BS EN 62129-1:2016

BSI Standards Publication

Calibration of wavelength/optical frequency measurement instruments

Part 1: Optical spectrum analyzers

National foreword

This British Standard is the UK implementation of EN 62129-1:2016. It is identical to IEC 62129-1:2016. It supersedes BS EN 62129:2006 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee GEL/86, Fibre optics.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Calibration of wavelength/optical frequency measurement instruments - Part 1: Optical spectrum analyzers (IEC 62129-1:2016)

Étalonnage des appareils de mesure de longueur d'onde/appareil de mesure de la fréquence optique - Partie 1: Analyseurs de spectre optique (IEC 62129-1:2016)

Kalibrierung von Messgeräten für die Wellenlänge/optische Frequenz - Teil 1: Optische Spektrumanalysatoren (IEC 62129-1:2016)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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European foreword

The text of document 86/477/CDV, future edition 1 of IEC 62129-1, prepared by IEC/TC 86 "Fibre optics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62129-1:2016.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2016-12-03
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2019-06-03

This document supersedes EN 62129:2006.

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The text of the International Standard IEC 62129-1:2016 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60793-2-50	NOTE	Harmonized as EN 60793-2-50.
IEC 61315	NOTE	Harmonized as EN 61315.
IEC 62129-2	NOTE	Harmonized as EN 62129-2.
IEC 62522	NOTE	Harmonized as EN 62522.
IEC 60359:2001	NOTE	Harmonized as EN 60359:2002 (not modified).
IEC 61290-3-1	NOTE	Harmonized as EN 61290-3-1.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 60050-731	-	International Electrotechnical Vocabulary - Chapter 731: Optical fibre communication	-	-
IEC 60793-2	series	Optical fibres - Part 2: Product specifications	EN 60793-2	series
IEC 60825-1	-	Safety of laser products - Part 1: Equipment classification and requirements	EN 60825-1	-
ISO/IEC 17025	-	General requirements for the competence of testing and calibration laboratories	EN ISO/IEC 17025	-
ISO/IEC Guide 98-3	2008	Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)	-	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

CALIBRATION OF WAVELENGTH/OPTICAL FREQUENCY MEASUREMENT INSTRUMENTS –

Part 1: Optical spectrum analyzers

FOREWORD

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International Standard IEC 62129-1 has been prepared by IEC technical committee 86: Fibre optics.

This first edition of IEC 62129-1 cancels and replaces the first edition of IEC 62129, published in 2006. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) update of term and definitions;
b) update of calibration conditions;
c) calculation change of uncertainties related to wavelength temperature dependence, power linearity, power level temperature dependence;
d) move of Annex E to the bibliography.

The text of this standard is based on the following documents:

CDV	Report on voting
86/477/CDV	86/483/RVC

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62129 series, published under the general title *Calibration of wavelength/optical frequency measurements instruments*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

CALIBRATION OF WAVELENGTH/OPTICAL FREQUENCY MEASUREMENT INSTRUMENTS –

Part 1: Optical spectrum analyzers

1 Scope

This part of IEC 62129 specifies procedures for calibrating an optical spectrum analyzer that is developed for use in fibre-optic communications and designed to measure the power distribution of an optical spectrum. It does not apply to an optical wavelength meter that measures only centre wavelengths, a Fabry-Perot interferometer or a monochromator that has no display unit.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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, *International Electrotechnical Vocabulary – Chapter 731: Optical fibre communication* (available at http://www.electropedia.org)

IEC 60793-2 (all parts), *Optical fibres – Part 2: Product specifications*

IEC 60825-1, *Safety of laser products – Part 1: Equipment classification and requirements*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

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

3.1
accredited calibration laboratory
calibration laboratory authorized by an appropriate national organization to issue calibration certificates that demonstrates traceability to national standards

3.2
calibration
set of operations that establish, under specified conditions, the relationship between the values of quantities indicated by a measuring instrument and the corresponding values realized by standards

Note 1 to entry: The results of a calibration permit either the assignment of measurand values to the indications or the determination of corrections with respect to the indications.

Note 2 to entry: A calibration may also determine other metrological properties such as the effects of influence quantities.

Note 3 to entry: The result of a calibration may be recorded in a document, called a calibration certificate or a calibration report.

[SOURCE: ISO/IEC Guide 99:2007, 2.39, modified — only the first part of the definition is used]

3.3
calibration under reference conditions

calibration which includes the evaluation of the test analyzer uncertainty under reference conditions (3.18)

3.4
calibration for operating conditions

calibration for operating conditions of an optical spectrum analyzer (3.15) including the evaluation of the test analyzer operational uncertainty

3.5
centre wavelength
centroidal wavelength

λ_c

power-weighted mean wavelength of a light source in vacuum

Note 1 to entry: The centre wavelength is expressed in nanometers (nm).

Note 2 to entry: For a continuous spectrum, the centre wavelength is defined as

$$\lambda_\mathrm{c} = \frac{\int p(\lambda)\lambda d\lambda}{P_\mathrm{total}} \tag{1}$$

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

$$\lambda_\mathrm{c} = \frac{\sum_i P_i \lambda_i}{\sum_i P_i} \tag{2}$$

where

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

λ_i is the vacuum wavelength of the i^th discrete line;

P_i is the power of the i^th discrete line, for example, in W;

P_total is the total power, for example, in W.

Note 3 to entry: The above integrals and summations theoretically extend over the entire spectrum of the light source.

3.6
confidence level

confidence interval

estimation of the probability that the true value of a measured parameter lies in the given range

Note 1 to entry: See expanded uncertainty (3.8)

3.7
coverage factor
k
factor by which the standard uncertainty (3.22), u, is multiplied to calculate the expanded uncertainty (3.8), U

Note 1 to entry: See 3.8.

3.8
expanded uncertainty
U
range of values within which the measurement parameter, at the stated confidence level (3.6), can be expected to lie

Note 1 to entry: It is equal to the coverage factor (3.7), k, times the combined standard uncertainty (3.22) u

$$U = ku \tag{3}$$

Note 2 to entry: When the distribution of uncertainties is assumed to be normal and a large number of measurements are made, then confidence levels (3.6) of 68,3 %, 95,5 % and 99,7 % correspond to k values of 1, 2 and 3 respectively.

Note 3 to entry: The measurement uncertainty of an optical spectrum analyzer (3.15) should be specified in the form of expanded uncertainty, U.

3.9
instrument state
complete description of the measurement conditions and state of an optical spectrum analyzer (3.15) during the calibration process

Note 1 to entry: Typical parameters of the instrument state are the displayed wavelength range in use, the resolution bandwidth (spectral resolution) (3.19), the display mode (W or dBm), warm-up time and other instrument settings.

3.10
measurement result
displayed or electrical output of any optical spectrum analyzer (3.15) 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)

3.11
measurement range
set of values of measurands for which the error of a measuring instrument is intended to lie within specified limits

3.12
national measurement standard
standard recognized by a national decision to serve, in a country, as the basis for assigning values to other standards of the quantity concerned

[SOURCE: ISO/IEC Guide 99:2007, 5.3, modified]

3.13
national standards laboratory
laboratory which maintains the national standard (3.12)

3.14
operating conditions
all conditions of the measured and influential quantities, and other important requirements which the expanded uncertainty (3.8) of an optical spectrum analyzer (3.15) is intended to meet

[SOURCE: ISO/IEC Guide 99:2007, 4.9, modified]

3.15
optical spectrum analyzer
OSA

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

Note 1 to entry: 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.

Note 2 to entry: This note applies to the French language only.

3.16
power level

power level indicated by an optical spectrum analyzer (3.15) undergoing calibration (3.2) at a specified wavelength resolution setting

Note 1 to entry: With an optical spectrum analyzer, the power level for a set resolution is measured and displayed.

3.17
power level deviation

D_P

difference between the power level measured by the test analyzer, P_{OSA}, and the corresponding reference power, P_{REF}, divided by the reference power

$$Dp = \frac{P_{\mathrm{OSA}} - P_{\mathrm{REF}}}{P_{\mathrm{REF}}} = \frac{P_{\mathrm{OSA}}}{P_{\mathrm{REF}}} - 1 \qquad (4)$$

3.18
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

Note 1 to entry: Each tolerance band includes both the possible uncertainty of the condition and the uncertainty in measuring the condition.

Note 2 to entry: 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 power level (3.16), reference fibre, reference connector-adaptor combination, reference wavelength, reference (spectral) bandwidth and resolution bandwidth (spectral resolution) (3.19) set.

[SOURCE: IEC 60359:2001, 3.3.10, modified]

3.19
resolution bandwidth

R

spectral resolution

full width at half maximum (FWHM) of the displayed spectrum obtained by the test analyzer when using a source whose spectral bandwidth (3.21) is sufficiently narrow, that is, very much less than the resolution bandwidth being measured

3.20
SMSR
side-mode suppression ratio

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 1 to entry: The side-mode suppression ratio is usually expressed in dB.

Note 2 à l'article: This note applies to the French language only.

3.21
spectral bandwidth

B

FWHM of the spectral width of the source

Note 1 to entry: If the source exhibits a continuous spectrum, then the spectral bandwidth, B, is the FWHM of the spectrum.

Note 2 to entry: 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).

$$B = 2{,}35\sqrt{\frac{1}{P_{\text{total}}}\sum_i P_i \lambda_i^2 - \lambda_\text{c}^2} \tag{5}$$

$$P_{\text{total}} = \sum_i P_i \tag{6}$$

where

λ_c is the centre wavelength (3.5) of the laser diode, in nm;

P_{total} is the total power, in W;

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

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

3.22
standard uncertainty

u

uncertainty of a measurement result expressed as a standard deviation

Note 1 to entry: For further information, see Annex A and ISO/IEC Guide 98-3.

3.23
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

Note 1 to entry: See ISO/IEC Guide 98-3.

3.24
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

Note 1 to entry: See ISO/IEC Guide 98-3.

Note 2 to entry: 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.

3.25
wavelength deviation

D_λ

difference between the centre wavelength (3.5) measured by the test analyzer, λ_{OSA}, and the reference wavelength, λ_{REF}

$$D_\lambda = \lambda_{\text{OSA}} - \lambda_{\text{REF}} \tag{7}$$

Note 1 to entry: The wavelength deviation is expressed in nm or µm.

4 Preparation for calibration

4.1 Organization

The calibration laboratory should satisfy requirements of ISO/IEC 17025.

There shall be a documented measurement procedure for each type of calibration performed, giving step-by-step operating instructions and equipment to be used.

4.2 Traceability

The requirements of ISO/IEC 17025 should be met.

All standards used in the calibration process shall be calibrated according to a documented programme with traceability to national standards laboratories or to accredited calibration laboratories.

It is advisable to maintain more than one standard on each hierarchical level, so that the performance of the standard can be verified by comparisons on the same level. Make sure that any other calibration equipment which has a significant influence on the calibration results is calibrated. Upon request, specify this calibration equipment and its calibration chain(s). The re-calibration period(s) shall be defined and documented.

4.3 Preparation

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 (refer to IEC 60825-1).

4.4 Reference calibration conditions

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

The calibration should be performed at a temperature of 23 °C ± 2 °C and relative humidity of (50 ± 20) % unless otherwise specified. Give the test equipment a minimum of two hours 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.

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

Document the conditions as specified in Clause 8.

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

5 Wavelength calibration

5.1 Overview

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

a) the intrinsic uncertainty of the test analyzer as found in the test under reference conditions including its resolution, resolution of the wavelength meter and temperature dependence for these conditions, and

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

Calibration under reference conditions described in 5.2 to obtain the intrinsic uncertainty is mandatory. However, calibration under operating conditions described in 5.3 is not mandatory. If the test analyzer is operated beyond the reference conditions, it shall be calibrated within the range of operating conditions. The wavelength is that in vacuum.

