INTERNATIONAL STANDARD

IEC 61280-1-4

First edition
2003-01

Fibre optic communication subsystem test procedures –

Part 1-4: General communication subsystems – Collection and reduction of two-dimensional nearfield data for multimode fibre laser transmitters

Procédures d'essai des sous-systèmes de télécommunication à fibres optiques –

Partie 1-4: Procédures d'essai des sous-systèmes généraux de télécommunication – Recueil et réduction de données à deux dimensions de champs proches pour les émetteurs de laser à fibres multimodales

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES –

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FOREWORD

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International Standard IEC 61280-1-4 has been prepared by subcommittee 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:

FDIS	Report on voting
86C/465/FDIS	86C/494/RVD

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.

The committee has decided that the contents of this publication will remain unchanged until 2008. At this date, the publication will be

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- withdrawn;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

FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES –

Part 1-4: General communication subsystems – Collection and reduction of two-dimensional nearfield data for multimode fibre laser transmitters

1 General

1.1 Scope and object

This part of IEC 61280 sets forth a standard procedure for the collection of two-dimensional fibre optic nearfield grayscale data and subsequent reduction to one-dimensional data expressed as a set of three sampled parametric functions of radius from the fibre's optical center. The object of this standard is to reduce measurement errors and inter-laboratory variation, supporting accurate mathematical prediction of minimum guaranteed link length in gigabit and ten gigabit fibre optic data communications systems.

These radial functions are intended to characterize fibre optic laser sources for use in mathematical models predicting the minimum guaranteed length of a communications link.

Although available as a byproduct, estimation of the nearfield diameter is not an objective.

1.2 Assumptions

The 50-micron or 62,5-micron core near-parabolic graded-index multimode fibre used as the "test jumper assembly" is treated as if it possessed perfect circular symmetry about its optical center, as asymmetries in the launched optical flux distributions will dominate any lopsidedness of the test jumper assembly. It is further assumed that all cladding modes will be stripped by passage through the specified ten meters or more of fibre. The modes of a mode group need not carry equal flux. (In fact, with such short fibres, one thousand meters or less, unequal distribution of flux in the modes of a group is the norm, not the exception.)

The fibre micropositioner that moves the fibre in the receiving camera's field of view, being used to calibrate the camera for geometric distortions, is used as a reference standard. The microscope objective, used to project the magnified nearfield onto the CCD chip, is treated as an optically perfect thick lens.

The flux detectors are required to be both linear and memoryless; this excludes for instance lead sulphide vidicon detectors. Detectors shall meet the detector requirements of IEC 60793-1-43. Absolute radiometric measurement of flux (optical power flow) is not required. A computer is required to perform the needed computations, which are too extensive to be performed manually. Although the present measurement method assumes a CCD camera, mechanically-scanned "slitscan" and pinhole cameras may also be used.

Safety: all procedures in which an LED or laser source is used as the optical source shall be carried out using safety precautions in accordance with IEC 60825-2.

2 Normative references

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

IEC 60793-1-20: *Optical fibres – Part 1-20: Measurement methods and test procedures – Fibre geometry*

IEC 60793-1-41: *Optical fibres – Part 1-41: Measurement methods and test procedures – Bandwidth*

IEC 60793-1-43: *Optical fibres – Part 1-43: Measurement methods and test procedures – Numerical aperture*

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

3 Apparatus

As the objective of this international standard is to optically characterize laser sources, many different laser sources will be used, while the rest of the apparatus is held constant. The apparatus is calibrated using a broadband incoherent calibration source (such as a light-emitting diode (LED) or a xenon arc lamp) in place of the lasers.

3.1 Sources

There are two kinds of sources used in the present measurement method: the incoherent broadband overfilled source used for calibration, and the various laser sources being tested, as described in the following paragraphs.

There is always an optical connector between the source and the test jumper assembly.

3.1.1 Calibration source

The purposes of the calibration source are to find the optical center of the test jumper assembly, and also to determine the geometric corrections needed to convert 2D nearfield measurements taken in camera ("TV") coordinates into the equivalent true geometric measurements, compensating for non-square pixels, imprecisely known magnification factors, and the like. For these purposes, an incoherent broadband source that overfills the modes of the test jumper assembly is used in place of the laser sources under test.

Any spectrally broad non-coherent light source, such as a tungsten-halogen lamp, a xenon arc lamp or a light-emitting diode (LED) may be used to overfill the test jumper assembly's fibre. The chosen calibration source shall be stable in intensity over a time period sufficient to perform the measurements.

Optionally, an IEC 60793-1-41 mode scrambler may be used with the chosen calibration source to ensure more uniform overfilling of the fibre.

