3 Selected Applications of Array Spectrometers

Modern array spectrometers as described in chapter 1 find more and more applications in research labs, production and education. Recent developments lead to cheaper spectrometers with improved parameters. One example for the extended application fields are spectral measuring hand held devices e.g. colorimeters. Such instruments were not possible in the past because of the space demanding spectrometer units. Furthermore, there are new light sources available, e.g. UV-LED's, and the read out electronic boards became smaller and cheaper, even with extended performance.

Selected applications, which are related to different JETI products, are described in the following. These are:

- the color measurement of opaque surfaces
- the photometric and colorimetric measurement of translucent media
- the radiometric and colorimetric measurement of self-luminous samples
- the measurement of fluorescence spectra
- multichannel spectral measurement

The basic rules of color measurement are described in chapter 3.1.

3.1 Color Measurement in General

Color measurement plays an increasing role in quality control of products. Especially the checking of color differences between reference materials and later produced samples is important for the customer acceptance. The easiest way is to observe the samples by the human eye in special cabins, but there arises the problem of objectivity and reproducibility. So color measuring instruments are used, which have to imitate the process of human color perception.

"Let us consider the ´classic island experiment´, in which a random collection of pebbles of all colors are classified by a lonely castaway. Thinking of color in terms of the common names red, blue, green, etc., her first step is to separate those, which have color from those, which have not. In other words, she separates the CROMATIC pebbles from the ACHROMATIC ones. The achromatic pebbles she now arranges from black through gray to white: i.e. she arranges them in order of LIGHTNESS. Turning her attention to the chromatic pebbles, she first separates them into piles of red, yellow, green, etc.: i.e. according to their HUE. Each of these piles she then sorts by lightness in the same way as for the achromatic pebbles. However, she notices that there are still pebbles, which appear different despite being of the same hue and lightness. After some thought, she realizes that this kind of difference relates to how much the colors differ from gray - in crude terms, how much color they contain. This third variable is called CHROMA or SATURATION. Any color can be uniquely specified by the three properties of HUE, LIGHTNESS and SATURATION." (From: Multi-channel detector applications. Andor Technology Ltd. Workshop Belfast October 26-29,1992. p.5).
In technical words: Color is a 3 dimensional quantity. The human eye can distinguish between more than 1 million chromaticity values. Each impression of color for a human being arises from the superposition of the illumination, the reflectivity/ transmittance of the object and the detectivity of the human eye (it contains three kinds of detectors (uvulas) with red, green and blue sensitivity).

Therefore, a color-measuring instrument has to "know" the spectral characteristics of the illumination and of the eye. The latter characteristics are different from person to person, so a standard detectivity was defined by the CIE (Commission International de Eclarage) in 1931 as an average of over 1000 testing persons and is called the normal observer (a new standard is currently under development). It consists of the three standardized uvula sensitivities as shown in fig. 18. They are called values of standard colorimetric observer or color matching functions $\bar{x}$, $\bar{y}$ and $\bar{z}$.

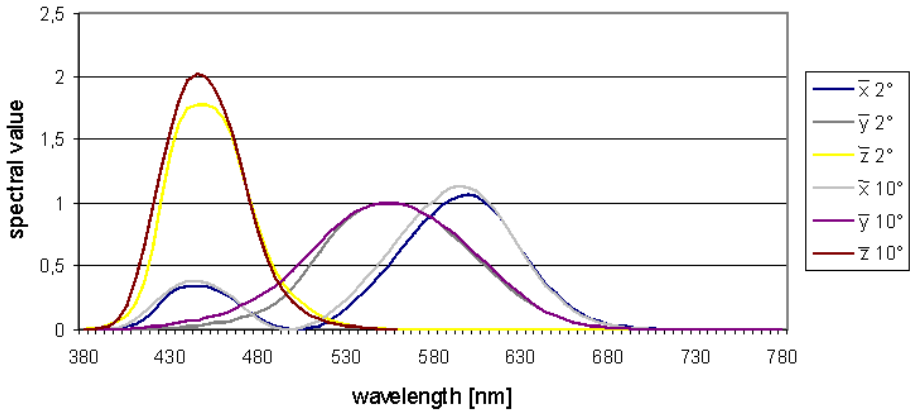


Fig. 19 Functions for the 2° and 10° standard colorimetric observer (available in tables with 5 nm step width, see e.g. DIN 5033/2 or CIE 15.2, data available at:www.cvrl.org/)

It can be seen from the diagram, that the eye sensitivity above 700 nm is neglectable. This is the reason that some color measuring instruments use only the range up to 700 nm.

Color perception is a subjective human observation; this makes the measurement of color very difficult. Influences besides the differing spectral sensitivity of individual persons are the age, the psychological feeling and the surrounding conditions, respectively.

The uvulas are distributed across the cornea with different density, resulting in a changed perception of colors with regard to the illuminated area. The above curves of fig. 19 show two data sets for a narrow viewing angle (2°) and a wider one (10°). The detectivity changes slightly for higher angles, so the characteristics for two observers were defined.

Color measuring instruments can be splitted up into two categories – filter-based and spectrometer-based devices. Filter devices use three special filters, whose transmission characteristics are matched to the three functions of the standard colorimetric observer as precisely as possible. Spectral measuring devices use a spectrometer and therefore have much more detectors with their sensitivity distributed across the VIS spectrum. The standard observer characteristics are used as calculation values, therefore they are more accurate than the filter approximation. JETI offers a device of this type with its specbos 4001. The object is illuminated by an internal light source and the signal remitted from the surface under test is measured by a spectrometer.

There exist three different methods to receive a color impression for the human eye: the color, observed in reflexion, e.g. of a car body (A), the color, observed in transmission, e.g. the colored windows of a church if seen from inside (B) and the color of a light source, e.g. of a light emitting diode (C). Spectral measuring instruments for A are commonly called spectrocolorimeters, for B spectrophotometers devices and for C spectroradiometers (see fig. 20).

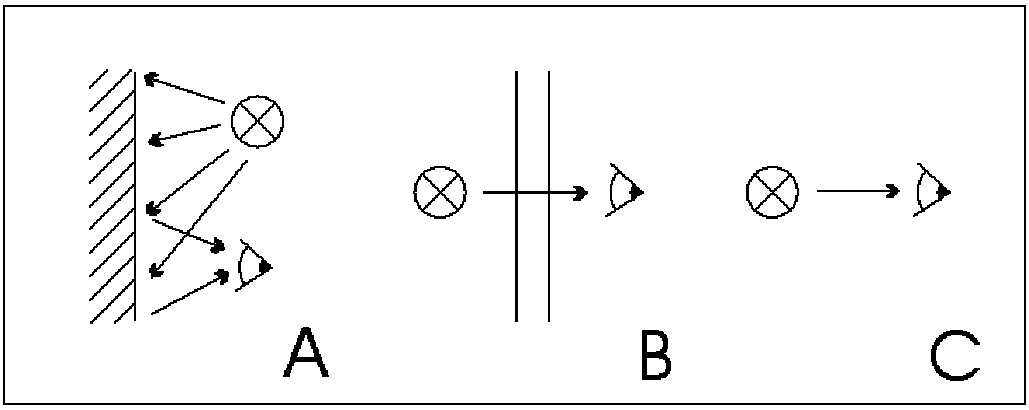


Fig. 20 Kinds of color impression (the physical terms are A – reflexion spectroscopy, B – transmission spectroscopy and C – emission spectroscopy)

Fig. 20 shows a light source illuminating an object, which is observed by the human eye. The illumination spectrum is remitted by the object and therefore weighted with its spectral reflexion behavior. The eye receives this signal and processes it with its own three sensitivity curves. The result is the color impression of the object, expressed by the tristimulus values X, Y and Z.

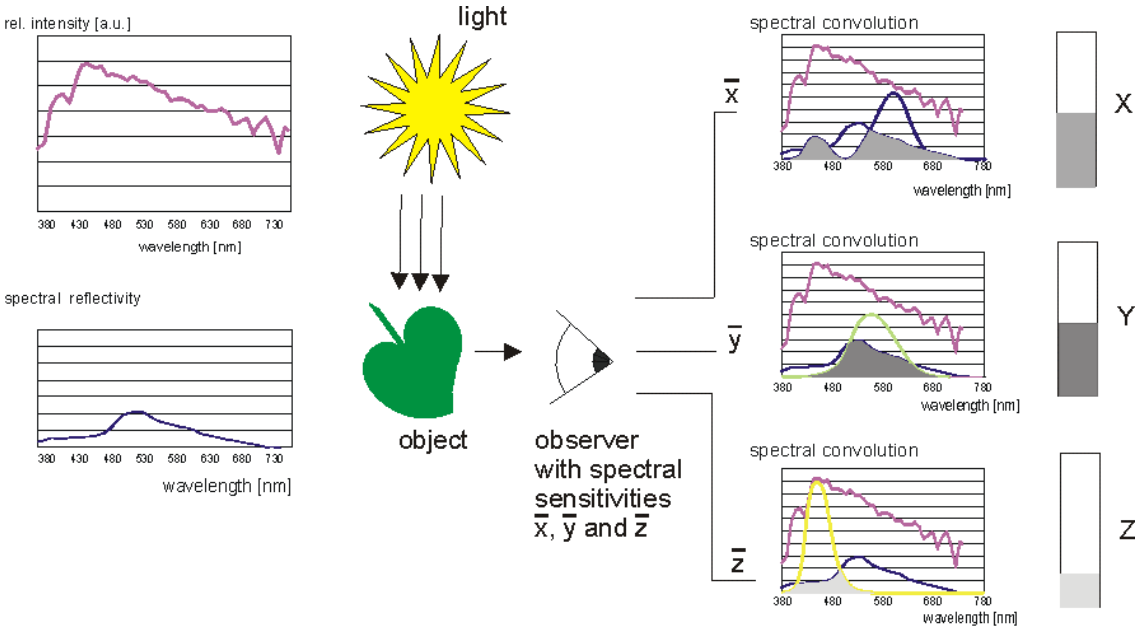


Fig. 21 Object with illuminant and observer

The physical quantity color is a three dimensional value. The following scheme shows the principal calculation process:

