BS EN 62129-2:2011

BSI Standards Publication

# Calibration of wavelength/optical frequency measurement instruments

## Part 2: Michelson interferometer single wavelength meters

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## National foreword

This British Standard is the UK implementation of EN 62129-2:2011. It is identical to IEC 62129-2:2011.

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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EUROPEAN STANDARD
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**EN 62129-2**

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English version

# Calibration of wavelength/optical frequency measurement instruments - Part 2: Michelson interferometer single wavelength meters
(IEC 62129-2:2011)

Etalonnage des appareils de mesure de longueur d'onde/appareil de mesure de la fréquence optique -
Partie 2: Appareils de mesure de longueur d'onde unique à interféromètre de Michelson
(CEI 62129-2:2011)

Kalibrierung von Messgeräten für die Wellenlänge/optische Frequenz -
Teil 2: Michelson-Interferometer-Einzelwellenlängen-Messgeräte
(IEC 62129-2:2011)

This European Standard was approved by CENELEC on 2011-06-30. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

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

**Management Centre: Avenue Marnix 17, B - 1000 Brussels**

# Foreword

The text of document 86/395/FDIS, future edition 1 of IEC 62129-2, prepared by IEC TC 86, Fibre optics, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 62129-2 on 2011-06-30.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN and CENELEC shall not be held responsible for identifying any or all such patent rights.

The following dates were fixed:

| | | |
|---|---|---|
| – latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement | (dop) | 2012-03-30 |
| – latest date by which the national standards conflicting with the EN have to be withdrawn | (dow) | 2014-06-30 |

Annex ZA has been added by CENELEC.

# Endorsement notice

The text of the International Standard IEC 62129-2:2011 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 60793-1-1 | NOTE Harmonized as EN 60793-1-1. |
| IEC 60825-1 | NOTE Harmonized as EN 60825-1. |
| IEC 60825-2 | NOTE Harmonized as EN 60825-2. |

# Annex ZA
(normative)

## Normative references to international publications with their corresponding European publications

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

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

| Publication | Year | Title | EN/HD | Year |
|---|---|---|---|---|
| IEC 60050-300 | 2001 | International Electrotechnical Vocabulary - Electrical and electronic measurements and measuring instruments -<br>Part 311: General terms relating to measurements -<br>Part 312: General terms relating to electrical measurements -<br>Part 313: Types of electrical measuring instruments -<br>Part 314: Specific terms according to the type of instrument | - | - |
| IEC 61315 | 2005 | Calibration of fibre-optic power meters | EN 61315 | 2006 |
| IEC/TR 61931 | 1998 | Fibre optic - Terminology | - | - |
| ISO/IEC 17025 | 2005 | General requirements for the competence of testing and calibration laboratories | EN ISO/IEC 17025 | 2005 |
| ISO/IEC Guide 99 | 2007 | International vocabulary of metrology - Basic and general concepts and associated terms (VIM) | - | - |
| ISO/IEC Guide 98-3 | 2008 | Uncertainty of measurement -<br>Part 3: Guide to the expression of uncertainty in measurement (GUM:1995) | - | - |

# CONTENTS

# INTRODUCTION

Wavelength meters, often based on the Michelson interferometer, are designed to measure the wavelength of an optical source as accurately as possible. Although the wavelength meters contain an internal absolute reference, typically a Helium-Neon laser, calibration is required to achieve the highest accuracies. The instrument is typically used to measure wavelengths other than that of the internal reference. Corrections are made within the instrument for the refractive index of the surrounding air. A precise description of the calibration conditions must therefore be an integral part of the calibration.

This international standard defines all of the steps involved in the calibration process: establishing the calibration conditions, carrying out the calibration, calculating the uncertainty, and reporting the uncertainty, the calibration conditions and the traceability.

The calibration procedure describes how to determine the ratio between the value of the input reference wavelength (or the optical frequency) and the wavelength meter's result. This ratio is called *correction factor*. The measurement uncertainty of the correction factor is combined following Annex A from uncertainty contributions from the reference meter, the test meter, the setup and the procedure.

The calculations go through detailed characterization of individual uncertainties. It is important to know that:

a) estimations of the individual uncertainties are acceptable;

b) a detailed uncertainty analysis is only necessary once for each wavelength meter type under test, and that all subsequent calibrations can be based on this one-time analysis;

c) some of the individual uncertainties can simply be considered to be part of a checklist, with an actual value which can be neglected.

A number of optical frequency references can be used to provide a traceable optical frequency. These are based on absorption by gas molecules under low pressure and using excited-state opto-galvanic transitions in atoms. Annex E lists the lines.

# CALIBRATION OF WAVELENGTH/OPTICAL FREQUENCY MEASUREMENT INSTRUMENTS –

## Part 2: Michelson interferometer single wavelength meters

## 1 Scope

This part of IEC 62129 is applicable to instruments measuring the vacuum wavelength or optical frequency emitted from sources that are typical for the fibre-optic communications industry. These sources include Distributed Feedback (DFB) laser diodes, External Cavity lasers and single longitudinal mode fibre-type sources. It is assumed that the optical radiation will be coupled to the wavelength meter by a single-mode optical fibre. The standard describes the calibration of wavelength meters to be performed by calibration laboratories or by wavelength meter manufacturers. This standard is part of the IEC 62129 series on the calibration of wavelength/optical frequency measurement instruments. Refer to IEC 62129 for the calibration of optical spectrum analyzers.

## 2 Normative references

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

IEC 60050-300:2001, International *Electrotechnical Vocabulary – Electrical and electronic measurements and measuring instruments – Part 311: General terms relating to measurements – Part 312: General terms relating to electrical instruments – Part 313: Types of electrical measuring instruments – Part 314: Specific terms according to the type of instrument*

IEC 61315 :2005, *Calibration of fibre-optic power meters*

IEC/TR 61931:1998, *Fibre optic – Terminology*

ISO/IEC 17025:2005, *General requirements for the competence of testing and calibration laboratories*

ISO/IEC Guide 99:2007, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

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 following terms and definitions apply.

**3.1**
**accredited calibration laboratory**
calibration laboratory authorized by the appropriate national organization to issue calibration certificates with a minimum specified uncertainty, which demonstrate traceability to *national standards*

### 3.2
### adjustment

set of operations carried out on an instrument in order that it provides given indications corresponding to given values of the measurand

[IEC 60050-300:2001 (311-03-16); see also ISO/IEC Guide 99:2007, 3.11, modified]

### 3.3
### 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

[ISO/IEC Guide 99:2007, 2.39, modified]

NOTE 1 The result of a calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.

NOTE 2 A calibration may also determine other metrological properties such as the effect of influence quantities.

NOTE 3 The result of a calibration may be recorded in a document, sometimes called a calibration certificate or a calibration report.

### 3.4
### calibration conditions

conditions of measurements in which the calibration is performed

### 3.5
### correction factor

$CF$

numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error

[ISO/IEC Guide 99:2007, 2.53, modified]

### 3.6
### detector

the element of the wavelength meter that transduces the radiant optical power into a measurable, usually electrical quantity

[IEC/TR 61931 and ISO/IEC Guide 99:2007, 3.9, modified]

### 3.7
### deviation

value minus its reference value

NOTE In this standard, the deviation is the difference between the indication of the test meter and the indication of the reference meter when excited under the same conditions.

### 3.8
### excitation (fibre-)

description of the distribution of optical power between the modes in the fibre

NOTE Single mode fibres are generally assumed to be excited by only one mode (the fundamental mode).

### 3.9
### instrument state

complete description of the state of the meter during the calibration

**3.10**
**measuring range**
set of values of measurands for which the error of a measuring instrument is intended to lie within specified limits

[ISO/IEC Guide 99:2007, 4.7, modified]

NOTE In this standard, the measuring range is the range of radiant power (part of the *operating range*), for which the uncertainty at operating conditions is specified. The term "dynamic range" should be avoided in this context.

**3.11**
**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

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

**3.12**
**national standards laboratory**
laboratory which maintains the *national standard*

**3.13**
**natural standard**
atomic or molecular transition that can be used to realise a reference standard

**3.14**
**operating conditions**
appropriate set of specified ranges of values of influence quantities usually wider than the reference conditions for which the uncertainties of a measuring instrument are specified

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

NOTE The operating conditions and uncertainty at operating conditions are usually specified by manufacturer for the convenience of the user.

**3.15**
**operating range**
specified range of values of one of a set of *operating conditions*

**3.16**
**optical input port**
physical input of the wavelength meter (or standard) to which the radiant power is to be applied or to which the optical fibre end is to be connected. An optical path (path of rays with or without optical elements like lenses, diaphragms, light guides, etc.) is assumed to connect the optical input port with the detector

**3.17**
**reference conditions**
conditions of use prescribed for testing the performance of a measuring instrument or for intercomparison of results of measurements

[ISO/IEC Guide 99:2007, 4.11, modified]

NOTE The reference conditions generally include reference values or reference ranges for the influence quantities affecting the measuring instrument.

**3.18**
**reference wavelength meter**
standard which is used as the reference to calibrate a test wavelength meter

### 3.19
**reference source**
laser stabilized by reference to an atomic or molecular transition, or a stabilized frequency comb, of known frequency/wavelength

### 3.20
**reference standard**
standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived

[ISO/IEC Guide 99:2007, 5.6, modified]

### 3.21
**test meter**
*wavelength meter* (or standard) to be calibrated by comparison with the *reference wavelength meter or the reference standard*

### 3.22
**traceability**
property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties

[ISO/IEC Guide 99:2007, 2.41, modified]

### 3.23
**traceability chain**
unbroken chain of comparison (see Figure 1)

[ISO/IEC Guide 99:2007, 2.41 and 2.42, modified]

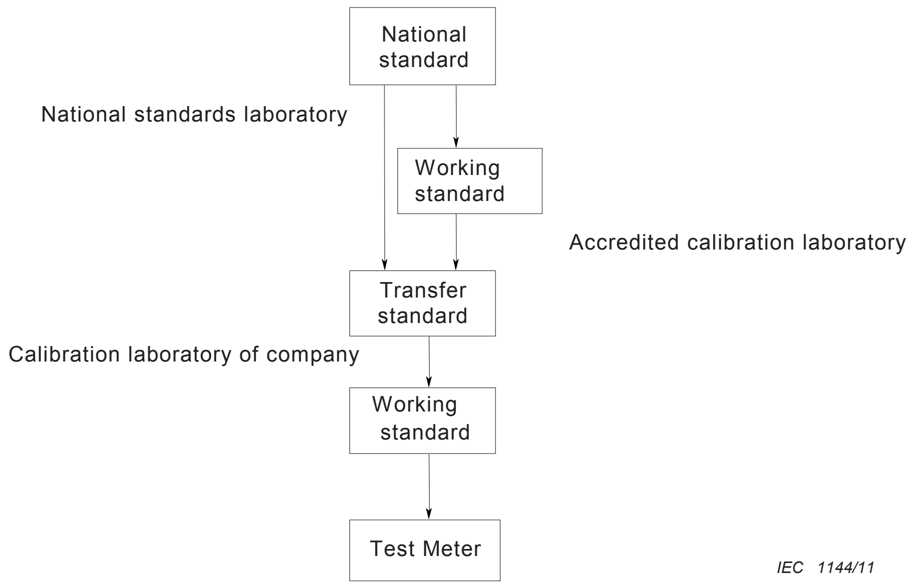


Figure 1 – Example of a traceability chain

### 3.24
**wavelength meter (Michelson interferometer single-)**
instrument, based on a Michelson interferometer, capable of measuring the wavelength of one source

NOTE Certain instrument designs can also measure the input power but with a larger uncertainty than most power meters.

### 3.25
### working standard

standard that is used routinely to calibrate measuring instruments

[ISO/IEC Guide 99:2007, 5.7, modified]

NOTE A working standard is usually calibrated against a reference standard.

## 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 test equipment which has a significant influence on the calibration results is calibrated. Upon request, specify this test equipment and its *traceability chain*(s). The re-calibration period(s) shall be defined and documented.

### 4.3 Advice for measurements and calibrations

This subclause gives general advice for all measurements and calibrations of wavelength meters.

The calibration should be made in a temperature-controlled environment. The recommended temperature is 23 °C. Depending on the desired uncertainty, the temperature, atmospheric pressure and humidity may need to be monitored during the measurement, as the air refractive index is a function of these parameters. Humidity control may be necessary to ensure that the environment is within the operating specification of the instrument.

The laboratory should be kept clean. Connectors and optical input ports should always be cleaned before measurement. The quality and cleanness of the connector in front of the wavelength meter should be checked. The wavelength meter is a precision mechanical instrument and so the fibre should be moved to the instrument rather than the other way round as required for power meter calibrations.

Laser diodes are sensitive to back reflections. To improve stability, it is advisable to use an optical isolator between the laser diode and the test meter.

For instruments that also report optical power, refer to IEC 61315 for calibration procedures. It is important to note that optical sources such as extended cavity laser diodes that may have a narrow linewidth (e.g. 50 kHz) and therefore give rise to a long coherence length. Coherent reflections will add as the vector sum of the electric fields rather than the sum of the optical powers.

The use of a reference source based on a natural standard will yield lower uncertainties than calibrations made using a reference wavelength meter.

### 4.4 Recommendations to customers

A single wavelength meter calibration within an ITU band (see Annex D) is expected to be sufficient for that band. The increase in uncertainties due to extrapolation of the calibration to adjacent bands must be determined for each design of instrument.

## 5 Single wavelength calibration

### 5.1 General

The wavelength calibration of the wavelength meter is based on a comparison with a reference standard and the uncertainty comprises the contribution of the stability of the instrument under test, its "On/Off repeatability," its wavelength dependence and the optical connector repeatability.

The correction is based on the calibration result.

The "On/Off repeatability" measurement provides a contribution to the instrument uncertainty calculation. The repeatability of the stabilization of the internal wavelength reference and the stability of the optical alignment are the main contributors to this uncertainty contribution.

The measurement of the wavelength dependence also provides a contribution to the instrument uncertainty calculation. This measurement has several purposes.

a) To verify that the correction for the air refractive index has been correctly implemented within the instrument.
b) To determine the uncertainty contributions caused by numerical truncation errors.
c) To determine the uncertainty contributions caused by the finite optical path length within the test instrument.
d) To determine systematic alignment effects such as wavelength dependent beam steering.

The calibration can be performed either using a reference source with a lock quality monitor or using a reference wavelength meter.

Acquiring the measurement results under computer control is highly recommended.

### 5.2 Establishing calibration conditions

Establishing and maintaining the calibration conditions is an important part of the calibration, because any change in these conditions is capable of producing erroneous measurement results. The calibration conditions should be a close approximation to the intended operating conditions. This ensures that the (additional) uncertainty in the operating environment is as small as possible. The calibration conditions should be specified in the form of nominal values with uncertainties when applicable. In order to meet the requirements of this standard, the calibration conditions shall at least consist of

a) the date of calibration,
b) the ambient temperature, with uncertainty, for example 23 °C ± 1 °C. The temperature may need to be monitored continuously to ensure that it remains within the prescribed limits,
c) the atmospheric pressure, for example 1020 hPa to1025 hPa. The atmospheric pressure may need to be monitored continuously to ensure that it remains within the prescribed limits,

d) the ambient relative humidity, for example 30 % to 50 %. The ambient relative humidity may need to be monitored continuously to ensure that it remains within the prescribed limits. A relative humidity below the condensation point is assumed by default,
e) the input optical power (that must fall within the allowable specification for the instruments),
f) the connector and polishing type,
g) details of the reference material or its identification number. Examples have been taken for a gas absorption cell:
   1) gas and isotope, e.g. $^{13}C_2H_2$
   2) path length, e.g. 15 cm
   3) pressure within the vessel, e.g. 1 000 Pa
   4) transition, e.g. R(21)
h) the centre vacuum wavelength or frequency of the exciting source with its uncertainty,
i) if a transition locked source is used then the quality of the lock must be continuously monitored during the measurements; a lock indicator can be sufficient.

NOTE The above conditions may not be exhaustive. There may be other parameters that have a significant influence on the measurement uncertainty and therefore should also be reported.

