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Lasers and laser-related equipment — Test method for angle resolved scattering

Lasers et équipements associés aux lasers — Méthodes d'essai pour déterminer la dispersion avec résolution angulaire

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Laser and electro-optical systems*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In 2004, increasing demands from industry for qualified angle resolved scattering (ARS) measurements led to a discussion note to start activities for a completely new standard on ARS measurements of optical components in SC 9/WG 6, which was later discussed again in 2008. This new attempt was in particular driven by, but not limited to, the development of optical components for the deep ultraviolet spectral region, where scatter losses by material and surface imperfections cause critical limitations. It was then agreed to support the development of a new working draft.

Since then, there has been an increased interest in a standard procedure that is easy to apply for practical applications ranging from high-end surfaces, coatings, and materials, structured components like diffraction gratings, to radiation shaping elements like display foils and diffusors used at wavelengths ranging from the EUV and DUV to the IR spectral regions.

Two standards exist that describe measurements of angle resolved scattering:

— ASTM E 2387-19[15];

— SEMI ME 1392-0116[16].

Another related document is ISO 13696 which describes procedures to measure the Total Scattering (TS) of optical components.

Radiation scattering caused by imperfections of optical components can critically affect the performance of optical systems. Radiation scattered into large angles usually means a loss of radiant power and thus reduced throughput. Radiation scattered into smaller angles can lead to image degradation. Knowledge of the angular distribution of scattered radiation is thus essential in order to assess the quality of optical components.

This standard describes a testing procedure for the corresponding quantity, the angle resolved scattering (ARS), which is defined by the measured scattered intensity (scattered radiant power normalized to incident radiant power and solid angle of detection) as a function of the scattering angles.

Angle resolved scattering data can be used as input for stray-radiation calculations in optical design software. Other information like the Total Scattering (defined in ISO 13696) or other integrated scattering quantities can be derived from angle resolved scattering by numerical integration. In addition, although not covered in this document, analysing angle resolved scattering can provide information about the origins of scattering such as interface roughness, particles, defects, sub-surface damage, and bulk inhomogeneities.

Lasers and laser-related equipment — Test method for angle resolved scattering

1 Scope

This document describes procedures for the determination of the angle resolved scattering by optical components such as coated or uncoated optical elements, photonic structures, and materials that can be transparent, translucent, or opaque. It comprises scattering into the scattering sphere around the specimen usually separated into the backward and forward hemispheres. The procedures apply to wavelengths of radiation ranging from 5 nm in the extreme ultraviolet to 15 µm in the infrared spectral ranges.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11145, *Optics and photonics — Lasers and laser-related equipment — Vocabulary and symbols*

ISO 14644-1, *Cleanrooms and associated controlled environments — Part 1: Classification of air cleanliness by particle concentration*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
scattered radiation
fraction of the incident radiation that is deflected from the specular optical path

[SOURCE: ISO 13696:2002, 3.1.1]

3.2
detector solid angle
$\Delta\Omega_s$
solid angle of the detector aperture with respect to the origin of coordinates

3.3
angle resolved scattering
ARS
radiant power ΔP_s scattered into a direction (θ_s, ϕ_s) relative to the incident radiant power P_i and the *detector solid angle* (3.2) $\Delta\Omega_s$:

$$\tilde{f}(\theta_s,\phi_s)=\frac{\Delta P_s(\theta_s,\phi_s)}{P_i\Delta\Omega_s}$$

Note 1 to entry: ARS can be transformed into the bidirectional reflectance, transmittance, or scattering distribution function, BRDF, BTDF, or BSDF (f_r) respectively, by dividing ARS by cosθ_s:

$$f_r(\theta_s, \phi_s) = \frac{\tilde{f}(\theta_s, \phi_s)}{\cos\theta_s}$$

Note 2 to entry: The total scattering[1)] defined in ISO 13696 can be derived from ARS through numerical integration within the corresponding scattering hemispheres. For normal incidence and reflective scattering, the integral is:

$$\sigma_{TS} = \int_{0}^{2\pi} \int_{\leq 2°}^{\geq 85°} \tilde{f}(\theta_s, \phi_s) \sin\theta_s \, d\theta_s \, d\phi_s$$

3.4
diffuse reflectance standard
diffuse reflector with known, preferably Lambertian, *ARS* (3.3)

