SDSS-V focal plane system high-precision metrology

Michael Engelman[1*], Thomas P. O'Brien[1], Richard W. Pogge[1], Mark Derwent[1], Conor Sayres[2], Daniel Pappalardo[1], Christopher Brandon[1], Jonathan Shover[1], Solange Ramírez[3], Stefanie Wachter[3]
[1]The Ohio State University, Columbus, OH 43210; [2]University of Washington, Seattle, WA 98195; [3]Carnegie Observatories, 813 Santa Barbara St, Pasadena, CA 91101

ABSTRACT

The Sloan Digital Sky Survey V (SDSS-V) is an all-sky spectroscopic survey of >6 million objects, designed to decode the history of the Milky Way, reveal the inner workings of stars, investigate the origin of solar systems, and track the growth of supermassive black holes across the Universe. The robotic Focal Plane System (FPS) carries 500 robotic fiber positioners, 60 stationary Fiber-Illuminated Fiducials (FIFs), and 6 Guide, Focus, and Acquisition cameras (GFAs). The GFAs find and use guide stars to compute target positions for the robots. The FIFs provide a reference basis against which precise measurements of the robot positions can be made using the Fiber Viewing Camera (FVC). Once imaged by the FVC, closed loop control allows the robots to reach their commanded positions to within 12 microns of precision. This paper discusses the metrology process for the FIFs and GFAs, thus allowing for accurate robot moves and reliable FVC measurements.

Keywords: SDSS-V, focal plane system, metrology, fiducials, guide cameras

1. INTRODUCTION

The Sloan Digital Sky Survey V (SDSS-V) is an all-sky spectroscopic survey of >6 million objects, designed to decode the history of the Milky Way, reveal the inner workings of stars, investigate the origin of solar systems, and track the growth of supermassive black holes across the Universe. The robotic Focal Plane System instrument (FPS) features 500 robotic fiber positioners, 60 fiber-illuminated fiducials (FIFs), and 6 guide, focus, and acquisition cameras (GFAs) that work together to position optical fibers in the focal plane to collect light from sky targets. Two FPS instruments exist. At the time of this conference (July 2022), one is already in use on the Sloan 2.5m Telescope at Apache Point Observatory (APO) in Sunspot, New Mexico, the other will begin commissioning phases at the end of Summer 2022 on the du Pont 2.5m Telescope at Las Campanas Observatory (LCO) in the Atacama region of Chile.

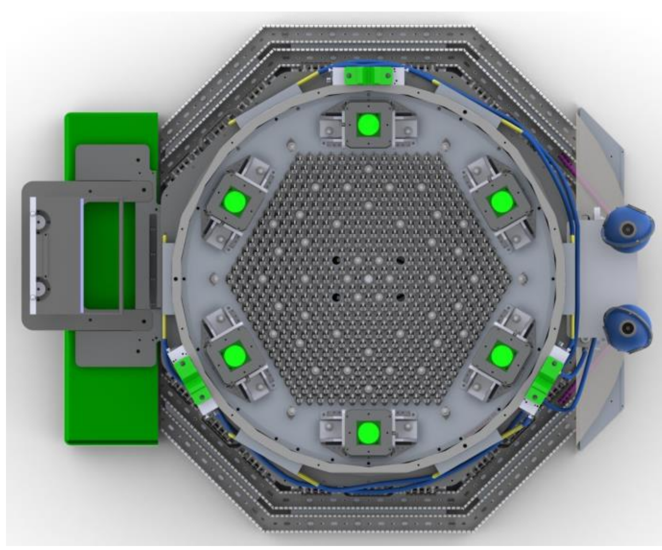


Figure 1. Top view of FPS from CAD model

*engelman.27@osu.edu, astronomy.osu.edu

1.1 FPS Make-Up

The positioners, FIFs, and GFAs, are all mounted on a common mechanical reference surface known as the "wok". The wok has a precision-machined surface curved to place the tips of the science fibers, the FIF fibers, and the GFA camera CCD detectors onto the telescope focal surface, as shown schematically below. The surfaces of the woks are very precise, fabricated to within ±20 microns RMS or less of the desired surface. The surface figure is designed so that the tips of the FIFs and robots mounted normal to the surface will intersect the computed focal plane shapes 143.1 mm above the wok front surface. The normal axis "focus" distance of 143.1 mm for the fiber faces is set at the time of fiber installation in the FIF or robot to ±20 microns RMS using a precision digital height gauge referenced to a steel gauge block to which the FIF or robot being measured is affixed. The target "focus" tolerance combining the wok surface figure and fiber tip metrology is ±70 microns to prevent losses due to de-focus of the beam entering the science fibers.

