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CALIBRATION OF OPTICAL SPECTRUM ANALYZERS

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86/202/NP	86/214/RVN

Following publication of this PAS, which is a pre-standard publication, the technical committee or subcommittee concerned will transform it into an International Standard.

CALIBRATION OF OPTICAL SPECTRUM ANALYZERS

1 Scope

This document provides procedures for calibrating an optical spectrum analyzer designed to measure the power distribution of an optical spectrum; this analyzer is equipped with an input port for use with a fibre-optic connector.

An optical spectrum analyzer is equipped with the following minimum features:

a) the ability to present a display of an optical spectrum with respect to absolute wavelength;
b) a marker/cursor that displays the optical power and wavelength at a point on the spectrum display.

NOTE This specification applies to optical spectrum analyzers developed for use in fibre-optic communications and is limited to equipment that can directly measure the optical spectrum output from an optical fibre, where the optical fibre is connected to an input port installed in the optical spectrum analyzer through a fibre-optic connector.

In addition, an optical spectrum analyzer can measure the spectral power distribution with respect to the absolute wavelength of the tested light and display the results of such measurements; it will not include an optical wavelength meter that measures only centre wavelengths, a Fabry-Perot interferometer or a monochromator that has no display unit.

The procedures outlined in this document are considered to be mainly performed by users of optical spectrum analyzers. The document, therefore, does not include correction using the calibration results in the main body. The correction procedures are described in Annex C. Of course, this document will be useful in calibration laboratories and for manufacturers of optical spectrum analyzers.

2 Normative references

The following referenced documents are indispensable for the application 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.

IEC 60050-731:1991, *International Electrotechnical Vocabulary (IEV) – Chapter 731: Optical fibre communication*

IEC 60359:2001, *Electrical and electronic measurement equipment – Expression of performance*

IEC 60793-1(all parts), *Optical fibres – Part 1: Measurement methods and test procedures*

IEC 60825-1:1993, *Safety of laser products – Part 1: Equipment classification, requirements and user's guide*

IEC 60825-2:2000, *Safety of laser products – Part 2: Safety of optical fibre communication systems*

IEC 61290-3-1:2003, *Optical amplifiers – Test methods – Part 3-1: Noise figure parameters – Optical spectrum analyzer method*

ISO 9000*: Quality management systems – Fundamentals and vocabulary*

ISO:1995, *Guide to the expression of uncertainty in measurement*

ISO:1993, *International vocabulary of basic and general terms in metrology*

3 Definitions

For the purposes of this document, the definitions contained in IEC 60050-731 and the following definitions apply.

3.1
calibration
set of operations which establishes, under specified conditions, the relationship between the values indicated by the measuring instrument and the corresponding known values of that quantity (see also ISO International vocabulary of basic and general terms in metrology, definition 6.11)

3.2
calibration under reference conditions
calibration which includes the evaluation of the test analyzer uncertainty under **reference conditions** (3.17)

3.3
calibration for operating conditions
calibration for operating conditions of an **optical spectrum analyzer** (3.16) including the evaluation of the test analyzer operational uncertainty

3.4
centre wavelength
$\boldsymbol{\lambda_{centre}}$
power-weighted mean wavelength of a light source in a vacuum, in nanometers (nm)

For a continuous spectrum, the centre wavelength is defined as

$$\lambda_{centre} = (1 / P_{total}) \int \rho(\lambda)\, \lambda \, d\lambda \quad (1)$$

For a spectrum consisting of discrete lines, the centre wavelength is defined as

$$\lambda_{centre} = \sum_i P_i \lambda_i \ / \sum_i P_i \quad (2)$$

where

$\rho(\lambda)$ is the power spectral density of the source, for example in W/nm;

λ_i is the i^{th} discrete wavelength;

P_i is the power at λ_i, for example, in watts;

P_{total} is ΣP_i = total power, for example, in watts.

NOTE The above integrals and summations theoretically extend over the entire spectrum of the light source.

3.5
confidence level
estimation of the probability that the true value of a measured parameter lies in the given range (see **expanded uncertainty** (3.11))

3.6
coverage factor
k
coverage factor, k, is used to calculate the **expanded uncertainty** (3.11) U from the **standard uncertainty** (3.21), σ (see 3.11)

3.7
displayed power level
DPL
power level indicated by an **optical spectrum analyzer** (3.16) undergoing **calibration** (3.1) at a specified wavelength resolution setting

NOTE With an **optical spectrum analyzer**, the power level for a set resolution is measured and displayed.

3.8
displayed power level deviation
ΔP
difference between the displayed power level measured by the test analyzer, P_{OSA}, and the corresponding reference power, P_{ref}, divided by the reference power

$$\Delta P = (P_{OSA} - P_{ref}) / P_{ref} = P_{OSA} / P_{ref} - 1 \tag{3}$$

3.9
displayed power level uncertainty, symbol $\sigma_{\Delta P}$
standard uncertainty (3.21) of the displayed power level deviation

$$\sigma_{\Delta P} = \sigma(P_{OSA} / P_{ref} - 1) \tag{4}$$

NOTE In the above formula, σ is to be understood as the **standard uncertainty** (3.21).

3.10
displayed wavelength range
complete wavelength range shown in an **optical spectrum analyzer** (3.16) display for a particular **instrument state** (3.12)

3.11
expanded uncertainty
U
expanded uncertainty, *U* (also called the confidence interval) is the range of values within which the measurement parameter, at the stated **confidence level** (3.5), can be expected to lie. It is equal to the **coverage factor** (3.6), *k*, times the combined **standard uncertainty** (3.21) σ:

$$U = k\,\sigma \tag{5}$$

NOTE When the distribution of uncertainties is assumed to be normal and a large number of measurements are made, then **confidence levels** (3.5) of 68,3 %, 95,5 % and 99,7 % correspond to *k* values of 1, 2 and 3 respectively.

The measurement uncertainty of an **optical spectrum analyzer** (3.16) should be specified in the form of expanded uncertainty, *U*.

3.12
instrument state
complete description of the measurement conditions and state of an **optical spectrum analyzer** (3.16) during the calibration process

NOTE Typical parameters of the instrument state are the **displayed wavelength range** (3.10) in use, the **resolution bandwidth (spectral resolution)** (3.18), the display mode (watt or dBm), warm-up time and other instrument settings.

3.13
measurement result
displayed or electrical output of any **optical spectrum analyzer** (3.16) in wavelength, in units of nm or µm, and in power level, in units of mW or dBm, after completing all operations suggested by the operating instructions, for example warm-up

3.14
measurement wavelength range
wavelength range of injected light over which an **optical spectrum analyzer** (3.16) performance is specified

3.15
operating conditions
all conditions of the measured and influential qualities, and other important requirements which the **expanded uncertainty** (3.11) of an **optical spectrum analyzer** (3.16) is intended to be met (modified from ISO International vocabulary of basic and general terms in metrology, definition 5.5)

3.16
optical spectrum analyzer
OSA
optical instrument for measuring the power distribution of a spectrum with respect to wavelength (frequency)

NOTE An OSA is equipped with an input port for use with a fibre-optic connector, and the spectrum is obtained from light injected into the input port; the instrument also includes a screen-display function.

3.17
reference conditions
appropriate set of influencing parameters, their nominal values and their tolerance bands, with respect to which the uncertainty at reference conditions is specified (modified from IEC 60359, 3.3.10)

NOTE Each tolerance band includes both the possible uncertainty of the condition and the uncertainty in measuring the condition.

The reference conditions normally include the following parameters and, if necessary, their tolerance bands: reference date, reference temperature, reference humidity, reference atmospheric pressure, reference light source, reference **displayed power level** (3.7), reference fibre, reference connector-adapter combination, reference wavelength, reference (spectral) bandwidth and **resolution bandwidth (spectral resolution)** (3.18) set.

3.18
resolution bandwidth (spectral resolution)
R
full width at half maximum (FWHM) of the displayed spectrum obtained by the test analyzer when using a source whose **spectral bandwidth** (3.20) is sufficiently narrow, that is, very much less than the resolution bandwidth being measured

3.19
side-mode suppression ratio
SMSR
peak power ratio between the main mode spectrum and the largest side mode spectrum in a single-mode laser diode such as a DFB-LD

NOTE The side-mode suppression ratio is usually described in dB.

3.20
spectral bandwidth
B
for the purpose of this document, the FWHM of the spectral width of the source.

If the source exhibits a continuous spectrum, then the spectral bandwidth, B, is the FWHM of the spectrum.

If the source is a laser diode with a multiple-longitudinal mode spectrum, then the FWHM spectral bandwidth B is the RMS spectral bandwidth, multiplied by 2,35 (assuming the source has a Gaussian envelope):

$$B = 2{,}35\ [\{(1 / P_{\text{total}}) \times \left[\sum_{i} P_i \lambda_i^{2}\right]\} - \lambda_{\text{centre}}^{2}]^{1/2} \qquad (6)$$

where

λ_{centre} is the **centre wavelength** (3.4) of laser diode, in nm;

P_{total} is $\sum P_i$ = total power, in watts;

P_i is the power of i^{th} longitudinal mode, in watts;

λ_i is the wavelength of i^{th} longitudinal mode, in nm.

3.21
standard uncertainty
σ
uncertainty of a measurement result expressed as a standard deviation

NOTE For further information, see Annex A and the ISO Guide to the expression of uncertainty in measurement.

3.22
uncertainty type A
type of uncertainty obtained by a statistical analysis of a series of observations, such as when evaluating certain random effects of measurement (see ISO Guide to the expression of uncertainty in measurement)

3.23
uncertainty type B
type of uncertainty obtained by means other than a statistical analysis of observations, for example an estimation of probable sources of uncertainty, such as when evaluating systematic effects of measurement (see ISO Guide to the expression of uncertainty in measurement)

NOTE Other means may include previous measurement data, experience with or general knowledge of the behaviour and properties of relevant materials, instruments, manufacturers' specifications, data provided in calibration and other certificates, and uncertainties assigned to reference data taken from handbooks.

3.24
wavelength deviation
$\Delta\lambda$
difference between the **centre wavelength** (3.4) measured by the test analyzer, λ_{OSA}, and the reference wavelength, λ_{ref}, in nm or µm

$$\Delta\lambda = \lambda_{OSA} - \lambda_{ref} \tag{7}$$

3.25
wavelength uncertainty
$\sigma_{\Delta\lambda}$
standard uncertainty (3.21) of the **wavelength deviation** (3.24), in nm or µm

4 Calibration test requirements

4.1 Preparation

The following recommendations apply.

Calibrations should be carried out in facilities that are separate from other functions of the organization. This separation should include laboratory accommodation and measurement equipment.

The calibration laboratory should operate a quality control system appropriate to the range of measurement it performs (for example, ISO 9000), when the calibration is performed in calibration laboratories. There should be independent scrutiny of the measurement results, intermediary calculations and preparation of calibration certificates.

The environmental conditions shall be commensurate with the degree of uncertainty that is required for calibration:

a) the environment shall be clean;

b) temperature monitoring and control is required;

c) all laser sources shall be safely operated (see IEC 60825-1).

Perform all tests at an ambient room temperature of 23 °C ± 3 °C with a relative humidity of (50 ± 20) % unless otherwise specified. Give the test equipment a minimum of 2 h prior to testing to reach equilibrium with its environment. Allow the optical spectrum analyzer a warm-up period in accordance with the manufacturer's instructions.

4.2 Reference test conditions

The reference test conditions usually include the following parameters and, if necessary, their tolerance bands: date, temperature, relative humidity, displayed power level, wavelength, light source, fibre, connector-adapter combination, (spectral) bandwidth and resolution bandwidth (spectral resolution) set. Unless otherwise specified, use a single-mode optical fibre input pigtail as prescribed by IEC 60793-1, having a length of at least 2 m.

Operate the optical spectrum analyzer in accordance with the manufacturer's specifications and operating procedures. Where practical, select a range of test conditions and parameters which emulate the actual field operating conditions of the analyzer under test. Choose these parameters so as to optimize the accuracy of the analyzer and resolution capabilities, as specified by the manufacturer's operating procedures.

Document the conditions as specified in Clause 8.

NOTE 1 The calibration results only apply to the set of test conditions used in the calibration process.

NOTE 2 Because of the potential for hazardous radiation, be sure to establish and maintain conditions of laser safety. Refer to IEC 60825-1 and IEC 60825-2.

4.3 Traceability

Make sure that any test equipment which has a significant influence on the calibration results is calibrated in an unbroken chain to the appropriate national standard or natural physical constant. Upon request, specify this test equipment and its calibration chain(s). The re-calibration period(s) shall be defined and documented.

5 Resolution bandwidth (spectral resolution) test

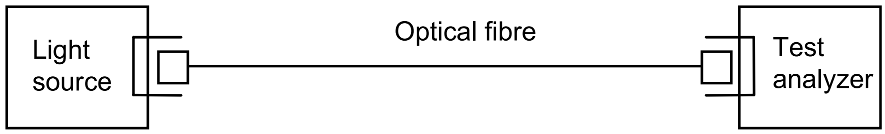
5.1 Overview

The resolution bandwidth (spectral resolution) of the test analyzer should be tested prior to displayed power level and wavelength calibration because the resolution bandwidth influences their calibration. This test is performed under reference calibration conditions. Wavelength is shown in a vacuum.