3.1.2 Laser under test

The only requirements on the lasers under test are that they have an operating wavelength compatible with the test jumper assembly and the detector, and have optical connectors or splices compatible with those of the test jumper assembly. The construction details of the laser sources are otherwise unspecified.

The laser drive current shall be sufficient to ensure that the laser always acts as a laser, rather than an LED.

3.2 Test jumper assembly

The purpose of the test jumper assembly is to strip cladding modes, and to allow speckle to be averaged out by mechanical flexing of a portion of the test jumper assembly.

The test jumper assembly shall be at least ten meters in length, made of germanium-doped near-parabolic graded-index fused-silica multimode "glass" category A1 fibre with a core diameter of either 50 µ or 62,5 µ and an overall glass diameter of 125 µs. The test jumper assembly shall consist of a single, uncut length of fibre with connectors at each end. The test jumper assembly connectors shall have single-mode mechanical tolerances, even though the fibre is multimode.

3.3 Fibre shaker

The purpose of the fibre shaker is to ensure that optical speckle is averaged out, with only a few percent of residual ripple or noise due to speckle being allowed to remain in the measured nearfields. Manual shaking of the fibre is generally not sufficient.

Part of the test jumper assembly shall be mechanically shaken continuously in each of three nominally orthogonal directions (using three independent shaker mechanisms) during the measurement, making at least one hundred shake cycles in each of the three directions during the measurement period. The shake frequencies in the three directions shall be chosen such that the three shake cycles synchronize no more often than once every five hundred cycles of the middle shake frequency.

A fibre shaker mechanism may be of any design as long as it induces large amplitude movements and flexing in the optical fibre. Fibre transverse displacements of more than 25 mm are suggested. The fibre shakers shall include a fibre-holding fixture for securely holding the fibre.

One exemplary mechanism design has three turns of fibre coiled into a 3-ply figure-eight arrangement, with the loops each being approximately 120 mm in diameter. A motor-driven eccentric drives a slider back and forth at about one stroke per second, alternately flattening and stretching one loop of the figure eight with 25 mm amplitude. Three such mechanisms in series will consume about $3 \times 3 \times (2 \times \pi \times 0{,}120) = 6{,}8$ meters of the test jumper assembly's fibre.

The fibre ends leading into and out of the fibre shakers shall be mechanically fixed or stabilized to prevent movement of fibres at connection points. In addition, the fibre shakers shall be mechanically isolated from the rest of the test setup so that vibrations are not transmitted to connection points throughout the apparatus, or to the micropositioner, camera, or microscope objective.

NOTE 1 Vibration reduction is easier if the fibre shaker is both statically and dynamically balanced, and if all moving components are light in weight.

NOTE 2 There is no required relation between the measurement period (containing the one hundred strokes) and the duration of a CCD camera exposure. Typically, in each measurement period, many exposures are taken and later summed, to avoid saturation of the CCD, and to ensure that speckle is in fact averaged out. Too short a total exposure time will prevent the desired averaging out of speckle.

3.4 Micropositioner

The purpose of the micropositioner is to bring the projected image of the fibre face into focus on the CCD chip within the camera, and also to support geometric calibration of the apparatus by making calibrated moves in X and Y, these axes being perpendicular to the optic axis Z.

The X-axis and Y-axis accuracy and resolution shall be one micron or less (finer), and it shall be possible to sweep the centroid of the calibration-source nearfield image from one edge of the CCD chip to the other, in both X and Y directions, by adjustment of the X and Y axes alone, with the nearfield image remaining substantially in focus on the CCD chip. The X-axis and Y-axis repeatability error shall be no larger than one third of a micron. It shall be possible to mechanically lock both the X and Y axes, to prevent drift in the apparent location of the test jumper assembly's optical center as tests are performed.

The Z-axis accuracy, repeatability, and resolution are unspecified, but shall be sufficient to bring the system into focus, and it shall be possible to mechanically lock the Z axis once focus is achieved, to prevent drift in the system magnification as tests are performed.

3.5 Microscope objective

Suitable optics shall be provided which project the magnified image of the output end of the test jumper assembly onto the receiving CCD chip such that the CCD can measure the entire nearfield flux distribution. These optics shall not restrict the numerical aperture of the formed image. (Based on IEC 60793-1-43.)

NOTE The actual magnification of the microscope objective as used in the present apparatus generally will not be the same as the nominal magnification factor engraved into the side of the objective, because the present apparatus differs from the standard microscope for which that nominal magnification factor was computed.

3.6 Detector

The flux detectors shall be both linear and memoryless; this excludes for instance lead sulphide vidicon detectors. Detectors shall satisfy the detector requirements of IEC 60793-1-43. Absolute radiometric measurement of flux (optical power flow) is not required.

Automatic gain control (AGC), if present, shall be disabled.