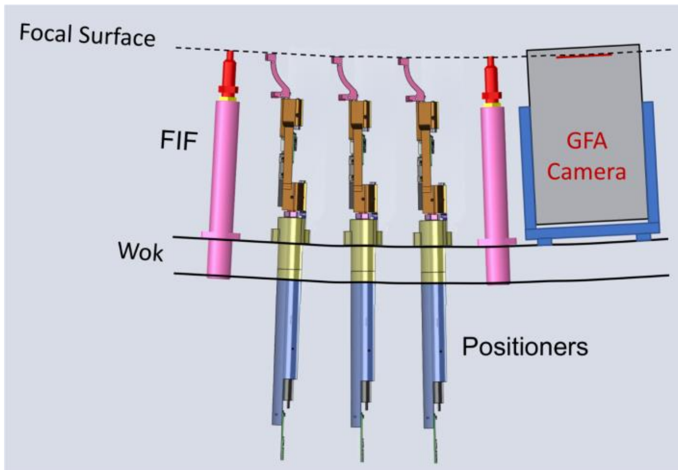


Figure 2. Schematic side view of the focal plane showing the positioners, FIFs, and a GFA CCD on the curved wok mounting plate.

Each robot holds three fibers: two for photon collection for BOSS and APOGEE spectrographs (science fibers) and one for metrology. The key problem to solve for this instrument is how to position science fibers accurately, precisely, and consistently for good data collection. The production robots have a measured blind positioning accuracy of ~50 mm RMS, but better performance is possible if robot-level calibration of nonlinearity in the alpha and beta actuators can be implemented efficiently. This should get a star onto or at the edges of the 120-micron science fiber cores without further refinement. The production robots are observed to make repeatable fine positional offsets of ~2-3 mm. The goal is to be able to place a science target within 12 microns of the center of a science fiber (10% of the fiber diameter: ~0.2 arcsec at APO, ~0.13 arcsec at LCO).

We deploy a fiber viewing camera (FVC) that images the FPS focal plane from above using the telescope optics and a custom 20:1 demagnification doublet lens and CCD. The metrology fiber of each robot is illuminated using the Fiber Back Illumination (FBI) system. A set of 48 fiber-illuminated fiducials (FIFs) are deployed throughout the focal plane and fixed to the wok and another 12 fiducials are co-mounted with the GFA cameras. The 60 fiducial fibers are illuminated by the same FBI system and use the same metrology fibers.

Because the FPS systems are mounted at the Cassegrain foci of their telescopes and we cannot look down directly onto the focal plane in any practical way, we deploy a pickoff mirror located in a periscope that looks down on the primary mirror from above and then use the telescope optics (primary and secondary mirrors and corrector lenses) in reverse (light coming from the focal plane instead of to it) to view the focal plane. Below we show the optomechanical layout of FVC system for the du Pont telescope FPS system that shows (the Sloan FVC works similarly but must contend with the new 3-element corrector lenses and includes an additional fold before the CCD camera to fit the unit onto the Sloan telescope).

