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An interlaboratory measurement comparison, dealing with geometrical parameters of convex spherically polished optical fiber connector ferrule endfaces, was coordinated by NIST. Most measurements were optical, using interferometric microscopes; a few were mechanical, using stylus profilometers. For radius of curvature, there were small systematic offsets between some participants' data, but these were not much greater than random uncertainties. When protrusion/undercut was defined as the distance between the fiber endface and the apex of a sphere fitted to the ferrule endface, there were only slight systematic offsets between participants' data, smaller than typical random uncertainties. When protrusion/undercut was defined as the distance between the fiber endface and a plane fitted to the bore edge of the ferrule endface, however, there were large systematic offsets between data of participants using interferometers from three different manufacturers. Even if these data sets are adjusted to correct for the systematic effects, the measurement spread is larger for the second definition than for the first. For apex offset, systematic offsets were much smaller than random uncertainties. Stylus measurements caused readily observable physical effects on the specimen endfaces.

Key words: apex offset; ferrule endface geometry; fiber connector ferrule; interferometric microscope; optical fiber; PC connector; protrusion/undercut; radius of curvature; stylus profilometer.

1. Introduction

Geometrical parameters of optical fibers and fiber connector ferrules have received increasing attention as the industry has moved toward more efficient coupling between connected fibers. The National Institute of Standards and Technology (NIST) previously published results of international and North American interlaboratory measurement comparisons dealing with geometrical parameters (mostly diameter, concentricity, and noncircularity) of fibers, fiber coatings, and fiber connector ferrules [1]. Results for some parameters measured in those

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comparisons, along with industry's desire for improved accuracy and agreement, led to the development of NIST calibration artifacts, referred to as Standard Reference Materials (SRMs) [2].

This publication reports results from an interlaboratory comparison, coordinated by NIST for the Telecommunications Industry Association (TIA), dealing with measurements of geometrical parameters of fiber connector ferrule endfaces. Measurements were made on typical single-mode physical-contact (PC) connectors. PC connectors have convex spherically polished (nominal radius of 10 to 25 mm) ferrule endfaces, and the fiber is nominally centered at the high point of the polish, insuring physical contact between the two mated fibers in a connection. Physical contact between the fibers is important, to minimize insertion loss and back reflection (optimizing return loss) in the finished connection. The measured parameters in this comparison were: radius of curvature of the spherically polished ferrule endface; protrusion/undercut of the fiber (the distance that the fiber protrudes or is recessed from the ferrule endface), by two different definitions; and apex offset (the transverse offset between the center (axis) of the ferrule/fiber and the high point of spherical endface).

Following a convention used in the report of earlier comparisons, we report what we call average measurement spread. We obtain this number, for a given parameter, by calculating the sample standard deviation for measurements on each measurement specimen, then calculating the arithmetic average of these standard deviations. The average measurement spread is not a statistically valid estimate of the overall spread of the population of all measurements on all specimens (such as a pooled standard deviation, which could not be meaningfully calculated for these parameters, due to large variations in standard deviations between specimens). Nevertheless, the average measurement spread estimates the standard deviation for the *average* measurement specimen and, hence, gives an indication of the relative agreement among participants.

Discussion of results and conclusions that can be reached are presented in individual sections of this publication. The data in this study are presented so as to not identify participants; any attempt to do so would be unreliable.

2. Overview

Eighteen connectors, randomly assigned numbers 1 through 18, were used as measurement specimens; all ferrules were ceramic. Twelve specimens (four each, from three suppliers) were standard off-the-shelf patchcord connectors. There were also six "rogue" specimens, which were purposely over-polished or had fibers that were physically pushed back, to give large undercuts, as might be seen with some used connectors in the field or with over-polished homemade connectors. Fourteen of the eighteen specimens were connector type FC/PC; the remaining four were type SC/PC. This difference did not account for any systematic measurement differences, since both types of connectors use identical ferrules; however, one participant's instrument could not accept the SC/PC specimens. For radius-of-curvature measurements only, there were two additional specimens, assigned numbers 19 and 20, which were two ends of a *calibration-artifact*-type plug. These two ends were spherically polished glass, with radius values at both extremes of the normal range of radii for PC connectors. Participants did not calibrate their measurement instruments with this artifact; it was simply used as two more specimens for radius measurements.

Nineteen participating laboratories submitted data. In some cases, participants submitted more than one data set; there were up to 24 data sets per measured parameter. Most participants were North American TIA members; additionally, a few European participants were members of the International Electrotechnical Commission (IEC). In this report, participants have been randomly assigned identification numbers within each measurement method. These participant numbers were re-randomized for each measurement parameter, both because there were different numbers of data sets for each parameter and in order to maintain confidentiality among participants and instruments. Measurement methods included two general definitions: interferometric and mechanical (stylus).

Interferometric measurements were all made using commercial interferometric microscopes (from three manufacturers). In an interferometric measurement, the relative height/depth of each point on the three-dimensional ferrule/fiber endface is determined from an interferogram. A few participants used what we call *contact* interferometers, based on a Fabry-Perot design, in which the high point of the ferrule endface must be in contact with a glass reference flat in the instrument. Most, however, used *noncontact* interferometers, all based on variations of the Michelson interferometer. In general (though not in every case), measurement precision was better for the noncontact than for the contact interferometers, likely partially due to operator-dependent variations in establishing contact with the reference flat in the contact instruments. We will not explicitly identify such differences, in order to maintain confidentiality between instrument vendors. We will, however, show some results based on noncontact interferometer measurements only, since these are the most commonly used instruments (at least in North America), contributing more than two thirds of all data sets in this comparison.

Mechanical measurements (of protrusion/undercut and radius of curvature) were made using stylus profilometers, in which a stylus (typically, a conical diamond tip, with radius of 1.5 to 2.5 μm) was dragged across the endfaces. At the time of the comparison, we know of no companies that made profilometers specifically for these measurements, so all such participants used modified commercial profilometers. A profilometer measurement gives a two-dimensional cross section of relative height/depth along a chord across the connector endface. One source of uncertainty, unique to this method, is related to the distance from the chord to the ferrule/fiber center. Participants were asked to make stylus measurements at 45° increments around the perimeter of the endface; the average of these scans was then compared to the interferometric measurements. Clearly, unique topological features on an endface, which would be seen in a three-dimensional interferometric measurement, could be missed in the relatively coarse sampling of four two-dimensional scans from stylus measurements. Regardless of this inequivalence between two such measurements, comparison can be of general interest and utility.

Both the IEC [3] and the TIA [4] publish documents that specify nominal values and tolerances for a variety of parameters relating to connectors. Neither, at the time of this publication, though, includes any values for endface parameters; specifications for these parameters are under study in both organizations. Written test procedures, prescribing standard measurement methods for the parameters measured in this comparison, will be discussed in appropriate sections later in this document.

Data were taken only from certain regions of the ferrule/fiber endfaces, for both interferometric and stylus measurements, as shown in figure 1. The averaging area is a region in the center of the fiber endface, over which the average height/depth of the fiber is determined. The fitting area is a region, away from the fiber, on the ferrule endface, over which a sphere is fitted. For this comparison, participants agreed to an averaging area diameter of 10 μm and a fitting area from diameter 150 μm to diameter 400 μm, all with tolerances of ±2 μm and measured from within 3 μm of the center of the fiber. *These values were for this comparison only and may be different in published IEC and TIA test procedures.* Changing these areas typically changes measured values; the ferrule endface is usually not a perfect sphere, and the fiber endface is usually not perfectly flat (using the average height/depth of the fiber endface implies that it can be approximated as being flat). In fact, fiber endfaces are typically spherical, to an extent similar to the ferrule endfaces. Arguably, a definition of protrusion/undercut based on fitting a sphere to the fiber endface and determining the average offset from that sphere to the sphere fitted to the ferrule endface would be more representative. The current IEC test can be interpreted as ambiguously allowing either of these definitions. The disagreement between these two definitions, for typical radii of curvature and the 10 μm diameter averaging area used in this comparison, would be subnanometer, which would be of little consequence with current measurement precision. However, for a 50 μm diameter averaging area, as specified in recent drafts of the IEC test procedure, this disagreement could exceed 10 nm. Differences between these definitions and any possible ambiguity in specifying which is preferred should be addressed in the test procedures.