In CCDs with anti-blooming provisions, "saturation" is considered to occur at the "white-clip" level, not ultimate saturation, to preserve linearity of response.

If more than one in one thousand of the CCD's pixels are bad, or if the camera's offsets and pixel crosstalk are too large to allow accurate measurements, replace the camera. See 5.2.2 for details.

NOTE 1 Detector saturation may often be avoided by taking a number of very short exposures and summing them pixel for pixel.

NOTE 2 Neutral-density (ND) filters, optionally used to prevent detector saturation, are most conveniently placed between the microscope objective and the detector, and should be slightly tilted (by a few degrees of angle) to prevent reflections from the filter from reaching the source.

4 Sampling and specimens

Laser sources to be tested shall be chosen and prepared as defined by the user of this standard, who shall document the sampling and preparation procedures used, as described in Clause 7 of this standard. See Clause 3 for technical requirements on sources.

5 Procedure

5.1 Overview of the measurement procedure

This procedure consists of the following steps:

a) calibrate the camera,
b) measure the calibration source's 2D nearfield flux distribution,
c) measure one or more laser launch 2D nearfield flux distributions,
d) perform the calculations, and
e) report the results.

Note that calibration of the apparatus is critical to the accuracy of this measurement procedure. (See A.5 for description of the kinds of noise and errors which calibration can correct.) There is one calibration procedure and one nearfield measurement procedure, each being used multiple times. The following paragraphs first describe these two basic procedures, and then describe how these two procedures are used to implement the overall procedure.

The receiver end of the test jumper assembly shall be firmly attached to the camera and micropositioner assembly and left undisturbed during this entire process. All three micro-positioner axes shall be locked once calibration is complete, so that the fibre optical center and geometric scale factors (magnifications) found with the calibration source will continue to apply to measurements of the laser-source nearfields, without undue drift.

Calibrate the camera setup again, after taking all the laser data, to detect any drift in the camera or setup. Drift in geometric calibration can cause severe errors in the computed radial data functions.

The equipment must remain stable over the course of all measurements. Unless it can be shown not to be required, the laboratory ambient temperature shall be stable to within 2 °C, the equipment shall be allowed to warm up for at least fifteen minutes before calibrations or measurements are made, and any automatic gain control (AGC) features shall be disabled.

NOTE The tight temperature tolerance is required to counter the temperature sensitivity of the optical flux detectors in the camera, particularly the dark current. See A.5 for details.

5.2 Camera calibration

Any data taken shall be conditioned before use is made of that data. Conditioning involves pixel-by-pixel removal of offsets (due to dark current and fixed-pattern noise and the like), normalization for differences in pixel sensitivity (responsivity), possible identification of bad pixels and correction for the camera's geometric distortions. These issues are discussed individually in the following paragraphs.

5.2.1 Camera geometric calibration

The purpose of geometric calibration is to obtain the measurement data needed to compute the transform matrix. The transform matrix will be used to compensate measured 2D nearfield data for the actual size and shapes of the pixels in the CCD camera, and to calculate the actual magnification of the microscope objective lens as used in the present apparatus.

To calibrate cameras for these geometric effects, a fibre micropositioner, which is mechanical and built for precision, will be used as the reference standard.

Perform the following steps.

a) Overfill the fibre with light from the calibration source.

b) Move the test jumper assembly’s receiver end to three well-separated non-collinear positions (calibration points) in the camera’s field of view.

c) Record both the fibre position in true space (micropositioner X and Y coordinates) and the location of the corresponding centroid of flux in TV space (camera coordinates).

d) Solve for the 3x3 transform matrix mapping from the one 2D space to the other, as detailed in 6.1 and 6.2.

e) The “three well-separated non-collinear positions” can be in a rough equilateral or right triangle; any reasonable triangle will work, but the closer to equilateral, the better. The triangle should be as large as possible without having any part of the nearfield clipped off by the encroaching edges of the TV frame. The broadband incoherent source’s intensity should be set such that the peak intensity is at about 75 % of camera saturation.

NOTE Beware of mechanical backlash in the micropositioner. Always approach a new position from the same direction, overshooting and coming back, if necessary, and moving between the three calibration points always in the same direction and order. Also beware of mechanical drift, which occurs despite locking of the micropositioner axes. Drift will limit how many lasers can be tested before the calibration source must be used to again find the optical center of the test jumper assembly's fibre as seen by the CCD camera. A reasonable rate would be five or ten laser nearfield tests per center finding, but this will depend on the actual drift rate of the apparatus.

5.2.2 Camera optical calibration

The purpose of optical calibration is to obtain the measurement data needed to compensate measured 2D nearfield data for the actual sensitivity and offset of the individual pixels making up the data.