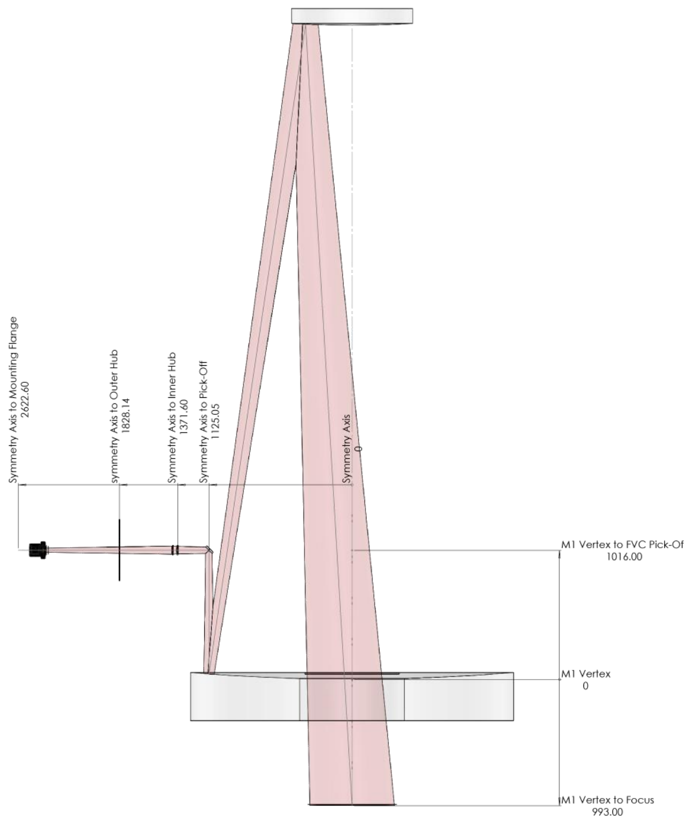


Figure 3. Cross section of CAD model showing ray trace of du Pont Telescope fiber viewing camera

Measuring the positions of the fiber robot tips only tells you where they are in the focal plane. The second step is to map focal plane locations onto the sky with the targets. This is done using measurements of guide/acquire stars in the six Guide/Focus/Acquisition (GFA) cameras located around the periphery of the hexagonal fiber positioner array. The guide cameras take images of stars in the field to verify the pointing of the telescope and provide an astrometric reference to know how XY locations in the focal plane map into celestial coordinates. Four of the GFA cameras are configured for guiding, two are configured to monitor telescope focus by forming intra- and extra-focal images using filters that are ±1 mm different in thickness than the 5 mm guiding filters (custom Gen2 SDSS r filters fabricated by Asahi Spectra, Ltd.).

1.2 FPS Coordinate Systems

Several different coordinate systems are used in the orchestration of FPS operations. The three primary coordinate systems used are outlined in this section.

1.2.1 Geometric Coordinate System

This is the **fundamental coordinate system** of the FPS focal plane. It is defined by the positions of the fibers of the 48 wok-mounted FIFs distributed across the focal plane and measured using a coordinate measuring machine (CMM). Because this is the foundational coordinate system, it carries the tightest tolerances on measurement. State-of-the-art CMM technology is capable of ±3–5 micron precision over the size of the FPS focal plane (~650 mm diameter).

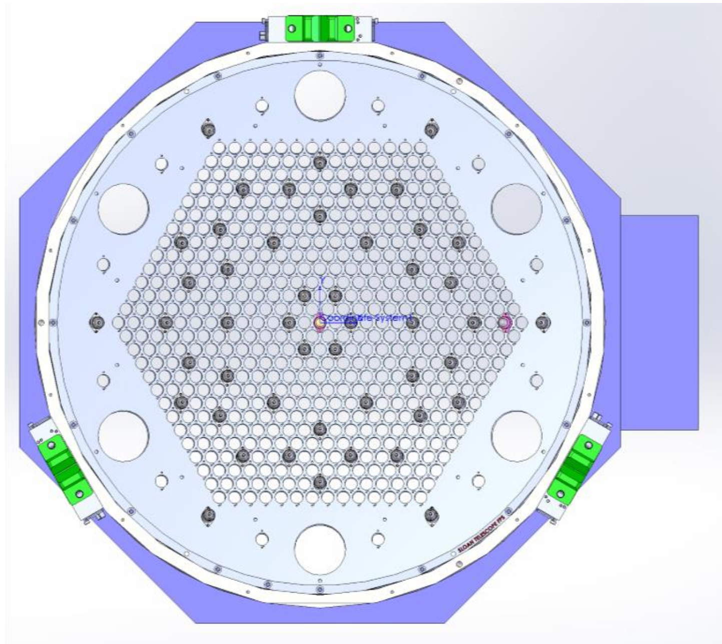


Figure 4. Top view of FPS showing only positions of wok-mounted fiducials

The arrangement of the 48 fixed wok-mounted FIFs is designed to give good sampling in radius and azimuth inside the hexagonal fiber positioner array and out to the periphery of the telescope field of view.

The outer 6 wok-mounted FIFs stepped radially beyond the corners of the hexagonal array seen in Figure 4 are augmented by 12 GFA-mounted FIFs integrated into the camera mounts. The resulting ring of 18 fiducials and 6 GFA CCDs are all spaced every 15-degrees around a 324 mm radius circle that passes roughly through the centers of the GFA detectors and the GFA-mounted fiducials (it does not pass exactly through the CCD center because we need to offset the GFA camera bodies to try to clear the sweep of the outermost robots and to make accommodations for routing camera data, power, and glycol cooling connections coming up from behind the wok).

