VARIATION IN LINEAR APEX OFFSET MEASUREMENTS OF ANGLED FIBER OPTIC CONNECTORS

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Introduction

The three-dimensional surface profile of a fiber optic connector endface is typically characterized by three parameters:

- *Radius of Curvature*
- *Spherical Fiber Height (Fiber Undercut/Protrusion)*
- *Linear Apex Offset*

Telecommunications Industry Association document TIA-455-218 “Measurement of Endface Geometry of Single Fiber Optical Connectors” describes the steps to measure the endface geometry of single fiber optical connectors. The PROMET International White Paper entitled “Fiber Optic Connector 3D Metrology” further describes how these parameters are measured using an interferometer such as PROMET International’s FiBO.

When using an interferometer to measure the *Linear Apex Offset* of an Angled Physical Contact (APC) connector endface, certain conditions can result in significant variation in the measurement results. The purpose of this White Paper is to discuss the origin and characteristics of this variation and how to minimize it.

Interferometry and Endface Geometry

In order to measure the three-dimensional (3D) properties of a physical contact (PC) connector endface, the axis of the ferrule of the connector (green dashed line) is aligned parallel to the optical axis of the interferometer (red dashed line), as in the following diagram:

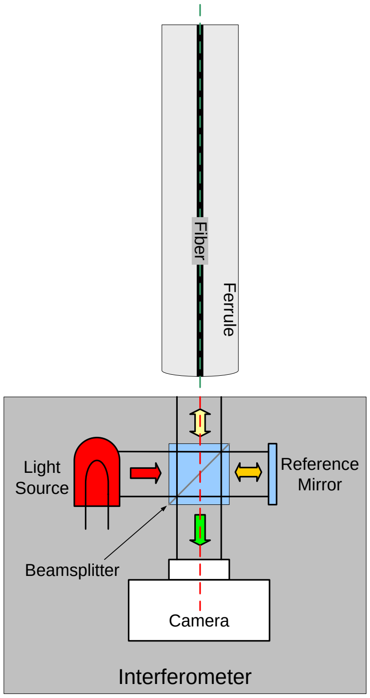


Fig. 1: Interferometer configuration for measuring the endface of a PC connector

Using the microscope mode of the interferometer (with the reference mirror blocked), the center portion of the connector endface appears as follows:

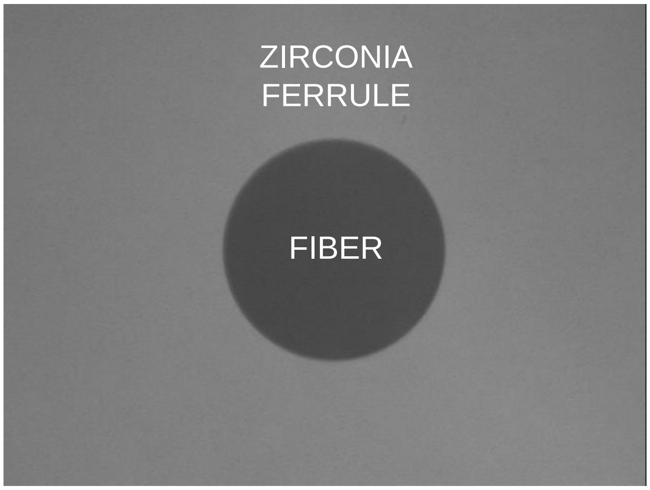


Fig. 2: Microscope image of a connector endface (with the fiber and ferrule areas labeled).

Switching the device into interferometric mode by unblocking the reference mirror introduces interferometric fringes to the image:

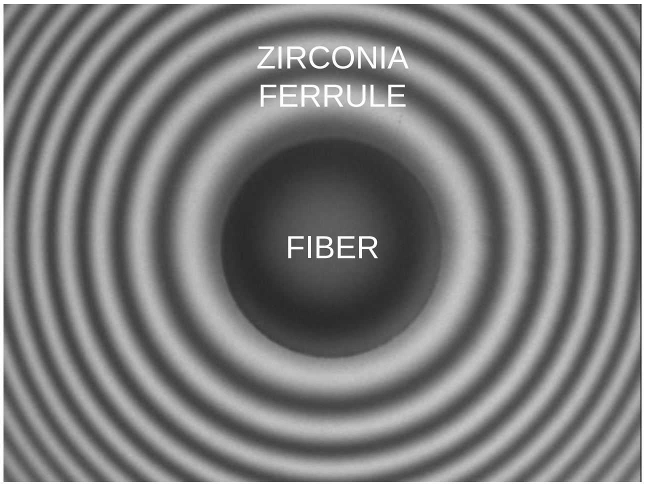


Fig. 3: Interferometric image of a connector endface.

The circular fringes are a result of the interference between the light reflecting from the spherical shape of the connector endface and the light reflecting from the flat reference mirror.

Even without obtaining quantitative 3D measurements by performing phase-shifting interferometry, some properties of the endface can be observed by interpreting the fringe pattern:

- If the fringes are irregularly shaped, the surface of the ferrule is irregular.
- The spacing of the fringes is directly related to the radius of curvature of the endface: the larger the spacing of the fringes, the larger the radius of curvature.

- The linear apex offset is directly related to the distance between the center of the fiber and the center of the fringes. If the two centers overlap, there is minimal linear apex offset.

The visual interpretation of fringes can be informative, but by using phase-shifting interferometry, the 3D shape of the endface can be measured and concrete numbers for parameters such as *Radius of Curvature*, *Fiber Undercut/Protrusion* and *Linear Apex Offset* can be objectively calculated:

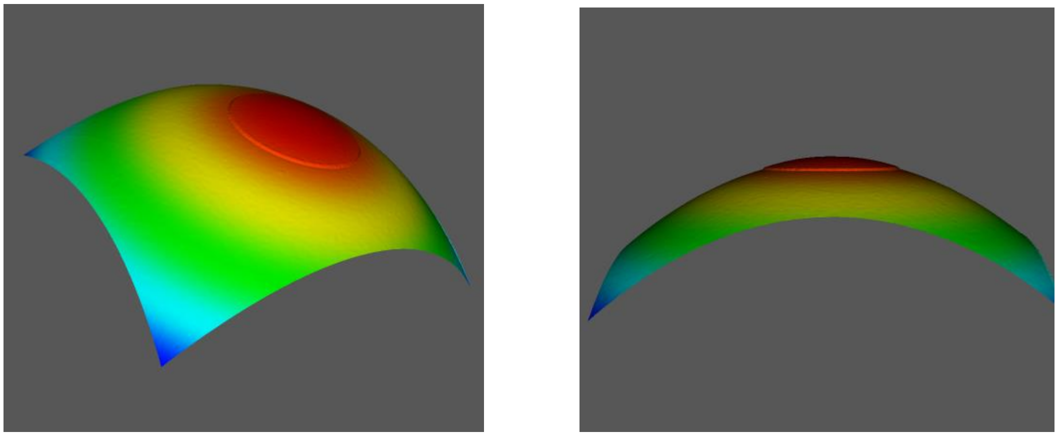


Fig. 4: 3D images of a connector endface with measured values of: Radius of Curvature = 13.5mm, Spherical Fiber Height =50nm and Linear Apex Offset = 5.0 microns.

