IEC 61757-2-2

Edition 1.0 2016-05

INTERNATIONAL STANDARD

colour inside

Fibre optic sensors –
Part 2-2: Temperature measurement – Distributed sensing

IEC 61757-2-2:2016-05(en)

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INTERNATIONAL
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COMMISSION

ICS 33.180.99 ISBN 978-2-8322-3363-4

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FIBRE OPTIC SENSORS –

Part 2-2: Temperature measurement – Distributed sensing

FOREWORD

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International Standard IEC 61757-2-2 has been prepared by subcommittee SC 86C: Fibre optic systems and active devices of IEC technical committee 86: Fibre optics.

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

CDV	Report on voting
86C/1323/CDV	86C/1354/RVC

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

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

A list of all parts in the IEC 61757 series, published under the general title *Fibre optic sensors*, can be found on the IEC website.

This International Standard is to be used in conjunction with IEC 61757-1:2012.

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

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- withdrawn,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

A bilingual version of this publication may be issued at a later date.

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

INTRODUCTION

It has been decided to restructure the IEC 61757 series with the following logic. From now on, the sub-parts will be renumbered as IEC 61757-*M*-*T* where *M* denotes the measure and *T* the technology.

The existing part IEC 61757-1:2012 will be renumbered as IEC 61757 when it will be revised and will serve as an umbrella document over the entire series.

FIBRE OPTIC SENSORS –

Part 2-2: Temperature measurement – Distributed sensing

1 Scope

This part of IEC 61757 defines detail specifications for distributed temperature measurement by a fibre optic sensor, also known as fibre optic distributed temperature sensing (DTS). DTS includes the use of Raman scattering, Brillouin scattering and Rayleigh scattering effects. In addition, Raman scattering and Rayleigh scattering based measurements are performed with a single-ended fibre configuration only. Brillouin scattering based measurements are performed with a single-ended fibre or fibre loop configuration. The technique accessible from both sides at same time (e. g. Brillouin optical time domain analysis, BOTDA) is referred to here as a loop configuration. Generic specifications for fibre optic sensors are defined in IEC 61757-1:2012.

This part of IEC 61757 specifies the most important DTS performance parameters and defines the procedures for their determination. In addition to the group of performance parameters, a list of additional parameters has been defined to support the definition of the measurement specifications and their associated test procedures. The definitions of these additional parameters are provided for informational purposes and should be included with the sets of performance parameters.

A general test setup is defined in which all parameters can be gathered through a set of tests. The specific tests are described within the clause for each measurement parameter. This general test setup is depicted and described in Clause 4 along with a list of general information that should be documented based upon the specific DTS instrument and test setup used to measure these parameters as per IEC 61757-2-2.

Annex A provides a blank performance parameter table which should be used to record the performance parameter values for a given DTS instrument and chosen optical test setup configuration.

Annex B provides guidelines for optional determination of point defect effects.

2 Normative references

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

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at http://www.electropedia.org)

IEC 61757-1:2012, *Fibre optic sensors – Part 1: Generic specification*

IEC TR 61931, *Fibre optic – Terminology*

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

3 Terms and definitions

For the purposes of this document, the definitions given in IEC 61757-1:2012, IEC 60050, IEC TR 61931, ISO/IEC Guide 99 (VIM), as well as the following apply.

3.1
attenuation range
total cumulated optical loss (one way loss) tolerated by the DTS system without affecting the specified measurement performance more than a given factor at a given location, spatial resolution, and measurement time

Note 1 to entry: Part of the total cumulative loss can be the fibre attenuation, point defect losses introduced by components such as connectors, splices, kink in the fibre, attenuators.

Note 2 to entry: The attenuation range is expressed in decibels (dB).

3.2
distance measurement range
maximum distance from the DTS instrument output connector along the fibre optic sensor within which the instrument measures a temperature with specified measurement performance under defined conditions

Note 1 to entry: This supporting parameter is closely related to the attenuation range of the instrument. In test cases used to prove or verify the reported specifications, the total fibre length shall be equal to or greater than the specified distance measurement range.

Note 2 to entry: The distance measurement range is expressed in length units (m or km).

3.3
environmental temperature repeatability
difference of the measured constant fibre optic sensor temperature at a specified instrument temperature (e. g. nominal operating temperature) before and after temperature cycling of the instrument across the entire instrument operating temperature range

Note 1 to entry: This parameter is derived from environmental temperature stability.

3.4
environmental temperature stability
difference of the measured constant fibre optic sensor temperature before, during and after temperature cycling of the DTS instrument across the entire instrument operating temperature range

Note 1 to entry: Worst case environmental temperature effect, high/low environmental temperature effect, and environmental temperature repeatability are derived from this definition.

3.5
high/low environmental temperature effect
difference of the measured constant fibre optic sensor temperature at the high and low temperature limit of the instrument temperature operating range

Note 1 to entry: This parameter is derived from environmental temperature stability.

3.6
hot spot
length of fibre optic sensor (ΔL) which is exposed by a measurable temperature change (ΔT) which is significantly bigger than the instrument temperature repeatability and which is confirmed by reference temperature devices in the two thermal chambers.

Note 1 to entry: See Clause 4 and Figure 7.

3.7
L
location
optical distance (specified in length units) from the DTS instrument output connector to a desired temperature sample point along the fibre optic sensor

Note 1 to entry: The furthest location from DTS instrument output connector for the particular test is quantified as Z m and is often chosen to be the same as the distance measurement range for purposes of comparing the measurement results with quoted specifications.

3.8
measurement time
time between independent temperature measurements when making successive measurements on a single fibre optic sensor

Note 1 to entry: This parameter includes acquisition time and processing time for measured data. This parameter is selectable by the user typically in some limited fashion. Multiple independent temperature measurements may be averaged together to provide an overall measurement time.

Note 2 to entry: Equivalently, it is the time interval between successive temperature trace timestamps under these conditions.

3.9
point defect
local deviation of a fibre optic sensor from its nominal optical and mechanical properties occurring at a single location, or over a length substantially less than the DTS spatial resolution

Note 1 to entry: The definition of a point defect encompasses a wide range of situations, which may produce similar effects on the temperature trace. Examples include

– a point loss, such as a bad fibre splice;
– a back reflection, such as may arise from a fibre connector;
– a localized region of high loss, such as a bend or kink in the fibre;
– a physical discontinuity in the fibre, such as a splice between two fibres of different core diameters.

3.10
point defect temperature offset
difference between the average values of the temperature sample points in two zones on the temperature trace, one each side of a point defect, where the actual fibre optic sensor temperatures are the same

Note 1 to entry: The point defect temperature offset may be positive, negative or zero.

3.11
sample spacing
distance between two consecutive temperature sample points in a single temperature trace

Note 1 to entry: See Figure 1.

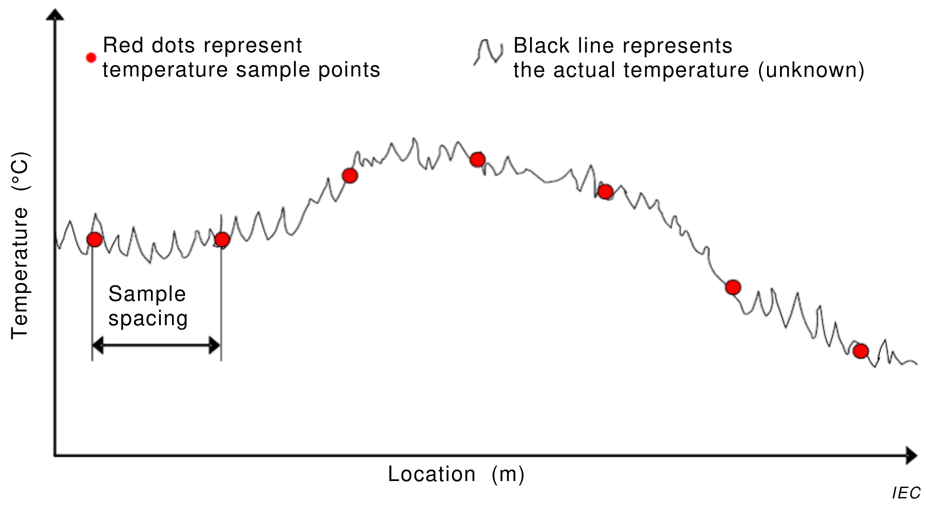

Figure 1 – Example of a temperature trace with temperature sample points

Note 2 to entry: Sample spacing may be a user-selectable instrument parameter.

Note 3 to entry: The distance measurement range is expressed in length units (in m).

Note 4 to entry: In case of very high spacing resolution, the distance measurement range can be expressed in cm or mm.