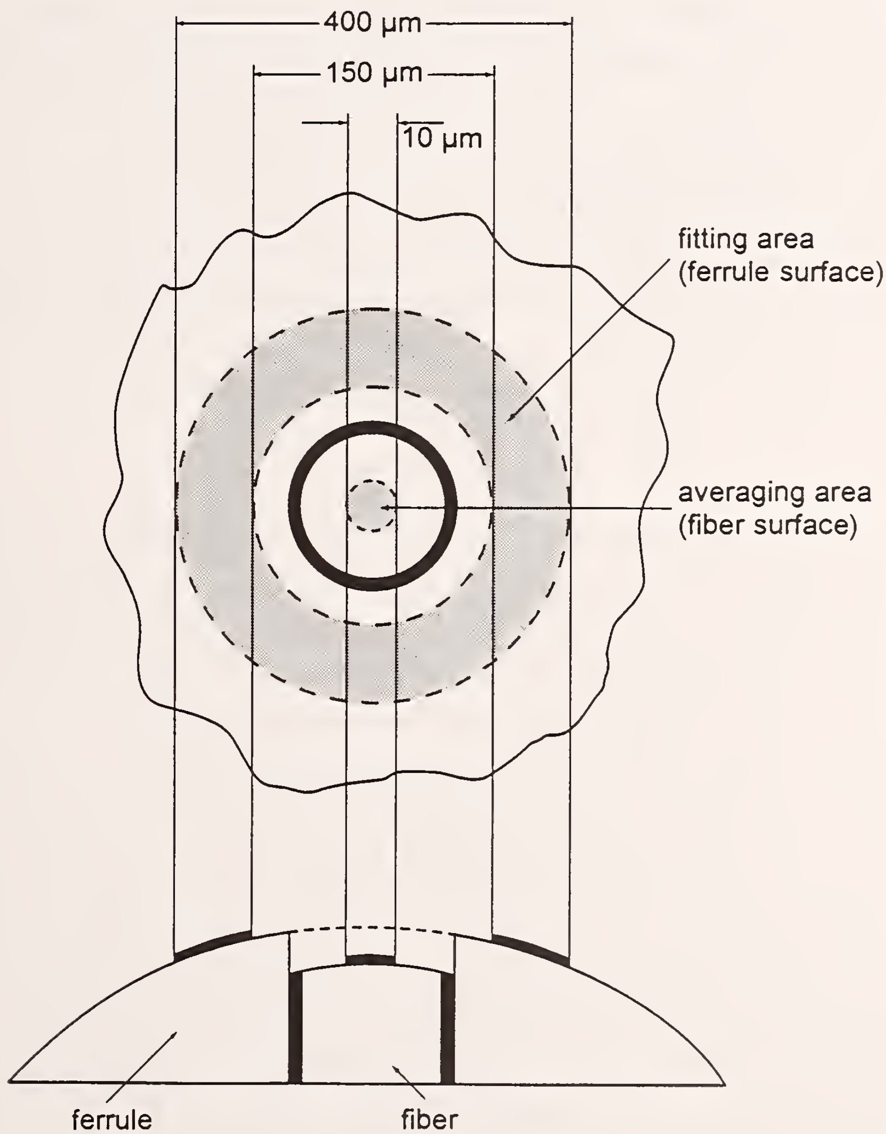

Figure 1. Diagram of the connector ferrule/fiber endface (curvature greatly exaggerated), showing measurement areas used in this comparison. The fitting area is a region over which a sphere is fitted, to determine the radius of curvature of the ferrule endface. The averaging area is a region over which the average height/depth of the fiber is determined.

3. Radius of Curvature

The convex spherical curvature of the ferrule endfaces gives PC connectors their unique characteristics and is related to other measurement parameters. The high point of the curvature figures into determination of the apex offset. More importantly, the radius of curvature goes directly into the formulation of one of the two definitions of protrusion/undercut. An error of 0.5 mm in radius measurement can cause a protrusion/undercut error on the order of 15 nm. There is a published IEC test procedure for radius-of-curvature measurements [5].

Table 1 shows the averages and standard deviations, per specimen, for radius-of-curvature measurements. There were 24 participant data sets submitted. PC connector endfaces typically have radii between 10 and 25 mm. Specimens 19 and 20, the calibration-artifact-type specimens, measured by nine participants, had average values at these two typical extremes. The other specimens had radii fairly evenly distributed within this range. The average measurement spread per specimen, including data from all participants, was 0.74 mm. This reduces to 0.44 mm if we include only noncontact interferometer measurements, and it further reduces to 0.29 mm if we do not include data for four specimens from one noncontact interferometer participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

Figure 2 shows the measured radii of curvature as a plot of offsets from noncontact interferometer average values versus participant. Up to 20 points are plotted per participant, representing the 20 specimens. The participants are grouped by measurement method; participants 1 through 20 used interferometers, while participants 21 through 24 used stylus profilometers. Open symbols denote measurements on specimens 19 and 20. These points typically fall within the offset scatter for each participant who measured them, with the exception of participant 12; their difference of sign, of offsets, between the calibration-artifact-type specimens (19 and 20) and all other specimens, likely indicates that they, contrary to comparison instructions, used specimens 19 and 20 to calibrate their instrument for all other radius-of-curvature measurements. This graph shows good overall agreement between most interferometers and two of the four stylus participants. A few participants (numbers 5, 12, 15, and 23) had very large random spreads in their offset values. A few participants, such as numbers 13, 14, and 22, showed definite systematic effects in their offsets. Most show some systematic effects along with some random spread in their offset values.

Two other meaningful quantities can be calculated from the statistics of these measurement offsets. For each participant, an average offset (average of the 20 plotted offset values) can be calculated, as can an offset spread (the standard deviation of the 20 offset values about that average). The average offset indicates systematic offset from average measured values, and, when compared to the same quantity for other participants, it indicates the extent of systematic disagreement. The magnitude of this quantity can be minimized by calibration. The offset spread is a reflection of the random uncertainty of the participant's measurements; this value would not be expected to improve with calibration.

These offset statistics are shown in table 2. Average offset magnitude (the average of the absolute values of participants' average offsets) and average offset spread are also given. These numbers are reported including all participants, as well as including only the noncontact interferometer participants. In these results, the average offset magnitude is only slightly larger than the average offset spread. This means that there are systematic differences between participants, but they are of about the same order as random uncertainties; accurate calibration could only slightly improve interlaboratory agreement.

Table 1. Radius of curvature statistics (averages and standard deviations) for each specimen. Average measurement spread (*see Introduction for definition*) is calculated using measurements from all participants and also using only noncontact interferometer measurements.

Specimen	Radius of curvature measurements, mm	
	Average	Standard deviation
1	14.7	0.3
2	19.1	0.5
3	19.3	0.7
4	18.3	0.9
5	16.1	1.7
6	18.7	1.2
7	22.9	0.8
8	11.6	0.4
9	12.5	0.3
10	19.6	0.6
11	17.4	1.4
12	20.9	0.7
13	23.7[a]	1.6[a]
14	17.8	1.8
15	14.5	0.4
16	20.4	0.6
17	14.4	0.3
18	14.3	0.3
19	10.1[b]	0.1[b]
20	25.2[b]	0.2[b]
Average measurement spread		**0.74** (0.44[c]) (0.29[d])

[a]One obvious outlier (measured value 34.2 mm) was removed.