3.5
instrument signature
intrinsic contribution to measured *ARS* (3.3) produced by the instrument itself, usually estimated by measuring *ARS* (3.3) without any specimen

4 Symbols and abbreviated terms

$\tilde{f}$	angle resolved scattering, ARS
$\Delta\Omega_s$	detector solid angle
ΔP_s	scattered radiant power
P_i	incident radiant power
ϕ_s	azimuthal scattering angle
θ_i	angle of incidence
θ_r	angle of specular reflection
θ_s	polar scattering angle

5 Scattering geometry

The scattering geometry is defined in spherical coordinates with respect to the specimen normal as shown in Figure 1. The origin of coordinates lies at the specimen as follows:

— for measuring reflective scattering, the origin lies at the entrance surface;

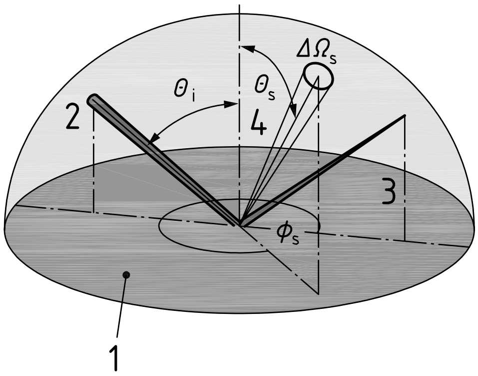
— for measuring transmissive scattering, the origin lies at the exit surface;

— for thin specimens (specimen thickness small compared to the field of view of the detector), the origin can be either at the entrance or the exit surface;

— for certain applications, it may be useful to place the origin at other locations, for example in the specimen.

The exact location of the origin shall be documented.

1) In ISO 13696:2002, total scattering is currently described by the symbol TS. This will be changed to the symbol, σ_{TS} , in the upcoming revision.



Key

1	specimen under test	θ_i	angle of incidence
2	incident beam	θ_s	polar scattering angle
3	specularly reflected beam	ϕ_s	azimuthal scattering angle
4	scattered radiation at (θ_s, ϕ_s)	$\Delta\Omega_s$	detector solid angle

NOTE The angle of the specular reflection (θ_r) is equal to the angle of incidence (θ_i).

Figure 1 — Scattering geometry

The scattering geometry is shown in Figure 1. The azimuthal scattering angle is zero for measurements within the incident plane containing both the incident and specularly reflected beams. In addition, a specimen orientation angle should be defined and documented. The direction of incidence and the surface normal define the incident plane.

6 Test method

6.1 Principle

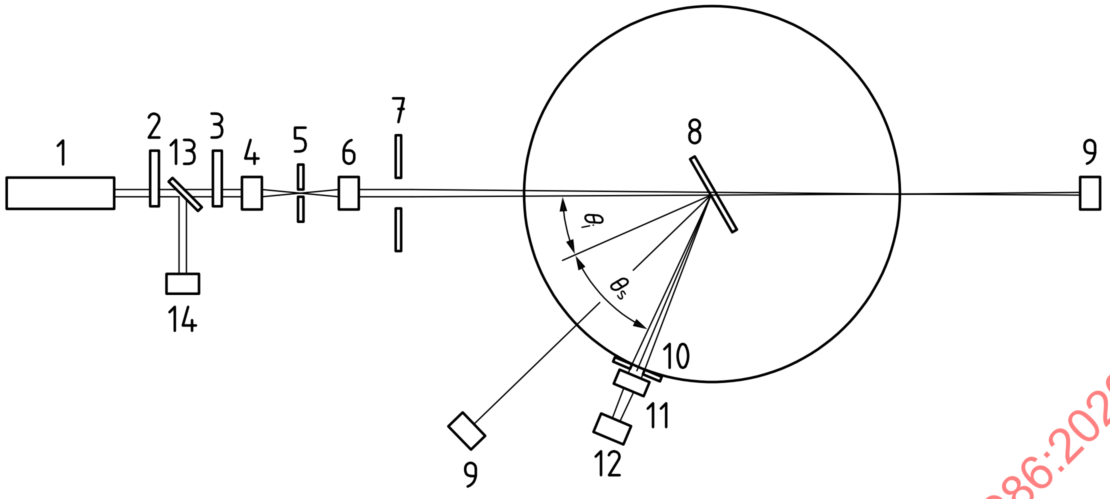
The fundamental operating principle of the instrument for ARS measurements (see Figure 2) is based on measuring the radiant power scattered from the specimen as a function of the scattering angles using a detector with a small but finite aperture that is scanned along a defined trajectory on or within the full scattering sphere about the specimen. The simplest type of measurement is a detector scan with the plane of incidence (in-plane scan).

