Metrology Research Institute
Helsinki University of Technology

Saulius Nevas
Farshid Manoocheri
Atte Haapalinna

Instruction Manual
of Reflectance Measurements

Version : 1.2
Date : 20.12.2005

Table of Contents

1. Definition

1.1. Scope

This quality manual describes the principle and operation of reflectance accessory of the reference spectrometer used to realize the national scale of specular spectral reflectance.

1.2. Object and field of application

Useful information can be obtained about the properties of many reflecting materials and surfaces by measuring the regular spectral reflectance of optical radiation from the sample surface. Most applications are in radiometric, photometric, and color measurements where different types of samples are used for calibration purposes. The reference instrument is well characterized and the total uncertainty can be as low as 0,001 reflectance units (1σ) in the visible region of the spectrum.

1.3. Features

The reference spectrometer, when using the reflectance accessory includes the following features:

- Automated instrument providing simultaneous measurement of several samples and scanning of the selected wavelength settings
- Collimated single-beam design allowing the determination of various uncertainty components
- Reflecting optics
- Detector turntable unit, including an averaging sphere and a silicon photodiode, which eliminates the beam-displacement error caused by imperfect insertion of samples, and the spatial responsivity errors of the detector
- Measurements of regular reflectance with nominal values from the range of 0.05 - 1.0 (angle of incidence 5°- 85°) over 250 - 1000 nm wavelengths

1.4. Regular spectral reflectance

Reflectance of radiation from a surface, without a change in the wavelength, is specular if the wavefront is reflected according to the law of reflection, i.e., the angle between the direction of the reflected flux and the normal of the reflecting surface equals the angle between the normal and the direction of the incoming flux, and both the direction of the incoming and the direction of the reflected flux lie in the plane of reflection.

The regular spectral reflectance R of a given surface is the ratio of the reflected spectral radiant flux $\Phi_{\lambda,R}$ to the incident spectral radiant flux Φ_λ [1]

$$R(\lambda,\theta_1) = \frac{\Phi_{\lambda,R}}{\Phi_\lambda} \; , \tag{1}$$

where λ is the wavelength of the radiation and θ_1 is the angle of incidence. The reflectance varies as the physical parameters of the sample and/or the properties of the incident light change. Variations in the incident light beam can be due to changes in polarization, degree of collimation or convergence, and coherence of the radiation.

To examine the above-mentioned dependencies, let us assume that the incident light is a perfectly monochromatic, plane-polarized, plane wave of wavelength λ. The sample is isotropic, homogenous, and forms a plane parallel slab of infinite extent and of thickness t. The initial and final dielectric media are the same and have an index of refraction of n_1. Let the complex index of refraction of the slab medium be $\hat{n}_2 = n_2(1+ik_2)$, where k_2 is the attenuation coefficient.

Based on the laws of reflection and refraction and by including the effect of multiple reflections between the slab surfaces, the regular spectral reflectance of the slab for both polarizations separately is given by

$$R(\lambda,\theta_1) = \left| \frac{2\,\hat{r}(\theta_1)^2 + 2\,\hat{r}(\theta_1)^2 \cos(2\beta)}{1+\hat{r}(\theta_1)^4 + 2\,\hat{r}(\theta_1)^2 \cos(2\beta)} \right|, \tag{2}$$

where $\hat{r}$ is the complex Fresnel coefficient of the amplitude reflectance at the first boundary, and β is defined as

$$\beta = \left(\frac{2\pi}{\lambda}\right) t\,\hat{n}_2 \cos\hat{\theta}_2 . \tag{3}$$

The complex angle $\hat{\theta}_2$ is given by Snell's law as

$$\sin\hat{\theta}_2 = \frac{n_1 \sin\theta_1}{\hat{n}_2} . \tag{4}$$

For s-polarization the coefficient of the amplitude reflectance is,

$$\hat{r} = \hat{r}_s(\theta_1) = \frac{n_1\cos\theta_1 - \hat{n}_2\cos\hat{\theta}_2}{n_1\cos\theta_1 + \hat{n}_2\cos\hat{\theta}_2} \tag{5}$$

and for p-polarization,

$$\hat{r} = \hat{r}_p(\theta_1) = \frac{\hat{n}_2 \cos\theta_1 - n_1 \cos\hat{\theta}_2}{\hat{n}_2 \cos\theta_1 + n_1 \cos\hat{\theta}_2}. \tag{6}$$