[b]Calibration-artifact-type specimen (measured by only nine participants).

[c]Including noncontact interferometer measurements only.

[d]Noncontact interferometer data, not including data for four specimens from one noncontact interferometer participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

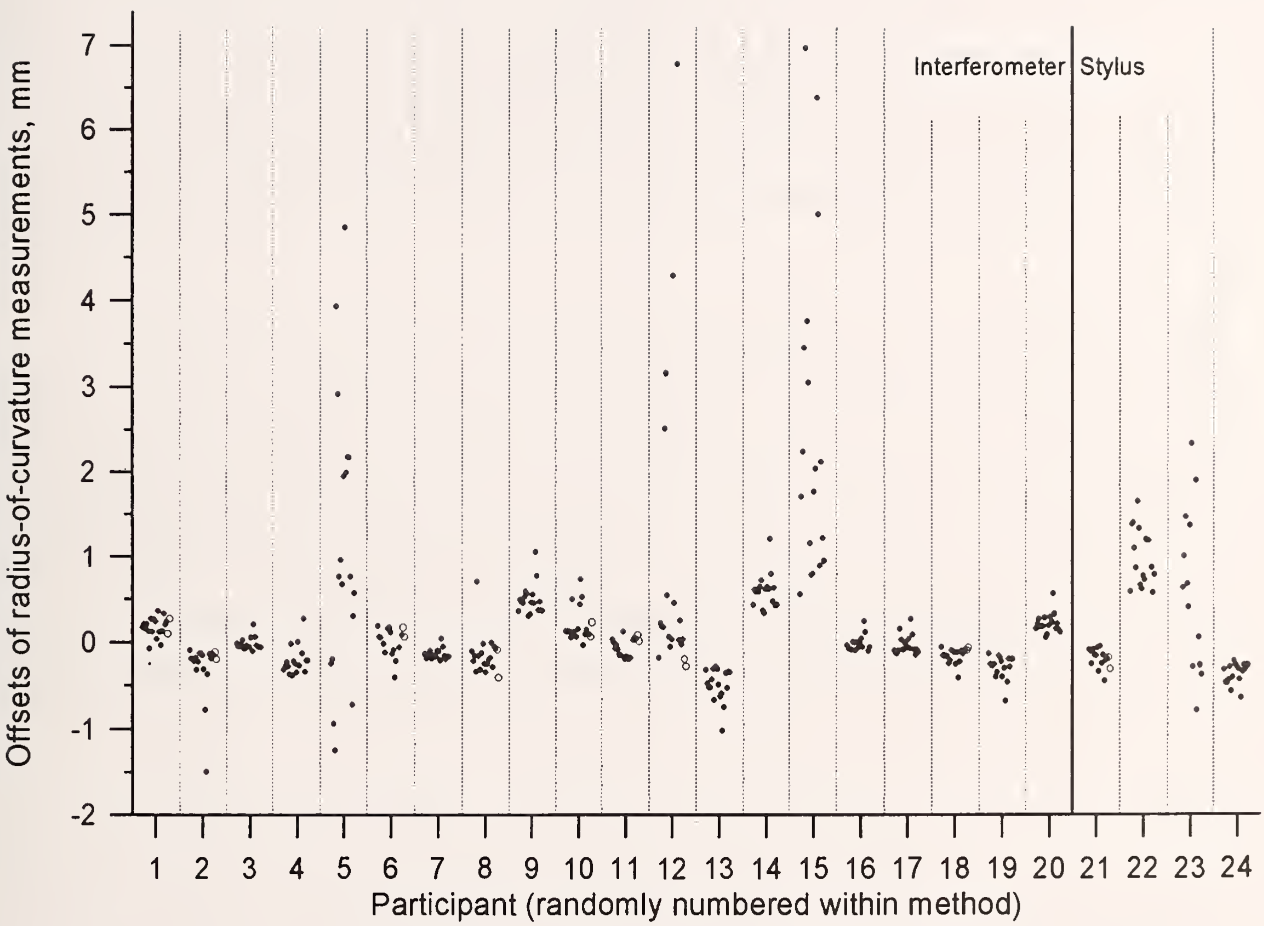

Figure 2. Offsets of participants' radius-of-curvature measurements from average noncontact interferometer values (*averages used for four specimens do not include data from one noncontact interferometer participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments*). Up to 20 points plotted, per participant, represent the 20 measurement specimens. Open symbols represent the two calibration-artifact-type specimens.

Table 2. Statistics for participants' radius of curvature measurement offsets from noncontact interferometer average[a] values.

Participant	Average offset, mm	Standard deviation of offsets, mm
1	0.17	0.11
2	-0.29	0.32
3	-0.02	0.07
4	-0.22	0.16
5	1.15	1.66
6	0.01	0.15
7	-0.14	0.06
8	-0.15	0.23
9	0.49	0.18
10	0.19	0.20
11	-0.05	0.11
12	0.94	1.89
13	-0.49	0.19
14	0.59	0.20
15	2.48	1.93
16	-0.03	0.09
17	-0.04	0.11
18	-0.16	0.08
19	-0.29	0.13
20	0.21	0.11
21	-0.19	0.11
22	0.97	0.34
23	0.62	0.95
24	-0.37	0.12
	Average offset magnitude,[b] mm	**Average offset spread,[c] mm**
	0.427 (0.255[d])	**0.396** (0.245[d])

[a]Averages used for determining offsets for four specimens do not include data from one noncontact interferometer participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

[b]Average of absolute values of participants' average offsets.

[c]Average of participants' offset standard deviations.

[d]Including noncontact interferometer participants only.

4. Protrusion/Undercut

The distance that the fiber protrudes from or is recessed (undercut) into the ferrule endface is the most critical of the endface geometrical parameters. Physical contact between the two fibers is essential in mated PC connectors; any air gap will diminish performance significantly. Obviously, undercut in one or both connectors can lead to such a gap, although small undercut is tolerable (perhaps even desirable), since there is some compression of the ferrule tips in a mated connection. Excessive protrusion clearly exposes the fiber to potential damage, but even relatively small protrusion can have detrimental effects, especially on the intermateability of connectors. Protrusion in one or both connectors can lead to excessive stress between the fibers in a connection, leading to adhesive failure and, hence, push-back undercut; this could cause a gap in subsequent connections or as environmental changes (temperature/humidity) affect the existing connection.

Two definitions of protrusion/undercut were used in this comparison. The first definition follows a draft IEC test procedure [6]. It is the height difference between the fiber and the peak (apex) of a sphere fitted, as in the radius-of-curvature measurement, to the ferrule endface. Uncertainty in such a measurement is related to the uncertainty of making a radius measurement. An objection, by some members of the industry, to this definition is that the fiber height is measured relative to a *virtual* spherical surface, so the measured protrusion/undercut may not accurately reflect the potential gap in a finished connection. A nominally flat fiber (not necessarily a valid assumption), protruding slightly from the ferrule endface at the edge of the ferrule bore, can be measured by this definition to be undercut.

The second protrusion/undercut definition addresses this objection and attempts, according to its supporters, to give a more physically meaningful value. Here, protrusion/undercut is defined as the height of the fiber relative to a plane defined at the edge of the bore of the ferrule endface. This definition is not affected by errors in measuring radius of curvature; it is, however, affected by uncertainties in determining the bore-edge plane. Such uncertainties, from the fitting of a plane to a sample of edge points, arise because of uneven polishing, roughness, and edge rounding. (There is seldom a sharp, distinct edge where the ferrule endface stops and the bore begins. It is typically a rounded edge, so each measurement instrument must define *the edge* as a point somewhere in the rounded edge area.)