The angle of incidence is kept constant during a single measurement. The ARS is either measured by rotating the detector with respect to the specimen and the illumination system, or, alternatively, the detector is fixed and the illumination system and the specimen are rotated with respect to the detector.

6.2 Measurement arrangement and test equipment

6.2.1 General

The instrument employed for the determination of ARS is divided into four functional sections which are described in detail in Figure 2.



Key

1 radiation source
2 chopper (optional)
3 variable attenuator (optional)
4 focussing element 1
5 pinhole
6 focussing element 2
7 baffles (optional)
8 specimen
9 beam dump
10 detector entrance aperture
11 field lens (optional)
12 detector
13 beam splitter (optional)
14 reference detector (optional)

Figure 2 — Instrument for ARS measurements

If radiant power fluctuations or drifts of the radiation source of more than 5 % are expected over the time scale comprising calibration and measurements, an additional reference channel shall be implemented into the setup shown in Figure 2. The back reflection of a tilted superpolished substrate of a material transparent in the relevant spectral region of the laser and positioned before the spatial filter as well as an appropriate detector, preferably similar to the actual scatter detector, should be used for this purpose.

6.2.2 Environmental conditions

The instrument should be located in a clean room environment or under a laminar flow system to prevent scattering from dust particles. Some applications, in particular in the UV range, require operation in vacuum or specific gas atmospheres to avoid absorption of radiation in air or to suppress Rayleigh scattering from air molecules. The environmental conditions during measurements shall be documented.

6.2.3 Radiation source

Excellent beam quality and sufficiently high incident radiant power are essential for ARS measurements of optical components. Therefore, lasers, laser diodes or narrow or broad band sources may be used as radiation sources. The source used shall be documented.

The temporal radiant power variation of the radiation source shall be measured and documented. This comprises long-term drifts as well as short-term fluctuations. Drifts and fluctuations smaller than 5 % are below the overall uncertainty of measurement and can be accepted. Larger drifts and fluctuations should be monitored and taken into account accordingly. For this purpose, a reference signal should be measured using a beam splitter and a reference detector.

An attenuator based on a combination of neutral density filters or other means is used to adjust the incident radiant power.

6.2.4 Beam preparation system

The beam preparation system consists of a spatial filter to generate a clean beam and, if necessary, additional baffles to suppress stray radiation from the illumination system. The beam profile should be a rotationally symmetric Gaussian. Other profiles, for example a top-hat profile can also be used provided that the instrument signature, particularly at scatter angles close to the specular directions, is not affected.

The last focussing element images the pinhole onto the plane of the detector aperture. That is, the specularly reflected or normally transmitted beam shall be focused on the detector aperture when the detector is viewing that direction and when the specimen being measured is in place.

If the focal point of the illumination system is at the specimen, at infinity (collimated beam) or at any other position other than the detector aperture, the user shall check, document, and quantify to which extent this affects the near-specular instrument signature and the compatibility with results obtained from TS measurements according to ISO 13696.

The focal length of the beam preparation system shall be adjustable so that the refractive power of the specimen can be compensated.

Single surface mirrors are preferred as optical components, because they usually produce less scattering and thus enable better (lower and narrower) instrument signatures to be achieved. Ideally the ARS of the mirrors should be lower than the ARS of the specimen to be measured.

If spherical mirrors are used, the angles of incidence should be as small as possible to reduce aberrations that can critically affect the instrument signature in the near-specular regions.

The beam diameter on the specimen shall be documented. It shall be smaller than the field of view of the detector at the specimen position. Typical diameters are between D = 0,4 mm and 10 mm. The field of view shall be adapted to the beam diameter.

NOTE Some applications require focussing onto the specimen. Thus, substantially smaller beam diameters down to the micrometre range can be achieved, but the larger beam size at the position of the detector aperture makes scattering into small angles close to the specular directions inaccessible. The actual near-angle limit can be assessed by inspecting the instrument signature.