Relationship between Linear and Angular Apex Offset

The TIA-455-218 document describes how to use the three-dimensional data acquired with an interferometer to calculate the *Radius of Curvature*, *Linear Apex Offset* and *Fiber Undercut/Protrusion. Linear Apex Offset* is the horizontal distance, in microns, between the center of the fiber and the peak of the polished sphere of the connector endface. The connection between *Linear Apex Offset* and *Angular Apex Offset* can be seen in the following diagram:

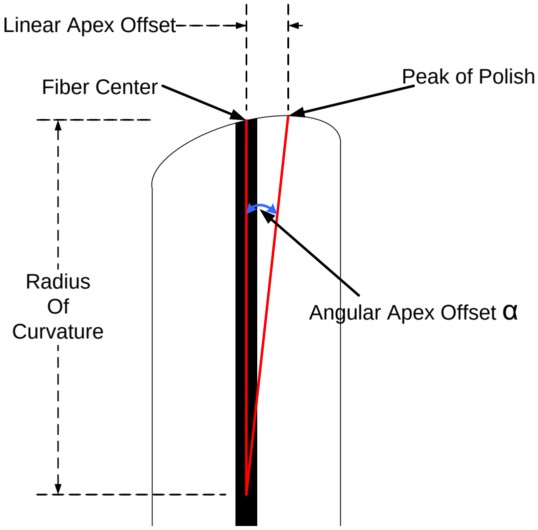


Fig. 5: Exaggerated connector side-view cross-section showing Linear and Angular Apex Offset. The thick black line represents the fiber.

The TIA document also gives the mathematical relationship between the measured *Linear Apex Offset* and the calculated *Angular Apex Offset* as:

I) $$\alpha = \arcsin\left(\frac{\text{Linear Offset}}{\text{Radius of Curvature}}\right)$$

Where α is the *Angular Apex Offset*.

From the above equation we can see the non-linear relationship between the *Radius of Curvature* and the *Angular Apex Offset*. This relationship is displayed in the following graph for a given linear apex offset of 50 microns (a typical maximum allowed value):

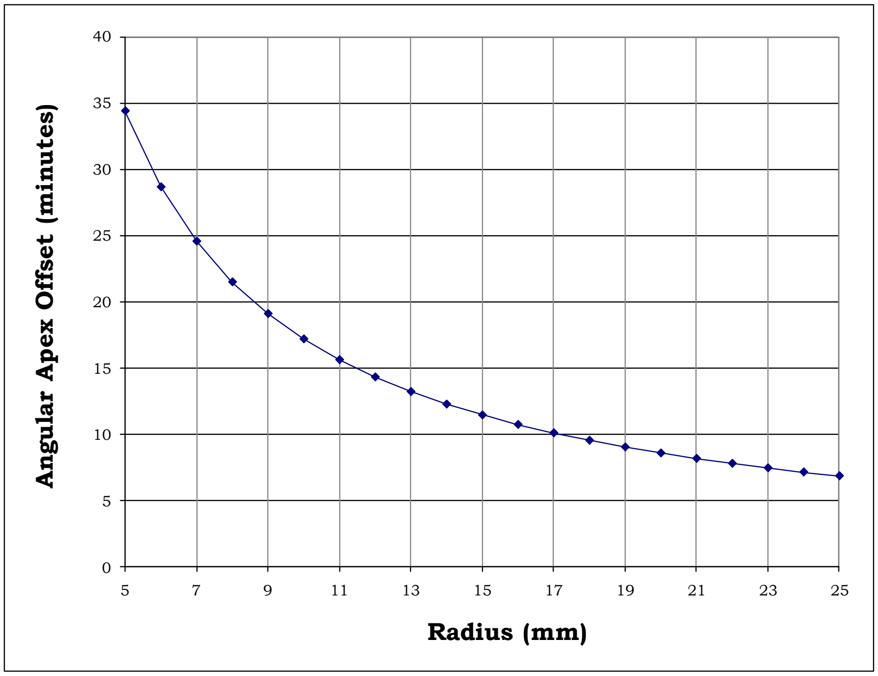


Fig. 6: Relationship between Angular Apex Offset and Radius of Curvature for a given Linear Apex Offset of 50 µm

The graph above illustrates that for a given *Linear Apex Offset*, as the *Radius of Curvature* increases, the *Angular Apex Offset* decreases.

Because of the spherical nature of the connector endface, the interferometer cannot tell the difference between any fixturing errors (when the ferrule of the connector is not exactly perpendicular to the plane of the interferometer) and polishing errors causing the apex to not be centered over the fiber. Thus we can see from the relationship between *Linear* and *Angular Apex Offset* that for PC connectors these angular fixturing errors will lead to excess *Linear Apex Offset* being reported.

As the *Radius of Curvature* of the connector's endface increases, these angular errors result in larger *Linear Apex Offset* errors. This relationship is depicted in the following graph:

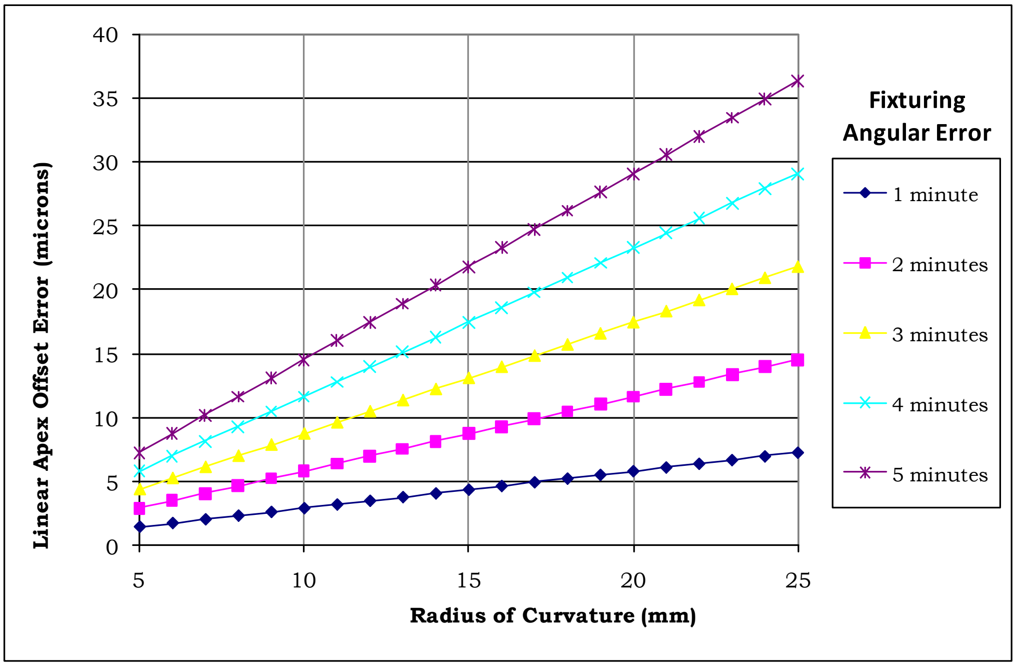


Fig. 7: Graph of relationship between Linear Apex Offset Error and Radius of Curvature for different fixturing angular errors.

Rotation of a PC Ferrule

If a PC ferrule is perfectly rotated about its axis (green dashed line in the following diagram) the direction of the Linear Apex Offset changes, but its magnitude stays the same.