NOTE The result of the resolution bandwidth (spectral resolution) test described here should be employed as the optical bandwidth (in wavelength units) for the measurement of optical-amplifier noise-figure. The calibration of optical bandwidth is described in IEC 61290-3-1.

5.2 Resolution bandwidth (spectral resolution) test

Alternative set-ups for the resolution bandwidth are shown in Figures 1, 2, and 3. In the Figure 1 set-up, a gas laser whose wavelength is known is used as the light source. Figure 2 shows a set-up in which a broadband source is used in conjunction with a transmission device with known (traceable) wavelengths of peak (or null) transmission. Figure 3 shows a set-up in which a laser diode (LD) whose wavelength is unknown is used for the light source.

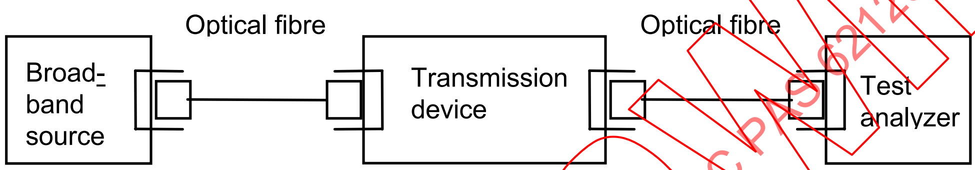


a) for resolution bandwidth test,

b) for wavelength calibration under reference conditions, and

c) for determining the wavelength dependence of wavelength uncertainty.

Figure 1 – Set-up using a gas laser whose wavelength is known

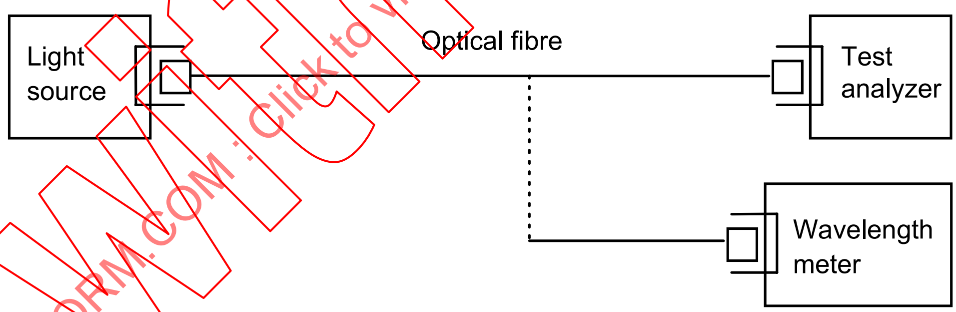


a) for resolution bandwidth test,

b) for wavelength calibration under reference conditions, and

c) for determining the wavelength dependence of wavelength uncertainty.

Figure 2 – Set-up using a broadband source with a transmission device



a) for resolution bandwidth test,

b) for wavelength calibration under reference conditions, and

c) for determining the wavelength dependence of wavelength uncertainty.

Figure 3 – Set-up using an LD with an unknown wavelength

5.2.1 Equipment for resolution bandwidth (spectral resolution) test

a) **Light source:** use the light source prescribed for calibrating the test analyzer; if a light source is not prescribed, use one with a spectral bandwidth and wavelength stability sufficient for the minimum resolution bandwidth prescribed for the test analyzer.

Recommended light sources are lasers such as those listed in Table 1, a laser diode (LD) or other laser (which may be tunable) having a spectral bandwidth much narrower than the resolution bandwidth of the test analyzer. Also, a broadband source may be used in conjunction with a transmission device with known (traceable) wavelengths of peak (or null) transmission. The transmission device may be, for example, a series of fixed narrowband filters, absorption lines in gaseous media, or Fabry-Perot interferometers. Annex D tabulates many stable wavelength references. The reference used should have a wavelength stability, spectral bandwidth, and power stability sufficient for the resolution bandwidth test.

Table 1 – Recommended light sources

Light source	Wavelength (nm) [vac]
Ar laser	488,122
	514,673
He-Ne laser	632,991
	1152,590
	1523,488

b) **Wavelength meter:** an instrument for measuring the wavelength of a light source. Its precision must be sufficiently better than the precision required in the wavelength test. This instrument is used when a laser diode (LD) with an unknown wavelength is used as the light source.

c) **Optical fibre:** single-mode optical fibre as prescribed by IEC 60793-1.

5.2.2 Test procedure for resolution bandwidth (spectral resolution)

Using the test set-up shown in Figure 1, 2 or 3, set the wavelength measurement range of the test analyzer so that it includes the wavelength of the light source.

a) Set the resolution bandwidth of the test analyzer to its specified value. Let the specified value be R_{set}.

b) Measure the resolution of the displayed spectral bandwidth, that is, the wavelength interval 3 dB below the peak value, as R_{OSAi}. Repeat this measurement at least ten times and calculate the average resolution.

$$R_{OSA} = \sum_{i=1}^{m} R_{OSAi} \;/\; m \qquad (8)$$

where m is the number of measurements.

c) Calculate the difference ratio of the OSA value from the resolution bandwidth setting using equation (9).

$$\Delta r_{diff} = R_{OSA} / R_{set} - 1 \qquad (9)$$

d) If necessary, repeat this procedure with different resolution bandwidth settings.

NOTE 1 When the test analyzer has a wavelength span linearity error, it is necessary to tune the light source slightly around the wavelength of interest, while making multiple measurements of the displayed 3 dB bandwidth to obtain an accurate measurement of the true resolution bandwidth at a given wavelength. The required tuning range is of the order of ±1 nm, so this measurement can be made with a temperature-tuned DFB laser, an external cavity laser or a tunable fibre laser. By averaging the resolution bandwidth readings, a more accurate measurement of the true resolution bandwidth can be obtained.

NOTE 2 If the resolution bandwidth should be corrected on the basis of the calibration results, this is typically implemented by making software corrections to the instrument, mathematical corrections to the results, or instrument hardware adjustments. Once the adjustments have been made, it is advisable to repeat the test to verify that the correction has operated correctly. See Annex C.

6 Displayed power level calibration

6.1 Overview

The factors making up uncertainty in the displayed power level of the test analyzer consist of

a) the intrinsic uncertainty of the test analyzer as found in the test under reference conditions, and

b) partial uncertainties due to wavelength dependence, polarization dependence, linearity and temperature dependence as found in tests under operating conditions.

If the test analyzer is used beyond the reference conditions, it is necessary to obtain the partial uncertainties.

The intrinsic uncertainty under the reference conditions is obtained by the calibration procedure described in 6.2. The partial uncertainties are obtained by the calibration procedure described in 6.3.1 to 6.3.4 in compliance with the individual factor, that is, wavelength, polarization, linearity and temperature. When the test analyzer is only used under reference conditions, the calibration procedures described in 6.3 are not essential, that is, they are not mandatory.

NOTE 1 Since the unit generally used for measurement values, dBm, is not appropriate for uncertainty accumulation, linear units (mW, µW) are used. Results of such accumulations can be converted back to dB to express overall uncertainty when needed.

NOTE 2 A power meter or a reference power meter will be needed to check the light source power each time a new source wavelength is used.

NOTE 3 The state of polarization should not be changed during calibration except controlling by an optional polarization controller.

6.2 Displayed power level (DPL) calibration under reference conditions

Figure 4 shows the test configuration for determining the uncertainty in the displayed power level (DPL). This test is performed under reference calibration conditions.

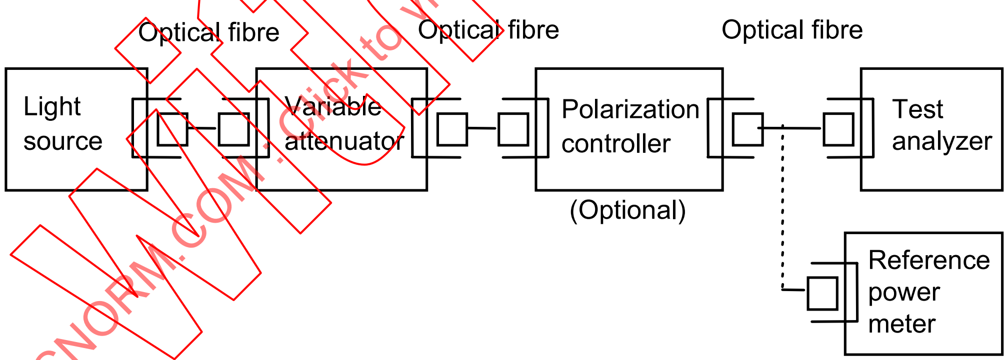


Figure 4 – Set-up for calibration of displayed power level under reference conditions

NOTE The light source used for the displayed power level calibration should be depolarized, or else a polarization controller should be used. This will calibrate the test analyzer at the mid-point of its variation due to polarization

6.2.1 Equipment for DPL calibration under reference conditions

a) **Light source:** use a light source which can emit stable optical-fibre light with an output from 0,1 mW (–10 dBm) to 1 mW (0 dBm), and which offers good suppression of side-modes and optical noise (>40 dB, when measured with a resolution bandwidth which is the same as that of the test analyzer) outside its spectral bandwidth. The source spectral bandwidth should, in turn, be sufficiently narrower than the resolution prescribed for the test analyzer. The light sources shown in Table 1, a laser diode (LD) (SMSR > 40 dB: see 3.19) or a fibre laser (also with SMSR > 40 dB) are recommended.

NOTE The wavelength of the light source should be measured in advance by using a wavelength meter if a laser diode (LD) or a fibre laser is used.

b) **Variable attenuator:** use a variable attenuator that can be adjusted over the optical power range used in the test.

c) **Reference optical power meter:** either of the following operated under reference calibration conditions:

   1) an optical power meter calibrated by an official institution that performs calibration services with a stated uncertainty; or

   2) an optical power meter calibrated according to standards specified by such an official institution with a stated uncertainty.

   Namely, the uncertainty of the reference power meter, σ_{PPM}, is already known and is described in its certification.

d) **Optional polarization controller:** a polarization controller is used which controls the state of polarization of incident light to obtain an optical fibre output with an extinction ratio of 20 dB or more. The level variation when the state of polarization is changed should be far smaller than the polarization dependence of the test analyzer. Some polarization controllers are combinations of a polarizer, a 1/2-wavelength plate and a 1/4-wavelength plate; some rotate two fibre loops.

6.2.2 Test procedure for DPL calibration under reference conditions

Using the test configuration shown in Figure 5, set the resolution of the test analyzer sufficiently larger than the spectral bandwidth of the light source. Adjust the variable attenuator so that the power level of the outgoing light to the test analyzer is optimized. If the wavelength of the light source is not already known, it should be measured by using a wavelength meter.

The measurement sequence is as follows.

a) Measure the value of the outgoing optical-fibre light as $P_{REF,i}$ using a reference optical power meter. If a polarization controller is used, measure multiple times at different states of polarization and average these values.

b) After this, connect the outgoing optical-fibre light to the test analyzer and read the peak power level measured by the test analyzer as P_{OSAi}; use a linear scale (in units of mW or μW) to read the value. If a polarization controller is used, measure multiple times at different states of polarization and average these values.

c) Calculate the difference ratio of the OSA value from the power meter measurement using equation (10).

$$\Delta P_{diff,i} = P_{OSAi} / P_{REF,i} - 1 \tag{10}$$

d) Repeat this measurement at least ten times.

6.2.3 Calculation of DPL uncertainty under reference conditions

Calculate the mean and standard deviation of the difference ratio using the following equations.

$$\Delta P_{diff} = \sum_{i=1}^{m} (\Delta P_{diff,i}) \ / \ m \tag{11}$$

$$\sigma_{\Delta P diff} = \left[\sum_{i=1}^{m} (\Delta P_{diff,i} - \Delta P_{diff})^2 / (m-1) \right]^{1/2} \tag{12}$$

where m is the number of measurements used.

The uncertainty $\sigma_{\Delta Pref}$ with respect to the displayed power level for the test analyzer operated under reference calibration conditions is given by equation (13).

$$\sigma_{\Delta Pref} = (\sigma_{PPM}^2 + \sigma_{\Delta Pdiff}^2)^{1/2} \quad (13)$$

where

σ_{PPM} is the uncertainty of the reference optical power meter described in its certification;

$\sigma_{\Delta Pdiff}$ is the standard deviation of the values measured during the test.

The displayed power level deviation ΔP_{ref} is given by equation (14), which is the same as the mean value of the difference ratio.

$$\Delta P_{ref} = \Delta P_{diff} \quad (14)$$

6.3 Displayed power level (DPL) calibration for operating conditions

The calibration described in this chapter is not mandatory. Perform the calibration procedure when the test analyzer is used beyond the reference calibrations.

Individual factors in the displayed power level uncertainty for the operating conditions may consist of the following:

1) wavelength dependence;
2) polarization dependence;
3) linearity; and
4) temperature dependence.