Beam traps surrounding the instrument shall be used and positioned to absorb all specularly reflected and normally transmitted beams. Additional beam traps might be necessary to absorb off-specular diffraction peaks from diffractive specimens.

6.2.5 Goniometer

Typically, a goniometer is used to measure the ARS.

The inner goniometer contains the specimen mount and allows for adjusting the angle of incidence. The angle of incidence shall be documented.

The specimen mount shall allow for adjusting the specimen in all three dimensions as well as its tilt. Motorized stages are preferred for performing automated specimen scans and scattering maps.

The outer goniometer arm carries the detector system.

Instruments with one degree of freedom allow for scanning in one plane – usually the plane of incidence. These measurements are referred to as “in-plane ARS measurements”.

The range of scatter angles shall be documented. For constant step size, this can be done by stating the minimum and maximum scatter angles as well as the step size.

More advanced instruments allow for scanning the detector within the entire sphere or along arbitrary paths around the specimen. The measurements are referred to as “3D ARS measurements” or “out-of-plane ARS measurements”, respectively.

The step width of scattering angles should be sufficiently small such that the solid angles covered by the detector aperture at two successive measurement positions overlap by at least 30 %.

The mechanical resolution of the goniometer arms and the reproducibility are documented if necessary for both general measurements and near-specular measurements. The mechanical resolution shall be adapted to the detector acceptance angle and shall be 0,1° or better.

The mechanical resolution or step size shall not be confused with the actual angular resolution, in particular the capability to separate specimen scattering from the specular beams at small scatter angles.

Larger step sizes with no overlap between solid angles may be used for certain applications. The risk of potentially missing significant features in the ARS data and the influence on the ARS function as well as TS values derived from the ARS by integration shall be considered and taken into account in the uncertainty analysis.

ARS measurements should always be performed with both the specimen and the illuminating beam fixed during scans in order to reduce the impact of alignment errors and ensure that the specularly reflected and transmitted beams hit the beam traps at all times.

An alternative method to measure ARS is based on a detector matrix with separate detector elements (pixels) for detecting the radiation at different scattering angles rather than using a single scanning detector.

6.2.6 Detection system

The detection system consists of an aperture, the photosensitive detector and amplifiers. Additional optical components can be used to limit the field of view of the detector (for example a field lens), to homogenize the incoming radiation in front of the detector, or to suppress stray radiation from reaching the detector on unwanted paths.

The effective detector aperture defines the detector solid angle. Using different aperture diameters is preferred to increase the sensitivity (large aperture) and the near-specular resolution (small aperture). The detector solid angle used during the measurements shall be documented. If different apertures are used for different scatter angles, the detector solid angle shall be documented for each scatter angle.

An integrating sphere or a diffuser should be used to reduce the position-dependent sensitivity of the detector.

Photomultiplier tubes, photodiodes, or any other photosensitive detectors are used to measure the scattered radiant power. An optical fibre may be used to collect the scattered radiation and transport it to an external detector. The spectral sensitivity and the temporal behaviour shall match the characteristics of the radiation source.

Lock-in techniques or other techniques to increase the signal-to-noise ratio are recommended to increase the sensitivity.

The dynamic range and the linearity shall be documented.

If a multi-element detector is employed without an imaging system (objective), the aperture diameter defining the detector solid angle corresponds to the effective area of each element. If there is an optical system at the entrance of the multi-element detector, the response of the ensemble (imaging system and detector elements) will define the solid angle of detection. Normally this would be the spatial point spread function.

6.2.7 Specimen preparation

The specimen shall have specified geometry and optical imaging properties. This test method is non-destructive and shall be applied to the actual part.

Wavelength, angle of incidence, polarization, and range of scattering angles shall be in accordance with the conditions for normal use. Modified conditions may be used for specific investigations.

Storage, cleaning, and preparation of the specimen are carried out according to directions given by the manufacturer for normal use.

In the absence of specimen handling specifications, the following procedures shall be applied:

a) The specimen shall be kept under cleanroom conditions in accordance with Table 1 and the cleanroom classes as defined in ISO 14644-1 without interruption and handled by the non-optical surfaces only.

b) The handling and measurement procedures shall be optimized for a minimum exposure time of the specimen to the test environment.

c) The relative humidity shall be higher than 40 % and should be lower than 60 %.