The two definitions clearly give different values for a given PC connector. For typical PC connector geometry (fiber/bore diameter), the fitted-sphere definition will measure, depending on radius, nominally between 75 and 200 nm less protrusion (more undercut) than the edge-plane definition. Results for the two definitions are presented separately, in two subsections.

In these results, positive values denote protrusion, and negative values denote undercut, following guidelines in the draft IEC test procedure [6] at the time the comparison started. *This sign convention has been reversed in more recent drafts.*

4.1 Protrusion/Undercut (from Fitted Spherical Surface)

Participants submitted 23 data sets. Participant numbers were re-randomized, so a given participant number here does not correspond to the same number from results of other measured parameters. Table 3 shows the averages and standard deviations, per specimen, for the measurements. Average values ranged from −326 to +70 nm (326 nm undercut to 70 nm protrusion). Measurement spreads (standard deviations) also covered a wide range, from 8 to 36 nm. The specimens with the largest undercuts tended to have relatively large spreads; this is not surprising, since some commercial interferometers switch modes, from monochromatic to white light, with a resolution/precision penalty, for large undercuts. However, some large spreads occurred for specimens with more moderate protrusion/undercuts. Specimens that had large radius-of-curvature spreads also usually had large protrusion/undercut spreads, as we would expect, since the two parameters are directly related. However, some specimens (numbers 2 and 8, in particular) had relatively small radius spreads but relatively large protrusion/undercut spreads. The average measurement spread of 16.9 nm reduces to 10.2 nm if we include only noncontact interferometer measurements. It further reduces to 5.7 nm if we use noncontact interferometer data but do not include data for six specimens from one participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments. The spread here is on the order of what would be predicted from the spread observed in radius-of-curvature results. This indicates that uncertainty in radius measurements is one of the primary contributions to errors in protrusion/undercut measurements by this definition.

Figure 3 shows the protrusion/undercut (from fitted spherical surface) results as a plot of offsets from noncontact interferometer average values versus participant. Up to 18 points are plotted per participant, representing the 18 specimens. Participants are grouped by measurement method; participants 1 through 19 used interferometers, while participants 20 through 23 used stylus profilometers. This graph shows very good agreement between most interferometers. A few participants had very large random spreads in their offset values. Stylus participants 21 and 22 have spreads nearly as small as typical interferometers but show definite systematic biases (though not the same bias) from typical interferometer values. At least one paper has been published, predicting a difference between such measurements by interferometers and by stylus profilometers [7], hypothesizing the difference to be due to a systematic bias in the interferometric measurements, resulting from phase shifts in the interferometric fringes at the ferrule/fiber boundary. Evaluation of such a theory was beyond the scope of this comparison, particularly with only four stylus participants and the relatively large systematic and random differences between those four.

The average offset and the standard deviation of the offsets about that average, for each participant's measurements, are shown in table 4. Average offset magnitude and average offset spread are reported including all participants, as well as including only the noncontact interferometer participants. The average offset magnitude is slightly smaller than the average offset spread, meaning random effects in these offset values are larger than systematic effects. Accurate calibration could only slightly improve (to less extent than for radius of curvature) interlaboratory agreement.

Table 3. Protrusion/undercut (from fitted spherical surface) statistics (averages and standard deviations) for each specimen. Positive values are protrusion; negative are undercut. Average measurement spread (*see Introduction for definition*) is calculated using measurements from all participants and also using only noncontact interferometer measurements.

Specimen	Protrusion/undercut (from fitted spherical surface) measurements, nm	
	Average	Standard deviation
1	−15	12
2	18	23
3	32	8
4	70	15
5	−193	21
6	−81	23
7	−79	14
8	−105	36
9	−117	10
10	−90	8
11	−326[a]	27[a]
12	−152[b]	10[b]
13	−248	24
14	−254	32
15	2	9
16	6	13
17	−5	9
18	5	10
Average measurement spread		**16.9** (10.2[c]) (5.7[d])

[a]One obvious outlier (measured value 0 nm) was removed.

[b]One obvious outlier (measured value +146 nm) was removed.

[c]Including noncontact interferometer measurements only.

[d]Noncontact interferometer data, not including data for six specimens from one noncontact interferometer participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

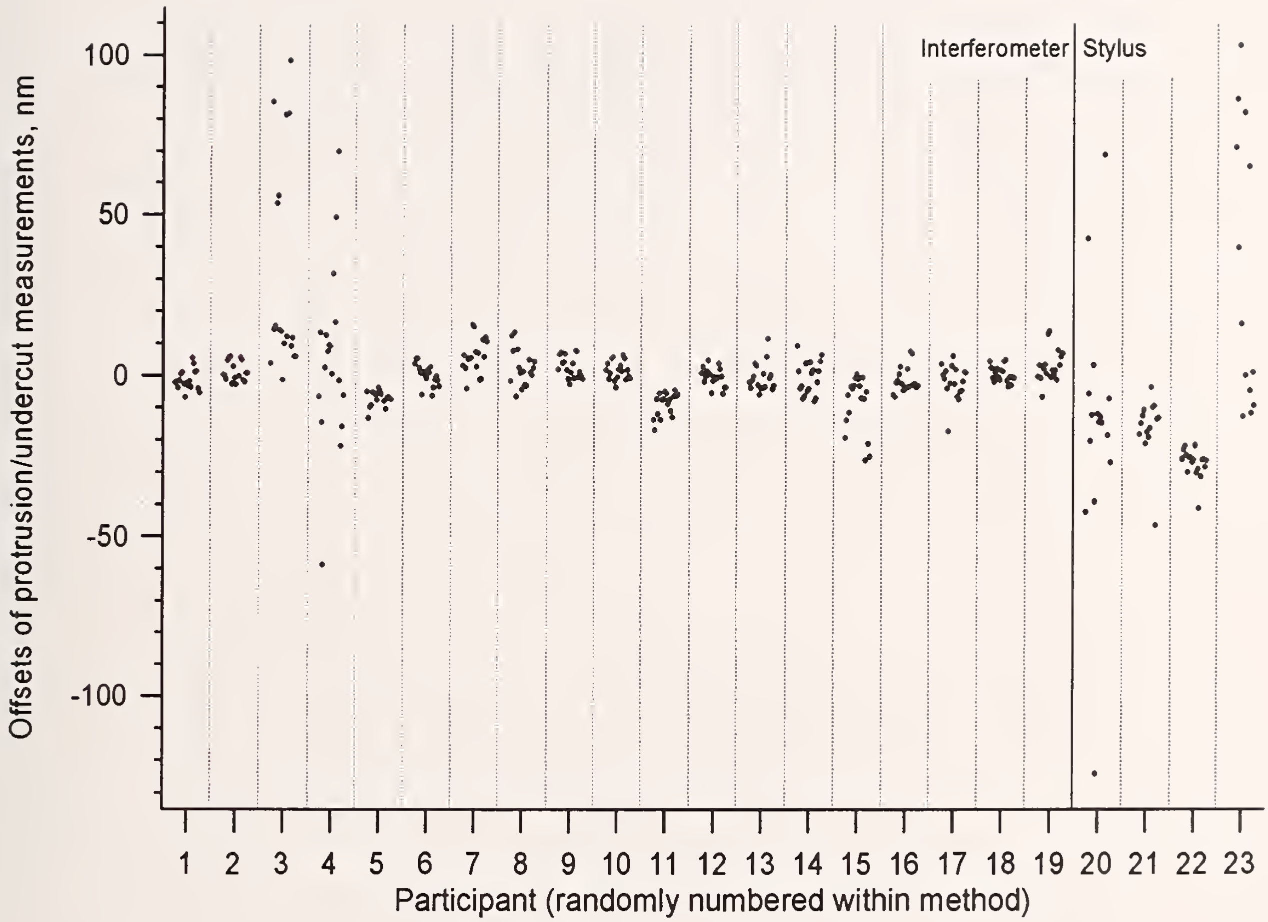

Figure 3. Offsets of participants' protrusion/undercut (from fitted spherical surface) measurements from average noncontact interferometer values (*averages used for six specimens do not include data from one noncontact interferometer participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments*). Up to 18 points plotted, per participant, represent the 18 measurement specimens.