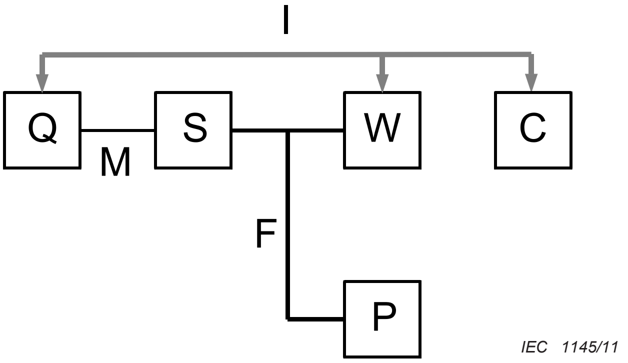
### 5.3 Calibration procedure

#### 5.3.1 General

a) Establish and record the appropriate calibration conditions (see 5.2). Switch on all instrumentation and wait for enough time to stabilize.
b) Set up the reference source.
c) In some of the older instrument designs a connector-adapter combination is used to couple light from the optical fibre into the instrument. A fraction of the light from the reference signal, typically a helium-neon laser, is emitted from the instrument. This beam defines the optical axis for the interferometer. Maximizing the residual reference signal from the test wavelength meter optimises the alignment of the connector-adapter. The optical power must be measured using a linear power meter.
d) Set up the instrument state of the test wavelength meter according to the instruction manual. Select appropriate units.
e) Record the instrument states of the wavelength meter.

#### 5.3.2 Measurement configuration

Figure 2 shows the configuration using a reference source S with a lock-quality monitor Q. The temperature, pressure and humidity of the environment may need to be monitored. The refractive index change due to humidity is less than $\pm 4 \times 10^{-7}$ at 1 550 nm. Monitoring of the relative humidity is optional and is required only to achieve the best specification.

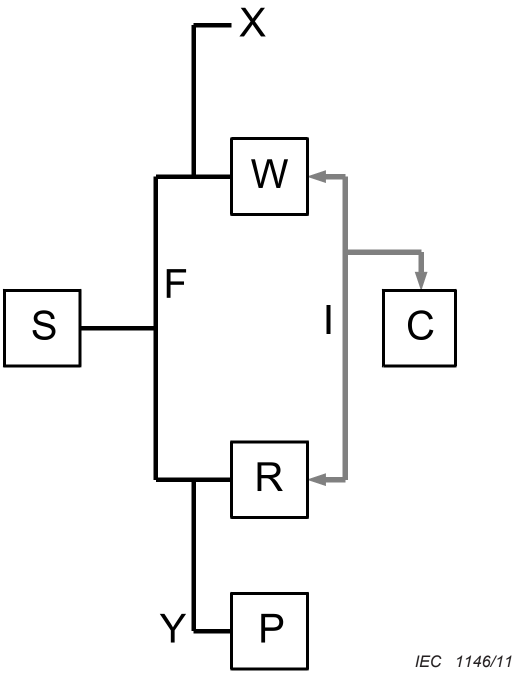


**Key**

| | | | |
|---|---|---|---|
| C | controlling computer | P | reference power meter |
| F | optical fibre link | Q | lock quality monitor |
| I | computer interface connection | S | reference source |
| M | monitor link | W | test wavelength meter |

Figure 2 – Wavelength meter measurement using a lock quality monitor signal

In the absence of a lock quality signal from the source, a reference wavelength meter must be used to monitor the lock quality (Figure 3). If the lock has been lost, the results drift considerably compared to the locked condition. It is important that the measurements are performed simultaneously on both the reference and the test wavelength meters.



**Key**

| | | | |
|---|---|---|---|
| C | controlling computer | R | reference wavelength meter |
| F | optical fibre link | S | reference source |
| I | computer interface connection | W | test wavelength meter |
| P | reference power meter | | |

NOTE The reference power meter may be used at locations X or Y to measure the optical power incident either on the test or on the reference wavelength meters.

Figure 3 – Wavelength meter measurement using a reference wavelength meter

### 5.3.3 Detailed procedure

The number of measurements averaged per reading affects the size of the results file, the rejection of data by the measurement routine and detection of lock failure. A large number of samples per measurement will increase the size of the data set used to check that the extreme data points are valid. If the number of samples is too large then the temporal resolution will be reduced. Also, loss of lock may not be detected. Typically, 50 samples ($n$) are taken per measurement. The same methodology used in 5.3.5 can be applied to determine the optimum value for $n$. The statistical rejection of outlying points (Annex B) is strongly recommended.

The measurement process is as follows.

a) Allow the equipment to reach equilibrium.

b) Configure the data acquisition software.

c) Ensure that the optical source is locked and is operating correctly.

d) Run the data acquisition software.

The correction factor is determined from the ratio of the mean values from each measurement:

$$CF = \frac{1}{n}\sum_{i=1}^{n}\frac{\lambda ref_i}{\lambda test_i} = \frac{\overline{\lambda ref}}{\overline{\lambda test}} \qquad (1)$$

where $\lambda ref$ is the reference wavelength and $\lambda test$ is the wavelength measured by the test wavelength meter. The uncertainty associated with the correction factor should be expressed as a dimensionless quantity. We can also determine the deviation $D$ as in Equation (2). The uncertainty associated with the deviation should be expressed as a length quantity.

$$D = \frac{1}{n}\sum_{i=1}^{n}\left(\lambda test_i - \lambda ref_i\right) = \overline{\lambda test} - \overline{\lambda ref} \qquad (2)$$

### 5.3.4 Stability test (if necessary)

The stability of the instrument measuring a single wavelength under normal operating conditions is measured to determine the instrument drift and its contribution to the uncertainty. The measurement duration must be longer than 1 hour (12 hours is recommended). The statistical rejection of outlying points (Annex B) is strongly recommended.

As for the calibration, the number of measurements averaged per reading affects the size of the results file, the rejection of data by the measurement routine and detection of lock failure. A large number of samples per measurement will increase the size of the data set used to check that the extreme data points are valid. If the number of samples is too large then the temporal resolution will be reduced. Also, loss of lock may not be detected. Typically, 50 samples ($n$) are taken per measurement. The same methodology used in 5.3.5 can be applied to determine the optimum value for $n$.

The measurement process is as follows:

a) Allow the equipment to reach equilibrium.

b) Configure the data acquisition software.

c) Ensure that the optical source is locked and is operating correctly.

d) Run the data acquisition software.

If the stability test is done during the calibration, the correction factor should be calculated using these results. If the instrument is not stable, the calibration will not be valid.

The mean centre wavelength for the $n$ measurements of each data point of the stability test is given by:

$$\lambda s_i = \frac{1}{n}\sum_{j=1}^{n} \lambda stest_{i,j} \tag{3}$$

where $\lambda s_{\mathrm{i}}$ is the mean wavelength for the $i^{\mathrm{th}}$ stability measurement ($i$ = 1…$N$) comprising each of $n$ measurements ($j$ = 1 …$n$) and $\lambda stest_{\mathrm{i,i}}$ is the measured value.

The contribution of the type A standard uncertainty of each centre wavelength measurement is given by Equation (4) (from Equation (A.3)).

$$ustest_i = \left[ \frac{1}{(n-1)n}\sum_{j=1}^{n} \left(\lambda stest_{i,j} - \lambda s_i\right)^2 \right]^{1/2} \tag{4}$$

The uncertainty contribution due to stability can be calculated from Equation (5) and Equation (6).

$$\overline{\lambda s} = \frac{1}{N}\sum_{i=1}^{N} \lambda s_i \tag{5}$$

$$us = \left[ \frac{1}{(N-1)}\sum_{i=1}^{N} (\lambda s_i - \overline{\lambda s})^2 + \frac{1}{N}\sum_{i=1}^{N} ustest_i^2 \right]^{\frac{1}{2}} \tag{6}$$

where $us$ is the uncertainty contribution from the stability measurement and $N$ is the number of data points of stability measurements. The number of measurements $n$ for each data point of the stability measurements should be chosen to be sufficiently large such that the second term in Equation (6) becomes negligible in relation to the first term, giving Equation (7).

$$us = \left[ \frac{1}{(N-1)}\sum_{i=1}^{N} (\lambda s_i - \overline{\lambda s})^2 \right]^{\frac{1}{2}} \tag{7}$$

### 5.3.5 "On/Off repeatability" measurement (optional if a specification is available)

#### 5.3.5.1 General

The measurements using a fixed wavelength reference source may be affected by the "On/Off repeatability" of the wavelength meter internal reference. This test is optional if already done in a qualification of the product. This test may be combined with the connector repeatability measurement (5.3.7) in order to simplify the overall calibration process.

The duration of each measurement must be sufficient that its measurement uncertainty will not significantly increase the uncertainty of the result. The uncertainty contribution determined from this measurement will comprise of a component due to the "On/Off repeatability" of the instrument and a component due to the measurement noise. Averaging is required to ensure that the dominant component of the uncertainty contribution is due to the "On/Off repeatability" of the instrument. The number of averages will depend on the measurement noise and can be calculated using Equation (8). Typical parameters are given in Table 1.

$$n = \frac{\sigma_{rms}^2}{\sigma_{\mathrm{target}}^2} \tag{8}$$

where $n$ is the number of averages for each measurement, $\sigma_{\mathrm{rms}}$ and $\sigma_{\mathrm{target}}$ are the estimated rms and target noise contributions. The statistical rejection of outlying points (Annex B) is strongly recommended.

**Table 1 – Typical parameters to calculate the "On/Off repeatability" measurement duration**

| Parameter | Value |
|---|---|
| Estimated rms noise | 1 pm |
| Target uncertainty contribution | 0,05 pm |
| Number of averages required | 400 |
| Measurement rate | 1 $s^{-1}$ |
| Duration | 7 min |

#### 5.3.5.2 Measurement process

a) Allow the equipment to reach equilibrium.

b) Configure the data acquisition software.

c) Power down the wavelength meter and ensure that the reference source has turned off completely.

d) Wait at least 10 min.

e) Turn on the wavelength meter and wait for it to complete its self-checks and stabilization of its reference laser. The time taken for the system to achieve maximum stability may be as long as 1 to 2 h, see manufacturers instructions for guidance.

f) Measure the wavelength using data acquisition software to acquire $n$ measurements.

g) Turn the wavelength meter off.

h) Repeat from c) until at least $N$ sets of measurements have been made.

i) "On/Off repeatability" measurement is complete.

The mean centre wavelength for the $n$ measurements of each cycle of the "On/Off repeatability" test is given by:

$$\lambda rep_i = \frac{1}{n}\sum_{j=1}^{n} \lambda test_{i,j} \tag{9}$$

where $\lambda rep_{\mathrm{i}}$ is the mean wavelength for the $i^{\mathrm{th}}$ "On/Off repeatability" measurement ($i$ = 1…$N$) comprising each of $n$ measurements ($j$ = 1 …$n$) and $\lambda test$ is the measured value.

The contribution of the type A standard uncertainty of each centre wavelength measurement is given by Equation (10) (from Equation (A.3)).

$$utest_i = \left[\frac{1}{(n-1)n}\sum_{j=1}^{n}\left(\lambda test_{i,j} - \lambda rep_i\right)^2\right]^{1/2} \tag{10}$$

The uncertainty contribution due to "On/Off repeatability" can be calculated from Equation (11) and Equation (12).

$$\overline{\lambda rep} = \frac{1}{N}\sum_{i=1}^{N} \lambda rep_i \tag{11}$$

$$urep = \left[ \frac{1}{(N-1)} \sum_{i=1}^{N} (\lambda rep_i - \overline{\lambda rep})^2 + \frac{1}{N} \sum_{i=1}^{N} utest_i^2 \right]^{\frac{1}{2}} \tag{12}$$

where $urep$ is the uncertainty contribution from the "On/Off repeatability" measurement and $N$ is the number of sets of "On/Off repeatability" measurements. The number of measurements $n$ for each cycle of the “On/Off repeatability” measurements should be chosen to be sufficiently large such that the second term in Equation (12) becomes negligible in relation to the first term, giving Equation (13).

$$urep = \left[ \frac{1}{(N-1)} \sum_{i=1}^{N} (\lambda rep_i - \overline{\lambda rep})^2 \right]^{\frac{1}{2}} \tag{13}$$

### 5.3.6 Wavelength dependence measurement (optional)

#### 5.3.6.1 General

Measurements made over a range of wavelengths will provide an improved correction factor and an improved estimate for the instrument uncertainty. The measurements require a number of transition-locked reference sources, a single source that can be locked to a number of transitions or multiple lines of a frequency comb of known values. This test is not required if the wavelength meter under test is to be used in only one ITU-T band, unless the highest levels of accuracy are required.

The number of measurements for each of the wavelength dependence measurements is calculated using Equation (8).

#### 5.3.6.2 Measurement process

a) Allow the equipment to reach equilibrium.

b) Configure the data acquisition software.

c) *Either* lock the laser to the reference transition and allow sufficient time for the system to stabilize *or* connect each of transition-locked references in turn.

d) Measure the wavelength using data acquisition software to acquire $n$ measurements.

e) Reset the wavelength of the reference source.

f) Repeat from c) until $N$ sets of wavelengths, (suggested minimum of 3) have been measured.

g) The wavelength dependence measurement is now complete.

The mean centre wavelength for $n$ measurements is given by:

$$\lambda wd_i = \frac{1}{n}\sum_{j=1}^{n} \lambda wtest_{i,j} \tag{14}$$

where $\lambda wd_\mathrm{i}$ is the mean wavelength for the $i^{\mathrm{th}}$ wavelength ($i$ = 1...$N$) performing $n$ measurements ($j$ = 1...$n$) for each and $\lambda wtest$ is the measured value.

The uncertainty of each centre wavelength measurement is given by Equation (15).

$$uwtest_i = \left[ \frac{1}{(n-1)n} \sum_{j=1}^{n} \left( \lambda wtest_{i,j} - \lambda wd_i \right)^2 \right]^{1/2} \tag{15}$$

The wavelength deviation $D_i$ is defined in Equation (16).

$$D_i = \lambda wd_i - \lambda ref_i \tag{16}$$

The uncertainty contribution due to wavelength dependence can be calculated from Equation (17) and Equation (18).

$$\overline{D} = \frac{1}{N} \sum_{i=1}^{N} D_i \tag{17}$$

$$uwd = \left[ \frac{1}{N-1} \sum_{i=1}^{N} (D_i - \overline{D})^2 + \frac{1}{N} \sum_{i=1}^{N} uwtest_i^2 \right]^{\frac{1}{2}} \tag{18}$$

where $uwd$ is the uncertainty contribution from the wavelength dependence measurement and $N$ is the number of wavelengths. The number of measurements $n$ for each cycle of the wavelength dependence measurements should be chosen to be sufficiently large such that the second term in Equation (18) becomes negligible in relation to the first term, giving Equation (19).

$$uwd = \left[ \frac{1}{N-1} \sum_{i=1}^{N} (D_i - \overline{D})^2 \right]^{\frac{1}{2}} \tag{19}$$

### 5.3.7 Connector repeatability measurement (optional)

#### 5.3.7.1 General

The connector repeatability measurement is required if the optical input to the wavelength meter couples directly to the interferometer, without an intervening optical fibre link. The premise is that small displacements of the optical fibre connector will cause changes to the optical alignment between the reference and unknown optical beams. This test may be combined with the “On/off repeatability” measurement (5.3.5) in order to simplify the overall calibration process.

The number of measurements for each of the connector repeatability measurements is calculated using Equation (8).

#### 5.3.7.2 Measurement process

a) Allow the equipment to reach equilibrium.

b) Configure the data acquisition software.

c) Measure the wavelength using data acquisition software to acquire $n$ measurements.

d) Disconnect the optical fibre from the wavelength meter.

e) Reconnect the optical fibre to the wavelength meter.

f) Repeat from c) until $N$ sets of measurements, typically 10, have been made.

g) The connector repeatability measurement is now complete.

The mean centre wavelength for $n$ measurements is given by:

$$\lambda con_i = \frac{1}{n}\sum_{j=1}^{n} \lambda ctest_{i,j} \tag{20}$$

where $\lambda con_\mathrm{i}$ is the mean wavelength for the $i^\mathrm{th}$ connector repeatability measurement ($i$ = 1...$N$) performing $n$ measurements ($j$ = 1...$n$) for each and $\lambda ctest$ is the measured value.