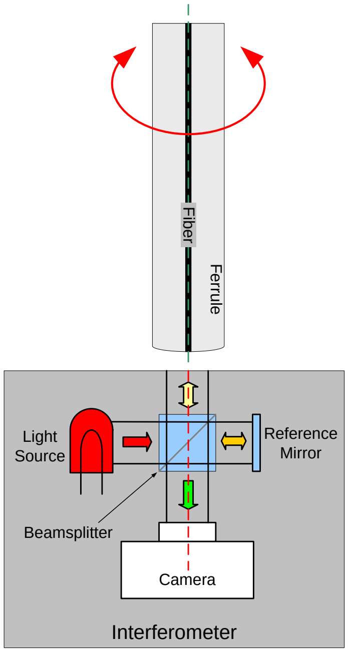
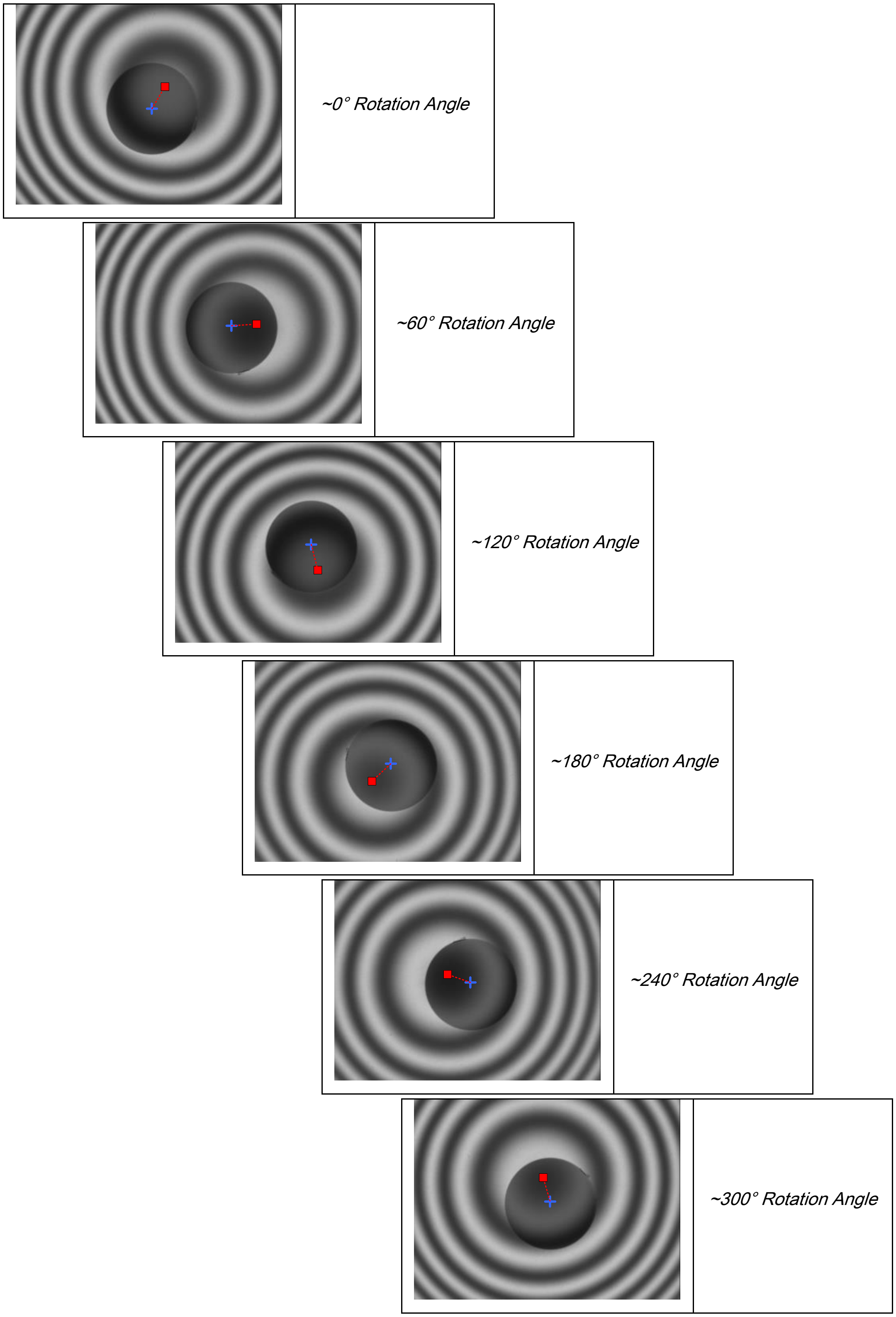


Fig. 8: PC ferrule rotation indicated by red arrow

This rotation is illustrated in the following fringe images where the ferrule was rotated in 60 degree steps:



~0° Rotation Angle

~60° Rotation Angle

~120° Rotation Angle

~180° Rotation Angle

~240° Rotation Angle

~300° Rotation Angle

Fig. 9: Interferometric endface images with different rotation angles

The center of the fiber is designated with a blue “+” and the center of the fringe pattern (which is the apex of the polish) is designated with a red square. The length of the red dashed line is the *Linear Apex Offset* and it stays the same length as the ferrule is rotated.

As shown in the following section, this same rotation performed on an APC ferrule gives very different results.

Angular Apex Offset for Angle Polished Fiber Optic Connectors

Because of a physical limitation of interferometry, the ferrule axis (green dashed line) of angle polished fiber optic connectors must be held at the polish angle relative to the interferometer axis (red dashed line) in order to properly measure the endface geometry.

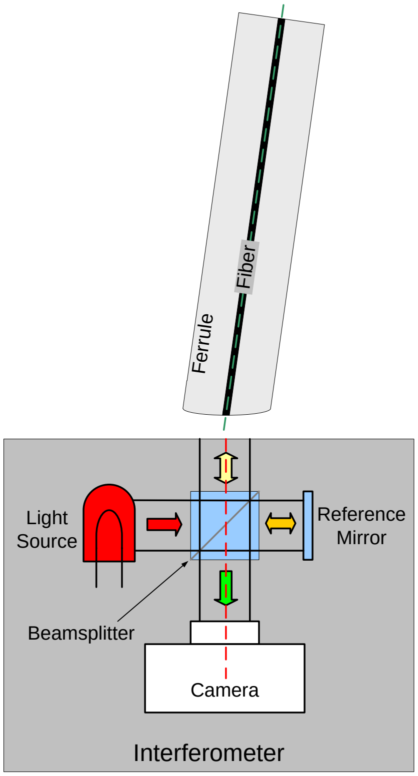


Fig. 10: The interferometer configuration for measuring the endface of an APC connector (note the ferrule tilted at 8 degrees).

The *Radius of Curvature*, *Linear Apex Offset* and *Fiber Undercut/Protrusion* are then measured in the same manner used for PC connectors.

According to TIA-455-218, the *Angular Apex Offset* can then be divided into two orthogonal angles: *Angle of Polish Error* and *Key Angle Offset Error*.

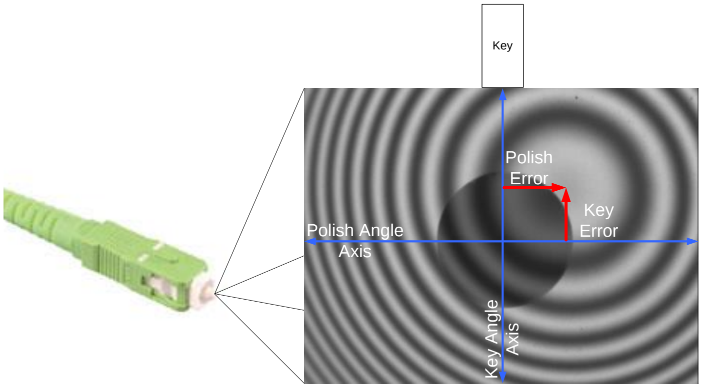


Fig. 11: Relationship between the endface of an APC connector and the Polish and Key error.

The *Angle of Polish Error* is the amount of *Angular Apex Offset* in the direction perpendicular to the key position of the connector. Any angle errors in the polish angle or the fixturing in this perpendicular direction will directly influence the *Angle of Polish Error* and in turn the *Linear Apex Offset*.