The reflectance is a complicated function of the angle of incidence, the polarization state of light, and the thickness of the sample. When the angle of incidence deviates from $\theta_1 = 0$ the internal transmittance will decrease due to the increased optical path length. The effect of polarization is due to different reflectance values for different polarization states of the light, as indicated in Eq. (5) and Eq. (6), and it causes further angular variations of the reflectance.

The dependence of the reflectance on the thickness t of the slab is seen from Eq. (3). For very thin samples the t/λ-term gives rise to interference effects which cause the reflectance to oscillate rapidly as the wavelength is varied. The effects of interference observed in practice are generally low for imperfect samples and for incoherent light. However, this effect is not negligible when discussing accuracies of a few parts in 10^4. For minimal effect of interference the sample should be relatively thick (>1mm) and the instrument bandwidth should be larger than 1 nm [1].

2. Equipment

2.1. Equipment used in reflectance measurements

Equipment used in measurements of spectral regular reflectance consists of the reference spectrometer, a turntable assembly, a linear translator, an averaging-sphere detector unit, a digital voltage meter (DVM), and a control computer. A schematic of the measurement setup is shown in Fig. 1. The reference spectrometer including light source, monochromator, input and output optics is described elsewhere [2, 3, 4]. The other components of the measurement system are:

A. Specular reflectance accessory
- Linear translator (ISEL LF4)
- Averaging sphere (Labsphere, USA)
- Averaging sphere detector (Hamamatsu S-1337-1010-photodiode)
- Detector power supply (15 V Signaali)
- Polarizing calcite prism (Glan-taylor, Optosigma, USA)
- Turntable assembly(built at MRI)

B. Data acquisition and control system
- Digital voltmeter (HP 3458A or HP 34401A)
- Microcomputer IBM/PC AT compatible
- Interface cards to parallel printer connector of the computer (built at MRI)

- Driver card for the motorized turntable (EDM-453, Portescap)
- Reflect3.pas – measurement program source code