The uncertainty of each connexion measurement is given by Equation (21).

$$uctest_i = \left[\frac{1}{(n-1)n}\sum_{j=1}^{n}\left(\lambda ctest_{i,j} - \lambda con_i\right)^2\right]^{1/2} \tag{21}$$

The uncertainty contribution due to connector repeatability can be calculated from Equation (22) and Equation (23).

$$\overline{\lambda con} = \frac{1}{N}\sum_{i=1}^{N} \lambda con_i \tag{22}$$

$$ucon = \left[\frac{1}{N-1}\sum_{i=1}^{N}(\lambda con_i - \overline{\lambda con})^2 + \frac{1}{N}\sum_{i=1}^{N} uctest_i^2\right]^{\frac{1}{2}} \tag{23}$$

where $ucon$ is the uncertainty contribution from the connector measurement and $N$ is the number of sets of measurements. The number of measurements $n$ for each cycle of the connector repeatability measurements should be chosen to be sufficiently large such that the second term in Equation (23) becomes negligible in relation to the first term, giving Equation (24).

$$ucon = \left[\frac{1}{N-1}\sum_{i=1}^{N}(\lambda con_i - \overline{\lambda con})^2\right]^{\frac{1}{2}} \tag{24}$$

## 5.4 Calibration uncertainty

Note that the following list may not be complete. Additional contributions may have to be taken into account, depending on the measurement setup and procedure. The mathematical basis, Annex A, should be used to calculate and state the uncertainty.

a) Stability measurement
b) "On/Off repeatability" measurement
c) Wavelength dependence measurement
d) Connector repeatability
e) Uncertainty of the reference standard
f) Source uncertainty (how well the source is stabilized to the natural standard)
g) Display resolution of the test wavelength meter

### 5.5 Reporting the results

The results of each calibration should be reported as required by ISO/IEC 17025. Calibration certificates referring to this standard shall at least include the following information:

a) All calibration conditions of the calibration process as described in 5.2.
b) The test meter's correction factor(s) or deviation(s), if the test meter was not adjusted.
c) On receipt correction factors or deviations **and** after adjustment correction factors or deviations in the case that an adjustment was carried out.
d) The calibration uncertainty in the form of an expanded uncertainty as described in 5.4 and Annex A.
e) The instrument state of the test meter during the calibration.
f) Evidence that the measurements are traceable (see ISO/IEC 17025:2005, 5.10.4.1 c).

## 6 Absolute power calibration

If the wavelength meter has a power measurement capability then it must be calibrated using the power meter calibration procedure (IEC 61315), while taking into account the restrictions on moving the instrument (4.3).

# Annex A
(normative)

# Mathematical basis

## A.1 General

This annex summarizes the form of evaluating, combining and reporting the uncertainty of measurement. It is based on the ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*. It does not relieve the need to consult this guide for more advice.

This document 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 $X_\mathrm{i}$, the arithmetic mean is:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \ . \tag{A.1}$$

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:

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

where

$\overline{X}$ is the arithmetic mean of the observed values;
$X_\mathrm{i}$ 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 $u_{\mathrm{typeA}}(x)$ associated with the estimate $x$ is the experimental standard deviation of the mean:

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

## 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.

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

If only upper and lower limit $X_{\mathrm{max}}$ and $X_{\mathrm{min}}$ can be estimated for the value of the quantity $X$ (for example a manufacturer's specifications or a temperature range), a rectangular probability distribution is assumed; the estimated value is

$$x = \frac{1}{2}(X_{max} + X_{min}) \tag{A.5}$$

and the standard uncertainty is

$$u(x) = \frac{1}{2\sqrt{3}}(X_{max} - X_{min}) \tag{A.6}$$

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

$$u(y) = c \cdot u(x) \tag{A.7}$$

where $c$ is the sensitivity coefficient associated with the input estimate $x$.

## 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:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} u_i^2(y)} \tag{A.8}$$

where

| | |
|---|---|
| $i$ | is the current number of individual contribution; |
| $u_{\mathrm{i}}(y)$ | are the standard uncertainty contributions; |
| $N$ | is the number of uncertainties. |

NOTE It is acceptable to neglect uncertainty contributions to this equation which are smaller than 1/10 of the largest contribution, because squaring them will reduce their significance to 1/100 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). In spite of its partially type A origin, $u_c$ should be considered as describing an uncertainty type B.

## A.5 Reporting uncertainties

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 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*); if these conditions are not met, larger coverage factors are to be used to reach these levels of confidence.

# Annex B
(informative)

# Rejection of outliers

## B.1 Overview

Wavelength meters can, on occasion, give spurious wavelength readings that are far removed from the true value. This can be caused by factors such as laser coherence, modulation of the optical power level, or incorrect operation of the fringe multiplier system. If these outliers are not removed then the mean values will be biased and the standard deviation of the data set will be over estimated.

## B.2 Assumptions

The analysis requires that a sample of the data used to obtain an estimate of the mean should be sufficiently large that the estimate for the standard deviation will be realistic. However, there is a trade-off between the statistical confidence, the sample size and the acquisition time.

## B.3 Measurement and analysis procedure

If the presence of outliers in a data set is suspected, the recommended procedure is to apply Grubbs' Test [1], [2], [3][1].

a) Acquire a data set.

b) Calculate the mean and standard deviation of the sample.

c) Taking the data point $x_{\mathrm{ext}}$ farthest from the mean, calculate $Z$ from Equation (B.1):

$$Z = \frac{\left| x_{ext} - \bar{x} \right|}{s(x)} \tag{B.1}$$

where $s(x)$ is given by Equation (A.2).

d) Compare the value of $Z$ with the critical values $Z_{\mathrm{c}}$ listed in Table B.1. If $Z$ is > $Z_{\mathrm{c}}$ then there is a 95 % probability that the extreme value $x_{\mathrm{ext}}$ is an outlier. Reject this value and repeat steps b) to d) until $Z < Z_{\mathrm{c}}$ for the appropriate sample size $N$. When $Z < Z_{\mathrm{c}}$, it is assumed that all the data values in the sample are valid readings.

---

[1] Numbers in square brackets refer to the Bibliography.

### Table B.1 – Critical values $Z_c$ as a function of sample size $N$

| $N$ | $Z_c$ | $N$ | $Z_c$ |
|---|---|---|---|
| 3 | 1,15 | 27 | 2,86 |
| 4 | 1,48 | 28 | 2,88 |
| 5 | 1,71 | 29 | 2,89 |
| 6 | 1,89 | 30 | 2,91 |
| 7 | 2,02 | 31 | 2,92 |
| 8 | 2,13 | 32 | 2,94 |
| 9 | 2,21 | 33 | 2,95 |
| 10 | 2,29 | 34 | 2,97 |
| 11 | 2,34 | 35 | 2,98 |
| 12 | 2,41 | 36 | 2,99 |
| 13 | 2,46 | 37 | 3,00 |
| 14 | 2,51 | 38 | 3,01 |
| 15 | 2,55 | 39 | 3,03 |
| 16 | 2,59 | 40 | 3,04 |
| 17 | 2,62 | 50 | 3,13 |
| 18 | 2,65 | 60 | 3,20 |
| 19 | 2,68 | 70 | 3,26 |
| 20 | 2,71 | 80 | 3,31 |
| 21 | 2,73 | 90 | 3,35 |
| 22 | 2,76 | 100 | 3,38 |
| 23 | 2,78 | 110 | 3,42 |
| 24 | 2,80 | 120 | 3,44 |
| 25 | 2,82 | 130 | 3,47 |
| 26 | 2,84 | 140 | 3,49 |

# Annex C
(informative)

## Example of a single wavelength calibration

The figures presented here refer to a wavelength meter and an external cavity laser, locked to an absorption transition (R19) in CO at 13,6 hPa with a wavelength of 1 561,257 709 ± 0,000 026 nm.

## C.1 Stability measurement

The typical uncertainty budget for the Type A contributions of a stability measurement is shown in Table C.1.

**Table C.1 – Type A uncertainty contributions for a stability measurement**

| Symbol | Source of uncertainty | Value<br>fm | PDF | Divisor | $u_i$<br>fm |
|---|---|---|---|---|---|
| $u_{as}$ | Individual measurement Type A | 1,85 | Gaussian | 1 | 1,85 |
| $u_{bs}$ | Stability of the centre wavelength | 1,78 | Gaussian | 1 | 1,78 |
| | Combined uncertainty $u_s$ | 2,57 | | | |

Where the parameters $u_{as}$ and $u_{bs}$ are the two terms of Equation (6) such that:

$$u_{as} = \left[ \frac{1}{N} \sum_{i=1}^{N} ustest_i^2 \right]^{\frac{1}{2}} \tag{C.1}$$

and

$$u_{bs} = \left[ \frac{1}{N-1} \sum_{i=1}^{N} (\lambda s_i - \overline{\lambda s})^2 \right]^{\frac{1}{2}} \tag{C.2}$$

## C.2 "On/Off repeatability" measurement

The typical uncertainty budget for a "On/Off repeatability" measurement is shown in Table C.2. The uncertainty contributions from the individual measurements are small compared to the "On/Off repeatability" of the centre wavelength.

**Table C.2 – Uncertainty contributions for a "On/Off repeatability" measurement**

| Symbol | Source of uncertainty | Value<br>fm | PDF | Divisor | $u_i$<br>fm |
|---|---|---|---|---|---|
| $u_{ar}$ | Individual measurement Type A | 7,7 | Gaussian | 1 | 7,7 |
| $u_{br}$ | "On/Off repeatability" of centre wavelengths | 26,0 | Gaussian | 1 | 26 |
| | Combined uncertainty $u_{rep}$ | 27,1 | | | |

Where the parameters $u_a$ and $u_r$ are the two terms of Equation (12) such that:

$$u_{ar} = \left[ \frac{1}{N} \sum_{i=1}^{N} utest_i^2 \right]^{\frac{1}{2}} \tag{C.3}$$

and

$$u_{br} = \left[ \frac{1}{N-1} \sum_{i=1}^{N} (\lambda rep_i - \overline{\lambda rep})^2 \right]^{\frac{1}{2}} \tag{C.4}$$

## C.3 Wavelength dependence measurement

The typical results and uncertainty budget for a wavelength dependence measurement are shown in Table C.3. The uncertainty contributions from the individual measurements are small compared to the wavelength dependence of the centre wavelength.

**Table C.3 – Uncertainty budget for wavelength dependence**

| Parameter | Line | Difference<br>fm | Uncertainty<br>fm |
|---|---|---|---|
| | P(27) | -7,3 | 7,6 |
| | P(28) | -5,8 | 7,7 |
| | P(29) | -44,1 | 7,8 |
| | P(30) | -15,7 | 7,7 |
| | P(31) | -39,9 | 7,5 |
| | P(32) | -13,9 | 7,6 |
| | P(33) | -21,6 | 7,4 |
| First term of Equation 17 | | | 15,2 |
| Second term of Equation 17 | | | 7,6 |
| Wavelength dependence uncertainty $u_{wd}$ | | | 17,0 |

## C.4 Wavelength meter calibration results

The results from the "On/Off repeatability" (which were obtained including the contribution from connector repeatability) and stability tests are combined with the uncertainty of the reference to give the total uncertainty for the measurement as shown in Table C.4. Contributions to the uncertainty budget due to imperfect locking of the laser to the transition have not been included explicitly. It has been assumed that these contributions will increase the Stability Type A component of the budget. The Type B contribution is due to the display resolution of the test wavelength meter.

**Table C.4 – Uncertainty budget for the wavelength meter calibration**

| Source of uncertainty | Value fm | PDF | Divisor | $u_i$ fm |
|---|---|---|---|---|
| Reference | 13,1 | Gaussian | 1 | 13,1 |
| "On/Off repeatability" $u_{rep}$ | 27,1 | Gaussian | 1 | 27,1 |
| Wavelength dependence uncertainty $u_{wd}$ | 17,0 | Gaussian | 1 | 17,0 |
| Stability Type A $u_s$ | 2,57 | Gaussian | 1 | 2,57 |
| Type B | 100 | Rectangular | √3 | 57,7 |
| Combined uncertainty $u_c$ | | | | 67,3 |
| Expanded uncertainty $U$ | | | | 134,6 |

# Annex D
(informative)

# ITU wavelength bands

The key telecommunication bands, defined by the ITU, are listed in Table D.1.

**Table D.1 – The ITU-T bands in different units**

| Band | Descriptor | Start | | | Stop | | |
|---|---|---|---|---|---|---|---|
| | | nm | GHz | $cm^{-1}$ | nm | GHz | $cm^{-1}$ |
| O-band | Original | 1 260 | 237 931 | 7 937 | 1 360 | 220 436 | 7 353 |
| E-band | Extended | 1 360 | 220 436 | 7 353 | 1 460 | 205 337 | 6 849 |
| S-band | Short wavelength | 1 460 | 205 337 | 6 849 | 1 530 | 195 943 | 6 536 |
| C-band | Conventional | 1 530 | 195 943 | 6 536 | 1 565 | 191 561 | 6 390 |
| L-band | Long wavelength | 1 565 | 191 561 | 6 390 | 1 625 | 184 488 | 6 154 |
| U-band | Ultralong wavelength | 1 625 | 184 488 | 6 154 | 1 675 | 178 981 | 5 970 |

# Annex E
(informative)

# Atomic and molecular reference transitions

## E.1 Overview

This annex provides lists of laser lines, absorption features, and opto-galvanic transitions that are known to sufficient accuracy to provide wavelength reference points for wavelength meter calibration. These tables give the vacuum wavelengths of the dominant transitions only. Other transitions with precisely known vacuum wavelengths may also be used.

## E.2 General

Gas laser lines, such as those listed in E.3 for the helium-neon laser, provide intense (>1 mW) and well-defined wavelength (frequency) sources. However, the helium-neon laser's wavelength may deviate from the centre of the gain curve by up to about 2 parts in $10^6$ (400 MHz at 1 523,488 nm) unless the laser cavity length is stabilized so that the emission is locked to a known point on the gain curve.

At low gas pressures, atomic or molecular absorption and emission lines are typically several hundred megahertz to a few gigahertz wide due to Doppler broadening. These transitions are normally used to stabilize the wavelength of a semiconductor laser and provide an active reference.

The centre wavelength of an atomic or molecular line will both shift and broaden with increasing gas pressure. It is therefore important to know the associated pressure shift and cell pressure when calculating the expected centre wavelength.

At high optical powers it is possible to saturate an atomic or molecular transition by using two counter-propagating optical beams. The natural linewidth of the transition may be significantly narrower than the Doppler broadened width. Doppler-free transitions offer the potential to provide the highest accuracy frequency references. In molecular absorptions, saturation often requires relatively high powers but the linewidths can be < 1 MHz. Strong atomic transitions out of the ground state or between excited states can be saturated at quite modest optical powers. However, the width of the saturated dip is considerably wider (5 MHz to 150 MHz).

## E.3 Helium-neon laser lines

### E.3.1 General

A He-Ne laser operates at a frequency near the centre of the Doppler-broadened neon gain curve. The exact frequency or vacuum wavelength of the laser depends on two factors:

a) the wavelength difference between the actual operating point and the centre of the gain curve and

b) the exact location of the centre of the curve.

The first factor above will probably never exceed ±2 parts in $10^6$ (hereafter written as $\pm 2/10^6$) for lasers of realistic design. The Doppler width of the gain curve at half-height is about $\pm 1{,}5/10^6$ and one would not expect the laser to operate far outside this range. The value $\pm 2/10^6$ is a conservative estimate of the range except (possibly) for tubes that have been enriched in $^{22}$Ne in order to broaden the gain curve.

The wavelength corresponding to the centre of the gain curve depends slightly on gas pressure and more significantly on the isotope of neon used in the tube. This isotope shift is discussed below for the 632,99, 1 152,6, and 1 523,5 nm lines, and Table E.1 shows the vacuum wavelength and frequency values of these lines with the corresponding uncertainty.

### E.3.2 632,991 nm helium-neon line summary

For $^{20}$Ne, the centre of the gain curve of the standard red transition ($3s_2 \rightarrow 2p_4$) lies within 1/10$^7$ of 632,991 4 nm [4], with the exact value depending on gas pressure. For $^{22}$Ne, the centre of this gain curve is shifted toward shorter wavelengths by about 2 parts in 10$^6$ [5]. Thus, if the laser tube is filled with $^{20}$Ne, the vacuum wavelength of a laser is 632,991 4 nm with a conservative estimate of the expanded uncertainty (coverage factor k=2; i.e., $2\sigma$) being 2/10$^6$. Existing evidence indicates that tubes filled with natural neon (approximately 90% $^{20}$Ne and 10% $^{22}$Ne) will also fall within 2/10$^6$ of this wavelength. The situation is a bit less clear for tubes containing more $^{22}$Ne, but in any event, even if the $^{22}$Ne content is entirely unknown, the wavelength must lie within ±3/10$^6$ of 632,990 8 nm, a value approximately half way between the centres of the $^{20}$Ne and $^{22}$Ne gain curves.