The *Key Angle Offset Error* is the amount of *Angular Apex Offset* in the direction parallel to the key position of the connector. Errors in the connector's key position are equivalent to rotating the connector about the axis of the connector's ferrule (green dashed line) as in the following diagram:

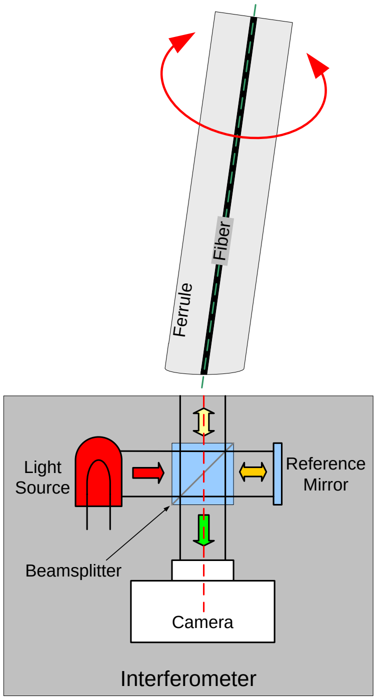
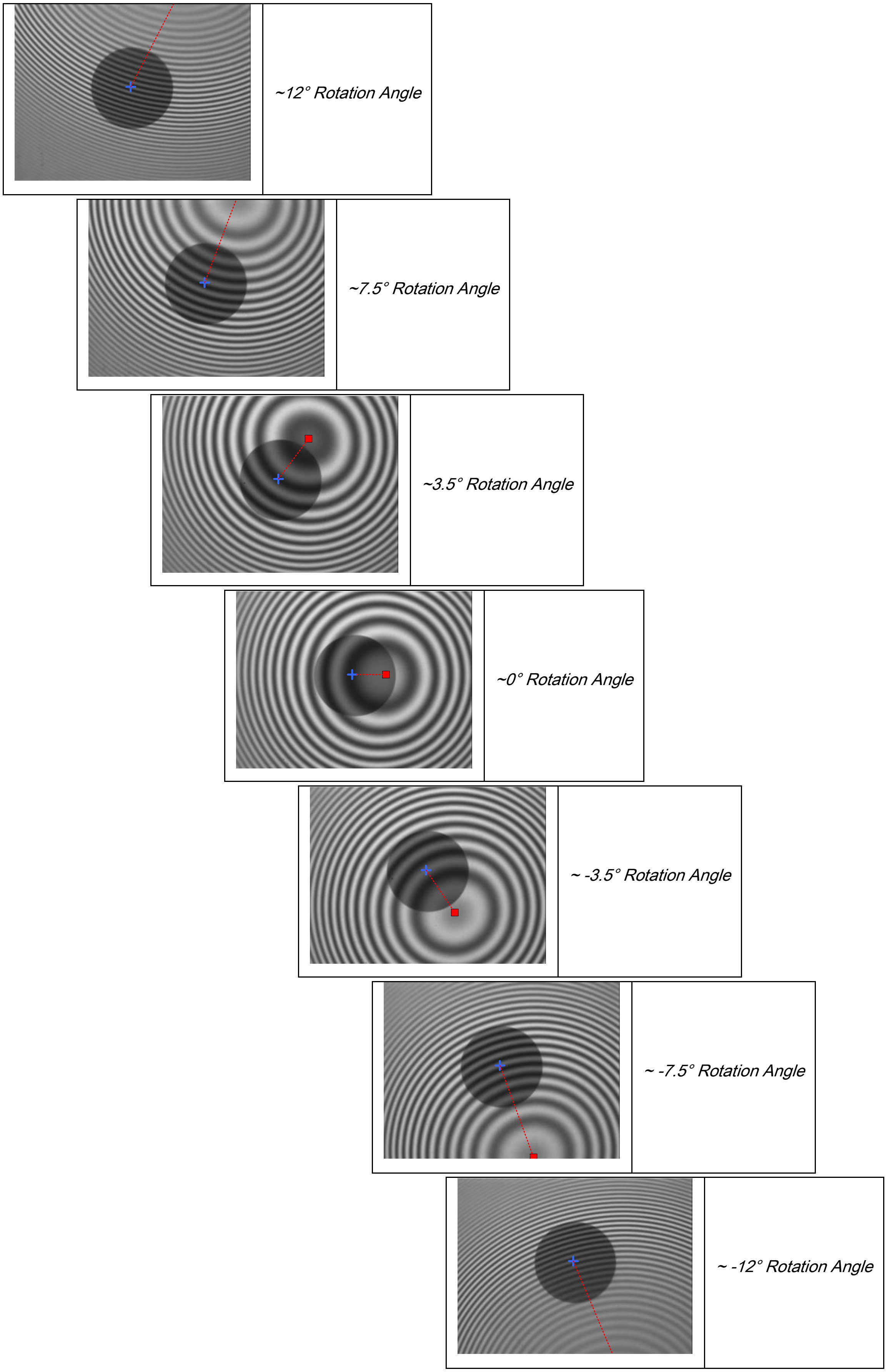


Fig. 12: APC ferrule rotation indicated by red arrow.

The following fringe images of a connector endface illustrate how the center of the interferometric fringe pattern moves as an APC ferrule (tilted at 8 degrees to the interferometer axis) is rotated. The ferrule is rotated in its holder from out of alignment, through correct key angle alignment and then out of alignment again (the connector key is at the top of the images). The center of the fiber is designated with a blue "+" and the center of the fringe pattern is designated with a red square.



~12° Rotation Angle

~7.5° Rotation Angle

~3.5° Rotation Angle

~0° Rotation Angle

~ -3.5° Rotation Angle

~ -7.5° Rotation Angle

~ -12° Rotation Angle

Fig. 13: Interferometric Endface Images with Different Key Orientation Angles

The center of the circular fringes corresponds to the peak of the endface's spherical shape. As the ferrule is rotated, the distance from the center of the fringe pattern to the center of the ferrule is the *Linear Apex Offset* (red dashed line) which can be divided into *Polish Angle Offset Error* (horizontal) and *Key Angle Offset Error* (vertical). When the center of the fringe pattern is aligned horizontally to the center of the fiber, there is zero *Key Orientation Angle* (KOA) *Error*, and the ferrule is properly rotated to align with the key of the connector.

Because the ferrule is held at its polish angle relative to the interferometric measurement device, this *Key Orientation Angle Error* does not directly correspond to changes in the *Key Angle Offset Error*, but are scaled. The objective is to determine this relationship theoretically.

Theoretical Angle Relationships for Rotating APC Ferrule

Derivation

The following diagram represents a non-rotated APC ferrule that has been properly tilted relative to the axis of the interferometer (red dashed line). The ferrule is shown in the diagram with a green dashed line representing its axis. The spherical endface of the ferrule is a small portion of a larger, theoretical sphere illustrated by the dashed circle in the diagram. Note that the lowest part of the circle representing the ferrule endface polish radius is at the same location as the ferrule (and fiber) center thus giving zero apex offset.

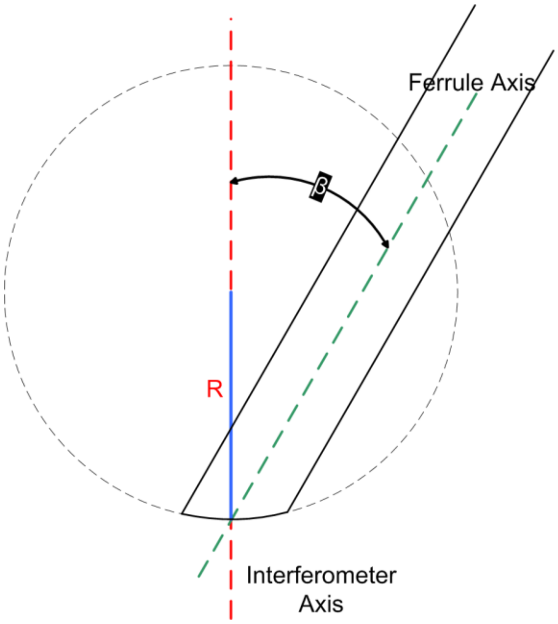


Fig. 14: Exaggerated diagram of a non-rotated APC ferrule with zero apex offset error. β is the polish angle, R is the radius of curvature.