Perform the following procedure to remove offsets. First record the camera output in total darkness, then again with the nearfield to be measured illuminating the camera, and finally subtract the darkness picture from the illuminated picture, pixel for pixel. The two pictures should be taken at exactly the same camera temperature and exposure duration, to get adequate cancellation of offsets. If camera gain changes, say to compensate for a brighter or dimmer source, optical calibration shall be repeated.

Perform the following procedure to remove pixel sensitivity variation: Record the camera output while the camera is viewing a uniformly (to within 1 %) illuminated white area bright enough to almost saturate the camera, about 75 % of saturation, and then subtract the darkness picture, as described above. The inside of a small integrating sphere works well as a uniformly illuminated area. Compute the average pixel value by adding up the offset-compensated values of all pixels and dividing the sum by the number of pixels summed. Compute each element in the normalization matrix, which has one element per pixel, by dividing the average pixel value by the value for the pixel corresponding to that element. The resulting element values will typically range from 0,90 to 1,10. They are to be multiplied by their corresponding pixels, to normalize those pixels to the average sensitivity of all pixels, for every measurement that is made.

5.3 Measuring 2D nearfield flux distributions

The step-by-step procedure to measure 2D nearfield flux distributions is as follows.

a) Power all equipment up and allow it to warm up for at least fifteen minutes. Turn any automatic gain control (AGC) features off.

b) Calibrate the camera, as needed, both optically and geometrically, as described in 5.2. This process yields two 2D optical matrices, the pixel offsets and the pixel normalization factors respectively, plus one 3x3 transform matrix.

Steps a) and b) may be done once and the results used for a number of measurements made at the same time.

c) Without disturbing the receiver assembly or camera, take a measurement. The effective source intensity and/or camera sensitivity shall have been adjusted so that no pixels are allowed to saturate or bloom. The middle of the fibre shall be shaken continuously during the measurement, making at least one hundred shake cycles during the measurement period, to ensure that speckle is averaged out. Measured data shall be corrected for offset and sensitivity, yielding "conditioned data".

Report the conditioned data and the transform matrix.

5.4 Finding the optical center of the test jumper assembly

This is the step-by-step procedure to find the optical center of a graded-index multimode fibre, specifically the test jumper assembly, from measurements on the 2D nearfield resulting from an overfilled launch from the calibration source.

a) Using the calibration source and the test jumper assembly, measure the nearfield 2D flux distribution, as described in 5.3, yielding conditioned data and the transform matrix.

b) Compute the centroid of flux, as described in 6.2.

c) The above step 2 yields the centroid location in TV coordinates. Using the transform matrix, also compute the centroid location in true coordinates, as detailed in 6.1.

d) Report the centroid, in both true and TV coordinates, as the location of the fibre's optical center.

5.5 Finding the nearfield distribution of a laser under test

The test jumper assembly's fibre is treated as if it were perfectly circular, because practical fibre is axisymmetric to within a few percent, which is negligible in this application. Although the nearfield from a laser launch is not assumed to be circular or even symmetric (even after passage through ten or more meters of the graded-index multimode fibre of the test jumper assembly), the following process will collapse all such distributions by circular summation around the fibre optical center.

a) Using the calibration source under test and the test jumper assembly, calibrate the camera and find the optical center of the test jumper assembly. This step shall be performed whenever the receiver end of the apparatus is changed or disturbed, as well as periodically (to detect mechanical drift in scale factors or fibre center position).

b) Using the laser source under test and the test jumper assembly, without disturbing the receiver-end setup, measure the nearfield 2D flux distribution, as described in 5.3, yielding conditioned data. Repeat this step for each laser source to be tested.

c) Compute the radial data functions as described in Clause 6, and report the results as described in Clause 7.

NOTE Do not use the centroid of the laser nearfield distribution as the summation center. The laser centroid is not an accurate indicator of the test jumper assembly's optical center if the nearfield distribution is not symmetric, which is quite often the case in short fibres, those not exceeding one thousand meters in length. The optical center of the fibre is required (rather than the physical center of the fibre or the laser flux centroid) because it is the optical properties of the fibre that determine that fibre's bandwidth, and thus communications performance.

6 Calculations or interpretation of results

This clause specifies the exact procedure to be used to convert measured 2D nearfield data into the radial data functions. There are many mathematically similar or even almost equivalent approaches to reduction of such datasets. However, we have chosen and documented this specific procedure to ensure that all laboratories obtain the same radial data functions given the same 2D-nearfield dataset despite the effects of finite pixel and summation ring sizes.

6.1 Coordinate transforms

The following procedure calculates the transformation matrix required to transform from TV (CCD image) coordinates to true (micropositioner) coordinates. This transform will also undo the reversed and upside-down effects of the objective lens on the nearfield image.

