Characterization of an alignment procedure using an air bearing and off-the-shelf optics

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ABSTRACT

We characterize the precision of five approaches used to align a series of targets over a distance of two meters. For many applications, an alignment telescope provides the necessary precision for positioning targets. However, for systems with tight tolerances, we must have a measure of the uncertainties in the alignment telescope to determine if it can truly meet the system requirements. We develop a procedure to measure the precision of each alignment approach and compare their performances. We use a telescope constructed from off-the-shelf optics and mechanics to determine if we can obtain alignment precision comparable to an alignment telescope of superior optical quality.

Keywords: alignment telescope, air bearing, alignment datum, alignment precision

1. INTRODUCTION

In this paper, we characterize the precision of five approaches used to align a series of targets over a distance of two meters. While it is possible to assemble an optical system on a large coordinate measuring machine (CMM), this method is sometimes impractical. A CMM or similar touch probe will not be an effective tool for aligning reference marks on optical flats. Furthermore, the mechanical support structure for the optical system can restrict the probe's access to the elements.

An alignment telescope is a common non-contact tool that can be used to align systems meters in length. For many applications, an alignment telescope provides the necessary precision for positioning targets [1]. However, we cannot determine if an alignment telescope meets the given tolerances if we do not have a measure of the uncertainties in the telescope itself. Our experiment provides a statistical measure of the overall alignment precision in an optical system for a given approach.

We compare the performance of a stationary alignment telescope to that of a stationary alignment telescope with a CCD camera attached to the eyepiece, an alignment telescope with camera and 180 degree reversal, and an alignment telescope with camera mounted on an air bearing. We also measure the precision of a telescope constructed from off-the-shelf optics and mechanics mounted on an air bearing.

1.1 Motivation

The Large Optics Fabrication and Testing Group is responsible for the fabrication, assembly and alignment of the 4 mirror Wide Field Corrector for the Hobby Eberly Telescope (HET). All four of the mirrors are aspheres and three are meter class optics. A schematic is shown in Fig. 1.

Each mirror will have a removable central window with an alignment mark. This mark must be coincident with the axis of the system to less than a few tens of microns depending on the mirror [2]. Because of the tight tolerances we must verify that the alignment approach used meets the system requirements.

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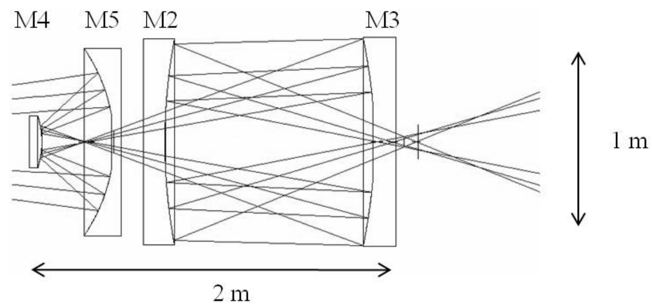

Figure 1. Schematic of 4 mirror Wide Field corrector for the Hobby Eberly Telescope. Approximate dimensions are shown.

1.2 The Alignment Datum

This research determines which approaches will have precision necessary to satisfy the alignment tolerances. The five approaches use two different alignment data – the optical axis of the telescope and the mechanical axis of the bearing.

Alignment telescopes are precision opto-mechanical devices. As we adjust focus to align each target, the telescope is designed to maintain a consistent optical axis. We rely on the stability of this axis for the precision of our stationary alignments. However, due to manufacturing limits there is some deviation in this axis as we adjust focus. The uncertainty in the position of the optical axis contributes to the overall alignment precision.

When we reverse the telescope or mount it on a bearing, we use the mechanical axis of the bearing as the alignment datum rather than the optical axis of the telescope. We locate the mechanical axis by rotating the bearing. For targets not aligned to the bearing axis, the target image will trace out a circle as the bearing spins. For a target aligned to the axis of the bearing, rotation does not affect the location of the target image. It is equally valid to say that the targets rotate around the mechanical axis while the bearing is stationary as in Fig. 2. As the target moves closer to the mechanical axis, it traces out a smaller circle, and when it does not move at all, it is aligned to the mechanical axis. An advantage of this datum is that the optical axis of the telescope does not need to be collinear with the mechanical axis of the bearing nor does it need to be consistent as we adjust focus. The orientation of the optical axis sets the location of the target image on the camera but does not affect the size of the circle formed by the target image.

