



International
Standard

ISO 13473-4

**Characterization of pavement
texture by use of surface profiles —**

**Part 4:
One third octave band spectral
analysis of surface profiles**

*Caractérisation de la texture d'un revêtement de chaussée à
partir de relevés de profils de la surface —*

*Partie 4: Analyse spectrale par bande d'un tiers d'octave des
profils de la surface*

**First edition
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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

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This document was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

This second edition cancels and replaces the first edition (ISO/TS 13473-4:2008), which has been technically revised.

The main changes are as follows:

- the pre-processing of the input data to the spectral analysis has been improved and is in line now with the procedure of ISO 13473-1
- an old analogue technique has been removed and there is one normative method of the spectral analysis defined;
- significant improvements have been made to the uncertainty analysis.

A list of all parts in the ISO 13473 series can be found on the ISO website.

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

Introduction

Pavement texture is a basic road surface characteristic and is related to many important functional characteristics, such as noise emission from tyre-road interaction, friction between tyre and road, rolling resistance, tyre wear and the technical condition of the road surface.

Spectral analysis is commonly used in various fields of signal processing and has been found to be a useful method of pavement characterization for pavement surface profiles including texture measurements.

There are many ways to perform spectral analysis. The current document describes the spectral analysis, in octave and one-third-octave bands.

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Characterization of pavement texture by use of surface profiles —

Part 4: One third octave band spectral analysis of surface profiles

1 Scope

This document describes the methods that are available to perform a spectral analysis of a pavement surface profile. It specifies a method for performing spatial frequency analysis (or texture wavelength analysis) of two-dimensional surface profiles that describe the pavement texture amplitude as a function of the distance along a straight or curved trajectory over the pavement. It also details an alternative (non-preferred) method to obtain these spectra:

- a) constant-percentage bandwidth obtained by digital filtering (normative method);
- b) constant narrow bandwidth frequency analysis by means of discrete Fourier transform (DFT), followed by a transformation of the narrow-band spectrum to an octave- or one-third-octave-band spectrum (informative).

The result of the frequency analysis will be a spatial frequency (or texture wavelength) spectrum in constant-percentage bandwidth bands of octave or one-third-octave bandwidth.

The objective of this document is to standardize the spectral characterization of pavement surface profiles. This objective is pursued by providing a detailed description of the analysis methods and related requirements for those who are involved in pavement characterization but are not familiar with general principles of frequency analysis of random signals. These methods and requirements are generally applicable to all types of random signals; however, they are elaborated in this document for their use in pavement surface profile analysis.

NOTE The spectral analysis as specified in this document cannot express all characteristics of the surface profile under study. In particular, the effects of asymmetry of the profile, e.g. the difference of certain functional qualities for “positive” and “negative” profiles cannot be expressed by the power spectral density, as it disregards any asymmetry of the signal (see [Annex B](#)).

2 Normative references

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

ISO 13473-2, *Characterization of pavement texture by use of surface profiles — Part 2: Terminology and basic requirements related to pavement texture profile analysis*

ISO 13473-3, *Characterization of pavement texture by use of surface profiles — Part 3: Specification and classification of profilometers*

IEC 61260-1, *Electroacoustics — Octave-band and fractional-octave-band filters — Part 1: Specifications*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13473-2 and the following apply.

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

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

drop-out

data in the measured profile indicated by the sensor as invalid

3.2

drop-out rate

percentage (%) of measured points within the *evaluation length* (3.3) which are identified as being invalid

3.3

evaluation length

l

length of a portion of a profile which has been or is to be analysed

Note 1 to entry: The evaluation length may or may not be equal to the *profile measurement length* (3.5) (but never greater).

Note 2 to entry: Evaluation length is normally expressed in metres (m) or millimetres (mm).

3.4

measurement speed

v

speed at which the *profilometer* (3.6) sensor traverses the surface to be measured

Note 1 to entry: Measurement speed is normally expressed in kilometres per hour (km/h) or metres per second (m/s).

3.5

profile measurement length

l_p

length of an uninterrupted profile measurement

Note 1 to entry: Profile measurement length is normally expressed in metres (m) or millimetres (mm).

3.6

profilometer

device used for measuring the two-dimensional (2D) profile of a pavement surface

Note 1 to entry: Any design of profilometer could be used if the requirements in ISO 13473-3 is fulfilled for the specific purpose of the analysis.

Note 2 to entry: Profilometers can be divided into stationary, mobile low speed or mobile high speed devices.

3.7

power spectral density

PSD

quantity expressing the power contained in a signal per unit frequency or per unit wavelength as a function of frequency or wavelength

Note 1 to entry: In the case of a discrete Fourier transform of a sampled signal, the PSD may be defined as the squared magnitude of the components of the Fourier series divided by the effective bandwidth of the (narrow) bands of the Fourier spectrum (see C.4).

Note 2 to entry: In the case of spectral analysis of a pavement surface profile, the signal is not a function of time but of evaluation length l . The Power Spectral Density may then be given as a function of the spatial frequency or the (texture) wavelength and will be expressed in the unit $\text{m}^2/\text{m}^{-1} = \text{m}^3$ or in the unit m^2/mm , respectively.

Note 3 to entry: The word “Power” in this designation originates from electric and acoustic signal terminology where signals incorporate actual power and where the squared amplitude is a measure of this power.

3.8 sampling interval

ΔX
distance between two adjacent data points of the surface profile, which is equal to the measurement speed divided by the sampling frequency of the sensor

Note 1 to entry: Sampling interval is normally expressed in millimetres (mm).

3.9 spatial frequency

f_{sp}
number of sinusoidal cycles per unit length

Note 1 to entry: Spatial frequency is normally expressed in reciprocal metres (m^{-1}); see also [3.12](#), Note 3.

Note 2 to entry: The term “frequency” used in the time domain, corresponds to “spatial frequency” in the space domain.

3.10 surface profile texture profile

$Z(X)$
upper contour of a vertical cross-section through a pavement

Note 1 to entry: Texture profile is similar to surface profile but limited to the texture range.

Note 2 to entry: The profile of the surface is described by two coordinates: one in the surface plane, called distance (the abscissa), and the other in the direction normal to the surface plane, called vertical displacement (the ordinate). The distance may be in the longitudinal or lateral (transverse) directions in relation to the travel direction on a pavement, or in a circle or any other direction between these extremes.

3.11 surface profile spectrum texture spectrum

spectrum obtained when a profile curve has been analysed by either digital filtering or Digital Fourier Transform (DFT) techniques to determine the magnitude of its spectral components at different *wavelengths* ([3.12](#)) or *spatial frequencies* ([3.9](#))

Note 1 to entry: Wavelengths between 0,5 mm and 500 mm belongs to the texture spectrum and 0,5 m to 50 m belongs to the unevenness spectrum^[12].

Note 2 to entry: A texture spectrum presents the magnitude of each spectral component as a function of either texture wavelength or spatial frequency.

3.12 texture wavelength

λ
quantity describing the horizontal dimension of the amplitude variations of a *surface profile* ([3.10](#))

Note 1 to entry: (Texture) wavelength is normally expressed in metres (m) or millimetres (mm).

Note 2 to entry: Wavelength is a quantity commonly used and accepted in electrotechnical and signal processing vocabularies. Since many users of this document might not be accustomed to use the term wavelength in pavement applications, and because electrical signals are often used in the analyses of road surface profiles, there is a possibility of confusion. Hence, the expression “texture wavelength” is preferred here to make a clear distinction in relation to other applications.

Note 3 to entry: Texture wavelength in ISO 13473 is the reciprocal of the spatial frequency, the unit of which is reciprocal metre (equivalent to cycles per metre). See also [3.9](#).

Note 4 to entry: Wavelengths are represented physically as the various lengths of periodically repeated parts of the profile.

3.13

texture profile level $L_{tx,\lambda}$

logarithmic transformation of an amplitude representation of a surface profile curve $Z(X)$, the latter expressed as a root mean square value

EXAMPLE $L_{tx,80}$ denotes the texture profile level for the one-third-octave band having a centre wavelength of 80 mm, see ISO 13473-2:2002, Table 1.

Note 1 to entry: Octave-band and one-third-octave-band filters are specified in ISO 13473-2:2002, 4.4.

Note 2 to entry: Texture amplitudes expressed as root-mean-square values, whether filtered or not, may have a range of several magnitudes, typically 10^{-5} m to 10^{-2} m. Spectral characterization of signals is used frequently in studies of acoustics, vibrations and electrotechnical engineering. In all those fields, it is most common to use logarithmic amplitude scales. The same approach is preferred in this document.

Note 3 to entry: Texture profile levels in practical pavement engineering typically range from 20 dB to 80 dB with these definitions.

4 Symbols and abbreviated terms

A list of symbols and abbreviations used in this document is given in [Table 1](#).

