflectance from the measured sample (6, 7). This can cause systematic errors in the measurement of matt or textured samples against a glossy white reflectance standard. Investigations using a laser probe are at an early stage and much more work is needed.

Time dependent changes of integrating spheres

Integrating sphere coatings are not completely stable with time. The reflectance can fall with time and if the fall is greatest in the blue region, yellowing of the sphere coating will occur. Contamination of spheres with dust is also a common problem and leads to non uniform changes in reflectance. Problems due to non uniformity of sphere coatings in the realisation of absolute scales of diffuse reflectance have been recognised for some years and corrections applied. However, the subject requires further research particularly into the ageing of integrating spheres of the types commonly used in commercial instruments. This report includes a preliminary study on this subject.

Gloss trap errors

This has been investigated in Workpackage 3 of the project using methods developed some years ago at NPL (14, 15). The system for measuring and correcting gloss trap errors requires transferring to industrial instruments.

Specular beam errors

This subject has also been investigated in Workpackage 3 of this project (14). The system for measuring and correcting these errors used at NPL also needs to be transferred to industry.

Polarization errors in 0/45 instruments

This subject has not been well researched, although the current European Community project "Harmonisation of National Scales of Surface Colour Measurements" (16) coordinated by NPL includes such a study. The problem is that the reflected radiance factors, particularly at 45°, can vary significantly with polarization. If the instrument has a polarization bias then a systematic error will occur. There are obvious solutions to this problem such as making measurements in two planes of polarization and taking the mean. However, this would increase the cost and time taken for making measurements. The subject needs further study to establish the significance of errors and the case for making improvements to instruments.

7.7 ERRORS IN THE INSTRUMENT PHOTOMETRIC SCALE

Some instruments fail to give a correct zero reading. However, the better instruments use a well designed light trap for setting a true optical zero. Thus the correct technical solution to this problem is already being applied by industry but not universally.

Another problem that can arise is that of optical detectors which give a signal not directly proportional to the incident light, the non-linearity error. Results at NPL have confirmed this effect for some instruments. However, currently available data suggest that the problem is not a major one although further data are needed. The current European Commission project "Harmonisation of National Scales of Surface Colour Measurements" (16) includes a study of non-linearity errors.

7.8 WAVELENGTH ERRORS

Wavelength errors are relatively simple to measure on scanning spectrophotometers using internal spectral lamp sources. However, the accuracy of determination can be limited by the mechanical details and alignment of the grating turntable. Fourier transform methods in which the peaks of absorption bands of a crystal are determined, followed by the crystal being used to calibrate the spectrophotometer, offer the potential for improvement.

However, spectral lamps and crystals are not suitable for calibrating the wavelength scales of diode array spectrophotometers. Although scanning spectrophotometers are often preferred in research laboratories for their greater degree of versatility, diode array spectrophotometers have become very widely used in industry for colour measurement because of their capability for rapid measurement in the workplace. Currently available ceramic tiles are often used to calibrate wavelength scales on diode array spectrophotometers but wavelength errors can be easily confused with temperature effects. A simple unambiguous method for calibrating the wavelength scale of diode array spectrophotometers is not yet available and research needs to be conducted to establish such a method.

7.9 ERRORS DUE TO FINITE BANDWIDTH AND DIFFERENCES IN COLOUR DATA DUE TO DIFFERENT METHODS OF CALCULATION FROM SPECTRAL DATA

The majority of commercial colour measuring spectrophotometers use a measuring interval of 10 nm or 20 nm. The bandwidth is usually slightly smaller than the measuring interval. Scanning spectrophotometers frequently use a measurement interval of 5 nm although larger and smaller intervals can be easily accommodated.

The effects of these differences in interval and bandwidth can be greatly reduced by the use of weighting functions in the colorimetric computations. However, not all manufacturers use the same weighting functions. The colour data from the NPL Spectrophotometry and Colorimetry intercomparison of colour measurements has been recalculated using common weighting functions in Workpackage 3 of this project (14) and the improvements in agreement between results from participants quantified.

A universally used system of weights is required. This is a problem for specification standards committees. The best candidate at present appears to be the ASTM set of weights (17) although some clarification on the use of alternative sets of tables within the document is required.

8. CONCLUSIONS

This report gives the results of a series of investigations into colorimetric errors. All of these are of a preliminary nature. Many of the results are tentative and indicate the need for further work to give definitive answers.

The study on the effects of field size tends to confirm the predictions of the CIE system for the 10° field within the experimental limits. For the 2° field the visual magnitudes of colour differences are more difficult to assess and therefore the predictions of the CIE are more difficult to verify. There is a need for a finer grey scale in order to achieve results of higher accuracy. Where colour measuring instruments are used to measure colour differences between large uniform areas of colour, then the 10° Standard Observer should be used in preference to the 2° Standard Observer.

The study on integrating sphere uniformity shows that the spheres do not collect all rays with equal efficiency. The biggest differences observed are between the two halves of the spheres. The results on the reflectance of plugs on the integrating sphere walls show small decreases with time but the differences are close to the experimental precision and the measurements need to be repeated over a much longer period of time. Studies of the stability of integrating spheres by direct measurement require a more stable laser probe. Problems with non uniformity of integrating spheres and changes with time have led to difficulties in the maintenance of scales of absolute diffuse reflectance by national laboratories. The scales of absolute diffuse reflectance and 0/45 radiance factor currently being realised by NPL do not use an integrating sphere but a gonireflectometer. However, integrating spheres will continue to be widely used for industrial measurements because of the relative simplicity of construction and efficient use of available light.

The CIE recommended geometries for colour measurement are based on either normal incidence or normal viewing. However, the majority of high quality commercial colour measuring instruments use an angle of about 10° rather than a zero angle. There is thus a case to be considered for a specification centred on a 10° angle (or thereabouts) rather than a zero angle. The results from experimental measurements reported here suggest a small difference on diffuse reflectance for ceramic colour standards between normal (0°) incidence and a 15° angle of incidence. The measurements need to be repeated a higher accuracy and on a wider range of materials.

The stability of surface colour standards has still to be quantified. Dedicated equipment is needed for this.

The number of sources of colorimetric error is large, greater than 10. There is a need for a reduction in uncertainties by at least a factor of 2. At NPL, the aim is to reduce uncertainties for absolute colour measurements from about 0.6 CIELAB units to 0.3 CIELAB units. Improvements in the uncertainty of absolute scales of diffuse reflectance and 0/45 radiance factor are fundamental to this. However, the number of different sources of systematic uncertainty is large and, at higher levels of accuracy, none of them can be said to be dominant. Therefore all of them need to be reduced in order to reduce the total uncertainty of measurement.

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