Surface contaminations may have a substantial impact onto the measured ARS. It shall be clarified whether potential contaminations of the specimen have to be considered as being part of the specimen or if they should be removed before or avoided during measurement.

Table 1 — Cleanroom classes for the specimen preparation environment

Expected ARS %	Environment for specimen preparation
$\tilde{f} > 0{,}01$	Cleanroom better than class 7
$0{,}01 \geq \tilde{f} > 0{,}001$	Cleanroom better than class 6
$\tilde{f} \leq 0{,}001$	Cleanroom better than class 5

NOTE 1 The cleanroom classes are defined according to ISO 14644-1.

NOTE 2 These values have been derived from the values as given in ISO 13696:2002, Table 3. σ_{TS} can be obtained using formula in 3.3.

7 Procedure

7.1 General

The fundamental principle (see Figure 2) of the measurement apparatus is based on measuring the radiant power scattered from the specimen as a function of the scattering angles using a detector with a small but finite aperture that is scanned around the specimen, usually but not necessarily along circles centred at the origin of coordinates.

7.2 Alignment procedure

7.2.1 General

The alignment of the experimental arrangement comprising the instrument itself as well as the specimen is of crucial importance for the accuracy of the measurement.

7.2.2 Alignment of the instrument

The instrument shall be aligned first without a specimen present.

It shall be ensured that the rotation axes of the inner and outer goniometer arms are collinear and that all rotation axes and the incoming beam meet in the origin of coordinates with an accuracy better than 0,5 mm.

The incident beam shall be adjusted such that the focal point, typically the image of the pinhole, is formed at the centre of the detector aperture. In case of collimated illumination, the incident beam shall be adjusted such that the transmitted and/or reflected beams are centred in the detector aperture.

After alignment of the instrument and calibration, the instrument signature shall be measured and documented.

7.2.3 Alignment of the specimen

The specimen is attached to the specimen mount and aligned such that the centre of the illuminated spot at the specimen as well as the centre of the specimen's region of interest are in the origin of coordinates.

The angle of incidence is adjusted according to the specifications.

If the specimen exhibits a significant refractive power, the focal shift has to be compensated by the beam preparation system such that the beam waist falls into the detector aperture. The user has to ensure that the axis alignment (see 7.2.2) remains accurate. The specimen's position shall be adjusted such that the incoming beam illuminates a spot at the specimen according to the specifications.

7.3 Calibration

7.3.1 General

Calibration of the instrument is essential in order to obtain reproducible and objective measurement results.

Two methods are described:

— Method 1 is based on measuring the detector solid angle and the signal corresponding to the incident radiant power directly.

— Method 2 is based on comparing the measured scattering signal of a diffuse reference specimen with its known ARS.

The calibration method used shall be documented.

7.3.2 Method 1

According to the definition, ARS can be measured if the ratio of the scattered radiant power to the incident radiant power and the detector solid angle are known.

If the diameter of the detector aperture is much smaller than the distance between the detector and the specimen, the detector solid angle can be calculated following Formula (1):

$$\Delta\Omega_\mathrm{s} = \frac{A}{r^2} \tag{1}$$

where

A is the area of the detector aperture;

r is the distance between the detector aperture and the specimen.

The incident radiant power can be measured by placing the detector directly in the incoming beam without any specimen present. In this case, the aperture of the detector shall be such that it accommodates the entire cross-section of the laser beam. Clipping shall be smaller than 1 % of the total beam radiant power or energy. (For more information see ISO 13694). Then ARS is given by the following Formula (2):

$$\tilde{f}(\theta_s,\phi_s)=cV_s(\theta_s,\phi_s) \quad \text{with} \quad c=\frac{1}{V_0\Delta\Omega_s} \tag{2}$$

where

V_0 is the signal at the detector, for example a voltage, when measuring the incident radiant power;

V_s is the signal at the detector when detecting the scattered radiation at some scattering angle.

NOTE The accuracy of this method crucially depends on the exact knowledge of the effective area of the detector aperture as well as on linearity over many orders of magnitude dynamic range.