It must be verified that the laser operates on the standard red transition ($3s_2 \rightarrow 2p_4$). Almost all commercially produced red He-Ne lasers operate on this line, but operation near 640 nm or 612 nm is also possible. If there is any doubt, it would be good to verify with the manufacturer that your particular laser model is indeed a 633 nm laser and not a 640 nm or 612 nm laser.

### E.3.3 1 152,590 nm helium-neon line summary

If the laser tube is filled with $^{20}$Ne, the vacuum wavelength of a laser operating on the 1 152,59 nm transition ($2s_2 \rightarrow 2p_4$) is 1 152,590 2 nm [6] with a conservative estimate of the expanded uncertainty being 2/10$^6$. For $^{22}$Ne, the centre of this gain curve is shifted toward shorter wavelengths by about 1 part in 10$^6$ [7]. In the situation where the $^{22}$Ne content is entirely unknown, the wavelength must lie within ±2,5 parts in 10$^6$ of 1 152,589 6 nm, a value approximately half way between the centres of the $^{20}$Ne and $^{22}$Ne gain curves.

### E.3.4 1 523,488 nm helium-neon line summary

If the laser tube is filled with $^{20}$Ne, the vacuum wavelength of a laser operating on the 1 523,488 nm transition ($2s_2 \rightarrow 2p_1$) is 1 523,488 0 nm [8] with a conservative estimate of the expanded uncertainty being 2/10$^6$. For $^{22}$Ne, the centre of this gain curve is shifted toward shorter wavelengths by about 1 part in 10$^6$ [8]. In the situation where the $^{22}$Ne content is entirely unknown, the wavelength must lie within ±2,5 parts in 10$^6$ of 1 523,487 2 nm, a value approximately half way between the centres of the $^{20}$Ne and $^{22}$Ne gain curves.

**Table E.1 – Helium-neon laser lines**

| **$^{20}$Ne Isotope** | | **Unknown ratio of $^{22}$Ne to $^{20}$Ne** | |
|---|---|---|---|
| **Wavelength** nm | **Frequency** GHz | **Wavelength** nm | **Frequency** GHz |
| 632,991 4(13) | 473 612,2(9) | 632,990 8(19) | 473 612,7(1,4) |
| 1 152,590(2) | 260 103,2(5) | 1 152,589(3) | 260 103,4(7) |
| 1 523,488(3) | 196 780,3(4) | 1 523,487(4) | 196 780,4(5) |

NOTE 1 Vacuum wavelength and optical frequency of selected helium-neon laser lines.

NOTE 2 Uncertainties in parentheses are expanded uncertainties (coverage factor $k$=2; i.e., $2\sigma$).

## E.4 Absorption lines

### E.4.1 General

There are numerous atomic and molecular absorption lines in the visible and near IR regions. All infrared active molecules have overtone absorption bands, and molecules with three or more atoms in addition have combination bands where two or more vibrational modes are excited simultaneously. Very often such bands will extend over the near infrared wavelength range of interest for optical telecommunication wavelength standards. The uncertainty stated in the tables is the expanded uncertainty ($2\sigma$).

### E.4.2 Acetylene

### E.4.2.1 General

Acetylene has so far been shown to be one of the most suitable molecules and the most widely used as a wavelength reference. Various carbon and deuterium isotopomers have been investigated and the Mise en pratique of the Consultative Committee for Length (metre convention) recommended an acetylene transition ($^{13}C_2H_2$ P(16)) as a reference in the telecomms' region with a provisional uncertainty of 0,010 MHz.

### E.4.2.2 Acetylene $^{12}C_2H_2$

This molecule has been used in self-contained units [9],[10],[11] as certified reference material [9],[12]. Pressure-induced shift and broadening have been measured for 15 lines of the $\nu_1 + \nu_3$ band [12]. There have been performed numerous FTIR and laser spectroscopic studies of the band involved and saturated absorption has been observed [13],[14],[15],[16],[17] allowing for very accurate determination of the molecular transition frequencies [18]. Vacuum wavelengths (nm) of absorption lines in the $\nu_1 + \nu_3$ band of $^{12}C_2H_2$ are given in Table E.2.

**Table E.2 – Centre vacuum wavelengths for acetylene $^{12}C_2H_2$**

| Wavelength nm | Uncertainty pm | Frequency GHz | Uncertainty MHz | Transition |
|---|---|---|---|---|
| 1 545,175 602 1 | 0,000 1 | 194 018,374 09 | 0,01 | P(31) |
| 1 544,434 617 1 | 0,000 1 | 194 111,459 74 | 0,01 | P(30) |
| 1 543,700 140 8 | 0,000 1 | 194 203,815 94 | 0,01 | P(29) |
| 1 542,972 171 8 | 0,000 1 | 194 295,440 63 | 0,01 | P(28) |
| 1 542,250 705 0 | 0,000 1 | 194 386,332 28 | 0,01 | P(27) |
| 1 541,535 739 1 | 0,000 1 | 194 476,488 86 | 0,01 | P(26) |
| 1 540,827 258 5 | 0,000 1 | 194 565,910 19 | 0,01 | P(25) |
| 1 540,125 271 0 | 0,000 1 | 194 654,593 13 | 0,01 | P(24) |
| 1 539,429 767 3 | 0,000 1 | 194 742,536 72 | 0,01 | P(23) |
| 1 538,740 743 0 | 0,000 1 | 194 829,739 42 | 0,01 | P(22) |
| 1 538,058 193 5 | 0,000 1 | 194 916,199 70 | 0,01 | P(21) |
| 1 537,382 114 2 | 0,000 1 | 195 001,916 07 | 0,01 | P(20) |
| 1 536,712 500 3 | 0,000 1 | 195 086,887 07 | 0,01 | P(19) |
| 1 536,049 347 4 | 0,000 1 | 195 171,111 21 | 0,01 | P(18) |
| 1 535,392 650 7 | 0,000 1 | 195 254,587 07 | 0,01 | P(17) |
| 1 534,742 405 7 | 0,000 1 | 195 337,313 21 | 0,01 | P(16) |
| 1 534,098 607 7 | 0,000 1 | 195 419,288 24 | 0,01 | P(15) |
| 1 533,461 252 1 | 0,000 1 | 195 500,511 75 | 0,01 | P(14) |

| **Wavelength** nm | **Uncertainty** pm | **Frequency** GHz | **Uncertainty** MHz | **Transition** |
|---|---|---|---|---|
| 1 532,830 334 3 | 0,000 1 | 195 580,979 37 | 0,01 | P(13) |
| 1 532,205 849 8 | 0,000 1 | 195 660,692 74 | 0,01 | P(12) |
| 1 531,587 793 9 | 0,000 1 | 195 739,649 52 | 0,01 | P(11) |
| 1 530,976 162 2 | 0,000 1 | 195 817,848 38 | 0,01 | P(10) |
| 1 530,370 950 0 | 0,000 1 | 195 895,288 00 | 0,01 | P(9) |
| 1 529,772 152 9 | 0,000 1 | 195 971,967 08 | 0,01 | P(8) |
| 1 529,179 766 4 | 0,000 1 | 196 047,884 35 | 0,01 | P(7) |
| 1 528,593 786 1 | 0,000 1 | 196 123,038 52 | 0,01 | P(6) |
| 1 528,014 207 6 | 0,000 1 | 196 197,428 35 | 0,01 | P(5) |
| 1 527,441 026 4 | 0,000 1 | 196 271,052 58 | 0,01 | P(4) |
| 1 526,874 238 2 | 0,000 1 | 196 343,910 00 | 0,01 | P(3) |
| 1 526,313 838 6 | 0,000 1 | 196 415,999 39 | 0,01 | P(2) |
| 1 525,759 823 4 | 0,000 1 | 196 487,319 56 | 0,01 | P(1) |
| 1 524,670 929 2 | 0,000 1 | 196 627,647 48 | 0,01 | R(0) |
| 1 524,136 041 7 | 0,000 1 | 196 696,652 92 | 0,01 | R(1) |
| 1 523,607 521 8 | 0,000 1 | 196 764,884 47 | 0,01 | R(2) |
| 1 523,085 365 3 | 0,000 1 | 196 832,341 01 | 0,01 | R(3) |
| 1 522,569 568 0 | 0,000 1 | 196 899,021 43 | 0,01 | R(4) |
| 1 522,060 126 0 | 0,000 1 | 196 964,925 63 | 0,01 | R(5) |
| 1 521,557 035 3 | 0,000 1 | 197 030,049 52 | 0,01 | R(6) |
| 1 521,060 291 7 | 0,000 1 | 197 094,395 03 | 0,01 | R(7) |
| 1 520,569 891 4 | 0,000 1 | 197 157,960 12 | 0,01 | R(8) |
| 1 520,085 830 3 | 0,000 1 | 197 220,743 74 | 0,01 | R(9) |
| 1 519,608 104 7 | 0,000 1 | 197 282,744 86 | 0,01 | R(10) |
| 1 519,136 710 5 | 0,000 1 | 197 343,962 48 | 0,01 | R(11) |
| 1 518,671 643 9 | 0,000 1 | 197 404,395 61 | 0,01 | R(12) |
| 1 518,212 901 0 | 0,000 1 | 197 464,043 28 | 0,01 | R(13) |
| 1 517,760 478 2 | 0,000 1 | 197 522,904 51 | 0,01 | R(14) |
| 1 517,314 371 3 | 0,000 1 | 197 580,978 38 | 0,01 | R(15) |
| 1 516,874 576 8 | 0,000 1 | 197 638,263 95 | 0,01 | R(16) |
| 1 516,441 090 8 | 0,000 1 | 197 694,760 33 | 0,01 | R(17) |
| 1 516,013 909 5 | 0,000 1 | 197 750,466 61 | 0,01 | R(18) |
| 1 515,593 029 1 | 0,000 1 | 197 805,381 94 | 0,01 | R(19) |
| 1 515,178 445 9 | 0,000 1 | 197 859,505 46 | 0,01 | R(20) |
| 1 514,770 156 1 | 0,000 1 | 197 912,836 34 | 0,01 | R(21) |
| 1 514,368 155 8 | 0,000 1 | 197 965,373 77 | 0,01 | R(22) |
| 1 513,972 441 3 | 0,000 1 | 198 017,116 98 | 0,01 | R(23) |
| 1 513,583 013 1 | 0,000 1 | 198 068,064 60 | 0,01 | R(24) |
| 1 513,199 855 5 | 0,000 1 | 198 118,217 44 | 0,01 | R(25) |
| 1 512,822 975 5 | 0,000 1 | 198 167,573 37 | 0,01 | R(26) |
| 1 512,452 366 1 | 0,000 1 | 198 216,132 11 | 0,01 | R(27) |
| 1 512,088 024 1 | 0,000 1 | 198 263,892 86 | 0,01 | R(28) |

| Wavelength nm | Uncertainty pm | Frequency GHz | Uncertainty MHz | Transition |
|---|---|---|---|---|
| 1 511,729 942 5 | 0,000 1 | 198 310,855 39 | 0,01 | R(29) |
| 1 511,378 113 4 | 0,000 1 | 198 357,019 56 | 0,01 | R(30) |
| 1 511,032 608 1 | 0,000 1 | 198 402,374 90 | 0,01 | R(31) |

### E.4.2.3 Acetylene $^{13}C_2H_2$

The $\nu_1 + \nu_3$ band in this isotopomer is weaker than the equivalent band in $^{12}C_2H_2$. The absorptions are shifted to longer wavelengths covering most of the C-band. As part of a more extensive study of $^{13}C_2H_2$ the line strengths, collision-broadening parameters, and pressure shifts have been determined [19]. A list of centre vacuum wavelengths for the $\nu_1+\nu_3$ and $\nu_1+\nu_2+\nu_4+\nu_5$ combination bands is shown in Table E.3, along with their associated frequency values [14], [20]. Heterodyne measured frequencies can be found in [13], [14], [15], [16], [17].

**Table E.3 – Frequency and vacuum wavelength values for the $\nu_1 + \nu_3$ and $\nu_1 + \nu_2 + \nu_4 + \nu_5$ bands of $^{13}C_2H_2$**

| Wavelength nm | Uncertainty pm | Frequency GHz | Uncertainty MHz | Band | Transition |
|---|---|---|---|---|---|
| 1 516,585 0 | 0,2 | 197 676,001 | 24 | $\nu_1 + \nu_3$ | R(40) |
| 1 516,876 2 | 0,2 | 197 638,053 | 24 | $\nu_1 + \nu_3$ | R(39) |
| 1 517,173 5 | 0,2 | 197 599,324 | 24 | $\nu_1 + \nu_3$ | R(38) |
| 1 517,476 9 | 0,2 | 197 559,817 | 24 | $\nu_1 + \nu_3$ | R(37) |
| 1 517,785 4 | 0,2 | 197 519,661 | 24 | $\nu_1 + \nu_3$ | R(36) |
| 1 518,094 5 | 0,2 | 197 479,444 | 24 | $\nu_1 + \nu_3$ | R(35) |
| 1 518,343 9 | 0,2 | 197 447,007 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(25) |
| 1 518,420 4 | 0,2 | 197 437,059 | 24 | $\nu_1 + \nu_3$ | R(34) |
| 1 518,725 9 | 0,2 | 197 397,343 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(24) |
| 1 518,746 9 | 0,2 | 197 394,614 | 24 | $\nu_1 + \nu_3$ | R(33) |
| 1 519,078 8 | 0,2 | 197 351,486 | 24 | $\nu_1 + \nu_3$ | R(32) |
| 1 519,114 7 | 0,2 | 197 346,822 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(23) |
| 1 519,416 9 | 0,2 | 197 307,571 | 24 | $\nu_1 + \nu_3$ | R(31) |
| 1 519,510 0 | 0,2 | 197 295,482 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(22) |
| 1 519,760 8 | 0,2 | 197 262,923 | 24 | $\nu_1 + \nu_3$ | R(30) |
| 1 519,911 9 | 0,2 | 197 243,313 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(21) |
| 1 520,110 578 4 | 0,000 1 | 197 217,532 90 | 0,01 | $\nu_1 + \nu_3$ | R(29) |
| 1 520,320 082 9 | 0,000 1 | 197 190,355 74 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(20) |
| 1 520,466 234 1 | 0,000 1 | 197 171,401 29 | 0,01 | $\nu_1 + \nu_3$ | R(28) |
| 1 520,734 712 9 | 0,000 1 | 197 136,591 58 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(19) |
| 1 520,827 966 9 | 0,000 1 | 197 124,503 57 | 0,01 | $\nu_1 + \nu_3$ | R(27) |
| 1 521,155 617 0 | 0,000 1 | 197 082,043 84 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(18) |
| 1 521,194 963 4 | 0,000 1 | 197 076,946 23 | 0,01 | $\nu_1 + \nu_3$ | R(26) |
| 1 521,568 164 3 | 0,000 1 | 197 028,608 40 | 0,01 | $\nu_1 + \nu_3$ | R(25) |
| 1 521,582 677 4 | 0,000 1 | 197 026,729 11 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(17) |
| 1 521,947 174 3 | 0,000 1 | 196 979,542 43 | 0,01 | $\nu_1 + \nu_3$ | R(24) |