Table 1 — Meaning of symbols and abbreviations

Symbol or term	unit	Explanation
DFT		Discrete (fast) Fourier transform
FFT		Fast Fourier transform
PSD		Power spectral density
l	m	Evaluation length
l_p	m	Profile measurement length
N	-	Number of samples
λ	m, mm	Texture wavelength,
$\lambda_{\max}$	m, mm	Longest (texture) wavelength
v	m/s	Measurement speed
$Z(X)$	m	Texture profile
Δf	Hz	Bandwidth of the frequency interval
$L_{TX,\lambda}$	dB	Texture profile level, in octave (wavelength) band λ
$L_{tx,\lambda}$	dB	Texture profile level, in one-third-octave (wavelength) band λ
a_λ	m	Root mean square value of the vertical displacement of the surface profile
a_{ref}	m	Reference value of the surface profile amplitude (= 10^{-6} m)
z_i	m	Amplitude of the i^{th} profile-value of a sampled profile
ΔX	m, mm	Step size of a sampled profile
α	-	Constant factor used as a limit for identifying spikes
f_s	m^{-1}	Sample frequency
f_{sp}	m^{-1}	Spatial frequency
$f_{\text{sp},m}$	m^{-1}	Centre frequency of fractional octave band
b_0	M	Offset of the surface profile
b_1	-	Slope of the surface profile
$w_{i,C}$	-	Split Cosine Bell Window
$Z_{i,\text{win}}$	m	Windowed surface profile
Z_k	m	Discrete Fourier transformation of the windowed profile

Table 1 (continued)

Symbol or term	unit	Explanation
$Z_{\text{PSD},k}$	m	Power spectral density of narrow band m
$Z_{\text{p},m}$	m	Power within fractional-octave band m
j	-	Imaginary unit ($j^2 = -1$)
m	-	Index for the fractional-octave band
n	-	Bandwidth designator

5 Basic outline of methodologies of spatial frequency analysis

Principally, there are two alternative methods to obtain a spatial frequency spectrum in constant-percentage bandwidth bands of octave- or one-third-octave width. These two methods are:

- Method 1 – digital constant-percentage bandwidth filtering.
- Method 2 – constant narrow bandwidth frequency analysis by means of Discrete Fourier Transform, followed by a transformation of the narrow band spectrum to an octave- or one-third-octave band spectrum.

Method 1 is the main normative method. Both methods yield similar results (within the confidence intervals arising from measurement and analysis uncertainty), on condition that the signal quality is high and that in each of the methods, all signal processing components fulfil the requirements specified in this document. In addition, the narrow bands (method 2) should be appropriately combined into the wider bands, which may be a problem at lower spatial frequencies. Method 2 also includes more steps than Method 1.

The signal processing steps are shown in the scheme of [Figure 1](#). The calculation steps are described in more detail in [Clause 6](#), [Clause 7](#) and [Annex C](#).

NOTE Method 1 and Method 2 yield very similar results for all texture wavelengths^[1].

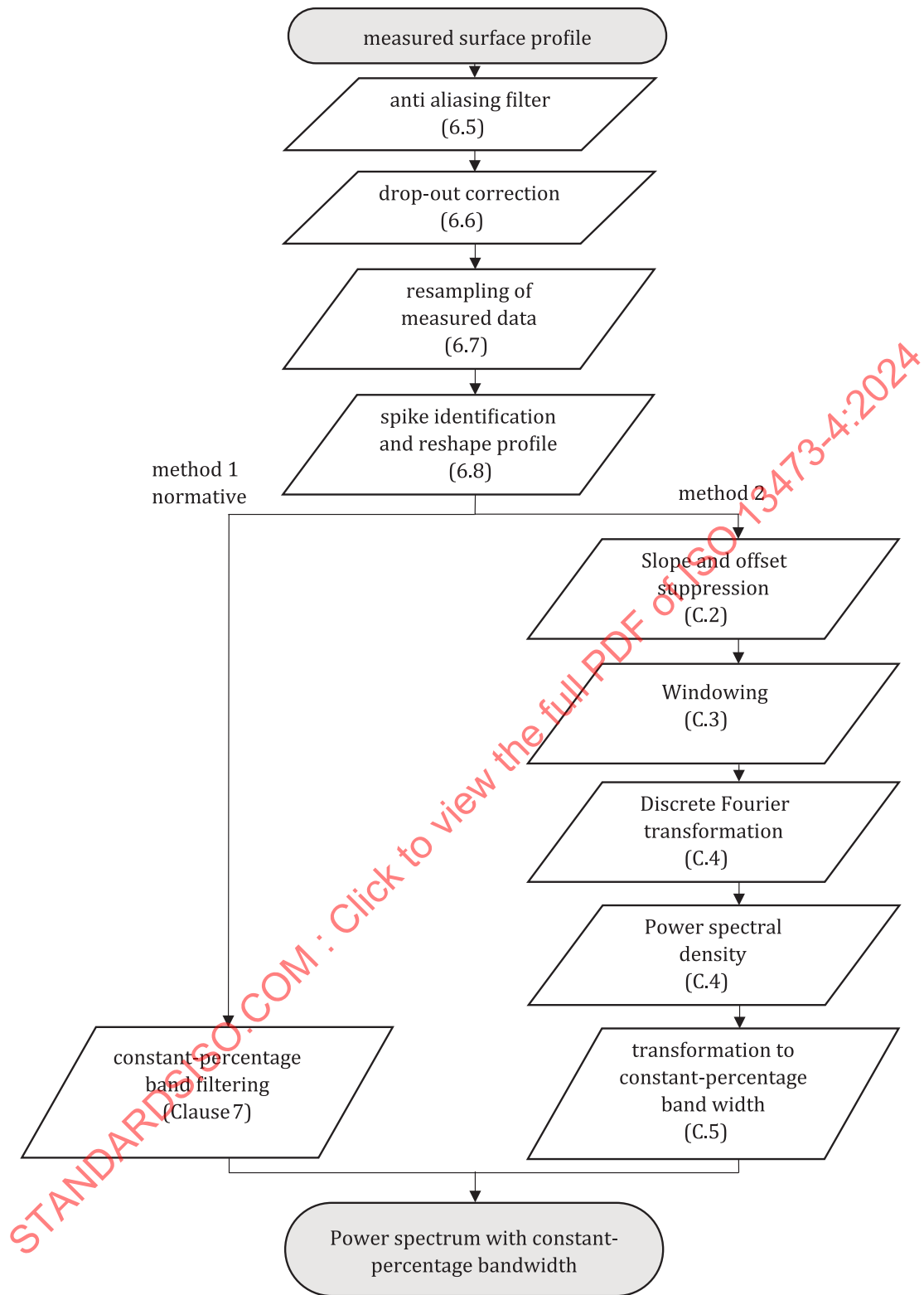


Figure 1 — Scheme for spectral analysis with reference to clauses and subclauses where the subject is described

6 Sampling of surface profiles

6.1 Requirements concerning profilometers and data preparations

The profilometer used to trace and/or sample the pavement texture irregularities shall comply with all requirements specified in ISO 13473-3 that are applicable to the wavelength range class under observation. If several wavelength range classes are being observed, the strictest requirements of these ranges shall be fulfilled.

6.2 Sampling of road sections

Sampling can be made either by a stationary or a mobile profilometer. The stationary profilometers may be sampling along a circular or straight line and in longitudinal or transversal direction. Mobile profilometers would most commonly sample along a longitudinal straight line but other sampling trajectories are possible according to the purpose of the survey.

In any case, the shape and position of the sampling trajectory should be noted and reported accurately. The spectral analysis shall only be performed on data sets which are derived from a single type of trajectory.

The required evaluation length depends on the frequency analysis to be performed. This leads to the following requirements, given by [Formulae \(1\)](#) and [\(2\)](#), for the minimum evaluation length, l :

$$l \geq 4 \cdot \lambda_{\max} \text{ for octave bands} \quad (1)$$

$$l \geq 12 \cdot \lambda_{\max} \text{ for one-third-octave bands} \quad (2)$$

where $\lambda_{\max}$ is the longest (one-third-) octave band centre wavelength used in the spectral analysis.

NOTE These requirements imply that the octave-band levels, respectively one-third-octave band levels, determined over these evaluation lengths will be within a 95 % confidence interval of approximately ± 3 dB around the true band levels (that would result from an infinitely long evaluation length).

For sampling of test sections in the longitudinal direction, the following procedure is recommended.

It is recommended to measure the entire section. Otherwise, several profile measurements evenly distributed over the length of the road section should be carried out. Each profile measurement length and/ or evaluation length shall be large enough to meet the requirement for the maximum wavelength of [Formulae \(1\)](#) and [\(2\)](#).

The number of profile measurements shall be such that the surface characteristics are well represented by the measured parts of the test section. The profiles measured shall be analysed separately. When the profiles measured constitute a representative sample from the test section under consideration, the relative standard deviation may be regarded as an estimate of the degree of variation of the surface characteristics along the test section.