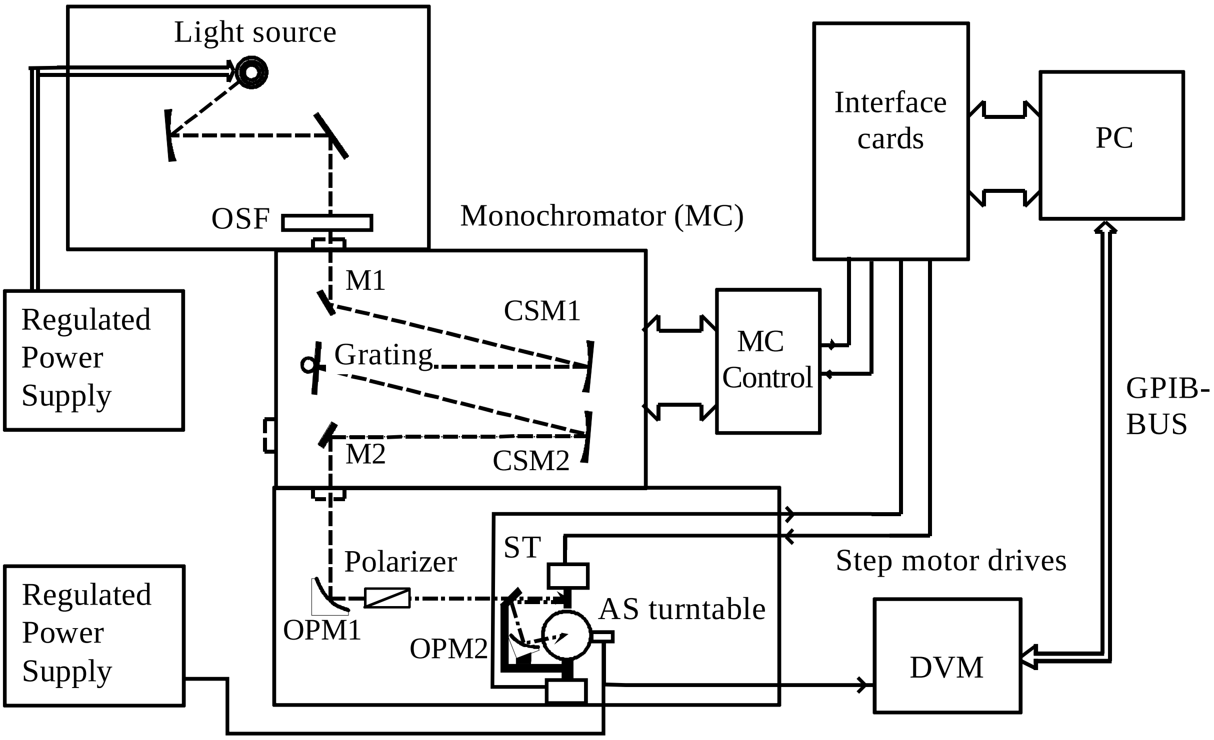

Figure 1. Schematic of the spectrometer for reflectance measurements. Abbreviations in the figure are: OSF, order-sorting filter; M1, M2, flat mirrors; CSM1, CSM2, collimating spherical mirrors; OPM1, OPM2, off-axis parabolic mirrors; ST, sample translator unit; AS, averaging sphere detector; DVM, digital volt meter.

2.2. Maintenance of the equipment

- Information on the maintenance of the reference spectrometer and details on its control electronics can be found in [2, 3, 4].
- The detector turntable unit is checked and calibrated before starting the measurements and if necessary the mechanics are renewed.
- The averaging sphere coating is visually checked each time before the measurements and if necessary renewed.
- The photodetector is tested for linearity every second year.
- The multimeter is autocalibrated every time before the start of the calibration measurements. Calibration of the multimeter is performed according to the calibration schedule of TKK/MRI.
- Delicate optical components such as filters and mirrors are handled and cleaned according to Publication [5].

3. Measurement traceability and calibration

The accuracy of the regular spectral reflectance is not defined by a fundamental standard but by the definition given in Sec. 1.4 and the calibration of instruments used during the measurements. The accuracy of the measurements can be verified by various procedures including measurements of known reference materials and comparisons of measurements made by independent instruments. The latter procedure is usually carried out in international intercomparisons between laboratories using different designs of reference spectrometers.

In order to calibrate the instrument various parameters and their effects on the measurements are investigated and controlled. During the calibration we utilize well-known methods and materials whose validity has been proven. In the following section the uncertainty components of reflectance measurements are estimated from the evaluation of the instrument parameters.

3.1. Uncertainty components

Table 1 summarizes the uncertainty components for high-quality non-fluorescent, absorption neutral density filters.

Table 1. Uncertainty components for regular spectral reflectance measurements of first surface reflecting samples at visible wavelengths for reflectance levels of higher than 10%. The uncertainty is given in reflectance units.

Component	1σ-uncertainty
Wavelength bias	4×10^{-5}
Detector linearity	6×10^{-5}
System drift and noise (m=9)	1×10^{-4}
Beam displacement	3×10^{-3}
Polarization	6×10^{-5}
Stray light	1×10^{-5}
Combined standard uncertainty (Root-sum-of-squares)	3×10^{-3}

m : number of measurement passes (see Sec. 5.2.)

Wavelength scale and band pass

The wavelength scale of the monochromator is checked periodically to ensure the best attainable wavelength accuracy. The uncertainty of the wavelength scale is $\Delta\lambda$=0,06 nm which causes a reflectance uncertainty of $\Delta R=\Delta\lambda(dR/d\lambda)$. This uncertainty depends on the sample and is estimated to be smaller than 1×10^{-4} reflectance units for first-surface reflecting samples, for which the change of reflectance per unit wavelength is usually about $dR/d\lambda=10^{-3}$ nm^{-1}.