Table 4. Statistics for participants' protrusion/undercut (from fitted spherical surface) measurement offsets from noncontact interferometer average[a] values.

Participant	Average offset, nm	Standard deviation of offsets, nm
1	-1.4	3.1
2	1.2	3.1
3	31.8	33.9
4	5.4	27.8
5	-7.1	2.4
6	0.1	3.4
7	6.0	5.5
8	2.3	5.6
9	2.5	3.4
10	1.5	2.9
11	-8.8	3.7
12	-0.6	2.9
13	-0.7	4.3
14	-0.9	5.2
15	-8.9	8.8
16	-1.7	4.0
17	-2.1	5.3
18	0.3	2.5
19	2.8	5.0
20	-14.9	40.1
21	-16.3	9.8
22	-27.3	4.4
23	32.6	43.1
	Average offset magnitude,[b] nm	**Average offset spread,[c] nm**
	7.7 (4.2[d])	**10.0** (5.7[d])

[a]Averages used for determining offsets for six specimens do not include data from one noncontact interferometer participant, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

[b]Average of absolute values of participants' average offsets.

[c]Average of participants' offset standard deviations.

[d]Including noncontact interferometer participants only.

4.2 Protrusion/Undercut (from Bore-Edge Plane)

For this definition of protrusion/undercut, eighteen data sets were submitted by participants. Participant numbers were again re-randomized, so a given participant number here does not correspond to the same number from results of other parameters. Table 5 shows the averages and standard deviations, per specimen, for the measurements. Average values ranged from −146 to +213 nm (146 nm undercut to 213 nm protrusion). These values were from 115 to 219 nm larger (more protrusion) than protrusion/undercut (from fitted spherical surface) measurements on the same specimens. Measurement spreads (standard deviations) ranged from 32 to 61 nm; the average measurement spread was 45.2 nm, which reduces only slightly, to 41.9 nm, if we include only noncontact interferometer data. For these measurements, examination of the data clearly showed systematic biases between interferometers from the three different represented interferometer manufacturers; these biases are likely primarily due to different ferrule bore-edge definitions, developed by the different manufacturers. If we correct for these biases, by removing the average bias for each given interferometer manufacturer from each measurement made with that manufacturer's interferometers, the average spread for noncontact interferometer measurements reduces significantly, to 19.6 nm. This is still roughly at least a factor of 2 larger than the average spread for noncontact interferometer protrusion/undercut (from fitted spherical surface) measurements.

The biases between interferometers from different manufacturers are shown clearly in figure 4, a plot of protrusion/undercut (from bore-edge plane) offsets from noncontact interferometer average values versus participant. Up to eighteen points are plotted per participant, representing the eighteen specimens. Participants are grouped by measurement method and, among interferometer participants, by interferometer manufacturer, designated A, B, and C. Participants 1 through 4 used interferometers from manufacturer A. Participants 5 through 9 used interferometers from manufacturer B. Participants 10 through 16 used interferometers from manufacturer C. Participants 17 and 18 used stylus profilometers.

Three out of four participants who used interferometers from manufacturer A show good agreement with each other. The fourth, participant 2, has a systematic offset from the others. This participant may have used a different bore-edge definition than the other three. This participant also has a relatively small offset spread, disregarding a much larger than typical offset on specimen 2. The other three participants have larger offset spreads, due mostly, however, to atypically large offsets on the same six specimens (specimens 1, 8, 9, 15, 17, and 18).

The five participants using interferometers from manufacturer B show relatively good agreement, although there are some small but noticeable systematic differences between them. They show similar offset spreads. These spreads would be small, except for a few relatively high offsets for each participant. Again, these participants have these large offsets on the same five specimens (all five participants on specimens 5, 11, and 14; four of five on specimen 6; and three of five on specimen 13).

The seven participants using interferometers from manufacturer C also show good agreement, with only very small systematic offsets between them. Each have similar offset spreads that are also similarly uniform. As with the results for interferometers from manufacturers A and B, these participants' data sets have relatively large offsets (negative values, in this case) on the same three specimens (all seven participants on specimens 11 and 14; four out of seven on specimen 5—these are three of the five specimens that gave the largest offsets for interferometers from manufacturer B.)

The two stylus participants show different average offsets and different amounts of offset spread.

The average offsets and the standard deviation of the offsets about that average, for each participant's measurements, are shown in table 6. Average offset magnitude and average offset spread are reported including all participants, as well as including only noncontact interferometers. Average offset magnitude improves significantly when data is corrected for the biases between instruments from different manufacturers; this value is also shown and is significantly smaller than the average offset spread, meaning that, other than these biases, random effects dominate the overall uncertainty. In practice, such biases should largely cease to exist, once test procedures rigorously define the bore edge for this definition of protrusion/undercut.

Table 5. Protrusion/undercut (from bore-edge plane) statistics (averages and standard deviations) for each specimen. Positive values are protrusion; negative are undercut. Average measurement spread (*see Introduction for definition*) is calculated using measurements from all participants, using only noncontact interferometer measurements, and using noncontact interferometer measurements corrected for instrument-dependent systematic bias.

Specimen	Protrusion/undercut (from bore-edge plane) measurements, nm	
	Average	Standard deviation
1	163	54
2	149	40
3	163	34
4	213	34
5	-10	47
6	76	38
7	36	32
8	114	61
9	84	58
10	40	33
11	-146	54
12	-29[a]	32[a]
13	-113[b]	44[b]
14	-82	49
15	173	57
16	131	33
17	167	57
18	178	57
Average measurement spread		**45.2** (41.9[c]) (19.6[d])

[a]One obvious outlier (measured value +180 nm) was removed.

[b]One obvious outlier (measured value +364 nm) was removed.

[c]Including noncontact interferometer measurements only.

[d]Noncontact interferometer data, corrected for average instrument-dependent bias. Average bias, for each interferometer manufacturer, was calculated over all measurements (using that manufacturer's instruments) on all specimens.