It is recommended that each evaluation length is at least 1 m; such an evaluation length enables a one-third-octave-band $\lambda_{\max}$ of approximately 0,08 m, which is sufficient to cover the macrotexture range.

6.3 Measurement of laboratory samples

When testing road surface samples in the laboratory, it is advisable to use the largest samples available and to make maximum use of the dimensions of the sample. Rectangular samples should be scanned by the profilometer along parallel lines. The evaluation length, l , will be equal to the length of one uninterrupted scanned line.

Round samples may be scanned along the diameter or along a spiral or circular trajectory. The evaluation length l will be equal to the length of the uninterrupted scanned trajectory.

The relationship between the evaluation length l and the longest centre wavelength ($\lambda_{\max}$) to be used in the spectral analysis according to [Formulae \(1\)](#) and [\(2\)](#) is also applicable in the case of laboratory sample testing.

NOTE It is advisable to maintain a distance between parallel sampling lines or between the subsequent parts of a spiral trajectory such that the digital samples on one line or part of the trajectory can be considered to be statistically independent from the digital samples on neighbouring lines, in relation to the range of wavelengths included in the spectral analysis.

6.4 Texture profile levels (logarithmic scale)

The texture amplitude (in mm RMS) may be presented as a function of texture wavelength or spatial frequency. However, in many cases it is more practical to express it on a logarithmic rather than a linear scale. On a logarithmic scale the amplitude would be transformed to a “texture profile level”. The texture profile level can be expressed by the following [Formula \(3\)](#):

$$L_{TX,\lambda} \text{ or } L_{tx,\lambda} = 10 \lg \frac{a_{\lambda}^2}{a_{\text{ref}}^2} = 20 \lg \frac{a_{\lambda}}{a_{\text{ref}}} \text{ dB} \quad (3)$$

where

- $L_{tx,\lambda}$ is the texture profile level in one-third-octave bands (ref. 10^{-6} m) in decibels'
- $L_{TX,\lambda}$ is the texture profile level in octave bands (ref. 10^{-6} m), in decibels
- a_{λ} is the root mean square value of the vertical displacement of the surface profile, in metres
- a_{ref} is the reference value ($= 10^{-6}$ m)
- λ is the subscript indicating a value obtained with a one-third-octave-band or octave-band filter having centre wavelength λ

6.5 Anti-aliasing filtering

As digital sampling is involved in the spectral analysis method, aliasing errors can occur^[7]. To avoid such errors, the signal representing the surface profile shall be filtered before digital sampling with a low-pass filter with a cut-off frequency lower than half the sampling frequency.

The filter characteristics shall be such that there is a flat response within 0,4 dB up to the highest frequency to be analysed. The attenuation of the filter at half the sampling frequency shall be 60 dB or more.

If the analogue signal is inherently filtered by the detection process of the profilometer itself (such as the filtering by the spot-size of a laser beam) or by a natural high frequency roll-off, the combined characteristics of this inherent filtering and the anti-aliasing filter shall meet the above-mentioned requirements.

The requirements with respect to the filter characteristics may be alleviated if it can be determined from preliminary information that the surface profile spectrum will be continuous and smooth in the frequency range of interest.

6.6 Drop-out correction and interpolation

Care shall be taken to eliminate invalid readings (drop-outs) from the profile. For example, invalid measurements can occur due to surface photometric properties or shadowing of light in deep surface troughs. Instead, the invalid part of the profile shall be replaced with interpolated data from the nearest valid points.

As illustrated in [Figure 2](#), several drop-outs may occur in succession. When a series of invalid samples is preceded and followed by valid samples, each of the invalid samples shall be replaced by an interpolated value between the nearest valid samples, at each side. Linear interpolation shall be used.

Regarding linear interpolation, the invalid samples are replaced by an interpolated value Z_i according to [Formula \(4\)](#):

$$z_i = \frac{z_n - z_m}{n - m} (i - m) + z_m \quad (4)$$

where

- i is the sample numbers where the value is invalid;
- m is the sample number of the nearest valid value before i ;
- n is the sample number of the nearest valid value after i ;
- z_i is the interpolated value for sample i ;
- z_m is the value of sample m ;
- z_n is the value of sample n .

When the invalid sample(s) constitute(s) the beginning or the end of a sampled profile, the invalid samples shall be replaced by the value of the nearest valid sample. This method of extrapolation shall be limited to a maximum length at either side of the sampled profile data series equal to 5 mm. Otherwise that part of the profile is to be considered invalid.

For the study of road surface singularities (like joints), such singularities can be intentionally included in the analysis, on condition that no drop-out readings of the sensor occur.

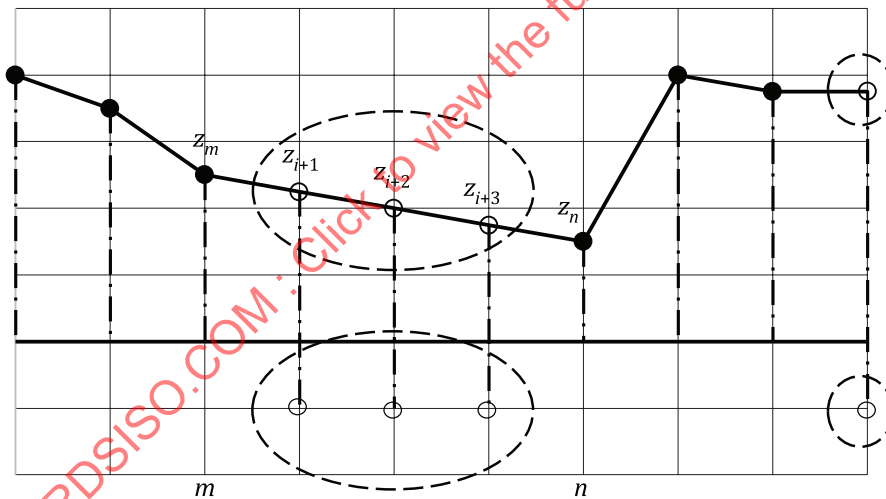


Figure 2 — Illustration of interpolation and extrapolation of drop-outs.

NOTE In the case illustrated in [Figure 2](#) there are three intermediate consecutive drop-outs, which are linearly interpolated between the samples at position m and n , and one drop-out in the end of the profile, which is extrapolated from the preceding valid sample.

The measurement on a particular pavement profile is considered valid only if the drop-out rate meets the following criterion:

Profiles with loss of data due to drop-outs greater than 10 % (of the total number of readings) shall be discarded.

6.7 Resampling to a constant spatial resolution

This requirement is applicable to the majority of profilometer systems, particularly those using the single-sensor triangulation principle. More advanced systems may not require this step if a similar process is performed within the measurement system.

The required spatial resolution depends on the shortest wavelength to be determined. The shortest wavelength should be at least 2,5 times the constant spatial resolution.

Resample the signal to the required spacing. Calculate the arithmetic average of all samples that fall within the required spacing. For example, if resampling is done to 1 mm spacing all texture profile samples in the spatial domain above 0 mm up to and including 1 mm are averaged.

In case the profile is extracted from a number of parallel profiles, which can be the case when analysing a three-dimensional representation of a surface, the total width of the selected profile lines should be less than 1 mm.

This resampling is needed also in the spatial domain if initial sampling was made at shorter intervals than the required spatial resolution.

6.8 Spike identification and reshaping the profile

The drop-out identification and interpolation will remove most “spikes”. However, there will be instances where the signal still contains spikes, the extent of which being dependent on the kind of surface measured. The purpose of the spike identification procedure is to determine whether these spikes are too sharp to be realistic or not and thus be a “true” or “false” reading. For the study of road surface singularities (like joints), such singularities can be intentionally included in the analysis, on condition that no drop-out readings of the sensor occur.

The spike removal procedure shall be as described in [Annex D](#). Spike removal is mandatory. For the profile to be valid, the removed spikes shall not correspond to more than 5 % of the total profile.

7 Spectral analysis in constant-percentage bandwidth bands (octave- or one-third-octave bands) by digital filtering

This last step shall be performed with digital octave- or one-third-octave-band filters. These filters shall have centre texture wavelengths and centre spatial frequencies according to ISO 13473-2, 4.4 and [Table 2](#), which were established to numerically correspond to the bands specified in IEC 61260-1. The upper and lower cut-off (-3 dB) frequencies of each band, as well as the shape of the filter frequency response shall conform to IEC 61260-1.