| **Wavelength** nm | **Uncertainty** pm | **Frequency** GHz | **Uncertainty** MHz | **Band** | **Transition** |
|---|---|---|---|---|---|
| 1 522,015 774 4 | 0,000 1 | 196 970,664 19 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(16) |
| 1 522,332 022 1 | 0,000 1 | 196 929,745 71 | 0,01 | $\nu_1 + \nu_3$ | R(23) |
| 1 522,454 783 6 | 0,000 1 | 196 913,866 49 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(15) |
| 1 522,722 619 1 | 0,000 1 | 196 879,230 82 | 0,01 | $\nu_1 + \nu_3$ | R(22) |
| 1 522,899 578 5 | 0,000 1 | 196 856,353 65 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(14) |
| 1 523,119 058 2 | 0,000 1 | 196 827,986 88 | 0,01 | $\nu_1 + \nu_3$ | R(21) |
| 1 523,350 033 4 | 0,000 1 | 196 798,143 19 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(13) |
| 1 523,521 287 8 | 0,000 1 | 196 776,021 71 | 0,01 | $\nu_1 + \nu_3$ | R(20) |
| 1 523,806 024 9 | 0,000 1 | 196 739,252 31 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(12) |
| 1 523,929 301 4 | 0,000 1 | 196 723,337 31 | 0,01 | $\nu_1 + \nu_3$ | R(19) |
| 1 524,267 433 9 | 0,000 1 | 196 679,697 62 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(11) |
| 1 524,343 090 6 | 0,000 1 | 196 669,935 95 | 0,01 | $\nu_1 + \nu_3$ | R(18) |
| 1 524,734 147 1 | 0,000 1 | 196 619,495 00 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(10) |
| 1 524,762 647 1 | 0,000 1 | 196 615,819 89 | 0,01 | $\nu_1 + \nu_3$ | R(17) |
| 1 525,187 962 9 | 0,000 1 | 196 560,991 36 | 0,01 | $\nu_1 + \nu_3$ | R(16) |
| 1 525,206 057 5 | 0,000 1 | 196 558,659 43 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(9) |
| 1 525,619 030 8 | 0,000 1 | 196 505,452 50 | 0,01 | $\nu_1 + \nu_3$ | R(15) |
| 1 525,683 065 9 | 0,000 1 | 196 497,204 89 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(8) |
| 1 526,055 846 8 | 0,000 1 | 196 449,205 07 | 0,01 | $\nu_1 + \nu_3$ | R(14) |
| 1 526,165 081 3 | 0,000 1 | 196 435,144 32 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(7) |
| 1 526,498 389 1 | 0,000 1 | 196 392,253 10 | 0,01 | $\nu_1 + \nu_3$ | R(13) |
| 1 526,652 021 4 | 0,000 1 | 196 372,489 47 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(6) |
| 1 526,946 677 3 | 0,000 1 | 196 334,595 35 | 0,01 | $\nu_1 + \nu_3$ | R(12) |
| 1 527,143 812 8 | 0,000 1 | 196 309,250 96 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(5) |
| 1 527,400 694 4 | 0,000 1 | 196 276,235 24 | 0,01 | $\nu_1 + \nu_3$ | R(11) |
| 1 527,640 391 3 | 0,000 1 | 196 245,438 20 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(4) |
| 1 527,860 439 3 | 0,000 1 | 196 217,174 21 | 0,01 | $\nu_1 + \nu_3$ | R(10) |
| 1 528,141 702 0 | 0,000 1 | 196 181,059 39 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(3) |
| 1 528,325 910 4 | 0,000 1 | 196 157,413 78 | 0,01 | $\nu_1 + \nu_3$ | R(9) |
| 1 528,647 699 3 | 0,000 1 | 196 116,121 55 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(2) |
| 1 528,797 149 3 | 0,000 1 | 196 096,949 90 | 0,01 | $\nu_1 + \nu_3$ | R(8) |
| 1 529,158 346 9 | 0,000 1 | 196 050,630 48 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(1) |
| 1 529,274 006 2 | 0,000 1 | 196 035,803 12 | 0,01 | $\nu_1 + \nu_3$ | R(7) |
| 1 529,673 617 7 | 0,000 1 | 195 984,590 79 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(0) |
| 1 529,756 623 4 | 0,000 1 | 195 973,956 52 | 0,01 | $\nu_1 + \nu_3$ | R(6) |
| 1 530,244 927 1 | 0,000 1 | 195 911,420 90 | 0,01 | $\nu_1 + \nu_3$ | R(5) |
| 1 530,717 967 2 | 0,000 1 | 195 850,878 11 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(1) |
| 1 530,738 886 5 | 0,000 1 | 195 848,201 58 | 0,01 | $\nu_1 + \nu_3$ | R(4) |
| 1 531,238 454 0 | 0,000 1 | 195 784,305 97 | 0,01 | $\nu_1 + \nu_3$ | R(3) |
| 1 531,247 038 0 | 0,000 1 | 195 783,208 43 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(2) |
| 1 531,743 566 1 | 0,000 1 | 195 719,743 58 | 0,01 | $\nu_1 + \nu_3$ | R(2) |
| 1 531,780 716 6 | 0,000 1 | 195 714,996 77 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(3) |

| **Wavelength** nm | **Uncertainty** pm | **Frequency** GHz | **Uncertainty** MHz | **Band** | **Transition** |
|---|---|---|---|---|---|
| 1 532,254 147 4 | 0,000 1 | 195 654,525 40 | 0,01 | $\nu_1 + \nu_3$ | R(1) |
| 1 532,319 022 2 | 0,000 1 | 195 646,241 85 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(4) |
| 1 532,770 121 5 | 0,000 1 | 195 588,662 51 | 0,01 | $\nu_1 + \nu_3$ | R(0) |
| 1 532,861 983 5 | 0,000 1 | 195 576,941 19 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(5) |
| 1 533,409 638 9 | 0,000 1 | 195 507,091 12 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(6) |
| 1 533,818 025 0 | 0,000 1 | 195 455,036 46 | 0,01 | $\nu_1 + \nu_3$ | P(1) |
| 1 533,962 036 2 | 0,000 1 | 195 436,686 78 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(7) |
| 1 534,349 921 7 | 0,000 1 | 195 387,280 14 | 0,01 | $\nu_1 + \nu_3$ | P(2) |
| 1 534,519 232 9 | 0,000 1 | 195 365,722 10 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(8) |
| 1 534,887 155 1 | 0,000 1 | 195 318,891 69 | 0,01 | $\nu_1 + \nu_3$ | P(3) |
| 1 535,081 296 2 | 0,000 1 | 195 294,189 79 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(9) |
| 1 535,429 792 6 | 0,000 1 | 195 249,863 88 | 0,01 | $\nu_1 + \nu_3$ | P(4) |
| 1 535,648 302 9 | 0,000 1 | 195 222,081 41 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(10) |
| 1 535,977 915 7 | 0,000 1 | 195 180,187 77 | 0,01 | $\nu_1 + \nu_3$ | P(5) |
| 1 536,220 339 4 | 0,000 1 | 195 149,387 30 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(11) |
| 1 536,531 605 6 | 0,000 1 | 195 109,854 50 | 0,01 | $\nu_1 + \nu_3$ | P(6) |
| 1 536,797 501 5 | 0,000 1 | 195 076,096 69 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(12) |
| 1 537,090 931 7 | 0,000 1 | 195 038,856 72 | 0,01 | $\nu_1 + \nu_3$ | P(7) |
| 1 537,379 893 5 | 0,000 1 | 195 002,197 74 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(13) |
| 1 537,655 947 7 | 0,000 1 | 194 967,189 15 | 0,01 | $\nu_1 + \nu_3$ | P(8) |
| 1 537,967 628 4 | 0,000 1 | 194 927,677 58 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(14) |
| 1 538,226 690 7 | 0,000 1 | 194 894,848 60 | 0,01 | $\nu_1 + \nu_3$ | P(9) |
| 1 538,560 826 3 | 0,000 1 | 194 852,522 48 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(15) |
| 1 538,803 241 5 | 0,000 1 | 194 821,826 42 | 0,01 | $\nu_1 + \nu_3$ | P(10) |
| 1 539,159 613 8 | 0,000 1 | 194 776,717 97 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(16) |
| 1 539,385 461 9 | 0,000 1 | 194 748,141 66 | 0,01 | $\nu_1 + \nu_3$ | P(11) |
| 1 539,764 122 4 | 0,000 1 | 194 700,248 98 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(17) |
| 1 539,973 510 0 | 0,000 1 | 194 673,775 91 | 0,01 | $\nu_1 + \nu_3$ | P(12) |
| 1 540,374 487 0 | 0,000 1 | 194 623,100 11 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(18) |
| 1 540,567 349 8 | 0,000 1 | 194 598,735 35 | 0,01 | $\nu_1 + \nu_3$ | P(13) |
| 1 540,990 843 8 | 0,000 1 | 194 545,255 87 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(19) |
| 1 541,166 989 1 | 0,000 1 | 194 523,020 61 | 0,01 | $\nu_1 + \nu_3$ | P(14) |
| 1 541,613 327 6 | 0,000 1 | 194 466,700 98 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(20) |
| 1 541,772 435 5 | 0,000 1 | 194 446,632 39 | 0,01 | $\nu_1 + \nu_3$ | P(15) |
| 1 542,242 069 1 | 0,000 1 | 194 387,420 76 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(21) |
| 1 542,383 712 4 | 0,000 1 | 194 369,569 39 | 0,01 | $\nu_1 + \nu_3$ | P(16) |
| 1 542,877 197 8 | 0,000 1 | 194 307,400 77 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(22) |
| 1 543,000 806 1 | 0,000 1 | 194 291,834 99 | 0,01 | $\nu_1 + \nu_3$ | P(17) |
| 1 543,518 7 | 0,2 | 194 226,645 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(23) |
| 1 543,623 745 3 | 0,000 1 | 194 213,427 28 | 0,01 | $\nu_1 + \nu_3$ | P(18) |
| 1 544,166 9 | 0,2 | 194 145,114 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(24) |
| 1 544,252 540 4 | 0,000 1 | 194 134,346 65 | 0,01 | $\nu_1 + \nu_3$ | P(19) |

| Wavelength nm | Uncertainty pm | Frequency GHz | Uncertainty MHz | Band | Transition |
|---|---|---|---|---|---|
| 1 544,823 2 | 0,2 | 194 062,633 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(25) |
| 1 544,887 205 3 | 0,000 1 | 194 054,593 10 | 0,01 | $\nu_1 + \nu_3$ | P(20) |
| 1 545,527 754 6 | 0,000 1 | 193 974,166 50 | 0,01 | $\nu_1 + \nu_3$ | P(21) |
| 1 546,174 203 4 | 0,000 1 | 193 893,066 73 | 0,01 | $\nu_1 + \nu_3$ | P(22) |
| 1 546,826 566 9 | 0,000 1 | 193 811,293 67 | 0,01 | $\nu_1 + \nu_3$ | P(23) |
| 1 547,484 858 3 | 0,000 1 | 193 728,847 42 | 0,01 | $\nu_1 + \nu_3$ | P(24) |
| 1 548,149 137 7 | 0,000 1 | 193 645,722 30 | 0,01 | $\nu_1 + \nu_3$ | P(25) |
| 1 548,819 315 7 | 0,000 1 | 193 561,931 32 | 0,01 | $\nu_1 + \nu_3$ | P(26) |
| 1 549,495 490 6 | 0,000 1 | 193 477,464 00 | 0,01 | $\nu_1 + \nu_3$ | P(27) |
| 1 550,177 639 4 | 0,000 1 | 193 392,325 10 | 0,01 | $\nu_1 + \nu_3$ | P(28) |
| 1 550,866 180 1 | 0,000 1 | 193 306,464 37 | 0,01 | $\nu_1 + \nu_3$ | P(29) |
| 1 551,560 141 4 | 0,000 1 | 193 220,004 82 | 0,01 | $\nu_1 + \nu_3$ | P(30) |
| 1 552,260 375 9 | 0,000 1 | 193 132,842 06 | 0,01 | $\nu_1 + \nu_3$ | P(31) |
| 1 552,966 8 | 0,2 | 193 044,989 | 24 | $\nu_1 + \nu_3$ | P(32) |
| 1 553,678 6 | 0,2 | 192 956,547 | 24 | $\nu_1 + \nu_3$ | P(33) |
| 1 554,397 5 | 0,2 | 192 867,306 | 24 | $\nu_1 + \nu_3$ | P(34) |
| 1 555,122 1 | 0,2 | 192 777,440 | 24 | $\nu_1 + \nu_3$ | P(35) |
| 1 555,853 3 | 0,2 | 192 686,841 | 24 | $\nu_1 + \nu_3$ | P(36) |
| 1 556,589 4 | 0,2 | 192 595,721 | 24 | $\nu_1 + \nu_3$ | P(37) |
| 1 557,332 1 | 0,2 | 192 503,871 | 24 | $\nu_1 + \nu_3$ | P(38) |
| 1 558,082 0 | 0,2 | 192 411,220 | 24 | $\nu_1 + \nu_3$ | P(39) |
| 1 558,836 9 | 0,2 | 192 318,041 | 24 | $\nu_1 + \nu_3$ | P(40) |

### E.4.3 HCN

HCN is a strong absorber in the C band. Although this molecule is toxic, the quantity contained in a well-designed gas cell is below the toxic limit.

The $2\nu_1$ overtone band of the $H^{12}C^{14}N$ (1,52 µm to 1,55 µm) and $H^{13}C^{14}N$ (1,53 µm to 1,56 µm) isotopomers has been studied [21] and pressure shift values have been measured [22]. The vacuum wavelength values reported in Reference [23] are listed in Table E.4.

**Table E.4 – List of H$^{13}$CN transitions**

| Wavelength nm | Uncertainty pm | Frequency GHz | Uncertainty MHz | Transition |
|---|---|---|---|---|
| 1 527,221 633 | 0,025 | 196 299,247 9 | 3,2 | R(27) |
| 1 527,633 273 | 0,018 | 196 246,352 6 | 2,3 | R(26) |
| 1 528,054 581 | 0,013 | 196 192,244 5 | 1,6 | R(25) |
| 1 528,485 564 | 0,010 | 196 136,924 7 | 1,3 | R(24) |
| 1 528,926 231 | 0,009 | 196 080,394 1 | 1,1 | R(23) |
| 1 529,376 588 | 0,008 | 196 022,654 2 | 1,0 | R(22) |
| 1 529,836 645 | 0,008 | 195 963,705 7 | 1,0 | R(21) |
| 1 530,306 408 | 0,008 | 195 903,550 1 | 1,0 | R(20) |

| **Wavelength** nm | **Uncertainty** pm | **Frequency** GHz | **Uncertainty** MHz | **Transition** |
|---|---|---|---|---|
| 1 530,785 886 | 0,008 | 195 842,188 5 | 1,0 | R(19) |
| 1 531,275 088 | 0,008 | 195 779,622 1 | 1,0 | R(18) |
| 1 531,774 020 | 0,008 | 195 715,852 4 | 1,0 | R(17) |
| 1 532,282 693 | 0,008 | 195 650,880 5 | 1,0 | R(16) |
| 1 532,801 112 | 0,008 | 195 584,708 1 | 1,0 | R(15) |
| 1 533,329 289 | 0,008 | 195 517,336 1 | 1,0 | R(14) |
| 1 533,867 229 | 0,008 | 195 448,766 6 | 1,0 | R(13) |
| 1 534,414 943 | 0,008 | 195 379,000 6 | 1,0 | R(12) |
| 1 534,972 439 | 0,008 | 195 308,039 7 | 1,0 | R(11) |
| 1 535,539 724 | 0,008 | 195 235,885 7 | 1,0 | R(10) |
| 1 536,116 810 | 0,008 | 195 162,539 8 | 1,0 | R(9) |
| 1 536,703 703 | 0,008 | 195 088,003 9 | 1,0 | R(8) |
| 1 537,300 413 | 0,008 | 195 012,279 6 | 1,0 | R(7) |
| 1 537,906 949 | 0,008 | 194 935,368 6 | 1,0 | R(6) |
| 1 538,523 321 | 0,008 | 194 857,272 5 | 1,0 | R(5) |
| 1 539,149 536 | 0,008 | 194 777,993 3 | 1,0 | R(4) |
| 1 539,785 605 | 0,008 | 194 697,532 6 | 1,0 | R(3) |
| 1 540,431 537 | 0,008 | 194 615,892 2 | 1,0 | R(2) |
| 1 541,087 341 | 0,008 | 194 533,074 2 | 1,0 | R(1) |
| 1 541,753 028 | 0,008 | 194 449,080 1 | 1,0 | R(0) |
| 1 543,114 084 | 0,008 | 194 277,572 3 | 1,0 | P(1) |
| 1 543,809 47 | 0,008 | 194 190,062 3 | 1,0 | P(2) |
| 1 544,514 78 | 0,008 | 194 101,384 5 | 1,0 | P(3) |
| 1 545,230 03 | 0,008 | 194 011,540 8 | 1,0 | P(4) |
| 1 545,955 21 | 0,008 | 193 920,533 0 | 1,0 | P(5) |
| 1 546,690 34 | 0,008 | 193 828,363 7 | 1,0 | P(6) |
| 1 547,435 44 | 0,008 | 193 735,034 9 | 1,0 | P(7) |
| 1 548,190 50 | 0,008 | 193 640,548 8 | 1,0 | P(8) |
| 1 548,955 55 | 0,008 | 193 544,907 3 | 1,0 | P(9) |
| 1 549,730 59 | 0,008 | 193 448,113 2 | 1,0 | P(10) |
| 1 550,515 63 | 0,008 | 193 350,168 4 | 1,0 | P(11) |
| 1 551,310 69 | 0,008 | 193 251,075 3 | 1,0 | P(12) |
| 1 552,115 77 | 0,008 | 193 150,836 3 | 1,0 | P(13) |
| 1 552,930 88 | 0,008 | 193 049,453 8 | 1,0 | P(14) |
| 1 553,756 04 | 0,008 | 192 946,930 2 | 1,0 | P(15) |
| 1 554,591 26 | 0,008 | 192 843,268 0 | 1,0 | P(16) |
| 1 555,436 54 | 0,008 | 192 738,469 5 | 1,0 | P(17) |
| 1 556,291 90 | 0,008 | 192 632,537 5 | 1,0 | P(18) |
| 1 557,157 35 | 0,008 | 192 525,474 3 | 1,0 | P(19) |
| 1 558,032 91 | 0,008 | 192 417,282 7 | 1,0 | P(20) |
| 1 558,918 57 | 0,008 | 192 307,965 3 | 1,0 | P(21) |

| Wavelength<br>nm | Uncertainty<br>pm | Frequency<br>GHz | Uncertainty<br>MHz | Transition |
|---|---|---|---|---|
| 1 559,814 36 | 0,008 | 192 197,524 6 | 1,0 | P(22) |
| 1 560,720 28 | 0,008 | 192 085,963 3 | 1,0 | P(23) |
| 1 561,636 35 | 0,009 | 191 973,284 3 | 1,1 | P(24) |
| 1 562,562 57 | 0,010 | 191 859,490 3 | 1,2 | P(25) |
| 1 563,498 96 | 0,013 | 191 744,584 0 | 1,6 | P(26) |
| 1 564,445 53 | 0,018 | 191 628,568 4 | 2,2 | P(27) |
| 1 565,402 30 | 0,025 | 191 511,446 2 | 3,1 | P(28) |

### E.4.4 CO

This diatomic molecule has a 0→3 CO overtone band in the L-band. The molecule has a regular spectrum for which the lines are easy to identify [24], [25]. ]The line-strength, pressure shift and pressure broadening characteristics of a number of lines have been measured [26], [27], [28], [29]. The transitions for $^{12}C^{16}O$ are given in Table E.5.

