3
Instrumental colour measurement

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3.1 Introduction

Colour measurement instrumentation is very varied. It varies from large top of the range scanning spectrophotometers, maybe coupled with reflectance accessories through bench-top instruments, to hand-held small portable instruments. The instrumentation may be set up to make a variety of different colour measurements or to only make measurements on one particular colour scale.

Colour measurements are essentially measurements of visible light shining through an object or visible light reflected from an object. There are many optical configurations to achieve the measurement of transmitted and reflected colour. There are standard or recommended geometries for making these measurements and nomenclature for describing them and the variations that are possible.[1] The choice of measurement geometry usually depends on the properties of the artefact to be measured, but may be due to historical use within a particular industry or product area. There are colour measuring instruments available that can measure transmitted colour, reflected colour or both.

3.2 Types of colour measurement

Colour measurement divides into two areas, reflectance and transmittance. Each of these can be further divided into diffuse and regular. Regular means the light travels through undeviated or is reflected off the sample in a mirror-like way without change of frequency, and diffuse means that the light is scattered as it is reflected by, or transmitted through, a sample, again without change of frequency of the light. The total reflectance or transmittance is the sum of the regular and diffuse parts. The geometry of illumination and detection with respect to the sample is used to define the measurement geometry. Reflectance and transmittance are defined in terms of the ratio of the incident light to the reflected or transmitted light. These are special cases of the more general definitions of radiance or luminance factor, which are defined in terms of measurements made for a specific illumination and detection geometry in comparison to the perfect reflecting diffuser identically illuminated.

3.2.1 Regular reflectance

Regular reflectance is the regularly reflected or specular component of the illumination, i.e. light that is reflected in a mirror-like way off a surface at the same angle and in the same plane as the illumination beam. It usually has the same spectral profile as the illuminating source. When measuring colour with an integrating sphere, this component is either included or excluded from the measurement. It is not usual when making colour measurements to measure this component separately, as it has the same spectral profile as the illumination. Regular reflectance is usually only measured on its own when the sample has a very high regular reflectance, such as a mirror.

3.2.2 Diffuse reflectance

Diffuse reflectance is probably the measurement that most people think of when referring to colour measurement. This is measurement of light scattered from a surface and is most commonly measured using an instrument incorporating an integrating sphere. Quite often, the measurement referred to as diffuse reflectance by some users is not strictly the diffuse reflectance, but includes the regular component and is actually the total reflectance. The simplest measurement geometry is illumination at the sample normal or near normal and detection over the whole hemisphere, but excluding the regular or specular component. The instrumentation could also be set up the other way, due to Helmholtz reciprocity and the reversibility of light paths, with diffuse illumination and detection at the normal or near normal. For reflectance measurements, the trade-off is between light level and the ratio of the sphere surface area to total port area. The more ports and/or the bigger the ports in a sphere, the larger the sphere needs to be. The CIE has recommended that the total area of ports in a sphere should be less than 10% of the total surface area.[2]

3.2.3 Regular transmittance

Regular transmittance is light that is undeviated as it passes through a sample. The sample may attenuate (absorb) the light but the direction is not changed. This is the normal type of light transmission such as looking through a clear pane of glass.

3.2.4 Diffuse transmission

Light that does not pass through a sample in a regular way is diffuse transmission, i.e. the light direction has been changed. An example of this is the covers to lamps that spread the illumination over a larger area than would be possible without them.

3.2.5 Radiance factor and transmission factor

Radiance factor and transmission factor are the fundamentals of the reflectance and transmittance measurement geometries, as the others can be made up from a series of radiance or transmittance factor measurements. At its simplest, the radiance factor refers to illumination of a sample in a specific direction, over a specific angular range, with detection at another specified direction and angular range. The most common colour measurement geometry of this type is illumination at the normal (0°) to a sample with detection at 45° to the sample normal (or vice versa).

3.2.6 Geometries of measurement

There are endless ways of arranging the optical system to make colour measurements. The colour of a sample varies, depending on the way it is measured. A sample may reflect differently depending on the illumination angle, whether the sample is translucent, the state of polarisation of the illumination, the detection angular range, the way the detector measures the reflected light, etc. For example, illuminating a sample from a particular direction may not give the same result as illuminating it from all directions equally (diffusely). For measurements made on the same sample on different instruments to be comparable they have to be made in a consistent way with regard to geometry, and also with respect to other parameters such as traceability, orientation, polarization, etc. To this end the CIE[1] recommends the use of three reflectance measurement geometries: specular included, specular excluded and 0°/45° and their reciprocal geometries. They have recommended geometric arrangements for directional, conic and integrating sphere illumination or influx angles, and detection or efflux angles. The beam cone sizes, and their tolerances are defined along with descriptive nomenclature for the measurement geometry. Use of these geometries is not mandatory but it makes sharing and comparing measurements with others a possibility.