If this ferrule is rotated 180° about its axis (the green dashed line), the following diagram results:

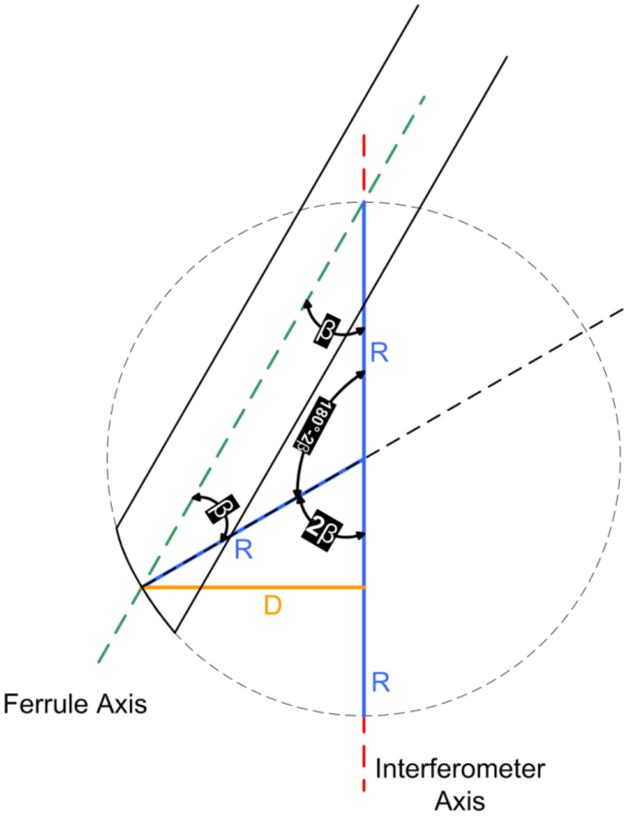


Fig. 15: Exaggerated diagram of APC ferrule rotated 180° about ferrule axis. β is the polish angle, R is the radius of curvature and D is the horizontal distance between circle minimum and center of ferrule.

Now the lowest point of the circle representing ferrule endface polish is not located at the same point as the ferrule center, but is a horizontal distance *D* away. This low point of the circle would be the center of the circular fringes if looking at the ferrule surface on the interferometer. The distance between the ferrule center and this low point is the *Linear Apex Offset* due to rotation of the ferrule. (In reality we could never rotate the ferrule this much and see the low point of the circle because it would be off the surface of the ferrule).

We want to determine the distance *D* because it describes the diameter of the circle that the minima of the ferrule circle travels as the ferrule is rotated about its axis. The relationship between the angles is determined by the geometry in the above diagram. Looking more closely at the part of the diagram that contains *D*:

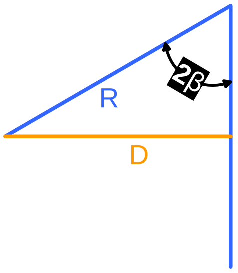


Fig. 16: Zoom in on previous figure containing D.

The relationship between D, Radius of Curvature R and polish angle β is then found as:

II) $$D = R \cdot \sin(2 \cdot \beta)$$

The circle that the minima travel around describes how the *Key Linear Apex Offset* changes and looks like:

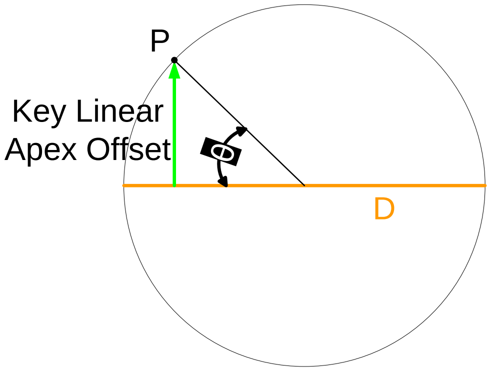


Fig. 17: Circle of Linear Apex Offset created as the APC ferrule is rotated.

D is the diameter of the travelled circle and *θ* is an arbitrary ferrule *Key Orientation Angle* where the point *P* shows the *Key Linear Apex Offset* in the Y direction. Looking at this diagram we can write the following relationship:

III) $$\text{Key Linear Apex Offset} = \frac{D}{2}\sin(\theta)$$

Using equation I that gives the relationship between *Linear* and *Angular Apex Offset*, it can be said:

IV) $$\text{Key Angle Offset Error} = \sin^{-1}\left(\frac{\frac{D}{2}\sin(\theta)}{\text{Radius of Curvature}}\right)$$

Using the result from equation II and noting *R* = *Radius of Curvature*, *θ* = *Key Orientation Angle* and β = *Polish Angle* we arrive at:

V) $$\boxed{\text{Key Angle Offset Error} = \sin^{-1}\left(\frac{1}{2}\sin(2 \cdot \text{Polish Angle}) \cdot \sin(\text{Key Orientation Angle})\right)}$$

Consequently, if the *Key Orientation Angle* is greater than 90 degrees or less than -90 degrees, the magnitude of the *Key Linear Apex Offset* will start getting smaller as the ferrule is further rotated, so Equation V is only valid for small angles. This has more to do with the limitations of how *Key Angle Error* is defined than the rest of the derivation.

Verification

The relationship of Equation V was verified by using an OGP Smartscope® CMM (Coordinate Measurement Machine) to independently measure the *Key Orientation Angle* of a ferrule while using a PROMET FiBO® interferometer to measure the *Angle of Polish* and *Key Angle Offse*t *Errors*. This measurement was repeated for four different ferrules with various radii. The following plot shows the measured relationship between the *Key Angle Offset Error* and *Key Orientation Angle* as well as a theoretical line from Equation V using 8 degrees as the *Polish Angle*:

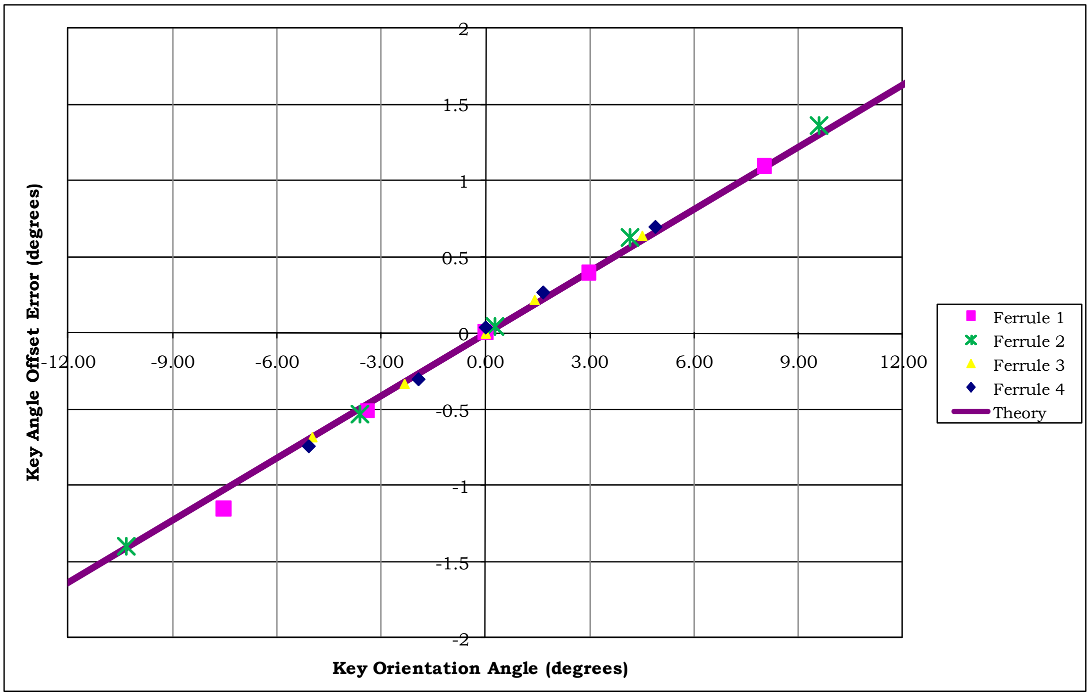


Fig. 18: Key Angle Offset Error vs. Key Orientation Angle.