For simplicity, "homogeneous coordinates" are used, which means that 2D points are represented as 3-element vectors (having only two varying elements), and transforms are represented as 3x3 matrices (having only six varying elements). The non-varying elements are either zero or one in value (See Foley [1][1]).

[1] Numbers in brackets refer to the bibliography.

In the following, x and y are in true coordinates, while x' and y' are in TV coordinates. The corresponding vectors are {x,y,1} and {x',y',1}, representing the same point as seen in true and TV coordinates respectively, both expressed in homogeneous form. To convert a measurement location in TV coordinates to the equivalent in true coordinates, the matrix {x',y',1} is matrix multiplied by the transform matrix M as shown:

$\{x,y,1\}^t = \{x',y',1\}^t \bullet M$

For this to work, the value of the transform matrix M is first determined, given the three non-collinear calibration points, which will be numbered 1, 2, and 3. By definition,

M = {{a,b,c},{d,e,f},{0,0,1}}.

There are six unknowns, and six data pairs (in three 2D points), so M can be found by solving the following system of equations by standard algebraic methods:

$\{x1,y1,1\}^t = \{x1',y1',1\}^t \bullet M$

$\{x2,y2,1\}^t = \{x2',y2',1\}^t \bullet M$

$\{x3,y3,1\}^t = \{x3',y3',1\}^t \bullet M$

In the above, the dot ("•") means matrix multiplication, and the superscript "t" in $\{...\}^t$ means transpose. The physical interpretations of the elements of M are discussed in A.6.

If M is the identity matrix, {{1,0,0},{0,1,0},{0,0,1}}, the transform has no effect, making {x,y,1} and {x',y',1} identical. In this case, true coordinates and TV coordinates are identical.

6.2 Centroid computation

Because computing the centroid is a linear operation, it suffices to collapse the 2D nearfield onto the one-dimensional X and Y axes, and compute the centroid of each of the two projections, rather than computing the centroid directly on the 2D distribution. Because the centroid is invariant under affine transforms (see Clause A.5), the centroid can be computed in TV coordinates, and then this centroid can be transformed into true coordinates; or, equivalently, it can be computed in true and then transformed to TV coordinates.

To eliminate position biases due to camera noise, especially pixel crosstalk noise, centroids shall be computed using only those pixels that exceed 10 % of the largest (peak) valid pixel value. Only centroid computations use this threshold.

NOTE The 10 % threshold is patterned after IEC 60793-1-20.

To find the X-coordinate and Y-coordinate of the flux centroid, perform the following steps in order. The Y-coordinate step or location is given in parentheses, for example, "X-coordinate (Y-coordinate)."

1) For each column (row), compute the sum of all intensity values in this column (row), yielding a 1D array of sums. This is called "collapsing" the 2D data onto the X axis (Y axis).
2) Compute the sum of the elements of the array of sums, yielding a single scalar number, the "sum of the sums".
3) Compute the product of each element of the array of sums with its TV-coordinate location. Sum these products to yield a single scalar number, the "sum of the products".
4) The X-coordinate (Y-coordinate) of the centroid is the "sum of the products" divided by the "sum of the sums".

6.3 Computation of radial data functions

1) Obtain the conditioned data and transform matrix by measurements of the 2D nearfields of the calibration source and the lasers under test.

2) Compute the raw, noisy r*I(r) function by circular summation of the conditioned data around the optical center of the fibre. This computation is done parametrically, with the radial index "i" being the parameter. Although tenth-micron steps are used here, the actual requirement is that the steps be half-micron or finer. This summation is performed by executing the following steps in the order given:

   a) Zero the s(i), rs(i), and c(i) arrays, which will carry the pixel intensity and radius summations, and the pixel counts, respectively. The integer index i ranges from zero to i_{max} which is typically chosen to be ten times the maximum integration radius of the test fibre, nominally 1,15 times the core-cladding boundary radius, with any factor in the range from 1,10 to 1,20 being allowed. In the case of 62,5-micron fibre, use i_{max} = (10)(62,5÷2)(1,15) = (10)(35,94) = 359,4 ≈ 360. For 50-micron core diameter fibre, instead use 290. This value "i" represents tenth-micron steps in distance from the fibre optical center, with i = 0 being all radii less than 0,1 μ, i = 1 being all radii from 0,1 μ to just under 0,2 μ, and so on.

   Data from beyond i_{max} cannot possibly come from the fibre core, as essentially all optical power will flow within the fibre core (and perhaps the immediately adjacent cladding), and thus apparent flux from beyond i_{max} shall be ignored. A confirmation should be made that there are no significant (non-noise) values beyond this point, which might indicate an error in the measurement.