3.12
spatial resolution
smallest length of a temperature-affected fibre optic sensor for which a DTS system can measure the reference temperature of the hot spot fibre condition within the specified temperature measurement error of the DTS system

3.13
spatial temperature uncertainty
uncertainty of location of temperature data in a single temperature trace expressed by twice the standard deviation of a specified number of adjacent temperature sample points, with the fibre optic sensor held at constant temperature

3.14
temperature dead zone
limited zone of a temperature trace, where the temperature sample points deviate from the undisturbed parts of the trace by a specified limit due to a point defect

3.15
temperature measurement error
maximum difference between a centred and uniformly weighted moving average of the measured temperature and a reference temperature for all data points of the fibre optic sensor over the full operating temperature range and all acquisition times

Note 1 to entry: Single value (worst case) is specified in temperature units (e.g. ± 0,8 °C).

Note 2 to entry: The number of elements used for the moving average is defined in Clause 5. In practical applications, other methods of smoothing might be applicable.

3.16
temperature repeatability
precision of temperature data based on repeated temperature traces at a given location expressed by twice the standard deviation of corresponding temperature sample points in each temperature trace, with the fibre optic sensor held at constant temperature

3.17
temperature sample point
measured temperature value associated with a single point at a known location along a fibre optic sensor

Note 1 to entry: Due to thermodynamic effects, the measured value represents the temperature along a very small section of the fibre optic sensor that includes the point.

3.18
temperature trace
set of temperature sample points distributed along a fibre optic sensor and spaced by the sample spacing

Note 1 to entry: All the sample points are associated with a common time of measurement, often called the trace timestamp. The measured values represent the temperature during a period that includes the timestamp.

Note 2 to entry: All the sample points in a temperature trace are measured values produced by the DTS instrument, and not interpolated or smoothed values produced by subsequent processing outside the instrument.

3.19
Z
total fibre length
distance from the DTS output connector to the final end of the fibre optic sensor

Note 1 to entry: Final end of the fibre optic sensor can either be a purposefully cut or terminated end of the fibre physically far from the instrument (in a single-ended configuration), or the end of a loop consisting of a connector that is connected to the same instrument (in a loop configuration).

Note 2 to entry: This parameter is either equal to or greater than the distance measurement.

Note 3 to entry: The distance measurement range is expressed in length units (m or km).

3.20
warm-up time
duration of time starting from the initiation of the first temperature measurement until the DTS instrument complies with specified measurement specifications

3.21
worst case environmental temperature effect
maximum difference of the measured constant fibre optic sensor temperature at different locations along the sensor during a complete temperature cycling of the DTS instrument across the entire instrument operating temperature range

Note 1 to entry: This parameter is derived from environmental temperature stability.

4 General test setups for measurement of performance parameters

4.1 General and test setup requirements

General test setups for single and loop configurations are schematically shown in Figure 2 and Figure 3 respectively. Their aim is to provide a common base for determining the measurement specifications while at the same time minimizing complexity, cost, reconfiguration requirements, and test execution time.

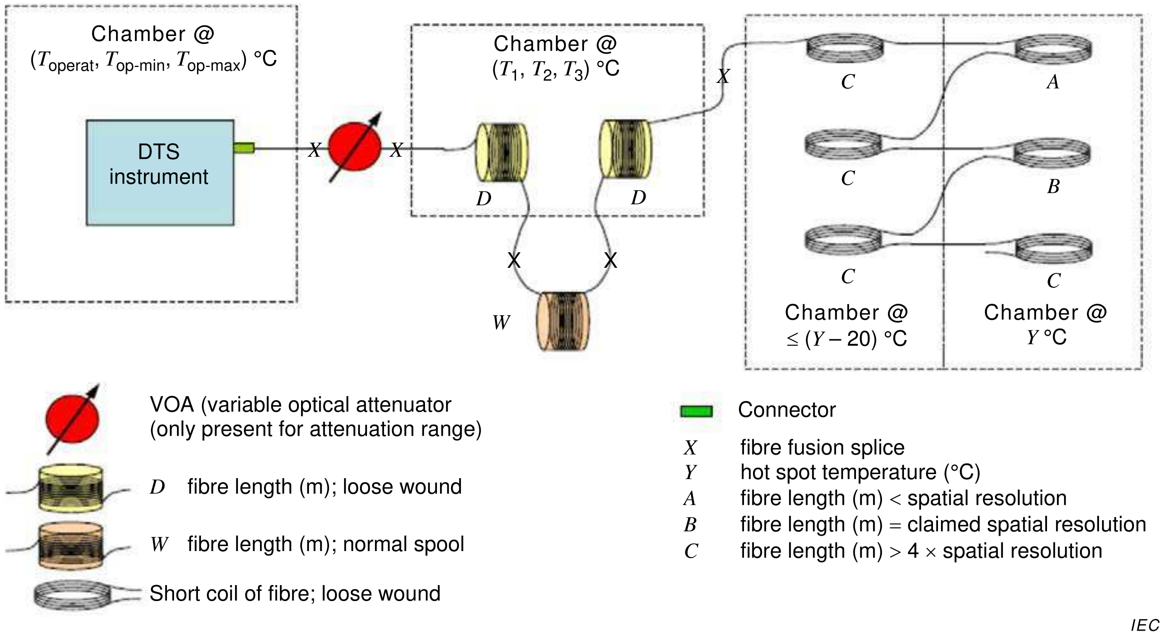

Figure 2 – General test setup: single-ended

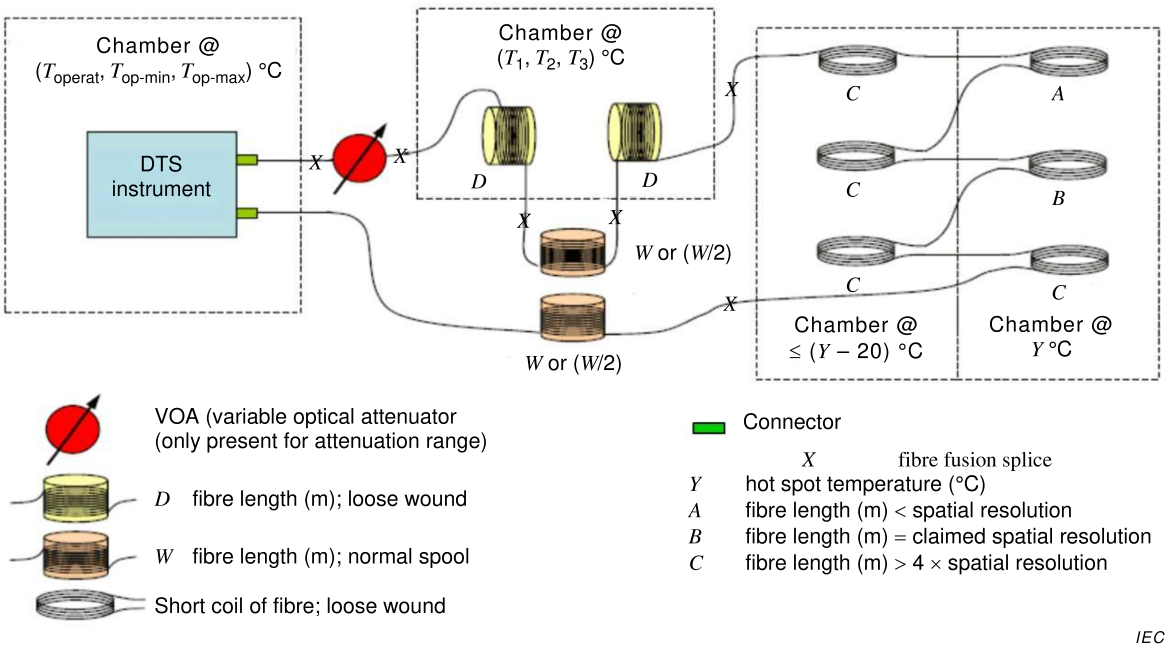

Figure 3 – General test setup: loop configuration

Individual evaluation procedures may be performed with a modified type of setup providing the required measurement conditions. In this case, a detailed setup description and documentation is required.

The fibre lengths A, B, C of the fibre coils in the thermal chambers at the end of the setup shall be selected based upon the expected spatial resolution of the DTS system. The fibre lengths D and W within and outside the centre chamber shall be chosen to make the total fibre length Z match the distance measurement range of the particular DTS model being tested. The use of fibre length D, located before and after a long length W of fibre (which makes up the total fibre length Z), provides a test setup capable of accommodating various instruments with different distance measurement ranges. Fibre length D shall be equal to 10 % of the total fibre length Z. However, the use of a length of fibre outside the central chamber is optional – all fibre may be contained within the chamber, if desired, as single or multiple coils. The total fibre length Z is equal to the total length of fibre from the instrument connector up to the end of the spatial resolution fibre section represented by fibre lengths A, B, C.