5.2 Wavelength calibration under reference conditions

5.2.1 General

Alternative setups for the calibration under reference conditions are shown in Figures 1, 2, and 3. In the Figure 1 setup, a gas laser whose wavelength is known is used for the light source. Figure 2 shows a setup 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 setup in which a laser diode (LD) whose wavelength is unknown is used for the light source. This test is performed under reference calibration conditions.

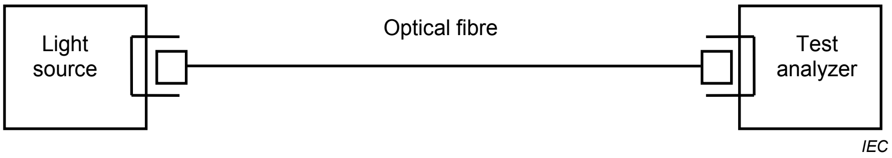

Figure 1 – Setup using a gas laser whose wavelength is known

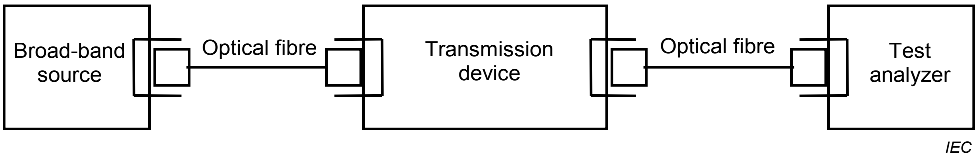

Figure 2 – Setup using a broadband source with a transmission device

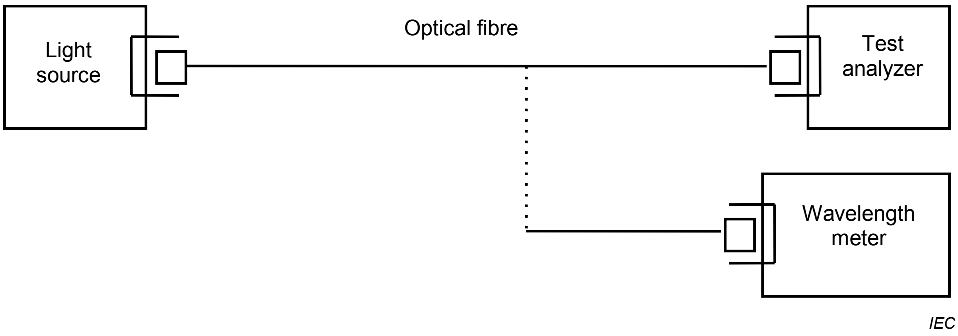

Figure 3 – Setup using an LD with an unknown wavelength

5.2.2 Equipment for wavelength calibration under reference conditions

The equipment for wavelength calibration is as follows.

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 tuneable) 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 shall 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 (see Figure 3).

5.2.3 Procedure for wavelength calibration under reference conditions

The procedures for wavelength calibration under reference conditions are as follows.

a) Using the test setup shown in Figure 1, Figure 2 or Figure 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 sampling resolution (S/N) of the test analyzer so that it satisfies Equation (8) and is better than the tested wavelength uncertainty.

$$\frac{S}{N} < \frac{R_{\text{set}}}{10} \tag{8}$$

   where

   S is the displayed wavelength range;

   N is the number of display points;

   R_{set} is the set resolution bandwidth (spectral resolution) of the optical spectrum analyzer under test. When using the test configuration shown in Figure 1 or Figure 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 $\lambda_{\text{OSA},i}$.

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

$$\lambda_{\text{OSA}_{\text{AV}}} = \frac{1}{m}\sum_{i=1}^{m} \lambda_{\text{OSA},i} \tag{9}$$

   where m is the number of measurements used.

5.2.4 Calculations of wavelength uncertainty under reference conditions

From the measured value, calculate the deviation, $D_{\lambda\text{ref}}$:

$$D_{\lambda\text{ref}} = \lambda_{\text{OSA}_{\text{AV}}} - \lambda_{\text{REF}} \tag{10}$$

Calculate the standard uncertainty $u_{\lambda\text{OSA}}$ of the measured $\lambda_{\text{OSA},i}$ values using Equation (11).

$$u_{\lambda\text{OSA}} = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(\lambda_{\text{OSA},i} - \lambda_{\text{OSA}_{\text{AV}}}\right)^2} \tag{11}$$

The uncertainty $u_{D_{\lambda\,\text{ref}}}$ of the test analyzer with regard to wavelength under the reference calibration conditions is given by Equation (12).

$$u_{D_{\lambda\text{ref}}} = \sqrt{u_{\lambda\text{REF}}{}^2 + \frac{u_{\lambda\text{OSA}}{}^2}{m} + u_{\text{res\_ref}}^2 + u_{\text{res\_OSA}}^2 + u_{D_{\lambda T}}{}^2} \tag{12}$$

where

$u_{\lambda\text{ref}} = \dfrac{U_{\lambda\text{ref}}}{k}$ is the uncertainty of the light source wavelength;

$u_{\lambda\text{OSA}}$ is the standard uncertainty of the values measured during the test;

$u_{\text{res\_ref}}$ is the uncertainty given by the display resolution of the wavelength meter (if used);

$u_{\text{res\_OSA}}$ is the uncertainty given by the display resolution of the OSA;

$u_{D_{\lambda T}}$ is the uncertainty given by the dependence on the temperature and can be evaluated as in 5.3.3, except using temperature range reference conditions. It can be neglected if it is about 10 times lower than $u_{D_{\lambda\text{ref}}}$.

The uncertainty of the light source wavelength, $u_{\lambda\text{REF}}$, 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, $u_{\lambda\text{REF}}$.

5.3 Wavelength calibration for operating conditions

5.3.1 General

The calibration described in 5.3 is not mandatory. Perform the calibration procedure when the test analyzer is used beyond the reference conditions.

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

a) wavelength dependence;

b) temperature dependence.

5.3.2 Wavelength dependence

5.3.2.1 General

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.

5.3.2.2 Equipment for determining wavelength dependence

The equipment for determining wavelength dependence is as follows:

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, tuneable 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 shall 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 (see Figure 3).

5.3.2.3 Test procedure for determining wavelength dependence

When using the test configuration shown in Figure 1 or 2, let the value of the known wavelength of the light source(s) or transmission artefact(s) be $\lambda_{\mathrm{REF},j}$, and for the test configuration shown in Figure 3, let $\lambda_{\mathrm{REF},j}$ 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 $\lambda_{\mathrm{OSA}j}$. Then determine the wavelength deviation $D_{\lambda\lambda j}$ with respect to $\lambda_{\mathrm{REF},j}$ using Equation (13).

$$D_{\lambda\lambda j} = \lambda_{\mathrm{OSA}j} - \lambda_{\mathrm{REF}j} \tag{13}$$

b) Next, change the source wavelength and perform the same test, again determining the deviation using Equation (13).

c) Let $D_{\lambda\lambda,\mathrm{max}}$ be the maximum value of the deviation values obtained.

5.3.2.4 Calculations of wavelength uncertainty due to wavelength dependence

By using the deviation of measurement values for several wavelengths, determine the uncertainty, $u_{D_{\lambda\lambda}}$ due to wavelength dependence by using Equation (14).

$$u_{D_{\lambda\lambda}} = \frac{\left|D_{\lambda\lambda}\right|_{\mathrm{MAX}}}{\sqrt{3}} \tag{14}$$

5.3.3 Temperature dependence

5.3.3.1 General

Figure 4 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.

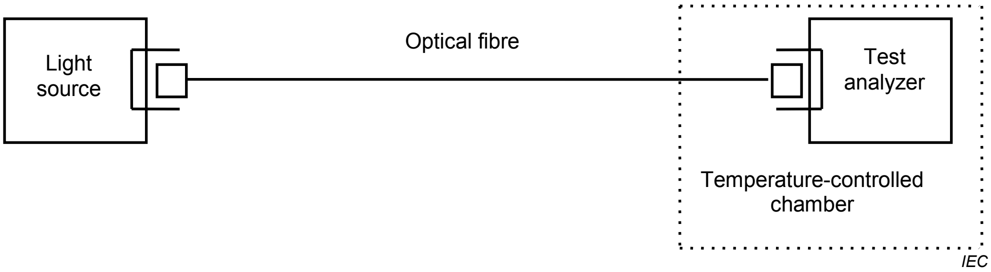

Figure 4 – Test configuration for determining the temperature dependence of wavelength uncertainty

5.3.3.2 Equipment for determining temperature dependence

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 broad band source with a transmission device. Annex D tabulates many stable wavelength references.

5.3.3.3 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 $\lambda_{\mathrm{OSA},j}$, determine the deviation in wavelength using Equation (15).

$$D_{\lambda_{Tj}} = \lambda_{\mathrm{OSA},j} - \lambda_{\mathrm{REF}} \tag{15}$$

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

c) Let $\left|D_{\lambda_T}\right|_{\mathrm{MAX}}$ be the maximum of all absolute values of $D_{\lambda_{Tj}}$ obtained.

5.3.3.4 Calculations of wavelength uncertainty due to temperature dependence

By using the deviations of measurement values at several temperatures, determine the uncertainty $u_{D_{\lambda_T}}$ due to temperature dependence using Equation (16).

$$u_{D_{\lambda_T}} = \frac{\left|D_{\lambda_T}\right|_{\mathrm{MAX}}}{\sqrt{3}} \tag{16}$$

5.4 Calculation of expanded uncertainty

When the test analyzer is only used under reference conditions, the expanded uncertainty, $U_{\lambda_{\mathrm{ref}}}$, can be calculated by Equation (17) with a coverage factor k.

$$U_{\lambda_{\mathrm{ref}}} = \pm k u_{D_{\lambda_{\mathrm{ref}}}} \tag{17}$$

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.

The uncertainty at operating conditions of the wavelength is calculated by using Equation (18) and Equations (12), (14) and (16).

$$u_{D\lambda_{\mathrm{op}}} = \sqrt{u_{\lambda\mathrm{REF}}{}^{2} + u_{\lambda\mathrm{OSA}}{}^{2} + u_{\mathrm{res\_ref}}^{2} + u_{\mathrm{res\_OSA}}^{2} + u_{D_{\lambda\lambda}}{}^{2} + u_{D_{\lambda T}}{}^{2}} \tag{18}$$

The expanded uncertainty, $U_{\lambda\mathrm{op}}$ with a coverage factor k is expressed by Equation (19):

$$U_{\lambda\mathrm{op}} = \pm k u_{D\lambda_{\mathrm{op}}} \tag{19}$$

If the wavelength needs to be corrected based on the results 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.

6 Power level calibration

6.1 Overview

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

a) the intrinsic uncertainty of the test analyzer as found in the test under reference conditions including its resolution, resolution of the reference power meter and temperature dependence for these 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 6.3.2 to 6.3.5 in compliance with the individual factor, i.e. 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 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.

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.

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

6.2 Power level calibration under reference conditions

6.2.1 General

Figure 5 shows the test configuration for determining the uncertainty in the power level. This test is performed under reference calibration conditions.