1.2.2 Dynamic Coordinate System

The 500 robotic fiber positioners carry a miniature **"dynamic" coordinate system** that rides at the end of each positioner's beta arm. Each beta arm carries 3 fibers: a back-lit metrology fiber and 2 science fibers (BOSS and APOGEE) bonded together in a fiber-in-glass capillary ferrule. Fiber face microscopy obtained during installation of the 3-fiber "robotails" into the robots measures the locations of the 3 fiber cores relative to the body of the robot beta arm tips. The metrology fibers are back-lit and measured relative to the fixed wok-mounted FIFs to give the instantaneous XY position of the metrology fiber in the FIF geometric coordinate system.

The fundamental "fixed" location of each robot in focal plane coordinates is the XY position of the intersection of the alpha arm axis of that robot with the focal plane, shown schematically in the Figure 5:

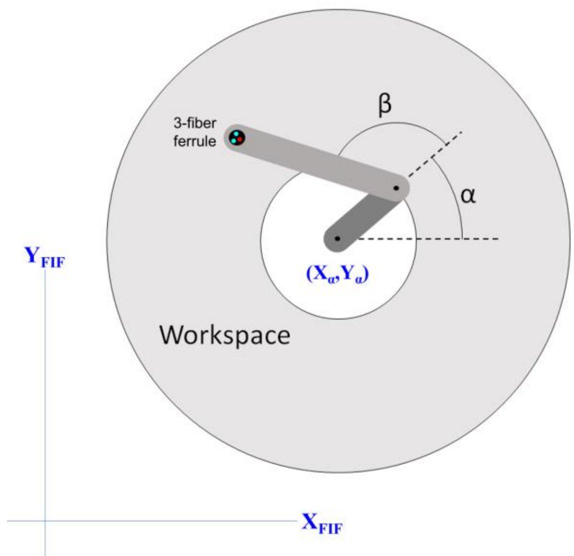


Figure 5. Robotic fiber positioner workspace shown in terms of FIF (fundamental geometric) coordinates. Only alpha arm axis is fixed in this coordinate system.

This is because the alpha-arm motor/gearbox actuator is the only part of the robot arm system that is fixed to the body of the positioner which is in turn affixed to the wok. This axis is embedded deep inside the robot and inaccessible to measurement by a CMM. This position is instead measured optically after installation in the FPS unit by measuring the center of motion about the alpha arm axis relative to the wok-mounted FIFs by taking images of a back-illuminated metrology fiber with a camera while the alpha arm is being scanned over the full range of alpha angle motion at fixed beta angle.

1.2.3 Astrometric Coordinate System

CCD images acquired with the GFAs are used to connect the XY focal plane coordinates of the FPS to the **astrometric coordinate**s on the night sky. This is done via a two-step calibration in which the GFA CCD pixels are measured relative to the GFA-mounted FIFs using optical CMM measurements, and then the GFA-mounted FIFs are tied into the fixed wok-mounted FIF coordinate system using FVC images.

Because the GFA camera units and their associated FIFs are *removable elements* (required to be able to service the CCD cameras over the FPS life cycle), the GFA-mounted FIFs are **not** measured by the CMM at the same time as the fixed wok-mounted FIFs. Instead, they are tied into that system later using FVC images on the telescopes.

When the GFA units (cameras, fiducials, and mounts) are installed on the wok, the 12 GFA-mounted fiducials augment the fixed fiducials on the wok and are used to tie GFA pixel coordinates into the geometric coordinate system in the focal plane defined by the fixed wok-mounted FIFs.

1.2.4 How They Tie Together

The **fundamental coordinate system** of the focal plane is the XY coordinate system defined by the wok-mounted FIFs. It is measured in the laboratory using a high-precision CMM *before* we install the positioner robots or GFA cameras onto the woks the FPS units.