A symmetric test setup represents the normal field operation setup. This is reflected by the test setup described in Figure 3. Fibre length W makes up the total fibre length Z. In case of a system comparison with a single-ended test setup, the length of the normal spools shall be ($2 \times W/2$). This guarantees the same overall attenuation. In all other cases the length of the normal spools shall be ($2 \times W$).

Fusion splices should be used for fibre connection to minimize additional optical losses and unwanted back-reflections. Low insertion loss and back-reflections shall be accomplished when connecting the fibres by connectors.

The fibres in the chambers shall be coiled in such a way (loose wound) that the fibre is completely exposed by the surrounding temperature, and that there is no fibre strain. Normal spool in this case means a fibre spool as delivered from the fibre supplier.

It shall be noted that the general test setup provides a schematic diagram only. The real implementation may differ in certain respects, such as replacing any of the fibre containing chambers with liquid filled calibration baths or replacing the double chamber with an alternative implementation that provides a large and sharp enough temperature difference between the coils (at least 20 °C occurring over no longer than 50 % of the rated spatial resolution).

It is required that the uncertainty of the reference temperature measurement is at least a factor of 5 smaller than the temperature measurement error that is being assessed. Such reference temperature sensors are not shown in the setup diagrams but are required to be present and properly calibrated within each temperature chamber and/or bath.

Setting requirements on the homogeneity or stability of the chambers or the sharpness of the realized temperature step is not necessary. Failure to realize these test setup qualities at a sufficient level will only produce measurement data that is more conservative (worse performance).

The DTS instrument-under-test shall be calibrated according to manufacturer's recommendations before performing any measurements.

4.2 General required information to be documented

The general required information to be documented is as follows:

- completion date of all testing;
- name of the organization executing the testing;
- test setup configuration;
- operating mode of the DTS instrument (single-ended or loop configuration as shown in Figures 2 and 3, or channel(s) tested in case of a multi-channel system using the same hardware);
- wavelength(s) of the launched signals (operating wavelength(s));
- manufacturer, model, and serial number of the DTS instrument;
- manufacturer, model, and length of the fibre optic sensor in the test setup (inside the temperature chamber(s));
- optical loss (one-way in dB) of the optical setup to the end of the sensor (Z m);
- wavelength used to measure the loss to end of the sensor (Z m);

- distance measurement range of the DTS instrument;
- sample spacing used for all measurements;
- spatial resolution setting used for all measurements;
- measurement time used during DTS instrument calibration;
- lengths of fibre coils A, B,C and D and spool(s) W;
- nominal temperatures of both parts of the double-chambers in °C;
- maximum (hot) and minimum (cold) operating temperature limits (°C) of the DTS instrument.

The general required information for the tested DTS instrument and the associated test setup shall be recorded along with the calculated measurement specifications.

5 Measurement procedures for performance parameters

5.1 Temperature measurement error

5.1.1 Test procedure and conditions

The following steps shall be performed:

1) Use a general test setup as shown in Clause 4.
2) Make the total fibre length Z equal to or greater than the distance measurement range quoted for the specific DTS instrument to be tested.
3) Place the DTS instrument in a thermal chamber and stabilize it at operating temperature (e. g. 20 °C ± 0,5 °C). Give the instrument sufficient time before performing the following steps to reach thermal equilibrium with the environment in accordance with the manufacturer's recommendations (start-up time). The operating temperature shall be defined by the manufacturer of the DTS instrument.
4) Calibrate the DTS instrument according to manufacturer's recommendations over a defined fibre temperature range that corresponds to the application. The fibre temperature range shall be agreed by the manufacturer and the customer.
5) Stabilize the temperature within ± 0,5 °C of controlled fibre length(s) D at three representative temperatures T_1, T_2, T_3 within the specified temperature range. The three representative temperatures shall be agreed by the manufacturer and the customer.
6) Collect 20 temperature traces at each of the three required measurement times (shortest time provided by the DTS instrument, recommended time, and longest possible provided by the DTS instrument) for each fibre temperature.

NOTE The same data sets can be used for the performance evaluation of spatial resolution, spatial temperature uncertainty, and temperature repeatability.

5.1.2 Parameter calculation

For calculation of the temperature measurement error, the following steps shall be performed (see Figures 4 through 5):

1) Compute the average of all 20 temperature traces for each temperature sample point over the entire location.
2) Calculate the smoothed average by computing a centred and uniformly weighted moving average over 51 of the averaged temperature data (DTS readings).
3) Compute the average error for each sample point by subtracting the smoothed average from the actual fibre temperature (as measured by an independent calibrated reference sensor) over the entire location. See Figure 5.
4) Calculate the absolute average error by taking the absolute value of each average error for each temperature sample point.

5) The temperature measurement error for that set of test conditions is the maximum value of all absolute average error values that correspond to measurements collected from the fibre length that was clearly inside the stabilized thermal chamber. Temperature data of fibre lengths outside the stabilized thermal chamber (e. g. end or lead in fibre lengths, W length of fibre) shall not be used for computation of the temperature measurement error. See Figure 6.
6) Repeat calculation steps 1 through 5 for all other sets of test conditions (a total of 3 conditions exist for each measurement time).
7) Record the test parameters and all 9 measured values for the temperature measurement error.