3.2.7 Sample-induced effects

Some samples will introduce other effects that make colour measurement difficult in a conventional way. These effects included translucency – the sideways spreading of light; fluorescence – emission of light at a different wavelength from the incident light; metallics – metal flakes within a surface coating that have mirror like properties, but are orientated parallel to the sample surface; interferometric effects – the colour is different depending on the illumination and viewing conditions. All of these are difficult to measure in a conventional manner with an integrating sphere or by using a single angle geometry. There are instruments available that can alter the angles of illumination and detection so that they can measure many combinations to build an overall picture of the sample.

3.3 Colour measuring instrumentation

There are many reasons for wanting to measure colour, but it is important to have a colour measuring instrument that will measure what is required with the necessary accuracy. Firstly, the user needs to determine what the instrument specification is for the task. This may mean defining the spectral range, the data interval, the bandwidth, the colorimetric data required, the measurement geometry, the measurement area, the accuracy, the precision, the traceability, reference artefacts, software, export of data options, etc. There may be a specification to meet in terms of measurement geometry, measurement area/instrument port size. Usually, the type of samples that are being measured will define the most suitable measurement geometry, but standards and common usage within certain industries will also have an influence. The CIE recommend measurement geometries[1] and parameters for port sizes and other geometric considerations.[2] ASTM also recommends geometries for colour measurement, especially for single colour scales.[3] Special effect/appearance materials will need careful consideration as to the choice of a suitable measurement instrument.

Precision is a measure of how well an instrument repeats a measurement. Accuracy is a measure of how well the instrument will make measurements compared to particular standard reference materials, which should be traceable to a national standards laboratory (see later section for more details). The instrument may come with a calibration artefact traceable to a particular national measurement institute. There may be differences in scales between national measurement institutes so the users need to be aware of the traceability route of their instruments and any with which they are comparing measurements.

3.3.1 Single-scale instruments

These are instruments that are primarily for measuring a specific colour measurement scale, in order to ascertain where the sample lies on the scale. These types of instruments are used in medicine, chemistry, manufacturing control, food processing, etc. Examples of scales and the regulatory body defining the scale are: edible oils – American Oil Chemists' Society (AOCS), honey – mm Pfund, maple syrup – USDA, Vermont Department of Agriculture, and Canadian; fruit juice such as apple, pear, white grape – International Fruit Juice Union (IFU), platinum–cobalt/hazon – water quality, solvent quality, beer – European Brewing Convention (EBC), colour – Gardner, Saybolt, ASTM colour, etc. These types of instruments are usually associated with measurements of a specific product such as petroleum, honey, beer, oil and chlorophyll. These are designed to assess the quality of a particular product by linking colour to purity, refinement level, impurity indicator, desirability, etc. Many of these instruments measure the colour of a liquid or require the product, e.g. waxes, to be measured in a liquid form. The most common instruments for this type of measurement are those from Tintometer Ltd such as the Comparator 2000/3000, PFX195, PFX880 and PFX995. Many of these instruments incorporate calibrated colour standards or come with calibrated reference materials for the particular scale of interest, and can be operated as a stand-alone instrument or as a computer-controlled instrument.

3.3.2 Visual instruments

Visual instruments are usually of a comparative nature. They allow a sample to be viewed under the same conditions as a reference artefact or artefacts and the user determines if they are a match. The most common of these would be a simple light box, which usually has neutral grey walls, and a choice of light sources designed to simulate recommended sources. The reference and the test samples can be viewed side by side. This is how the textile industry used to do much of its colour matching. Alternative instruments are those such as The Tintometer model F, for visual assessment of transmitting samples using the Lovibond RYBN scale.[4] A light source and white diffuser provide the illumination, with the viewing being done through an eyepiece. A bipartite field is presented to the user. The test sample is placed in one side of the field and the user moves neutral, red, blue and yellow glass filters into the other half of the field to match the colour. The filters used will indicate the colour in terms of Lovibond units. Other instruments act as comparators and glass discs of values of the single colour scales mentioned above can be rotated into place to match the sample.