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

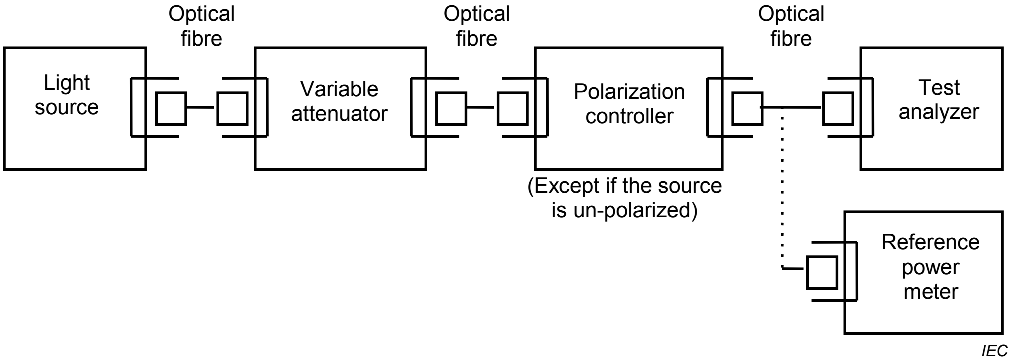

Figure 5 – Setup for calibration of power level under reference conditions

6.2.2 Equipment for power level calibration under reference conditions

The equipment for power level calibration under reference conditions is as follows:

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 be in turn 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 3.20) or a fibre laser (also with SMSR > 40 dB) are recommended.

   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:* use 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, U_{PMref}, is already known and is described in its certification.

d) *Polarization controller*: unless the source is non-polarized, a polarization controller is used.

6.2.3 Procedure for power level 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 $P_{\mathrm{REF}i}$ 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 $P_{\mathrm{OSA}i}$; 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, as D_{Pi} , from the power meter measurement using Equation (20).

$$D_{Pi} = \frac{P_{\mathrm{OSA}i}}{P_{\mathrm{REF}i}} - 1 \tag{20}$$

d) Repeat this measurement at least ten times.

6.2.4 Calculation of power level uncertainty under reference conditions

Calculate the power level deviation, D_P, and standard deviation, u_{D_P} , of the difference ratio using Equations (21) and (22):

$$D_P = \frac{1}{m}\sum_{i=1}^{m} D_{Pi} \tag{21}$$

$$u_{D_P} = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(D_{Pi} - D_P\right)^2} \tag{22}$$

where m is the number of measurements used.

The uncertainty $u_{D_{P\mathrm{ref}}}$ with respect to the power level for the test analyzer operated under reference calibration conditions is given by Equation (23).

$$u_{D_{P\mathrm{ref}}} = \sqrt{u_{\mathrm{PMref}}^2 + \frac{u_{D_P}^2}{m} + u_{\mathrm{res\_ref}}^2 + u_{\mathrm{res\_OSA}}^2 + u_{D_{P\mathrm{TMP}}}{}^2} \tag{23}$$

where

$u_{\mathrm{PMref}} = \dfrac{U_{\mathrm{PMref}}}{k}$	is the uncertainty, at the measured power, of the reference optical power meter described in its certification;
u_{D_P}	is the standard deviation of the values measured during the test;
$u_{\mathrm{res\_ref}}$	is the uncertainty given by the display resolution of the reference power meter;
$u_{\mathrm{res\_OSA}}$	is the uncertainty given by the display resolution of the OSA;

$u_{D_{P\text{TMP}}}$ is the uncertainty given by the dependence on the temperature and can be evaluated as in 6.3.5, except using temperature range reference conditions. It can be neglected if it is about 10 times lower than $u_{D_{P\text{ref}}}$.

The power level deviation $D_{P\text{ref}}$ is given by Equation (24), which is the same as the mean value of the difference ratio.

$$D_{P\text{ref}} = D_P \tag{24}$$

6.3 Power level calibration for operating conditions

6.3.1 General

The calibration described in 6.3 is not mandatory. Perform the calibration procedure when the test analyzer is used beyond the reference conditions.

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

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

6.3.2 Wavelength dependence

6.3.2.1 General

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

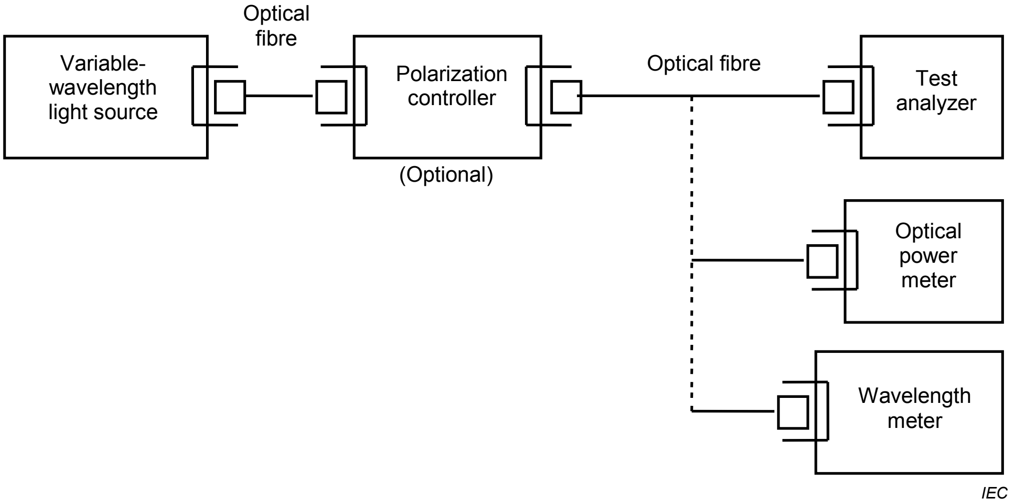

Figure 6 – Test configuration for determining the wavelength dependence of power level uncertainty

6.3.2.2 Equipment for determining wavelength dependence of power level

The equipment for determining the wavelength dependence of power level is as follows.

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 according to IEC 62522.
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 half-wavelength plate and a quarter-wavelength plate; some rotate three fibre loops.

6.3.2.3 Test procedure for determining wavelength dependence of power level

Use the test configuration shown in Figure 6.

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 $P_{\mathrm{REF},\lambda_j}$. 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 $P_{\mathrm{OSA},\lambda_j}$. 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, $D_{P_{\lambda_j}}$, is given by Equation (25).

$$D_{P_{\lambda_j}} = \frac{P_{\mathrm{OSA},\lambda_j}}{P_{\mathrm{REF},\lambda_j}} - 1 \tag{25}$$

d) Repeat this procedure with different wavelength settings (change λ_j). If the test analyzer is to be used to measure broad spectrum sources such as surface-emitting light-emitting diodes (LED), especially multimode ones at 1 300 nm, the wavelength dependence of the power level should be measured at several wavelengths within the source spectrum.
e) Let $\left|D_{P_\lambda}\right|_{\mathrm{MAX}}$ be the maximum of all absolute values of $D_{P_{\lambda_j}}$ obtained.

6.3.2.4 Calculation of power level uncertainty due to wavelength dependence

The standard uncertainty due to wavelength dependence, $u_{D_{P_\lambda}}$ is given by Equation (26).

$$u_{D_{P_\lambda}} = \frac{\left|D_{P_\lambda}\right|_{\mathrm{MAX}}}{\sqrt{3}} \tag{26}$$

6.3.3 Polarization dependence

6.3.3.1 General

Figure 7 shows the test configuration for determining polarization dependence. This test is performed under reference calibration conditions except for the polarization.

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

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

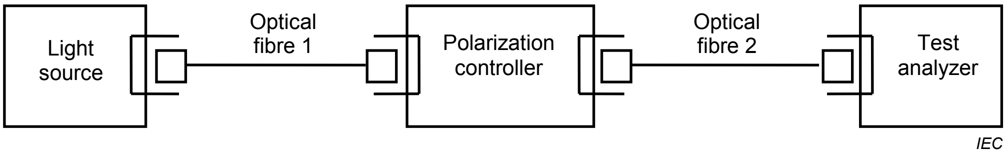

Figure 7 – Test configuration for determining the polarization dependence of power level uncertainty

6.3.3.2 Equipment for determining polarization dependence of power level

The equipment for determining the polarization dependence of power level is as follows:

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 3.20) 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 half-wavelength plate and a quarter-wavelength plate; some rotate three fibre loops.

c) *Optical fibre:* use a single-mode optical fibre class B as defined in IEC 60793-2 and having a length of 1 m to 2 m. A polarization-maintaining fibre is preferred to the input fibre of some polarization controllers.

6.3.3.3 Test procedure for determining polarization dependence of power level

Using the test configuration shown in Figure 7, set the resolution bandwidth of the test analyzer sufficiently larger than the spectral bandwidth of the light source.

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 Poincaré sphere. Observe the peak-to-peak change in power level caused by changing the polarization state. Record the maximum and minimum readings as $P_{\mathrm{MAX}}(\lambda j)$ and $P_{\mathrm{MIN}}(\lambda j)$, respectively.

c) The variations in power level due to polarization with wavelengths of λj, $DP_{\mathrm{UL}}(\lambda j)$ and $DP_{\mathrm{LL}}(\lambda j)$ are given by Equations (27) and (28).

$$DP_{\mathrm{UL}}(\lambda j) = \frac{P_{\mathrm{MAX}}(\lambda j)}{P_{\mathrm{AVE}}(\lambda j)} - 1 \tag{27}$$

$$DP_{\mathrm{LL}}(\lambda j) = \frac{P_{\mathrm{MIN}}(\lambda j)}{P_{\mathrm{AVE}}(\lambda j)} - 1 \tag{28}$$

where, $P_{\mathrm{AVE}}(\lambda j)$ is the average power level due to polarization with a wavelength of λj, and is given by Equation (29).

$$P_{\mathrm{AVE}}(\lambda j) = \frac{P_{\mathrm{MAX}}(\lambda j) + P_{\mathrm{MIN}}(\lambda j)}{2} \tag{29}$$

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

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

6.3.3.4 Calculation of uncertainty due to polarization dependence

The uncertainty of power level variations due to polarization, $u_{D_{P\mathrm{POL}}}$, is given by Equation (30).

$$u_{D_{P\mathrm{POL}}} = \frac{D_{P\mathrm{POL,MAX}} - D_{P\mathrm{POL,MIN}}}{2\sqrt{3}} \tag{30}$$

6.3.4 Linearity

6.3.4.1 General

Use the superposition method given in IEC 61315 or the method depicted in Figure 8. This test is performed under reference calibration conditions except for the power level.

The light source used shall 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.

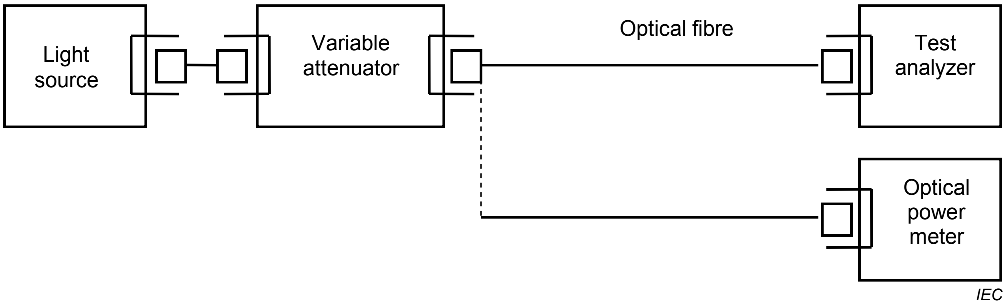

Figure 8 – Configuration for testing linearity error of power level uncertainty

6.3.4.2 Equipment for determining power level linearity error

The equipment for determining the power level linearity error is as follows.

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 3.20) 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.