   NOTE The purpose of the cutoff at 1,15 times the core radius is to prevent pixel crosstalk noise (see A.5) from unduly affecting the radial data functions, especially the encircled flux.

   b) For each and every pixel, compute the distance from that pixel to the optical center, using true coordinates (as detailed in 6.1), and compute the corresponding index i from the radius by taking the integer part of ten times the radius r. If, due to roundoff errors, i is negative, set it to zero. If i exceeds i_{max} (for example, 360 or 290 respectively for 62,5- or 50-micron fibre), skip this pixel. Otherwise, increment c(i) by one, add the conditioned pixel value to s(i), add r (the actual distance from optical center to the current pixel) to rs(i), and continue to the next pixel.

   c) When all pixels have been processed, the array s(i) contains a noisy approximation to the function "r*I(r)", the array rs(i) contains the sum of the distances from optical center to the pixels, and the array c(i) contains the number of pixels that contributed to the corresponding elements of s(i) and rs(i). The noise, here called "pixel granularity noise", is due to beats (Moiré patterns) between the radial sampling period (one-tenth of a micron here) and the pixel-grid X and Y periods, and is multiplicative, not additive, affecting s(i), rs(i), and c(i) in equal proportion. Simply put, at some values of i, more pixels will be seen than expected from 2 π r, while at other values of i, fewer pixels than expected will be seen. The presence of this noise requires r*I(r) to be computed indirectly, rather than directly from s(i) alone, allowing the granularity noise to be canceled.

3) Smoothing of pixel partition noise: (not to be confused with pixel granularity noise.) It is a property of the present measurement procedure that a pixel can belong to at most one summation ring. This causes severe pixel partition noise if there are too few pixels to adequately fill all rings, because some rings will be sparse and ragged and thus will be too sensitive to natural variations in the distribution of flux. Pixel partition noise can be largely suppressed by allowing each sample to take contributions from multiple rings. In practice, because of the fixed-sum nature of pixel partition noise, it suffices to pool adjacent pairs of rings. The following procedure accomplishes this by pooling the pixel data from adjacent overlapping rings to compute each smoothed sample, where each summation ring (and thus pixel) contributes to two adjacent samples, and each sample contains data from two adjacent rings.

   This procedure uses the per-ring arrays s(i), rs(i), and c(i) computed in step 2 above. Direct use of the un-normalized sums and counts allows the relative weight of the rings to automatically be taken into account in the following smoothing procedure.

a) Extend the s(i), rs(i), and c(i) arrays by prefixing them with their first few values (in reverse order), with the new rs(i) elements negated as well. The initial element of these arrays will therefore appear twice in the corresponding extended arrays. This extension is done to allow the resulting smoothed samples to go right down to zero radius, by taking advantage of the fact that s(i) and c(i) are even functions (so s(i) = s(–i)), while rs(i) is an odd function (so rs(i)=–rs(–i)).

Specifically,

es(i) = {s(0), s(0), s(1), s(2), s(3), ...} and

ec(i) = {c(0), c(0), c(1), c(2), c(3), ...}, while

ers(i) = {–rs(0), rs(0), rs(1), rs(2), rs(3), ...}.

NOTE In the following, “i” indexes over the extended arrays.

b) Perform the following pseudo-code. Be careful not to run off the end of the arrays in either direction, a detail for simplicity and clarity neglected here.

```
For i = 0 to N-1, compute the following:
    esSums(i) = 0
    ecSums(i) = 0
    ersSums(i) = 0
    For j = 0 to 1, compute the following:
        esSums(i) = esSums(i) + es(i+j)
        ecSums(i) = ecSums(i) + ec(i+j)
        ersSums(i) = ersSums(i) + ers(i+j)
    Next j
    Next i
```

c) When this computation is done, the arrays esSums(i), ersSums(i), and ecSums(i) contain pixel intensity and radius sums, and pixel counts, respectively, just as would result from direct accumulation from 2D data using wide overlapping rings, one wide ring per sample.

4) The intensity function “I(r)”, being a parametric function of the radial index “i”, is computed in two pieces, “I(i)” and “r(i)”. For I = 0 to i_{max}, do the following: If ecSums(i) = 0, skip this ring and go to the next ring. The intensities are computed by dividing each esSums(i) element by the corresponding non-zero ecSums(i) element. The corresponding radii are computed by dividing ersSums(i) by the same non-zero ecSums(i) element. Pixel granularity noise cancels out perfectly in these divisions. Normalize I(r) such that it has unit peak value.

The SI (metric) units of optical intensity are watts per square meter, which has dimension power per unit area. Because we are not interested in absolute measurements, the intensity is normalized to have unity peak value, so the units of measure become arbitrary, but the dimension remains optical power per unit area. The area of the sampling aperture (ring or pixel) will also cancel in the peak normalization, yielding the average intensity over the aperture. I(r) therefore gives the average nearfield flux versus radius function that one would measure using a line-scan rather than a 2D camera, albeit better smoothed.