Table 2 — List of one-third-octave-band centre texture wavelengths and centre spatial frequencies

Centre texture wavelength mm	One-third-octave-band centre spatial frequency m ⁻¹
500	2,00
400	2,50
315	3,15
250	4,00
200	5,00
160	6,30
125	8,00
100	10,0
80,0	12,5
63,0	16,0

Table 2 (continued)

Centre texture wavelength mm	One-third-octave-band centre spatial frequency m ⁻¹
50,0	20,0
40,0	25,0
31,5	31,5
25,0	40,0
20,0	50,0
16,0	63,0
12,5	80,0
10,0	100
8,00	125
6,30	160
5,00	200
4,00	250
3,15	315
2,50	400
2,00	500
1,60	630
1,25	800
1,00	1 000
0,80	1 250
0,63	1 600
0,50	2 000
0,40	2 500

Due to filter response time, a lead-in distance is required to allow for filter stabilization. The length of the lead-in distance shall meet the length requirements in 6.2. This condition is usually satisfied because most measurement systems have a measurement length greater than the evaluation length. The part of the measurement length before the evaluation length can be used for the lead-in distance. If the profile does not have data before the part to be evaluated, a lead-in can be generated using mirroring at the beginning of the profile. Use a mirror length equal to the minimum length requirement in 6.2. The mirroring procedure shall be as described in Annex E.

8 Uncertainty of analysis results

The uncertainty of results obtained from spectral analysis of pavement surface profiles according to this standard shall be evaluated in accordance with ISO/IEC Guide 98-3. Guidance on the determination of the expanded uncertainty is given in Annex A.

The uncertainty of the results of spectral analysis of pavement surface profiles will be determined by contributions from two main origins:

- the uncertainty of the measured surface profile signal, which constitutes the data input for the spectral analysis process;
- the added uncertainty caused by the spectral analysis process itself.

For the evaluation of the combined standard uncertainty and the expanded uncertainty of the octave-, one-third-octave- or fractional-octave-band levels resulting from the spectral analysis methods, the contributions from both origins shall be taken into account. In this document, the emphasis is on the contribution of the spectral analysis process.

9 Reporting of analysis results

When reporting analysis results, the following information shall be included:

- identification of the measurement equipment, its operating organization and the operators;
- date of measurement;
- location and identification of the test sections;
- description of the type of surface;
- description of surface contamination (if any): e.g. leaves, dirt, debris, sand, possible moisture;
- remarks about prominent surface conditions such as the existence of joints, excessive cracking, potholes;
- direction of the measured profile (longitudinal, transversal, circular, etc);
- measurement speed, or range of speed;
- evaluation length;
- spatial resolution;
- description of the characteristics of the analysis: method, octave, one-third-octave or fractional-octave band;
- rate of invalid measurement/interpolated values (drop-out);
- number of measurements (including number of runs over the tested surface and number of profile records in each run);
- octave-, one-third-octave- or fractional-octave band levels presented as an arithmetic average over all evaluation lengths of a test section, presented in tabular or in graphic form;
- optional: standard deviations of the individual octave-, one-third-octave- or fractional-octave-band levels over all evaluation lengths of a test section, presented as numerical values in tabular form and as uncertainty areas on either side of the average values in the graphic form;
- optional: the octave, one-third-octave or fractional-octave band levels for each evaluation length of the test section, presented in tabular form or in graphic form;
- expanded uncertainty of the results determined in accordance with the method given in [Annex A](#).

Annex A (normative)

Uncertainty of spectral analysis results

A.1 General

The results of the spectral analysis methods treated in this document consist of octave-, third-octave or fractional-octave-band levels, which together constitute a spectral representation of a road surface profile. It does not constitute a complete measurement method, but only describes the processing of data that are acquired according to measurement methods that are not treated in this document.

Therefore, the uncertainty of the final result can only partially be attributed to factors discussed in this document. Other contributions to this uncertainty will be determined by factors related to the measurement process. The uncertainty contributions from the first group of factors will be analysed and discussed in this annex. The uncertainty contributions from the second group shall be derived from standards describing the measurement methods. The measured surface profiles will be considered as input data and the propagation of the uncertainty of the input data to the output of the spectral analysis process will be discussed in this annex too.

The format for expression of uncertainties in this annex is in conformity with ISO/IEC Guide 98-3. This format incorporates an uncertainty budget, in which all the various sources of uncertainty are identified and quantified, from which the combined standard uncertainty can be obtained. The (quantitative) data necessary to calculate the combined standard uncertainty are only partially available at the moment. In so far as the uncertainty contributions cannot be quantified, indications are given of possible assessment methods for such quantification.

Finally, in accordance with ISO/IEC Guide 98-3, the combined standard uncertainty shall be multiplied with a coverage factor in order to achieve an expanded uncertainty with a coverage probability of 95 %.

A.2 Expression for the calculation of the fractional-octave-band levels

The general expression for the calculation of the fractional-octave-band level, $L_{tx,m}$, is given by the following [Formula \(A.1\)](#):

$$L_{tx,m} = \overline{L_{tx,m}} + \delta_{meas} + \delta_{length} + \delta_{spatial} + \delta_{drop} + \delta_{alias} + \delta_{slope} + \delta_{window} + \delta_{filter} \quad (A.1)$$

where

- $\overline{L_{tx,m}}$ is the expectation (mean value) of the result of the spectral analysis, expressed as the fractional-octave-band level);
- δ_{meas} is the Fourier transform of an input quantity to allow for any deviation caused by the measurement process of the surface profile [which is transformed into a deviation of the spectral values by propagation through the spectral analysis process (see [A.3.2](#))];
- δ_{length} is an input quantity to allow for any deviation caused during the spectral analysis process by possible limitations of the evaluation length;
- $\delta_{spatial}$ is an input quantity to allow for any deviation caused during the spectral analysis process by possible limitations due to spatial resolution of the resampling;

δ_{drop}	is an input quantity to allow for any deviation caused during the spectral analysis process by the occurrence of drop-outs;
δ_{alias}	is an input quantity to allow for any deviation caused during the spectral analysis process by imperfections of the anti-aliasing filter;
δ_{slope}	is an input quantity to allow for any deviation caused during the spectral analysis process by imperfections in the slope and offset suppression;
δ_{window}	is an input quantity to allow for any deviation caused during the spectral analysis process by a reduction of the effective signal length due to windowing;
δ_{filter}	is an input quantity to allow for any deviation caused during the spectral analysis process by imperfections of the pass band characteristics of the octave-, one-third octave- or fractional-octave filters.

NOTE The input quantities included in [Formula \(A.1\)](#) to allow for uncertainty contributions are those thought to be applicable in the state of knowledge at the time of preparing this document, but further research could reveal other types of uncertainty contributions.

A.3 Contributions to the spectral analysis uncertainty

A.3.1 General

As expressed in [Formula \(C.13\)](#), the expectation (mean value) of the fractional-octave-band level $\overline{L_{\text{tx},m}}$ is a logarithmic function of the power $Z_{p,m}$ contained within the fractional-octave band m , which in turn is obtained from the measured quantity Z_i in a series of conversion steps, expressed by the [Formulae \(C.3\)](#), [\(C.6\)](#), [\(C.7\)](#), [\(C.10\)](#) and [\(C.12\)](#).

Consequently, the input quantity Δ_{meas} to account for the combined deviations resulting from the measurement process, shall be derived from the measurement uncertainty of the measured quantity Z_i . This uncertainty will be specified in the International Standard describing the specifications for profilometers (see ISO 13473-3). The way the measurement uncertainty of Z_i is propagated through the spectral analysis process into a (partial) uncertainty associated with $L_{\text{tx},m}$ is described in [A.3.2](#).

The uncertainties associated with the input quantities δ are assumed to be of a stochastic nature and a probability distribution (normal, rectangular, etc.) is associated with each of these quantities. Its expectation (mean value) is the best estimate for the value of the quantity and its standard deviation is a measure of the dispersion of values, termed standard uncertainty. It is presumed that the mean values of all the input quantities given in [Formula \(A.1\)](#) are equal to zero. However, in any particular determination of a fractional-octave-band level during the spectral analysis of a road surface profile, the uncertainties do not vanish, and they contribute to the combined standard uncertainty associated with the values of the fractional-octave-band levels.

The estimation of the uncertainties associated with the input quantities should preferably be carried out for the actual parameter values and conditions that apply to a specific spectral analysis case. In [A.3.3](#), there is a discussion of how the uncertainties can be evaluated and indications are given of typical values of the standard uncertainties that may be expected for the spectral analysis method discussed in [Clause 7](#).

A.3.2 Propagation of measurement uncertainty through the spectral analysis process

If the measurement uncertainty of the measured profile signal Z_i has the character of a stochastic non-correlated deviation, this may be written as [Formula \(A.2\)](#):

$$Z_i = \overline{Z}_i + \delta_{\text{meas},i} \quad (\text{A.2})$$

where

$\overline{Z_i}$ is the expectation (“true” value) of the sampled displacement value of the profile Z_i ;

$\delta_{\text{meas},i}$ is the random deviation added to each sample i due to inaccuracies of the measurement process.