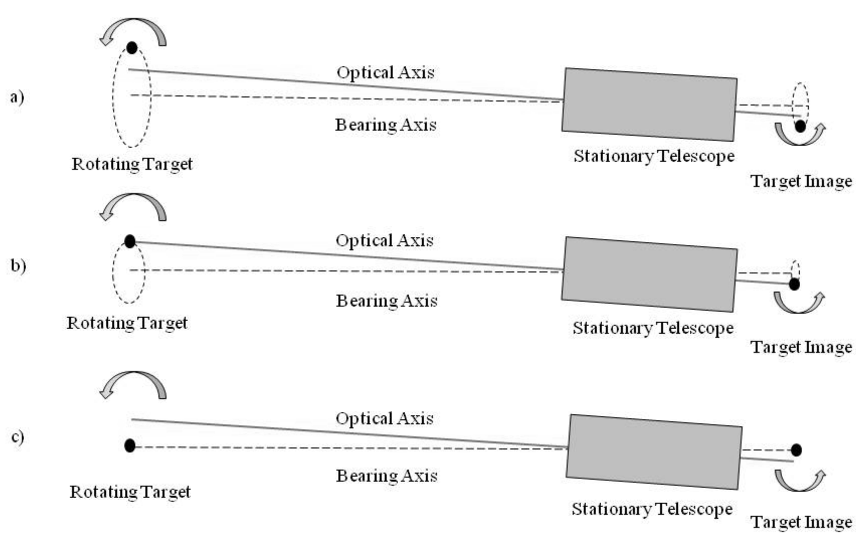

Figure 2. Rotation of target around bearing axis with stationary telescope for a) target poorly aligned to bearing axis b) target moved closer to bearing axis c) target aligned to bearing axis. Note the optical axis does not need to be collinear with the bearing axis to align the target.

In this case, instability in the bearing drives the alignment precision because the mechanical axis does not change with focus and we do not rely on the optical axis for the alignment. We include the off-the-shelf telescope to determine if optical quality affects alignment precision when using a mechanical axis as the datum.

Carnell et al. use a similar concept to align lenses using a precision spindle [3]. They consider a lens to be centered when a set of interference fringes remain stationary as the lens rotates on a bearing. While their procedure makes use of the same principles as our experiment, it cannot be used to center alignment marks on an optical flat.

2. METHODOLOGY

2.1 Measuring Precision

We characterize the precision of each approach by aligning three targets over a distance of two meters. The targets used are the output of a fiber coupled laser ("source"), a Fresnel zone plate ("FZP") and a 10 um pinhole target ("pinhole"). The FZP was made with a laser writer used for fabrication of photo-masks and the center can be marked with sub-micron precision. We use a FZP instead of a lens because its center is well known and it is more representative of the center plugs which will be used in the final alignment of the HET system. The FZP has a primary focal length of 0.5 meters and images the source onto the plane of the pinhole. When the source, center of the FZP and the pinhole are all on a line, the image of the source will be coincident with the pinhole as shown in Fig. 3. If there is decenter in the targets, the source image will be displaced from the pinhole. After all three targets are aligned, the distance between the source image and the pinhole is a measure of the total alignment precision of the system. We cannot measure the precision of individual targets, but will present an estimation of the errors in Section 4. We repeat each alignment approach fifteen times to create a statistical distribution used to calculate the precision.

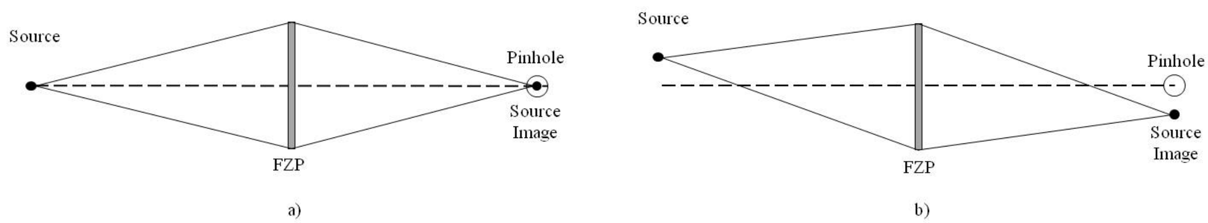

Figure 3. a) Three targets are centered. Pinhole and source image are coincident. b) Source is decentered from alignment axis. Source image is displaced from pinhole.