3.3.3 Hand-held/portable instruments

Hand-held instruments come in a variety of types, from small spectrophotometers to much simpler colourimeters. Generally, these are small instruments, measuring a small area. They have the advantage that they can be taken to the object to be measured instead of bringing the sample to the instrument. This means that finished products such as cars, vehicle interiors, large objects and interior decoration can be measured *in situ* without the need to remove samples for testing. The disadvantage of these types of instruments is that there are compromises in measurement performance in order to achieve portability. Sphere-based instruments will generally have a smaller size sphere than the benchtop equivalent, functions available may be more limited, and data resolution is likely to be lower. If the user has a held-hand colorimeter, it may be limited to certain illuminants and observer combinations for colorimetric data. However, many have the capability to store a large number of measurements, for downloading later to a computer.

The measurement uncertainty from one of these instruments is almost certainly higher than a larger benchtop instrument because of these factors. In some cases the measurement geometry available is not truly one of the recommended CIE geometries, but a compromise between these and realising a practical result. So long as the user is aware of the limitation, this type of instrument is more than adequate for a lot of colour measurements.

Example instruments are Minolta spectrophotometers and colorimeters; some of these can be used to obtain displays as well as other measurements. Tintometer and X-Rite have a range of portable 0°/45° and integrating sphere instruments. Aventes produces the Ava-mouse, which plugs into a computer and has a similar shape and size to a computer mouse, but gives 45°/0° data.

3.3.4 Multiangle instruments

Multiangle instruments have a lot of the features of other instrumentation, but offer several fixed angle geometries, rather than just 0°/45° or a sphere-based geometry. They are an attempt to measure appearance or special effect samples. By looking at their properties at several angles, the user can pick out the best angles for meaningful results on the sample types being investigated. These are a cheap alternative to goniometric measurements. One popular instrument of this type is the X-Rite MA68, measuring at five detection angles, and variants which have found favour with the automotive industry as they can provide useful results on metallic paints.

3.3.5 Benchtop instruments

Most of the colour measuring instrument manufacturers sell more instruments of this type than any other. For reflectance measurements, these instruments generally incorporate diode array detectors in their optical systems. The light source is generally a xenon flash tube. Because of these features, measurements can be made very rapidly. Some are quite sophisticated in that they have double gratings and arrays in them, one viewing the sphere wall or reference and the other the sample, enabling them to compensate for the light source. Others achieve this by using one array with moveable optics and two xenon flashes, one for viewing the sample and the other for viewing the sphere wall or reference. The geometry of these instruments is usually in the alternative configuration from scanning instruments. Bench-top instruments usually have diffuse or directional illumination with detection at the normal or near normal, e.g. *d*/8° geometry.

Bench-top instruments are mainly set up to perform comparisons of one sample against a reference, for example, in a dye house for matching a production sample to the required reference colour. The software allows for easy comparison of samples and references. Tolerances on the closeness of colour match can be set to the user's requirements.

For reflectance instruments the data resolution may vary from 5 nm at the top end through 10 nm to 20 nm. The spectral range available is also variable. All spectral instruments will include the range 400 nm to 700 nm, but the better instruments will offer wavelengths outside this range, down to 360 nm and up to 780 nm. For transmittance instruments measurements in the range 200 nm to 800 nm plus will generally be available with at least 1 nm resolution. Spectral range and resolution are important for the type of samples to be measured. Those with sharp or rapidly changing features will require more point measurements to avoid features being smoothed out or missed.

Bench-top reflectance instruments are usually supplied with a white reference standard. The user needs to be aware as to where it is traceable to. The instrument should also come with a good black reference that approximates to zero – a black trap for integrating sphere geometries and a black glass for 0°/45° geometry.

Typical manufacturers are Datacolor, GretagMacbeth, X-Rite, Tintometer and Analytik.

3.3.6 Scanning instruments

Scanning instruments are the most complex of the colour measuring instruments available. They require the user to have a good knowledge of the type of measurements they wish to take. The user is able to have control of, and set, a large range of parameters, and may be able to set some parameters such that the measurement made is nonsense or highly distorted, for example, a high scanning speed coupled with a long measurement time on a sample with a lot of spectral structure. What scanning instruments do allow is the expert user to change parameters such as bandwidth, scan speed and wavelength interval, to suit the type of sample being measured. Scanning instruments are slower than other types of instrumentation, but they offer wider spectral ranges, such as into the UV and NIR, which may not be useful for colour measurement but may be useful for other applications or research.