The Fourier transform of such a simple sum of two variables is equal to the sum of the Fourier transforms. If, according to A.3, the profile Z_i is multiplied with a window function w_i in the spatial domain, this will result in a convolution and a summation in the frequency domain as follows in Formula (A.3):

$$Z_k = W_k \cdot \overline{Z_k} + W_k \cdot \Delta_{\text{meas},k} \quad (\text{A.3})$$

where

Z_k is the Fourier transform of the sampled displacement values of the profile z_i ;

W_k is the Fourier transform of the windowing function w_i ;

$\overline{Z_k}$ is the Fourier transform of the expectation of the sampled displacement values of the profile Z_i ;

$\Delta_{\text{meas},k}$ is the Fourier transform of the random deviation due to inaccuracies of the measurement process $\delta_{\text{meas},i}$.

From this generally formulated result, it may be inferred that if the uncertainty in the spatial domain has a stochastic nature there will not be a frequency dependency of the uncertainty in the frequency domain.

If the uncertainty has the character of a white noise-like contribution to the profile signal, the spectrum of the uncertainty will be a constant in the frequency domain. This means that the uncertainty will cause a frequency independent increase of the Power Spectral Density of the “true” profile. If this influence is visualized on a logarithmic amplitude scale, the influence will seem larger for those parts of the spectrum with a low value of the PSD.

If presented in octave, third-octave or fractional-octave-band levels on a logarithmic frequency scale, the spectrum of a white noise increases with 3 dB per octave with increasing mid-band frequency. This means that for octave, third-octave or fractional-octave-band representations of the spectrum the influence of this type of uncertainty will increase with frequency.

A.3.3 Uncertainty associated with the input quantities, δ

A.3.3.1 Spectral analysis uncertainty originating from evaluation length limitations

As indicated in 6.2, the minimum evaluation length should be 4 times the longest centre wavelength for octave-band analysis and 12 times the longest centre wavelength for one-third octave-band analysis. The uncertainty thus depends on wavelength or more precise on the ratio between the evaluation length and the centre wavelength. Consequently, it can be expressed as a function of the ratio between the evaluation length and the centre wavelength.

Table A.1 — Standard uncertainties as a function of evaluation length

Ratio between evaluation length and centre wavelength		Standard uncertainty
Octave bands	One third octave bands	
4	12	1,5 dB
7	21	1,3 dB
15	45	1,0 dB
80	240	0,5 dB
360	1 080	0,25 dB

A.3.3.2 Spectral analysis uncertainty originating from the occurrence of drop-outs

The values of the standard uncertainty originating from drop-out occurrence may be assessed with the aid of results of a study, see for example Reference [11].

6.6 describes how to handle invalid readings. Drop-outs influence the texture level of the shorter wavelengths. The uncertainty depends thus on the wavelength or more precise on the ratio between the centre wavelength and the spatial resolution.

If drop-outs are linearly interpolated and the drop-out percentage does not exceed 10 %, the standard uncertainty may be estimated at 0,5 dB for wavelengths that are equal to or less than 10 times the spatial resolution. For wavelengths that are longer than 10 times the spatial resolution, the standard uncertainty may be estimated at less than 0,1 dB.

A.3.3.3 Spectral analysis uncertainty originating from imperfections of anti-aliasing filters

The values of the standard uncertainty originating from imperfections of anti-aliasing filters, as given in Table A.2, are estimated in view of the requirements of 6.5. The use of more appropriate values taken from actual specifications or test results of applied anti-aliasing filters is advisable.

A.3.3.4 Spectral analysis uncertainty due to influence of resampling

As indicated in 6.7, the shortest wavelength should be at least 2,5 times longer than the spatial resolution. The uncertainty due to the influence of resampling depends on the wavelengths or more exact on the ratio between the centre wavelength and the spatial resolution. It can thus be expressed as a function of this ratio.

Table A.2 — Standard uncertainties as a function of spatial resolution

Ratio between centre wavelength and spatial resolution	Standard uncertainty
2,5	1,0 dB
5	0,5 dB
10	0,1 dB
20	0,03 dB
40	0,01 dB

A.3.3.5 Spectral analysis uncertainty originating from imperfections of the octave, one-third octave or fractional-octave-band filters

IEC 61260 describes the classes of the filters and gives acceptance limits on the minimum and maximum relative attenuation for octave, third octave and fractional-octave band filters. In IEC 61260 the limits for the attenuation are a function of the ratio between the actual frequency and the centre frequency of the filter. Since the spectral value is mainly determined by the values between the band-pass frequencies it is justified to determine the uncertainty on that region. This results in an uncertainty of 0,4 dB for Class 1 filters and 0,6 dB for Class 2 filters.

A.3.3.6 Spectral analysis uncertainty originating from imperfections in the slope and offset suppression

The uncertainty due to imperfections in the slope and offset suppression depends on the wavelengths or more exact on the ratio between the evaluation length and the centre wavelength. It can thus be expressed as a function of this ratio. If this ratio is less than 20, the standard uncertainty can be estimated at 0,3 dB. Higher ratios may be estimated at less than 0,1 dB.

A.3.3.7 Spectral analysis uncertainty due to influence of signal windowing

The influence of the imperfections due to the signal windowing does not depend on the wavelength and can be estimated at 0,5 dB.

A.3.4 Assessment of uncertainty contributions

The contributions to the combined uncertainty associated with the value of the fractional-octave-band levels depend on each of the input quantities, their respective probability distributions and sensitivity coefficients, c_i . The sensitivity coefficients are a measure of how the values of the fractional-octave-band level are affected by changes in the values of the respective input quantities. In the model used in [Formula \(A.1\)](#), all sensitivity coefficients have the value 1. The contributions of the respective input quantities to the overall uncertainty are then given by the products of the standard uncertainties and their associated sensitivity coefficients. Thus, the information needed to derive the overall uncertainty is given in [Table A.3](#).

Table A.3 — Uncertainty budget for the determination of the fractional-octave-band level

Quantity	Estimate	Standard Uncertainty	Further information	Probability distribution	Sensitivity Coefficient	Uncertainty Contribution
	dB	u_i dB			c_i	$c_i u_i$ dB
δ_{meas}	0	a	See A.3.2	Normal	1	a
δ_{length}	0	a	See A.3.3.1	Normal	1	a
δ_{drop}	0	a	See A.3.3.2	Normal	1	a
δ_{alias}	0	0,1	See A.3.3.3	Normal	1	a
δ_{spatial}	0	a	See A.3.3.4	Normal	1	0,1
δ_{filter}	0	a	See A.3.3.5	Normal	1	a
δ_{slope}	0	a	See A.3.3.6	Normal	1	a
δ_{window}	0	a	See A.3.3.7	Normal	1	a

^a To be determined according to specific conditions.

NOTE As explained in [A.1](#), the uncertainty budget given above only contains uncertainty contributions due to spectral analysis. For uncertainty contributions related to the profile measurement process, reference is given to the relevant measurement standard.

A.4 Expanded uncertainty of the spectral analysis

The combined standard uncertainty of the determination of the fractional-octave-band level $u(L_{\text{tx},m})$ is given by the following [Formula \(A.4\)](#):

$$u(L_{\text{tx},m}) = \sqrt{\sum_{i=1}^8 (c_i u_i)^2} \quad (\text{A.4})$$

ISO/IEC Guide 98-3 requires an expanded uncertainty, U , to be specified, such that the interval $[L_{\text{tx},m} - U, L_{\text{tx},m} + U]$ covers 95 % of the values of $L_{\text{tx},m}$ that might reasonably be attributed to $L_{\text{tx},m}$. To that purpose, a coverage factor, k , is used that depends on the probability distribution associated with the quantity. The expanded uncertainty, U , shall be calculated according to [Formula \(A.5\)](#):

$$U(L_{\text{tx},m}) = k \cdot u(L_{\text{tx},m}) \quad (\text{A.5})$$

If the uncertainties may be assumed to have a normal distribution, the coverage factor k equals 1,95, which means that the expanded uncertainty is about twice the standard uncertainty.