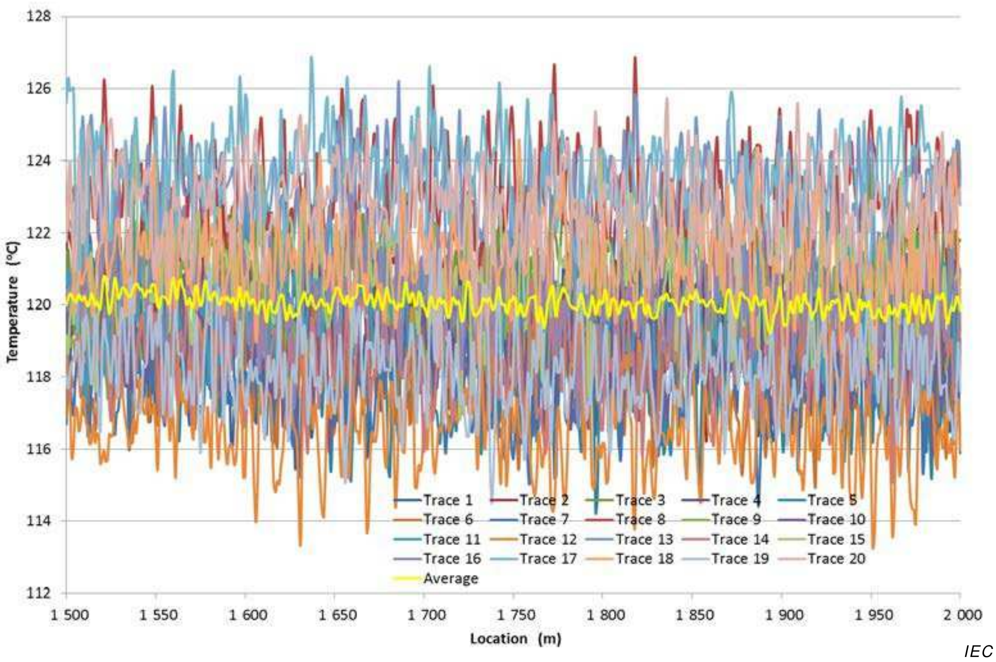

Figure 4 – Temperature measurement error calculation: step 1

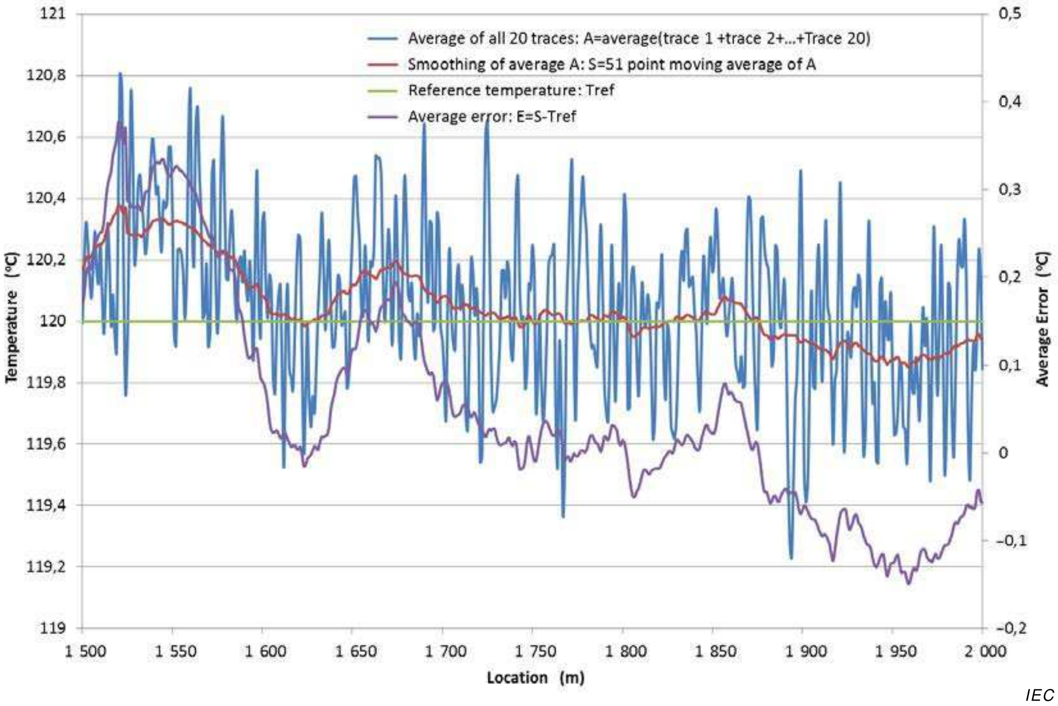

Figure 5 – Temperature measurement error calculation: steps 2 through 3

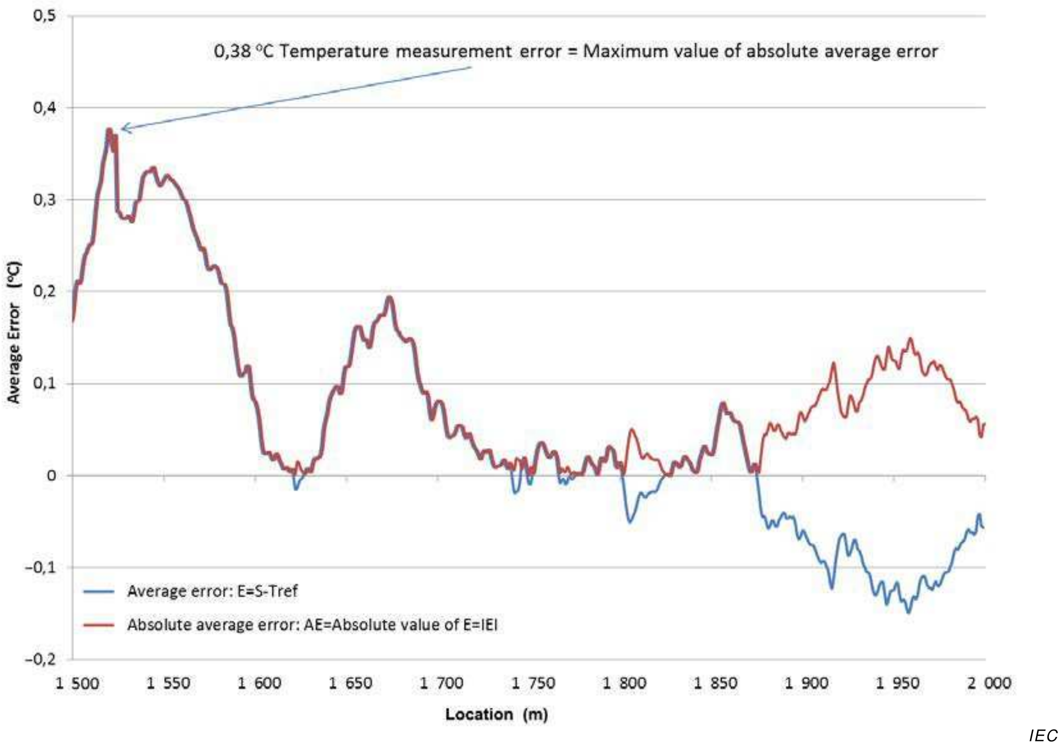

Figure 6 – Temperature measurement error calculation: steps 4 through 5

5.2 Spatial resolution

5.2.1 Test procedure and conditions

The following steps shall be performed:

1) Give equipment sufficient time before the test to reach thermal equilibrium with the environment in accordance with the manufacturer's recommendations.
2) Use a general test setup as shown in Clause 4.
3) The hot spot fibre segment lengths shall be equal to the following:
   a) The A length shall be less than the claimed DTS instrument spatial resolution, such that no single temperature point will show the hot spot reference temperature.
   b) The B length shall be equal to the claimed spatial resolution for the DTS instrument being tested, such that one data point shows a temperature value increase > 90 % of the segment reference temperature.
   c) The C length shall be greater than 4 times the claimed spatial resolution for the DTS instrument being tested.
4) The sample spacing shall be less than or equal to one-half the claimed spatial resolution.
5) Hot spots shall be generated according to 3.6.
6) Collect performance data set as specified in 5.1 using a measuring time which corresponds to the needs of the application (e. g. 10 min).

5.2.2 Parameter calculation

For calculation of the spatial resolution (Figure 7) the following steps shall be performed:

1) Spatial resolution is equal to the B fibre segment length, and is validated with this test by at least one data point in the B segment fibre calculating a temperature > 90 % of the hot spot reference temperature increase above the surrounding fibre temperature.
2) The A fibre segment shall validate that no data points show the hot spot reference temperature.
3) Afterwards, the spatial resolution length, the C fibre hot spot segment, shall show all data points equal to the hot spot reference temperature within the expected spatial temperature uncertainty.
4) Record the B fibre segment length as spatial resolution.

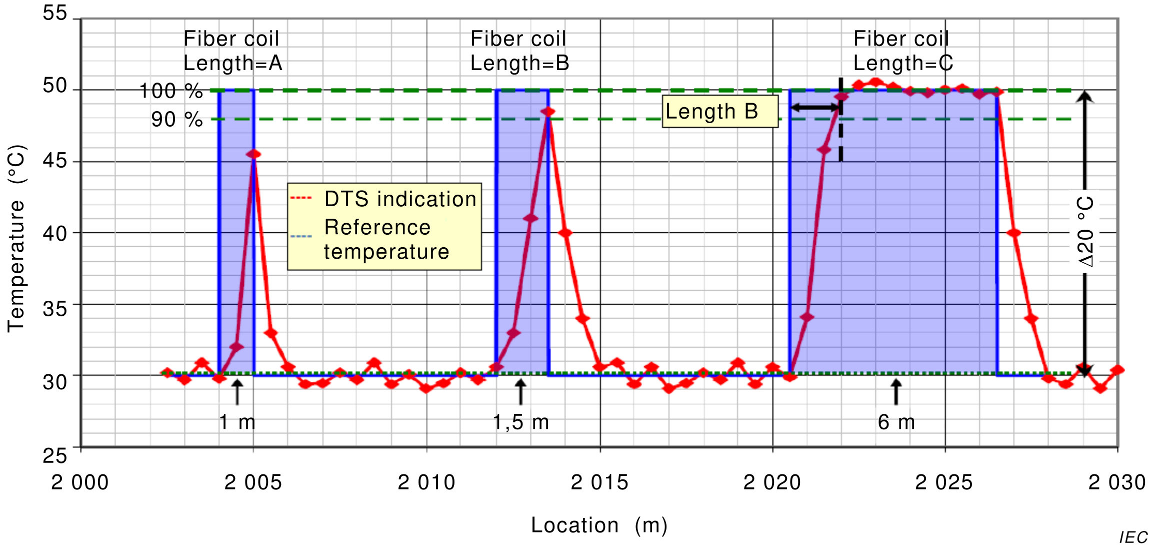

Figure 7 – Spatial resolution illustration

5.3 Temperature repeatability

5.3.1 Test procedure and conditions

The following steps shall be performed:

1) Give equipment sufficient time before the test to reach thermal equilibrium with the environment in accordance with the manufacturer's recommendations.
2) Use a general test setup as shown in Clause 4.
3) Collect performance data set as specified in 5.1.
4) Collect 20 consecutive traces with a quoted spatial resolution over the total fibre length Z after the fibre temperature is stabilized:
   a) for each measurement time (shortest time provided by the DTS instrument, recommended time, and longest possible provided by the DTS instrument); and
   b) for three representative fibre temperatures (T_1, T_2, T_3) according to the desired application.
5) The performance data set comprises 9 data subsets for above specified pairs of measurement time and fibre temperature.
6) Each subset is used to evaluate the values of temperature repeatability over length.