**Table E.5 – List of $^{12}C^{16}O$ transitions**

| Wavelength<br>nm | Uncertainty<br>pm | Frequency<br>GHz | Uncertainty<br>MHz | Transition |
|---|---|---|---|---|
| 1 559,562 335 | 0,004 | 192 228,583 | 0,5 | R(24) |
| 1 559,848 373 | 0,004 | 192 193,333 | 0,5 | R(23) |
| 1 560,160 931 | 0,004 | 192 154,830 | 0,5 | R(22) |
| 1 560,500 006 | 0,003 | 192 113,077 | 0,4 | R(21) |
| 1 560,865 596 | 0,003 | 192 068,080 | 0,4 | R(20) |
| 1 561,257 704 | 0,003 | 192 019,842 | 0,4 | R(19) |
| 1 561,676 332 | 0,003 | 191 968,369 | 0,4 | R(18) |
| 1 562,121 489 | 0,003 | 191 913,664 | 0,4 | R(17) |
| 1 562,593 183 | 0,003 | 191 855,731 | 0,4 | R(16) |
| 1 563,091 427 | 0,003 | 191 794,576 | 0,4 | R(15) |
| 1 563,616 236 | 0,003 | 191 730,203 | 0,4 | R(14) |
| 1 564,167 627 | 0,003 | 191 662,615 | 0,4 | R(13) |
| 1 564,745 620 | 0,003 | 191 591,818 | 0,4 | R(12) |
| 1 565,350 239 | 0,003 | 191 517,815 | 0,4 | R(11) |
| 1 565,981 507 | 0,003 | 191 440,612 | 0,4 | R(10) |
| 1 566,639 453 | 0,003 | 191 360,212 | 0,4 | R(9) |
| 1 567,324 108 | 0,003 | 191 276,620 | 0,4 | R(8) |
| 1 568,035 506 | 0,003 | 191 189,840 | 0,4 | R(7) |
| 1 568,773 681 | 0,003 | 191 099,877 | 0,4 | R(6) |
| 1 569,538 673 | 0,003 | 191 006,735 | 0,4 | R(5) |
| 1 570,330 523 | 0,003 | 190 910,419 | 0,4 | R(4) |
| 1 571,149 275 | 0,003 | 190 810,932 | 0,4 | R(3) |
| 1 571,994 976 | 0,003 | 190 708,280 | 0,4 | R(2) |
| 1 572,867 675 | 0,003 | 190 602,466 | 0,4 | R(1) |
| 1 573,767 423 | 0,003 | 190 493,496 | 0,4 | R(0) |

## E.5 Excited state transitions

In an optogalvanic transition, the discharge voltage will vary proportionally with the optical intensity as the laser is tuned through the transition frequency. Table E.6 shows the wavelength of reported transitions covering the wavelength range 1 240 nm - 1 600 nm [30], [31]. The transitions for which Doppler-free (saturated) frequency measurements have been made are shown in bold [32], [33].

**Table E.6 – Excited state optogalvanic transitions**

| Element | Wavelength nm | Uncertainty pm | Element | Wavelength nm | Uncertainty pm |
|---|---|---|---|---|---|
| Ar | 1 249,111 | 2 | Kr | 1 501,914 | 2 |
| Ar | 1 270,581 | 2 | Ar | 1 505,064 | 2 |
| Ar | 1 273,696 | 2 | Ar | 1 517,694 | 2 |
| Ar | 1 274,977 | 2 | Kr | 1 521,376 | 2 |
| Ar | 1 280,629 | 2 | Ne | 1 523,448 8 | 2 |
| Kr | 1 286,541 | 2 | Kr | 1 524,380 | 2 |
| Ne | 1 291,555 | 2 | Kr | 1 533,065 | 2 |
| Ar | 1 293,675 | 2 | Ar | 1 533,350 | 2 |
| Ar | 1 296,025 | 2 | **Kr** | **1 533,915** | **2** |
| Kr | 1 298,886 | 2 | **Kr** | **1 537,625** | **2** |
| Ar | 1 301,118 | 2 | **Kr** | **1 543,795** | **2** |
| Kr | 1 318,104 | 2 | **Kr** | **1 547,825 99** | **0,20** |
| Kr | 1 473,841 | 2 | **Kr** | **1 563,978** | **2** |
| Kr | 1 476,666 | 2 | **Kr** | **1 568,530 81** | **0,36** |
| Kr | 1 476,954 | 2 | **Kr** | **1 582,441 37** | **0,36** |
| Kr | 1 496,597 | 2 | **Ar** | **1 599,385 78** | **0,36** |
| Kr | 1 500,943 | 2 | | | |

NOTE Values shown in bold can be saturated.

# Annex F
(informative)

# Reference locked laser example

## F.1 General

There are many ways to lock a tunable laser to a natural reference. This annex outlines two systems and a diagnostic approach if difficulties are encountered.

## F.2 Laser sources

The main single frequency laser sources are distributed feedback lasers (DFB), external cavity (EC) lasers, fibre Bragg reflector lasers (FB) and single-mode fibre lasers (SMF).

DFB lasers have broadband modulation characteristics and can be tuned by varying the laser current and temperature. The tuning characteristics will depend on the laser design; typical values are 10 GHz/°C (0,1 nm/°C) and 750 MHz/mA (0,01 nm/mA). Modulation of the laser current gives rise to correlated frequency and amplitude modulation.

Because of the broad bandwidth it is important to ensure that a low noise laser current supply is used.

Typically, a DFB laser can be thermally tuned over 1 nm to 2 nm and will have a linewidth in the 0,1 MHz to 10 MHz range.

The modulation characteristics of EC lasers are determined by the mechanical design. Typically, the achievable modulation frequencies are < 500 Hz. Typically, an EC laser can be tuned over 100 nm and will have a linewidth of 50 kHz.

Because these EC lasers are mechanically tuned, they are vibration sensitive.

A typical SMF laser will have a linewidth of a few kHz or less.

## F.3 Gas cell example

The length of the optical path in the gas will depend on the absorption strength of the line and the gas pressure. Compact, packaged reference gas cells for many of the gases listed in Annex E are commercially available. For weakly absorbing gases, such as carbon monoxide, multi-path absorption cells can be used. A typical measurement layout that includes lock-quality monitoring is shown in Figure F.1.

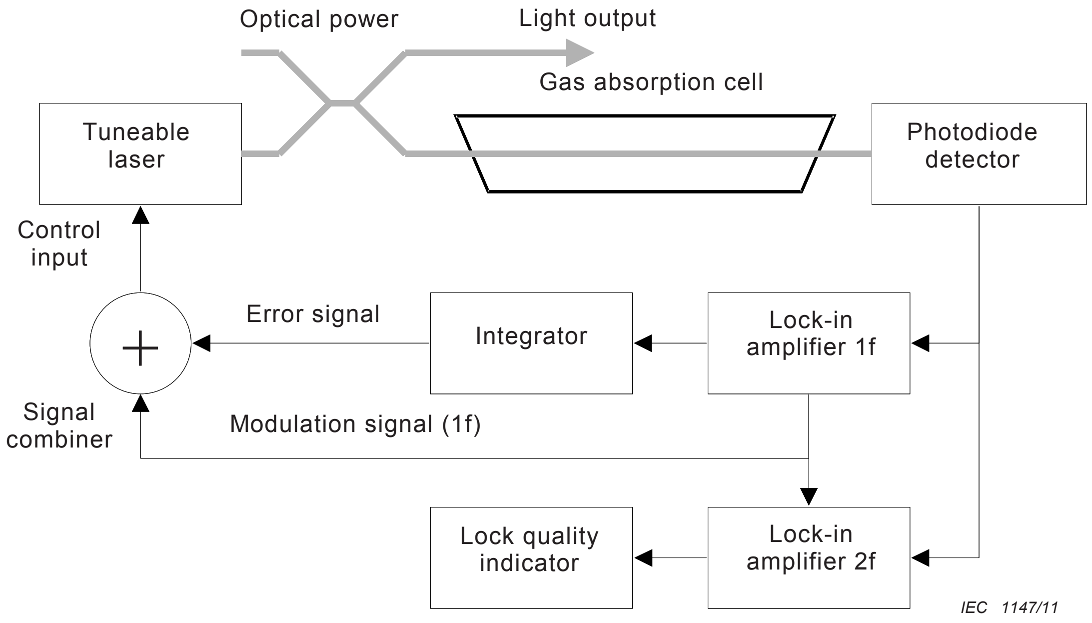


Figure F.1 – Typical measurement arrangement to lock laser to gas absorption line

# Annex G
(informative)

# Balance between accuracy and calibration time

## G.1 General

This annex provides additional supporting guidance, in addition to the information provided in 4.3, designed to help the user of this standard choose the appropriate systems to realise different calibration accuracies.

## G.2 Reference sources

Different natural reference sources will affect the achievable calibration accuracy. Reference sources with a higher natural accuracy can be used to provide lower accuracy calibrations and so the choice of optical reference must be fit for purpose.

Commercial reference source implementations offer considerable convenience and will have specified uncertainties. An example of this would be a sub-system containing a diode laser and power supply and control electronics, locked to a linear absorption in an acetylene or similar reference material. These instruments can be calibrated against higher accuracy reference sources.

Typically, the accuracy that can be achieved for a good implementation of a laser locked to a low-pressure absorption feature is in the range between 1 % and 10 % of the Doppler broadened linewidth. An acetylene absorption line would have a linewidth of about 450 MHz, so the achievable accuracy of a locked reference would be in the range ±5 MHz to ±50 MHz (±40 fm to ±400 fm).

As stated in Annex E, the line-centre and linewidth will vary with gas pressure. This contributes to the limiting uncertainty achievable.

## G.3 Instrument resolution

Wavelength meter designs based on the Michelson interferometer count the number of interference fringes for the unknown and internal reference wavelengths. A correction is applied to compensate for the refractive index of the air. Depending on the instrument design, some degree of fringe sub-division will be used to enhance the instrument resolution. The resolution will ultimately be set by the size of the number counted.

### G.3.1 Optional measurements

The use of manufacturer-supplied values for the optional parameters allows a decision to be taken to trade calibration effort against accuracy of the results. Calibrations that use the manufacturer-supplied values are likely to have a lower accuracy but the calibration can be completed more quickly.

### G.3.2 Summary of choices

A range of typical choices are presented in Table G.1 to achieve different calibration accuracies.

**Table G.1 – Summary of choices**

| Fractional uncertainty | Reference | Measurement requirements |
|---|---|---|
| $10^{-9}$ | Saturated reference standard | Very difficult to obtain this uncertainty using a wavelength meter. Consult manufacturer about system limitations. Refractive index models may become inaccurate. Consider using other instrumentation such as direct frequency measurement |
| $10^{-8}$ | Saturated reference standard or very careful implementation of unsaturated, locked transition of known pressure, isotope material. | Refractive index corrections include humidity and $CO_2$ concentration |
| $10^{-7}$ | Unsaturated locked transition (molecular or excited state) | Simpler refractive index corrections can be used. Some manufacturers' parameters can be used |
| $10^{-6}$ | Unstabilized gas lasers | Simple measurements, use optional manufacturers' parameters to reduce time |

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**Tableau E.3 – Valeurs de fréquence et de longueur d'onde dans le vide pour les bandes $\nu_1 + \nu_3$ et $\nu_1 + \nu_2 + \nu_4 + \nu_5$ de $^{13}C_2H_2$**

| Longueur d'onde nm | Incertitude pm | Fréquence GHz | Incertitude MHz | Bande | Transition |
|---|---|---|---|---|---|
| 1 516,585 0 | 0,2 | 197 676,001 | 24 | $\nu_1 + \nu_3$ | R(40) |
| 1 516,876 2 | 0,2 | 197 638,053 | 24 | $\nu_1 + \nu_3$ | R(39) |
| 1 517,173 5 | 0,2 | 197 599,324 | 24 | $\nu_1 + \nu_3$ | R(38) |
| 1 517,476 9 | 0,2 | 197 559,817 | 24 | $\nu_1 + \nu_3$ | R(37) |
| 1 517,785 4 | 0,2 | 197 519,661 | 24 | $\nu_1 + \nu_3$ | R(36) |
| 1 518,094 5 | 0,2 | 197 479,444 | 24 | $\nu_1 + \nu_3$ | R(35) |
| 1 518,343 9 | 0,2 | 197 447,007 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(25) |
| 1 518,420 4 | 0,2 | 197 437,059 | 24 | $\nu_1 + \nu_3$ | R(34) |
| 1 518,725 9 | 0,2 | 197 397,343 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(24) |
| 1 518,746 9 | 0,2 | 197 394,614 | 24 | $\nu_1 + \nu_3$ | R(33) |
| 1 519,078 8 | 0,2 | 197 351,486 | 24 | $\nu_1 + \nu_3$ | R(32) |
| 1 519,114 7 | 0,2 | 197 346,822 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(23) |
| 1 519,416 9 | 0,2 | 197 307,571 | 24 | $\nu_1 + \nu_3$ | R(31) |
| 1 519,510 0 | 0,2 | 197 295,482 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(22) |
| 1 519,760 8 | 0,2 | 197 262,923 | 24 | $\nu_1 + \nu_3$ | R(30) |
| 1 519,911 9 | 0,2 | 197 243,313 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(21) |
| 1 520,110 578 4 | 0,000 1 | 197 217,532 90 | 0,01 | $\nu_1 + \nu_3$ | R(29) |
| 1 520,320 082 9 | 0,000 1 | 197 190,355 74 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(20) |
| 1 520,466 234 1 | 0,000 1 | 197 171,401 29 | 0,01 | $\nu_1 + \nu_3$ | R(28) |
| 1 520,734 712 9 | 0,000 1 | 197 136,591 58 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(19) |
| 1 520,827 966 9 | 0,000 1 | 197 124,503 57 | 0,01 | $\nu_1 + \nu_3$ | R(27) |
| 1 521,155 617 0 | 0,000 1 | 197 082,043 84 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(18) |
| 1 521,194 963 4 | 0,000 1 | 197 076,946 23 | 0,01 | $\nu_1 + \nu_3$ | R(26) |
| 1 521,568 164 3 | 0,000 1 | 197 028,608 40 | 0,01 | $\nu_1 + \nu_3$ | R(25) |
| 1 521,582 677 4 | 0,000 1 | 197 026,729 11 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(17) |
| 1 521,947 174 3 | 0,000 1 | 196 979,542 43 | 0,01 | $\nu_1 + \nu_3$ | R(24) |
| 1 522,015 774 4 | 0,000 1 | 196 970,664 19 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(16) |
| 1 522,332 022 1 | 0,000 1 | 196 929,745 71 | 0,01 | $\nu_1 + \nu_3$ | R(23) |
| 1 522,454 783 6 | 0,000 1 | 196 913,866 49 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(15) |
| 1 522,722 619 1 | 0,000 1 | 196 879,230 82 | 0,01 | $\nu_1 + \nu_3$ | R(22) |
| 1 522,899 578 5 | 0,000 1 | 196 856,353 65 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(14) |
| 1 523,119 058 2 | 0,000 1 | 196 827,986 88 | 0,01 | $\nu_1 + \nu_3$ | R(21) |
| 1 523,350 033 4 | 0,000 1 | 196 798,143 19 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(13) |
| 1 523,521 287 8 | 0,000 1 | 196 776,021 71 | 0,01 | $\nu_1 + \nu_3$ | R(20) |
| 1 523,806 024 9 | 0,000 1 | 196 739,252 31 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(12) |
| 1 523,929 301 4 | 0,000 1 | 196 723,337 31 | 0,01 | $\nu_1 + \nu_3$ | R(19) |
| 1 524,267 433 9 | 0,000 1 | 196 679,697 62 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(11) |
| 1 524,343 090 6 | 0,000 1 | 196 669,935 95 | 0,01 | $\nu_1 + \nu_3$ | R(18) |
| 1 524,734 147 1 | 0,000 1 | 196 619,495 00 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(10) |