5) Compute the incremental flux r*I(r) = r(i)*I(i) from the just-computed I(i). Normalize r*I(r) to have unit peak value. r × I(r) gives the increment of total flux versus radius, in effect averaging I(r) over the area of a narrow annulus of average radius r.

Incremental flux is the product of Intensity(r) and the differential of area dA(r). In a circular fibre, $dA(r) = 2\,\pi\,r\,dr$, so the overall incremental flux function is $dFlux(r) = 2\,\pi\,I(r)\,r\,dr$. Again, we normalize to unity peak value, yielding $F(r) = P(r)/P(r_p) = [2\,\pi\,I(r)\,r\,dr]/[2\,\pi\,I(r_p)\,r_p\,dr] = [I(r)\,r]/[I(r_p)\,r_p]$, so $F(r) = [I(r)\,r]/[I(r_p)\,r_p]$. The units of measure are again arbitrary, but have dimension optical power per differential of radius (as a function of radius). In practice, we compute only r × I(r) and peak-normalize the result, because the other terms will cancel out in the normalization.

6) Compute the normalized encircled flux function as follows: Compute the cumulative sum of r*I(r) for all steps from i = 0 to i = i_{max}. Divide each element of the cumulative sum by the final (largest) value of the cumulative sum, yielding normalized values ranging from zero to one in magnitude.

   Encircled flux is simply the integral of flux from zero (fibre center) to r, where r varies from zero to 36 μ(for 62,5-micron fibre) or 29 μ(for 50-micron fibre), again normalized to have unity peak value (at 36 μ or 29 μ), so the units of measure are arbitrary but have dimension optical power (as a function of radius).

7) Report the encircled flux value at the radial positions required by the detail specification. Also, report any other per-ring results as may be required. Have available for reporting the sample-radius, intensity, incremental-flux, encircled-flux, and pixel-count arrays as described in Clause 7.

NOTE The average ring radii r(i) may not be exactly uniformly spaced, especially near the center of the fibre.

7 Documentation

Report the following information for each test:

a) test date;

b) this International Standard number;

c) specimen/sample identification;

d) the encircled flux at each radial point as required in the detailed specifications, or the radial data functions as described below, or both.

- The radial data functions

All functions are reported with at least two points per micron.

1) Report the following data:

   a) the ring's average radius r(i),

   b) the peak-normalized intensity I(i),

   c) the peak-normalized incremental flux r(i)*I(i),

   d) the peak-normalized encircled flux function “Fe(i)”, and

   e) the number of pixels contributing to the ring ecSums(i).

NOTE 1 Use of a comma-separated tabular format such as Microsoft Excel “CSV” format is recommended because of its wide support by spreadsheets, databases, and analytical software for engineering or scientific applications.

   The units of r(i) are microns. The function I(i) has dimension optical power per unit area. The function r(i)*I(i) has dimension optical power per differential of radius. The normalized encircled flux has units of total optical power flow. The pixel counts are dimensionless. Encircled flux is sometimes called encircled energy.

2) Report the raw and conditioned 2D nearfield data, the calibration data, nominal fibre core diameter and outer diameter in microns, and the transform matrix.

NOTE 2 Again, use of a comma-separated tabular format such as Microsoft Excel “CSV” format is recommended

NOTE 3 CSV (comma-separated values) is the format of the “~.img” files from many cameras. Microsoft Excel “text” format (tab separated values) would also be acceptable. CSV and “text” export formats are available under the Microsoft Excel “save as” menu. Space-delimited text format may be used in place of CSV. However, be aware that with space-delimited formats, what you see may not be what you get, as both spaces and control characters all print as whitespace.

8 Specification information

Specify the following items in the detail specification:

a) sources to be tested;

b) sampling requirements, if any;

c) criteria to be met by the sources;

d) any special setup or deployment requirements.

Annex A
(informative)

Camera data reduction

A.1 Reduction of linear-scan 1D nearfield data

The following procedure defines how to reduce linear-scan camera data to the same radial data functions as are generated from 2D nearfield data, allowing direct comparison of the resulting radial data functions.

It is assumed that the linear-scan camera data resulted from a scan along a fibre diameter which passes precisely through the fibre's optical center, and that the camera has been calibrated by some unspecified process, yielding two input data arrays, one array x(j) specifying the locations of the raw intensity samples, the other array y(j) giving the corresponding raw intensity values. Locations are expressed in microns along the scan. Intensities are in arbitrary units having dimension optical power per unit area.