5.3.2 Parameter calculation

For calculation of the temperature repeatability (Figure 8) the following steps shall be performed:

1) Collect 20 consecutive traces for each data subset (e. g. traces for 10 min measurement time at one representative fibre temperature (T_1, T_2, T_3) as shown in Figure 4).
2) Calculate twice the standard deviation of temperature for each sample point over time (20 consecutive traces). Plot above calculated values versus distance.
3) Create a 51-point centred and uniformly weighted moving average curve S_i to use to select the reported distance based temperature repeatability values for each measurement time at each fibre temperature.
4) Report the maximum temperature repeatability value of the data set created in step 3.

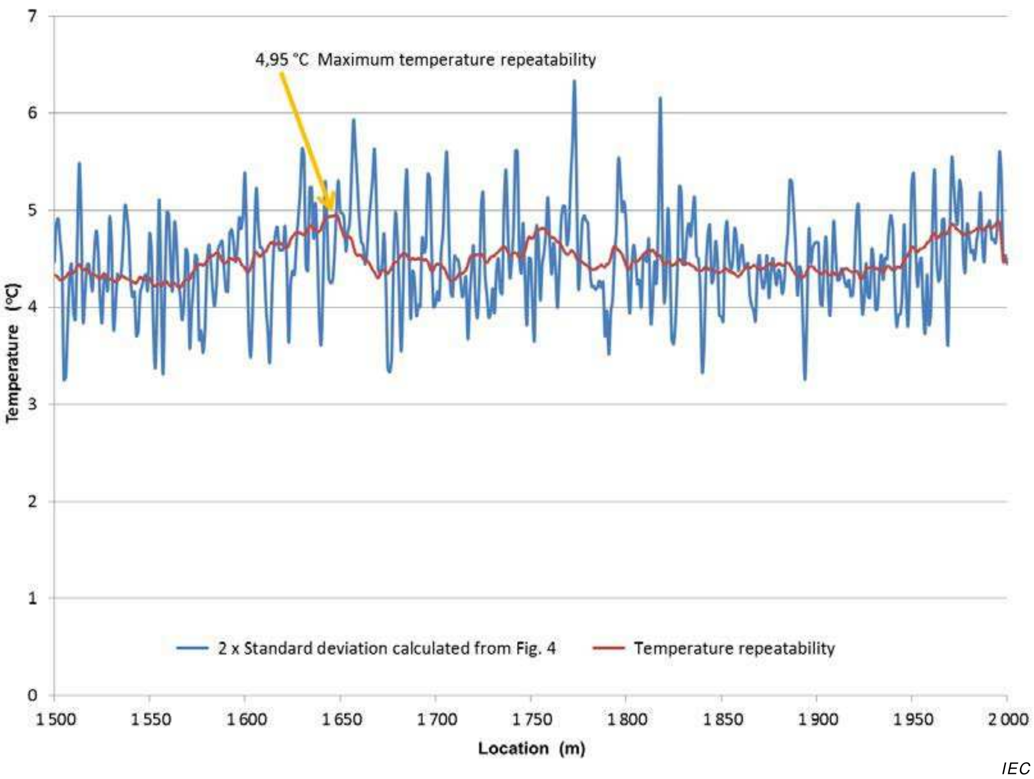

Figure 8 – Temperature repeatability calculated from Figure 4

5) Repeat this procedure at each measurement time for the remaining two representative fibre temperatures (T_1, T_2, T_3).

5.3.3 Formulas

Standard deviation in 5.3.2, step 2 is calculated by:

$$S_x(i) = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(T_j(i) - \frac{1}{N}\sum_{j=1}^{N}T_j(i)\right)^2} \qquad (1)$$

where

$T_j(i)$ is the collected temperature data at i^{th} location of j^{th} trace;

$S_x(i)$ is the standard deviation for each data point (i^{th} location within a trace) over time (N consecutive traces);

N is the number of traces (N = 20).

The temperature repeatability S using the moving average applied on twice the standard deviation is calculated by:

$$S(i) = \frac{1}{51}\sum_{k=(i-25)}^{i+25} 2 \cdot S_x(k) \qquad (2)$$

where

$S(i)$ is the temperature repeatability at i^{th} location.

5.4 Spatial temperature uncertainty

5.4.1 Test procedure and conditions

The following steps shall be performed:

1) Give equipment sufficient time before the test to reach thermal equilibrium with the environment in accordance with the manufacturer's recommendations.
2) Use a general test setup shown in Clause 4.
3) Collect 20 consecutive traces of temperature data over total fibre length Z set as specified in 5.1 after the fibre temperature has stabilized:
   a) for each measurement time (shortest time provided by the DTS instrument, recommended time, and longest possible provided by the DTS instrument);
   b) for three representative fibre temperatures (T_1, T_2, T_3) according to the desired application.

5.4.2 Parameter calculation

For calculation of the spatial temperature uncertainty (Figure 9) the following steps shall be performed:

1) Calculate twice the standard deviation over 51 points (centred and uniformly weighted) of collected temperature $T_j(i)$ for each data point of a single temperature trace.

$$S_j(i) = \sqrt{\frac{1}{n-1}\sum_{l=(i-25)}^{(i+25)}\left(T_j(l) - \frac{1}{n}\sum_{k=(i-25)}^{(i+25)}T_j(k)\right)^2} \qquad (3)$$

where

$T_j(i)$ is the collected temperature data at i^{th} location of j^{th} trace;

$S_j(i)$ is the standard deviation over 51 points at i^{th} location of j^{th} trace;

n is the number of data points for calculation (n = 51).

2) Calculate the spatial temperature uncertainty $A(i)$ by averaging $2 \times S_j(i)$ for N = 20 traces collected over time at i^{th} location.

$$A(i) = \frac{1}{N}\sum_{j=1}^{N} 2 \cdot S_j(i) \quad (4)$$

where

$A(i)$ is the spatial temperature uncertainty;

$S_j(i)$ is the standard deviation over 51 points at i^{th} location of j^{th} trace;

N is the number of traces (N = 20).

3) Report the maximum spatial temperature uncertainty value $A(i)$ for the data set created in step 2).

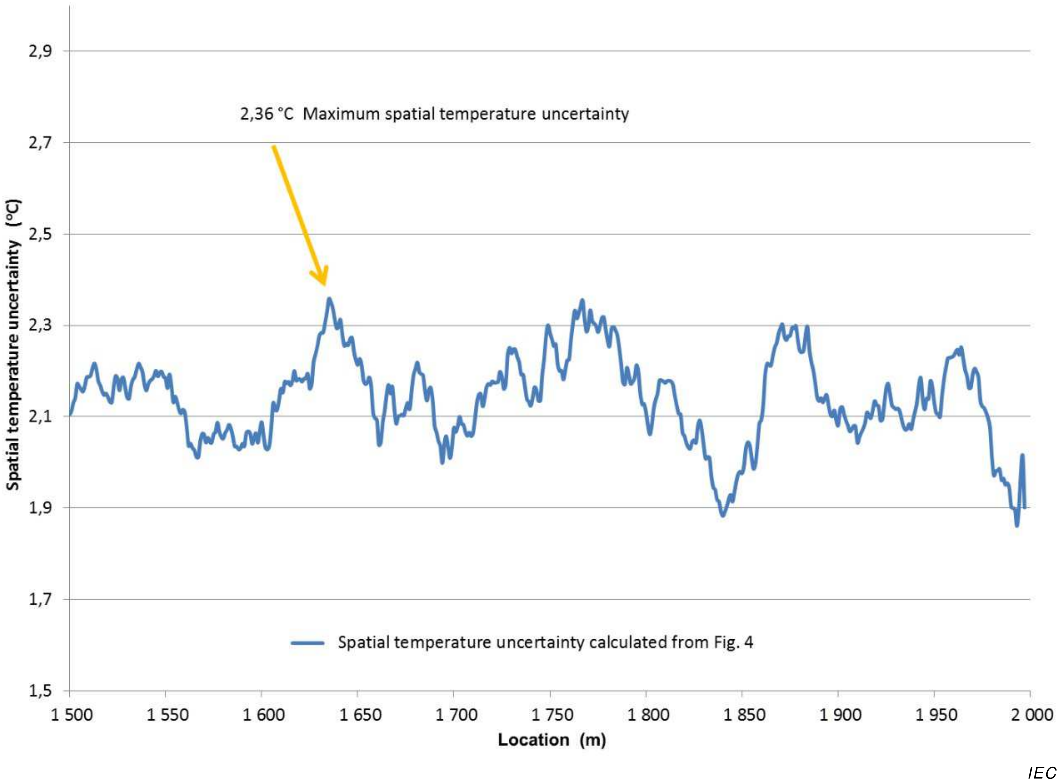

Figure 9 – Spatial temperature uncertainty calculated from Figure 4

5.5 Environmental temperature stability

5.5.1 Test procedure and conditions

The following steps shall be performed:

1) Give equipment sufficient time before the test to reach thermal equilibrium with the environment in accordance with the manufacturer's recommendations.