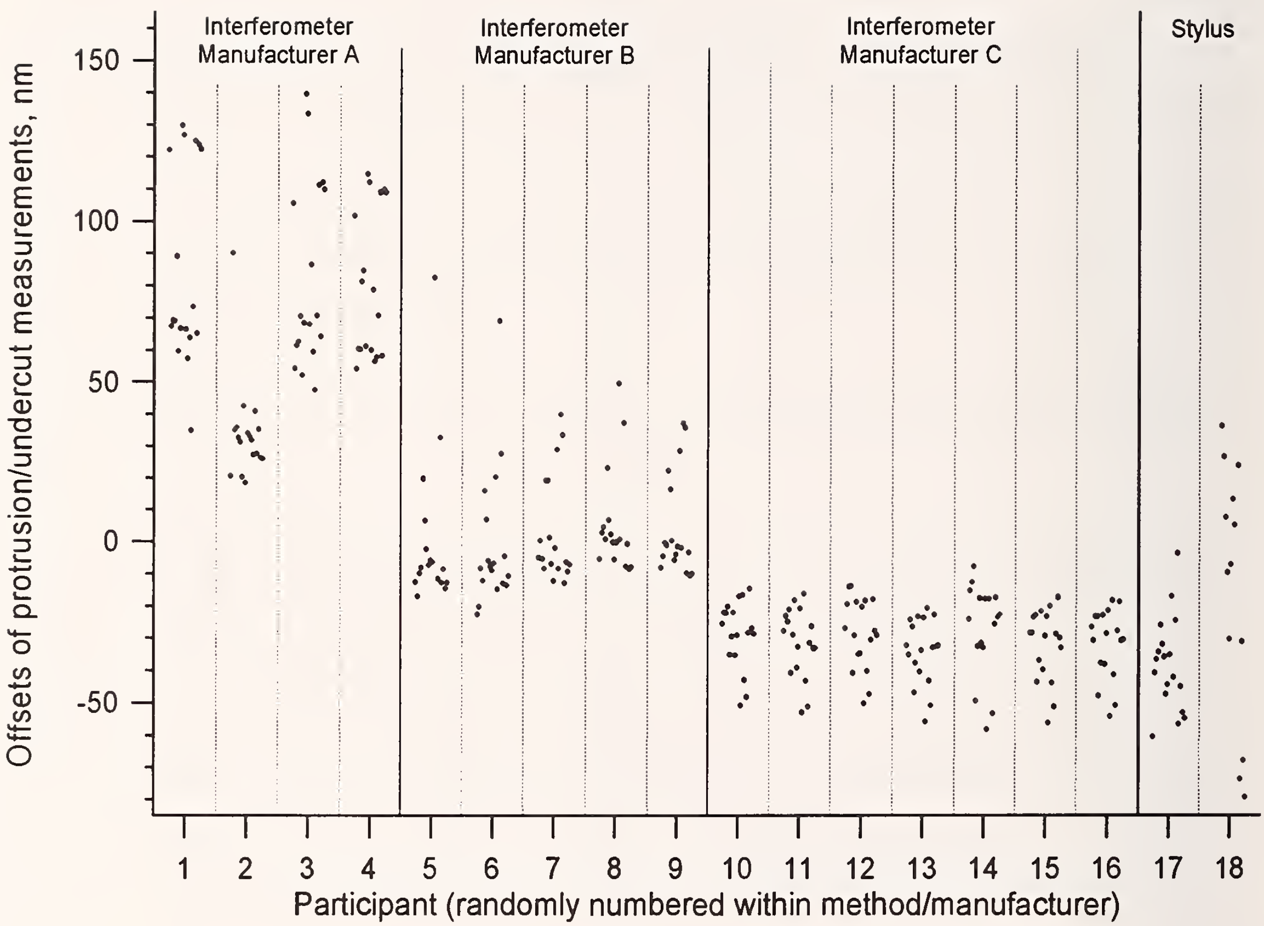

Figure 4. Offsets of participants' protrusion/undercut (from bore-edge plane) measurements from average noncontact interferometer values. Participants are grouped by method as well as, within interferometer participants, by interferometer manufacturer, to illustrate clear systematic differences between instruments from the three manufacturers. Up to 18 points plotted, per participant, represent the 18 measurement specimens.

Table 6. Statistics for participants' protrusion/undercut (from bore-edge plane) measurement offsets from noncontact interferometer average values.

Participant	Average offset, nm	Standard deviation of offsets, nm
1	85.2	30.7
2	33.8	15.6
3	82.1	28.9
4	80.0	23.2
5	0.7	24.7
6	-0.5	22.1
7	3.2	16.9
8	5.4	16.3
9	4.4	16.0
10	-28.6	10.4
11	-31.3	10.7
12	-28.6	11.1
13	-34.1	10.1
14	-27.0	14.5
15	-32.1	11.0
16	-31.7	10.9
17	-38.3	14.5
18	-14.3	39.3
	Average offset magnitude,[a] nm	**Average offset spread,[b] nm**
	31.2 (28.5[c]) (6.0[d])	**18.2** (16.3[c])

[a]Average of absolute values of participants' average offsets.

[b]Average of participants' offset standard deviations.

[c]Including noncontact interferometer participants only.

[d]Noncontact interferometer data, corrected for average instrument-dependent bias. Average bias, for each interferometer manufacturer, was calculated over all measurements (using that manufacturer's instruments) on all specimens.

5. Apex Offset

Apex offset is defined, in an IEC test procedure [8], as the distance between the axis (center) of the ferrule and the line, parallel to that axis, which passes through the apex or highest point on the dome formed by spherically polishing the ferrule. (At least some commercial instruments perform the measurement relative, instead, to the center of the *fiber*, which in many cases can be determined with greater precision than can be the center of the ferrule. All ferrules have some amount of concentricity error, between the centers of the ferrule and of the bore, and fibers may not be centered in the bores, if bore diameter and fiber diameter are not carefully matched. So, there can be a discrepancy between defined and measured apex offset. This discrepancy should be no more than a couple micrometers, though, if ferrules and fibers are well-matched and meet normal IEC or TIA specifications.) Large enough apex offset, possibly caused by polishing at a slight angle, can result in contact between ferrules rather than fibers, in a mated pair of connectors; this would result in an air gap between fibers and, hence, a degradation in performance.

Participants submitted 21 data sets. All measurements were interferometric; coarsely spaced stylus measurements would likely miss the true apex offset. A handful of participants, as with the other reported parameters, used contact interferometers, although most used noncontact interferometers. Participant numbers were re-randomized yet again, so a given participant number here does not correspond to the same number from results of other measured parameters. Table 7 shows the averages and standard deviations, per specimen, for the measurements. Average values ranged from 7 to 43 μm. Measurement spreads (standard deviations) covered a range from 4 to 11 μm. The average measurement spread of 6.8 μm reduces to 5.8 μm if we include only noncontact interferometer measurements. It slightly further reduces to 5.1 μm if we use noncontact interferometer data but do not include data for three specimens from one of two participants, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

Figure 5 shows the apex offset results as a plot of offsets from noncontact interferometer average values versus participant. Up to 18 points are plotted per participant, representing the 18 specimens. Most participants' data sets appear to agree fairly well; only a few (participants 2, 13, 19, 20, and 21) show definite systematic offsets from the others. A few participants (numbers 5, 6, 9, 11, 15, and 18) show similar, relatively low amounts of offset spread. Several others (participants 1, 3, 8, 10, 12, 16, 17, and 21) would have similarly low offset spreads, were it not for their large offset values on just a few specimens; in this case, the same specimens are *not* causing this problem for all of these participants. Finally, there are a few participants (numbers 2, 13, 14, 19, and 20) whose data have fairly evenly distributed offset spreads that are substantially larger than what is typical in this comparison.

Participants' offset statistics (average offsets and offset spreads) are shown in table 8. Average offset magnitude and average offset spread are reported including all participants, as well as including only noncontact interferometer participants. The average offset spread is about twice as large as the average offset magnitude, meaning random effects in these offsets are significantly larger than systematic effects. Therefore, the typical participant's uncertainty in making an apex offset measurement is limited primarily by the precision of the measurement test set; accurate calibration, if it were available, would result in virtually negligible improvement in interlaboratory agreement.

Table 7. Apex offset statistics (averages and standard deviations) for each specimen. Average measurement spread (*see Introduction for definition*) is calculated using measurements from all participants and also using only noncontact interferometer measurements.