The metrology fibers carried by the robotic fiber positioners are back-lit along with the fixed, wok-mounted FIFs, and FVC images are used to compute the **instantaneous XY coordinates of each metrology fiber in the FIF geometric coordinate system**. The XY positions of the APOGEE or BOSS science fibers in the FIF geometric coordinate system are derived from a calibration of the positions of each of these fibers relative to their metrology fibers (the calibration is described later in this document but involves both beta-arm microscopy of the installed 3-fiber ferrules prior to mounting each robot on the wok and then lab test camera and FVC imaging of science fibers back-lit by special illuminators during lab AIT and on-telescope commissioning).

The astrometric system ties the 6 views of the sky provided by the GFA cameras to the XY focal plane coordinate system, telling us how to transform the XY CCD pixel-space locations of the centroids measured for stars in GFA camera images to XY coordinates in the FIF geometric coordinate system. This transformation requires a two-fold calibration. The first is done in the lab using optical metrology with a point-source microscope mounted on a CMM or similar precision XY stage to measure the physical positions of the two GFA-mounted FIFs relative to their CCD camera's pixels. This measurement is done before the GFA units are mounted onto the woks. The second calibration is done first with the Lab Test Camera during lab testing and then again on the telescope with the FVC to measure the positions of the back-illuminated GFA-mounted FIFs relative to the back-illuminated wok-mounted FIFs.

For all of this to work together, the fundamental coordinate system must first be well established to support all future operations. This document details the metrology procedures that were conducted to successfully establish the fundamental coordinate system (Section 3), as well as to lay the groundwork for a connection between the fundamental and astrometric coordinate systems (Section 4).

2. WOK AND LATCH RING METROLOGY

The curved woks and latch rings were fabricated by Tapemation Large Precision Machining of Scott's Valley, CA and delivered to OSU in June 2020. Each wok has a slightly different curvature to accommodate the different focal surfaces on the Sloan and du Pont Telescopes. The woks were designed so that robots, FIFs, and GFA cameras mount normal to the wok front surface. This guarantees two properties of the robot and FIF fibers after installation: (a) they will be in the focal plane of the telescope located 143.10 mm along the normal vector above the wok front surface, and (b) they will be normal to the focal surface and thus telecentric with the incoming beam.

The surface shapes of the wok were measured by Tapemation as part of the final part inspection using with a high-precision Hexagon CMM. The summary measurements can be expressed in terms of two critical surfaces:

- The wok surface profile rms: measures the rms deviation of the wok curved surface from the design surface in microns, measured center-to-edge
- The wok top mounting surface flatness rms: measures the rms deviation of the face of the outer flat diameter that is used to mount the wok to the latch ring from flat.

The wok surface figure and latch ring mounting surface measurements are summarized in Table 1.

Table 1. Wok manufacturing inspection report

FPS Unit	Curved surface profile rms	Mounting surface flatness rms
Sloan	16-microns	16-microns
du Pont	18-microns	30-microns
Specification	30-microns	50-microns

Both woks exceed the design specification in surface curvature and mounting surface flatness.

When robots and FIFs are integrated with their fiber assemblies, a precision vertical height gauge us used to set the normal (local Z-axis) distance between the fiber face and the base of the mounting flange that is bolted to the wok surface to a height of 143.10±0.02 mm (±20 microns rms).

The overall focus stack-up specification is ±70 microns which includes the height of the fiber face above the mounting flanges and the wok surface profile errors, which for the measured wok figure and actual measured rms for height measurement in the lab amounts to about 26-27 microns, exceeding the original specification of 36 microns for the target 30-micron rms surface error on the woks.

The positions of the robot and wok-mounted FIF mounting holes are measured precisely for a subset of 120 of the 565 mounting holes (547 in the central hexagonal array and 18 at the outer ring) and given in the test reports for the woks. The RMS deviation of the measured from the design XY locations of the mounting holes was 24 microns, and deviation in the drill angle relative to normal was 0.008-degrees.

3. WOK-MOUNTED FIDUCIAL METROLOGY

Precisely locating the positions of the fiducials in the FPS is the foundation on which the rest of the metrology and coordinate systems can be built. The locations of the robotic fiber positioners are measured relative to the fiducial field, which is why it is so important that the fiducial positions are known to extremely high precision. This section describes the measurement process conducted to achieve the high precision locations of the fixed fiducial field. A quality assurance analysis of the measurement data is also featured in the back half of this section.