6.3.1 Wavelength dependence

Figure 5 shows the test configuration for determining wavelength dependence. This test is performed under reference calibration conditions except for the wavelength.

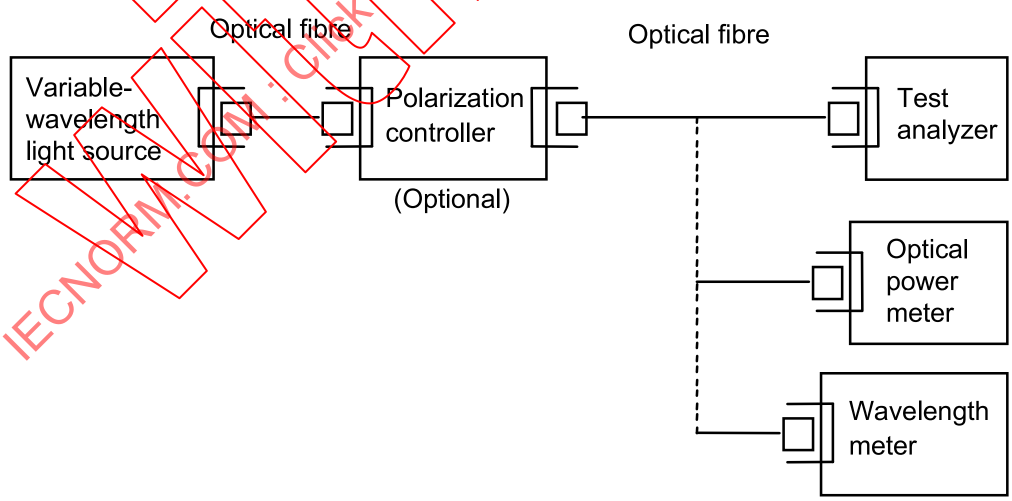


Figure 5 – Test configuration for determining the wavelength dependence of displayed power level uncertainty

6.3.1.1 Equipment for determining DPL wavelength dependence

a) **Light source:** use a variable-wavelength light source such as a tunable laser. It should supply the needed amount of light power stably within the test wavelength range of the test analyzer, and its spectral bandwidth should be far narrower than the specified resolution bandwidth of the test analyzer.

b) **Wavelength meter:** use to measure the wavelength of the variable-wavelength light source. It is unnecessary if the light source has been calibrated.

c) **Optical power meter:** use a non-wavelength-dependent optical power meter, or one whose wavelength dependence has been calibrated.

d) **Optional polarization controller:** a polarization controller is used which controls the state of polarization of incident light to obtain an optical fibre output with an extinction ratio of 20 dB or more. The level variation when the state of polarization is changed should be far smaller than the polarization dependence of the test analyzer. Some polarization controllers are combinations of a polarizer, a 1/2-wavelength plate and a 1/4-wavelength plate; some rotate two fibre loops.

6.3.1.2 Test procedure for determining DPL wavelength dependence

Use the test configuration shown in Figure 5.

The test procedure is as follows.

a) After the environmental temperature is completely stabilized, input light from the light source to the wavelength meter for wavelength measurement. The reading provided by the wavelength meter is defined as λ_j.

b) Using the optical power meter, measure the optical power of the light source. The reading provided by the optical power meter is defined as $P_{REF,j}$. If a polarization controller is used, measure multiple times at different states of polarization and average values.

c) Input light from the light source to the test analyzer. The resolution bandwidth (spectral resolution) of the test analyzer should be preset so as to be wider than the spectral bandwidth of the incident light. The peak power level measured by the test analyzer is defined as P_{OSAj}. If a polarization controller is used, measure multiple times at different states of polarization and average the values.

   The deviation error at wavelength λ_j, $\Delta P(\lambda_j)$, is given by equation (15).

$$\Delta P(\lambda_j) = P_{OSAj} / P_{REF,j} - 1 \qquad (15)$$

d) Repeat this procedure with different wavelength settings (change λ_j).

e) Let $\Delta P_{\lambda,MAX}$ and $\Delta P_{\lambda,MIN}$ be the maximum and minimum obtained values of $\Delta P(\lambda_i)$, respectively.

6.3.1.3 Calculation of DPL uncertainty due to wavelength dependence

The deviation of measured values dependent on the wavelength, ΔP_λ, is given by equation (16).

$$\Delta P_\lambda = (\Delta P_{\lambda,MAX} + \Delta P_{\lambda,MIN}) / 2 \qquad (16)$$

The standard uncertainty due to wavelength dependence, $\sigma_{\Delta P\lambda}$ is given by equation(17).

$$\sigma_{\Delta P\lambda} = (\Delta P_{\lambda,MAX} - \Delta P_{\lambda,MIN}) / 2\sqrt{3} \qquad (17)$$

6.3.2 Polarization dependence

Figure 6 shows the test configuration for determining polarization dependence. This test is performed under reference calibration conditions except for the polarization.

NOTE 1 The light source used should be at the reference wavelength. However, it is recommended that this test should be undertaken at several wavelengths at which the test analyzer is used, since the polarization dependence may differ according to the wavelength.

NOTE 2 The extinction ratio of the output from the polarization controller of the measurement system is assumed to be 20 dB at the output port of the fibre. The extinction ratio affects the precision of the polarization dependence test results; specifically, it reduces the measurement precision by about 2 % at 20 dB.

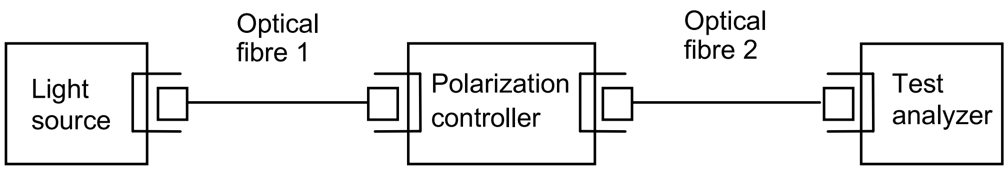


Figure 6 – Test configuration for determining the polarization dependence of displayed power level uncertainty

6.3.2.1 Equipment for determining DPL polarization dependence

a) **Light source:** use a stable light source with an output of 0,1 mW (–10 dBm) to 1 mW (0 dBm) and which has a spectral bandwidth sufficiently narrower than the resolution prescribed for the test analyzer. The light sources shown in Table 1, a laser diode (LD) (SMSR > 40 dB: see 3.19) or a fibre laser (also with SMSR > 40 dB) are recommended.

b) **Polarization controller:** a polarization controller is used which controls the state of polarization of incident light to obtain an optical fibre output with an extinction ratio of 20 dB or more. The level variation when the state of polarization is changed should be far smaller than the polarization dependence of the test analyzer. Some polarization controllers are combinations of a polarizer, a 1/2-wavelength plate and a 1/4-wavelength plate; some rotate two fibre loops.

c) **Optical fibre:** single-mode optical fibre, as prescribed by IEC 60793-1, having a length of 1 m to 2 m. A polarization maintaining fibre is preferred to the input fibre of some polarization controllers.

6.3.2.2 Test procedure for determining DPL polarization dependence

Using the test configuration shown in Figure 6, set the resolution bandwidth of the test analyzer sufficiently larger than the spectral bandwidth of the light source. Fix optical fibres in place to prevent them from moving, because the state of polarization in the fibre can vary due to motion of the fibre.

The test procedure performed at many wavelengths is as follows.

a) Input the light output from the light source into the polarization controller through optical fibre 1, and input the output from the controller into the test analyzer through optical fibre 2.

b) Adjust the polarization controller so that a large number of polarization states are produced which essentially cover the entire Poincare sphere. Observe the peak-to-peak change in displayed power level caused by changing the polarization state. Record the maximum and minimum readings as $P_{MAX}(\lambda j)$ and $P_{MIN}(\lambda j)$, respectively.

c) The variations in power level due to polarization with wavelengths of λj, $\Delta P_{UL}(\lambda j)$ and $\Delta P_{LL}(\lambda j)$, are given by equations (18) and (19).

$$\Delta P_{UL}(\lambda j) = P_{MAX}(\lambda j) / P_{AVE}(\lambda j) - 1 \qquad (18)$$

$$\Delta P_{LL}(\lambda j) = P_{MIN}(\lambda j) / P_{AVE}(\lambda j) - 1 \qquad (19)$$

where $P_{AVE}(\lambda j)$ is the average variation in power level due to polarization with a wavelength of λj, and is given by equation (20).

$$P_{AVE}(\lambda j) = [\, P_{MAX}(\lambda j) + P_{MIN}(\lambda j) \,] / 2 \qquad (20)$$

d) Repeat this procedure with different wavelength settings (change λj).

e) Let $\Delta P_{POL,\ MAX}$ be the maximum value of $\Delta P_{UL}(\lambda j)$, and $\Delta P_{POL,\ MIN}$ be the minimum value of $\Delta P_{LL}(\lambda j)$.

6.3.2.3 Calculation of uncertainty due to polarization dependence

The deviation of measured values dependent on the polarization and wavelength, ΔP_{POL}, is given by equation (21).

$$\Delta P_{POL} = (\Delta P_{POL,MAX} + \Delta P_{POL,MIN}) / 2 \quad (21)$$

The uncertainty of power level variations due to polarization, $\sigma_{\Delta PPOL}$, is given by equation (22).

$$\sigma_{\Delta PPOL} = (\Delta P_{POL,MAX} - \Delta P_{POL,MIN}) / 2\sqrt{3} \quad (22)$$

6.3.3 Linearity

Figure 7 shows the set-up for the linearity test. This test is performed under reference calibration conditions except for the power level.

NOTE The light source used must be at the reference wavelength. If there is more than one reference wavelength and the detector for the test analyzer is in danger of wavelength dependence, the linearity test should be performed at each of the reference wavelengths.

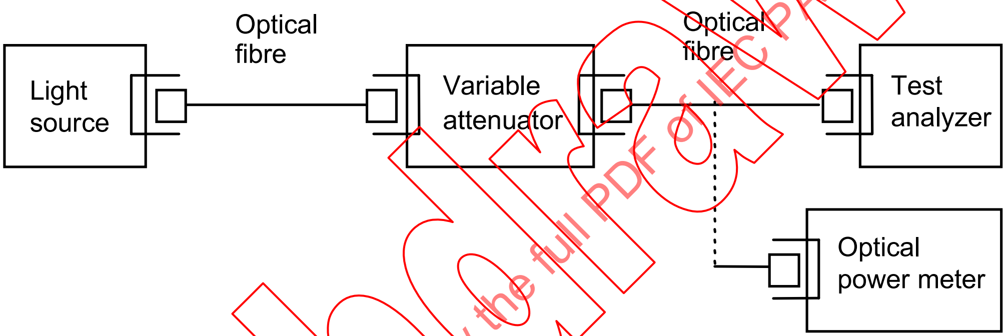


Figure 7 – Configuration for testing linearity error of displayed power level uncertainty

6.3.3.1 Equipment for determining DPL linearity error

a) **Light source:** Use a stable light source with an output of 0,1 mW (-10 dBm) to 1 mW (0 dBm) which has a spectral bandwidth sufficiently narrower than the resolution prescribed for the test analyzer. The light sources shown in Table 1, a laser diode (LD) (SMSR > 40 dB: see 3.19) or a fibre laser (also with SMSR > 40 dB) are recommended.

b) **Variable attenuator:** use a variable attenuator that can be adjusted over the optical power range used in the test.

c) **Optical power meter:** use an optical power meter that can accurately cover the power, wavelength and temperature ranges measured in the test.

6.3.3.2 Test procedure for determining DPL linearity error

a) With the test set-up shown in Figure 7, set the resolution bandwidth of the test analyzer so that it is far larger than the spectral bandwidth of the light source used for the measurement. Adjust the variable attenuator so that the power level of the light sent to the test analyzer is the same as that used for the power level calibration test under reference conditions.

   The readings from the test analyzer and the optical power meter at that time are defined as P_{OSA} and P_{REF}, respectively, and the ratio of the two as $P_{LIN,ref}$.

$$P_{LIN,ref} = P_{OSA} / P_{REF} \quad (23)$$

b) Then, change the power level of the light sent to the test analyzer, using the variable attenuator. The power level is defined as P_j. The readings from the test analyzer and the power meter are defined as P_{OSAj} and $P_{REF,j,}$ respectively, and the ratio of the two as $P_{LIN,j}$.

$$P_{LIN,j} = P_{OSAj} / P_{REF,j} \quad (24)$$

The linearity error at a power level of P_j, $\Delta P_{LIN,}$ (P_j), is given by equation (25).

$$\Delta P_{LIN,}(P_j) = P_{LIN,j} / P_{LIN,ref} - 1 \quad (25)$$

c) Repeat this procedure with different light power levels (change P_j) for at least five points within the input power level range specified in the test analyzer.

d) Let $\Delta P_{LIN,MAX}$ be the maximum value of $\Delta P_{LIN}(Pj)$ obtained, and $\Delta P_{LIN\ ,MIN}$ the minimum.