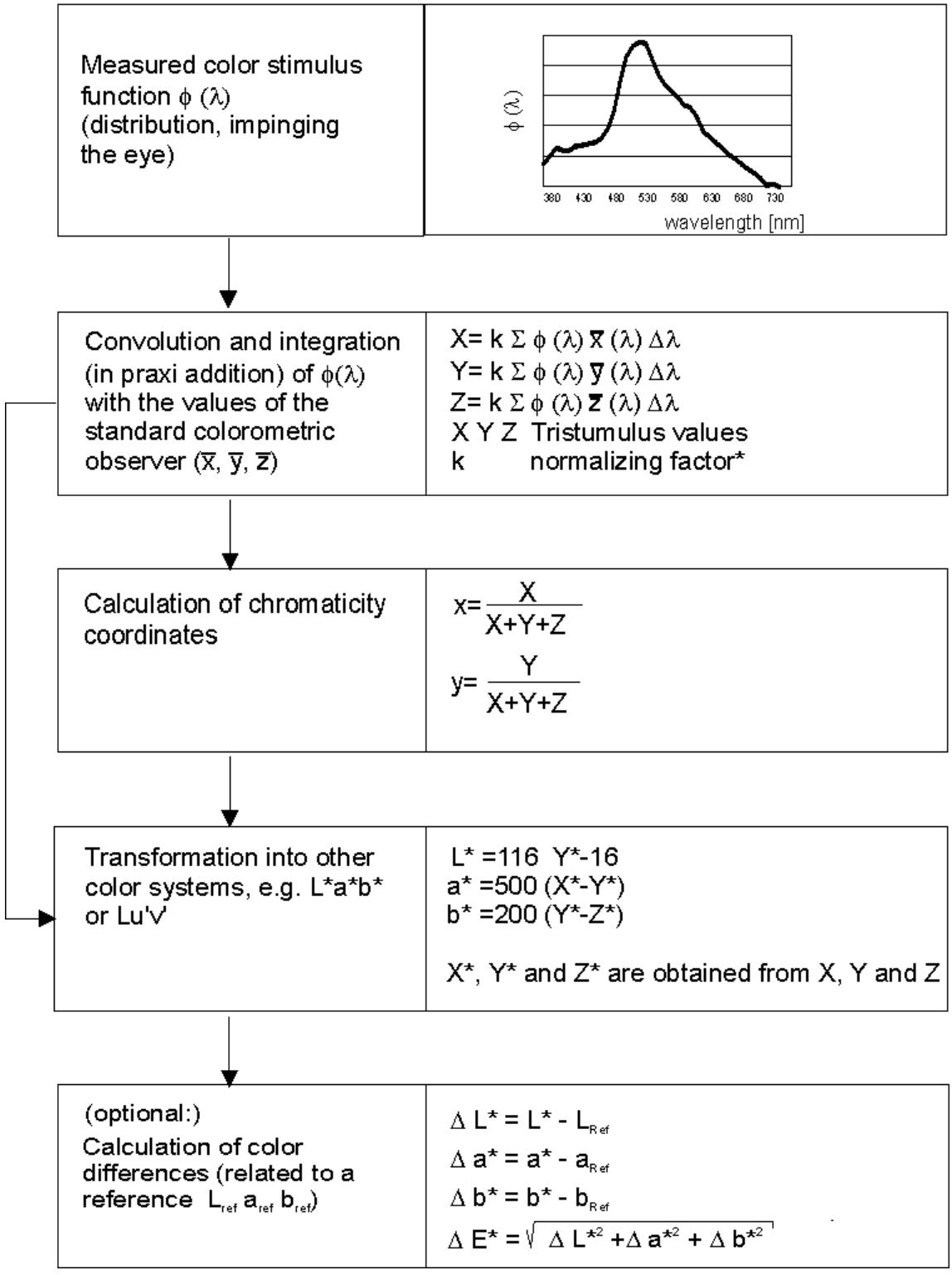


Fig. 22 Procedure of colorimetric calculation (see DIN 5033/2 and /3)
** k is used for the normalization of the tristimulus values like that Y equals 100 for the pure matt white body*

The tristimulus values of X, Y and Z do not offer information about lightness, hue and saturation (see the beginning of this chapter). Therefore, they are transformed into other color systems.
Since the perceived color only depends on the relative amplitudes of X, Y and Z, the chromaticity coordinates x and y are defined as in fig. 22. Additionally z = Z/(X+Y+Z). Because of

$$x + y + z = \frac{(X + Y + Z)}{(X + Y + Z)} = 1 \qquad (10)$$

in the majority of cases only x and y are mentioned. These two values do not give an information about the intensity; therefore they will be extended by Y. The triple xyY is often used to characterize a color impression.
The x,y diagram has the shape of a sole, the pure wavelengths (spectrum locus) and the so-called purpur line form its boundaries.

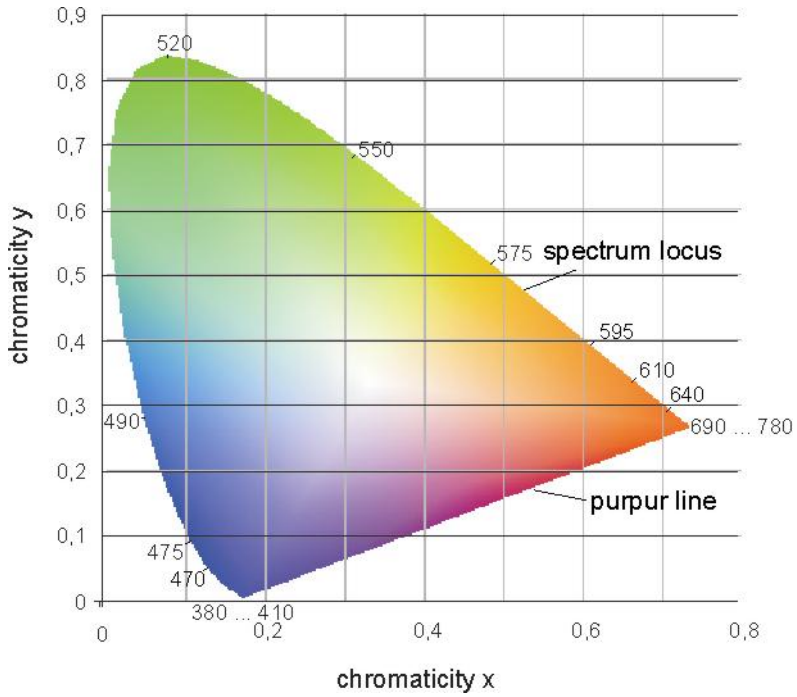


Fig. 23 xy diagram

The intension of color measuring theory during the last decades was to create systems, which are better adapted to the feeling of the human eye. One of the mainly used systems is L*a*b* in which visible color differences (ΔE*) in the whole 3D space are reflected with approximately the same value. The distinction of the asterix values (e.g. Y*) to the values without asterix (e.g. Y) is not indicated in figure 22 for simplicity. The L*a*b* system is better adapted to the subjective color feeling of the human eye than the xyY system.

As mentioned above, a main task of color measuring is color comparison. The geometrical distance of the 3 dimensional color values of reference and sample is used for easier handling of the measuring results (ΔE*).

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \qquad (11)$$

Examples of color measurement can be seen on the demo program JETI color, which can be downloaded from www.jeti.com/Downloads/SD.html.

3.2 Color Measurement of Opaque Surfaces

3.2.1.1 Colorimetry (Spectral Reflexion Measurement)

The color impression of an opaque body is a result of the scattering of the illuminating light on colored pigments in the surface region and the following diffuse escaping of the scattered light. This process is called remission. The remissioned light is influenced by the illumination **and** the illuminated surface (see fig. 20 and 21). Regularly reflected light contains no color information of the reflecting surface.