2.2 Approach 1 – Alignment Telescope

The first approach used was to align each target by eye to the crosshairs of the alignment telescope as shown in Fig. 4. For all five approaches, the targets were mounted on XY stages and the source, located farthest from the telescope, was aligned first, followed by the FZP and then the pinhole. We measure the location of the pinhole with a separate imaging system, then remove the pinhole to measure the displacement of the source image.

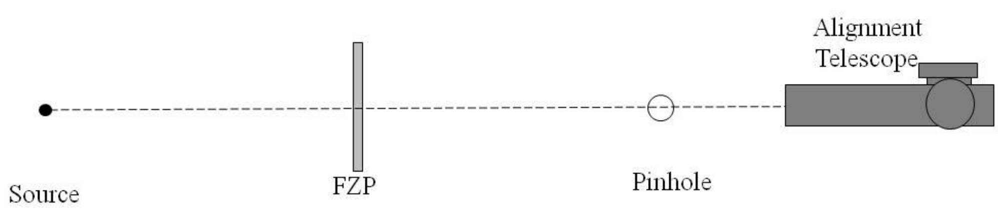

Figure 4. Experimental Setup for Approach 1

Because a single operator collected all the data, we do not have a rigorous measure of the precision for this method. To improve our calculation, multiple operators would be required. However, this method provides an interesting comparison for the other alignment approaches.

2.3 Approach 2 – Alignment Telescope with CCD Camera

For the next approach, we attach a CCD camera to the eyepiece of the alignment telescope and align each target to the crosshairs using the image from the camera. The setup is shown in Figure 5.

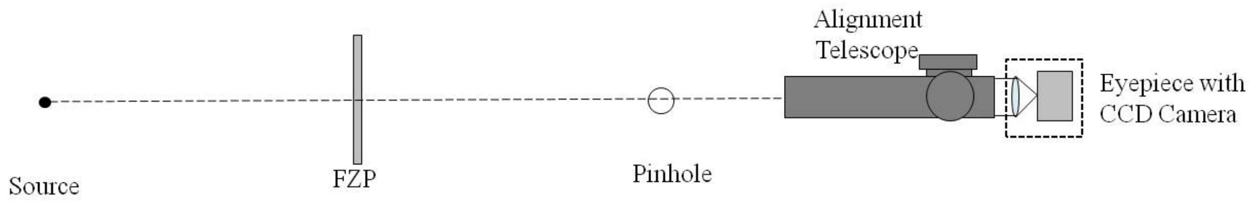

Figure 5. Experimental Setup for Approach 2

When adding a camera, it is important to consider how the pixels on the camera map to the target being aligned. If a single pixel images a 40 μm area on the target, we have less sensitivity than if a pixel imaged a 10 μm area. We want to determine how optical quality and choice of alignment datum affect alignment precision, so we set consistent target magnifications for all five methods. We chose a lens for the CCD camera eyepiece such that the magnification for each target is comparable to the off-the-shelf telescope. We also considered how our choice of magnifications affected the field of view and its impact on the ease of the alignment.

2.4 Approach 3 – Alignment Telescope with Reversal

When we rotate the alignment telescope by hand in a four cone mount, we create a crude bearing whose rotation axis sets the alignment datum as in Fig. 6. Using the same CCD camera attachment, we adjust the position of each target until a 180 degree rotation of the telescope does not change the location of the target image. It is equivalent to consider the telescope to be stationary while the target rotates about the bearing axis. If the location of the target image is not affected by rotation, it is well aligned to the mechanical axis of the bearing.

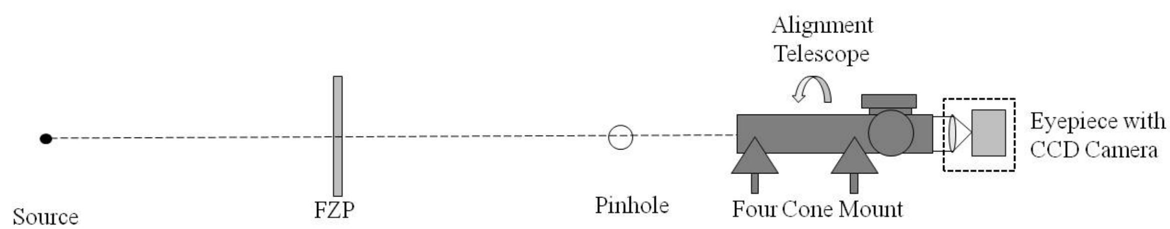

Figure 6. Experimental Setup for Approach 3

Unlike the previous methods, we are not concerned with the location of the target image with respect to the crosshairs since we no longer rely on the optical axis for alignment. However, since the optical axis is well controlled in the alignment telescope, we expect that the change in the position of the target image as we adjust focus will be small.