Specimen	Apex offset measurements, µm	
	Average	Standard deviation
1	8	10
2	25	6
3	21	7
4	23	6
5	11	7
6	17	4
7	31	8
8	21	4
9	43	5
10	34	6
11	9	9
12	11	11
13	38	10
14	7	7
15	19	4
16	11	8
17	13	5
18	9	6
Average measurement spread		**6.8** (5.8[a]) (5.1[b])

[a]Including noncontact interferometer measurements only.

[b]Noncontact interferometer data, not including data for three specimens from one of two noncontact interferometer participants, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

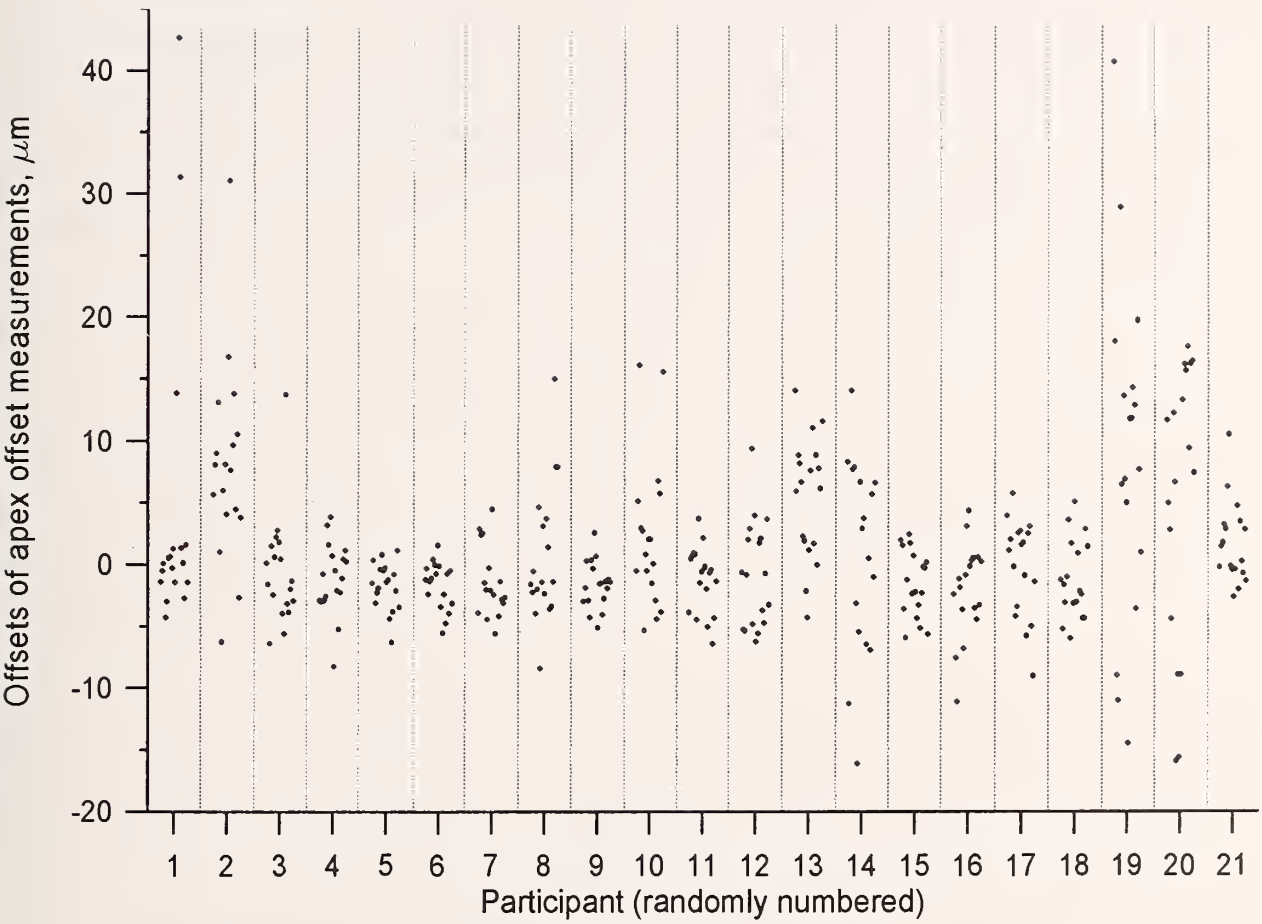

Figure 5. Offsets of participants' apex offset measurements from average noncontact interferometer values (*averages used for three specimens do not include data from one of two noncontact interferometer participants, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments*). Up to 18 points plotted, per participant, represent the 18 measurement specimens.

Table 8. Statistics for participants' apex offset measurement offsets from noncontact interferometer average[a] values.

Participant	Average offset, µm	Standard deviation of offsets, µm
1	4.4	12.6
2	8.0	8.0
3	-0.6	4.5
4	-1.2	2.9
5	-1.8	1.9
6	-1.7	1.9
7	-1.5	2.9
8	0.7	5.5
9	-1.7	1.9
10	2.2	6.0
11	-1.3	2.7
12	-0.9	4.4
13	5.4	5.0
14	0.8	8.0
15	-1.6	2.7
16	-2.2	3.8
17	-0.2	3.9
18	-1.3	3.2
19	8.9	13.7
20	5.3	11.3
21	1.6	3.3
	Average offset magnitude,[b] µm	**Average offset spread,[c] µm**
	2.5 (2.2[d])	**5.2** (4.2[d])

[a]Averages used for determining offsets for three specimens do not include data from one of two noncontact interferometer participants, whose values for those specimens, relative to other participants' values, were far outside typical precision for such instruments.

[b]Average of absolute values of participants' average offsets.

[c]Average of participants' offset standard deviations.

[d]Including noncontact interferometer participants only.

6. Stability of Specimens over Time

Included in the design of this comparison was the desire to monitor drift in any of the specimens, for any of the measured parameters, over time. Such drift could be caused by exposure to varied (especially extreme) temperatures during shipment between participants. The specimens were shipped in an insulated container, by overnight delivery, to try to minimize temperature fluctuations. Weekend shipment was avoided, so recipients could take delivery and get specimens inside to a stable ambient temperature as soon as possible after receipt. A thermometer, with memories for minimum and maximum exposed temperatures, was enclosed in the shipping container, and the memories were cleared before each shipment. Each participant was asked to record the minimum and maximum shipment temperatures, as well as the ambient temperature at which measurements were made. The specimens were routinely exposed, during shipment, to a temperature range of 10 to 30 °C. The one-time low temperature was about 0 °C, and the one-time high may have been as high as about 45 °C. These extremes may have been marginal (although not in great excess) for the specifications of some adhesives routinely used in connectors. Ambient measurement temperatures ranged roughly between 21 and 26 °C. Near the completion of the comparison, one specimen failed catastrophically (likely due to excessive force applied to its fiber pigtail), when it suddenly exhibited an undercut of several micrometers, making it unmeasurable for the last couple of participants.

Such drift could also be caused by physical contact between something and the specimen endfaces. These specimens were never, during the comparison, mated with other connectors, in order to avoid fiber push-back or any potential cumulative changes to the contact area of the ferrule endfaces. The applied forces in contact micrometers are small (excessive force can easily break the contacted thin glass reference flat), and there is no static load, as there would be in a mated connection, so effects should be negligible. There is also contact within stylus measurements, but the area of contact is small enough that effects would, except for push-back undercut if large forces were applied to the fiber region, be expected to be localized (*see next section for a discussion of such effects*).

The three interferometer manufacturers represented in this comparison agreed to repeat measurements, submitting data from a total of four instruments, to track any fluctuations. All four instruments measured the specimens at the start of the comparison. Two of the four repeated measurements after almost all interferometer measurements (including some contact interferometers) but before any stylus measurements. The remaining two repeated measurements after some stylus measurements. All repeated measurements were performed between 5 and 9 months after original measurements had been made.