The measuring geometry, especially the method of illumination, has a significant influence on the measurement. Two standardized geometries are used for the color impression measurement. The main criterion for the selection of the suited geometry for an application is the kind of the sample surface. Smooth surfaces, e.g. of plastics and varnished materials demand a directed illumination by an angle of 45°, related to the measuring direction. It is preferably arranged cylindrically symmetric around the perpendicular measurement axis. This arrangement avoids the influence of gloss on the measuring result (remember: the regular reflex contains no color information). Rough surfaces, as those of textiles and brickwork, demand a diffuse illumination, obtained by a lamp arranged in an integrating sphere. Two kinds of measurement are possible in this case – gloss included and excluded. The exclusion is obtained by a special gloss trap. The detection of the remission is done directly in both cases. Schemes of both measuring geometries are shown in the following figure:

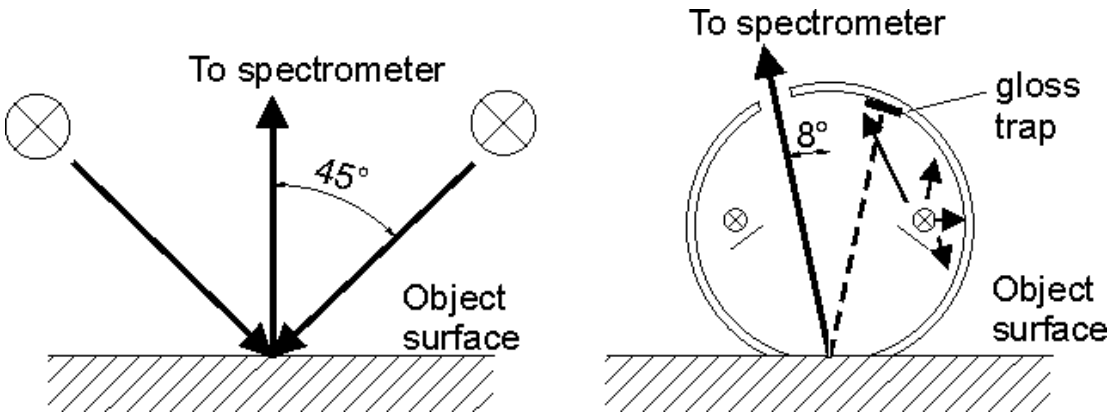


Fig. 24 *Both kinds of geometries for reflective measurement of body colors*
Left: Directed 45° illumination and 0° measurement (illumination preferably symmetrically) (45°/ 0°)
Right: Diffuse illumination by an integrating sphere and 8° measurement (d/8°)

Light source and detector can be exchanged (Helmholtz reproducibility). This statement is exactly valid only for samples without fluorescence properties. The measuring geometry is described by the specification of the illumination, followed by the specification of the observation path (according to ASTM and CIE e.g. d/8°). The specbos 4001 of JETI has a fiberoptic 45°/ 0° measuring geometry. Its measuring head has to be placed in direct contact to the object under test.
The results of a color measurement are strongly influenced by the details of the used measuring geometry, e.g. by the aperture of illuminant and detector. This is the reason for different results obtained by different instruments, especially if different manufacturers have designed them. The main criterion of an instrument is the comparability between devices of the same type – the device intercomparability.
As outlined in the general chapter about color measurement the color impression of an object is dependent on the illumination spectrum and on the colorimetric observer. To obtain comparable measuring results the observer (see fig. 19) as well as the illumination (e.g. daylight or the light of an incandescent lamp under specified conditions, see fig. 25) are standardized. Every measuring result has to include the related measuring conditions.
It is not possible to obtain a standardized illumination spectrum in an ideal way for measuring purposes, but if the individual illumination spectrum of the measuring device is known, it can be mathematically converted into such standardized characteristics.
The calculation of the color values is proceeded according to the general scheme of fig. 22. The only addition is that the measured spectrum $\varphi(\lambda)$ is the product of the standard illuminating spectrum S_λ, which shall be used as reference for the color coordinates, and the spectral reflexion coefficient (spectral density) of the sample $R(\lambda)$

$$\varphi(\lambda) = S_\lambda \cdot R(\lambda) \qquad (12)$$

The sample spectral density is determined by the ratio of the spectrum measured with the sample to the spectrum measured with a white standard of known spectral reflectivity. Therefore, it is not necessary to illuminate with a standard illumination.

$$R(\lambda) = \frac{I_{sample}(\lambda)}{I_{ref}(\lambda)} \qquad (13),$$

with $I_{sample}(\lambda)$ the measured spectrum with the sample and $I_{ref}(\lambda)$ the measured spectrum with the reference standard. It is a fundamental condition for this measurement that the instrument illuminant spectrum is kept constant during the measuring period (measurement of standard and of sample), if no referencing is used.
The instrument illumination spectrum can have an arbitrary distribution, but has to include all parts of the visible range from 380 to 780 nm or at least from 400 to 700 nm. Best results are obtained by a homogeneous distribution across the spectrum due to an equal dynamics.

Fig. 25 shows two different standardized illuminations, which are often used. Several more spectra, as daylight of other color temperatures, artificial daylight, Xe lamp light, etc. are defined (see DIN 5033/7).

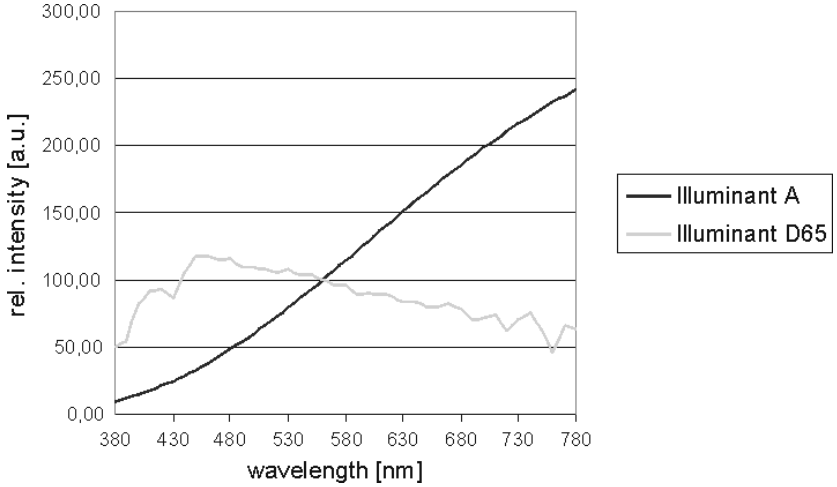


Fig. 25 Standardized spectra D65 (daylight with a color temperature of 6500 K) and A (incandescent lamp)

Two samples with different remission (or transmission) spectra, which give the same color values with one illuminant, mainly show different color values for other illuminants. This effect is called metamery. The value characterizing this behavior, is the metamery index. It describes the color difference of the samples measured at a specified illuminant and related to the reference illuminant where the color difference is zero.

Every body color measurement instrument is delivered with at least one reference standard. This standard, a white sample, has to be traceable to measurements of a standardization institute. It is used for calibration of the instrument before a measurement series to know the instrument properties (illuminant spectrum $I_{ref}(\lambda)$ and sensitivity $E(\lambda)$). So the measuring results are fitted to this normal and internal effects of the instrument (as degradation of the light source) are excluded.

Fig. 26 Colorimeter specbos 4001 with calibration standard

3.3 Photometric and Color Measurement of Transmittive Samples

Spectralphotometry (Transmission Measurement of Liquids, Filters and Transparencies)
Modern spectrophotometers, e.g. the specbos 3001 of JETI, are easy to use instruments for non-destructive testing in many application fields. They basically consist of a regulated light source with collimation optics, a test cell holder, a focusing optics, a spectrometer, the read out electronics and a microprocessor for data management and calculations.

Fig. 27 Spectrophotometer specbos 3001

The basic measurement of a spectrophotometer is the determination of the spectral transmission of the sample according to the following formula:

$$\tau(\lambda) = \frac{I_{sample}(\lambda)}{I_{ref}(\lambda)} \cdot 100\% \qquad (14)$$

$I_{sample}(\lambda)$ and $I_{ref}(\lambda)$ are the measured intensities with sample and with reference at the different wavelengths λ. The unit of $\tau(\lambda)$ is % or 1. Several application fields prefer to use the logarithmical expression of absorbance according to the formula

$$A(\lambda) = -\log \frac{I_{sample}(\lambda)}{I_{ref}(\lambda)} = -\log \tau(\lambda) \qquad (15)$$

The unit of absorbance is AU (Absorbance Units). Other physical synonyms with the same meaning of absorbance are extinction or optical density.
The main parameter in analysis is the concentration of a sample. So it is necessary to implement the calibration of the concentration – absorbance relationship into the instrument.

3.3.1 Optical Parameters

The main parameters of a spectrophotometer are:

- wavelength range
- optical resolution
- wavelength accuracy
- wavelength precision
- photometric linearity
- photometric precision
- photometric accuracy
- stray light

In the following there is given an overview of the meaning and test of these quantities. The issues of wavelength range, optical resolution and stray light are treated in the general section (see chapter 1.2. Spectrometer Parameter).

3.3.1.1 Wavelength Accuracy and Precision

The primary wavelength calibration of a spectrophotometer can be done in two different ways:

- Transmission measurement of media with strong absorption bands of known wavelengths
  Commonly used liquids for UV and VIS are solutions of Holmium Oxide and Samarium perchlorate. They are available in permanently sealed cells. More convenient standards are filter glasses with strong absorption bands (Didymium = Neodymium and Praseodymium or Holmium glass). Examples for theses glasses are BG 36 and BG 20 (Schott). The latter has absorption bands at 528.7 and 684.3 nm, which are used for the calibration test of the specbos 3000.
- Emission measurement of a line lamp (e.g. low pressure HgAr for the VIS range)
  During this calibration only the detecting part of the photometer (the spectrometer with input optics) is used. The spectral peaks of the lamp are applied for the calibration (see chapter 1.2.7.).