There is excellent agreement between the measured points and the theoretical line.

Further implications

Equation I, relating the *Angular Apex Offset* to the *Linear Apex Offset* and the *Radius of Curvature*, still holds for angled connectors. Rewriting the equation to solve for *Linear Apex Offset results in*:

VI) $$\text{Linear Offset} = \text{Radius of Curvature} \cdot \sin(\text{Angular Apex Offset})$$

If it is assumed that the entire *Angular Apex Offset* is from *Key Angle Offset*, equations V and VI can be combined to formulate the following equation:

VII) $$\text{Linear Offset} = \text{Radius of Curvature} \cdot \frac{1}{2} \sin(2 \cdot \text{Polish Angle}) \cdot \sin(\text{Key Orientation Angle})$$

Using this equation with different amounts of *Key Orientation Angle Error* for various *Radii of Curvature* at an 8 degree *Polish Angle* produces the following plot of *Linear Apex Offsets*:

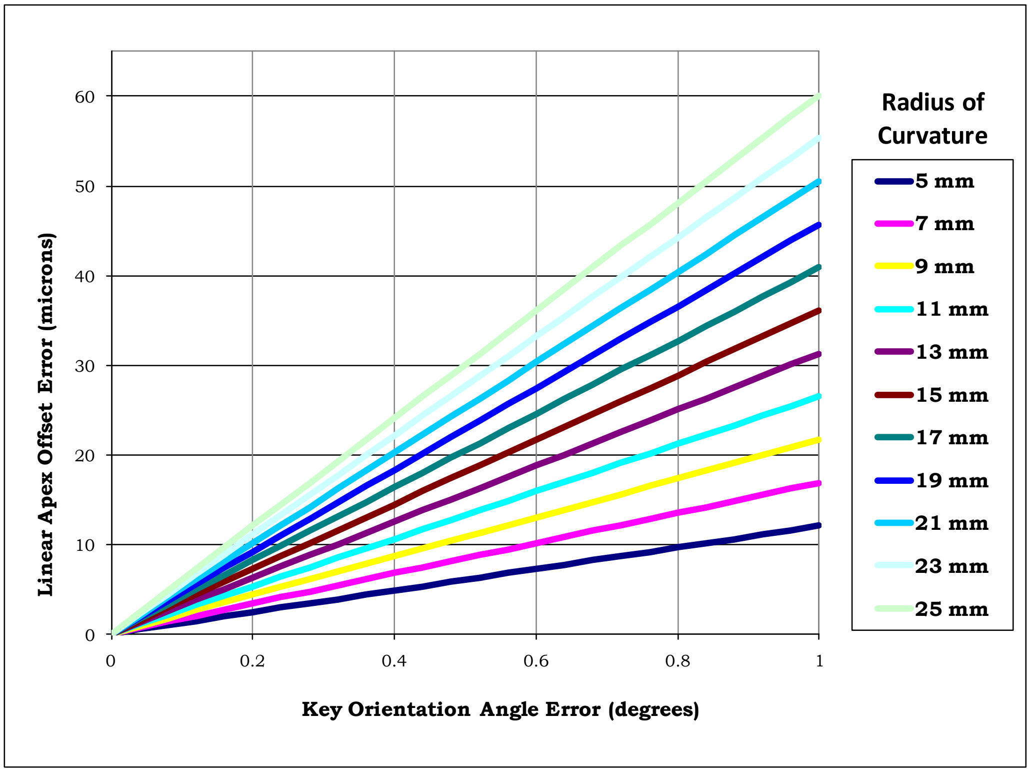


Fig. 19: Linear Apex Offset Error versus Key Orientation Angle Error for an 8 degree Polish Angle and various Radii of Curvature

This plot demonstrates that as the *Radius of Curvature* increases, the sensitivity of *Linear Apex Offset Error* to *Key Orientation Angle Error* increases. A typical maximum allowed amount of *Linear Apex Offset* is 50 microns, so problems with *Key Orientation Angle Error* could use up a large portion of this tolerance, especially for a connector with a larger *Radius of Curvature*. Any mechanical tolerance interactions that allow the ferrule to rotate relative to the measurement holder will contribute to errors in *Linear Apex Offset measurements*.

Possible Sources for Key Orientation Angle (KOA) Errors

Some possible sources of KOA errors that can lead to excess Linear Apex Offset measurements include:

1. Connectors that intentionally hold the ferrules loose to allow two mating ferrules to rotate for best fit
2. Poorly made connectors with keys that do not fit keyways properly or tolerance issues between keys and keyways
3. Angle errors caused by the ferrule not being held correctly relative to the optical axis of the measuring interferometer
4. Angle and measurement errors in the interferometer itself

To examine possible error source #1, measurements were made by firmly clamping ferrules in a FiBO® clamping adapter and then rotating the outside plastic of the connector that contains the key. The angle that the key rotation varied was then measured on a Smartscope®. Here is an example of what this rotation looks like from along the ferrule axis using the video microscope capabilities of the Smartscope®:

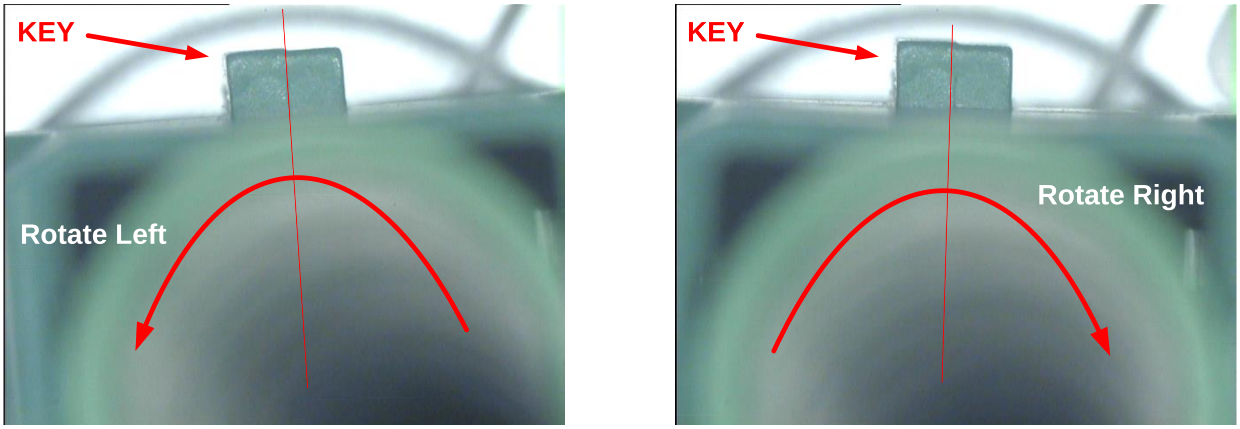


Fig. 20: Microscope images of SC/APC connector body being rotated Left and Right with ferrule firmly clamped. Note the oddly shaped key as well.