2) Use a general test setup shown in Clause 4.

3) The fibre is to be held at a constant temperature (T_{const} ± 0,5 °C) for the entire environmental test. T_{const} shall be agreed between manufacturer and user.

4) Place DTS instrument in a thermal chamber and change the temperature according to the environmental temperature cycle described in Figure 10. T_{min}, T_{mid} and T_{max} shall be agreed between manufacturer and user. Each temperature level shall be held for 3 h. Temperature changes shall be performed with a rate of 20 °C/h.

Step time (h)	Total time (h)	Temperature (°C)
	0	20
3	3	20
1	4	0
3	7	0
2	9	40
3	12	40
1	13	20
3	16	20

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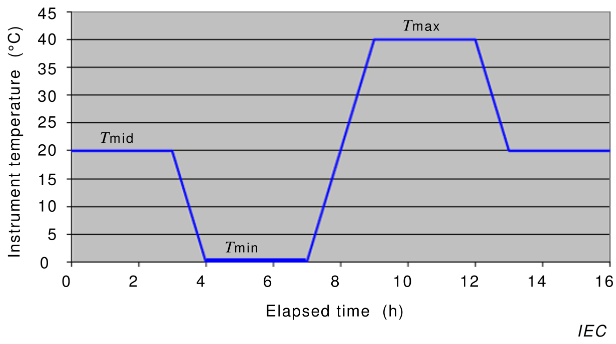


a) Temperature profile table **b) Temperature profile graph**

Figure 10 – Environmental temperature cycle (example for a DTS instrument with an operating temperature range of 0 °C to 40 °C)

5) Collect temperature traces throughout the environmental cycle using a measurement time of 10 min.

5.5.2 Parameter calculation

For calculation of the environmental temperature stability, the following steps shall be performed:

1) Calculate a 101 point moving average (centred and uniformly weighted) of the temperature sample points from every collected temperature trace. Front and rear end in fibre length (101 points) shall not be used for computation below.

2) Determine the peak-to-peak variation in moving average temperatures at each distance point of the temperature stabilized fibre across all temperature traces taken during the environmental temperature cycle.

3) The worst case environmental temperature effect shall be quoted and reported as the worst case peak-to-peak (maximum – minimum) value calculated in the previous step.

4) Average the 101 point moving average temperatures for each temperature sample point calculated above (step 1) for the last 6 temperature traces taken during each hold period, i.e. average the last hour of measurements taken at the hold temperatures of middle, minimum, maximum, and middle again of the instrument operating range.

5) Calculate and report the difference between these values, collected at the maximum operating temperature and the initial middle operating temperature, and take the maximum difference for any temperature sample point as the high environmental temperature effect.

6) Calculate and report the difference between the values in step 4, collected at the minimum operating temperature and the initial middle operating temperature, and take the maximum difference for any temperature sample point as the low environmental temperature effect.

7) Calculate and report the difference between the values in step 4, collected at the initial middle operating temperature and the final middle operating temperature, and take the maximum difference for any temperature sample point as the environmental temperature repeatability.

Figure 11 gives a better understanding of the calculations required.

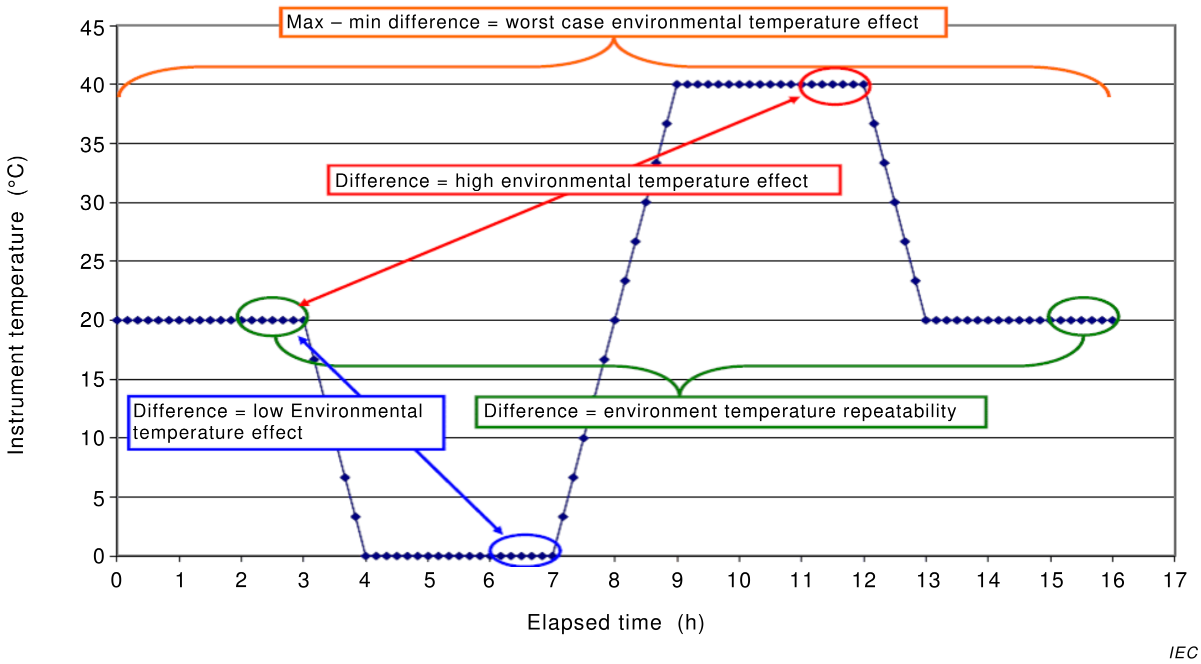


Figure 11 – Environmental temperature stability parameter calculation method

5.6 Warm-up time

5.6.1 Test procedure and conditions

The following steps shall be performed:

1) Use a general test setup shown in Clause 4. All main measurement parameters shall have been previously determined.
2) The fibre is to be held at a constant temperature (T_{const} ± 0,5 °C) for the entire environmental test. The instrument is to be contained within a chamber set to the nominal operating temperature (T_{operat} ± 0,5 °C). The instrument shall be powered off completely, and shall be allowed to stabilize within the chamber for at least 3 h.
3) After the 3 h soak, power on the instrument normally, but do not initiate a temperature measurement.
4) Allow the instrument to wait the start-up time specified by the manufacturer for the corresponding operating temperatures, then begin the first temperature measurement with the measurement time set to 30 s, and start a timer. If a warm-up time of less than 10 min is possible and desired, then a shorter measurement time than 30 s may be used. In this case, the main measurement specifications used as thresholds in this standard shall also be generated and reported in the same way with the same shorter measurement time.
5) Continue collecting temperature traces at the 30 s measurement time.
6) Calculate the temperature measurement error, the spatial temperature uncertainty, and the temperature repeatability using the same methods as described in this standard with the following exceptions:
   a) For all three of these measurement parameters, the location at which they shall be measured and recorded is at 90 % of the total fibre length Z only.
   b) For temperature measurement error, no averaging over time shall be performed – the value is calculated from each individual trace.
   c) For spatial temperature uncertainty, a moving average of the last 20 temperature traces collected over time shall be used.
   d) For temperature repeatability, a moving standard deviation of the last 20 temperature traces collected over time shall be used.

7) Once the measured values of all three main instrument parameters meet or exceed the claimed values for those parameters at a 30 s measurement time, then the timer is stopped and the time duration is recorded.

8) Record the time duration as the warm-up time for the nominal operating temperature.

9) Repeat steps 2 through 7, except set the initial temperature of the chamber that contains the instrument to the minimum operating temperature T_{op_min}. Do not allow the instrument to cool down at a rate greater than 20 °C/h. Record the time duration as the warm-up time for the minimum instrument operating temperature.

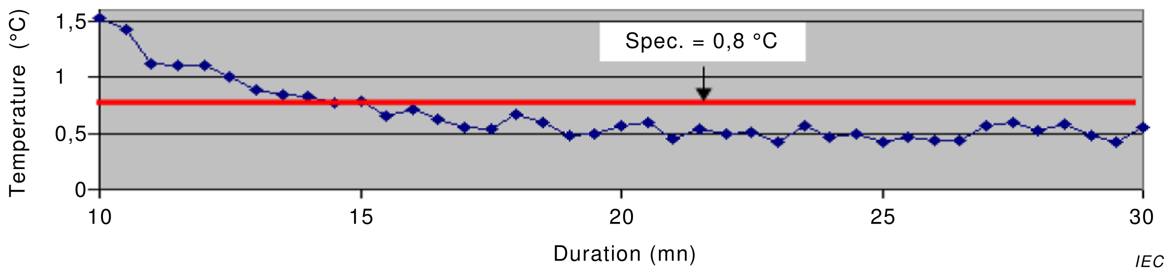
10) Repeat steps 2 through 7, except set the initial temperature of the chamber that contains the instrument to the maximum operating temperature T_{op_max}. Do not allow the instrument to warm-up at a rate greater than 20 °C/h. Record the time duration as the warm-up time for the maximum instrument operating temperature.