6.3.3.3 Calculation of uncertainty due to DPL linearity error

The deviation of measured values dependent on the light power levels, ΔP_{LIN}, is given by equation (26).

$$\Delta P_{LIN} = (\Delta P_{LIN,MAX} + \Delta P_{LIN,MIN})/2 \quad (26)$$

The uncertainty of linearity, $\sigma_{\Delta PLIN}$, is given by equation (27).

$$\sigma_{\Delta PLIN} = (\ \Delta P_{LIN,MAX} - \Delta P_{LIN,MIN}\ ) / 2\sqrt{3} \quad (27)$$

6.3.4 Temperature dependence

Figure 8 shows the test configuration for temperature dependence. This test is performed under reference calibration conditions with the exception of temperature.

NOTE The light source used must be at the reference wavelength. If there is more than one reference wavelength and the detector for the test analyzer is in danger of wavelength dependence and temperature dependence, the temperature dependence test should be performed at each of the reference wavelengths.

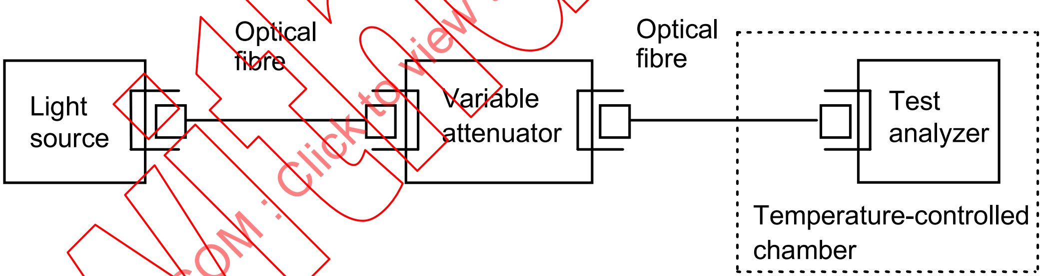


Figure 8 – Test configuration for determining the temperature dependence of displayed power level uncertainty

6.3.4.1 Equipment for determining DPL temperature dependence

a) **Light source:** Use a stable light source with an output of 0,1 mW (–10 dBm) to 1 mW (0 dBm) which has a spectral bandwidth sufficiently narrower than the resolution prescribed for the test analyzer. The light sources shown in Table 1, a laser diode (LD) (SMSR > 40 dB: see 3.19) or a fibre laser (also with SMSR > 40 dB) are recommended.

b) **Variable attenuator:** use a variable attenuator that can be adjusted over the optical power range used in the test.

6.3.4.2 Test procedure for determining DPL temperature dependence

a) With the test configuration shown in Figure 8, set the resolution bandwidth of the test analyzer so that it is far larger than the spectral bandwidth of the light source used for the measurement. After the temperature of the test analyzer is stabilized as specified under reference test conditions, adjust the attenuator so that the power level of the light sent to the test analyzer is the same as that used for the calibration under reference conditions. The reading provided by the test analyzer at that time is defined as $P_{OSA,Tref}$.

b) Then, change the temperature of the temperature-controlled chamber. Sufficient time (for example 2 h) must be allowed for the OSA undergoing calibration to reach thermal equilibrium at each temperature used. The new temperature is defined as T_j, and the test analyzer reading is defined as P_{OSAj}.

   The sensitivity error at temperature T_j, $\Delta P(T_j)$, is given by equation (28).

$$\Delta P(Tj) = P_{OSAj} / P_{OSA},Tref - 1 \tag{28}$$

c) Repeat this procedure with different temperature settings (change T_j).

d) Let $\Delta P_{TMP,MAX}$ be the maximum value of $\Delta P(T_j)$ obtained, and $\Delta P_{TMP,MIN}$ the minimum.

6.3.4.3 Calculation of uncertainty due to DPL temperature dependence

The deviation of measured values dependent on the temperature, ΔP_{TMP}, is given by equation (29)

$$\Delta P_{TMP} = (\Delta P_{TMP,MAX} + \Delta P_{TMP,MIN}) / 2 \tag{29}$$

The uncertainty due to temperature dependence, $\sigma_{\Delta PTMP}$, is given by equation (30):

$$\sigma_{\Delta PTMP} = (\Delta P_{TMP,MAX} - \Delta P_{TMP,MIN}) / 2\sqrt{3} \tag{30}$$

6.4 Calculation of expanded uncertainty in displayed power level

When the test analyzer is only used under reference conditions, the expanded uncertainty, U_{Pref}, can be calculated by equation (31) with a coverage factor k.

$$UPref = \pm k\ \sigma \Delta Pref \tag{31}$$

When the test analyzer is operated beyond the reference conditions, the accumulative power level uncertainty of the test analyzer, $\sigma_{\Delta Pcu}$, should be calculated using equation (32) with the results of equations (13), (17), (22), (27) and (30) when all the calibration procedures are performed under operating conditions.

$$\sigma_{\Delta Pcu} = (\sigma_{\Delta Pref}{}^2 + \sigma_{\Delta P\lambda}{}^2 + \sigma_{\Delta PPOL}{}^2 + \sigma_{\Delta PLIN}{}^2 + \sigma_{\Delta PTMP}{}^2)^{1/2} \tag{32}$$

where

$\sigma_{\Delta Pref}$ is the uncertainty of the test analyzer under reference conditions;

$\sigma_{\Delta P\lambda}$ is the uncertainty due to wavelength dependence;

$\sigma_{\Delta PPOL}$ is the uncertainty due to polarization dependence;

$\sigma_{\Delta PLIN}$ is the uncertainty due to linearity;

$\sigma_{\Delta PTMP}$ is uncertainty due to temperature dependence .

The expanded uncertainty, U_{Pcu}, with a coverage factor k is expressed by the following equation:

$$U_{Pcu} = \pm k\ \sigma_{\Delta Pcu} \tag{33}$$

The accumulative displayed power level deviation, ΔPcu, is given by equation (34) with the results of equations (14), (16), (21), (26) and (29).

$$\Delta P_{cu} = \Delta P_{ref} + \Delta P_{\lambda} + \Delta P_{POL} + \Delta P_{LIN} + \Delta P_{TMP} \tag{34}$$

The deviation, uncertainty and expanded uncertainty of the displayed power level, ΔP, σ_P and U_P, at the displayed power level indicated by P(mW) are given by the equations below, when the aim is to obtain these values in absolute power units.

$$\Delta P = \Delta P_{cu} P \quad \text{(mW)} \tag{35}$$

$$\sigma_P = \sigma_{\Delta Pcu} P \quad \text{(mW)} \tag{36}$$

$$U_P = U_{Pcu} P \quad \text{(mW)} \tag{37}$$

When the deviation or uncertainty must be expressed as dB units, use the following equation to convert to dB units:

$$10 \log_{10}(1 + X) \quad \text{(dB)} \tag{38}$$

where $X = \Delta P_{cu}$ or $\sigma_{\Delta Pcu}$.

NOTE If the displayed power level should be corrected on the basis of the calibration results, this is typically implemented by making software corrections to the instrument, mathematical corrections to the results, or instrument hardware adjustments. Once the adjustments have been made, it is advisable to repeat the test to verify that the correction has operated correctly. See Annex C.

7 Wavelength calibration

7.1 Overview

The factors making up the uncertainty in the wavelength of the test analyzer consist of

1) the intrinsic uncertainty of the test analyzer as found in the test under reference conditions, and

2) partial uncertainties due to wavelength dependence and temperature dependence as found in the tests under operating conditions.

Calibration under reference conditions described in 7.2 to obtain the intrinsic uncertainty is mandatory. However, calibration under operating conditions described in 7.3 is not mandatory. If the test analyzer is operated beyond the reference conditions, it must calibrated within the range of operating conditions. The wavelength is that in a vacuum.

7.2 Wavelength calibration under reference conditions

Alternative set-ups for the calibration under reference conditions are shown in Figures 1, 2, and 3. In the Figure 1 set-up, a gas laser whose wavelength is known is used for the light source. Figure 2 shows a set-up in which a broad band source may be used in conjunction with a transmission device with known (traceable) wavelengths of peak (or null) transmission. Figure 3 shows a set-up in which a laser diode (LD) whose wavelength is unknown is used for the light source. This test is performed under reference calibration conditions.

7.2.1 Equipment for wavelength calibration under reference conditions

a) **Light source:** use the light source prescribed for calibrating the test analyzer; if a light source is not prescribed, use one with a spectral bandwidth and wavelength stability sufficient for the wavelength uncertainty prescribed for the test analyzer.

   The recommended light sources are lasers such as those listed in Table 1, a laser diode (LD) or laser (which may be tunable) which has a single-mode spectrum. In addition, a broadband source may be used in conjunction with a transmission device with known (traceable) wavelengths of peak (or null) transmission. The transmission device may be, for example, a series of fixed narrowband filters, absorption lines in gaseous media, or Fabry-Perot interferometers.

Annex D tabulates many stable wavelength references. The reference used should have wavelength stability, and a spectral bandwidth, and power stability sufficient for the uncertainty of wavelength required for the test analyzer.

b) **Wavelength meter:** an instrument for measuring the wavelength of the light source. Its precision must be sufficiently better than the precision required in the wavelength test. This instrument is used when a laser diode (LD) with an unknown wavelength is used as the light source (Figure 3).

7.2.2 Test procedure for wavelength calibration under reference conditions

a) Using the test set-tup shown in Figures 1, 2 or 3, set the displayed wavelength range of the test analyzer so that it includes the wavelength of the light source around the centre of the display. In addition, set the wavelength resolution of the test analyzer so that it satisfies equation (39) and is better than the tested wavelength uncertainty.

$$R_{set} > 10 * S / N \tag{39}$$

where

R_{set} is the set resolution bandwidth (spectral resolution) of the optical spectrum analyzer under test;

S is the displayed wavelength range;

N is the number of display points.

When using the test configuration shown in Figures 1 or 2, let the value of the known wavelength of the light source or transmission artefact be λ_{REF}, and when using the test configuration shown in Figure 3, let λ_{REF} indicate the wavelength of the light source as measured by the wavelength meter.

With respect to λ_{REF} of the light source, let the centre wavelength measured by the test analyzer be λ_{OSAi}.

b) Repeat this measurement at least ten times and calculate the average wavelength.

$$\lambda_{OSA_{AV}} = \sum_{i=1}^{m} \lambda_{OSAi} \ / \ m \tag{40}$$

where m is the number of measurements used.

7.2.3 Calculations of wavelength uncertainty under reference conditions

From the measured value, calculate the deviation, $\Delta\lambda_{ref}$:

$$\Delta\lambda_{ref} = \lambda OSA_{AV} - \lambda REF \tag{41}$$

Calculate the standard uncertainty $\sigma_{\lambda OSA}$ of the measured λ_{OSAi} values using equation (42).

$$\sigma_{\lambda OSA} = \left[\sum_{i=1}^{m} (\lambda_{OSAi} - \lambda_{OSA_{AV}})^2 / (m-1) \right]^{1/2} \tag{42}$$

The uncertainty $\sigma_{\Delta\lambda ref}$ of the test analyzer with regard to wavelength under the reference calibration conditions is given by equation (43).

$$\sigma_{\Delta\lambda ref} = (\sigma_{\lambda REF}{}^2 + \sigma_{\lambda OSA}{}^2)^{1/2} \tag{43}$$

where

$\sigma_{\lambda REF}$ is the uncertainty of the light source wavelength;

$\sigma_{\lambda OSA}$ is the standard uncertainty of the values measured during the test.

NOTE The uncertainty of the light source wavelength, $\sigma_{\lambda REF}$, can be ignored if a laser or transmission device with a stable wavelength is used as the light source and its performance is sufficiently better than the wavelength uncertainty of the test analyzer. When an LD is used for the light source, measure the wavelength several times with the wavelength meter and let the uncertainty of the light source be its standard deviation, $\sigma_{\lambda REF}$.

7.3 Wavelength calibration for operating conditions

The calibration described in this subclause is not mandatory. Perform the calibration procedure when the test analyzer is used beyond the reference calibrations.

Individual factors in wavelength uncertainty for the operating conditions may consist of the following:

1) wavelength dependence and
2) temperature dependence.

7.3.1 Wavelength dependence

Figures 1, 2 and 3 show the test configurations for determining wavelength dependence. These are the same as those used for calibration under the reference conditions. This test is performed under reference calibration conditions with the exception of the source wavelengths.

7.3.1.1 Equipment for determining wavelength dependence

a) **Light source:** use a light source with 1) a spectral bandwidth sufficiently narrower than the resolution bandwidth (spectral resolution) of the test analyzer, and 2) wavelength and power stability sufficient for the wavelength uncertainty prescribed for the test analyzer.

   The recommended light sources are lasers, such as those listed in Table 1, and a laser diode (LD) with a single-mode spectrum (for example, tunable laser diode source). Also, a broadband source may be used in conjunction with a transmission device with known (traceable) wavelengths of peak (or null) transmission. The transmission device may be for example a series of fixed narrowband filters, absorption lines in gaseous media, or Fabry-Perot interferometers.