The wavelength-pixel relation is given as a polynom as described in the general section.
Wavelength accuracy is the deviation of the average wavelength reading at an absorption or emission band from the known wavelength of this band, while precision means the ability of a spectrophotometer to reproduce the measured wavelengths. The test measurement procedures are described in the Standard Practice E 275 of ASTM (available from www.astm.org).

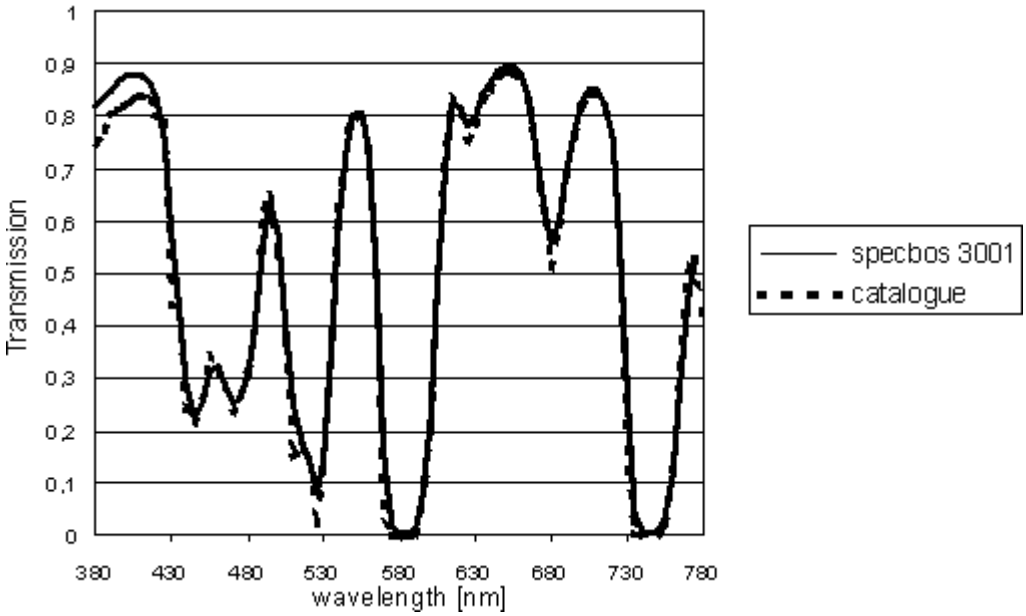


Fig. 28 Transmission spectrum of a Schott filter BG 36, thickness 1 mm

3.3.1.2 Photometric Linearity

It is important to know the range of linearity for the absorbance measurement, and therefore, in case of analytics, the range for a correct concentration measurement. Potassium dichromate solutions of different concentrations are commonly used as photometric linearity standard in the UV range. For the VIS range neutral density filters of different absorbances (e.g. between 0.2 .... 2.5 AU) are used. They are more practicable and stable, but less precise and more scratch sensitive. With these standards the determination of the linearity is possible by plotting the measured absorbance against the known one. Details can be obtained from the above-mentioned ASTM practice.

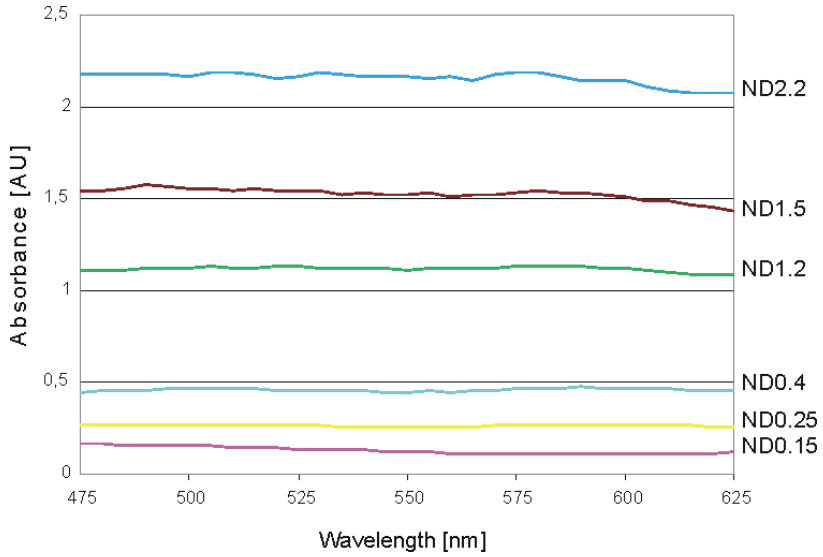


Fig. 29 Diagram with different ND filters, useable for photometric linearity measurement

The following diagram shows a typical result of such a measurement.

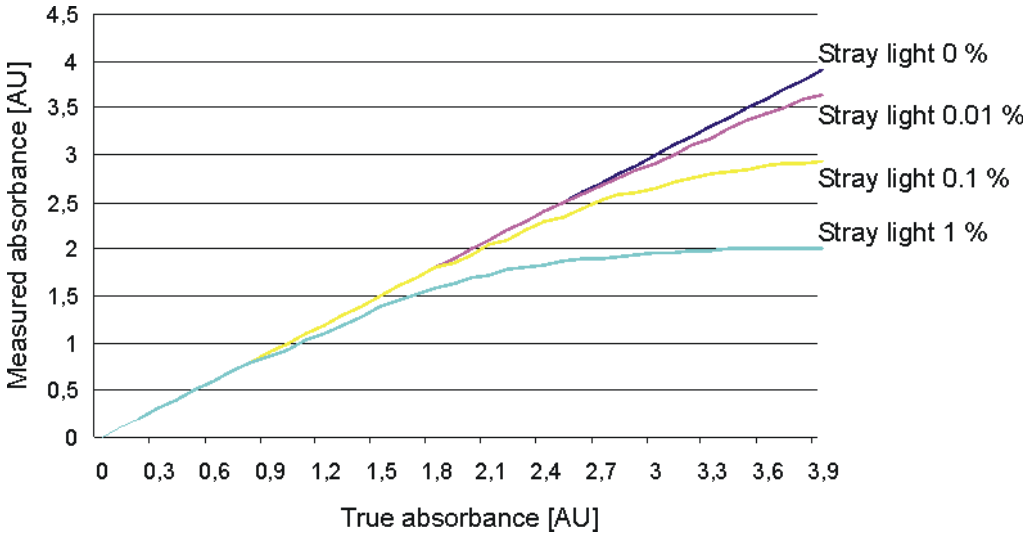


Fig. 30 Photometric linearity of a spectrophotometer

It can be seen that the range of linearity is strongly influenced by the stray light behavior of the spectrometer. The lower the stray light the larger is the absorbance range, which can be used for a precise measurement.

3.3.1.3 Photometric Precision

It represents the ability of the photometer to reproduce the result in successive measurements. The parameter for the photometric precision is the standard deviation. The value is determined by at least ten transmission measurements of ND absorbance filters or perforated screens of defined absorbance, followed by the standard deviation calculation.

3.3.1.4 Photometric Accuracy

Sometimes, not in all applications, the accuracy of the photometric measurement is of interest, e.g. if absorption measurements of different labs have to be compared. The accuracy gets determined with transmission samples, which are traceable to national standard laboratories, e.g. NIST standard reference materials. The accuracy is the difference between the true absorbance/ transmittance values and the average of ten measured values.

3.3.2 Measuring Geometry

The measuring geometry with transmission of a collimated beam through the test sample, as described in the beginning of this chapter is only useful for samples with low scattering, e.g. colored liquids or colored glasses (0°/0° geometry). In case of higher scattering media, such as milk or filters with a rough surface, it is necessary to use a diffuse illumination by means of a lamp in an integrating sphere and leaving the detection path with a focusing optics (d/ 0° geometry). Again it is possible to exchange illumination and detection path. A 0°/ 90° measuring geometry is used for fluorescence applications to reduce the influence of the exciting beam on the measured spectrum (see chapter 3.5.).