5.6.2 Parameter calculation

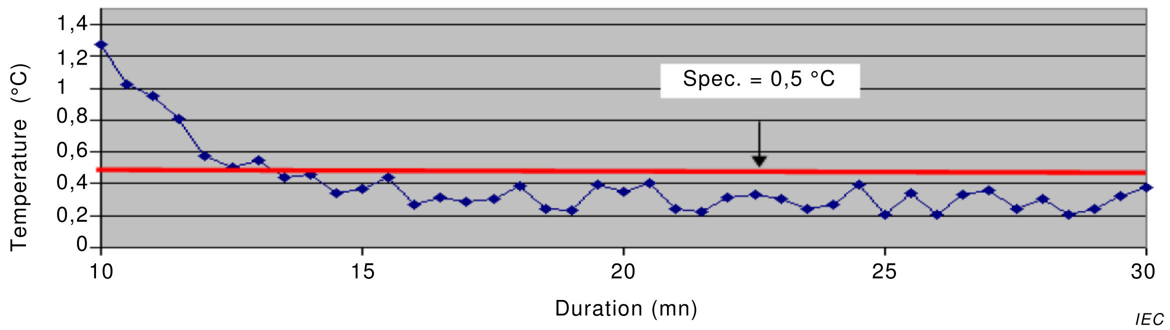
For calculation of the warm-up time the following step shall be performed:

- Use the calculation methods described for the three main measurement parameters with the exceptions described in step 6 of 5.6.1.

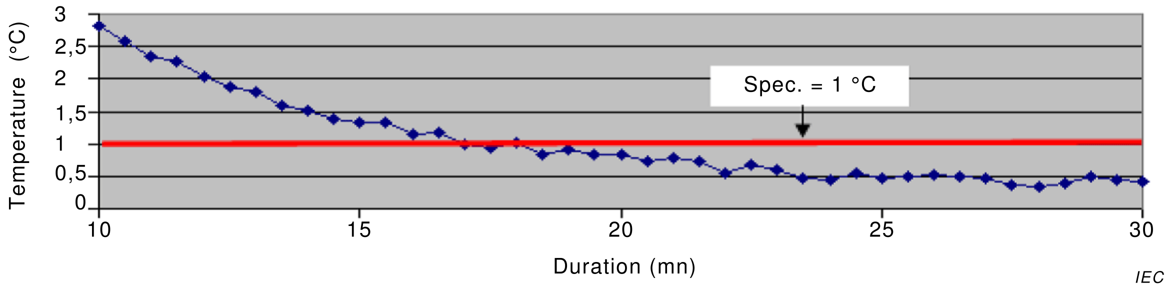
Figure 12 demonstrates the parameter calculation by means of hypothetical results from tests where the DTS instrument started at the nominal operating temperature. The reported value is determined as the longest time for any of the three main specification parameters to reach its specified value.



a) Temperature repeatability



b) Spatial temperature uncertainty



c) Temperature measurement error

Figure 12 – Example illustrating calculation of warm-up time

Each point in the graphs represents a 10 min (20 points over time) moving average or 2 × moving standard deviation, depending on the measurement specification. The X-axis begins at 10 min, as this is the minimum time required to gather 20 temperature traces at a 30 s measurement time.

The temperature repeatability (see Figure 12a)) meets the specification at 15,0 min (all points starting at 15,0 min are below the specification value of 0,8 °C). The spatial temperature uncertainty (see Figure 12b)) meets the specification at 13,0 min (all points starting at 13,0 min are below the specification value of 0,5 °C). The temperature measurement error (see Figure 12c)) meets the specification at 18,0 min (all points starting at 18,0 min are below the specification value of 1,0 °C).

Since the longest time to meet all three measurement specifications is 18,0 min, this is the reported value for the warm-up time for the nominal operating temperature.

5.7 Attenuation range

5.7.1 Test procedure and conditions

The attenuation range for a given wavelength, spatial resolution and measurement time is measured by evaluating the effect of additional loss introduced in the optical system on the temperature repeatability and/or spatial temperature uncertainty. The additional loss (typically created by a variable optical attenuator) is then added to the total cumulative loss measured at the same location at 90 % of total fibre length Z to compute the attenuation range.

In the following test procedure, the attenuation range is evaluated with respect to the temperature repeatability performance, as an example. The same procedure shall be used to evaluate the attenuation range for spatial temperature uncertainty.

The temperature repeatability is measured using the general test setups in Figure 2 (single-ended) or Figure 3 (loop configuration) while the additional loss is introduced by means of a variable optical attenuator (VOA). The VOA is placed outside the two thermal chambers where the DTS instrument and spools of fibre length D are placed. It is connected to the DTS output fibre and to the first fibre spool of length D. The spatial resolution test section is optional for this test.

The fibre spools of length D are maintained at a constant temperature (e. g. 75 °C ± 0,5 °C). The additional attenuation is gradually increased, and both the temperature repeatability and spatial temperature uncertainty are measured until the maximum acceptable temperature repeatability is exceeded at a location at 90 % of total fibre length Z.

The attenuation range reported value shall correspond to the VOA attenuation plus the cumulated fibre and point defect losses over the distance of 90 % of total fibre length Z (measured at the system operating wavelength). The attenuation range shall be evaluated for a given spatial resolution and for a 10 min acquisition time.

The detailed procedure is as follows:

1) Use a general test setup shown in Clause 4, but with the modifications as shown in Figure 2. Preferably by fusion splicing, insert a VOA into the fibre path between the chamber containing the instrument and the chamber containing the long length of fibre. All main measurement specifications shall have been previously determined per the procedures described in this document.
2) Insure that the variable optical attenuator is set to its minimum value; this should ideally result in an insertion loss of less than 1,0 dB at the operating wavelengths of the instrument.
3) The fibre optic sensor is to be held at a constant temperature (e. g. 75 °C ± 0,5 °C) for the entire test. The instrument is to be contained within a chamber set to the nominal

operating temperature (20 °C ± 0,5 °C). Allow sufficient time for the instrument to stabilize within the chamber (normally 3 h).

4) Collect 20 temperature traces at a 10 min measurement time.
5) Calculate the temperature repeatability and spatial temperature uncertainty using the same methods as described in 5.3 and 5.4 for both measurements.
6) Compare the obtained temperature repeatability with the maximum acceptable temperature repeatability.
7) Change the VOA setting in order to increase the attenuation by steps of about 0,5 dB.
8) Repeat steps 4 through 7 until the calculated temperature repeatability is larger than the maximum acceptable temperature repeatability at a location at 90 % of total fibre length Z.
9) Disconnect the test fibre and measure the VOA attenuation preferably using a cut-back method.

5.7.2 Parameter calculation

For calculation and evaluation use the calculation instructions described in steps 1 to 9 of 5.7.1.

Report the attenuation range values as the sum of the VOA attenuation, all point defect/connector losses (excluding that at the instrument) plus the fibre loss over the distance of 90 % of total fibre length Z (measured at the system operating wavelength). Also report the considered maximum acceptable temperature repeatability.

Annex A
(informative)

Measurement parameter performance table

For better comparability, Table A.1 should be used to record the measured parameter values. A similar table may be used to provide a set of quoted specifications for the same measurement parameters.