The nominal instrument band pass is calculated as the product of the reciprocal linear dispersion (1,3 nm/mm) and the slit width of the monochromator. In routine measurements a band pass of 1,5 nm is chosen. It has been checked that the band pass of the monochromator has no effect on the wavelength calibration.

Detector linearity

The working principle of the present spectrometer is based on measuring ratios of light intensities at each selected wavelength. Any deviation from linearity will cause an error in the measured reflectance.

The linearity of the Si-detector has been measured by comparing the detector’s responsivity with the responsivity of an absolutely calibrated reference detector. The dynamic range studied reached power levels that yielded signals of several volts, which is higher than the maximum value encountered in typical reflectance measurements. The linearity of the responsivity of the reference detector has been established with the beam addition method. The relative deviation from linearity of the detector used in reflectance measurements is within 17 parts in 10^4, throughout the dynamic range studied. The uncertainty caused by the deviation from linearity of the detectors is calculated as $\Delta R=R(1-R)\Delta L$.

Stability of source and detection system

For single-beam spectrometers the stability of the light source is important. Simultaneous measurements of the voltage across the QTH-lamp terminals and the detector output voltage proves that there are fluctuations in the source and that the detector signal closely follows these fluctuations. However, these fluctuations are of random nature and can be considered as noise. An integration time of 5 seconds was found to give a smooth detector output signal. Temperature variations may also cause fluctuations in the throughput due to thermal expansion of the mechanical and optical components. This effect is avoided by using a chimney-like structure in the input optics enclosure that guides the heat away from the instrument.

The total system drift is measured for several wavelength settings. The detector signal is monitored every minute for a period of 60 minutes with a 5-second integration time. The result of a typical measurement is shown in Fig. 2 where the data are fitted to a linear function. The slope of $-1{,}7\times10^{-5}$ volts per minute is considered to be due to a systematic drift, and the residuals give a measure of the random noise component whose relative standard deviation is approximately 0,07%. The system drift introduces a measurement uncertainty of smaller than 3×10^{-5} due to the time-symmetrical procedure of the measurements (see Sec. 5.2). The standard deviation of the reflectance measurements is about 2×10^{-4} for 9 readings. This is in agreement with the effect of fluctuations in the beam intensity as shown in Fig. 2.

Beam displacement

The precision of the detection turntable alignment has been checked using a laser beam. At the visible wavelengths it has been established that if the normal alignment procedure has been followed the random displacement of the flat tracking mirror is below 2 mm when the turntable is rotated between measurement geometries. For UV-wavelengths this uncertainty is 4mm. This uncertainty in the positioning of the mirror gives rise to a similar uncertainty in the beam position at the center of the off-axis mirror used to reflect the beam in to the sphere. The corresponding uncertainty in the intensity of the beam entering the sphere is due to the spatial and angular dependence of the reflectance of the off-axis mirror. The resulting relative variation of the detector signal has been measured to be less than 2 and 4 parts in 10^3 for visible and UV wavelengths, respectively. As the measurement set-up for NIR wavelengths is aligned at the visible wavelengths the uncertainty in visible applies for those measurements as

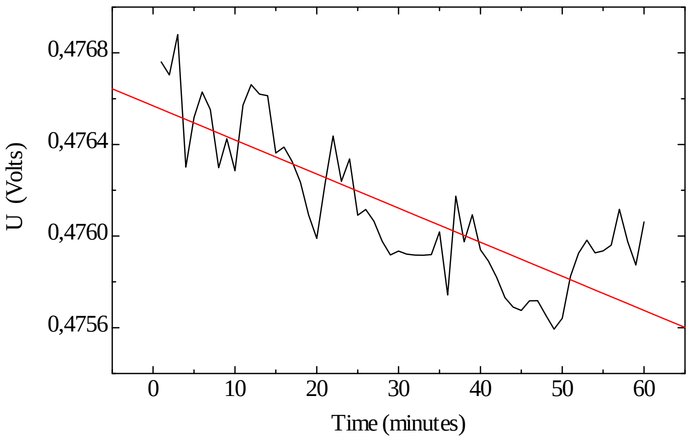

Figure 2. Drift of the detector output signal U with time. The total system drift is 0,003% per minute calculated from the linear fit (dashed line). The relative standard deviation of the measured values is 0,07%.