2.5 Approach 4 – Alignment Telescope on Air Bearing

We mount the alignment telescope vertically on an air bearing as in Fig. 7 and measure the location of the target image continuously as the bearing rotates. If the target is not well aligned to the bearing axis, it will trace out a circle as the bearing rotates.

We fit a circle to the raw data and calculate its center. Due to bearing runout, vibrations and other sources of noise, the RMS deviation of the data points from the best fit circle is on the order of 1-3 μm. We adjust the target until its image on the camera is coincident with the center of the best fit circle.

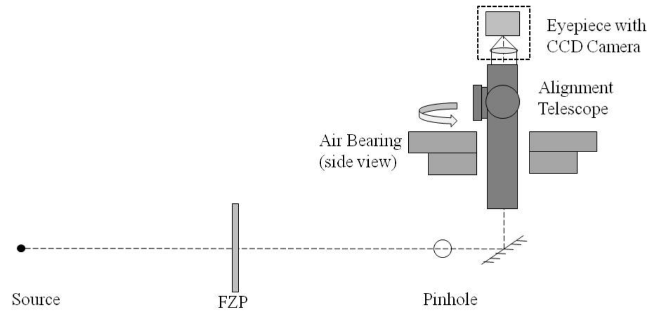

Figure 7. Experimental Setup for Approach 4

2.6 Approach 5 – Off-the-shelf Telescope on Air Bearing

For the final approach, we replace the alignment telescope with a telescope constructed from off-the-shelf optics and mechanics. In the previous two approaches, while we did not rely on the optical axis for alignment, it was still consistent as we changed focus. In the off-the-shelf telescope, no effort was made to keep the optical axis stable – lenses were centered using threads and lenses in tubes were interchanged to adjust focus. Again, we fit a circle to the data points and calculate the center, then align the target image to it. The setup for the system used to align the pinhole is shown in Fig. 8. The 500 and 300 mm lenses are removed and other lenses added to image the FZP and source.

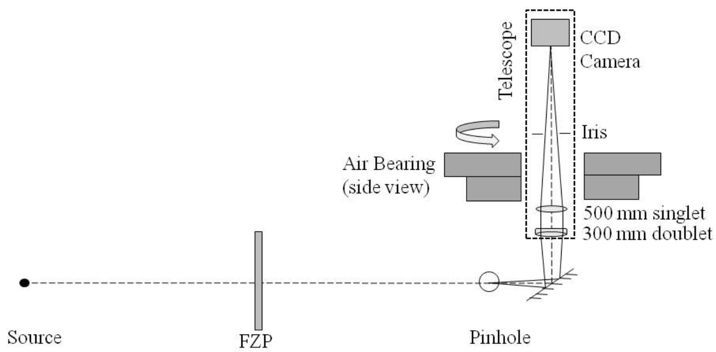

Figure 8. Experimental Setup for Approach 5 when aligning the pinhole.

3. DATA

3.1 Alignment Precision

Each of the 5 alignment approaches was repeated 15 times in order to build up a statistical distribution. Fig. 9 contains scatter plots of the displacement of the source image from the pinhole for each approach. The standard deviations in the x and y directions were calculated, then used to find the standard deviation in radius. The overlaid circle has a radius of twice the standard deviation, representing the 95% confidence limit that for a single alignment, the magnitude of the source image displacement will be less than 2σ. Table 1 contains the value of 2σ for each method.

Table 1. Standard Deviations for Five Approaches

Approach	2σ (μm)
1. Alignment Telescope	248
2. Alignment Telescope with CCD Camera	162
3. Alignment Telescope with Reversal	76.6
4. Alignment Telescope on Air Bearing	31.1
5. Off-the-shelf Telescope on Air Bearing	35.4