The precise locations of the wok-mounted fiducials for both FPS units were determined by measuring them with a Coordinate Measuring Machine (CMM) in collaboration with Hexagon Manufacturing Intelligence in Novi, Michigan. These measurements were conducted with a combination of using a touch probe and an optical probe with the specific goal of determining an axis for each fiducial as well as an XY position measurement of the fiber tip of each fiducial. Of the 60 fiducials in each FPS unit, the 48 of them that are mounted directly on the wok were measured with this process. The remaining 12 fiducials are mounted in the GFA subassemblies, and their positions are measured as part of a separate operation later discussed.

3.1 Metrology Equipment and Associated Errors

Hexagon used their own equipment for these measurements. This includes the following:

- Hexagon Global S Chrome 12.22.10 CMM
- Hexagon HH-AS8-2.5 Motorized Wrist
- Hexagon HP-S-X1H Tactile Probe
- Hexagon HP-C-VE Optical Probe

The CMM being used has a measurement range of 1200x1500x1000 mm (X, Y, Z), which is suitable to measure anything on or in the FPS. The machine itself has a defined measurement accuracy error of $2+L/333$ microns, where L is the distance of the feature being measured away from the datum in millimeters. The datum for each FPS was located at the center point of the wok, which means the largest value L will ever be is 420 mm. This suggests a maximum measurement error induced by the machine of 3.3 microns.

$$CMM\ Error\ [microns] = 2.0 + \frac{L\ [mm]}{333} \tag{1}$$

The wrist that holds the probes also has a characterized repeatability error of 0.5 microns, though because it was locked in a downward facing position the entire time, this should not play a factor in the error stack up. The contact probe is defined as having a resolution within 0.1 microns, while the optical probe has an error of up to 6 microns. Given this, the expected precisions for contact probe measurements are less than 4 microns and less than 10 microns for the optical probe.

Figure 6. CMM Probes used for wok-mounted FIF metrology. Left: touch probe. Right: optical probe

Figure 7. Hexagon Manufacturing Intelligence Global S Chrome 12.22.12 CMM

Table 2. Expected measurement errors from CMM metrology

Error Source	Tactile Probe Error (microns)	Optical Probe Error (microns)
CMM	3.3	3.3
Motorized Wrist	n/a	n/a
Tactile Probe	0.1	-
Optical Probe	-	6
Total Expected Error	3.4	9.3

3.2 CMM Coordinate System Definition

Before measurements could start, a coordinate system for the FPS had to be defined on the CMM. The coordinate system used was essentially the fundamental geometric system described in the previous chapter, with a tooling ball placed in the central position of the wok used as a physical origin reference. The height of the tooling ball center was 143.1 mm off the wok, the same prescribed height as the focal surface. In this coordinate system, X and Y are transverse across the FPS while positive Z points up, out of the FPS.

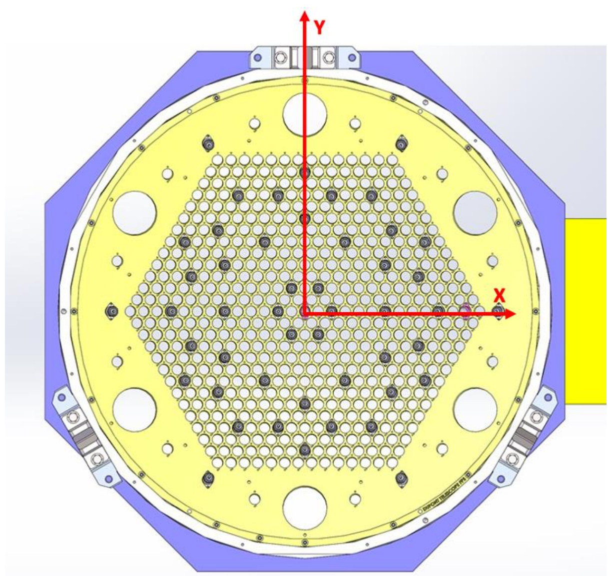


Figure 8. FPS top view in CAD model overlayed with defined CMM coordinate system

On the machine, the X axis was defined by measuring a second tooling ball located towards one end of the center row of the wok. The Z axis was defined by measuring the top face of the latch ring to construct a plane and calling this plane's normal vector the Z axis. From here, the Y axis was let to be the vector normal to the now defined XZ plane.

3.3 CMM Measurement Procedure

There were two distinct parts to the wok-mounted fiducial metrology program – measurements with the tactile probe and measurements with the optical probe. The tactile probe was used to determine the axis of each fiducial, and the optical probe was used to determine XY coordinates of the fiducial fiber core centers. The Z location can be found with a projection along the found axis since the height of the fiber tips off the wok have already been finely controlled earlier in the assembly process.