   Annex D tabulates many stable wavelength references. The reference used should have wavelength stability, and a spectral bandwidth, and power stability sufficient for the uncertainty of wavelength required for the test analyzer.

b) **Wavelength meter:** an instrument for measuring the wavelength of the light source. Its precision must be sufficiently better than the precision required in the wavelength test. This instrument is used when a laser diode (LD) whose wavelength is unknown is used as the light source (Figure 3).

7.3.1.2 Test procedure for determining wavelength dependence

When using the test configuration shown in Figures 1 or 2, let the value of the known wavelength of the light source(s) or transmission artefact(s) be $\lambda_{REF,j}$, and, for the test configuration shown in Figure 3, let $\lambda_{REF,j}$ be the wavelength of the light source(s) as measured by the wavelength meter.

a) Input light from the light source into the test analyzer and read the indicated value λ_{OSAj}. Then, determine the wavelength deviation $\Delta\lambda_{\lambda j}$ with respect to $\lambda_{REF,j}$ using equation (44).

$$\Delta\lambda_{\lambda j} = \lambda_{OSAj} - \lambda_{REF,j} \quad (44)$$

b) Next, change the source wavelength and perform the same test, again determining the deviation using equation (44).

c) Let $\Delta\lambda_{\lambda,\mathrm{MAX}}$ be the maximum value of the deviation values obtained and $\Delta\lambda_{\lambda,\mathrm{MIN}}$ the minimum.

7.3.1.3 Calculations of wavelength uncertainty due to wavelength dependence

By using the deviation of measurement values for several wavelengths, determine the deviation, $\Delta\lambda_{\lambda}$ and uncertainty, $\sigma_{\Delta\lambda\lambda}$ due to wavelength dependence by using equations (45) and (46), respectively.

$$\Delta\lambda_{\lambda} = (\Delta\lambda_{\lambda,\mathrm{MAX}} + \Delta\lambda_{\lambda,\mathrm{MIN}}) / 2 \qquad (45)$$

$$\sigma_{\Delta\lambda\lambda} = (\Delta\lambda_{\lambda,\mathrm{MAX}} - \Delta\lambda_{\lambda,\mathrm{MIN}}) / 2\sqrt{3} \qquad (46)$$

7.3.2 Temperature dependence

Figure 9 shows the test configuration for determining the temperature dependence of wavelength uncertainty. This test is performed under reference calibration conditions with the exception of temperature.

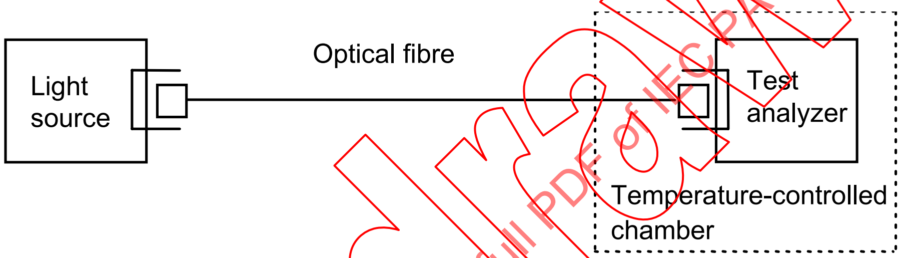


Figure 9 – Test configuration for determining the temperature dependence of wavelength uncertainty

7.3.2.1 Equipment for determining temperature dependence

a) **Light source:** use the light source prescribed for calibrating the test analyzer; if a light source is not prescribed, use one with a spectral bandwidth and wavelength stability sufficient for the wavelength uncertainty prescribed for the test analyzer.

   The recommended light sources are the gas lasers listed in Table 1, a laser diode (LD) or a laser with a single-mode spectrum, and a broadband source with a transmission device. Annex D tabulates many stable wavelength references.

7.3.2.2 Test procedure for determining temperature dependence

Under reference calibration conditions and within the temperature range prescribed for the test analyzer, measure the wavelength of the light input from the light source for at least five temperature points (T_j).

a) Letting the wavelength of the input light be λ_{REF} and the indicated value on the test analyzer be λ_{OSAj}, determine the deviation in wavelength by equation (47).

$$\Delta\lambda_{\mathrm{Tj}} = \lambda_{\mathrm{OSAj}} - \lambda_{\mathrm{REF}} \qquad (47)$$

b) Next, change the temperature and repeat the test and deviation calculation. Sufficient time (for example, 2 h) must be allowed for the OSA undergoing calibration to reach thermal equilibrium at each temperature used.

c) Let $\Delta\lambda_{\mathrm{T,MAX}}$ be the maximum value of $\Delta\lambda_{\mathrm{Tj}}$ obtained, and $\Delta\lambda_{\mathrm{T,MIN}}$ the minimum.

7.3.2.3 Calculations of wavelength uncertainty due to temperature dependence

By using the deviations of measurement values at several temperatures, determine the deviation $\Delta\lambda_T$ and uncertainty $\sigma_{\Delta\lambda T}$ due to temperature dependence, using equations (48) and (49), respectively.

$$\Delta\lambda_T = (\Delta\lambda_{T,MAX} + \Delta\lambda_{T,MIN}) / 2 \qquad (48)$$

$$\sigma_{\Delta\lambda T} = (\Delta\lambda_{T,MAX} - \Delta\lambda_{T,MIN}) / 2\sqrt{3} \qquad (49)$$

7.4 Calculation of expanded uncertainty in wavelength

When the test analyzer is only used under reference conditions, the expanded uncertainty, $U_{\lambda ref}$, can be calculated by equation (50) with a coverage factor k.

$$U_{\lambda ref} = \pm k\ \sigma_{\Delta\lambda ref} \qquad (50)$$

The overall wavelength uncertainty is calculated using the uncertainty under reference calibration conditions and the uncertainty under operating conditions which are determined through individual uncertainty tests of the wavelength dependence and temperature dependence, when the test analyzer is used beyond the reference conditions.

Cumulative wavelength deviation $\Delta\lambda_{cu}$ is calculated by using equation (51) with the results of equations (41), (45), and (48):

$$\Delta\lambda_{cu} = \Delta\lambda_{ref} + \Delta\lambda_{\lambda} + \Delta\lambda_T \qquad (51)$$

The uncertainty of wavelength $\sigma_{\Delta\lambda cu}$ is calculated by using equation (52) with cumulative dispersions with the results of equations (43), (46) and (49):

$$\sigma_{\Delta\lambda cu} = (\sigma_{\Delta\lambda ref}{}^2 + \sigma_{\Delta\lambda\lambda}{}^2 + \sigma_{\Delta\lambda T}{}^2)^{1/2} \qquad (52)$$

The expanded uncertainty, $U_{\lambda cu}$ with a coverage factor k is expressed by the following equation:

$$U_{\lambda cu} = \pm k\ \sigma_{\Delta\lambda cu} \qquad (53)$$

NOTE If the wavelength should be corrected on the basis of the calibration results, this is typically implemented by making software corrections to the instrument, mathematical corrections to the results, or instrument hardware adjustments. Examples of evaluation and calculations of corrections for certain parameters are given in Annex C. Once the adjustments have been made, it is advisable to repeat the test to verify that the correction has operated correctly.

8 Documentation

8.1 Measurement data and uncertainty

Calibration certificates claiming to be in compliance with this document shall include the following data and their uncertainties, and the uncertainties shall be stated in the form of estimated confidence intervals by multiplying the relevant standard deviation by ±k.

a) Resolution bandwidth (spectral resolution) test result, if measured. For example, difference ratio, ΔR_{diff}. The wavelength is that in a vacuum. See the detailed requirements in Clause 5.

b) The displayed power level deviation, ΔP_{cu}, and its uncertainty, $\pm k\sigma_{\Delta Pcu}$, for example, in mW or dB. See the detailed requirements in Clause 6.

c) The wavelength deviation, $\Delta\lambda_{cu}$, and its uncertainty, $\pm k\sigma_{\Delta\lambda cu}$, for example, in nm, in a vacuum. See the detailed requirements in Clause 7.

8.2 Measurement conditions

The calibration method(s) and the method(s) of obtaining the measurement results shall be stated.

Each specification should also be accompanied by a statement of the instrument state(s) and the measurement conditions to which they apply. The most important parameters are: calibration date, displayed power level, horizontal and vertical display resolution, temperature, humidity, atmospheric pressure and displayed wavelength range.

NOTE The calibration results only apply to the set of test conditions used for the calibration process.

Annex A
(normative)

Mathematical basis for calculation of calibration uncertainty

A major part of the calibration effort goes into evaluating uncertainties. This annex suggests a standard format for reporting and accumulating uncertainties.

The following is based on the ISO Guide to the expression of uncertainty in measurement. This document distinguishes three types of deviations (see Clause A.1) between an actual measurement result and the "true" value of the measured quantity: known deviations, which can be corrected, uncertainties of type A, which are obtained from a series of measurements on the same measurand, and uncertainties of type B which are obtained from other knowledge. Each of these may be caused by a number of influencing quantities. This annex indicates a standardized form of evaluating, accumulating and reporting these contributions.

A.1 Deviations

A deviation characterizes a known error in a measurement result. Note that the term "error" is equivalent to "deviation".

It is useful to distinguish between measurement results in linear form, for example, wavelength or per cent, and measurement results in logarithmic form, for example, optical power in dBm. In both cases, the deviation or error, Δ_y, quantifies the difference between an actual measurement result, y_{actual}, and the "true" value of the measured quantity, y_{ref}.

$$\Delta y = y_{actual} - y_{ref} \tag{A.1}$$

Correction is possible by subtracting the deviation from the measurement result.

A.2 Uncertainty type A

Randomly changing measurement results should be characterized as an uncertainty of type A. A normal (Gaussian) distribution of measurement samples is usually assumed. It is recommended that these uncertainties be kept as small as possible by averaging the results for a number of measurement samples. To save time in the calibration of an individual instrument from a series of instruments, it is suggested that each random (type A) uncertainty be evaluated in two steps.

As the first step, determine the experimental standard deviation, S_{typeA}, of a typical measurement situation from a large number of measurements, m. The centre of the distribution is assumed to coincide with zero that is, the reference standard value.

The experimental standard deviation, characterizing an uncertainty type A, is approximately:

$$S_{typeA} = \left[\sum_{i=1}^{m} (y_i - y_{mean})^2 / (m - 1) \right]^{1/2} \tag{A.2}$$

where

y_i is the measurement sample of a series of measurements;

y_{mean} is the mean value of the data;

m is the number of characterizing measurements in determining the standard deviation; m is assumed to be large, for example, > 30.

As the second step, determine the uncertainty of the individual case, σ_{typeA}, from a smaller number of measurements, n. Often, n = 1, to save measurement time. The result is the standard uncertainty type A:

$$\sigma_{typeA} = S_{typeA} / n^{1/2} \tag{A.3}$$

σ_{typeA} expresses the uncertainty of the mean, which assumes an averaging of results for the n measurement samples. Note that the two steps may be combined in to a single step, by making m = n. Additional statistical techniques for example t-statistics may be required.

Uncertainties type A may be expressed in linear form, for example, in per cent, or in logarithmic form, in dB. Their mathematical treatment is identical as long as the uncertainties are small.

A.3 Uncertainty type B

An uncertainty type B usually quantifies an unknown fixed offset between a measurement result and the "true" value of a measured quantity. These uncertainties can be described by the width of an uncertainty band, as illustrated in Figure A.1. The measurement results are assumed to have a uniform (rectangular) distribution.

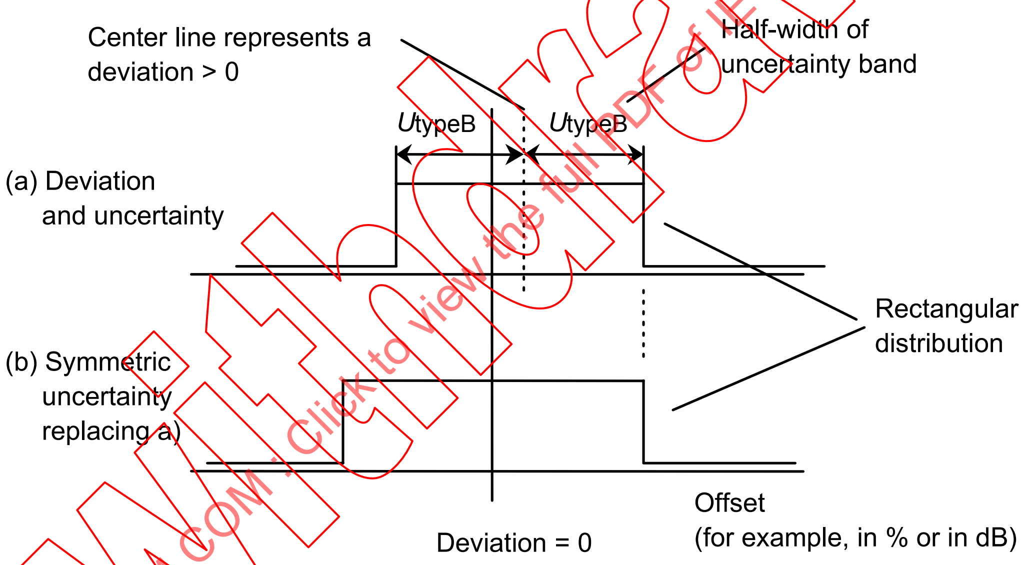


Figure A.1 – Deviation and uncertainty type B, and how to replace both with an appropriately larger uncertainty

This document suggests specifying the half-width, U_{typeB}, of the band of relative uncertainties. The uncertainty band can be calculated by multiplying the tolerance band of the influencing condition, for example, of the temperature, with the instrument's worst-case dependence on this condition. These calculations should be based on known physical relations, manufacturer's specifications, data provided in calibration certificates or on a sufficiently large number of characterizing measurements of the same type of instrument. In these measurements, type A uncertainties are to be kept as small as possible, for example, by averaging.