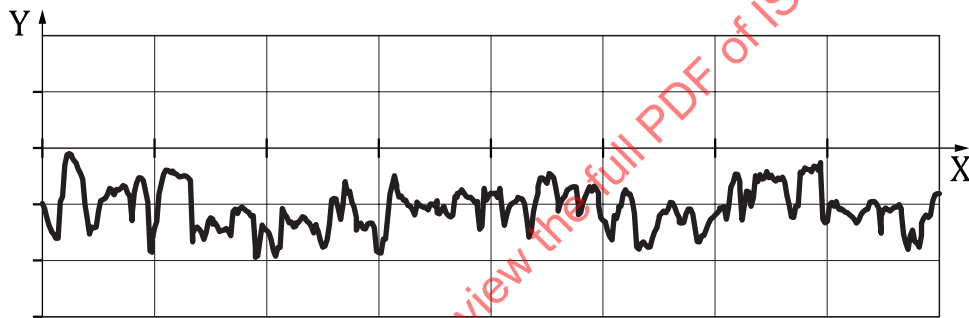
Annex B (informative)

Spectral analysis and profile asymmetry

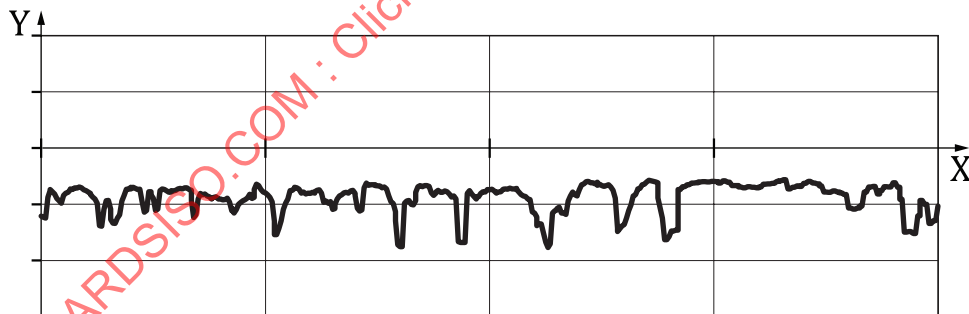
The method of spectral analysis given in this document, in a statistical sense a second moment analysis, cannot reveal all relevant characterizations of the pavement surface profile. The mathematical operations involved e.g. in the discrete Fourier transform and the determination of the power spectral density disregard any asymmetry of the signal under analysis.

Therefore, the user of this method should be aware that some relevant information contained in the profile may be lost during the process of spectral analysis. A possible asymmetry of the profile, resulting in a “positive” or “negative” texture will not be detected in the results of the analysis. It would require an analysis of the skewness, i.e. the third statistical moment of the quantity, to reveal this aspect of the profile.

Nevertheless, a “positive” texture (exhibiting protrusions) may show a significantly different behaviour in functional qualities, like skid resistance or noise generation, than a negative texture (exhibiting depressions).



a) Surface profile of positive macrotexture (surface dressing with maximum stone size 11 mm)



b) Surface profile of negative macrotexture (stone mastic asphalt with maximum stone size 16 mm)

Key

- X distance, in longitudinal direction
Y profile height, in vertical direction

Figure B.1 — Examples of surface profiles

Although the method of spectral analysis does have these shortcomings, it is sufficiently relevant as a method of characterization of road surfaces and is therefore elaborated in this document with the aim to standardize the method and to improve the uniformity of the determination of road surface characteristics. For the moment, the conclusion shall be that no solution for a more comprehensive spectral description of road surface profiles is ready for standardization.

Annex C (informative)

Spectral analysis by means of discrete (fast) Fourier transform methods

C.1 Overview of methodology

The methodology to derive a constant-percentage bandwidth power spectrum from a road surface profile by Discrete Fourier Transform or Fast Fourier Transform consists of the steps listed in [Table C.1](#).

Table C.1 — List of steps to be performed for discrete Fourier transform analysis

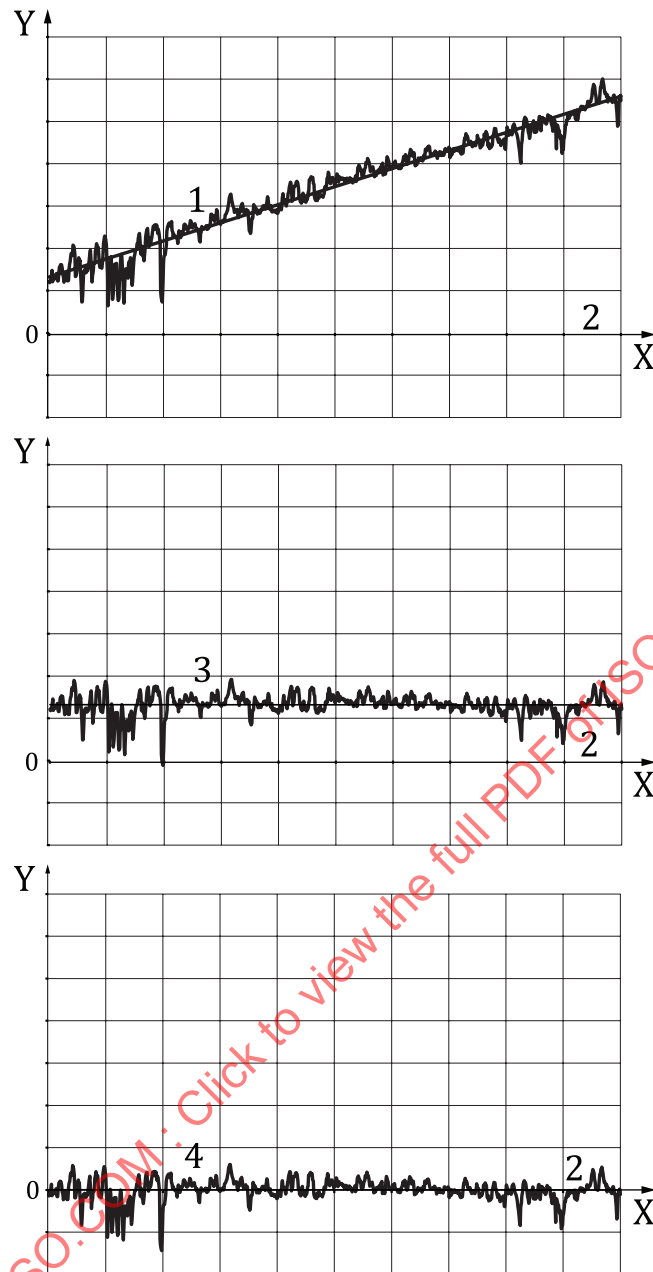
Step	Result	Discussed in
Anti-aliasing filtering	Analogue signal	6.5
Interpolation of drop-outs	Digital signal with interpolated values at drop-outs	6.6
Digital sampling	Digital signal sampled at intervals $\Delta (=v/f_s)$	6.7
Offset suppression	Digital signal with zero average	C.2
Slope suppression	Digital signal with zero slope	C.2
Windowing	Finite sampled signal with length $l = \Delta X \times N$ with N being the number of samples	C.3
Discrete Fourier Transform	Complex spectrum with constant bandwidth $\Delta f_{sp} = 1/l$ at frequencies $0 \dots (N - 1) \Delta f_{sp}$	C.4
Transformation to Power Spectral Density	Power density spectrum with constant bandwidth $\Delta f_{sp} = 1/l$ at frequencies $0 \dots (N - 1) \Delta f_{sp}$	C.4
Transformation to constant relative bandwidth spectrum	Profile level spectrum with constant-percentage bandwidth	C.5

NOTE The discrete Fourier transform is a Fourier transform of a sampled signal with a finite number of samples. Mostly, it is referred to as fast Fourier transform (FFT). The adjective “fast” refers to the efficient algorithm that is used for the transformation. The algorithm works most efficiently when the number of samples is a power of 2. In many programming languages where the Fourier transform is referred to as FFT, the language simply uses the fastest possible algorithm. Some programming languages might require that the number of samples be a power of 2. A Fourier transform for an arbitrary number of samples could be indicated as DFT (discrete Fourier transform). In this document, no distinction will be made between discrete Fourier transform and fast Fourier transform; both will be indicated as DFT.

C.2 Slope and offset suppression

To obtain a profile curve useful for mathematical calculations, it is necessary to remove any slope or long-wavelength component (slope suppression), as well as to bring the mean level of the profile over the evaluation length to zero (offset suppression). This can be accomplished by subtracting a least-squares fitted straight line from the profile. The resulting mean line of the profile is then at zero level. See illustration in [Figure C.1](#).

The features in [Figure C.1](#) are exaggerated in order to make the illustration clearer. If subtracting a least-squares fit from the profile, the two steps from left to right in the figure are performed in one operation (which can be performed also by high-pass filtering).



Key

X	horizontal distance	Y	vertical distance
1	original profile	2	zero level
3	slope suppression applied	4	offset suppression applied

Figure C.1 — Illustration of slope and offset suppressions

Let z_i be the measured signal value for sample i at x_i and N be the number of samples within the evaluated signal, then the slope b_1 of the surface profile is given by [Formula \(C.1\)](#):

$$b_1 = \frac{12 \sum_{i=0}^{N-1} iz_i - 6(N-1) \sum_{i=0}^{N-1} z_i}{N(N+1)(N-1)} \quad (C.1)$$

The offset b_0 of the surface profile is given by [Formula \(C.2\)](#):

$$b_0 = \frac{1}{N} \sum_{i=0}^{N-1} z_i - b_1 \cdot \frac{1}{2}(N-1) \quad (C.2)$$

The measured signal value Z_i shall be corrected for slope and offset according to [Formula \(C.3\)](#) resulting in the corrected sampled signal value Z_i :

$$Z_i = Z_i - b_1 i - b_0 \quad \text{for } i=0, \dots, N-1 \quad (C.3)$$

NOTE For the calculation of the slope and offset correction, the surface profile is treated as a function of the sample number i , and not of the measured distance x ($= i \Delta x$).