Instrument polarization

The degree of polarization of the measurement beam in the reflection plane is estimated to deviate by 7 parts in 10^4 from unity for both states of polarization. This is due to the uncertainty in the alignment of the polarizer (1°). This effect causes a sample-dependent uncertainty component in reflectance measurements. For a silica sample this uncertainty component has a maximum relative value of 4 parts in 10^{-3} at Brewster's angle.

Stray light

Stray light effects in the measurements are caused by unwanted radiation present in the beam and the light scattered from various components in the measurement compartment. In order to estimate the level of radiation having a different wavelength from that of the beam, the transmittance of a number of Schott color glass filters of 3-mm thickness was measured at 10 nm intervals using the transmittance set-up of the reference spectrometer. For the RG 665 filter with a sharp cut-off wavelength of 665 nm, the results are 10^{-4} and 10^{-5} units for wavelengths ranging from 380 nm to 450 nm and from 460 nm to 600 nm, respectively. The transmittance is less than 10^{-5} for a green filter (Oriel 59070) and for a black filter (Oriel 59562) for wavelengths longer than 650 nm.

Beam uniformity

The uniformity of the beam at the position of the sample was investigated by recording the detector signal corresponding to the intensity of individual small spots in the beam. For this purpose a 3-mm circular aperture was mounted in front of the entrance port of the averaging sphere which was located in the position of the sample-holder unit. The beam was scanned by moving the sphere in the horizontal and vertical directions in steps of 2 mm. The beam, with a rectangular shape (18 mm × 20 mm), the uniformity was better in the vertical than in the horizontal direction. The maximum variation was 8% along the 18-mm vertical dimension of the beam. In the horizontal direction the maximum variation was about 20%. Usually, the beam is made circular in shape by passing it through an aperture with a diameter of 15 mm. The intensity roll-off at the edge of the beam is about 10% of the maximum. The beam uniformity was found to have similar profiles at different wavelengths (450 nm; 550 nm; 650 nm) and different slit widths (0,7 mm; 1,2 mm; 2 mm).

The effect of the beam nonuniformity is most significant when the sample inhomogeneity is larger than 1%. The uncertainty introduced by this effect should be determined separately for each sample with different profile of inhomogeneity.

3.2. Measurement of the reference sample

It has been possible to verify the measurement accuracy of our instrument by measuring a sample of UV grade synthetic fused silica whose refractive index is known with an uncertainty of 1×10^{-5} [6]. The refractive index is homogeneous and stable with respect to time and temperature. The measured sample of this reference material has a thickness of 3 mm, a diameter of 25 mm, flatness of $\lambda/10$ on both sides, and parallel surfaces to within 10 arc-sec. The results of a measurement using a 1,5 nm band pass over the spectral range from 400 nm to 700 nm are shown in Fig. 3. The measured reflectance values are in agreement with the calculated values to within 5 parts in 10^3.

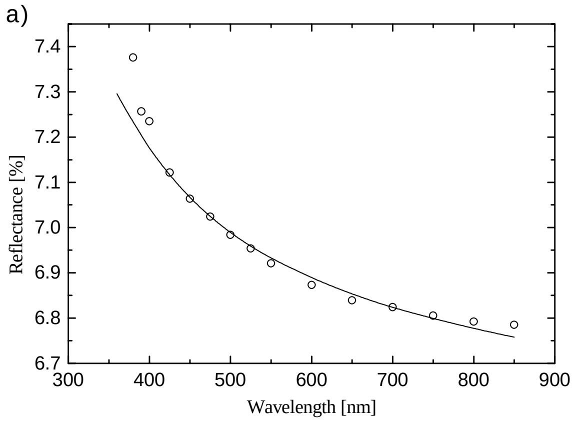

Figure 3. Measured spectral reflectance of the reference material (◦) and the corresponding calculated values (___) determined from the refractive index.