As indicated in Figure A.1, it is possible to omit the deviation by specifying a wider and symmetrical uncertainty band. The expanded uncertainty band can alternatively be expressed by an equivalent standard uncertainty, σ_{typeB}:

Uncertainty type B (half-width):

$$U_{typeB} = \text{half-width of condition's tolerance band} \times \text{instrument's sensitivity} \qquad (A.4)$$

Standard uncertainty type B (calculated):

$$\sigma_{typeB} = U_{typeB} / 3^{1/2} \qquad (A.5)$$

Type B uncertainties may be expressed in linear form, for example, in per cent, or in logarithmic form, in dB. Their mathematical treatment is identical as long as the uncertainties are small.

A.4 Accumulation of uncertainties

The "combined standard uncertainty" is used to collect a number, *i*, of individual uncertainties into a single number. The combined standard uncertainty is based on the statistical independence of the individual uncertainties; this provides a root-sum-square of their standard deviations. In compliance with the ISO Guide to the expression of uncertainty in measurement, the following formulae shall determine the cumulative deviation and the combined standard uncertainty and expanded uncertainty.

$$\text{Cumulative deviation (error): } \Delta_y{}^* = \sum \Delta y_i \qquad (A.6)$$

$$\text{Combined standard uncertainty: } \sigma_{std} = \left(\sum_{i=1}^{n} \sigma_{typeB,i}{}^2 + \sum_{j=1}^{l} \sigma_{typeA,j}{}^2 \right)^{1/2} \qquad (A.7)$$

where

i is the current number of individual contributions;

$\sigma_{typeB,i}$ is the (calculated) standard uncertainty representing systematic (type B) uncertainty, (see formula A.5);

$\sigma_{typeA,j}$ is the standard uncertainty characterizing a random (type A) uncertainty (see formula A.3);

n is the number of type B uncertainties;

l is the number of type A uncertainties.

NOTE The first part of equation (A.7) collects all type B uncertainties, and the second part collects all type A uncertainties. It is acceptable to ignore uncertainty contributions to this equation which are smaller than 1/10 of the largest contribution, because squaring them will reduce their significance to 1/100 that of the largest contribution.

When the quantities above are to be used as the basis for further uncertainty computations, then the combined standard deviation, σ_{std}, can be re-inserted into the formulae (A.6) and (A.7). Despite its partially type A origin, σ_{std} should be considered as describing a type B uncertainty.

Combined standard uncertainties, as well as type A and B uncertainties, may be expressed in linear or logarithmic form, with no difference in mathematical treatment. See Clause A.2.

$$\text{Expanded uncertainty: } U_{exp} = \pm k\, \sigma_{std} \qquad (A.8)$$

where k is the coverage factor.

If the number of measurements made in determining type A uncertainties is large, and an estimated confidence level of 95 % is chosen (default), then $k = 2$; if an estimated confidence level of 99 % is chosen (this should be specifically stated), then $k = 3$. Larger coverage factors are to be used when the number of measurements made in determining the type A uncertainties is small, for example, <10. See ISO Guide to the expression of uncertainty in measurement.

A.5 Reporting

In calibration reports and technical data sheets, combined standard uncertainties shall be reported in the form of expanded uncertainties, together with the applicable confidence level. The default confidence level is 95 %.

A deviation shall be specified if necessary.

$$\text{Deviation: } \Delta y = \Delta y^{*} \qquad (A.9)$$

Annex B
(informative)

Examples of calculation of calibration uncertainty

Examples of the calculation of calibration uncertainty related to displayed power level and wavelength are shown in the following.

B.1 Displayed power level calibration

B.1.1 Uncertainty under reference conditions: $\sigma_{\Delta Pref}$

The uncertainty of the test analyzer, $\sigma_{\Delta Pref}$, with regard to displayed power level under reference calibration conditions is calculated using equation (13):

$$\sigma_{\Delta Pref} = (\sigma_{PPM}{}^2 + \sigma_{\Delta Pdiff}{}^2)^{1/2}$$

where

σ_{PPM} is the uncertainty of the reference optical power meter;

$\sigma_{\Delta Pdiff}$ is the standard deviation of the values measured during the test.

Here, the uncertainty of the reference power meter is given as 2,0 % in its certification, then

$$\sigma_{PPM} = 0{,}02 \tag{B.1}$$

Using the next 10 pairs of $P_{ref,i}$ and $P_{OSA,i}$ measured with the reference optical power meter and the test analyzer, we can find the uncertainty of the test analyzer.

P_{ref1} = 0,200 mW	P_{OSA1} = 0,210 mW
P_{ref2} = 0,202 mW	P_{OSA2} = 0,205 mW
P_{ref3} = 0,201 mW	P_{OSA3} = 0,203 mW
P_{ref4} = 0,200 mW	P_{OSA4} = 0,215 mW
P_{ref5} = 0,199 mW	P_{OSA5} = 0,195 mW
P_{ref6} = 0,199 mW	P_{OSA6} = 0,190 mW
P_{ref7} = 0,200 mW	P_{OSA7} = 0,197 mW
P_{ref8} = 0,201 mW	P_{OSA8} = 0,213 mW
P_{ref9} = 0,201 mW	P_{OSA9} = 0,215 mW
P_{ref10} = 0,202 mW	P_{OSA10} = 0,220 mW

The difference ratio between the OSA result and the power meter result is calculated using equation (10).

ΔP_{diff1} = 0,05	ΔP_{diff2} = 0,015
ΔP_{diff3} = 0,010	ΔP_{diff4} = 0,075
ΔP_{diff5} = –0,02	ΔP_{diff6} = –0,045
ΔP_{diff7} = –0,015	ΔP_{diff8} = 0,06
ΔP_{diff9} = 0,07	ΔP_{diff10} = 0,089

The mean and standard deviations of the difference ratio are calculated using equations (11) and (12).

$$\Delta P_{\text{diff}} = \sum_{i=1}^{m} (\Delta P_{\text{diff},\ i}) \ / \ m = 0{,}289 \ / \ 10 = 0{,}0289 \qquad \text{(B.2)}$$

$$\sigma_{\Delta P\text{diff}} = \left[\sum_{i=1}^{m} (\Delta P_{\text{diff},\ i} - \Delta P_{\text{diff}})^2 \ / \ (m-1) \right]^{1/2} = (\ 0{,}01917 \ /9\ )^{1/2} = 0{,}0462 \qquad \text{(B.3)}$$

The standard deviation of the difference ($\sigma_{\Delta P\text{diff}}$ = 0,0462) is larger than the uncertainty of the power meter (σ_{PPM} = 0,02). This means it should be considered as a type A uncertainty of the test analyzer.

From equation (13), the uncertainty $\sigma_{\Delta P\text{ref}}$ is,

$$\sigma_{\Delta P\text{ref}} = (\sigma_{PPM}{}^2 + \sigma_{\Delta P\text{diff}}{}^2)^{1/2} = (0{,}02^2 + 0{,}0462^2)^{1/2} = 0{,}0503 \qquad \text{(B.4)}$$

The displayed power level deviation is found from equation (14).

$$\Delta P_{\text{ref}} = \Delta P_{\text{diff}} = 0{,}0289 \qquad \text{(B.5)}$$

B.1.2 Uncertainty under operating conditions

The following example shows the uncertainty calculation when calibrations are performed individually on four factors, that is, wavelength, polarization, linearity and temperature.

B.1.2.1 Wavelength dependence

The wavelength dependence will be derived for the displayed peak power levels (P_{OSAj}) of the test analyzer and reference values on the optical power meter ($P_{\text{REF,j}}$) for the wavelengths shown below:

λ_1 = 488 nm	P_{OSA1} = 0,1225 µW	P_{REF1} = 0,1202 µW
λ_2 = 632,8 nm	P_{OSA2} = 0,1307 µW	P_{REF2} = 0,1205 µW
λ_3 = 780 nm	P_{OSA3} = 0,1310 µW	P_{REF3} = 0,1230 µW
λ_4 = 850 nm	P_{OSA4} = 0,1532 µW	P_{REF4} = 0,1470 µW
λ_5 = 1500 nm	P_{OSA5} = 0,1605 µW	P_{REF5} = 0,1758 µW
λ_6 = 1550 nm	P_{OSA6} = 0,1520 µW	P_{REF6} = 0,1620 µW
λ_7 = 1600 nm	P_{OSA7} = 0,1207 µW	P_{REF7} = 0,1155 µW

From equation (15):

$\Delta P(\lambda_1) = P_{\text{OSA1}} / P_{\text{REF1}} - 1 = 0{,}1225 / 0{,}1202 - 1 = 0{,}01913$

$\Delta P(\lambda_2) = P_{\text{OSA2}} / P_{\text{REF2}} - 1 = 0{,}1307 / 0{,}1205 - 1 = 0{,}08465$

$\Delta P(\lambda_3) = P_{\text{OSA3}} / P_{\text{REF3}} - 1 = 0{,}1310 / 0{,}1230 - 1 = 0{,}06504$

$\Delta P(\lambda_4) = P_{\text{OSA4}} / P_{\text{REF4}} - 1 = 0{,}1532 / 0{,}1470 - 1 = 0{,}04218$

$\Delta P(\lambda_5) = P_{\text{OSA5}} / P_{\text{REF5}} - 1 = 0{,}1605 / 0{,}1758 - 1 = -0{,}08703$

$\Delta P(\lambda_6) = P_{\text{OSA6}} / P_{\text{REF6}} - 1 = 0{,}1520 / 0{,}1620 - 1 = -0{,}06173$

$\Delta P(\lambda_7) = P_{\text{OSA7}} / P_{\text{REF7}} - 1 = 0{,}1207 / 0{,}1155 - 1 = 0{,}04502$

From these values:

$\Delta P_{\lambda,MAX} = \Delta P(\lambda_2) = 0{,}08465$
$\Delta P_{\lambda,MIN} = \Delta P(\lambda_5) = -0{,}08703$

From equation (16):

$$\Delta P_\lambda = (\Delta P_{\lambda,MAX} + \Delta P_{\lambda,MIN}) / 2 = (0{,}08465 - 0{,}08703) / 2 = -0{,}0012 \quad \text{(B.6)}$$

The uncertainty due to wavelength dependence, $\sigma_{\Delta P\lambda}$, is given by equation (17).

$$\sigma_{\Delta P\lambda} = (\Delta P_{\lambda,MAX} - \Delta P\lambda_{,MIN}) /\ 2\sqrt{3} = 0{,}1716 /\ 2\sqrt{3} = 0{,}0496 \quad \text{(B.7)}$$

B.1.2.2 Polarization dependence

The polarization dependence will be derived using the following values of $P_{MAX}(\lambda_j)$ and $P_{MIN}(\lambda_j)$ measured by rotating a 1/2-wavelength plate to move the light source polarization plane from 0 through 180 degrees.

λ_1 = 850 nm $P_{MAX}(\lambda_1)$ = 0,310 mW $P_{MIN}(\lambda_1)$ =0,292 mW
λ_2 = 1310 nm $P_{MAX}(\lambda_2)$ = 0,204 mW $P_{MIN}(\lambda_2)$ =0,194 mW
λ_3 = 1550 nm $P_{MAX}(\lambda_3)$ = 0,206 mW $P_{MIN}(\lambda_3)$ =0,193 mW

From equations (18) and (19), variations $\Delta P_{UL}(\lambda_j)$ and $\Delta P_{LL}(\lambda_j)$ and the average variation $P_{AVE}(\lambda_j)$ in power level due to polarization with wavelength λ_j, are given as

$P_{AVE}(\lambda_1)$ = 0,301 mW $\Delta P_{UL}(\lambda_1) = 0{,}310 / 0{,}301 - 1 = 0{,}0299$
$\Delta P_{LL}(\lambda_1) = 0{,}292 / 0{,}301 - 1 = -0{,}0299$
$P_{AVE}(\lambda_2)$ = 0,199 mW $\Delta P_{UL}(\lambda_2) = 0{,}204 / 0{,}199 - 1 = 0{,}0251$
$\Delta P_{LL}(\lambda_2) = 0{,}194 / 0{,}199 - 1 = -0{,}0251$
$P_{AVE}(\lambda_3)$ = 0,1995 mW $\Delta P_{UL}(\lambda_3) = 0{,}206 / 0{,}1995 - 1 = 0{,}0326$
$\Delta P_{LL}(\lambda_3) = 0{,}193 / 0{,}1995 -1 = -0{,}0326$

From these values:

$\Delta P_{POL,MAX} = \Delta P_{UL}(\lambda_3) = 0{,}0326$
$\Delta P_{POL,MIN} = \Delta P_{LL}(\lambda_3) = -0{,}0326$

The deviation of measured values depending on the polarization and wavelength, ΔP_{POL}, is given by equation (21).

$$\Delta P_{POL} = (\Delta P_{POL,MAX} + \Delta P_{POL,MIN}) / 2 = (0{,}0326 - 0{,}0326) / 2 = 0 \quad \text{(B.8)}$$

The uncertainty of power level variations due to polarization, $\sigma_{\Delta PPOL}$, is given by equation (22).

$$\sigma_{\Delta PPOL} = (\Delta P_{POL,MAX} - \Delta P_{POL,MIN}) /\ 2\sqrt{3} = (0{,}0326 + 0{,}0326) /\ 2\sqrt{3} = 0{,}0188 \quad \text{(B.9)}$$

B.1.2.3 Linearity

The linearity will be derived using the following values for the ratio $P_{LIN,ref}$ of the value measured by the test analyzer to the value obtained from the power meter, and the ratio $P_{LIN,j}$ of the value measured by the test analyzer to the value obtained from the power meter when the power level is varied using a variable attenuator. The linearity error ΔP_{LIN} (P_j) at the power level P_j is given by equation (25).