7.3.3 Method 2

If the measured detector signal is a voltage, ARS can be measured by recording the detector signal V_s corresponding to the scattered radiation and calibrating using a constant calibration factor *c* following Formula (3).

$$\tilde{f}(\theta_s,\phi_s)=cV_s(\theta_s,\phi_s) \tag{3}$$

The calibration factor can be determined by measuring the scattering signal V_{ref} of a reference specimen with known ARS following Formula (4):

$$c=\frac{\tilde{f}_{ref}(\theta_s,\phi_s)}{V_{ref}(\theta_s,\phi_s)} \tag{4}$$

The calibration measurement should be performed over a range of scatter angles followed by least square curve fitting to reduce the impact of speckle effects.

NOTE The ARS of a Lambertian reference specimen with the entire reflected and scattering light in reflective hemisphere, ρ, at normal incidence is given by Formula (5):

$$\tilde{f}_{ref}=\frac{\rho}{\pi}\cos\theta_s \tag{5}$$

Care shall be taken in case a volume diffuser is used as the diffuse reflectance standard. Volume scattering materials may cause a broadening of the diffuse emission profile of the diffuse reflectance standard. In particular the field of view of the detector shall be larger than the emitting area of the calibration specimen.

7.4 Measurement procedure

Before the actual measurement, it has to be ensured that the instrument is well aligned and calibrated and the current state of the instrument has not changed.

The method used for calibration as well as the corresponding measurement data of the calibration procedure shall be documented.

The detector solid angle(s) shall be documented including a description of how it was determined and its associated uncertainty of measurement.

The instrument signature shall be measured by measuring the ARS function without the specimen in place.

The influence of stray radiation, aberrations, noise, and other factors can only be estimated based on the measured instrument signature. The noise-equivalent ARS can be estimated from the instrument signature. It is usually estimated by the average of the instrument signature in the regions of lowest ARS. The dynamic range is the ratio of the highest signal (usually the incident or specular peak) and the noise equivalent ARS. Inserting the specimen may lead to additional effects influencing the measured ARS function of the specimen. One example is stray radiation from the beam dump for the specularly reflected beam.

The measured instrument signature shall be documented and taken into consideration when analysing the ARS data of the specimen.

Angular regions in which the signal of the specimen is below the instrument signature or in the same order of magnitude shall not be used. Depending on the nature of the specimen, however, the instrument signature might affect the scatter signal from the specimen differently.

EXAMPLE Instrument signature measured at 532 nm and s-polarized incident light using a detector with $\Delta\Omega_s = 3{,}1\times10^{-6}$ sr and as the radiation source a Nd:YAG-Laser. The peak at 180° corresponds to the specularly transmitted beam. The width of this peak limits the near angular resolution. The peak around 0° results from backscattering from the beam dump and Rayleigh scatter in the air. The level of scatter between the peaks is ultimately limited by Rayleigh scatter in the air. The noise level between the peaks is an indication of the electronic noise ultimately limiting the sensitivity of the measurement in this example. See Figure 3.