For apex offset, no general systematic fluctuations were observed; measured fluctuations were random and small, easily contained within typical measurement uncertainties of the instruments. For the other parameters, though, there were definite systematic trends. For radius of curvature, all 4 repeat instruments measured smaller radii for ten specimens; 3 out of 4 measured smaller values for an additional 7 specimens; and 2 out of 3 measured smaller values for an additional 2 specimens. So, radii seemed to reduce during this comparison, according to repeated measurements, for 19 out of 20 specimens, by an average measured amount of about 0.15 mm. A decreased radius would correspond to *more* curvature; this would not be an obvious effect of contact, nor are there any obvious mechanisms that would cause such an effect. Also, decreased radius and, hence, increased curvature, is expected to contribute to increased *undercut* for the fitted-sphere definition of protrusion/undercut. The opposite was observed.

For repeated measurements of protrusion/undercut (from fitted spherical surface), all 4 data sets showed an increase in *protrusion* for 13 specimens, and 3 out of 4 agreed on increased protrusion for the other 5 specimens. Furthermore, repeated protrusion/undercut (from bore-edge plane) measurements seemed to agree; there were only 2 such data sets, but both agreed on increased protrusion for 15 of the specimens. Both definitions agreed on the average amount of protrusion increase, with the fitted-sphere definition giving about 8 nm and the bore-edge definition giving about 7 nm. There was *not* good correlation in general, though, between the two definitions, pertaining to which specimens had relatively smaller or larger amounts of increased protrusion.

Attempts were made, without much success, to verify these effects, by plotting all measurements chronologically and finding the best-fit *drift* line through them. The confidence-of-fit for these lines ranged from mediocre, at best, to very poor; often, deleting a single point would radically change the fitted line. Slopes varied widely and in a few cases were even of opposite sign from what repeat measurements predicted.

In all cases, average suspected drifts were smaller than typical (*one* standard deviation) measurement spreads, so the effects, if real, are completely contained within other measurement uncertainties. Attempting to correct participants' data for these effects, given the limited information gathered in this comparison, would have been difficult and unreliable; for instance, there is no certainty that such fluctuations would occur steadily and linearly. The systematic observations of these fluctuations certainly support the existence of real effects. Such effects, being smaller than other systematic and random uncertainties, probably did not significantly change overall results of this comparison.

7. Physical Effects of Stylus Measurements

After the completion of the comparison, the specimens were examined with a video microscope, to check the conditions of the endfaces. Most specimens had some damage or were contaminated to some extent. The specimens were not mated with other connectors at any time during the comparison, so such effects had to be pre-existing, due to handling, or the result of contact measurements. All specimens showed long lines across endfaces, and most had a symmetric pattern of lines, like spokes of a wheel, that seem clearly to be the result of stylus measurements. An example is shown in figure 6, a captured video frame of the endface of specimen 1. The dark circle is the fiber endface; the lighter surrounding surface is the ferrule. The lines across the center occur at roughly 45° increments, which are the measurement increments that stylus participants were instructed to use. Some lines go more nearly through the center than others, and some lines are more fine or faint than others. We were unable to accurately determine of the depths or widths of these lines.

Such physical effects from stylus measurements seem to be detrimental. Repeated stylus measurements could be anticipated to *mark* or *scratch* the endface to such an extent that there would be increased noise and, hence, uncertainty in subsequent stylus or interferometer measurements. Furthermore, since most of these lines, as intended in such measurements, go through the center and, therefore, *core* region of the fiber, it would not be surprising for the optical performance of the connector to be affected.

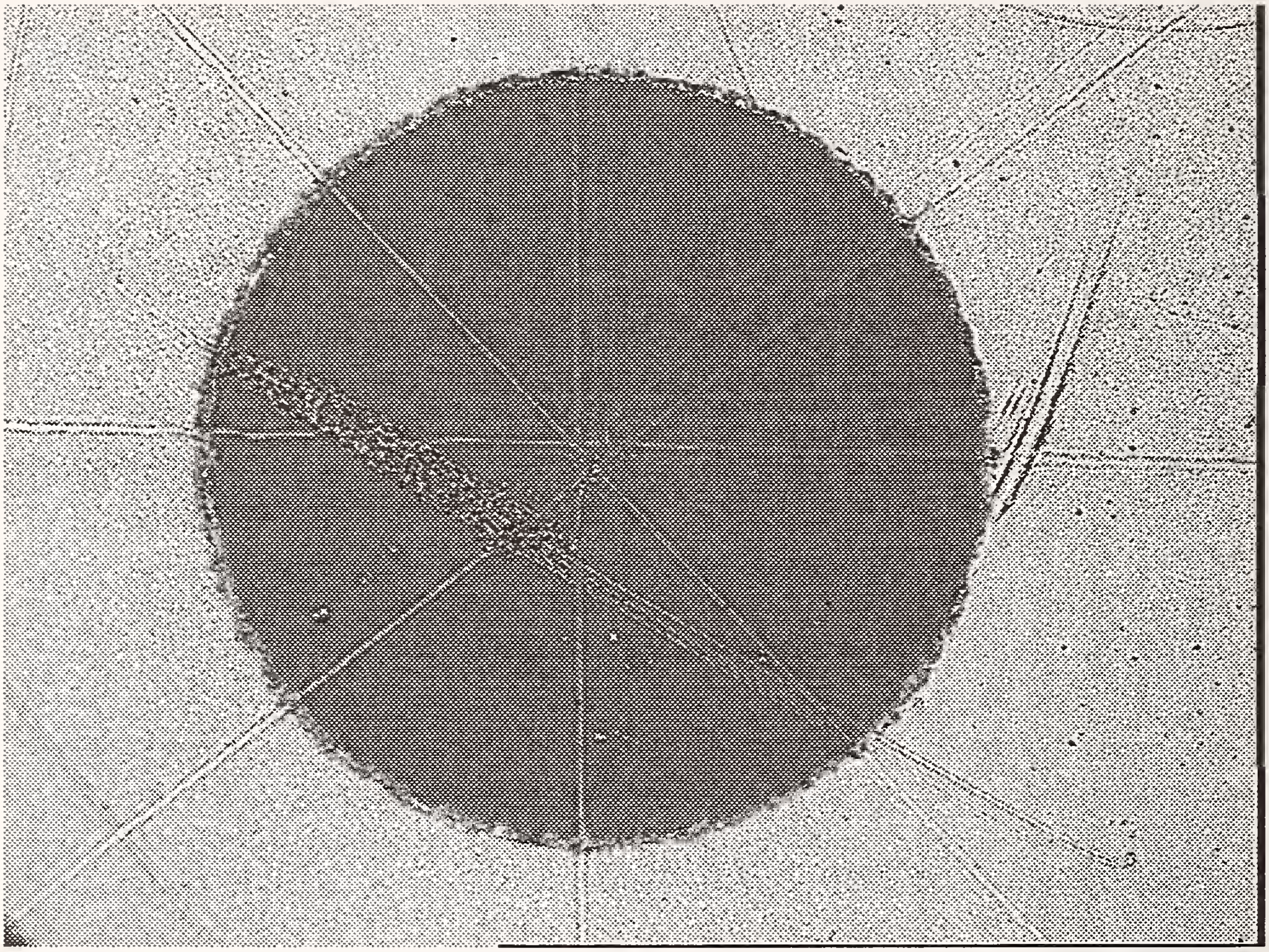

Figure 6. Video microscope image (magnification about 800×) of the endface of specimen 1, after the completion of the comparison. Dark area is the fiber endface; surrounding lighter area is the ferrule endface. In addition to other damage or contamination, effects of stylus measurements are clearly apparent, as the series of lines crossing near the center.

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