6.3.4.3 Test procedure for determining power level linearity error

The test procedure for determining the power level linearity error is as follows.

a) With the test setup 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. 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 $P_{\mathrm{LIN,ref}}$.

$$P_{\mathrm{LIN,ref}} = \frac{P_{\mathrm{OSA}}}{P_{\mathrm{REF}}} \tag{31}$$

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 $P_{\mathrm{OSA},j}$ and $P_{\mathrm{REF},j,}$ respectively, and the ratio of the two as $P_{\mathrm{LIN},j}$.

$$P_{\mathrm{LIN},j} = \frac{P_{\mathrm{OSA},j}}{P_{\mathrm{REF},j}} \tag{32}$$

   The linearity error at a power level of P_j, $DP_{\mathrm{LIN},}$ (P_j), is given by Equation (33).

$$DP_{\mathrm{LIN},}\left(P_j\right) = \frac{P_{\mathrm{LIN},j}}{P_{\mathrm{LIN,ref}}} - 1 \tag{33}$$

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 $\left|D_{P_{\mathrm{LIN}}}\right|_{\mathrm{MAX}}$ be the maximum of all absolute values of $DP(P_j)$ obtained.

6.3.4.4 Calculation of uncertainty due to power level linearity error

The uncertainty of linearity, $u_{D_{P_{\mathrm{LIN}}}}$, is given by Equation (34).

$$u_{D_{P_{\mathrm{LIN}}}} = \frac{\left|D_{P_{\mathrm{LIN}}}\right|_{\mathrm{MAX}}}{\sqrt{3}} \tag{34}$$

6.3.5 Temperature dependence

6.3.5.1 General

Figure 9 shows the test configuration for temperature dependence. This test is performed under reference calibration conditions with the exception of temperature. The light source used shall 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.

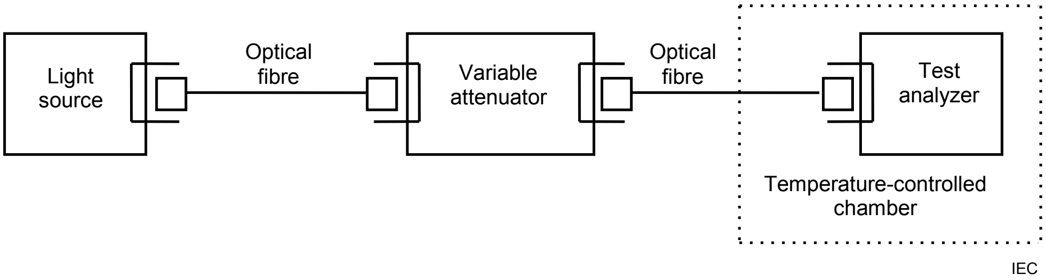

Figure 9 – Test configuration for determining the temperature dependence of power level uncertainty

6.3.5.2 Equipment for determining temperature dependence of power level

The equipment for determining the temperature dependence of power level is as follows.

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 3.20) 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.

6.3.5.3 Test procedure for determining temperature dependence of power level

The test procedure for determining the temperature dependence of power level is as follows.

a) With the test configuration shown in Figure 9, 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 $P_{\mathrm{OSA},T\mathrm{ref}}$.

b) Then change the temperature of the temperature-controlled chamber. Sufficient time (for example 2 h) shall 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 $P_{\mathrm{OSA}j}$.

   The sensitivity error at temperature T_j, $DP(T_j)$, is given by Equation (35).

$$DP(T_j) = \frac{P_{\mathrm{OSA}j}}{P_{\mathrm{OSA},T\mathrm{ref}}} - 1 \qquad (35)$$

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

d) Let $\left|D_{P\mathrm{TMP}}\right|_{\mathrm{MAX}}$ be the maximum of all absolute values of $DP(T_j)$ obtained.

6.3.5.4 Calculation of uncertainty due to temperature dependence of power level

The uncertainty due to temperature dependence, $u_{D_{P\mathrm{TMP}}}$, is given by Equation (36).

$$u_{D_{P\mathrm{TMP}}} = \frac{\left|D_{P\mathrm{TMP}}\right|_{\mathrm{MAX}}}{\sqrt{3}} \tag{36}$$

6.4 Calculation of expanded uncertainty

When the test analyzer is only used under reference conditions, the expanded uncertainty, $U_{P\mathrm{ref}}$, can be calculated by Equation (37) with a coverage factor k.

$$U_{P\mathrm{ref}} = \pm k u_{D_{P\mathrm{ref}}} \tag{37}$$

When the test analyzer is operated beyond the reference conditions, the accumulative power level uncertainty of the test analyzer, $u_{D_{P\mathrm{op}}}$, should be calculated using Equation (38) with the results of Equations (23), (26), (30), (34) and (36) when all the calibration procedures are performed under operating conditions.

$$u_{D_{P\mathrm{op}}} = \sqrt{u_{\mathrm{PMref}}^2 + u_{D_P}^2 + u_{\mathrm{res\_ref}}^2 + u_{\mathrm{res\_OSA}}^2 + {u_{D_{P\lambda}}}^2 + {u_{D_{P\mathrm{POL}}}}^2 + {u_{D_{P\mathrm{LIN}}}}^2 + {u_{D_{P\mathrm{TMP}}}}^2} \tag{38}$$

where

$u_{\mathrm{PMref}} = \frac{U_{\mathrm{PMref}}}{k}$	is the uncertainty, at the measured power, of the reference optical power meter described in its certification;
u_{D_P}	is the standard deviation of the values measured at reference conditions;
$u_{\mathrm{res\_ref}}$	is the uncertainty given by the display resolution of the reference power meter;
$u_{\mathrm{res\_OSA}}$	is the uncertainty given by the display resolution of the OSA;
$u_{D_{P\lambda}}$	is the uncertainty due to wavelength dependence;
$u_{D_{P\mathrm{POL}}}$	is the uncertainty due to polarization dependence;
$u_{D_{P\mathrm{LIN}}}$	is the uncertainty due to linearity;
$u_{D_{P\mathrm{TMP}}}$	is uncertainty due to temperature dependence.

The expanded uncertainty, $U_{P\mathrm{op}}$, with a coverage factor k is expressed by Equation (39):

$$U_{P\mathrm{op}} = \pm k u_{D_{P\mathrm{op}}} \tag{39}$$

The deviation, uncertainty and expanded uncertainty of the power level, D_P, u_P and U_P, at the power level indicated by P(mW) are given by Equations(40) and (41), when the aim is to obtain these values in absolute power units.

$$D_P = D_{P_{\text{ref}}} P\,(\text{mW}) \tag{40}$$

$$U_{P\text{ref}} = U_{P\text{ref}} P\,(\text{mW}) \tag{41}$$

When the deviation or uncertainty shall be expressed as dB units, use Equation (42) to convert to dB units:

$$U(\text{dB}) = 10\log_{10}(1+X) \tag{42}$$

where $X = D_{P_{\text{ref}}}$ or $U_{D_{P_{\text{ref}}}}$

If this is the power level which shall be corrected based on 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 Resolution bandwidth (spectral resolution) test

7.1 Overview

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

NOTE The result of the resolution bandwidth (spectral resolution) test described here is 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.

7.2 Resolution bandwidth (spectral resolution) test

7.2.1 General

Alternative setups for resolution bandwidth test are shown in Figures 1, 2, and 3. In the Figure 1 setup, a gas laser whose wavelength is known is used as the light source. Figure 2 shows a setup 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 setup in which a laser diode (LD) whose wavelength is unknown is used for the light source.

7.2.2 Equipment for resolution bandwidth (spectral resolution) test

The equipment for the resolution bandwidth (spectral resolution) test is as follows.

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 tuneable) 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[a]	632,991
	1 152,590
	1 523,488

[a] In the He-Ne laser at 1 152 nm wavelength, there may be two modes. Ensure the correct line is used.

b) *Wavelength meter:* use an instrument for measuring the wavelength of a light source. The wavelength meter needs to be calibrated and corrected for possible deviations. This instrument is used when a laser diode (LD) with an unknown wavelength is used as the light source. This instrument should be calibrated in accordance with IEC 62129-2.

c) *Optical fibre:* use a single-mode optical fibre class B as defined in IEC 60793-2.

7.2.3 Test procedure for resolution bandwidth (spectral resolution)

The test procedure for resolution bandwidth (spectral resolution) is as follows.

a) Using the test setup shown in Figure 1, 2 or 3, set the wavelength measurement range of the test analyzer to a narrow value that includes the entire spectrum of the light source. 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, i.e. the wavelength interval 3 dB below the peak value, as $R_{\text{OSA}i}$. Repeat this measurement at least ten times and calculate the average resolution using Equation (43).

$$R_{\text{OSA}} = \frac{1}{m}\sum_{i=1}^{m} R_{\text{OSA}i} \tag{43}$$

where m is the number of measurements.

c) Calculate the difference ratio of the OSA value from the resolution bandwidth setting using Equation (44).

$$D_R = \frac{R_{\text{OSA}}}{R_{\text{set}}} - 1 \tag{44}$$

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

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 tuneable fibre laser. By averaging the resolution bandwidth readings, a more accurate measurement of the true resolution bandwidth can be obtained.

8 Documentation

8.1 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, 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.

8.2 Measurement data and uncertainty

Calibration certificates claiming to be in compliance with this document shall include the following data and their uncertainties. The uncertainties shall be stated in the form of estimated confidence intervals by multiplying the relevant standard uncertainty by $\pm k$.

a) The wavelength deviation, $D_{\lambda_{\text{ref}}}$, and its uncertainty, $\pm k u_{D_{\lambda_{\text{ref}}}}$, for example, in nm, in vacuum. See the detailed requirements in Clause 5.

b) The power level deviation, $D_{P_{\text{ref}}}$, and its uncertainty, $\pm k u_{D_{P_{\text{ref}}}}$, for example, in % or dB. See the detailed requirements in Clause 6.

c) Resolution bandwidth (spectral resolution) test result, if measured, for example, difference ratio, D_R. The wavelength is that in vacuum. See the detailed requirements in Clause 7.

Annex A
(normative)

Mathematical basis

A.1 General

Annex A summarizes the form of evaluating, combining and reporting the uncertainty of measurement. It is based on ISO/IEC Guide 98-3 but does not relieve the need to consult this guide for more advice.

This standard distinguishes two types of evaluation of uncertainty of measurement. Type A is the method of evaluation of uncertainty by the statistical analysis of a series of measurements on the same measurand. Type B is the method of evaluation of uncertainty based on other knowledge.

A.2 Type A evaluation of uncertainty

The type A evaluation of standard uncertainty can be applied when several independent observations have been made for a quantity under the same conditions of measurement.

For a quantity X estimated from n independent repeated observations X_k, *the* arithmetic mean is:

$$\overline{X} = \frac{1}{n}\sum_{k=1}^{n} X_k \tag{A.1}$$

This mean is used as the estimate of the quantity, that is $x = \overline{X}$. The experimental standard deviation of the observations is given by:

$$s(X) = \left[\frac{1}{n-1}\sum_{k=1}^{n}\left(X_k - \overline{X}\right)^2\right]^{1/2} \tag{A.2}$$

where

$\overline{X}$ is the arithmetic mean of the observed values;

X_k are the measurement samples of a series of measurements;

n is the number of measurements; it is assumed to be large, for example, $n \geq 10$.

The type A standard uncertainty $u_{\text{typeA}}(x)$ associated with the estimate x is the experimental standard deviation of the mean:

$$u_{\text{typeA}}(x) = s(\overline{X}) = \frac{s(X)}{\sqrt{n}} \tag{A.3}$$

A.3 Type B evaluation of uncertainty

The type B evaluation of standard uncertainty is the method of evaluating the uncertainty by means other than the statistical analysis of a series of observations. It is evaluated by scientific judgement based on all available information on the variability of the quantity.