A variety of LC and SC connectors (both PC and APC) from different manufacturers were measured using this method. This survey was by no means comprehensive of all manufacturers nor all connector types, but the results showed a surprisingly wide range of angles as can be seen in the following table:

				Measured Key
				Orientation Angle Range
Type	**Patchcord #**	**Manufacturer**	**End**	**Degrees**
SC/PC	1	1	A	14.9
	2	2	A	7.9
			B	7.8
	3	3	A	2.9
	4	4	A	7.1
			B	7.4
	5	5	A	5.4
			B	6.8
SC/APC	6	4	A	7.0
			B	7.2
	7	6	A	3.3
			B	2.3
LC/PC	8	7	A	5.1
			B	3.2
	9	8	A	23.7
			B	22.1
			C	24.4
			D	24.8
LC/APC	10	6	A	0.5
	11	6	A	2.3
	12	6	A	0.5
			B	1.7
	13	9	A	4.3

Table 1: Measured Key Orientation Angle for different brands and types of connectors

LC/APC connectors from one manufacturer had *Key Orientation Angles* that varied only ± a few tenths of a degree while LC/PC connectors from a different manufacturer had KOAs that varied by more than ±12 degrees. Most of the other connector brands had KOA's that varied by ± a few degrees.

A few degrees may not sound excessive, but as we saw in the graph in Fig. 19, one degree of KOA error can lead to many tens of microns of *Linear Apex Offset* error.

Reference Planes

To address possible error source #3 listed above, it is apparent there is a need to have very well defined reference planes for both *Key Angle* and *Polish Angle* values in the measurement system. The theoretical planes used as the reference for the *Polish Angle* and *Key Angle* values can be described as follows:

The *Polish Angle* reference plane is a plane normal to the optical axis and passing through the origin (i.e. center of the fiber).

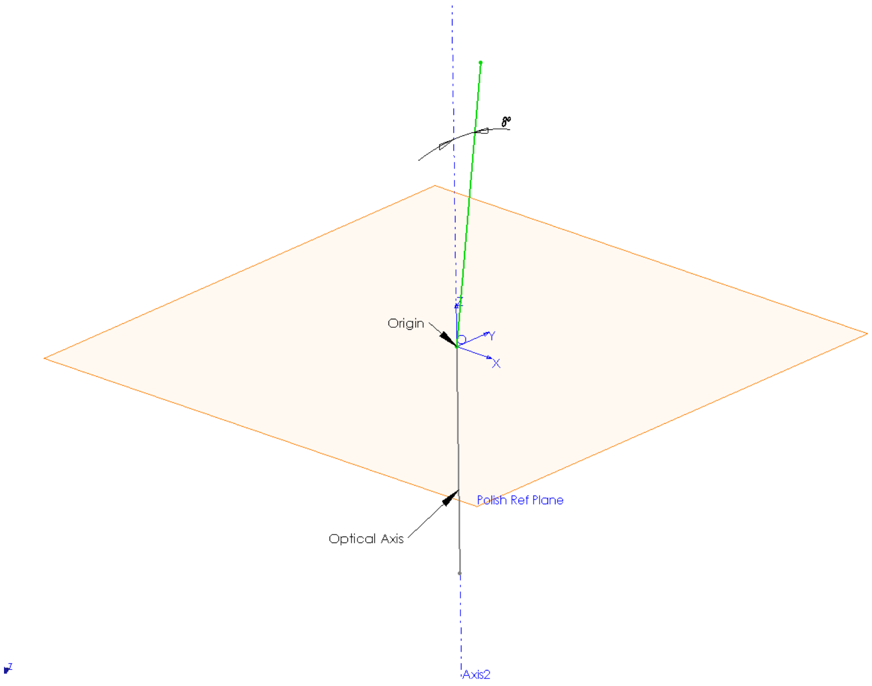


Fig. 21: Polish Angle Reference Plane

The *Key Angle* reference plane is a plane normal to the Polish Angle reference plane and passing through the origin.

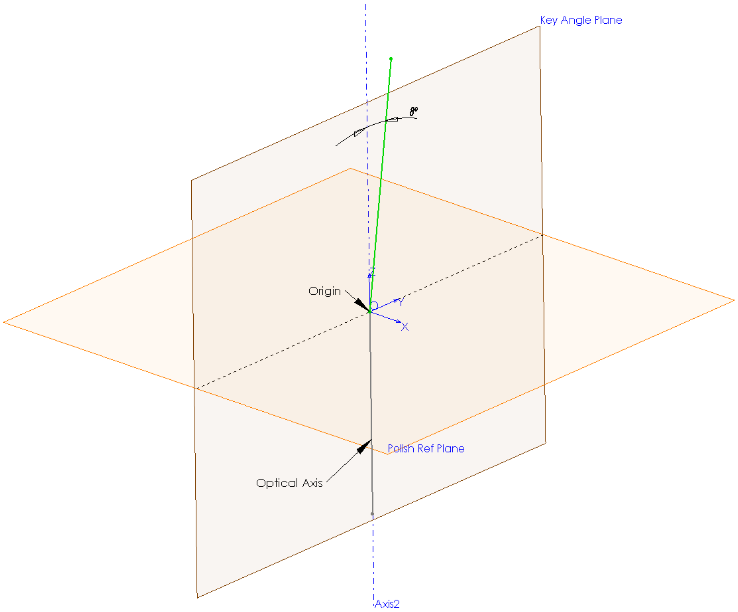


Fig. 22: Key Angle Reference Plane

Although these reference planes are clearly defined in geometrical space, it is challenging to effectively transfer these reference planes to real world mechanical systems. One of the most effective methods of accurately mechanically defining theoretical orientation planes and axis is through the use of symmetric, kinematically defined contact points. The FiBO® Interferometer implements this method to clearly define theoretical reference planes used in calculating *Linear Apex Offset* measurements to achieve absolute accuracy.

A 3-ball (6 contact point) kinematic arrangement in conjunction with interchangeable kinematic adapters is used to define a nominal local coordinate system at the point of the connector endface. This arrangement is mechanically reproducible to within ± 1 microns corresponding to about ± 15 arc seconds of angular error for the reference planes used to calculate *Linear Apex Offset*.

The reference plane for the *Polish Angle* value is mechanically defined as follows:

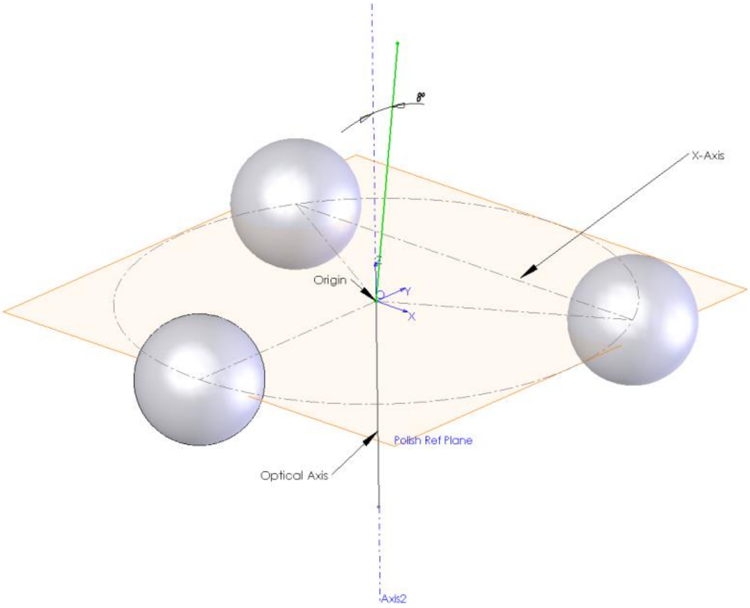


Fig. 23: Mechanically defining the Polish Angle reference plane with a 3-ball kinematic arrangement

The plane through the center of the three balls is determined by indexing the kinematic interface assembly and taking three measurements at 120 degree clocking angles. The resulting three points define the *Polish Angle* reference plane with the *Origin* located at the center of the three-point circle. The *X-Axis* of the *Polish Angle* plane is defined as a line going through the centers of two of the balls.