4. Measurement ranges and best measurement capabilities

The best measurement capability of the reference spectrometer for regular spectral reflectance has been given in Publications [7, 8, 9]. Table 2 summarizes the uncertainty components in reflectance measurements of a high-quality fused silica sample and a windowless silicon photodiode at 8° and 45° angle of incidence, respectively. Table 3 summarizes the uncertainty components in reflectance measurements of a fused silica sample and of a multilayer interference filter at nominal angle of incidence of 45° and 8°, respectively. In addition, filter induced uncertainties such as material homogeneity are to be added as sum of squares to the measurement standard uncertainty.

Table 2. Uncertainty components in measurements of a synthetic silica sample at 8° with a nominal 0.07 specular reflectance and a windowless silicon-photodiode at 45° with a nominal 0.45 specular reflectance at a UV, visible, and NIR (800-1000 nm) wavelength for s-polarization state of the measurement beam. The numbers are absolute values.

	Standard uncertainty in reflectance / 10^{-4}					
Component	silica sample at 8°			silicon-photodiode at 45°		
	UV	Visible	NIR	UV	Visible	NIR
Wavelength scale	0.1	0.01	0.02	5.5	0.5	0.9
Detector linearity	1.3	1.1	1.1	4.2	4.2	4.2
Stray light	0.2	0.1	0.1	1.1	0.5	0.5
System drift and noise	0.4	0.2	0.2	2.8	0.9	1.3
Beam displacement	0.5	0.4	0.4	3.4	2.8	2.6
Polarization	0.1	0.01	0.1	0.1	0.1	0.1
Angular positioning of the sample	2.8	1.4	1.4	22.4	18.4	17.2
Combined standard uncertainty	3.2	1.8	1.8	23.9	19.1	18.0
Expanded uncertainty (*k*=2)	6.4	3.2	3.2	47.8	38.2	36.0

Table 3. Uncertainty components for the cases of a synthetic fused silica slab and a UV-interference filter, at measurement angles of 45 and 8 degrees, respectively. The calculations have been made for s-polarized measurement beam. Uncertainties are calculated for UV, visible, and NIR wavelengths. The numbers quoted in the table are relative values.

Component	Relative standard uncertainty in reflectance / 10^{-4}					
	45° Silica			UV-interference filter		
	UV	Visible	NIR	UV	Visible	NIR
Type A						
Standard deviation	5	2	2	5	2	2
Combined type A (1σ)	5	2	2	5	2	2
Type B						
Wavelength scale	0.4	0.4	0.4	15	0.4	0.4
Detector linearity	0.8	0.8	0.8	5	5	5
Stray light	0.4	0.03	0.07	12	0.4	0.5
Alignment uncertainty	23	12	12	23	12	12
Polarization	4	4	4	0.2	0.2	0.2
Angular positioning of the sample	21	21	21	4	4	4
Combined type B	31	25	25	31	14	14
Combined standard uncertainty (1σ)	32	25	25	31	14	14
Expanded uncertainty (*k*=2)	64	50	50	61	28	28

5. Calibration methods and procedures

5.1. Procedure for calibration of the wavelength scale

Wavelength calibration is performed by means of emission lines from spectral lamps and laser radiation sources as described in [4].

5.2. Reflectance measurement method and procedures

The spectrometer can measure regular spectral reflectances automatically. The spectrum of the QTH lamp is scanned by the monochromator and the reflectance of one or several samples is measured at the desired wavelengths. The emerging beam from the monochromator during the scanning is directed into the averaging sphere via the sample and tracking mirrors, or tracking mirrors alone. The intensity of the beam is converted to a voltage signal, which is measured by an 8-digit voltmeter (DVM). The DVM is read by a microcomputer via a GPIB-488 bus. Simultaneously, the computer controls the operations of the detector turntable unit, linear translator, the shutter, and the monochromator via the corresponding interface and driver units.

The slit width setting of 0,002 to 2.2 mm and beam-diameter selection of 2 to 18 mm are handled manually, but these settings are seldom changed. The measurement procedures are generally straightforward. Measurements involving unusual sample sizes, however, require special attention.