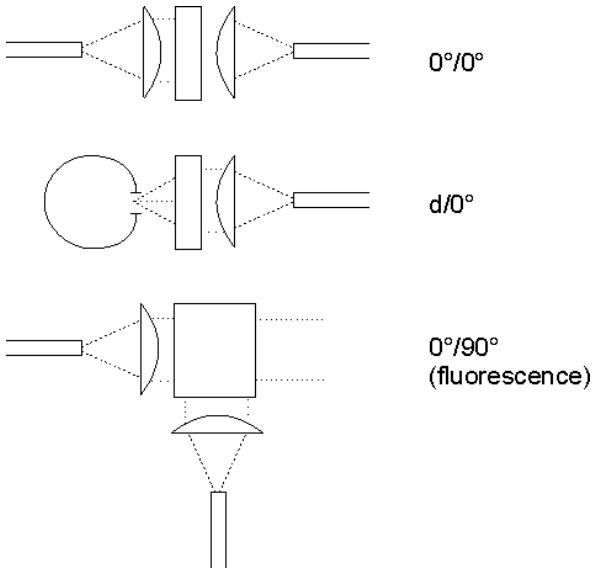


Fig. 31 Set-ups for transmission and fluorescence measurement

Liquids are normally measured in test cells. There are several models on the market: round and rectangular, made from plastics (non-returnable), optical glass, Spectrosil quartz and UV silica. The standard width is 12.5 mm and the optical path length can vary between 1 and approx. 100 mm. The standard path length is 10 mm. A very important point is the z height dimension, this is the distance from the bottom of the cell holder to the center of the incident light beam (standard values are 8.5 and 15 mm, JETI´s 3001 has 15 mm). The z height becomes very important when the aperture of the cell is small. For continuous (online) measurements flow cells with liquid in and output are used.
If test cells are used, the sample of the liquid under test has to be brought to the instrument. This procedure is not convenient for several applications, e.g. in process control. In this case dip probes are used, which are inserted into the test liquid to proceed in situ measurements. Such probes are mainly fiber coupled.
JETIs specbos 3100 is an example for an instrument with dip probe. It has a fiberoptic output connector for the illumination and an input guiding the signal to the spectrometer. The dip probe (see Fig. 32) consists of two fibers, which are linked to these connectors. Furthermore it includes a collimating optics, a protective window and a mirror with protective layer, housed in a stainless steel tube. The illumination light, escaping from one fiber, gets collimated, transfers the distance from the window to the mirrow and backwards, until it is focused into the second fiber. The optical path length (measuring length) is the double window – mirror distance (in most of the cases). There are dip probes with fixed (e.g. 1 mm, 2 mm, 5 mm) as well as with variable path lengths on the market. There exist several mounting technologies to protect diffusion of test liquid into the probe, these technologies have strong influence on the price of the probe (e.g. glued, sealed with O rings or connected by diffusion welding). Furthermore, the surrounding conditions can be very different (e.g. temperature, pH factor, pressure), so it has to be checked carefully whether a probe is suited for a certain application or not.
The influence of a possible fiber movement lies in the 1.. 3 % range, therefore it is recommended to fix the fibers before proceeding the measurement.

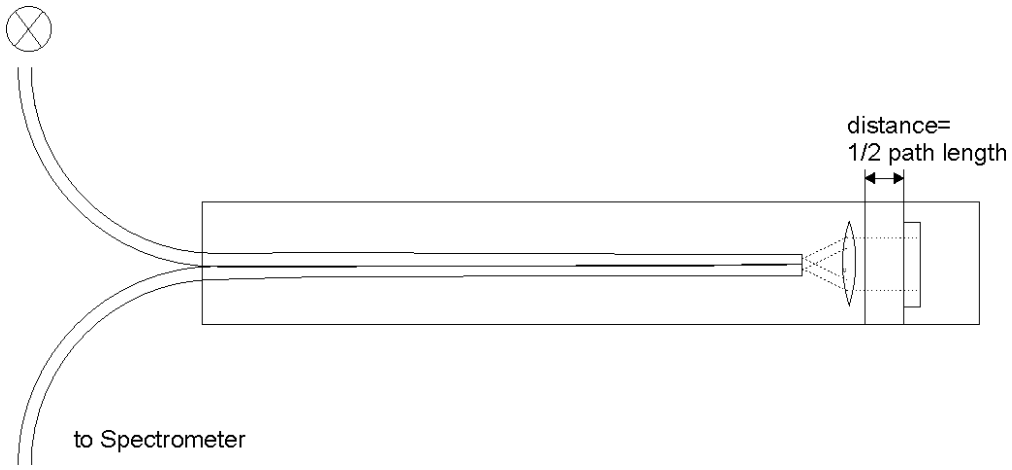


Fig. 32 Fiberoptic dip probe

3.3.3 Color measurement

The color measurement of transmissive media, e.g. liquids or transparent solid media (color filters, transparencies), has the same physical background as described for the reflectance measurement. The illumination can be diffuse or directed and is usually of the C type. The observation is normally under 0° on the opposite side of the sample (standard EN 1557). The calculation procedure is the same as in case of reflexion measurement. Therefore, the JETI spectrophotometer specbos 3001, normally delivered with a spectral measuring software, can be used with the color measuring software JETI color for such applications. The only difference is that an aqua dest. filled test cell or an uncolored sheet of material is used as the reference standard. The spectrum of this reference is set to 100 % for the whole wavelength range or a traceable spectral transmission across the wavelength range of interest is available. The simplification with the 100 % reference is especially useful in applications with color comparison only.
In former times, the color determination of liquids was based on a comparison with master solutions. Based on this, several color scales depending on the concentration were created for different application fields.
There are the following examples:

- Iod number – describes the color depth of clear liquids as solvents, softening agents, resins, oil (DIN 6062)
- Hazen number – characterization of roughly water clear liquids, especially with pale yellow color (ISO 6271)
- Gardner – used for pale yellow samples, e.g. fat (ISO 4630)
- Lovibond number – originally for beer mash characterization, today used in fat and oil industry (AOCS Cc 13e)
- Seyboldt number – water clear to pale yellow liquids (for pharmaceutical white oil, paraffin and mineral oil, ASTM D 156)
- Klett number – photometrical value for cosmetics industry

These numbers are only valid for the same and similar chromaticities. Such color measuring numbers were defined empirically. Today these color scales are implemented in the software of spectrophotometers, so it is easy to use the instruments in different industrial fields. The following figure shows the Iod, Hazen and Gardner color numbers in the chromaticity diagram for specific test conditions.

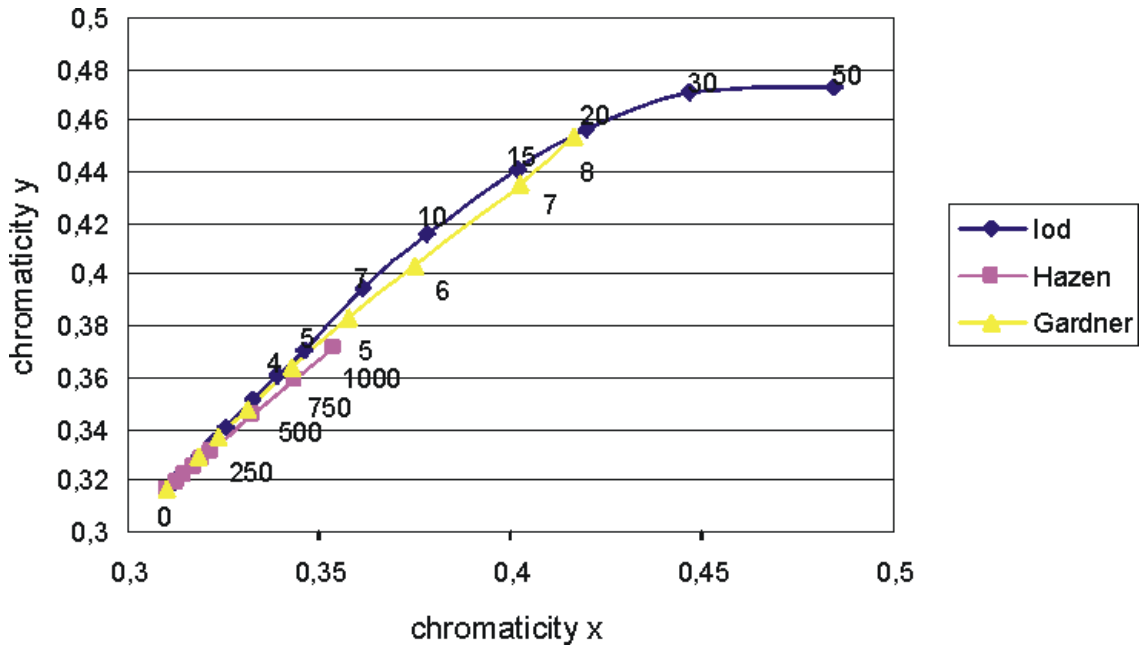


Fig. 33 *Iod, Hazen and Garner color numbers in the chromaticity diagram (standard illuminant C, 2° observer, test cell thickness 10 mm) From: Standard EN 1557*

3.4 Measurement of Self-luminous Objects

3.4.1.1 Spectroradiometry

For the color measurement of light sources like CRT´s and illuminated areas like projection screens again filter as well as spectrometer based instruments are used. Such instruments are called Spectroradiometers. The calculation of color values is based on the same rules as described in the general chapter. In contradiction to body color, there are only necessary the light source (in this case as object) and an observer (detector) (see fig. 20 C).