C.3 Windowing

The discrete Fourier transform assumes that the input signal repeats itself with a period equal to the signal duration. For instance, a signal sampled over a distance l is considered to repeat itself at $\dots, -2l, -l, 0, l, 2l, \dots$, etc. At the edges of the signal, there might be a jump in the composite signal, this effect is known as leakage. Leakage has its effect on the spectrum that is obtained. To prevent leakage, a window, which reduces the signal to zero at the edges, shall be applied.

The window type to be used for spectral analysis of surface profiles is the split cosine bell window (SCBW; sometimes indicated as cosine digital tapering window) The shape of the SCBW is that of an increasing squared cosine in the first tenth of the window length ($0 \leq i < N/10$) and a decreasing squared cosine in the last tenth ($9N/10 < i \leq N$). In the intermediate section of eight tenths of the length, the window is equal to unity, as follows:

$$w_{i,C} := \begin{cases} \cos^2\left(\frac{5\pi i}{N} - \frac{\pi}{2}\right) & \text{for } 0 \leq i < \frac{N}{10} \\ 1 & \text{for } \frac{N}{10} \leq i \leq \frac{9N}{10} \\ \cos^2\left(\frac{5\pi i}{N} - \frac{9\pi}{2}\right) & \text{for } \frac{9N}{10} < i \leq N \end{cases} \quad (C.4)$$

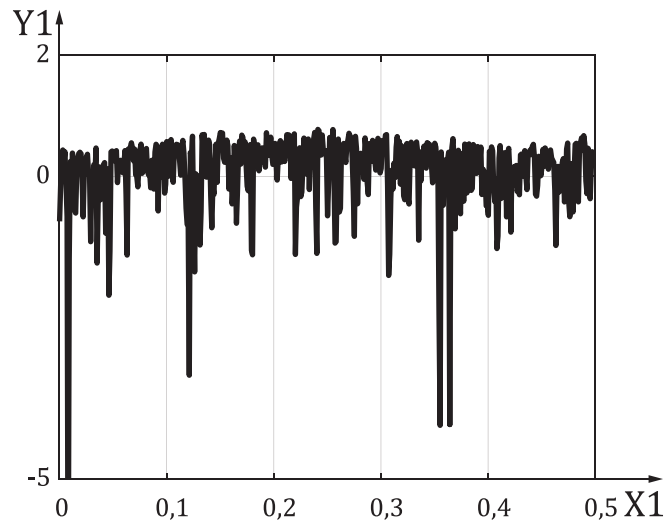
The window shall be applied by simply multiplying the signal with the filter function (see [Figure C.2](#)). Because the signal will be attenuated by this operation, it shall be normalized by dividing the product by the integral of the window. Therefore, the window shall be applied as follows by [Formula \(C.5\)](#):

For the Split Cosine Bell Window:

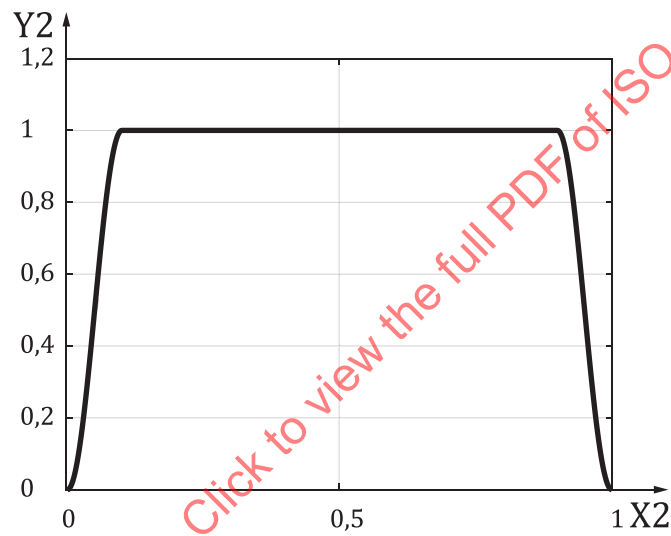
$$Z_{i,\text{win}} = \frac{w_{i,C} Z_i}{0,9354} \quad \text{for } i=0, \dots, N-1 \quad (C.5)$$

The general formula for determining the windowed profile is given in [Formula \(C.6\)](#)

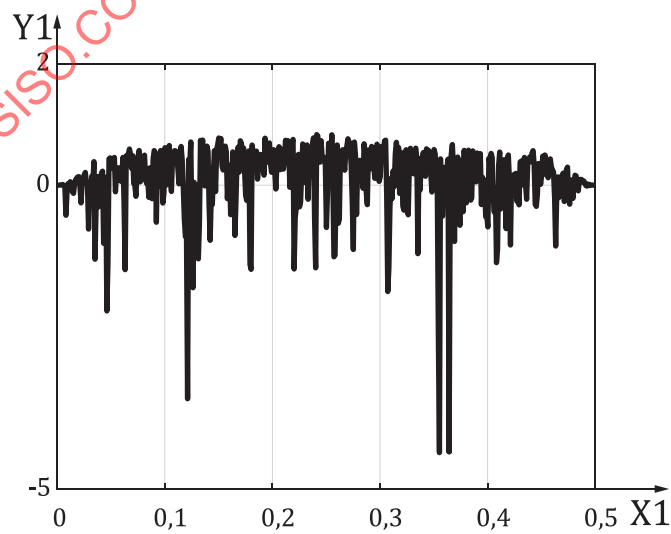
$$Z_{i,\text{win}} = \frac{w_i Z_i}{\sqrt{\frac{1}{N} \sum_{i=0}^{N-1} w_i^2}} \quad \text{for } i=0, \dots, N-1 \quad (C.6)$$



a)



b)



c)

Key

- X1, X2 distance, in metres
- Y1, Y2 amplitude, in millimetres
- a measured road surface
- b split Cosine Bell Window (SCBW)
- c measured road surface after windowing (SCBW)

Figure C.2 — Illustration of the application of a split cosine Bell window

C.4 Discrete Fourier transform and power spectral density

The discrete Fourier transform (DFT) Z_k of the windowed profile is defined by [Formula \(C.7\)](#):

$$Z_k = \frac{1}{N} \sum_{i=0}^{N-1} Z_{i,\text{win}} e^{-j \left(\frac{2\pi k}{N} \right) i} \quad \text{for } k=0, \dots, N-1 \quad (\text{C.7})$$

in which j is the imaginary unit ($j^2 = -1$).

NOTE 1 Z_k is a function of the spatial frequency, while $Z_{i,\text{win}}$ is a function of the measured distance. Thus, the DFT comprises a transformation from the distance domain to the spatial frequency domain.

In some software packages that provide a DFT or FFT, this definition may be different, where the factor $\frac{1}{N}$ is sometimes disregarded or replaced by $\frac{1}{\sqrt{N}}$. This can be checked by applying Parseval's theorem defined by [Formula \(C.8\)](#):

$$\sum_{i=0}^{N-1} |Z_{i,\text{win}}|^2 = N \sum_{k=0}^{N-1} |Z_k|^2 \quad (\text{C.8})$$

If [Formula \(C.8\)](#) proves to be true, the DFT is in accordance with [Formula \(C.7\)](#); if not, the documentation of the software should be checked for the definition used.

NOTE 2 [Formula \(C.8\)](#) compares the total power of the signal in the distance domain with the total power of the signal in the spatial frequency domain and thus checks whether the law of the conservation of energy is satisfied.

The result of the DFT is a constant bandwidth narrow band spectrum with complex values. The bandwidth depends on the evaluation length l and is equal to [Formula \(C.9\)](#):

$$\Delta f_{\text{sp}} = \frac{1}{l} \quad (\text{C.9})$$

The frequency scale starts at 0 with steps equal to Δf_{sp} until $(N-1)\Delta f_{\text{sp}}$ (note: $N\Delta f_{\text{sp}} = \frac{1}{\Delta x}$). Only the frequencies up to $(\frac{1}{2}N-1)\Delta f_{\text{sp}}$ shall be used for further evaluation.