| **Longueur d'onde** nm | **Incertitude** pm | **Fréquence** GHz | **Incertitude** MHz | **Bande** | **Transition** |
|---|---|---|---|---|---|
| 1 524,762 647 1 | 0,000 1 | 196 615,819 89 | 0,01 | $\nu_1 + \nu_3$ | R(17) |
| 1 525,187 962 9 | 0,000 1 | 196 560,991 36 | 0,01 | $\nu_1 + \nu_3$ | R(16) |
| 1 525,206 057 5 | 0,000 1 | 196 558,659 43 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(9) |
| 1 525,619 030 8 | 0,000 1 | 196 505,452 50 | 0,01 | $\nu_1 + \nu_3$ | R(15) |
| 1 525,683 065 9 | 0,000 1 | 196 497,204 89 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(8) |
| 1 526,055 846 8 | 0,000 1 | 196 449,205 07 | 0,01 | $\nu_1 + \nu_3$ | R(14) |
| 1 526,165 081 3 | 0,000 1 | 196 435,144 32 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(7) |
| 1 526,498 389 1 | 0,000 1 | 196 392,253 10 | 0,01 | $\nu_1 + \nu_3$ | R(13) |
| 1 526,652 021 4 | 0,000 1 | 196 372,489 47 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(6) |
| 1 526,946 677 3 | 0,000 1 | 196 334,595 35 | 0,01 | $\nu_1 + \nu_3$ | R(12) |
| 1 527,143 812 8 | 0,000 1 | 196 309,250 96 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(5) |
| 1 527,400 694 4 | 0,000 1 | 196 276,235 24 | 0,01 | $\nu_1 + \nu_3$ | R(11) |
| 1 527,640 391 3 | 0,000 1 | 196 245,438 20 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(4) |
| 1 527,860 439 3 | 0,000 1 | 196 217,174 21 | 0,01 | $\nu_1 + \nu_3$ | R(10) |
| 1 528,141 702 0 | 0,000 1 | 196 181,059 39 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(3) |
| 1 528,325 910 4 | 0,000 1 | 196 157,413 78 | 0,01 | $\nu_1 + \nu_3$ | R(9) |
| 1 528,647 699 3 | 0,000 1 | 196 116,121 55 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(2) |
| 1 528,797 149 3 | 0,000 1 | 196 096,949 90 | 0,01 | $\nu_1 + \nu_3$ | R(8) |
| 1 529,158 346 9 | 0,000 1 | 196 050,630 48 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(1) |
| 1 529,274 006 2 | 0,000 1 | 196 035,803 12 | 0,01 | $\nu_1 + \nu_3$ | R(7) |
| 1 529,673 617 7 | 0,000 1 | 195 984,590 79 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | R(0) |
| 1 529,756 623 4 | 0,000 1 | 195 973,956 52 | 0,01 | $\nu_1 + \nu_3$ | R(6) |
| 1 530,244 927 1 | 0,000 1 | 195 911,420 90 | 0,01 | $\nu_1 + \nu_3$ | R(5) |
| 1 530,717 967 2 | 0,000 1 | 195 850,878 11 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(1) |
| 1 530,738 886 5 | 0,000 1 | 195 848,201 58 | 0,01 | $\nu_1 + \nu_3$ | R(4) |
| 1 531,238 454 0 | 0,000 1 | 195 784,305 97 | 0,01 | $\nu_1 + \nu_3$ | R(3) |
| 1 531,247 038 0 | 0,000 1 | 195 783,208 43 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(2) |
| 1 531,743 566 1 | 0,000 1 | 195 719,743 58 | 0,01 | $\nu_1 + \nu_3$ | R(2) |
| 1 531,780 716 6 | 0,000 1 | 195 714,996 77 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(3) |
| 1 532,254 147 4 | 0,000 1 | 195 654,525 40 | 0,01 | $\nu_1 + \nu_3$ | R(1) |
| 1 532,319 022 2 | 0,000 1 | 195 646,241 85 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(4) |
| 1 532,770 121 5 | 0,000 1 | 195 588,662 51 | 0,01 | $\nu_1 + \nu_3$ | R(0) |
| 1 532,861 983 5 | 0,000 1 | 195 576,941 19 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(5) |
| 1 533,409 638 9 | 0,000 1 | 195 507,091 12 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(6) |
| 1 533,818 025 0 | 0,000 1 | 195 455,036 46 | 0,01 | $\nu_1 + \nu_3$ | P(1) |
| 1 533,962 036 2 | 0,000 1 | 195 436,686 78 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(7) |
| 1 534,349 921 7 | 0,000 1 | 195 387,280 14 | 0,01 | $\nu_1 + \nu_3$ | P(2) |
| 1 534,519 232 9 | 0,000 1 | 195 365,722 10 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(8) |
| 1 534,887 155 1 | 0,000 1 | 195 318,891 69 | 0,01 | $\nu_1 + \nu_3$ | P(3) |
| 1 535,081 296 2 | 0,000 1 | 195 294,189 79 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(9) |
| 1 535,429 792 6 | 0,000 1 | 195 249,863 88 | 0,01 | $\nu_1 + \nu_3$ | P(4) |
| 1 535,648 302 9 | 0,000 1 | 195 222,081 41 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(10) |

| Longueur d'onde nm | Incertitude pm | Fréquence GHz | Incertitude MHz | Bande | Transition |
|---|---|---|---|---|---|
| 1 535,977 915 7 | 0,000 1 | 195 180,187 77 | 0,01 | $\nu_1 + \nu_3$ | P(5) |
| 1 536,220 339 4 | 0,000 1 | 195 149,387 30 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(11) |
| 1 536,531 605 6 | 0,000 1 | 195 109,854 50 | 0,01 | $\nu_1 + \nu_3$ | P(6) |
| 1 536,797 501 5 | 0,000 1 | 195 076,096 69 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(12) |
| 1 537,090 931 7 | 0,000 1 | 195 038,856 72 | 0,01 | $\nu_1 + \nu_3$ | P(7) |
| 1 537,379 893 5 | 0,000 1 | 195 002,197 74 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(13) |
| 1 537,655 947 7 | 0,000 1 | 194 967,189 15 | 0,01 | $\nu_1 + \nu_3$ | P(8) |
| 1 537,967 628 4 | 0,000 1 | 194 927,677 58 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(14) |
| 1 538,226 690 7 | 0,000 1 | 194 894,848 60 | 0,01 | $\nu_1 + \nu_3$ | P(9) |
| 1 538,560 826 3 | 0,000 1 | 194 852,522 48 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(15) |
| 1 538,803 241 5 | 0,000 1 | 194 821,826 42 | 0,01 | $\nu_1 + \nu_3$ | P(10) |
| 1 539,159 613 8 | 0,000 1 | 194 776,717 97 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(16) |
| 1 539,385 461 9 | 0,000 1 | 194 748,141 66 | 0,01 | $\nu_1 + \nu_3$ | P(11) |
| 1 539,764 122 4 | 0,000 1 | 194 700,248 98 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(17) |
| 1 539,973 510 0 | 0,000 1 | 194 673,775 91 | 0,01 | $\nu_1 + \nu_3$ | P(12) |
| 1 540,374 487 0 | 0,000 1 | 194 623,100 11 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(18) |
| 1 540,567 349 8 | 0,000 1 | 194 598,735 35 | 0,01 | $\nu_1 + \nu_3$ | P(13) |
| 1 540,990 843 8 | 0,000 1 | 194 545,255 87 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(19) |
| 1 541,166 989 1 | 0,000 1 | 194 523,020 61 | 0,01 | $\nu_1 + \nu_3$ | P(14) |
| 1 541,613 327 6 | 0,000 1 | 194 466,700 98 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(20) |
| 1 541,772 435 5 | 0,000 1 | 194 446,632 39 | 0,01 | $\nu_1 + \nu_3$ | P(15) |
| 1 542,242 069 1 | 0,000 1 | 194 387,420 76 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(21) |
| 1 542,383 712 4 | 0,000 1 | 194 369,569 39 | 0,01 | $\nu_1 + \nu_3$ | P(16) |
| 1 542,877 197 8 | 0,000 1 | 194 307,400 77 | 0,01 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(22) |
| 1 543,000 806 1 | 0,000 1 | 194 291,834 99 | 0,01 | $\nu_1 + \nu_3$ | P(17) |
| 1 543,518 7 | 0,2 | 194 226,645 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(23) |
| 1 543,623 745 3 | 0,000 1 | 194 213,427 28 | 0,01 | $\nu_1 + \nu_3$ | P(18) |
| 1 544,166 9 | 0,2 | 194 145,114 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(24) |
| 1 544,252 540 4 | 0,000 1 | 194 134,346 65 | 0,01 | $\nu_1 + \nu_3$ | P(19) |
| 1 544,823 2 | 0,2 | 194 062,633 | 24 | $\nu_1 + \nu_2 + \nu_4 + \nu_5$ | P(25) |
| 1 544,887 205 3 | 0,000 1 | 194 054,593 10 | 0,01 | $\nu_1 + \nu_3$ | P(20) |
| 1 545,527 754 6 | 0,000 1 | 193 974,166 50 | 0,01 | $\nu_1 + \nu_3$ | P(21) |
| 1 546,174 203 4 | 0,000 1 | 193 893,066 73 | 0,01 | $\nu_1 + \nu_3$ | P(22) |
| 1 546,826 566 9 | 0,000 1 | 193 811,293 67 | 0,01 | $\nu_1 + \nu_3$ | P(23) |
| 1 547,484 858 3 | 0,000 1 | 193 728,847 42 | 0,01 | $\nu_1 + \nu_3$ | P(24) |
| 1 548,149 137 7 | 0,000 1 | 193 645,722 30 | 0,01 | $\nu_1 + \nu_3$ | P(25) |
| 1 548,819 315 7 | 0,000 1 | 193 561,931 32 | 0,01 | $\nu_1 + \nu_3$ | P(26) |
| 1 549,495 490 6 | 0,000 1 | 193 477,464 00 | 0,01 | $\nu_1 + \nu_3$ | P(27) |
| 1 550,177 639 4 | 0,000 1 | 193 392,325 10 | 0,01 | $\nu_1 + \nu_3$ | P(28) |
| 1 550,866 180 1 | 0,000 1 | 193 306,464 37 | 0,01 | $\nu_1 + \nu_3$ | P(29) |
| 1 551,560 141 4 | 0,000 1 | 193 220,004 82 | 0,01 | $\nu_1 + \nu_3$ | P(30) |
| 1 552,260 375 9 | 0,000 1 | 193 132,842 06 | 0,01 | $\nu_1 + \nu_3$ | P(31) |

| **Longueur d'onde** nm | **Incertitude** pm | **Fréquence** GHz | **Incertitude** MHz | **Bande** | **Transition** |
|---|---|---|---|---|---|
| 1 552,966 8 | 0,2 | 193 044,989 | 24 | $\nu_1 + \nu_3$ | P(32) |
| 1 553,678 6 | 0,2 | 192 956,547 | 24 | $\nu_1 + \nu_3$ | P(33) |
| 1 554,397 5 | 0,2 | 192 867,306 | 24 | $\nu_1 + \nu_3$ | P(34) |
| 1 555,122 1 | 0,2 | 192 777,440 | 24 | $\nu_1 + \nu_3$ | P(35) |
| 1 555,853 3 | 0,2 | 192 686,841 | 24 | $\nu_1 + \nu_3$ | P(36) |
| 1 556,589 4 | 0,2 | 192 595,721 | 24 | $\nu_1 + \nu_3$ | P(37) |
| 1 557,332 1 | 0,2 | 192 503,871 | 24 | $\nu_1 + \nu_3$ | P(38) |
| 1 558,082 0 | 0,2 | 192 411,220 | 24 | $\nu_1 + \nu_3$ | P(39) |
| 1 558,836 9 | 0,2 | 192 318,041 | 24 | $\nu_1 + \nu_3$ | P(40) |

### E.4.3 HCN

HCN est un absorbeur puissant dans la bande C. Bien que cette molécule soit toxique, la quantité contenue dans une cellule de gaz bien conçue est inférieure à la limite toxique.

La bande partielle $2\nu_1$ des isotopomères de $H^{12}C^{14}N$ (1,52 µm à 1,55 µm) et de $H^{13}C^{14}N$ (1,53 µm à 1,56 µm) a été étudiée [21] et les valeurs de décalage de pression ont été mesurées [22]. Les valeurs de longueur d'onde dans le vide rapportées dans la référence [23] sont énumérées dans le Tableau E.4.

**Tableau E.4 – Liste des transitions $H^{13}CN$**

| **Longueur d'onde** nm | **Incertitude** pm | **Fréquence** GHz | **Incertitude** MHz | **Transition** |
|---|---|---|---|---|
| 1 527,221 633 | 0,025 | 196 299,247 9 | 3,2 | R(27) |
| 1 527,633 273 | 0,018 | 196 246,352 6 | 2,3 | R(26) |
| 1 528,054 581 | 0,013 | 196 192,244 5 | 1,6 | R(25) |
| 1 528,485 564 | 0,010 | 196 136,924 7 | 1,3 | R(24) |
| 1 528,926 231 | 0,009 | 196 080,394 1 | 1,1 | R(23) |
| 1 529,376 588 | 0,008 | 196 022,654 2 | 1,0 | R(22) |
| 1 529,836 645 | 0,008 | 195 963,705 7 | 1,0 | R(21) |
| 1 530,306 408 | 0,008 | 195 903,550 1 | 1,0 | R(20) |
| 1 530,785 886 | 0,008 | 195 842,188 5 | 1,0 | R(19) |
| 1 531,275 088 | 0,008 | 195 779,622 1 | 1,0 | R(18) |
| 1 531,774 020 | 0,008 | 195 715,852 4 | 1,0 | R(17) |
| 1 532,282 693 | 0,008 | 195 650,880 5 | 1,0 | R(16) |
| 1 532,801 112 | 0,008 | 195 584,708 1 | 1,0 | R(15) |
| 1 533,329 289 | 0,008 | 195 517,336 1 | 1,0 | R(14) |
| 1 533,867 229 | 0,008 | 195 448,766 6 | 1,0 | R(13) |
| 1 534,414 943 | 0,008 | 195 379,000 6 | 1,0 | R(12) |
| 1 534,972 439 | 0,008 | 195 308,039 7 | 1,0 | R(11) |
| 1 535,539 724 | 0,008 | 195 235,885 7 | 1,0 | R(10) |
| 1 536,116 810 | 0,008 | 195 162,539 8 | 1,0 | R(9) |
| 1 536,703 703 | 0,008 | 195 088,003 9 | 1,0 | R(8) |