1) Find the centroid of intensity using the following procedure.
   a) Compute the sum of the intensities y(j), yielding a single scalar number, the "sum of the intensities".
   b) Compute the product of each element intensity array with its location coordinate, y(j)*x(j). Sum these products to yield a single scalar number, the "sum of the products".
   c) The centroid "c" is computed as the "sum of the products" divided by the "sum of the intensities". This is the location of the center of the raw intensity function, in location coordinates, expressed in microns.
2) Compute the array of distances by subtracting the centroid from each element of the locations array: d(j) = x(j) – c.
3) Sort the distances d(j) into ascending-distance order, with the intensities y(j) being carried along in the sort, resulting in a list of intensity-distance pairs in order of increasing distance from the centroid. This has the effect of "folding" the linear scan about the centroid of intensity.

NOTE The spacing of samples in the folded array will not in general be uniform.

4) Generate each smoothed intensity radial data intensity function array element I(i) from the average of four sorted y(j) elements, and the corresponding array elements r(i), from the average of the four sorted x(j) elements corresponding to the four y(j) elements, as follows:

   For i = 0 to N-4, compute the following:

   I(i) = (y(i+0)+ y(i+1)+ y(i+2)+ y(i+3))/4

   r(i) = (x(i+0)+ x(i+1)+ x(i+2)+ x(i+3))/4

   Next i

One may extend the sorted x(i) and y(i) arrays before the above averaging operation, by prefixing them by their first few values, as was done in step 3(a) of Clause 6. This would be done to allow the smoothed intensity and radius values to reach all the way to zero radius.

5) Given the intensity function computed above, the incremental flux and encircled flux functions are computed as specified in Clause 6.

A.2 Finding the core-cladding boundary from the intensity function

The basic approach is to fit functions to the overfilled intensity function I(r) on either side of the core-cladding boundary, and then to find the intersection of these two functions. This intersection approach is used in place of the [IEC 60793-1-20] 2,5 % and linear-fit rules for increased accuracy and robustness in the face of noisy data and non-zero background illumination. In particular, a quadratic function fits the skirts of an overfilled nearfield intensity function much better than a linear function, making the fit insensitive to details such as how much of the skirt is used in the fit. The specific procedure follows.

a) Using the calibration source also as the laser under test, measure the nearfield and compute the radial data functions as described in Clauses 5 and 6.
b) Fit a quadratic function to the part of the intensity function I(r) falling between 10 % of peak and 75 % of peak intensity. This will yield a quadratic fitted to the skirt of the intensity function.
c) Solve the quadratic for the positive-valued radius that yields zero intensity. This zero-intensity radius will approximate the fibre core radius.
d) Fit a linear function to the intensity function I(r) for all radii exceeding the above zero-intensity radius by 10 %. This will yield a linear function fitted to the background alone.
e) Find the positive-valued radius at which the quadratic and linear functions intersect. The intersection radius should be within 10 % of the previously calculated zero-intensity radius. Report this intersection radius as the radius of the core-cladding boundary.

A.3 Debugging tricks

The basic approach to top-level debugging is to co-plot derived data with the underlying raw data. For example, using unnormalized data, for each 2D pixel, plot a dot at (radius, raw intensity). These dots should visually coalesce into a dense curved line, perhaps with a halo of outliers. Plot the unnormalized intensity function on top of the dotplot. The intensity function should precisely bisect the dotplot's coalesced line. Another useful display is to plot the 2D intensities of the calibration source as a grayscale TV picture, with the summation center shown as a red dot, and a few of the summation rings shown in blue. If all is well, the dots and rings will be both concentric and well-centered upon the 2D nearfield. Because the human eye is very sensitive to deviations from concentricity, this is a very strong test, despite its simplicity and informality.

A.4 Correlated double sampling

One can use "correlated double sampling" (CDS) to almost completely eliminate CCD camera offsets, and their temperature sensitivity, at the cost of some added equipment complexity. Correlated double sampling is also quite effective against uncorrelated stray light. Makers of specialized instruments intended to perform the measurements described in the present standard would be well advised to implement correlated double sampling.

To implement CDS: One blinks the laser or incoherent calibration source at something like 50 Hz to 60 Hz, and electrically synchronizes the camera to the blinking such that odd frames are dark (source off), while the even frames see the nearfield being measured (source on), later subtracting the odd frames from the preceding even frames pixel for pixel, yielding an offset-corrected 2D nearfield flux distribution. For best cancellation, the on time should exactly equal the off time. If one is averaging a series of frames, add all even frames, subtract all odd frames, and divide by the number of even frames. CDS would replace the entire offset correction scheme in 5.2, but pixel sensitivity correction will still be required. If many measurements are to be made, such as in a factory, this approach can be a time saver, as many sources of inaccuracy that would otherwise require time and care to prevent manually are simply eliminated. The chosen blink rate should be an exact sub-multiple of the local power-line frequency, 50 Hz or 60 Hz, to ensure maximum discrimination against stray