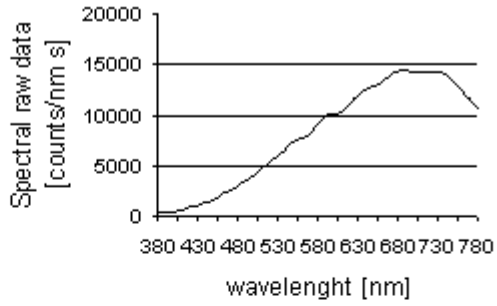
Therefore, equation (12) will be replaced by

$$\varphi(\lambda) = S(\lambda) \qquad (16)$$

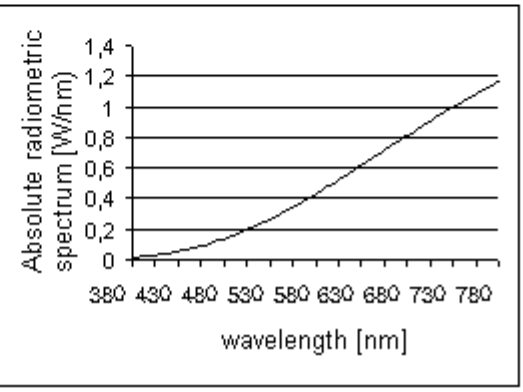
where S(λ) is the spectral power distribution of the light source under test.
Normally, spectroradiometers have a field of view between 1 and 3° to obtain a small measuring diameter. The measured radiation is focused onto the input of a spectrometer by a lens or a lens system. The spectrum is used for the calculation of quantities as radiance, luminance, chromaticity and correlated color temperature according to the following scheme:

Measurement of light source spectrum $S(\lambda)$

(at suitable integration time) t_{int} → Spectral raw data [counts/ nm s]



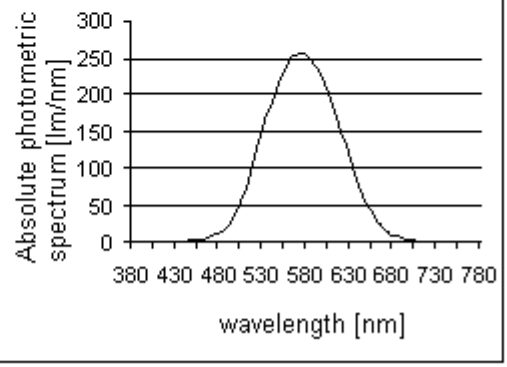
Division by the spectral sensitivity of the measuring system[counts/Ws] → absolute spectrum $S_{abs}(\lambda)$ [W/ nm]



Integration (addition) → integral physical value (radiant flux)

- related to viewing angle and light source area → **radiance**
- related to viewing → **radiant intensity**
- related to illuminated area → **irradiance**

Convolution with luminous efficiency function($v(\lambda)$) → absolute photometric spectrum



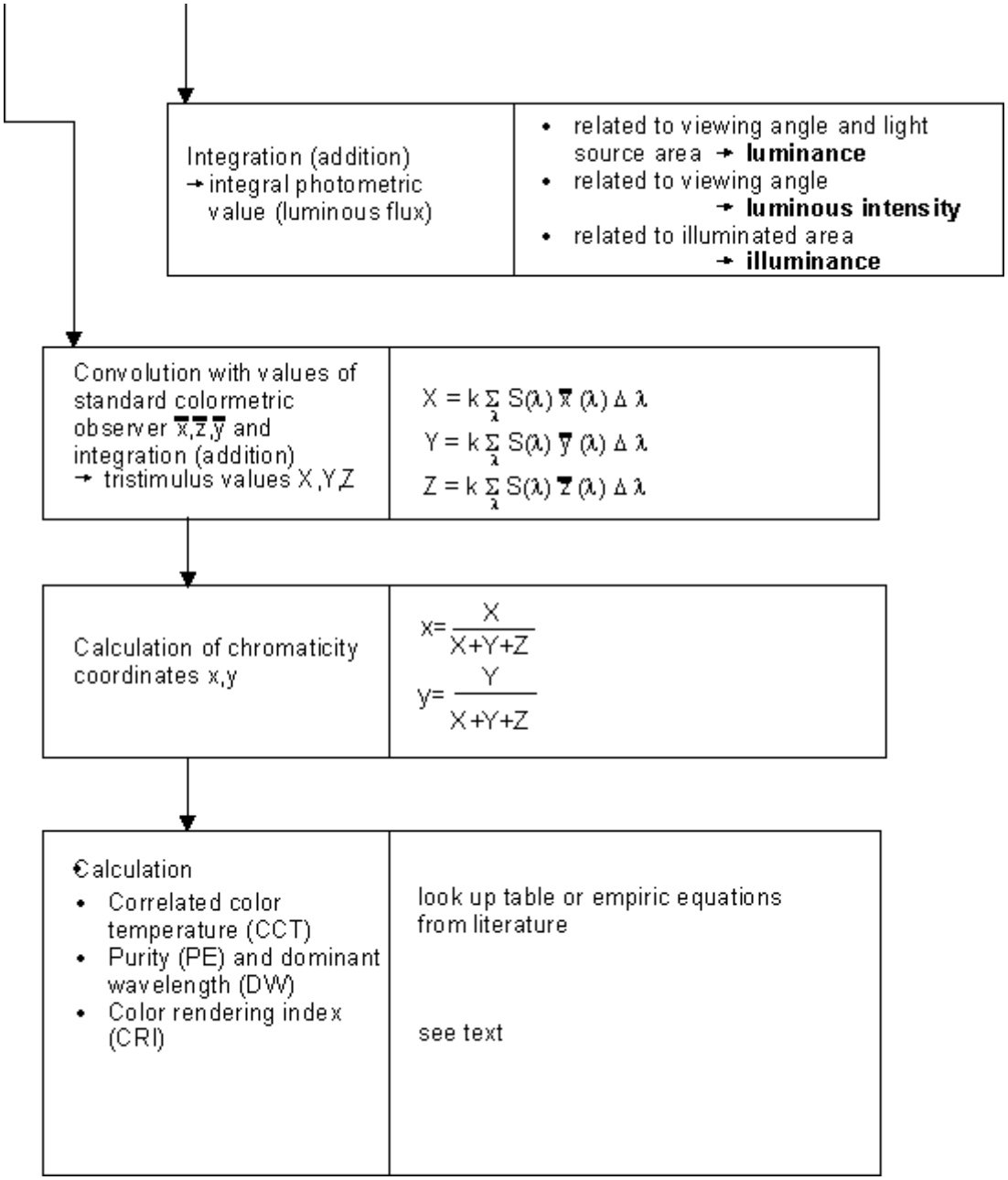


Fig. 34 Scheme of spectroradiometric calculation

It can be seen from the second step that it is necessary to calibrate the spectrometer intensity axis for spectroradiometric measurements to know the sensitivity of the system. Normally the manufacturer or supplier of the instrument does the calibration of a spectroradiometer. Halogen lamps with an integrating sphere (luminance standards) and standard lamps for luminous intensity are mainly used. The recalibration of the instrument is necessary and normally recommended once a year.

Fig. 35 Stand alone spectroradiometer spectraval CAM and miniaturized instrument specbos 1201

The color measuring values are the same as of body colors, in particular the chromaticity values x y or u´v´ are used. Another kind of description for a position in the chromaticity diagram is a combination of dominant wavelength and color purity. The following figure shows the determination of both values.

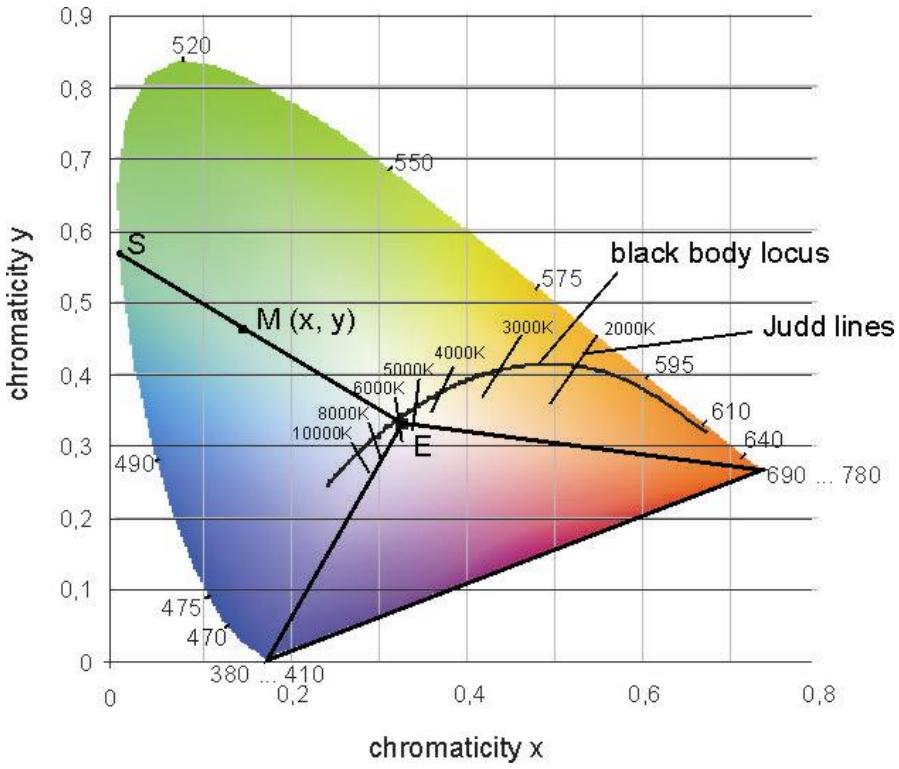


Fig. 36 Chromaticity diagram with indication of the dominant wavelength/ color purity definition and the blackbody locus with Judd lines

The **dominant wavelength** is determined by the extension of the connecting line between the location of the equi-energy spectrum E (x = 0.333, y = 0.333) and the

location of the measured chromaticity M (x,y) to the outer border of the diagram, the spectrum locus. The wavelength of this point of intersection S is the dominant wavelength (DW). The ratio between the distance EM to the distance ES indicates the **color purity** (PE). The more narrow the spectrum, the higher is the color purity. Monochromatic sources have a purity of 100 %. The locations on the purpur line have no assigned wavelengths. If the measured color point M lies inside the triangle 380 nm – E – 780 nm, than the extension is made from M beyond E to the intersection with the spectral locus. The resulting wavelength is indicated by a negative sign and called the complementary wavelength.