Table A.1 – Blank measurement parameter performance table

Parameter: ___________________ **DTS instrument:** ___________________

Measurement time	Unit	Shortest time provided by the DTS instrument			Recommended time			Longest time possible provided by the DTS instrument		
Fibre temperature	°C	T1	T2	T3	T1	T2	T3	T1	T2	T3
Temperature measurement error	°C									
Temperature repeatability	°C									
Spatial temperature uncertainty	°C									
Spatial resolution	m									
Worst case environmental temperature effect	°C									
Low environment temperature effect	°C									
High environment temperature effect	°C									
Environmental temperature repeatability	°C									
Attenuation range	dB									

Warm-up time – nominal	sec		at a constant fibre temperature (T_{const} ± 0,5 °C) of: °C
Warm-up time – minimum	sec		
Warm-up time – maximum	sec		

			Measurement time used for calibration (min)**:**
Test setup	**Single-ended:**	**Loop configuration:**	**Wavelength(s) of launched signal(s)** (nm)**:**
DTS manufacturer:		**DTS model/serial number:**	*A* **coil length** (m)**:**
Fibre manufacturer:		**Fibre model:**	*B* **coil length** (m)**:**
Distance measurement range (m)**:**		**Sample spacing** (m)**:**	*C* **coil length** (m)**:**
Total fibre length *Z* (m)**:**		**Optical loss at** *Z* (dB)**:**	*D* **coil length** (m)**:** *W* **spool length** (m)**:**
Spatial resolution setting (m)**:**		**Wavelength of loss measurement** (nm)**:**	**Nominal temperatures of both parts of the double-chamber** (°C)**:**
Maximum instrument operating temperature (°C)**:**		**Minimum instrument operating temperature** (°C)**:**	**Warm-up time** (min)**:**
Considered test parameters for			
Warm-up time: **Temperature repeatability** (°C)**:** **Spatial temperature uncertainty** (°C)**:** **Temperature measurement error** (°C)**:**		**Attenuation range:** **Maximum acceptable temperature repeatability** (°C)**:** **Maximum acceptable spatial temperature uncertainty** (°C)**:**	

All different fibre manufactures and types used in any of the coils within the configurations should be individually identified. If a shorter measurement time has been used to specify the warm-up time, then the temperature measurement error, spatial temperature uncertainty, and temperature repeatability shall also be reported on a separate table.

Annex B
(informative)

Point defect effects

B.1 General

This procedure allows the effect of a specific point defect on the measurement performance of a DTS (and associated fibre) to be measured in a controlled way. For example, the point defect might be a wet-mate connector with its own particular levels of loss, back reflection, and other properties. Because of the difficulty of creating a test point defect which is both representative of real world defects, and reproducible between test setups, it is recommended that the parameters measured by the following procedure be used only to compare the effects of the same point defect on different instruments.

For these reasons, the response to a point defect is not a recommended DTS specification item.

This test does not make use of the general test setup described in Clause 4.

B.2 Point defect

The effect of a point defect on the measurement performance of a DTS is characterized by the following parameters:

- The temperature dead zone caused by the point defect. The zone of temperature disturbance is defined as that length of the temperature trace where the error on the indicated temperature is outside the expected bounds for the performance of the DTS under test on undisturbed fibre.
- The temperature offset caused by the point defect. The offset is the difference between the average indicated temperatures along two lengths of the temperature trace immediately on each side of the zone of temperature disturbance.
- The temperature measurement error decrease caused by the point defect. The point defect may cause a decrease in temperature measurement error, measured over a specified fibre length each side of, but excluding the zone of temperature disturbance.

This procedure applies to any type of point defect.

B.3 Test procedures and conditions

The following steps shall be performed:

1) The point defect to be tested shall be fusion-spliced between two equal lengths of fibre, each of which shall be a minimum of 1 km long. The two fibres shall be loose wound or wrapped on collapsible spools, and the point defect and both fibre lengths shall be placed in a temperature-controlled chamber. The fibre type and length, a description of the point defect, and any available measurements such as its forward and return losses, shall be recorded.

   For a DTS operating in a loop configuration mode, both fibre ends are connected to the DTS, so the point defect is at the centre of the loop.

2) Configure the DTS as for normal operation with an undisturbed fibre, including calibration of the fibre, if this is standard for normal operation. The DTS shall be configured to provide a full temperature measurement for all temperature sample points including those at the location of the point defect. The spatial resolution used shall be stated.

3) Stabilize the test fibre, including the point defect, at a constant temperature (e.g. 75 °C ± 0,5 °C).
4) Collect 20 consecutive temperature traces at measurement times of the shortest time provided by the DTS instrument and of 10 min. The following steps (5 through 10) shall be repeated for each measurement time.
5) Calculate the average temperature along a 51 point section of each averaged trace, 25 m each side of the (nominal) location of the point defect (these are the points highlighted in red in Figure B.1): the nominal location of the point defect is shown in cyan. The two average temperatures are shown in blue and green. The sample spacing in this example is 0,5 m.

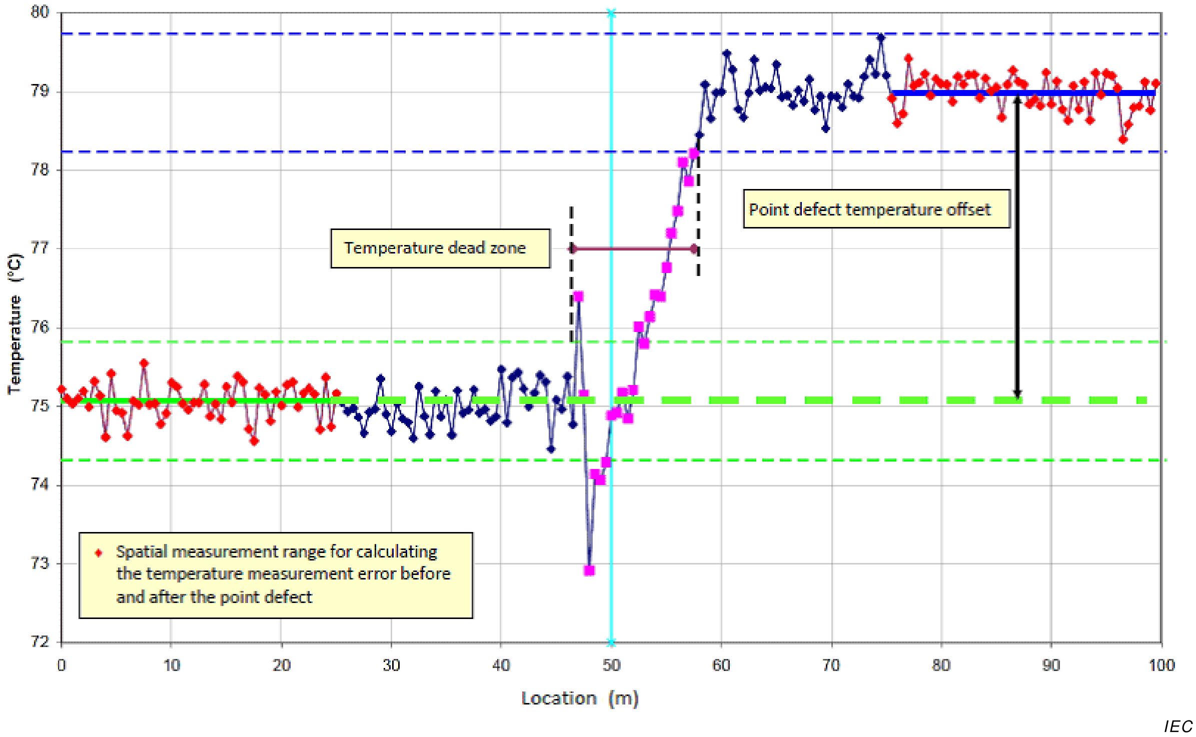


Figure B.1 – Point defect measurement (example)

6) Repeat the calculation of the two average temperatures for the entire set of 20 traces, and form the grand average of each. Report the difference between the two grand averages, the point defect temperature offset. One point defect temperature offset shall be calculated for each measurement time.
7) Calculate the standard deviation of the 51 points in each of the two sections. Repeat the calculation for the entire set of 20 traces, and take the average of the 20 results to obtain the temperature standard deviation σ of each section.
8) For each trace, use the two measured temperature standard deviations to obtain error bounds at ± 3σ about the two average temperatures on each side of the nominal location of the point defect (these are shown as dashed lines).
9) Calculate the location of the first sample point within ± 25 m of the nominal defect location to lie outside the left (green) error bounds, and the location of the last sample point within ± 25 m of the nominal defect location to lie outside the right (blue) error bounds. Repeat the calculation for the entire set of 20 traces, and calculate the median of the 20 results to obtain the temperature dead zone. One temperature dead zone shall be calculated for each measurement time.
10) Use the parameter calculation method from 5.1 to calculate the temperature measurement error for the test fibre, excluding the 25 m each side of the nominal location of the point defect. One temperature measurement error value shall be calculated for each measurement time.

11) The test results shall be reported including the following information:

a) the type of point defect introduced and its location; as well as measurements of loss, back-reflection, or other parameters, if available;
b) the measurement times and spatial resolution used;
c) the measured temperature dead zone;
d) the measured point defect temperature offset;
e) the measured temperature measurement error.

If an appropriate baseline exists (i.e. a measurement of temperature measurement error using the same length and type of fibre as in the point defect test), the baseline calibration uncertainty shall also be reported. It is recommended that the baseline temperature measurement error is always reported.

Bibliography

SEAFOM-MSP-01:2010, *Measurement Specification for Distributed Temperature Sensing*

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