The reference plane for the *Key Angle* value is defined as a plane which is normal to both the *Polish Angle* reference plane and the *X-Axis* of the *Polish Angle* reference plane and passes through the *Origin*.

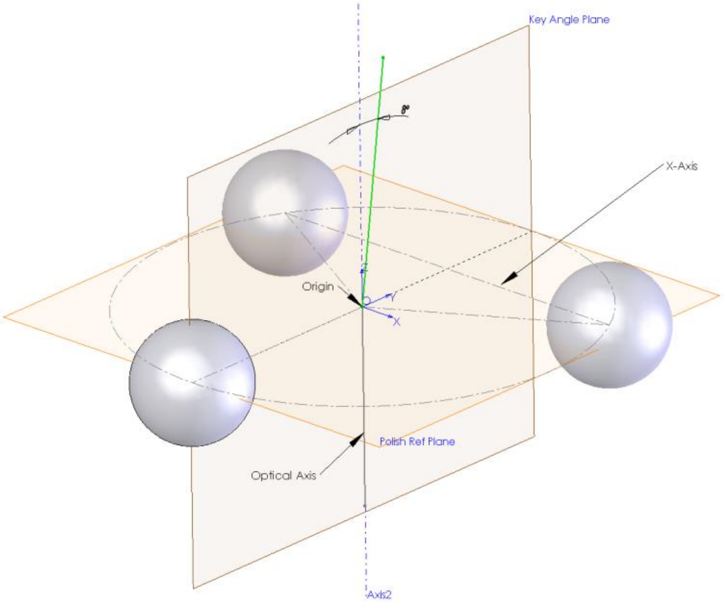


Fig. 24: Key Angle reference plane with a 3-ball kinematic arrangement

The location of the *Key Angle* reference plane is actually determined using a CMM method and the three reference balls.

Once both the *Polish Angle* and *Key Angle* reference planes are mechanically defined, the kinematic adapters can be actively aligned to the desired accuracy using proprietary alignment methods. The three ball kinematic interface ensures a very high-level of repeatability and allows for interchangeability between different interferometer systems.

Minimizing KOA Errors when Measuring

In light of the relationship between the KOA and the resulting excess Apex offset, it is obvious that the measurement of *Linear Apex Offset* in APC connectors is not straightforward. Rotating the APC ferrule in the connector body or rotating the connector body inside a loose keyway can result in *Linear Apex Offset* measurements that vary by tens of microns, or more, for the same connector.

Minimizing the error due to KOA error reduces measured *Linear Apex Offset* and leaves *Linear Apex Offset* due to the *Polish Angle* error. KOA is minimized when the interferometric circular fringes are centered on the X-axis of the image, for example:

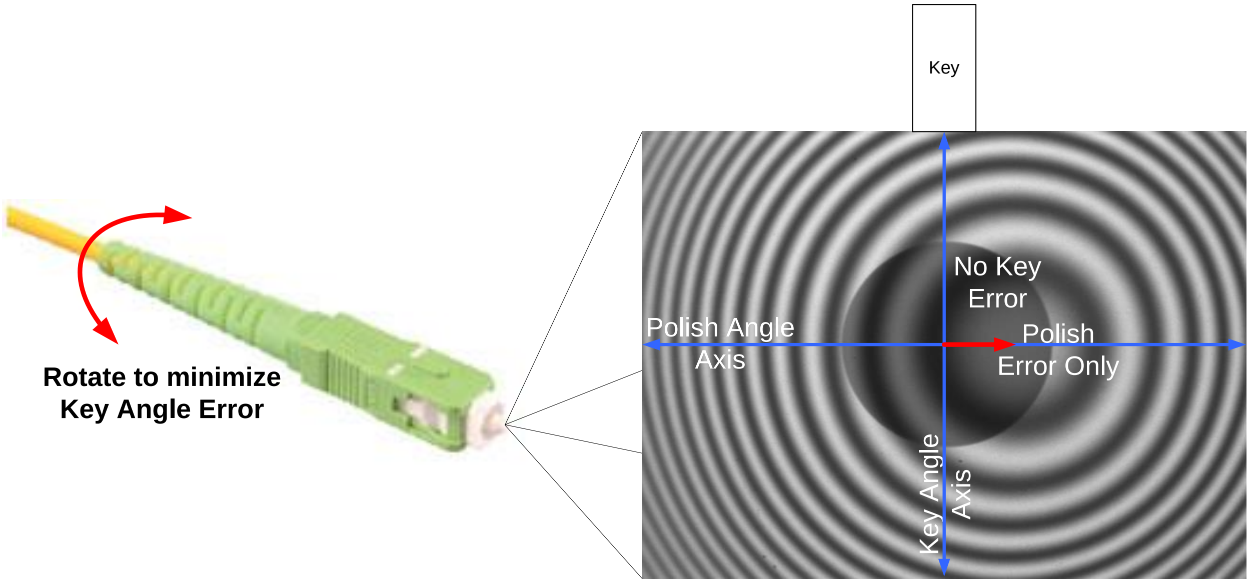


Fig. 25: Interferometric image of APC ferrule rotated to achieve minimum KOA error

This manual rotation to minimize the KOA effect can be achieved while viewing the live interferometric image. This may be a philosophically unsatisfactory method for measuring *Linear Apex Offset*, but if there is intentionally designed looseness between the ferrule and the connector body, then the *Linear Apex Offset* will vary as the ferrule rotates and this may be the only way to minimize the variation. This method of measurement is also not compliant with any industry standards documents and should only be used only in very specific situations.

Summary

There is a direct relationship between *Linear Apex Offset* and *Key Orientation Angle* error in APC fiber optic connector endface measurements. The theoretical relationship between *Linear Apex Offset* error, *Key Orientation Angle* and *Radius of Curvature* was derived theoretically, experimentally verified and results plotted. This error can result from intentional looseness between the connector body and the ferrule, key and keyway construction and tolerance, as well as the fixturing of the connector while being measured. To minimize the measurement system errors, it is important to clearly define the reference planes, and relate them to mechanical reference points. A symmetric kinematic arrangement is a very reproducible and accurate method of mechanically defining these planes. The rotation errors inherent in APC connectors can lead to large variations in *Linear Apex Offset*, but these effects can be minimized by manually rotating the *Key Angle Offset* when making measurements.

About PROMET International®

PROMET International specializes in the design, manufacturing and testing of high-precision optomechanical systems for various industries including security, biomedical , manufacturing, aerospace and defense. Since 1993, PROMET has been providing its customers with the unique expertise, technology, and precision components that are necessary to successfully implement theoretical optical designs into real-world solutions.

FiBO® true phase-shifting Michelson interferometers are designed and manufactured by PROMET International's experienced staff of engineers and technicians. FiBO® facilitates non-contact analysis of fiber optical connector endfaces and micro-components, setting new standards for portable, vibration-insensitive interferometry by combining **3D** surface mapping and visual inspection capabilities into compact, rugged designs.

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