Following sample insertion and alignment, the measurements are performed according to the settings supplied to the computer control program. To eliminate the effects of the small drifts of the instrument, the reflectance measurements are performed in a time-symmetrical sequence. After the wavelength is selected, each set of measurements begins with measuring the detector signal for an empty filter holder in order to initialize the DVM for the full-scale reading. Depending on the number of samples to be measured, the following series of readings are taken:

one sample,

$$\text{m times } \{ I_b, I_0, I_{S1}, I_{S1}, I_0 \},$$

Symbols I_b and I_0 denote the signal readings for the detector dark current and for the beam intensity in the reference measurement position. Symbol I_{S1} is signal reading for the reflected beam, and m is the number of repetitions chosen by the operator. Two readings are taken for each individual sample for the sake of preserving the time symmetry of the detector exposure resulting in the mean value $\bar{I}_{S1}$, $\bar{I}_{S2}$, etc. The signal-reading data are processed by taking the average value of closest I_b and I_0 readings on both side of I_{sj} readings, giving mean values $\bar{I}_b$ and $\bar{I}_0$. Then the reflectance R_j is computed for each sample according to

$$R_j = \frac{\bar{I}_{sj} - \bar{I}_b}{\bar{I}_0 - \bar{I}_b},$$

where j is 1, 2; etc. The corresponding sample reflectance values are then averaged over the 2m passes to obtain $\bar{R}_j$. The standard deviation corresponding to the R_j values is also calculated.

5.3. Operating instructions for the reflectance accessory of the reference spectrometer

The following steps are recommended to be taken for proper operation of the spectrometer for reflectance measurement of a sample. It is assumed that the input optics is in proper alignment and the desired slit width is adjusted. The operator is supposed to give priority to and also follow the operation by the measurement program of the PC.

1) Switch on the power supply of the QTH lamp and adjust the voltage to 12 V by using the voltage control knob. Insert an order-sorting filter, if required.
2) Turn on the DVM and the detector power supply.
3) Switch on the PC and type ”turbo”. Load and run the program “REFLECT3”

4) Turn on the interface electronics and then the MC control unit.
5) Press any key on the PC keyboard so that the main menu of the program appears.
6) Give on hour for the lamp to stabilize and the electronics to warm up.
7) Install the sample, within a suitable holder, to the turntable mounted to the liner translator. Make sure that the holder is mounted in such a way, that the sample surface coincides with the rotational axis of the manual rotation stage. It is assumed that the travel length (number of steps) set for the linear translator is compatible with the sample width, so that a translation takes the sample completely out of the beam.
8) Select a wavelength between 550 nm and 650 nm by using the "Drive mc" command in the main menu. (Note that the commands are executed by pressing the key for the letter written in capital). If the wavelength setting which appears on the top line of the monitor, is below 500 nm use the "go_Home" command to set the MC at the starting point wavelength, then, go to step 8.
9) Insert the sample into the beam by using the adjustment knob on the linear translator.
10) Align the sample in such a way that the beam strikes the sample at the center area and the beam is reflected back to the iris aperture, and ultimately onto the slit aperture.
11) Rotate the sample to the desired angle of incidence using the manual rotation stage.
12) Position the detector turntable directly below the sample, so that the rotational axis of the motorized turntable coincides with the sample surface, and thus also with the rotational axis of the manual rotation stage.
13) Align the rotation plane of the detector turntable to be parallel to the measurement beam, i.e., verify that the tracking mirror’s relative height to the measurement beam is constant when rotating the turntable.
14) Align the tracking mirrors so that in the reference measurement position the beam is reflected from the center of the flat tracking mirror onto the center of the OPM2, and focused at the center of the input port of the averaging sphere detector.
15) Adjust the angle of rotation for the detector turntable by first setting the constant **steps** in the program “REFLECT3” to the calculated, theoretical value.
16) Run the program, and try the command “Rotation turntable”. Observe the rotation, and check whether the reflected beam has an identical path through the tracking mirror, OPM2 and input port of the averaging sphere.
17) Correct the constant **steps** according to observations described in 16 (repeat 16).
18) Start the measurement by using the "Measurement" command. One of the input parameters to this command is the number of ratio measurements (m). The maximum allowable is m=19 but usually m=9 is sufficient. NPLC determines the integration time of the signal by the voltmeter. NPLC=100 is routinely used.
19) After completion of the measurements the main menu is displayed again. The results of the measurement are saved in the file "MEAS.TXT" and can be read (or printed) by using the "Read data" (or "Write data") command.