If the estimate x of a quantity X is taken from a manufacturer's specification, calibration certificate, handbook, or other source and its quoted uncertainty $U(x)$ is stated to be a multiple k of a standard deviation, the standard uncertainty $u(x)$ is simply the quoted value divided by the multiplier.

$$u(x) = \frac{U(x)}{k} \tag{A.4}$$

If only upper and lower limit X_{max} and X_{min} can be estimated for the value of the quantity X, a rectangular probability distribution is assumed, the standard uncertainty is:

$$u(x) = \frac{\left(\left|X_{\mathrm{max}}\right|, \left|X_{\mathrm{min}}\right|\right)_{\mathrm{MAX}}}{\sqrt{3}} \tag{A.5}$$

The contribution to the standard uncertainty associated with the output estimate y resulting from the standard uncertainty associated with the input estimate x is:

$$u(y) = c\, u(x) \tag{A.6}$$

where c is the sensitivity coefficient associated with the input estimate x, that is the partial derivative of the model function $y(x)$, evaluated at the input estimate x.

$$c = \frac{\partial y}{\partial x} \tag{A.7}$$

The sensitivity coefficient c describes the extent to which the output estimate y is influenced by variations of the input estimate x. It can be evaluated by Equation (A.7) or by using numerical methods, that is by calculating the change in the output estimate y due to a change in the input estimate x from a model function. Sometimes it may be more appropriate to find the change in the output estimate y due to the change of x from an experiment.

A.4 Determining the combined standard uncertainty

The combined standard uncertainty is used to collect a number of individual uncertainties into a single number. The combined standard uncertainty is based on statistical independence of the individual uncertainties; it is calculated by root-sum-squaring all standard uncertainties obtained from type A and type B evaluation.

$$u_{\mathrm{c}}(y) = \sqrt{\sum_{i=1}^{n} u_i^2(y)} \tag{A.8}$$

where

i is the current number of individual contributions;

$u_i(y)$ are the standard uncertainty contributions;

n is the number of uncertainties.

NOTE It is acceptable to neglect uncertainty contributions to this equation that are smaller than 1/10 of the largest contribution, because squaring them will reduce their significance to 1/100 of the largest contribution.

When the quantities above are to be used as the basis for further uncertainty computations, then the combined standard uncertainty, u_c, can be re-inserted into Equation (A.8). Despite its partially type A origin, u_c should be considered as describing an uncertainty of type B.

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 level of confidence. Correction factors or deviations shall be reported. The expanded uncertainty U is obtained by multiplying the standard uncertainty $u_c(y)$ by a coverage factor k.

$$U = k \cdot u_c(y) \tag{A.9}$$

For a level of confidence of approximately 95 %, the default level, then k = 2. If a level of confidence of approximately 99 % is chosen, then k = 3. The above values for k are valid under some conditions (see ISO/IEC Guide 98-3). If these conditions are not met, larger coverage factors are to be used to reach these levels of confidence.

Annex B
(informative)

Examples of calculation of calibration uncertainty

B.1 General

Examples of the calculation of calibration uncertainty related to wavelength and power level are shown in Clauses B.2 and B.3.

B.2 Wavelength calibration

B.2.1 Uncertainty under reference conditions: $u_{D_{\lambda\text{ref}}}$

The uncertainty under reference conditions of the test analyzer, $u_{D_{\lambda\text{ref}}}$, with regard to wavelength is calculated using Equation (12).

Using the following 10 values of centre wavelength $\lambda_{\text{OSA}i}$ for a He-Ne laser with a wavelength of λ_{REF} = 633,0 nm measured by the test analyzer, the uncertainty can be obtained.

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

The standard deviation of the measured values is calculated as follows.

Calculate the standard uncertainty $u_{\lambda\text{OSA}}$ of the measured $\lambda_{\text{OSA},i}$ values using Equation (11).

$$u_{\lambda\text{OSA}} = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(\lambda_{\text{OSA},i} - \lambda_{\text{OSA}\,\text{AV}}\right)^2} =$$

$$\sqrt{\frac{(632{,}9-632{,}84)^2 + (633{,}0-632{,}84)^2 + \cdots + (632{,}7-632{,}84)^2}{10-1}} = 0{,}107\ (\text{nm}) \qquad (\text{B.1})$$

The wavelength uncertainty of the light source is $u_{\lambda\text{REF}}$ = 10^{-5} ~ 10^{-6}, which is good enough to allow the use of the approximation $u_{\lambda\text{REF}}$ = 0. Therefore, the uncertainty under reference conditions, $u_{D_{\lambda\text{ref}}}$, of the test analyzer can be found using simplified Equation (12) if the resolution and the temperature dependence are negligible for the reference conditions.

$$u_{D_{\lambda\text{ref}}} = \sqrt{{u_{\lambda\text{REF}}}^2 + \frac{{u_{\lambda\text{OSA}}}^2}{m}} = \sqrt{0{,}0^2 + \frac{0{,}107^2}{10}} = 0{,}034\ (\text{nm}) \qquad (\text{B.2})$$

As required in Clause A.5, results of uncertainty calculation shall be reported in the form of expanded uncertainties. If the coverage factor is chosen equal to 2 the expanded uncertainty $U_{D_{\lambda\text{ref}}}$ is:

$$U_{D_{\lambda\text{ref}}} = k \times u_{D_{\lambda\text{ref}}} = 2 \times 0{,}034 = 0{,}068\ (\text{nm}) \tag{B.3}$$

The average value of the measured values $\lambda_{\text{OSA}_\text{AV}}$ is found from Equation (9).

$$\lambda_{\text{OSA AV}} = \frac{1}{m}\sum_{i=1}^{m} \lambda_{\text{OSA},i} = \frac{6\,328{,}4}{10} = 632{,}84\ (\text{nm}) \tag{B.4}$$

The deviation of the measured values, $D_{\lambda\text{ref}}$, is found from Equation (10).

$$D_{\lambda\text{ref}} = \lambda_{\text{OSAAV}} - \lambda_{\text{REF}} = 632{,}84 - 633{,}0 = -0{,}16\ (\text{nm}) \tag{B.5}$$

B.2.2 Uncertainty under operating conditions

B.2.2.1 General

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

B.2.2.2 Wavelength dependence

The wavelength dependence will be derived using the following centre wavelength values measured for five light sources having wavelengths other than $\lambda_{\text{ref.}}$

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} = 1 310,5 nm	λ_{REF4} = 1 310,7 nm
λ_{OSA5} = 1 552,1 nm	λ_{REF5} = 1 552,0 nm

The deviation of the measured value for the individual light source is calculated from Equation (13), for each wavelength.

$D_{\lambda\lambda1}$ = 650,4 – 650,6 = –0,2 (nm)

$D_{\lambda\lambda2}$ = 780,5 – 780,3 = 0,2 (nm)

$D_{\lambda\lambda3}$ = 850,2 – 850,1 = 0,1 (nm)

$D_{\lambda\lambda4}$ = 1 310,5 – 1 310,7 = –0,2 (nm)

$D_{\lambda\lambda5}$ = 1 552,1 – 1 552,0 = 0,1 (nm)

From these values:

$D_{\lambda\lambda,\text{MAX}}$ = 0,2 nm and $D_{\lambda\lambda,\text{MIN}}$ = –0,2 nm

therefore $\left|D_{\lambda\lambda}\right|_{\text{MAX}}$ = 0,2 nm.

The uncertainty of the wavelength dependence error, $u_{D_{\lambda\lambda}}$, is given by Equation (14).

$$u_{D_{\lambda\lambda}} = \frac{\left|D_{\lambda\lambda}\right|_{\text{MAX}}}{\sqrt{3}} = \frac{0{,}2}{\sqrt{3}} = 0{,}115 \tag{B.6}$$

B.2.2.3 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

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

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

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

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

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

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

From Equation (16):

$$u_{D_{\lambda T}} = \frac{\left|D_{\lambda_{T,\text{MAX}}}\right|}{\sqrt{3}} = \frac{0{,}3}{\sqrt{3}} = 0{,}173\,(\text{nm}) \tag{B.7}$$

B.2.3 Expanded uncertainty calculation

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

The accumulated uncertainty can be obtained using Equation (18) and setting resolutions as negligible.

$$u_{D_{\lambda\text{op}}} = \sqrt{0{,}107^2 + 0{,}115^2 + 0{,}173^2}$$

$$= \sqrt{0{,}054} = 0{,}23\,(\text{nm}) \tag{B.8}$$

Accordingly, the expanded uncertainty, $U_{\lambda_{\text{op}}}$ is obtained with a coverage factor k = 2 for a confidence level of 95 %.

$$U_{\lambda_{\text{op}}} = \pm k u_{D_{\lambda_{\text{op}}}} = \pm 2 \times 0{,}23 = \pm 0{,}46\ (\text{nm}) \tag{B.9}$$

B.3 Power level calibration

B.3.1 Uncertainty under reference conditions: $u_{D_{P\text{ref}}}$

The uncertainty of the test analyzer, $u_{D_{P\text{ref}}}$, with regard to power level under reference calibration conditions is calculated using Equation (23).

Here, the uncertainty of the reference power meter is given as 4,0 % in its certification, with a coverage factor k equal to 2:

$$u_{P_{\text{PM}}\text{ref}} = 0{,}02 \tag{B.10}$$

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

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 (20).

D_{P1} = 0,05 D_{P2} = 0,015
D_{P3} = 0,010 D_{P4} = 0,075
D_{P5} = –0,02 D_{P6} = –0,045
D_{P7} = –0,015 D_{P8} = 0,06
D_{P9} = 0,07 D_{P10} = 0,089

The mean and standard deviations of the difference ratio are calculated using Equations (21) and (22).

$$D_P = \frac{1}{m}\sum_{i=1}^{m} D_{Pi} = 0{,}289/10 = 0{,}028\,9 \tag{B.11}$$

$$u_{D_P} = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(D_{Pi} - D_P\right)^2} = \sqrt{0{,}019\,17/9} = 0{,}046\,2 \qquad \text{(B.12)}$$

The standard deviation of the difference (u_{D_P} = 0,046 2) is larger than the uncertainty of the power meter ($u_{P_{\text{PM}}}$ = 0,02).