$P_{LIN,ref}$ = 1,025

P_{LIN1} = 0,998 $\Delta P_{LIN}(P_1)$ = –0,02634

P_{LIN2} = 0,985 $\Delta P_{LIN}(P_2)$ = –0,03902

P_{LIN3} = 1,011 $\Delta P_{LIN}(P_3)$ = –0,01366

P_{LIN4} = 1,009 $\Delta P_{LIN}(P_4)$ = –0,01561

P_{LIN5} = 1,055 $\Delta P_{LIN}(P_5)$ = 0,02927

From these values:

$\Delta P_{LIN,MAX}$ = 0,02927

$\Delta P_{LIN,MIN}$ = –0,03902

The deviation of measured values, ΔP_{LIN}, is obtained from equation (26):

$$\Delta P_{LIN} = (\Delta P_{LIN,MAX} + \Delta P_{LIN,MIN}) / 2 = (0{,}02927 - 0{,}03902) / 2 = -0{,}0049 \quad \text{(B.10)}$$

The uncertainty of linearity, $\sigma_{\Delta PLIN}$, is obtained from equation (27):

$$\sigma_{\Delta PLIN} = (\Delta P_{LIN,MAX} - \Delta P_{LIN,MIN}) / \ 2\sqrt{3} = (0{,}02927 + 0{,}03902) / 2\sqrt{3} = 0{,}0197 \quad \text{(B.11)}$$

B.1.2.4 Temperature dependence

The temperature dependence is obtained from the following values. These are the reference values, $P_{OSA,Tref}$, of the test analyzer at the temperature specified by the reference calibration conditions, and the power level values, P_{OSAj}, measured by the test analyzer at the various temperatures shown, for light input from a semiconductor laser λ = 1 310 nm with an input optical power of 0,200 mW (the value used for the test under reference conditions). The sensitivity error at a temperature of T_j, $\Delta P(T_j)$, is given by equation (28) as follows.

*P*OSA, Tref =0,200 mW

T1 = 10 °C	*P*OSA1 = 0,202 mW	ΔP(T1) = 0,010
T2 = 15 °C	*P*OSA2 = 0,204 mW	ΔP(T2) = 0,020
T3 = 20 °C	*P*OSA3 = 0,199 mW	ΔP(T3) = –0,005
T4 = 25 °C	*P*OSA4 = 0,197 mW	ΔP(T4) = –0,015
T5 = 30 °C	P_{OSA5} = 0,200 mW	$\Delta P(T_5)$ = 0,0
T6 = 35 °C	P_{OSA6} = 0,207 mW	$\Delta P(T_6)$ = 0,035

From these values:

$\Delta P_{TMP,MAX}$ = 0,035

$\Delta P_{TMP,MIN}$ = –0,015

The deviation of measured values, ΔP_{TMP}, is obtained from equation (29):

$$\Delta P_{TMP} = (\Delta P_{TMP,MAX} + \Delta P_{TMP,MIN}) / 2 = (0{,}035 - 0{,}015) / 2 = 0{,}010 \quad \text{(B.12)}$$

The uncertainty due to temperature dependence, $\sigma_{\Delta PTMP}$, is obtained from equation (30):

$$\sigma_{\Delta PTMP} = (\Delta P_{TMP,MAX} - \Delta P_{TMP,MIN}) / \ 2\sqrt{3} = (0{,}035 + 0{,}015) / \ 2\sqrt{3} = 0{,}0144 \quad \text{(B.13)}$$

B.1.3 Expanded uncertainty calculation

The following example shows the expanded uncertainty calculation when calibration is performed under operating conditions.

The accumulative displayed power level deviation is found from equation (34):

$$\Delta P_{cu} = \Delta P_{ref} + \Delta P_{\lambda} + \Delta P_{POL} + \Delta P_{LIN} + \Delta P_{TMP}$$

$$= 0{,}0289 - 0{,}0012 + 0 - 0{,}0049 + 0{,}010$$

$$= 0{,}0328 \qquad \text{(B.14)}$$

The uncertainty of the displayed power level is obtained from equation (32):

$$\sigma\Delta P\text{cu} = (\sigma\Delta P\text{ref}^2 + \sigma\Delta P\lambda^2 + \sigma\Delta P\text{POL}^2 + \sigma\Delta P\text{LIN}^2 + \sigma\Delta P\text{TMP}^2)^{1/2}$$

$$= (0{,}0503^2 + 0{,}0496^2 + 0{,}0188^2 + 0{,}0197^2 + 0{,}0144^2)^{1/2}$$

$$= (0{,}00594)^{1/2} = 0{,}0771 \qquad \text{(B.15)}$$

Accordingly, the deviation and uncertainty, ΔP and σ_P, in the measured values for P = 0,2 mW can be found from equations (35), (36):

$$\Delta P = \Delta P_{cu}\ P = 0{,}0328 \times 0{,}2 = 0{,}0066 \quad \text{(mW)} \qquad \text{(B.16)}$$

$$\sigma_P = \sigma_{\Delta P cu}\ P = 0{,}0771 \times 0{,}2 = 0{,}0154 \quad \text{(mW)} \qquad \text{(B.17)}$$

The expanded uncertainty, U_P, with a coverage factor k = 2 for a confidence level of 95,5 % is obtained from equation (37):

$$U_P = U_{Pcu}\ P = \pm k\ \sigma_{\Delta Pcu}\ P = \pm k\ \sigma_P = \pm 2 \times 0{,}0154 = \pm 0{,}0308 \quad \text{(mW)} \qquad \text{(B.18)}$$

ΔP and σ_P in dB unit are obtained from equation (38):

$$\Delta P\ (\text{in dB}) = 10\ \log_{10}(1 + 0{,}0328\ ) = 0{,}14 \quad \text{(dB)} \qquad \text{(B.19)}$$

$$\sigma_{\Delta Pcu}\ (\text{in dB}) = 10\ \log_{10}(1 + 0{,}0771\ ) = 0{,}32 \quad \text{(dB)} \qquad \text{(B.20)}$$

B.2 Wavelength calibration

B.2.1 Uncertainty under reference conditions: $\sigma_{\Delta\lambda ref}$

The uncertainty under reference conditions of the test analyzer, $\sigma_{\Delta\lambda ref}$, with regard to wavelength is calculated using equation (43):

$$\sigma_{\Delta\lambda ref} = (\sigma_{\lambda REF}{}^2 + \sigma_{\lambda OSA}{}^2)^{\ 1/2}$$

where

$\sigma_{\lambda REF}$ is the uncertainty of the light source's wavelength

$\sigma_{\lambda OSA}$: is the standard uncertainty of the values measured during the test

Using the following ten values of centre wavelength λ_{OSAi} for a He-Ne laser with a wavelength of λ_{REF} = 633,0 nm measured by the test analyzer, we can find the uncertainty:

λ_{OSA1} = 632,9 nm	λ_{OSA6} = 633,0 nm
λ_{OSA2} = 633,0 nm	λ_{OSA7} = 632,8 nm
λ_{OSA3} = 632,8 nm	λ_{OSA8} = 632,7 nm
λ_{OSA4} = 632,8 nm	λ_{OSA9} = 632,8 nm
λ_{OSA5} = 632,9 nm	λ_{OSA10} = 632,7 nm

From equation (42), the standard deviation of the measured values is calculated as follows:

Calculate the standard uncertainty $\sigma_{\lambda OSA}$ of the measured λ_{OSAi} values using equation (42).

$$\sigma_{\lambda OSA} = \left[\sum_{i=1}^{m} (\lambda_{OSA_i} - \lambda_{OSA_{AV}})^2 / (m-1)\right]^{1/2}$$

$$= [((632{,}9 - 632{,}84)^2 + (633{,}0 - 632{,}84)^2 + \ldots + (632{,}7 - 632{,}84)^2) / (10-1)]^{1/2}$$

$$= 0{,}107 \text{ (nm)} \qquad \text{(B.21)}$$

The wavelength uncertainty of the light source is $\sigma_{\lambda REF} = 10^{-5} \sim 10^{-6}$, which is good enough to allow the use of the approximation $\sigma_{\lambda REF} \approx 0$. So the uncertainty under reference conditions, $\sigma_{\Delta\lambda ref}$, of the test analyzer can be found using equation (43):

$$\sigma_{\Delta\lambda ref} = (\sigma_{\lambda REF}{}^2 + \sigma_{\lambda OSA}{}^2)^{1/2} = (0{,}0 + 0{,}107^2)^{1/2} = 0{,}107 \text{ (nm)} \qquad \text{(B.22)}$$

The average value of the measured values $\lambda_{OSA_{AV}}$ is found from equation (40):

$$\lambda_{OSA_{AV}} = \sum_{i=1}^{m} \lambda_{OSAi} / m = 6328{,}4 / 10 = 632{,}84 \text{ (nm)} \qquad \text{(B.23)}$$

The deviation of the measured values, $\Delta\lambda_{ref,}$ is found from equation (41):

$$\Delta\lambda_{ref} = \lambda_{OSA_{AV}} - \lambda_{REF} = 632{,}84 - 633{,}0 = -0{,}16 \text{ (nm)} \qquad \text{(B.24)}$$

B.2.2 Uncertainty under operating conditions

The following example shows the uncertainty calculation when the wavelength and temperature dependence are calibrated.

B.2.2.1 Wavelength dependence

The wavelength dependence will be derived using the following centre wavelength values measured for five light sources having wavelengths other than λ_{ref}:

λ_{OSA1} = 650,4 nm	λ_{REF1} = 650,6 nm
λ_{OSA2} = 780,5 nm	λ_{REF2} = 780,3 nm
λ_{OSA3} = 850,2 nm	λ_{REF3} = 850,1 nm
λ_{OSA4} = 1310,5 nm	λ_{REF4} = 1310,7 nm
λ_{OSA5} = 1552,1 nm	λ_{REF5} = 1552,0 nm

The deviation of the measured value for the individual light source is calculated from equation (44), for each wavelength.