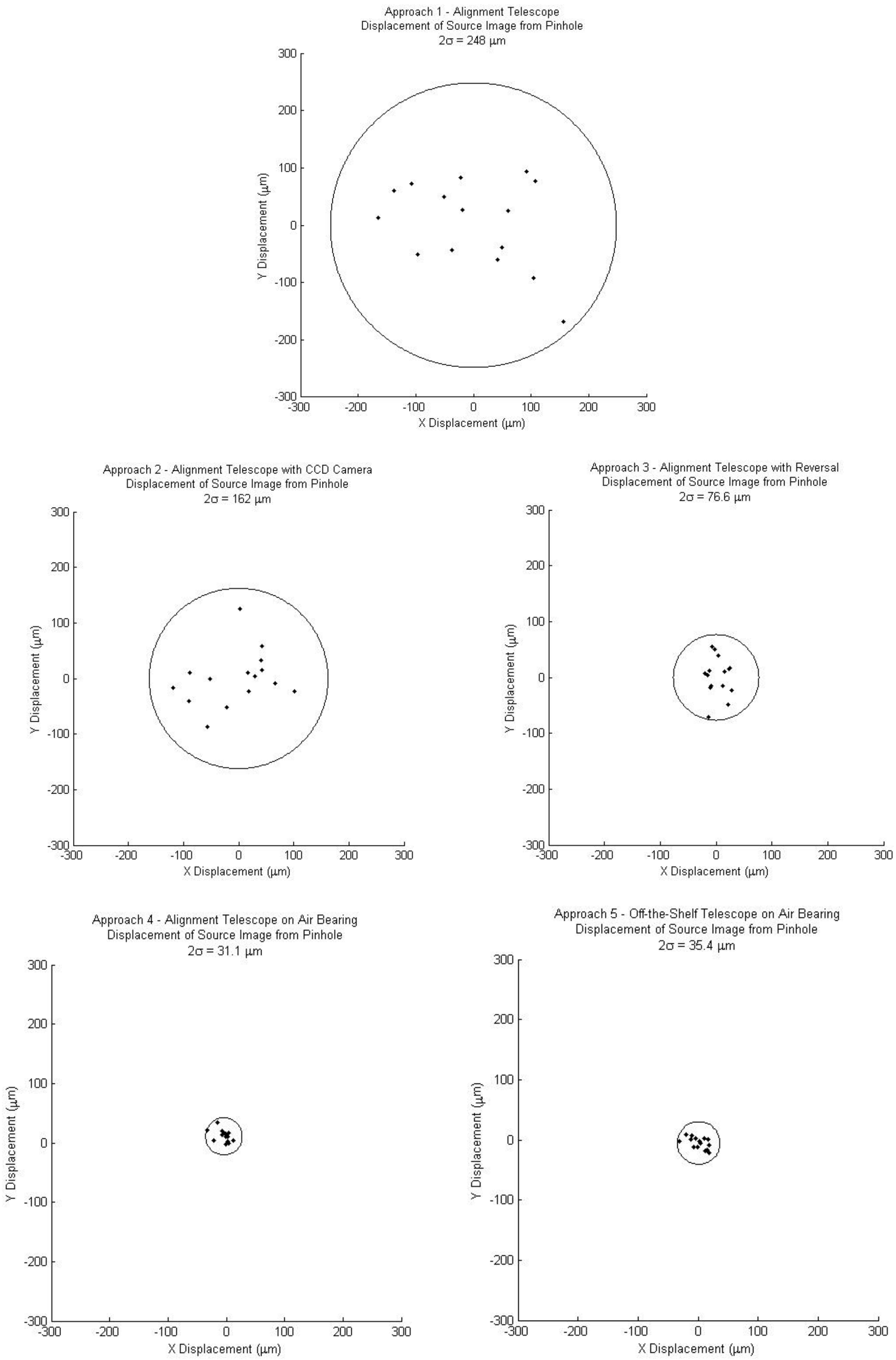

Figure 9. Scatter plots showing 15 measurements of the displacement of the source image from the pinhole for each of 5 approaches. Circle shows 95% confidence limit.

We use the value of 2σ as a measure of the alignment precision for each approach. The average value of the 15 displacements determines the accuracy of the approach, but since its magnitude is small compared to the standard deviation, it is the value 2σ which determines how well we can align the targets.

4. ANALYSIS

4.1 Target Errors

When analyzing the errors in each approach, we must consider both the sources we can identify and those that are unknown. We can estimate some contributions, such as total indicated runout from the air bearing or instability in the position of the target image on the camera due to vibration, air currents, or software artifacts. However, the majority of the error cannot be attributed to a particular source or cannot be quantified. This unknown error can be distributed equally among each target or scaled based on magnification. It is reasonable to assume that the error in the source would be larger than the pinhole since it is two meters farther away from the telescope and has a larger magnification. Table 2 lists the estimated values for the error in each target. We assume the errors are uncorrelated so the total error is calculated by adding the known and unknown error for each target and root sum squaring them. Figure 10 displays the data graphically. The known errors are zero for the first two procedures because we are aligning the targets to the crosshairs by eye. We do not calculate an ideal location for the source image and thus cannot quantify the deviation from it as we do the with approaches 3, 4 and 5. There is also no effect from a bearing.