From Equation (23), if the resolutions and the temperature dependence are negligible for the reference conditions, the uncertainty $u_{D_{P\text{ref}}}$ is:

$$u_{D_{P\text{ref}}} = \sqrt{u_{\text{PM}_\text{ref}}^2 + \frac{u_{D_P}^2}{m}} = \sqrt{0{,}02^2 + \frac{0{,}046\,2^2}{10}} = 0{,}024\,8 \qquad \text{(B.13)}$$

As required in Clause A.5, results of uncertainty calculation shall be reported in the form of expanded uncertainties. If the coverage factor is chosen equal to 2 the expanded uncertainty $U_{D_{P\text{ref}}}$ is:

$$U_{D_{P\text{ref}}} = k \times u_{D_{P\text{ref}}} = 2 \times 0{,}024\,8 = 0{,}049\,6 \qquad \text{(B.14)}$$

The power level deviation is found from Equation (24).

$$D_{P\text{ref}} = D_P = 0{,}028\,9 \qquad \text{(B.15)}$$

B.3.2 Uncertainty under operating conditions

B.3.2.1 General

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

B.3.2.2 Wavelength dependence

The wavelength dependence will be derived for the displayed peak power levels ($P_{\text{OSA}j}$) 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} = 0,122 5 µW	P_{REF1} = 0,120 2 µW
λ_2 = 633 nm	P_{OSA2} = 0,130 7 µW	P_{REF2} = 0,120 5 µW
λ_3 = 780 nm	P_{OSA3} = 0,131 0 µW	P_{REF3} = 0,123 0 µW
λ_4 = 850 nm	P_{OSA4} = 0,153 2 µW	P_{REF4} = 0,147 0 µW
λ_5 = 1 500 nm	P_{OSA5} = 0,160 5 µW	P_{REF5} = 0,175 8 µW
λ_6 = 1 550 nm	P_{OSA6} = 0,152 0 µW	P_{REF6} = 0,162 0 µW
λ_7 = 1 600 nm	P_{OSA7} = 0,120 7 µW	P_{REF7} = 0,115 5 µW

From Equation (25):

$D_{P_\lambda 1}$ = P_{OSA1} / P_{REF1} – 1 = 0,122 5 / 0,120 2 – 1 = 0,019 13

$D_{P_\lambda 2}$ = P_{OSA2} / P_{REF2} – 1 = 0,130 7 / 0,120 5 – 1 = 0,084 65

$D_{P_\lambda}3 = P_{\mathrm{OSA3}} / P_{\mathrm{REF3}} - 1 = 0{,}131\,0 / 0{,}123\,0 - 1 = 0{,}065\,04$

$D_{P_\lambda}4 = P_{\mathrm{OSA4}} / P_{\mathrm{REF4}} - 1 = 0{,}153\,2 / 0{,}147\,0 - 1 = 0{,}042\,18$

$D_{P_\lambda}5 = P_{\mathrm{OSA5}} / P_{\mathrm{REF5}} - 1 = 0{,}160\,5 / 0{,}175\,8 - 1 = -0{,}087\,03$

$D_{P_\lambda}6 = P_{\mathrm{OSA6}} / P_{\mathrm{REF6}} - 1 = 0{,}152\,0 / 0{,}162\,0 - 1 = -0{,}061\,73$

$D_{P_\lambda}7 = P_{\mathrm{OSA7}} / P_{\mathrm{REF7}} - 1 = 0{,}120\,7 / 0{,}115\,5 - 1 = 0{,}045\,02$

From these values:

$D_{P_\lambda}\mathrm{MAX} = D_{P_\lambda}5 = 0{,}087\,03$

The uncertainty due to wavelength dependence, $u_{D_{P_\lambda}}$, is given by Equation (26).

$$u_{D_{P_\lambda}} = \frac{\left|D_{P_\lambda}\right|_{\mathrm{MAX}}}{\sqrt{3}} = \frac{0{,}087\,03}{\sqrt{3}} = 0{,}050\,2 \tag{B.16}$$

B.3.2.3 Polarization dependence

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

$\lambda_1 = 850$ nm $P_{\mathrm{MAX}}(\lambda_1) = 0{,}310$ mW $P_{\mathrm{MIN}}(\lambda_1) = 0{,}292$ mW
$\lambda_2 = 1\,310$ nm $P_{\mathrm{MAX}}(\lambda_2) = 0{,}204$ mW $P_{\mathrm{MIN}}(\lambda_2) = 0{,}194$ mW
$\lambda_3 = 1\,550$ nm $P_{\mathrm{MAX}}(\lambda_3) = 0{,}206$ mW $P_{\mathrm{MIN}}(\lambda_3) = 0{,}193$ mW

From Equations (27) and (28), variations $DP_{\mathrm{UL}}(\lambda_j)$, $DP_{\mathrm{LL}}(\lambda_j)$ and the average variation $P_{\mathrm{AVE}}(\lambda_j)$ in power level due to polarization with wavelength λ_j, are given as:

$P_{\mathrm{AVE}}(\lambda_1) = 0{,}301$ mW $DP_{\mathrm{UL}}(\lambda_1) = 0{,}310 / 0{,}301 - 1 = 0{,}029\,9$
$DP_{\mathrm{LL}}(\lambda_1) = 0{,}292 / 0{,}301 - 1 = -0{,}029\,9$
$P_{\mathrm{AVE}}(\lambda_2) = 0{,}199$ mW $DP_{\mathrm{UL}}(\lambda_2) = 0{,}204 / 0{,}199 - 1 = 0{,}025\,1$
$DP_{\mathrm{LL}}(\lambda_2) = 0{,}194 / 0{,}199 - 1 = -0{,}025\,1$
$P_{\mathrm{AVE}}(\lambda_3) = 0{,}199\,5$ mW $DP_{\mathrm{UL}}(\lambda_3) = 0{,}206 / 0{,}199\,5 - 1 = 0{,}032\,6$
$DP_{\mathrm{LL}}(\lambda_3) = 0{,}193 / 0{,}199\,5 - 1 = -0{,}032\,6$

From these values:

$D_{P_{\mathrm{POL,MAX}}} = DP_{\mathrm{UL}}(\lambda_3) = 0{,}032\,6$

$D_{P_{\mathrm{POL,MIN}}} = DP_{\mathrm{LL}}(\lambda_3) = -0{,}032\,6$

The uncertainty of power level variations due to polarization, $u_{D_{P_{\mathrm{POL}}}}$, is given by Equation (30).

$$u_{D_{P_{\mathrm{POL}}}} = \frac{D_{P_{\mathrm{POL,MAX}}} - D_{P_{\mathrm{POL,MIN}}}}{2\sqrt{3}} = \frac{0{,}032\,6 + 0{,}032\,6}{2\sqrt{3}} = 0{,}018\,8 \tag{B.17}$$

B.3.2.4 Linearity

The linearity will be derived using the following values for the ratio $P_{\mathrm{LIN,ref}}$ of the value measured by the test analyzer to the value obtained from the power meter, and the ratio $P_{\mathrm{LIN},j}$ 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 DP_{LIN} (P_j) at the power level P_j is given by Equation (33).

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

P_{LIN1} = 0,998	$DP_{\mathrm{LIN}}(P_1)$ = –0,026 34
P_{LIN2} = 0,985	$DP_{\mathrm{LIN}}(P_2)$ = –0,039 02
P_{LIN3} = 1,011	$DP_{\mathrm{LIN}}(P_3)$ = –0,013 66
P_{LIN4} = 1,009	$DP_{\mathrm{LIN}}(P_4)$ = –0,015 61
P_{LIN5} = 1,055	$DP_{\mathrm{LIN}}(P_5)$ = 0,029 27

From these values:

$D_{P_{\mathrm{LIN,MAX}}}$ = 0,029 27

$D_{P_{\mathrm{LIN,MIN}}}$ = –0,039 02

The uncertainty of linearity, $u_{D_{P_{\mathrm{LIN}}}}$, is obtained from Equation (34).

$$u_{D_{P_{\mathrm{LIN}}}} = \frac{\left|D_{P_{\mathrm{LIN}}}\right|_{\mathrm{MAX}}}{\sqrt{3}} = \frac{0{,}039\,02}{\sqrt{3}} = 0{,}022\,5 \tag{B.18}$$

B.3.2.5 Temperature dependence

The temperature dependence is obtained from the following values. These are the reference values, $P_{\mathrm{OSA},T_{\mathrm{ref}}}$, of the test analyzer at the temperature specified by the reference calibration conditions, and the power level values, $P_{\mathrm{OSA}j}$, 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, $DP(T_j)$, is given by Equation (35) as follows:

$P_{\mathrm{OSA},T_{\mathrm{ref}}}$ = 0,200 mW

T_1 = 10 °C	P_{OSA1} = 0,202 mW	$DP(T_1)$ = 0,010
T_2 = 15 °C	P_{OSA2} = 0,204 mW	$DP(T_2)$ = 0,020
T_3 = 20 °C	P_{OSA3} = 0,199 mW	$DP(T_3)$ = –0,005
T_4 = 25 °C	P_{OSA4} = 0,197 mW	$DP(T_4)$ = –0,015
T_5 = 30 °C	P_{OSA5} = 0,200 mW	$DP(T_5)$ = 0,0
T_6 = 35 °C	P_{OSA6} = 0,207 mW	$DP(T_6)$ = 0,035

From these values:

$D_{P_{\mathrm{TMP,MAX}}}$ = 0,035

$D_{P_{\mathrm{TMP,MIN}}}$ = –0,015

The uncertainty due to temperature dependence, $u_{D_{P_{\mathrm{TMP}}}}$, is obtained from Equation (36).

$$u_{D_{P\mathrm{TMP}}} = \frac{\left|D_{P\mathrm{TMP,MAX}}\right|}{\sqrt{3}} = \frac{0{,}035}{\sqrt{3}} = 0{,}020\,2 \qquad \text{(B.19)}$$

B.3.3 Expanded uncertainty calculation

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

The uncertainty of the power level is obtained from Equation (38) and with setting resolutions as negligible.

$$u_{D_{P\mathrm{op}}} = \sqrt{0{,}050\,3^2 + 0{,}050\,2^2 + 0{,}018\,8^2 + 0{,}022\,5^2 + 0{,}020\,2^2}$$

$$= \sqrt{0{,}006\,33} = 0{,}079\,5 \qquad \text{(B.20)}$$

U_P in dB units is obtained from Equation (42).

$$U_p(\mathrm{dB}) = 10\log_{10}\left(1 + 2 \times 0{,}079\,5\right) = 0{,}64\ \left(\mathrm{dB}\right) \qquad \text{(B.21)}$$

Annex C
(informative)

Using the calibration results

C.1 General

C.1.1 Overview

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 Annex C.

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 Annex C 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 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 Annex C is not applicable to the following parameter:

- polarization dependence.

C.1.3 Restrictions

The interpolation method outlined in Annex C is subject to certain restrictions.

1) The operator shall 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 shall always be provided.
6) If the distribution of calibration points is not uniform then it may be necessary to weigh 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 Clause C.2 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 $\lambda_{\text{corr},}$ by rearranging Equation (13) as shown:

$$\lambda_{\text{corr}} = \lambda_{\text{OSA}} - D_{\lambda_\lambda} \tag{C.1}$$

where

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

D_{λ_λ} is the wavelength deviation obtained from the calibration results.

The uncertainty in the corrected wavelength, $u_{\lambda_{\text{corr}}}$, is found by summing the measurement and correction contributions

$$u_{\lambda_{\text{corr}}} = \sqrt{{u_{D_{\lambda_\lambda}}}^2 + {u_{\lambda_{\text{OSA}}}}^2} \tag{C.2}$$

where

$u_{D_{\lambda_\lambda}}$ is the uncertainty of the test analyzer due to wavelength dependence;

$u_{\lambda_{\text{OSA}}}$ 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:

$$D\lambda_{\text{OSA}}(\lambda_{\text{OSA}}) = DS_\lambda \lambda_{\text{OSA}} + D\lambda_0 \tag{C.3}$$

where DS_λ is a scale factor which ideally should be zero and $D\lambda_{\text{o}}$ is an offset which again ideally should be zero. The relationship between the measured wavelength and the true vacuum wavelength is given by:

$$\lambda_{\text{vac}}(\lambda_{\text{OSA}}) = \lambda_{\text{OSA}} + D\lambda_{\text{OSA}}(\lambda_{\text{OSA}}) + \varepsilon(\lambda_{\text{OSA}}) \tag{C.4}$$

where λ_{vac} (λ_{OSA}) is the vacuum wavelength. The term $\varepsilon(\lambda_{\text{OSA}})$ 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 DS_λ, and $D\lambda_{\text{o.}}$

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 shall be taken to choose a fit equation appropriate for the characteristics of $\varepsilon(\lambda)$ and for the number of reference wavelengths used.