These types of instruments have the potential to offer the highest accuracy and precision of all the commercially available instruments. They are available in double beam and single beam options, the double beam generally giving more stable results as they compensate for fluctuations in the light source. These instruments are primarily designed for regular transmittance measurements; examples are available from Perkin-Elmer, Varian, Shimadzu, Thermo (Unicam) and Hitachi, among others. For diffuse reflectance and diffuse transmittance measurements, it is usually possible to buy a standard or custom reflectance accessory, either from the instrument manufacturer or from a specialist supplier such as Labsphere. These accessories either replace the regular transmittance accessory or can be fixed into place on the transmittance accessory or fit inside the transmitting sample compartment. The results obtained are usually just the spectral data. The processing of the data to correct its traceability and calculation of the colorimetric data may not be possible with the instrument manufacturer's software, but may need to be done outside of the instrument software or by purchasing special software.

3.3.7 Goniometric instruments

Goniometric instruments are the most exciting instruments and more will become available in the future. These instruments allow light to be put onto a sample at a wide variety of angles, and then detected at a wide variety of angles, quite often over the hemisphere. This makes this type of instrument very useful when measuring special effect samples, as the best parameters in terms of illumination and detection can be chosen by the user. These instruments are very versatile, but also require a lot of specialist knowledge to operate them. Some of this type of instrument are self-built and operated by national standards laboratories. Such instruments included the STARR at NIST and the reference reflectometer at the National Physical Laboratory (NPL). The operation of these instruments can be quite time consuming. Faster commercial instruments are available from Murakami in Japan,[5] and Tintometer have developed a gonio apparent spectrophotometer (GASP), the first one being for NPL, UK.[6]

3.3.8 Camera

Cameras are a growing area for colour measurement. A camera is used to view a sample with the red (R), green (G) and blue (B) values being evaluated and used to generate colorimetric data. The advantage of a camera is that an image can be taken and colorimetry conducted throughout the image on a pixel-by-pixel basis. This relies on a good light source approximating to a standard illuminant and some good camera characterisation to map the *R*, *G* and *B* values to *X*, *Y* and *Z* colour functions. The advantage of this is that small sample areas, or samples that are non-uniform, can be measured. There are systems available that can do this: basically a lightbox with light sources for one or more standard illuminants. The illumination can be arranged to approximate to a standard geometry. The sample is placed in the light box and then viewed by the camera. Usually a test target, such as one of the Macbeth colour checker charts, is used to calibrate and characterise the camera. Associated software will control the calibration and measure the sample under test. These systems are well suited to measuring products that are variable and consist of multiple similar items, for example foodstuff such as cereals. The camera can be combined with software to pick out individual samples, and makes it possible to discern the variation in the product.

One of the systems available – DigiEye,[7] in addition uses algorithms based on colour inconstancy indexes to compute a synthesised reflectance spectrum for the test sample, which has a stable colour across several standard illuminants. Texture and gloss measurements can also be made by using only one of the pair of lamps for each illuminant, resulting in a directional illumination. This provides a shadow, and software can analyse the pattern of light and dark pixels to provide texture and gloss information. Another camera system is Tintometer's CAM 500 system for colorimetry and product colour quality control.

3.3.9 Custom instruments

Custom instruments include any system that does not readily fall into the other categories. It could be a home-built system, such as at a national standards laboratory, a commercial system with user specified enhancements or it might be a system for measuring a specific product on-line. These types of systems are usually put together from a variety of standard components, but integrated with custom software, etc.

3.3.10 Fluorimeter

This instrument is specifically designed to get round the problems of measurements on fluorescent samples without using standard illumination sources. True fluorimeters are able to illuminate and detect independently, by using two monochromator systems, or filters in such a way that the fluorescent component can be separated from the normal reflectance or transmittance component. The overall colour for any observer and illuminant combination can then be calculated

3.4 Inter-instrument agreement and traceability

Agreement and traceability are important issues for the user who has several colour measuring instruments or who wishes to share or compare measurements with another user's instrument. If the user has several identical instruments from the same manufacturer purchased at the same time, they should agree with each other. If they are different models or have been purchased over a longer time period, the probability of good agreement is much less.

The instruments to be compared should have the same geometric specification for there to be a chance of agreement. Then the two instruments need to be traceable to the same measurement scale. Traceability refers to showing an unbroken link from a scale disseminated by a national measurement institute, such as NPL in the UK, NIST in the USA, BAM in Germany, etc., to the scale the instrument is using, with an appropriate uncertainty statement. The scales disseminated by the national measurement institutes are the most accurate, with the lowest uncertainties. As the scale is disseminated downwards, each level adds a further degree of uncertainty.

For two instruments from the same manufacturer, the scale to which they are traceable is likely to be the same. Most manufacturers have a master instrument to which all the instruments they produce are compared, and this instrument in turn is traceable to a national measurement institute.