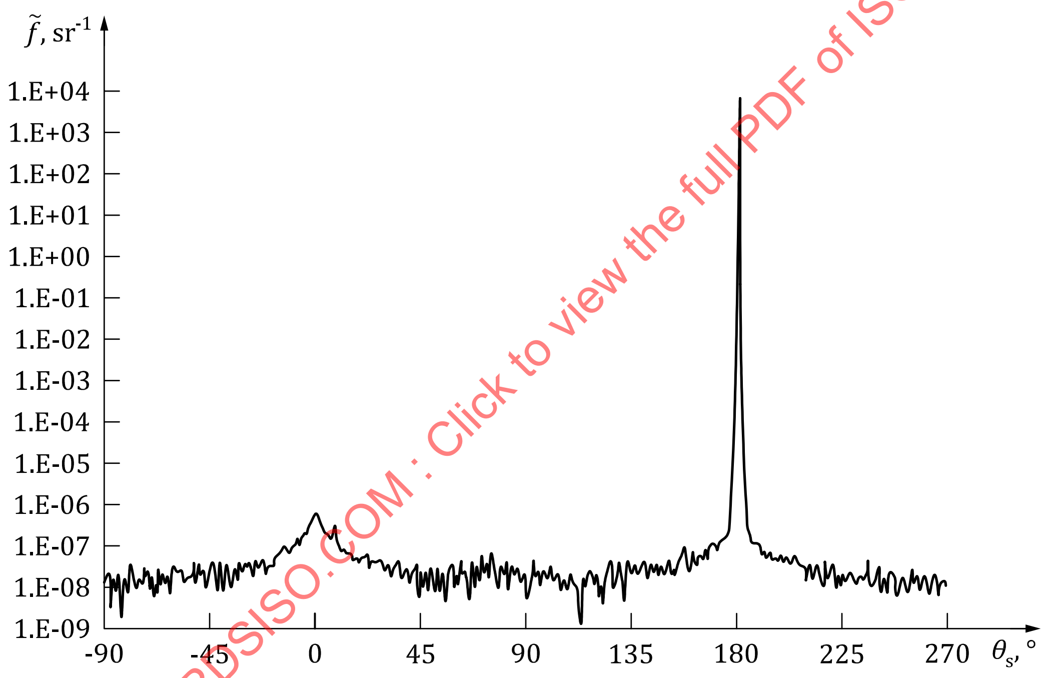


Figure 3 — Example of instrument signature

7.4.1 Selection of specimen position

The lateral position of the specimen with respect to the illuminating beam or the origin of coordinates shall be selected according to the specifications and characterization task.

If no specific specimen position is given, a number of measurements is performed on a defined grid or line of equally spaced measurement positions on the specimen as follows: The number N of measurement positions is defined.

For all ARS curves $\tilde{f}$ the TS value σ_{TS} is calculated according to the formula given in 3.3.

Either all ARS curves or at least the following ARS curves shall be documented:

— The minimum ARS $\tilde{f}_{min}$, which is the ARS curve with the smallest TS value;

— The maximum ARS $\tilde{f}_{\text{max}}$, which is the ARS curve with the largest TS value;

— The average ARS $\tilde{f}_{\text{avg}}$ calculated following Formula (6):

$$\tilde{f}_{avg}(\theta_s,\phi_s)=\frac{1}{N}\sum_{n=1}^{N}\tilde{f}_n(\theta_s,\phi_s) \quad (6)$$

From a statistical point of view it is clear that the more specimen points are selected the more robust the resulting average becomes. However this has to be balanced with the increasing total measurement time and available specimen area.

EXAMPLE For a test specimen with a diameter of 25 mm, a spot diameter of 2 mm, a 3 × 3 grid with a spacing of 2 mm is selected. Nine ARS curves are measured, and the minimum, maximum and average curves are documented.

7.4.2 Selection of illumination conditions

The angle of incidence and polarization conditions shall be adjusted according to the specifications and documented.

7.4.3 Selection of angular scan range

The range of scattering angles to be scanned and their increments shall be selected according to the specifications and documented.

7.4.4 Determination of the ARS

The ARS as a function of the scattering angles is determined following Formula (7):

$$\tilde{f}(\theta_s,\phi_s)=cV_s(\theta_s,\phi_s) \quad (7)$$

with the calibration factor c determined according to one of the methods described in 7.3.

The ARS data shall be documented as a function of the scattering angles.

7.5 Uncertainty considerations

Critical sources of measurement uncertainty are errors caused by misalignment, stray radiation from the beam preparation system, fluctuations of the source radiant power, and non-linearities and noise in the detection system.

The dominating source of noise in photodiodes is dark current. In photomultipliers, the primary noise source is shot noise of the dark current arising from the quantum nature of the photons, the uncertainty in photon arrival rates, and electron emission probability. These can be assessed by repeating the measurement N times and taking the standard deviation of the mean.

In addition, electromagnetic disturbances may couple into the detection system through cables and connectors. Sources of error are deviations from linearity as well as statistical fluctuations of the dynode gain (excess noise).

A detailed uncertainty analysis can be performed based on knowledge of the individual contributions and error propagation. However, not all contributions to measurement uncertainty can be taken into account without further approximations using this approach. A more detailed analysis of measurement uncertainty is possible through Monte-Carlo simulations or a combination of both approaches.

An example of an uncertainty analysis as a function of the scattering angle is shown in Figure 4. One main result is that the uncertainty substantially varies depending on the scattering geometry, the specimen properties, and the scattering angle. At very large angles, the uncertainty is dominated by