5.4. Automation software

In order to control the related operations of the instrument a computer program package has been developed. The program, "Reflect3", is a menu-driven PC program written in Turbo Pascal version 6.0. The program controls the operation of each automated device of the spectrometer not only during the reflectance measurement procedures but also whenever their action is required. The DVM is controlled via a GPIB-488 controller card and the monochromator, the shutter, and the detector turntable unit are automated with separate interface cards via a parallel printer port.

The "reflectance measurements" main menu command of the program offers choices of measurement procedures. The program allows a choice of the number wavelength scans at equally spaced intervals or arbitrary specific wavelengths. The results of the reflectance measurements are saved in a file, which can be monitored by a program menu command after the measurements are done. Detailed information on the instrument automation is available in publication [2].

6. Laboratory accommodation

Reference spectrometer laboratory is located in room I137 in the basement of the department of electrical engineering. The laboratory is a clean room. Instructions for using the clean rooms have been given in [10].
During reflectance calibrations:

- The Clean Zone -aggregate should be on to prevent dust.
- Temperature should be monitored.

Temperature relative humidity values during the calibrations are written to calibration certificates.

7. Records

The measurement data coming from calibrations and development of equipment is archived. The measurement notes (comments on the measurement setup etc.) are written down to a dedicated notebook (titled as “Reference Spectrometer – Calibrations & Measurements”) and/or measurement data file. The raw data files are stored in the reference-spectrometer control computer and backed-up in responsible person’s PC.

8. Certificates

Calibration certificates are handled according to [11]. In the calibration certificates included are:

- Ambient temperature and relative humidity,
- Regular spectral reflectance values at the measured wavelengths.

9. Intercomparisons

Comparison measurements of regular reflectance performed with the reference spectrometer are reported in [12]. The spectral reflectance of a silicon photodiode was measured over the wavelength range from 250 to 850 nm. The results were compared with the corresponding values predicted by a model based on thin-film Fresnel formulas and the known refractive indices of silicon and silicon dioxide. An agreement at the level of 2×10^{-3} in the visible wavelengths range was obtained.

10. References

[1] K.D. Mielenz, "Physical Parameters in High-Accuracy Spectrophotometry", NBS Special publication **378**, 81-93 (1973)

[2] F. Manoochehri, Licentiate Thesis, "High Precision Spectrometer for Reflectance Measurements", Helsinki University of Technology, 1993.

[3] F. Manoochehri and E. Ikonen, "High-accuracy spectrometer for measurement of regular spectral transmittance", Appl. Optics **34**, 3686-3692(1995).

[4] Quality manual of reference spectrometer laboratory.

[5] ORIEL, *Guide to Cleaning Research Optics*, (Tutorial text).

[6] Dynasil corporation of America, NJ, Catalog 702-B and I.H. Malitson, "Interspecimen comparison of the refractive index of Fused Silica", Journal of the Optical Society **55**, 1205-1209 (1965).

[7] A. Haapalinna, S.Nevas, F. Manoocheri, and E. Ikonen, “Precision spectrometer for measurement of specular reflectance”, Rev. Sc. Inst. **73**, 2237-2241 (2002).

[8] F. Manoochehri, A. Haapalinna, and E. Ikonen, “High-accuracy measurement of regular spectral transmittance and reflectance in UV-visible-NIR”, *in Proc. XIV IMEKO World Congress* Vol. II, pp 108-113.

[9] A. Haapalinna, F. Manoochehri, and E. Ikonen, “High-accuracy measurement of specular spectral reflectance and transmittance”, Analytica Chimica Acta **380**, 3170-325 (1999).

[10] P.Kärhä, “Clean room instructions / Puhdastilaohjeet”, *MRI publication*.

[11] *Instructions on writing calibration certificates*.

[12] A. Haapalinna, P. K.arhä, and E. Ikonen, Spectral Reflectance of Silicon Photodiodes, Appl. Optics **37**, 729-732 (1998).