However, there are, at the time of writing, differences between national measurement institute scales of reflectance, and scales from national measurement institutes can change with time. National measurement institutes compare their scales with each other, work to understand the causes of differences and then try to minimise these differences in their scales.

The best way to check that instruments are traceable to the same scale is to use an independent check, rather than relying on the scale the manufacturer has used. The easiest way to do this is to purchase some calibrated colour transfer standards from a national measurement institute or from an ISO 17025 accredited laboratory. Suitable accredited laboratories are those that are UKAS or equivalently accredited. The standards can then be measured using your own instruments and the results compared to the calibration values for the standards. If they do not agree within the combination of the uncertainty of the measurement and the uncertainty of the calibration of the standard, appropriate corrections can be calculated to correct the measurements on your instruments.

Another issue that raises itself here is the different way in which each manufacturer's instrument communicates the measurement results. This is usually in some proprietary way that is incompatible with anyone else's way. The NPL, The Society of Dyers and Colourists and The University of Leeds with others, mainly in the UK, are working with instrument manufacturers and users to define a format for the exchange of colorimetric data. This format is HTML based. This means that the data files produced are totally text based. The format has been defined and is currently being proposed as an ISO standard. The aim is for instrument manufacturers and software writers to incorporate the format into instruments and into their control software in order to make it easy to import and export measurement results so that measurements can be compared. This, along with suitable traceability, makes it possible for a particular colour to be specified numerically for matching, without needing to send a sample of the colour for measurement, and without being restricted to one manufacturer in the choice of instrument for measuring the samples.

3.5 Future trends

Trends are towards smaller instruments with more elements to their diode arrays, providing better spectral measurement resolution. Coupled with this, instrumentation of all types will become cheaper in real terms and offer more features to the user as advances in electronics lead to cost savings on electronic parts. Better and faster computers mean that instruments can be much more basic in terms of onboard processing with only the raw measurements being taken and passed directly to computer software for very fast manipulation before presentation as the measurement result.

Transfer of data between instruments and other colour evaluation software will increase, as users are able to afford a variety of instruments from different manufacturers, but want to process results with the same piece of software. Software will also allow better portability of databases of samples built up over many years.

The issue of traceability will become easier to handle as the demand increases for colour and spectral data standards to be transmitted electronically rather than with physical samples. Electronic transmission demands that instruments are calibrated to the same source scale for the data to be meaningful. Manufacturers' software will allow data for the instrument calibration standards to be defined for several traceable sources. The improved measurement software will also offer better export of data and supporting information, and for exchanging measurement data.

More and faster goniometric instruments will become available as they become relatively cheaper and as people attempt to measure and quantify samples by appearance effects. Software for controlling these instruments and providing data manipulation and analysis of the measurement results will allow 3D visualisation of the results.

Cameras will be used increasingly for colour measurement as their resolution increases greatly and the need to do separate *r*, *g* and *b* measurements using filters in front of the camera becomes eliminated by cameras incorporating a matrix of *r*, *g* and *b* sensitive pixels to measure colours directly.

3.6 Sources of further information and advice

Accredited laboratories	www.ukas.org.uk
NPL ORM Club	www.npl.co.uk/opticalradiation/orm
Society of Dyers and Colourists	www.sdc.org.uk
Colour group GB	www.colour.org.uk

3.6.1 Instrument manufacturers websites

Avantes	www.avantes.com
Analytik UK	www.analytik.co.uk
Bentham	www.bentham.co.uk
BYK-Gardner	www.bykgardner.com
Carl Zeiss	www.zeiss.co.uk
Cecil Instruments	www.cecilinstruments.com
Datacolor	www.datacolor.com
Digieye	www.digieyeplc.com
D R Lange	www.drlange.co.uk
GretagMacbeth	www.gretagmacbeth.com
Hitachi	www.hitachi-hta.com
Hunterlab	www.hunterlab.com
International Light	www.intl-light.com
Jovin-Yvon	www.jyhoriba.co.uk
Kirstol	www.kirstol.co.uk
Labsphere	www.labsphere.com
Murakami	www.colourmeasure.com
Konica Minolta	www.konicaminolta.com
Ocean Optics	www.oceanoptics.com
Perkin-Elmer	www.perkinelmer.com
Photo Research	www.photoresearch.com
Spectro Solutions	www.spectrosolutions.ch
Shimadzu	www.shimadzu.com
Thermo	www.thermo.com
The Tintometer Ltd	www.tintometer.com
Tricor Systems	www.tricor-systems.com
Varian	www.varian.com
Verivide	www.verivide.com
X-rite	www.xrite.com

3.7 References

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