To obtain the power spectral density (PSD) from the results of a DFT the amplitude of each narrow band shall be squared and divided by the spectral bandwidth according to [Formula \(C.10\)](#):

$$Z_{\text{PSD},k} = \frac{1|Z_k|^2}{\Delta f_{\text{sp}}} \quad \text{for } k=0, \dots, \left(\frac{1}{2}N-1\right) \quad (\text{C.10})$$

The narrow band spectral value of the profile level $L_{\text{tx},k}$ is calculated with [Formula \(C.11\)](#):

$$L_{\text{tx},k} = 10 \lg \left(2 \left| \frac{Z_k}{a_{\text{ref}}} \right|^2 \right) \quad \text{for } k=0, \dots, \left(\frac{1}{2}N-1\right) \quad (\text{C.11})$$

where

a_{ref} is the reference value of the surface profile amplitude ($= 10^{-6}$ m);

$L_{\text{tx},k}$ is the profile level within frequency band f_k with bandwidth Δf_{sp} (dB).

C.5 Transformation of constant bandwidth spectral data to constant-percentage bandwidth spectral data

The transformation of a constant bandwidth spectrum to a constant-percentage bandwidth spectrum can be performed according to the procedure specified below, which is valid only for a transformation on the spatial frequency scale. A procedure for a transformation on the wavelength scale would require other, more complex formulae.

For the derivation of a constant-percentage bandwidth spectrum from a constant bandwidth spectrum, the band pass (fractional-octave-band) filters may be assumed to be “ideal”, i.e. the pass-band is a square window in the frequency domain. The total power within this window is obtained by summation of all narrow band power contributions falling within this square window (see [Figure C.3](#)). The power of a narrow band that coincides with the boundary between two consecutive fractional-octave bands is divided proportionally over these fractional-octave bands.

The power $Z_{\text{p},m}$ within the fractional-octave band m is thus calculated from the narrow band power spectral density according to [Formula \(C.12\)](#).

$$Z_{\text{p},m} = Z_{\text{PSD},\text{lo}} \cdot \left(f_{\text{sp},\text{lo}} + \frac{1}{2} \cdot \Delta f_{\text{sp}} - 10^{\frac{-1,5}{10n}} f_{\text{sp},m} \right) + \sum_{k=\text{lo}+1}^{\text{up}-1} Z_{\text{PSD},k} \cdot \Delta f_{\text{sp}} + Z_{\text{PSD},\text{up}} \cdot \left(10^{\frac{1,5}{10n}} f_{\text{sp},m} - f_{\text{sp},\text{up}} + \frac{1}{2} \cdot \Delta f_{\text{sp}} \right) \quad (\text{C.12})$$

where

$f_{\text{sp},m}$ is the centre frequency of the fractional-octave band m ;

$f_{\text{sp},\text{lo}}$ is the centre frequency of the narrow band that coincides with the lower boundary of the fractional-octave band;

$Z_{\text{PSD},\text{lo}}$ is the power spectral density of the narrow band that coincides with the lower boundary of the fractional-octave band;

$f_{\text{sp},\text{up}}$ is the centre frequency of the narrow band that coincides with the upper boundary of the fractional-octave band;

$Z_{\text{PSD,up}}$ is the power spectral density of the narrow band that coincides with the upper boundary of the fractional-octave band.

n bandwidth designator to designate the fraction of an octave-band (1/1, 1/3...)

NOTE [Formula \(C.12\)](#) consists of three parts: 1) the proportional part of the power of the narrow band coinciding with the lower boundary of the fractional octave; 2) the summation of all narrow bands falling within the fractional-octave; and 3) the proportional part of the power of the narrow band coinciding with the upper boundary of the fractional octave.

The lower boundary frequency of the fractional-octave band m is: $10^{\frac{-1,5}{10n}} f_{\text{sp,m}}$:

and has the following relationship to $f_{\text{sp,lo}}$

$$f_{\text{sp,lo}} - \frac{1}{2} \Delta f_{\text{sp}} < 10^{\frac{-1,5}{10n}} f_{\text{sp,m}} < f_{\text{sp,lo}} + \frac{1}{2} \Delta f_{\text{sp}}$$

The upper boundary frequency of the fractional-octave band m is: $10^{\frac{1,5}{10n}} f_{\text{sp,m}}$:

and has the following relationship to $f_{\text{sp,up}}$

$$f_{\text{sp,up}} - \frac{1}{2} \Delta f_{\text{sp}} < 10^{\frac{1,5}{10n}} f_{\text{sp,m}} < f_{\text{sp,up}} + \frac{1}{2} \Delta f_{\text{sp}}$$

The fractional-octave band (texture) profile level is calculated with:

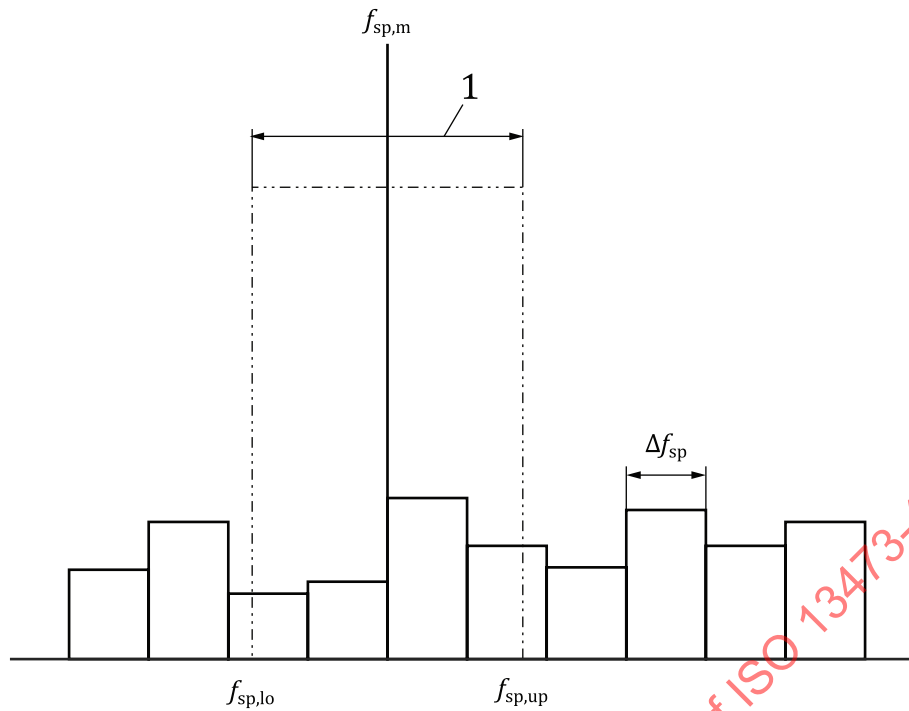
$$L_{\text{tx},m} = 10 \lg \left(\frac{Z_{\text{p},m}}{a_{\text{ref}}^2} \right) \text{ dB} \quad (\text{C.13})$$

where

a_{ref} is the reference value of the surface profile amplitude ($= 10^{-6} \text{ m}$);

$L_{\text{tx},m}$ is the (texture) profile level within fractional-octave band m (ref. 10^{-6} m), in decibels.

In the case of octave-band filtering, the profile level shall be indicated as $L_{\text{TX},m}$ (TX written as capitals).



Key

1 passband of 1/n-octave band

The power contained within the narrow bands coinciding with the upper and lower fractional-octave-band boundaries is allocated proportionally to the adjacent fractional-octave bands

Figure C.3 — Illustration of the allocation of the power contained within the narrow bands to a specific fractional-octave band

Annex D (normative)

Spike removal procedure

D.1 General

It is recommended that the laser sensors are equipped with a system to detect invalid readings. For every data point, the observed light intensity of the laser spot should be measured and if the light intensity is below a given threshold, the corresponding data point should be labelled as invalid or a “drop-out”. Nevertheless, this system can make mistakes and sometimes drop-outs are not recognized as such, which can lead to “phantom” peaks (spikes) in the profile which can negatively affect the results.

Therefore, a posteriori procedure should be applied to a measured texture profile to remove “suspect” high and sharp peaks from the profile. The procedure outlined in this Annex is intended to be inserted in the data processing chain after the resampling of the profile as described in [6.7](#).

The procedure basically consists of assigning the status of “invalid” reading to data points which meet certain criteria, even if the sensor did not recognize them as a drop out during the measurement. The procedure used is linear interpolation:

Consider a profile with amplitude Z_i , belonging to horizontal position index i and step size Δx . The criterion for assigning a posteriori the status of invalid reading to the i -th data point is [Formula \(D.1\)](#):

$$|Z_i - Z_{i-1}| \geq \alpha \cdot \Delta x \quad (\text{D.1})$$

with α a constant factor = 3.

NOTE It has been found that $\alpha = 3$ is a good choice [\[6\]](#).

The identification of spikes is done in the forward and reverse directions before any profile samples are replaced with interpolated values. The criterion ([D.1](#)) is checked for all the data points i of the profiles. After the spikes are identified the same interpolation procedure is used as for the drop out treatment, as described in [6.6](#).

D.2 Example

The procedure is illustrated with an example; see [Figures D.1, D.2, D.3 and D.4](#).

A texture profile is the input to the procedure ([Figure D.1](#)).