The RMS error due to the imperfect fit $u_{\varepsilon\lambda}$ can be calculated from the residual errors at the reference values.

$$u_{\varepsilon\lambda} = \sqrt{\frac{\sum_{i=1}^{n} \left(D\lambda_{\lambda,i} - D\lambda_{\mathrm{OSA}}\left(D\lambda_{\mathrm{OSA},i}\right)\right)^2}{n-2}} \tag{C.5}$$

NOTE Number of data points is n – 2 which arises from two parameters, i.e. the slope and intercept being fitted.

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

$$\lambda_{\mathrm{corr}} = \lambda_{\mathrm{OSA}} - D\lambda\left(\lambda_{\mathrm{OSA}}\right) \tag{C.6}$$

The uncertainty in the calculated wavelength error/correction, $u_{D\lambda}$ is given by:

$$u_{D\lambda} = \sqrt{{u_{\lambda\mathrm{OSA}}}^2 + {u_{\lambda\mathrm{REF}}}^2 + {u_{\varepsilon\lambda}}^2} \tag{C.7}$$

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

C.3 Multiplicative corrections

C.3.1 Parameters

In Clause C.3, 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 (20) can be rearranged to give:

$$P_{\mathrm{c}} = \frac{P_{\mathrm{OSA}}}{1 + D_P} \tag{C.8}$$

The uncertainty in the corrected power, $u_{P_{\mathrm{c}}}$, 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.

$$u_{P_{\mathrm{c}}} = P_{\mathrm{c}} \sqrt{{u_{D_P}}^2 + \frac{{u_{P_{\mathrm{OSA}}}}^2}{{P_{\mathrm{OSA}}}^2}} \tag{C.9}$$

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.

$$DP_{\text{diff}}(\lambda_{\text{OSA}}) = DS_P \lambda_{\text{OSA}} + DP_0 \quad \text{(C.10)}$$

where DS_P is a scale factor which ideally should be zero and DP_0 is an offset which again ideally should be zero. The relationship between the measured power and the true power is given by:

$$P_{\text{true}}(\lambda_{\text{OSA}}) = \frac{P_{\text{OSA}}}{1 + DP_{\text{diff}}(\lambda_{\text{OSA}}) + \varepsilon_P(\lambda_{\text{OSA}})} \quad \text{(C.11)}$$

The term $\varepsilon_P(\lambda_{\text{OSA}})$ 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 DS_P and DP_0. The RMS error due to the imperfect fit $u_{\varepsilon p}$ can be calculated from the residual errors at the reference values.

$$u_{\varepsilon p} = \sqrt{\frac{\sum_{i=1}^{n} \left(DP_{\text{diff},\lambda i} - DP_{\text{diff}}(\Delta\lambda_i)\right)^2}{n-2}} \quad \text{(C.12)}$$

NOTE Number of data points is n – 2 which arises from two parameters, i.e. the slope and intercept being fitted.

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

$$P_{\text{c}}(\lambda_{\text{OSA}}) = \frac{P_{\text{OSA}}}{1 + DP_{\text{diff}}(P_{\text{OSA}})} \quad \text{(C.13)}$$

The uncertainty in the calculated power correction is similar to Equation (C.9) with an additional term for the fitting error $u_{\varepsilon p}$.

$$u_{P_{\text{c}}}(\lambda_{\text{OSA}}) = P_{\text{c}}(\lambda_{\text{OSA}}) \sqrt{u_{DP\text{diff}}{}^2 + u_{\varepsilon p}{}^2 + \frac{u_{P_{\text{OSA}}}{}^2}{P_{\text{OSA}}(\lambda_{\text{OSA}})^2}} \quad \text{(C.14)}$$

C.4 OSA calibration results (additive correction)

In the following example (see Table C.1, Table C.2 and Figure C.1), 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 C.1 – OSA calibration results

λ_{REF} (nm)	λ_{OSA} (nm)	$\lambda_{\mathrm{OSA}} - \lambda_{\mathrm{REF}}$ (pm)	$\lambda_{\mathrm{corr}} - \lambda_{\mathrm{REF}}$ [a] (pm)	$u_{D\lambda}$ (pm)
1 182,261	1 181,721	–540	–0,8	±15
1 318,102	1 317,532	–570	–7,0	±15
1 363,795	1 363,231	–564	7,0	±15
1 443,074	1 442,495	–579	5,9	±15
1 473,846	1 473,251	–595	–4,7	±15
1 524,378	1 523,786	–592	7,1	±15
1 533,915	1 533,308	–607	–6,2	±15
1 678,971	1 678,343	–628	–1,8	±15
		<–584,4> 88 pk–pk	<–0,8> 14,2 pk–pk	

[a] $\lambda_{\mathrm{corr}} - \lambda_{\mathrm{REF}}$ is dominated by the contribution from u_{ε}.

Table C.2 – Summary of OSA calibration parameters

Parameter	**Symbol**	**Value**	**Unit**
Minimum wavelength	λ_{MIN}	1 183	nm
Maximum wavelength	λ_{MAX}	1 678	nm
Slope	DS	$-1,753 \times 10^{-4}$	–
Intercept	$D\lambda_0$	–332	pm
Wavelength correction uncertainty	u_{ε}	±6,4	pm
Wavelength offset	$D\lambda_{\lambda}$	–584,4	pm
Wavelength uncertainty	$u_{D\lambda_{\lambda}}$	±27,3	pm

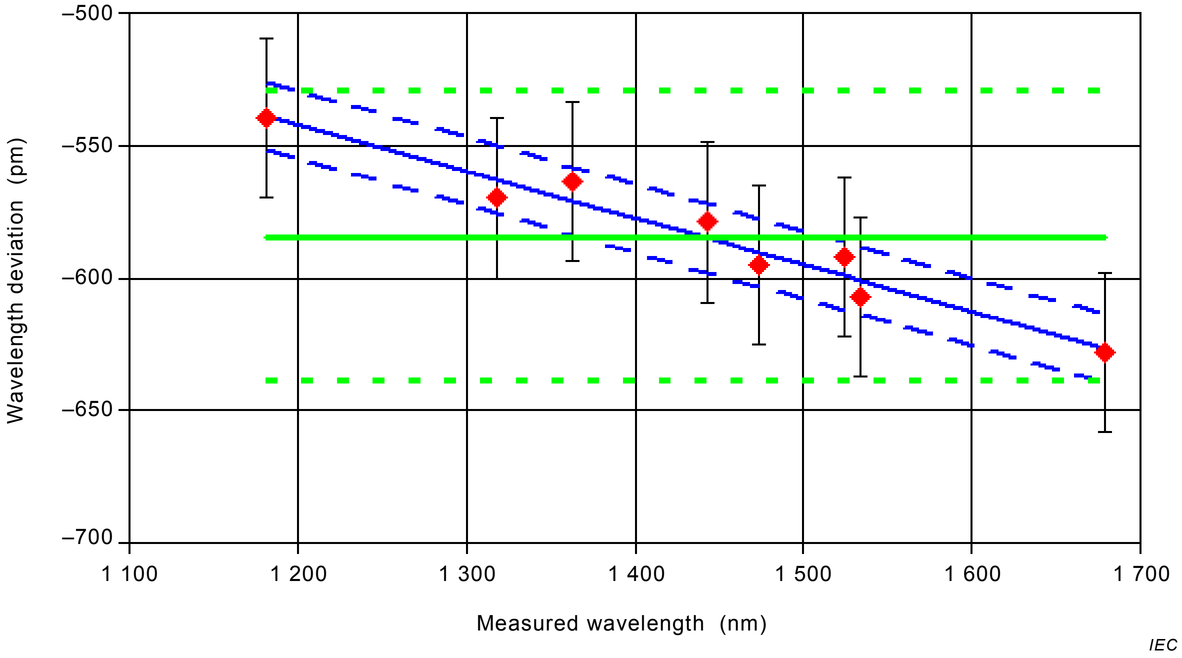

Figure C.1 – Calibration of OSA wavelength scale using krypton emission lines; 95 % confidence intervals shown

Annex D
(informative)

Wavelength references

D.1 General

Annex D provides lists of laser and lamp emission lines, absorption features and optogalvanic transitions that are known to have sufficient precision to provide wavelength reference points for OSA calibration. These tables give the vacuum wavelengths of the dominant transitions only.

Gas laser lines provide intense (> 1 mW) and well-defined wavelength (frequency) sources. Lamp emission lines are low intensity features, typically a few nanowatts can be launched into single-mode fibre. At low gas pressures, absorption and optogalvanic transitions are narrow features, typically several hundred megahertz wide. These transitions are normally used to stabilize the wavelength of a semiconductor laser and provide an active reference. At high pressures, absorption transitions are broadened and can be viewed directly by the OSA using a lamp or light-emitting diode as a source. At higher pressures, all of these reference lines can shift slightly due to collisions. This "pressure shift" has not been characterized for all of the references listed in Annex D. Measurements have been made at the National Institute of Standards and Technology (NIST) for the $\nu_1+\nu_3$ band of acetylene $^{12}C_2H_2$ and the $2\nu_3$ band of hydrogen cyanide $H^{13}C^{14}N$ [11,12][1]. These measurements show that the pressure shift can be as large as 2 pm for hydrogen cyanide gas at a pressure of 13 kPa (about 100 Torr). The acetylene pressure shift is less, but can exceed 1 pm at higher pressures. The line centres listed below were measured in the low pressure regime. Although some of these line centres have been measured to higher accuracy, the tables list the wavelengths to a precision of 1 pm due to possible variations of the line centres at this level.

D.2 Gas laser lines

The vacuum wavelengths of selected gas laser lines are given in Table D.1.

Table D.1 – Vacuum wavelengths (nm) of selected gas laser lines

Ar laser	488,122	He-Ne laser[a]	632,991
	514,673		1 152,590
			1 523,488

[a] In the He-Ne laser at 1 152 nm wavelength, there may be two modes. Ensure the correct line is used.

D.3 Noble gas reference lines

The noble gasses He, Ne, Kr, Ar and Xe have transition lines that are well known and can be used as wavelength reference points. Table D.2 lists a number of the stronger lines [13,14].

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[1] Numbers in brackets refer to the Bibliography.

Table D.2 – Vacuum wavelengths (nm) of noble gas reference lines

Kr	810,659	Ne	1 114,607	Kr	1 298,884[a]	Kr	1 496,598[a]
Kr	811,513	Ne	1 118,059	Ar	1 301,182[a]	Kr	1 500,941[a]
Kr	819,231	Ne	1 139,355	Kr	1 318,102[a]	Kr	1 501,914[a]
Kr	826,551	Ne	1 141,226	Ne	1 321,761[a]	Ar	1 505,062[a]
Kr	830,039	Ne	1 152,590	Ne	1 322,286[a]	Ar	1 517,694[a]
Kr	851,121	Ne	1 152,818	Ar	1 323,172	Kr	1 521,368[a]
Kr	877,916	Ne	1 153,950	Ar	1 327,627	Ne	1 523,488[a]
Kr	893,114	Ne	1 161,726	Ar	1 331,685	Kr	1 524,378[a]
Ar	912,547	Ne	1 177,001	Ar	1 337,077	Kr	1 533,067[a]
Ar	922,703	Ne	1 179,227	Ar	1 350,788	Ar	1 533,353[a]
Ar	935,679	Kr	1 182,261	Kr	1 362,614	Kr	1 533,915[a]
Ar	966,044	Ne	1 198,819	Ar	1 362,638	Kr	1 537,624[a]
Ne	966,807	Ne	1 206,964	Kr	1 363,795	Xe	1 542,261
Kr	975,443	Ne	1 246,280	Xe	1 366,079	Kr	1 543,795[a]
Ar	978,719	Ar	1 249,108[a]	Kr	1 366,213	Kr	1 547,825[a]
Xe	980,239	Xe	1 262,684	Ar	1 372,233	Kr	1 563,978[a]
Xe	992,591	Ne	1 269,267	Kr	1 374,261	Kr	1 568,533[a]
Kr	1 022,426	Ar	1 270,576[a]	Kr	1 404,950	Kr	1 577,614[a]
Ne	1 029,824	Ar	1 273,690[a]	Xe	1 414,631	Kr	1 582,441[a]
Ar	1 047,292	Ar	1 274,972[a]	Xe	1 424,485	Xe	1 605,767
Ne	1 056,530	Ar	1 280,624[a]	Kr	1 443,074	Xe	1 673,272
Ne	1 080,103	Kr	1 286,541[a]	Xe	1 473,680	Kr	1 678,971
He	1 083,322	Ne	1 291,555[a]	Kr	1 473,846[a]	Kr	1 685,809
He	1 083,331	Ar	1 293,673[a]	Kr	1 476,671[a]	Kr	1 690,137
Ne	1 084,745	Ar	1 296,020[a]	Kr	1 476,951[a]	Kr	1 694,043
						Xe	1 733,050

[a] Gases which have already been observed using the optogalvanic effect [15−19].