| Longueur d'onde nm | Incertitude pm | Fréquence GHz | Incertitude MHz | Transition |
|---|---|---|---|---|
| 1 537,300 413 | 0,008 | 195 012,279 6 | 1,0 | R(7) |
| 1 537,906 949 | 0,008 | 194 935,368 6 | 1,0 | R(6) |
| 1 538,523 321 | 0,008 | 194 857,272 5 | 1,0 | R(5) |
| 1 539,149 536 | 0,008 | 194 777,993 3 | 1,0 | R(4) |
| 1 539,785 605 | 0,008 | 194 697,532 6 | 1,0 | R(3) |
| 1 540,431 537 | 0,008 | 194 615,892 2 | 1,0 | R(2) |
| 1 541,087 341 | 0,008 | 194 533,074 2 | 1,0 | R(1) |
| 1 541,753 028 | 0,008 | 194 449,080 1 | 1,0 | R(0) |
| 1 543,114 084 | 0,008 | 194 277,572 3 | 1,0 | P(1) |
| 1 543,809 47 | 0,008 | 194 190,062 3 | 1,0 | P(2) |
| 1 544,514 78 | 0,008 | 194 101,384 5 | 1,0 | P(3) |
| 1 545,230 03 | 0,008 | 194 011,540 8 | 1,0 | P(4) |
| 1 545,955 21 | 0,008 | 193 920,533 0 | 1,0 | P(5) |
| 1 546,690 34 | 0,008 | 193 828,363 7 | 1,0 | P(6) |
| 1 547,435 44 | 0,008 | 193 735,034 9 | 1,0 | P(7) |
| 1 548,190 50 | 0,008 | 193 640,548 8 | 1,0 | P(8) |
| 1 548,955 55 | 0,008 | 193 544,907 3 | 1,0 | P(9) |
| 1 549,730 59 | 0,008 | 193 448,113 2 | 1,0 | P(10) |
| 1 550,515 63 | 0,008 | 193 350,168 4 | 1,0 | P(11) |
| 1 551,310 69 | 0,008 | 193 251,075 3 | 1,0 | P(12) |
| 1 552,115 77 | 0,008 | 193 150,836 3 | 1,0 | P(13) |
| 1 552,930 88 | 0,008 | 193 049,453 8 | 1,0 | P(14) |
| 1 553,756 04 | 0,008 | 192 946,930 2 | 1,0 | P(15) |
| 1 554,591 26 | 0,008 | 192 843,268 0 | 1,0 | P(16) |
| 1 555,436 54 | 0,008 | 192 738,469 5 | 1,0 | P(17) |
| 1 556,291 90 | 0,008 | 192 632,537 5 | 1,0 | P(18) |
| 1 557,157 35 | 0,008 | 192 525,474 3 | 1,0 | P(19) |
| 1 558,032 91 | 0,008 | 192 417,282 7 | 1,0 | P(20) |
| 1 558,918 57 | 0,008 | 192 307,965 3 | 1,0 | P(21) |
| 1 559,814 36 | 0,008 | 192 197,524 6 | 1,0 | P(22) |
| 1 560,720 28 | 0,008 | 192 085,963 3 | 1,0 | P(23) |
| 1 561,636 35 | 0,009 | 191 973,284 3 | 1,1 | P(24) |
| 1 562,562 57 | 0,010 | 191 859,490 3 | 1,2 | P(25) |
| 1 563,498 96 | 0,013 | 191 744,584 0 | 1,6 | P(26) |
| 1 564,445 53 | 0,018 | 191 628,568 4 | 2,2 | P(27) |
| 1 565,402 30 | 0,025 | 191 511,446 2 | 3,1 | P(28) |

### E.4.4 CO

Cette molécule diatomique a une bande partielle 0→3 CO dans la bande L. La molécule possède un spectre régulier pour lequel les raies sont faciles à identifier [24], [25]. Les caractéristiques d'intensité des raies, de décalage de pression et d'élargissement de pression d'un certain nombre de raies ont été mesurées [26], [27], [28], [29]. Les transitions pour $^{12}C^{16}O$ sont données dans le Tableau E.5.

**Tableau E.5 – Liste des transitions $^{12}C^{16}O$**

| Longueur d'onde<br>nm | Incertitude<br>pm | Fréquence<br>GHz | Incertitude<br>MHz | Transition |
|---|---|---|---|---|
| 1 559,562 335 | 0,004 | 192 228,583 | 0,5 | R(24) |
| 1 559,848 373 | 0,004 | 192 193,333 | 0,5 | R(23) |
| 1 560,160 931 | 0,004 | 192 154,830 | 0,5 | R(22) |
| 1 560,500 006 | 0,003 | 192 113,077 | 0,4 | R(21) |
| 1 560,865 596 | 0,003 | 192 068,080 | 0,4 | R(20) |
| 1 561,257 704 | 0,003 | 192 019,842 | 0,4 | R(19) |
| 1 561,676 332 | 0,003 | 191 968,369 | 0,4 | R(18) |
| 1 562,121 489 | 0,003 | 191 913,664 | 0,4 | R(17) |
| 1 562,593 183 | 0,003 | 191 855,731 | 0,4 | R(16) |
| 1 563,091 427 | 0,003 | 191 794,576 | 0,4 | R(15) |
| 1 563,616 236 | 0,003 | 191 730,203 | 0,4 | R(14) |
| 1 564,167 627 | 0,003 | 191 662,615 | 0,4 | R(13) |
| 1 564,745 620 | 0,003 | 191 591,818 | 0,4 | R(12) |
| 1 565,350 239 | 0,003 | 191 517,815 | 0,4 | R(11) |
| 1 565,981 507 | 0,003 | 191 440,612 | 0,4 | R(10) |
| 1 566,639 453 | 0,003 | 191 360,212 | 0,4 | R(9) |
| 1 567,324 108 | 0,003 | 191 276,620 | 0,4 | R(8) |
| 1 568,035 506 | 0,003 | 191 189,840 | 0,4 | R(7) |
| 1 568,773 681 | 0,003 | 191 099,877 | 0,4 | R(6) |
| 1 569,538 673 | 0,003 | 191 006,735 | 0,4 | R(5) |
| 1 570,330 523 | 0,003 | 190 910,419 | 0,4 | R(4) |
| 1 571,149 275 | 0,003 | 190 810,932 | 0,4 | R(3) |
| 1 571,994 976 | 0,003 | 190 708,280 | 0,4 | R(2) |
| 1 572,867 675 | 0,003 | 190 602,466 | 0,4 | R(1) |
| 1 573,767 423 | 0,003 | 190 493,496 | 0,4 | R(0) |

## E.5 Transitions d'état excité

Dans une transition optogalvanique, la tension de décharge varie proportionnellement à l'intensité optique lorsque le laser est syntonisé en passant par la fréquence de transition. Le Tableau E.6 représente la longueur d'onde des transitions rapportées couvrant la plage de longueurs d'onde de 1 240 nm à 1 600 nm [30], [31]. Les transitions pour lesquelles des mesures de fréquence exemptes d'effet Doppler (saturées) ont été effectuées sont représentées en gras [32], [33].

### Tableau E.6 – Transitions optogalvaniques d'état excité

| **Elément** | **Longueur d'onde** nm | **Incertitude** pm | **Elément** | **Longueur d'onde** nm | **Incertitude** pm |
|---|---|---|---|---|---|
| Ar | 1 249,111 | 2 | Kr | 1 501,914 | 2 |
| Ar | 1 270,581 | 2 | Ar | 1 505,064 | 2 |
| Ar | 1 273,696 | 2 | Ar | 1 517,694 | 2 |
| Ar | 1 274,977 | 2 | Kr | 1 521,376 | 2 |
| Ar | 1 280,629 | 2 | Ne | 1 523,448 8 | 2 |
| Kr | 1 286,541 | 2 | Kr | 1 524,380 | 2 |
| Ne | 1 291,555 | 2 | Kr | 1 533,065 | 2 |
| Ar | 1 293,675 | 2 | Ar | 1 533,350 | 2 |
| Ar | 1 296,025 | 2 | **Kr** | **1 533,915** | **2** |
| Kr | 1 298,886 | 2 | **Kr** | **1 537,625** | **2** |
| Ar | 1 301,118 | 2 | **Kr** | **1 543,795** | **2** |
| Kr | 1 318,104 | 2 | **Kr** | **1 547,825 99** | **0,20** |
| Kr | 1 473,841 | 2 | **Kr** | **1 563,978** | **2** |
| Kr | 1 476,666 | 2 | **Kr** | **1 568,530 81** | **0,36** |
| Kr | 1 476,954 | 2 | **Kr** | **1 582,441 37** | **0,36** |
| Kr | 1 496,597 | 2 | **Ar** | **1 599,385 78** | **0,36** |
| Kr | 1 500,943 | 2 | | | |

NOTE Les valeurs représentées en gras peuvent être saturées.

# Annexe F
(informative)

# Exemple de laser verrouillé de référence

## F.1 Généralités

Il existe un grand nombre de manières de verrouiller un laser syntonisable sur une fréquence naturelle. Cette annexe présente deux systèmes et une approche de diagnostic si des difficultés sont rencontrées.

## F.2 Sources laser

Les principales sources laser à fréquence unique sont les lasers DFB (à rétroaction répartie, *Distributed Feedback*), les lasers EC (à cavité externe, *External Cavity*), les lasers à réflecteur de Bragg et les lasers SMF (à fibres unimodales, *Single-Mode Fibre*).

Les lasers DFB ont des caractéristiques de modulation à large bande et peuvent être syntonisés en faisant varier le courant et la température du laser. Les caractéristiques de syntonisation dépendent de la conception du laser; les valeurs types sont de 10 GHz/°C (0,1 nm/°C) et 750 MHz/mA (0,01 nm/mA). La modulation du courant laser donne naissance à une modulation de fréquence et d'amplitude corrélées.

En raison de la grande largeur de bande, il est important de garantir l'utilisation d'une alimentation en courant du laser à faible bruit.

Un laser DFB peut généralement être syntonisé thermiquement sur 1 nm à 2 nm et possède une largeur de raie située dans la plage de 0,1 MHzà 10 MHz.

Les caractéristiques de modulation des lasers EC sont déterminées par la conception mécanique. Les fréquences de modulation pouvant être atteintes sont généralement $<$ 500 Hz. Un laser EC peut généralement être syntonisé sur 100 nm et possède une largeur de raie de 50 kHz.

Puisque ces lasers EC sont syntonisés mécaniquement, ils sont sensibles aux vibrations.

Un laser SMF type possède une largeur de raie de quelques kilohertz ou moins.

## F.3 Exemple de cellule à gaz

La longueur du trajet optique dans le gaz dépend de l'intensité d'absorption de la raie et de la pression de gaz. Des cellules à gaz de référence compactes conditionnées pour un grand nombre des gaz énumérés à l'Annexe E sont disponibles dans le commerce. Pour des gaz faiblement absorbants, tels que le monoxyde de carbone, on peut utiliser des cellules d'absorption à trajets multiples. Une configuration de mesure type incluant le contrôle de la qualité du verrouillage est représentée à la Figure F.1.

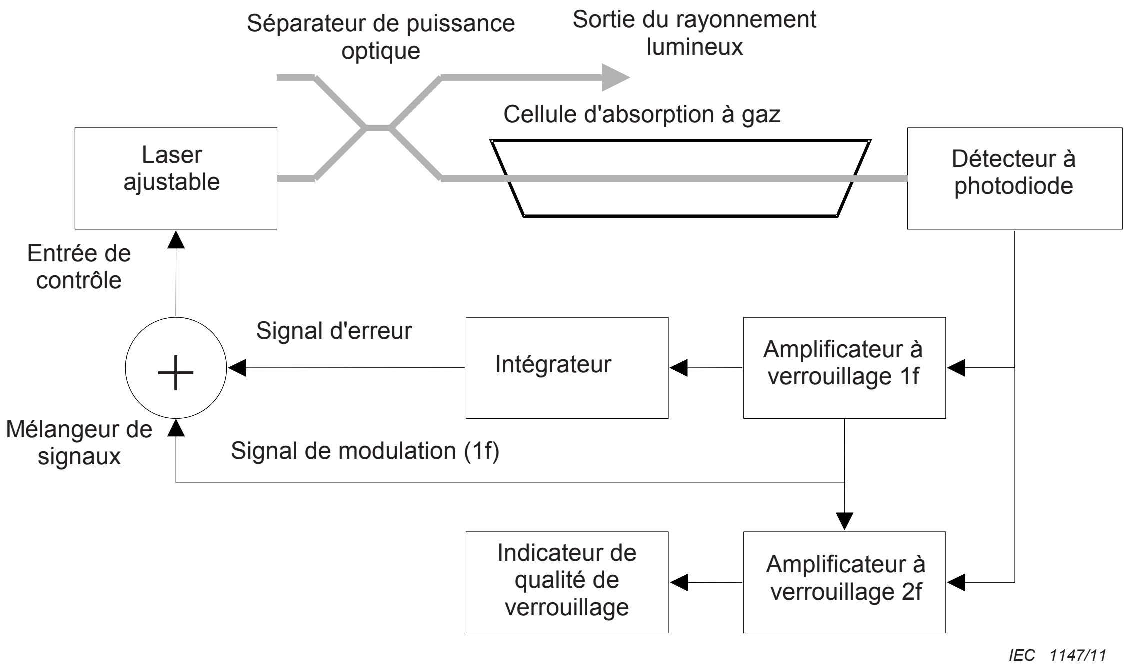

**Figure F.1 – Agencement de mesure type pour verrouiller un laser sur une raie d'absorption de gaz**

# Annexe G
(informative)

# Equilibre entre la précision et le temps d'étalonnage

## G.1 Généralités

Cette annexe fournit des directives d'aide supplémentaires s'ajoutant aux informations fournies en 4.3, conçues pour aider l'utilisateur de la présente norme à choisir les systèmes appropriés pour obtenir différentes précisions d'étalonnage.

## G.2 Sources de référence

Différentes sources de référence naturelles influent sur la précision d'étalonnage pouvant être obtenue. On peut utiliser des sources de référence avec une précision naturelle supérieure pour fournir des étalonnages de précision inférieure et il faut adapter le choix de la référence optique à cet effet.

Des mises en œuvre de sources de référence du commerce offrent une commodité considérable et ont des incertitudes spécifiées. Un exemple en serait un sous-système contenant une diode laser et une alimentation ainsi que des circuits électroniques de contrôle, verrouillé sur une absorption linéaire dans l'acétylène ou dans une matière de référence similaire. Ces instruments peuvent être étalonnés par rapport à des sources de référence d'une précision supérieure.

La précision pouvant généralement être obtenue pour une bonne mise en œuvre d'un laser verrouillé sur un élément d'absorption à basse pression se situe dans la plage comprise entre 1 % et 10 % de la largeur de raie Doppler élargie. Une raie d'absorption d'acétylène a une largeur de raie d'environ 450 MHz, la précision d'une référence verrouillée pouvant être atteinte se situe donc dans la plage de ± 5 MHz à ± 50 MHz (± 40 fm à ± 400 fm).

Comme indiqué à l'Annexe E, le centre de la raie et la largeur de raie varient avec la pression du gaz. Ceci contribue à la limitation de l'incertitude pouvant être atteinte.

## G.3 Résolution de l'instrument

Les conceptions d'appareil de mesure de longueur d'onde basées sur l'interféromètre de Michelson comptent le nombre de franges d'interférences pour les longueurs d'onde inconnues et les longueurs d'ondes de référence interne. Une correction est effectuée pour compenser l'indice de réfraction de l'air. Selon la conception de l'instrument, on utilise un certain degré de subdivision de frange pour améliorer la résolution de l'instrument. La résolution est finalement déterminée par la taille du nombre compté.

### G.3.1 Mesures facultatives

L'utilisation de valeurs fournies par le fabricant pour les paramètres facultatifs permet de prendre une décision de compromis entre l'effort d'étalonnage et la précision des résultats. Les étalonnages utilisant les valeurs fournies par le fabricant sont susceptibles d'avoir une précision inférieure mais l'étalonnage peut être réalisé plus rapidement.

### G.3.2 Résumé des choix

Une gamme de choix types est présentée au Tableau G.1, permettant d'obtenir différentes précisions d'étalonnage.

### Tableau G.1 – Récapitulatif des choix

| Incertitude fractionnaire | Référence | Exigences de mesure |
|---|---|---|
| $10^{-9}$ | Etalon de référence saturé | Il est très difficile d'obtenir cette incertitude en utilisant un appareil de mesure de longueur d'onde. Consulter le fabricant en ce qui concerne les limitations du système. Les modèles d'indice de réfraction peuvent devenir imprécis. Envisager l'utilisation d'autres instruments, par exemple une mesure de fréquence directe |
| $10^{-8}$ | Etalon de référence saturé ou mise en œuvre très soigneuse d'une transition verrouillée non saturée d'une matière isotope de pression connue | Les corrections de l'indice de réfraction comportent l'humidité et la concentration en $CO_2$ |
| $10^{-7}$ | Transition verrouillée non saturée (état moléculaire ou excité) | On peut utiliser des corrections d'indice de réfraction plus simples. On peut utiliser certains paramètres du fabricant |
| $10^{-6}$ | Lasers à gaz non stabilisés | Mesures simples, utiliser des paramètres facultatifs du fabricant pour diminuer le temps |

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