Table 2. Errors in Source, FZP, and Pinhole for 5 Alignment Approaches

			Source (μm)	FZP (μm)	Pinhole (μm)	Total (μm)
1	Alignment Telescope	Known Error	0.0	0.0	0.0	248
		Unknown Error: Equal	143.0	143.0	143.0	
		Unknown Error: Scaled	204.6	129.9	53.0	
2	Alignment Telescope with CCD Camera	Known Error	0.0	0.0	0.0	162
		Unknown Error: Equal	94.0	94.0	94.0	
		Unknown Error: Scaled	133.6	84.8	34.6	
3	Alignment Telescope with Reversal	Known Error	5.8	3.6	2.2	77
		Unknown Error: Equal	40.5	40.5	40.5	
		Unknown Error: Scaled	57.9	36.8	15.0	
4	Alignment Telescope on Air Bearing	Known Error	4.7	3.6	3.0	31
		Unknown Error: Equal	14.0	14.0	14.0	
		Unknown Error: Scaled	19.6	13.3	7.0	
5	Off-the-Shelf Telescope on Air Bearing	Known Error	4.6	3.5	2.6	35
		Unknown Error: Equal	16.5	16.5	16.5	
		Unknown Error: Scaled	25.3	17.5	3.5	

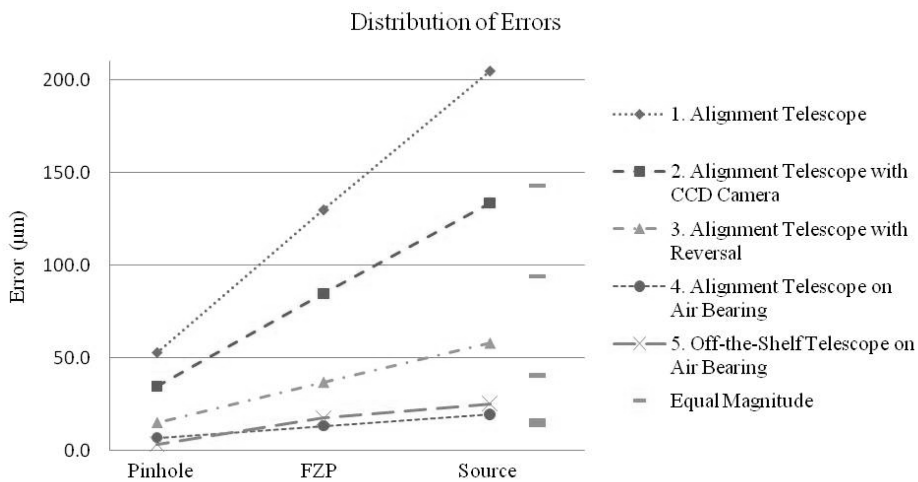

Figure 10. Displays errors in pinhole, FZP, and source for 5 approaches. The 5 lines to the right indicate the error in each target if they are assigned equally.

It is likely that some sources of error are constant for each target and some scale with distance. We estimate that the error in each target falls between the equal and scaled magnitudes in Table 2.

5. CONCLUSION

We have measured the alignment precision for five approaches. The approaches with the highest precision were the alignment telescope and off-the shelf telescope both mounted on an air bearing. The comparable values of 2σ suggest that if a high quality bearing is used, the optical quality of the telescopes does not have a significant impact on the alignment precision.

The data also shows that using a mechanical axis rather than an optical one as the alignment datum increases alignment precision. Moving from a four cone mount with rotation by hand to an air bearing further increases the precision. We can collect data continuously as the air bearing spins while we only measure 4 data points with reversal. The larger number of data points measured with the air bearing may reduce noise and thus give higher precision. The air bearing is likely a better quality bearing than the four cone mount with less friction, total indicated runout, etc. We obtain a factor of two improvement over the stationary telescope with CCD camera by using reversal and more than a factor of four improvement with the air bearing.

Most importantly, we have determined which approaches will give the necessary precision to align the HET system. We have estimated that targets closest to the telescope will have the lowest alignment error, so we can set the position of our telescope near the mirrors with the tightest tolerances. Our characterization of a variety of alignment procedures will also prove useful for determining which approaches are "good enough" for future alignment tasks.

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