D.4 Molecular absorption lines

Tables D.3, D.4 and D.5 and Figure D.1 and Figure D.2 list a selection of molecular absorption lines in the 1 510 nm to 1 565 nm region for wavelength calibration in this telecommunications window [20].

Table D.3 – Vacuum wavelengths (nm) for the $\nu_1+\nu_3$ band of acetylene $^{12}C_2H_2$ absorption lines [21-23]

R31	1 511,033	R15	1 517,314	P1	1 525,760	P17	1 535,393
R30	1 511,378	R14	1 517,760	P2	1 526,314	P18	1 536,049
R29	1 511,730	R13	1 518,213	P3	1 526,874	P19	1 536,713
R28	1 512,088	R12	1 518,672	P4	1 527,441	P20	1 537,382
R27	1 512,452	R11	1 519,137	P5	1 528,014	P21	1 538,058
R26	1 512,823	R10	1 519,608	P6	1 528,594	P22	1 538,741
R25	1 513,200	R9	1 520,086	P7	1 529,180	P23	1 539,430
R24	1 513,583	R8	1 520,570	P8	1 529,772	P24	1 540,125
R23	1 513,972	R7	1 521,060	P9	1 530,371	P25	1 540,827
R22	1 514,368	R6	1 521,557	P10	1 530,976	P26	1 541,536
R21	1 514,770	R5	1 522,060	P11	1 531,588	P27	1 542,251
R20	1 515,178	R4	1 522,570	P12	1 532,206	P28	1 542,972
R19	1 515,593	R3	1 523,085	P13	1 532,830	P29	1 543,700
R18	1 516,014	R2	1 523,608	P14	1 533,461	P30	1 544,435
R17	1 516,441	R1	1 524,136	P15	1 534,099	P31	1 545,176
R16	1 516,875	R0	1 524,671	P16	1 534,742		

NOTE The lines with odd numbers are the stronger lines.

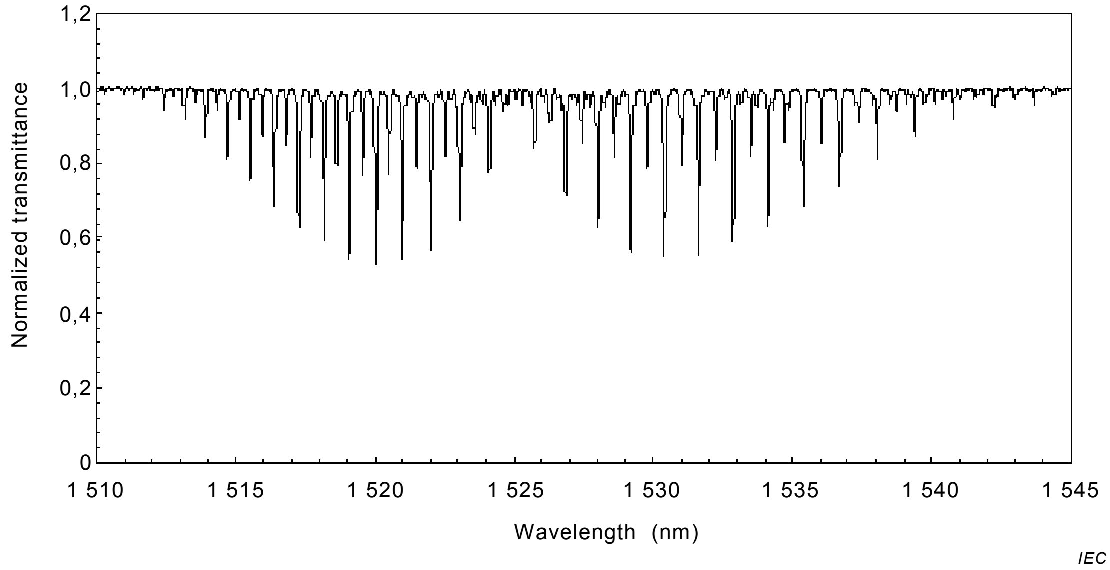

Figure D.1 – Absorption of LED light by acetylene ($^{12}C_2H_2$)

Table D.4 – Vacuum wavelengths (nm) for the $\nu_1+\nu_3$ band of acetylene $^{13}C_2H_2$ absorption lines [21-23]

R29	1 520,111	R13	1 526,498	P1	1 533,818	P17	1 543,001
R28	1 520,466	R12	1 526,947	P2	1 534,350	P18	1 543,624
R27	1 520,828	R11	1 527,401	P3	1 534,887	P19	1 544,253
R26	1 521,195	R10	1 527,860	P4	1 535,430	P20	1 544,887
R25	1 521,568	R9	1 528,326	P5	1 535,978	P21	1 545,528
R24	1 521,947	R8	1 528,797	P6	1 536,532	P22	1 546,174
R23	1 522,332	R7	1 529,274	P7	1 537,091	P23	1 546,827
R22	1 522,723	R6	1 529,757	P8	1 537,656	P24	1 547,485
R21	1 523,119	R5	1 530,245	P9	1 538,227	P25	1 548,149
R20	1 523,521	R4	1 530,739	P10	1 538,803	P26	1 548,819
R19	1 523,929	R3	1 531,238	P11	1 539,385	P27	1 549,495
R18	1 524,343	R2	1 531,744	P12	1 539,974	P28	1 550,178
R17	1 524,763	R1	1 532,254	P13	1 540,567	P29	1 550,866
R16	1 525,188	R0	1 532,770	P14	1 541,167	P30	1 551,560
R15	1 525,619			P15	1 541,772	P31	1 552,260
R14	1 526,056			P16	1 542,384		
NOTE The lines with even numbers are the stronger lines.							

Table D.5 – Vacuum wavelengths (nm) of selected hydrogen cyanide ($H^{13}C^{14}N$) absorption lines [24]

R25	1 528,054	R12	1 534,415	P1	1 543,114	P14	1 552,931
R24	1 528,485	R11	1 534,972	P2	1 543,809	P15	1 553,756
R23	1 528,926	R10	1 535,540	P3	1 544,515	P16	1 554,591
R22	1 529,376	R9	1 536,117	P4	1 545,230	P17	1 555,436
R21	1 529,836	R8	1 536,704	P5	1 545,955	P18	1 556,292
R20	1 530,306	R7	1 537,300	P6	1 546,690	P19	1 557,157
R19	1 530,786	R6	1 537,907	P7	1 547,435	P20	1 558,033
R18	1 531,275	R5	1 538,523	P8	1 548,190	P21	1 558,919
R17	1 531,774	R4	1 539,149	P9	1 548,955	P22	1 559,814
R16	1 532,283	R3	1 539,786	P10	1 549,731	P23	1 560,720
R15	1 532,801	R2	1 540,431	P11	1 550,516	P24	1 561,636
R14	1 533,329	R1	1 541,087	P12	1 551,311	P25	1 562,563
R13	1 533,867	R0	1 541,753	P13	1 552,116	P26	1 563,499

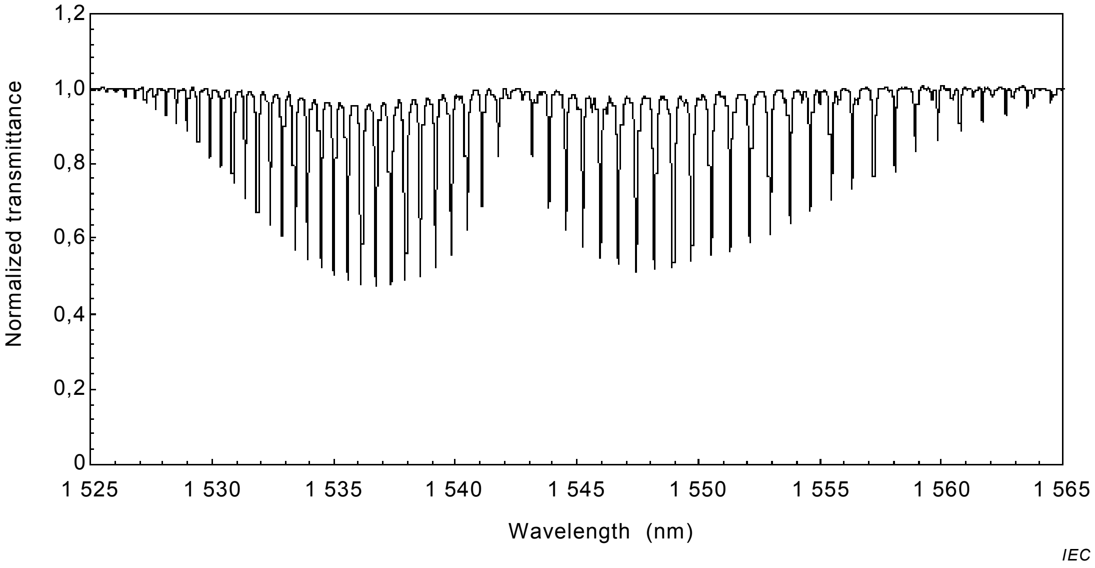

Figure D.2 – Absorption of LED light by hydrogen cyanide ($H^{13}C^{14}N$)

Bibliography

International standards:

[1] IEC 60050-311, *International Electrotechnical Vocabulary – Electrical and electronic measurements – General terms relating to measurements* (available at http://www.electropedia.org)

[2] IEC 60050-312, *International Electrotechnical Vocabulary – Electrical and electronic measurements – General terms relating to electrical measurements* (available at http://www.electropedia.org)

[3] IEC 60050-313, *International Electrotechnical Vocabulary – Electrical and electronic measurements – Types of electrical measuring instruments* (available at http://www.electropedia.org)

[4] IEC 60050-314, *International Electrotechnical Vocabulary – Electrical and electronic measurements – Specific terms according to the type of instrument (available at http://www.electropedia.org)*

[5] IEC 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode* fibres

[6] IEC 61315, *Calibration of fibre-optic power meters*

[7] IEC 62129-2, *Calibration of wavelength/optical frequency measurement instruments – Part 2: Michelson interferometer single wavelength meters*

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Operation of an OSA at high altitude may affect the accuracy of the wavelength scale. Such effects may be negligible in some brands of OSAs, but they may be significant in others. This is because the index of refraction of air depends on pressure and humidity as well as temperature. Good references on this subject are:

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