A further parameter of light sources is the **Correlated Color Temperature** (CCT). The chromaticities of black and gray bodies with different temperatures lie on the blackbody locus in the chromaticity diagram (see fig. 36). This statement is only in rare cases exactly valid for other spectra. Nevertheless, the color temperature is an advantageous and simple indication. For chromaticities near the blackbody locus it is common to give the temperature of the gray body which chromaticity is nearest to that of the concerning light source. This is the Correlated Color Temperature (CCT). The CCT tells nothing about the spectrum of the light source under test. It is the temperature of the blackbody radiator when the color appearance is the same as the source being tested. So it is not a measurement of the physical temperature of the light source.

The connecting lines of the chromaticity locations with the same CCT are called Judd lines. The bigger the distance between a color point and the blackbody locus the higher is the uncertainty of the CCT. If it is too far away, the information will become senseless.

The transformation from the chromaticity coordinates to the CCT can be done by look up tables or, as in case of the JETI spectroradiometer specbos 1201, by approximation with empirical formula.

The **Color Rendering Index** (CRI) is a calculation value to specify the color rendering properties of light sources, based on a test color sample method. It indicates the color differences of defined (theoretical) samples, illuminated by the lamp under test and a reference illuminant. 14 samples are defined by their spectral radiance factors, 8 of them are selected to cover the hue circle, but moderate in saturation and approximately the same in lightness and the other six representing a strong red, yellow, green and blue as well as complexion and foliage colors (vary widely in color). CRI is always related to a certain reference illuminant, which has to be indicated.
The first step of CRI calculation is to determine the set of tristimulus values X, Y and Z, resulting from the illumination of the defined samples by the light source under test and the reference illuminant (see fig. 22). Then the corresponding chromaticity values u and v are calculated, followed by a correction for the adaptive color shift due to the different state of chromatic adaptation under the lamp to be tested and under the reference illuminant. After transformation of all color data into special uniform space coordinates the color differences ΔE_i for all samples, illuminated with both illuminants, are calculated.

The special CRI is given by a set of R_i according to the formula

$$R_i = 100 - 4.6 \cdot \Delta E_i \quad \text{with i= 1 ... 14} \qquad (17),$$

whereas the general CRI is the arithmetical means of the eight special CRI for the test samples 1 ... 8 (see CIE publication 13.3 – 1995, www.cie.co.at).
Furthermore, from the absolute spectral data of light sources integral intensity data can be calculated. The selection of the proper lighttechnic value depends on the kind of light source. E.g. the „intensity“ of a LED detected by the human eye is given as luminous intensity (cd), whereas homogeneous sources as CRT screens are specified by their luminance (cd/m^2). The following figure shows the suited measurement set-ups for different kinds of light sources.

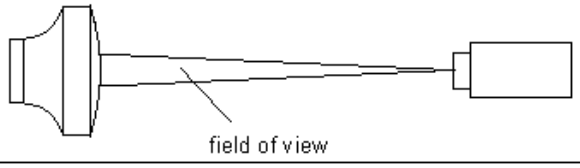
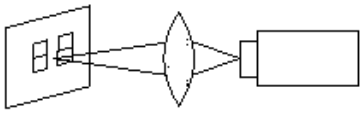
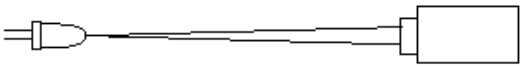
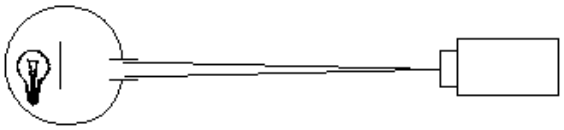
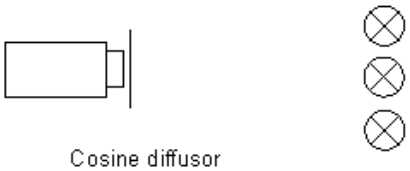
Object	Measurement set-up	Measurement value
Screen, displays		**Luminance** $[\frac{cd}{m^2}]$
Segments of displays		**Luminance** $[\frac{cd}{m^2}]$
Directed bright light source (reflectorlamps, lensed lamps, LED)		**Luminous intensity** $[cd]=[\frac{lm}{sr}]$
Total radiation of diffuse light source (bulbs, fluorescence lamps)		**Luminous flux** [lm]
Illuminated areas (work place), digital projectors		**Illuminance** $[lx]=[\frac{lm}{m^2}]$

Fig. 37 Measurement set-ups for different kinds of light sources

As stated before, it is necessary for all absolute intensity measurements to calibrate the intensity axis of the spectrometer. This can be done by means of a lamp in an integrating sphere, whose spectral power data at the output port are known. The field of view of the spectroradiometer will be precisely directed into the port of the sphere in case of luminance measurement. For illuminance measurement the spectroradiometer gets a diffusor in front of the optics to create a cosine detection behavior. The calibration can be done with a light source of known luminous flux (e.g. incandescent lamp) or luminance (incandescent lamp in integrating sphere) and corresponding conversion into irradiance/ illuminance.

Spectroradiometers (luminance as well as illuminance meters) are classified according to definitions to be found in standards (DIN 5032/6 and /7 as well as CIE publication 69). Several measuring errors, e.g. the deviation from the $v(\lambda)$ function, the deviation in directional response, the effect of polarized light, the linearity deviation, etc. and the maximum ranges of the errors are fixed in these papers. The instruments are classified into four categories from highest (class L) to lower precision (class C).

3.5 Spectral Fluorescence Measurement

Photo luminescence is the property of a substance or body to absorb light of a certain wavelength and emit at a higher wavelength with lower energy and slightly later. The difference between the exciting and the emitted wavelength is called Stokes shift. If the process duration lies in the µs or ns range, it is called fluorescence, in case of a longer time delay between excitation and emission it is called phosphorescence.
Common industrial applications of fluorescent materials are:

- Characteristic features against forgery of bank notes and stamps
- Luminous layers in CRT
- Endangering signs
- Optical brightening agents for paper, textiles and polymers
- Analytical applications

The application of such materials makes it necessary to measure their spectral behavior, e.g. for quality control purposes.

The scheme of a spectral fluorescence measuring system is shown in the following figure. An excitation monochromator is tuned to the absorption band of the material to be measured, which almost equals the region with most effective fluorescence excitation. This monochromator can be replaced by a monochromatic light source (laser or LED with a short pass filter) in case of applications where the wavelength flexibility is not necessary and the sample is always the same (e.g. in check of characteristic features against forgery). This solution offers the possibility of economic systems for QC processes in the production. The sample is illuminated in reflexion or transmission. A polychromator measures the fluorescence signal over the full wavelength range. So it is possible to detect different fluorescence peaks simultaneously.

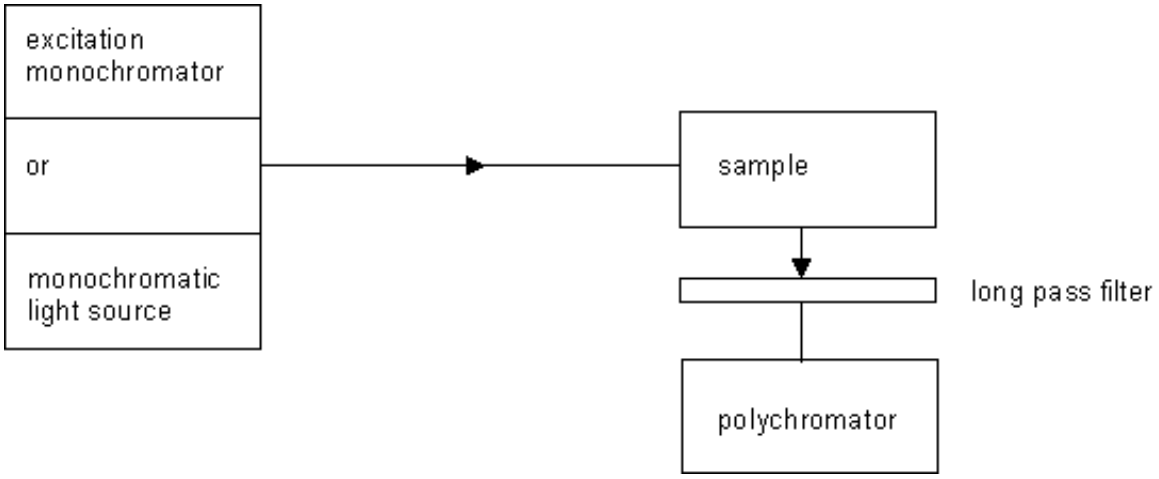


Fig. 38 Fluorescence measuring set-up

The differentiation of the reflected/ transmitted and the fluorescence signal is only possible by a spectral separation on excitation **and** emission side. This measuring set-up is called bispectral. Laboratory set-ups consist of two monochromators (one of excitation, one for emission, which both are tuned. Such arrangements have a high sensitivity, but a long measuring time. The result is a three dimensional spectrum (reflexion/ transmission and fluorescence over the wavelength).
The measuring geometries of reflexion set-ups are equal to those in pure reflexion spectroscopy (see fig. 24). In case of illumination by a sphere the emitted fluorescence light acts as a secondary source for the probe. Furthermore, glance effects have to be taken into account. In 45°/ 0° set-ups these effects do not matter.
The measurement of liquids or dissolved materials is commonly done in special test cells, suited for fluorescence measurement. The illumination angle is 0°, the fluorescence signal is measured under an angle of 90° to the illuminant to reduce the influence of the excitation energy (see fig. 31).