$\Delta\lambda_{\lambda 1}$ = 650,4 – 650,6 = –0,2 (nm)

$\Delta\lambda_{\lambda 2}$ = 780,5 – 780,3 = 0,2 (nm)

$\Delta\lambda_{\lambda 3}$ = 850,2 – 850,1 = 0,1 (nm)

$\Delta\lambda_{\lambda 4}$ = 1310,5 – 1310,7 = –0,2 (nm)

$\Delta\lambda_{\lambda 5}$ = 1552,1 – 1552,0 = 0,1 (nm)

From these values:

$\Delta\lambda_{\lambda,\mathrm{MAX}}$ = 0,2 nm,

$\Delta\lambda_{\lambda,\mathrm{MIN}}$ = –0,2 nm

The uncertainty of the wavelength dependence error, $\sigma_{\Delta\lambda\lambda}$, is given by equation (46):

$$\sigma_{\Delta\lambda\lambda} = (\Delta\lambda_{\lambda,\mathrm{MAX}} - \Delta\lambda_{\lambda,\mathrm{MIN}}) \,/\, 2\sqrt{3} = 0{,}4 \,/\, 2\sqrt{3} = 0{,}115 \qquad \text{(B.25)}$$

Also, the deviation due to wavelength dependence is given by equation (45):

$$\Delta\lambda_{\lambda} = (\Delta\lambda_{\lambda,\mathrm{MAX}} + \Delta\lambda_{\lambda,\mathrm{MIN}}) \,/\, 2 = 0 \qquad \text{(B.26)}$$

B.2.2.2 Temperature dependence

The following centre wavelength values, measured for various temperatures using a He-Ne laser

λ_{REF} = 633,0 nm will be used to show the temperature dependence:

T1 = 10 °C λ_{OSA1} = 632,8 nm

T2 = 15 °C λ_{OSA2} = 632,7 nm

T3 = 20 °C λ_{OSA3} = 632,8 nm

T4 = 25 °C λ_{OSA4} = 632,9 nm

T5 = 30 °C λ_{OSA5} = 633,1 nm

T6 = 35 °C λ_{OSA6} = 633,2 nm

$\Delta\lambda_{\mathrm{T1}}$ = 632,8 – 633,0 = –0,2 (nm)

$\Delta\lambda_{\mathrm{T2}}$ = 632,7 – 633,0 = –0,3 (nm)

$\Delta\lambda_{\mathrm{T3}}$ = 632,8 – 633,0 = –0,2 (nm)

$\Delta\lambda_{\mathrm{T4}}$ = 632,9 – 633,0 = –0,1 (nm)

$\Delta\lambda_{\mathrm{T5}}$ = 633,1 – 633,0 = 0,1 (nm)

$\Delta\lambda_{\mathrm{T6}}$ = 633,2 – 633,0 = 0,2 (nm)

From equations (49) and (48):

$$\sigma_{\Delta\lambda\mathrm{T}} = (\Delta\lambda_{T,\mathrm{MAX}} - \Delta\lambda_{T,\mathrm{MIN}})\ 2\sqrt{3} = (0{,}2 + 0{,}3) /\ 2\sqrt{3} = 0{,}144\ \text{(nm)} \qquad \text{(B.27)}$$

$$\Delta\lambda_{\mathrm{T}} = (\Delta\lambda_{T,\mathrm{MAX}} + \Delta\lambda_{T,\mathrm{MIN}}) \,/\, 2 = (0{,}2 - 0{,}3) \,/\, 2 = -0{,}05\ \text{(nm)} \qquad \text{(B.28)}$$

B.2.3 Expanded uncertainty calculation

The following example shows the expanded uncertainty calculation when the calibration is performed under operating conditions.

We can find the accumulated uncertainty using equation (52):

$$\sigma_{\Delta\lambda cu} = (\sigma_{\Delta\lambda ref}{}^{2} + \sigma_{\Delta\lambda\lambda}{}^{2} + \sigma_{\Delta\lambda T}{}^{2})^{1/2}$$

$$= (0{,}107^{2} + 0{,}115^{2} + 0{,}144^{2})^{1/2}$$

$$= (0{,}045)^{1/2} = 0{,}213 \quad (\mathrm{nm}) \tag{B.29}$$

The wavelength deviation can be found from equation (51):

$$\Delta\lambda_{cu} = \Delta\lambda_{ref} + \Delta\lambda_{\lambda} + \Delta\lambda_{T} = -0{,}16 + 0{,}0 - 0{,}05 = -0{,}21 \quad (\mathrm{nm}) \tag{B.30}$$

Accordingly, we obtain the expanded uncertainty, $U_{\lambda cu}$ with a coverage factor k = 2 for a confidence level of 95 %:

$$U_{\lambda cu} = \pm k\ \sigma_{\Delta\lambda cu} = \pm 2 \times 0{,}213 = \pm 0{,}43 \quad (\mathrm{nm}) \tag{B.31}$$

Annex C
(informative)

Using the calibration results

C.1 General

C.1.1 Scope

Calibrated measurements may be required for conditions that differ from those under which the instrument was calibrated. For example, the measurement of a source at a wavelength that falls between two wavelength calibration points. Therefore, it is necessary to employ the interpolation techniques outlined in this annex.

Interpolation of calibration results will only be valid for certain parameters and restrictions will apply to the ranges over which the interpolation is valid.

C.1.2 Parameters

The method outlined in this annex can be applied to the following parameters:

1) calibration of the wavelength scale correction as a function of vacuum wavelength;
2) calibration of the instrument resolution bandwidth as a function of vacuum wavelength;
3) calibration of the instrument displayed power level as a function of vacuum wavelength;
4) calibration of the instrument power linearity as a function of vacuum wavelength.

The method outlined in this annex is not applicable to the following parameter:

5) polarization dependence.

C.1.3 Restrictions

The interpolation method outlined in this annex is subject to certain restrictions.

1) The operator must ensure that sufficient calibration points are available to verify that the interpolation model is valid.
2) Prediction of calibration corrections for parameters falling outside the range of the calibration points (extrapolation) is not allowed.
3) Certain OSA designs use a diffractive element to select the wavelength and may also use different detectors to cover the wavelength range of the instrument. Interpolation of calibration corrections across such changes in the instrument state is not allowed.
4) If a polynomial fit model is used then the degree of the polynomial should be significantly less than the number of calibration points.
5) The validity range of any interpolating function must always be provided.
6) If the distribution of calibration points is not uniform then it may be necessary to weight the calibration values when fitting the interpolation model. A statistician or other suitably qualified staff should certify that the choice of weighting values is justified.

C.2 Additive corrections

C.2.1 Parameters

In this subclause all examples and symbols will relate to the calibration of the wavelength scale of an OSA using a linear fit.

C.2.2 Measurements close to a calibration reference wavelength

If the OSA is used to measure a wavelength sufficiently close to one of the reference wavelengths used in the calibration, then the measured wavelengths can be corrected to give an approximation to the vacuum wavelength $\lambda_{c,}$ by rearranging equation (44) as shown:

$$\lambda_c = \lambda_{OSA} - \Delta\lambda_{\lambda j} \qquad (C.1)$$

where

λ_{OSA} is the wavelength measured by the test analyzer;

$\Delta\lambda_\lambda$: is the wavelength deviation obtained from the calibration results.

The uncertainty in the corrected wavelength, $\sigma_{\lambda c}$, is found by summing the measurement and correction contributions:

$$\sigma_{\lambda c} = (\sigma_{\Delta\lambda_\lambda}{}^2 + \sigma_{\lambda osa}{}^2)^{1/2} \qquad (C.2)$$

where

$\sigma_{\Delta\lambda_\lambda}$ is the uncertainty of the test analyzer due to wavelength dependence,

$\sigma_{\lambda osa}$ is the standard uncertainty of the values measured during calibration.

C.2.3 Measurements at other wavelengths

In general, only a few reference wavelengths may have been used spread over a wide wavelength range. In this case it may be appropriate to describe the wavelength deviation by

$$\Delta\lambda_{osa}(\lambda_{osa}) = \Delta S_\lambda.\lambda_{osa} + \Delta\lambda_o \qquad (C.3)$$

where ΔS_λ is a scale factor which ideally should be zero and $\Delta\lambda_o$ is an offset which again ideally should be zero. The relationship between the measured wavelength and the true vacuum wavelength is given by

$$\lambda_{vac}(\lambda_{osa}) = \lambda_{osa} + \Delta\lambda_{osa}(\lambda_{osa}) + \boldsymbol{\varepsilon}(\lambda_{osa}) \qquad (C.4)$$

where λ_{vac} (λ_{osa}) is the vacuum wavelength. The term $\varepsilon(\lambda_{osa})$ represents an additional error the form of which may depend on the particular instrument. For example, in an instrument using a sine-bar mechanism, it might represent a periodic sine-bar error. This term also includes type A (random) uncertainty contributions.

Fitting the calibration results to equation (C.3) using a least squares procedure will give ΔS_λ, and $\Delta\lambda_{o.}$

NOTE Provided sufficient reference wavelengths are used, the wavelength differences can be fitted to an equation of higher order. Systematic or functional features in $\varepsilon(\lambda)$ will emerge as higher order term(s) and can therefore be used to correct the measured wavelengths. Appropriate care must be taken to choose a fit equation appropriate for the characteristics of $\varepsilon(\lambda)$ and for the number of reference wavelengths used.

The r.m.s. error due to the imperfect fit $\sigma_{\varepsilon\lambda}$ can be calculated from the residual errors at the reference values:

$$\sigma_{\varepsilon\lambda} = \left[\sum_{i=1}^{n}(\Delta\lambda_{\lambda,i} - \Delta\lambda_{osa}(\Delta\lambda_{osa,i}))^2 / (n-2)\right]^{1/2} \qquad (C.5)$$

NOTE The number of data points n – 2 arises from two parameters, that is, the slope and intercept being fitted.

The wavelengths measured by the OSA can be corrected by subtracting $\Delta\lambda(\lambda_{OSA})$ from λ_{OSA}.

$$\lambda_c = \Delta\lambda_{OSA} - \Delta\lambda(\lambda_{OSA}) \quad (C.6)$$

The uncertainty in the calculated wavelength error/correction, $\sigma_{\Delta\lambda}$ is given by

$$\sigma_{\Delta\lambda} = [\sigma_{\lambda OSA}^2 + \sigma_{\lambda REF}^2 + \sigma_{\varepsilon\lambda}^2]^{1/2} \quad (C.7)$$

where $\sigma_{\lambda REF}$ is the uncertainty in the reference wavelengths used in the calibration. As several wavelengths are used, $\sigma_{\lambda REF}^2$ may be taken as the average of the $(\sigma_{\lambda REF,i})^2$ used in the calibration. If laser/gas emission lines are used for the calibration then this term will be negligible.

C.3 Multiplicative corrections

C.3.1 Parameters

In this subclause all examples and symbols will relate to the calibration of the displayed power scale of an OSA as a function of wavelength.

C.3.2 Measurements close to a calibration reference wavelength

If the OSA is used to measure a power close to one of the reference wavelengths used in the power calibration, then the measured power can be corrected to give an approximation of the true power P_c. Equation. (10) can be rearranged to give

$$P_c = P_{OSA} / (1 + \Delta P_{diff}) \quad (C.8)$$

The uncertainty in the corrected power, σ_{Pc}, is determined by combining the uncertainties in the measured power and the displayed power calibration.

NOTE The measured and corrected power uncertainties are additive, whereas the uncertainty in the displayed power is multiplicative.

$$\sigma_{Pc} = P_c\,(\sigma_{\Delta P diff}^2 + \sigma_{Posa}^2 / P_{OSA}^2)^{1/2} \quad (C.9)$$

C.3.3 Measurements at other wavelengths

In general, only a few display calibrations may have been used spread over a wide wavelength range. In this case, it may be appropriate to describe the calibration error by a function:

$$\Delta P_{diff}(\lambda_{osa}) = \Delta S_P . \lambda_{osa} + \Delta P_o \quad (C.10)$$

where ΔS_P is a scale factor which ideally should be zero and ΔP_o is an offset which again ideally should be zero. The relationship between the measured power and the true power is given by:

$$P_{true}(\lambda_{osa}) = P_{OSA} / (1 + \Delta P_{diff}(\lambda_{osa}) + \varepsilon_P(\lambda_{osa})) \quad (C.11)$$

The term $\varepsilon_P(\lambda_{osa})$ represents an additional error the form of which may depend on the particular instrument. For example, in an instrument using a cooled photodetector this might represent the derivative of the detector response. This term also includes type A (random) uncertainty contributions.

Fitting the calibration results to equation (C.10) using a least-squares procedure will give ΔS_P, and ΔP_o. The r.m.s. error due to the imperfect fit $\sigma_{\varepsilon p}$, can be calculated from the residual errors at the reference values:

$$\sigma_{\varepsilon p} = \left[\sum_{i=1}^{n} (\Delta P_{\text{diff},\lambda i} - \Delta P_{\text{diff}}(\Delta\lambda_i))^2 / (n-2)\right]^{1/2} \qquad \text{(C.12)}$$

NOTE The number of data points n - 2 arises from two parameters, that is the slope and intercept being fitted.

The power measured by the OSA can be corrected as follows:

$$P_c(\lambda_{OSA}) = P_{OSA} / (1 + \Delta P_{\text{diff}}(P_{OSA})) \qquad \text{(C.13)}$$

The uncertainty in the calculated power correction is similar to equation C.9 with an additional term for the fitting error $\sigma_{\varepsilon p}$:

$$\sigma_{Pc}(\lambda_{OSA}) = P_c(\lambda_{OSA}) [\sigma_{\Delta P\text{diff}}{}^2 + \sigma_{\varepsilon p}{}^2 + \sigma_{Posa}{}^2 / P_{OSA}(\lambda_{OSA})^2]^{1/2} \qquad \text{(C.14)}$$

C.4 OSA calibration results (additive correction)

In the following example the procedure outlined in Clause C.2 is used to calibrate the wavelength scale of an OSA. The reference wavelengths were krypton gas emission lines (see Annex D).

Table C1 – OSA calibration results

λ_{REF} (nm)	λ_{OSA} (nm)	$\lambda_{OSA} - \lambda_{REF}$ (pm)	$\lambda_C - \lambda_{REF}$ (pm)	$\sigma_{\Delta\lambda C}$ (pm)
1182,261	1181,721	–540	–0,8	±15
1318,102	1317,532	–570	–7,0	±15
1363,795	1363,231	–564	7,0	±15
1443,074	1442,495	–579	5,9	±15
1473,846	1473,251	–595	–4,7	±15
1524,378	1523,786	–592	7,1	±15
1533,915	1533,308	–607	–6,2	±15
1678,971	1678,343	–628	–1,8	±15
		<–584,4> 88 pk–pk	<–0,8> 14,2 pk–pk	