In fluorescence measurement it is necessary to pay attention to several main points:

- The absorption band of the sample has to be known or has to be measured (to know the wavelength for most effective excitation).
- The fluorescence intensity is relatively low, therefore it is necessary to suppress the influence of the excitation energy on the measuring signal (filters, geometry).
- The quantum yield of materials is very different, e.g. Rhodamine B has a very high yield, Eosin and Chlorophyll a substantial lower one.
- Fluorescence analysis is 100 ... 1000 x more sensitive than absorption spectroscopy. There can be analyzed mixtures with only one fluorescent part or media with different fluorescent components.
- The fluorescence intensity can be strongly temperature dependent. Furthermore, it can be quenched, especially by dissolved oxygen.

- The broadband excitation light can cause photochemical reactions, which can influence the fluorescence intensity,
- Impurities of the sample, of the solvent or the test cell can influence the fluorescence signal.
- Stray light (Rayleigh) can cause additional peaks, which have to be distinguished from the fluorescence signal.

The following figure shows an examplary fluorescence spectrum, obtained by the reflexion measurement of a fluorescence marker in a bank note. Furthermore, the excitation spectrum (UV LED) as well as the transmission spectra of two blocking filters are shown.

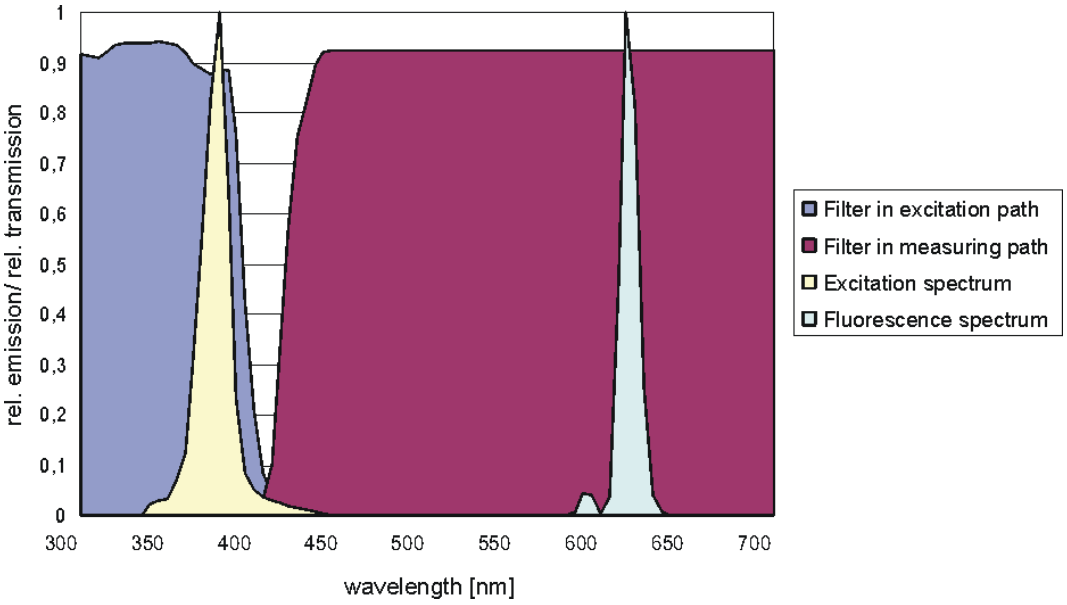


Fig. 39 Fluorescence spectrum example (Fluorescence marker of a bank note)

From this short survey can be seen that line array spectrometers show several advantages in fluorescence measuring applications especially for economic set-ups for production control.

3.6 Multichannel Spectral Measurement

The simplest multichannel measurement has been used for many years – the referencing of a light source with a second spectrometer. During the last 10 years applications with more channels have become more and more of interest.
First, there is to clarify one misunderstanding: Some publications define the detection of one spectrum as multichannel detection due to the parallel read out of the pixel of the line array – which contains much more information than available from a filter instrument. Multichannel in our sense means the read out of at least two separate measuring spectra. Application examples are quality control of light sources during fabrication process, color measurement and pharmaceutical high throughput measuring instrumentation.

This read out of the spectra can be done in two ways – serial or parallel. Both kinds show specific advantages and disadvantages.

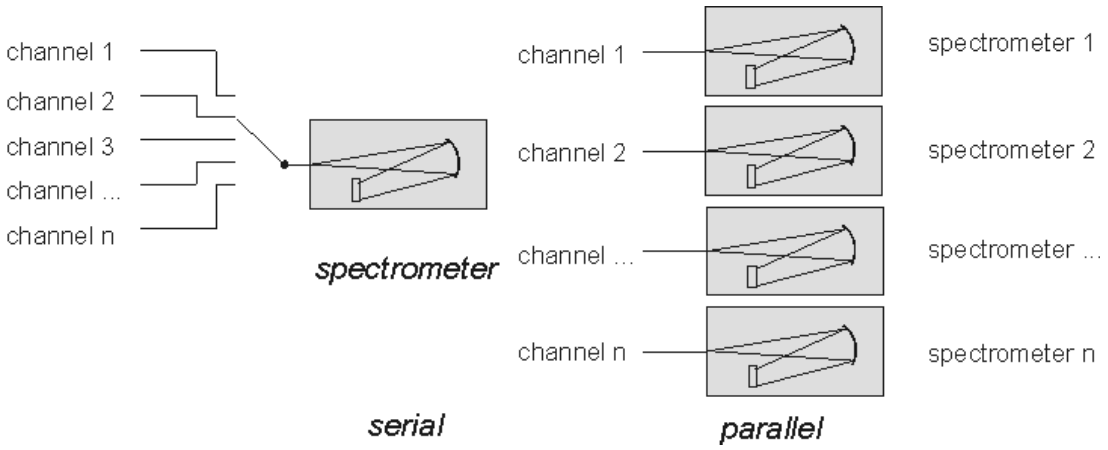


Fig. 40 Serial and parallel multichannel spectral measurement

	Serial read out	**Parallel read out**
Set-up	Optical switch (mainly fiber switch) + one spectrometer	One spectrometer per channel
Measuring time	long (Channel number * measuring time per channel)	Short (only one integration + read out time)
Calibration/ referencing	only one spectrometer	Each spectrometer separately
Reproducibility	Reproducibility of switch is included in the measuring result	No mechanical movement – higher reproducibility
	Changes of measuring object are possible during sequential channel read out	Same conditions for all channels during read out
Costs	Considerable costs of optical switch	Costs for several spectrometers
Applications	Mainly where high end spectrometers are needed	Fast measuring applications

The multichannel spectrometer of JETI is based on a simultaneous (parallel) measurement with a separate spectrometer per channel. The costs of miniaturized spectrometers decreased during the last years, so this solution becomes more and more of interest. The following figure shows a 9 channel spectroradiometer MCR-n with the software displaying all spectra simultaneously. This instrument contains up to 12 channels with spectroradiometers working seperately. It is equipped with a fiber shutter for dark correction.
Examples for applications of this technical solution are:

- Spectral measurement of multi LED equipped PCB´s
- Long term observation of lamp burn in tests
- Multi angle color measurement
- Homogeneity measurement of digital projectors

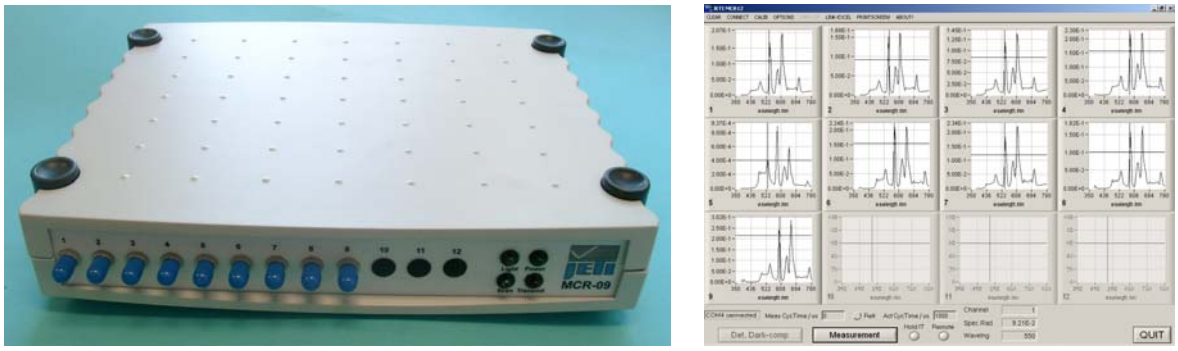


Fig. 41 9 channel spectroradiometer and screen shot of the PC software

Parameters of the spectrometric multichannel system are:

- Channel number 2 ... 12
- Integration time 10 ms ..... 1 s
- Read out time 4 ... 20 ms
- Repetition rate up to 10 Hz
- Interfaces USB; RS232 and CAN (optional)

The read out of the JETI multichannel instruments is proceeded pixelwise. The single pixel signals from all channels are fitted into each other. So it is guaranteed that no jitter appears between the spectra.