First, the tactile probe was used with a cylinder defining routine on the stainless-steel sleeves of the fiducials. This consisted of touching off around the sleeve six times each at three different heights. At each height, a center point was calculated automatically using the six points where the machine touched off. The 18 contact points were used to create a cylindrical surface representing the fiducial sleeve, while the three center points were then used to define an axis along the cylinder. A projected fiber location was then calculated by the CMM software by placing a point that intersects the newly created axis at 143.1 mm off the wok surface, which was the precise height the fibers were set to during the fiducial assembly process. This projected location assumes that the fibers are perfectly centered in the sleeves, which is not necessarily true, but it does give a good approximation of the fiber's location in Z.

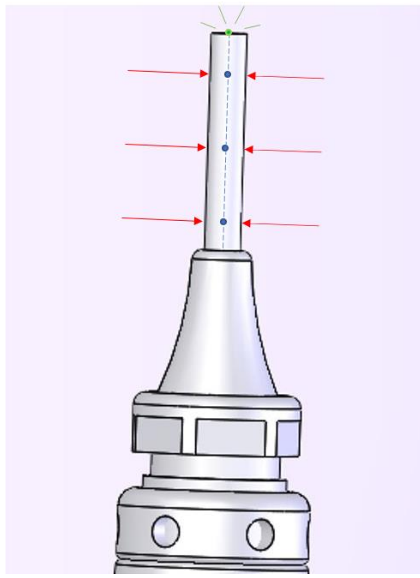


Figure 9. Touch probe methodology for establishing FIF axis

This procedure with the tactile probe was repeated for all 48 wok mounted fiducials on both FPS units.

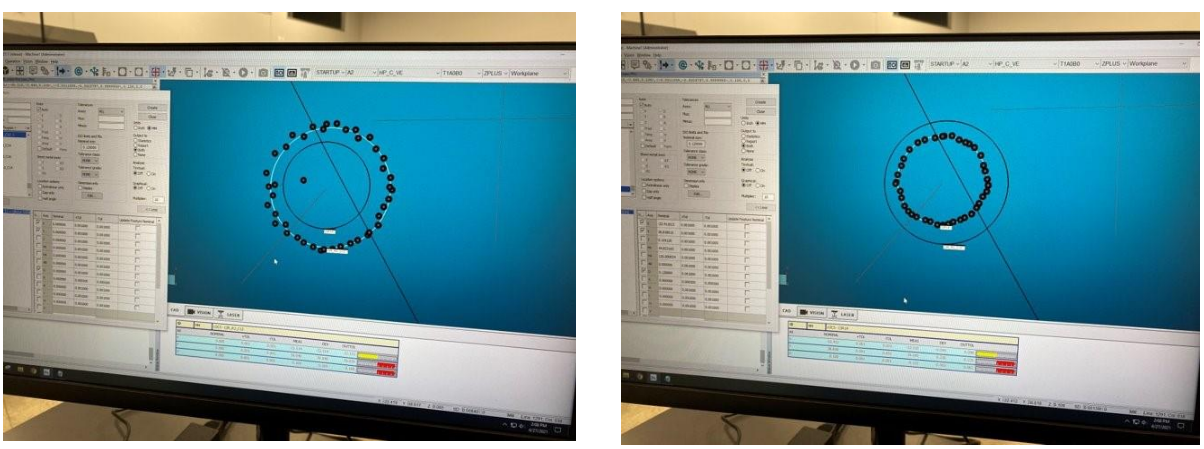
After the tactile measurements were complete, the tactile probe was swapped out for the optical probe. The optical probe featured a CCD camera with live feed capabilities and was equipped with a software package designed to pick up on specified features using color contrast. To create this contrast, it uses green LED lights built into the front of the probe to illuminate the object it is inspecting.

Figure 10. Optical probe on Hexagon CMM measuring a fiducial fiber core

When using the optical probe to measure the XY coordinates of the fiber centers, it was considered whether the fibers should be back-illuminated while being measured. Backlighting would provide a direct measurement of the fiber core instead of measuring the black buffer that surrounds it, but it runs the risk of saturating the CCD of the optical probe and degrading the measurement quality. Not backlighting, however, would allow for a simpler and more consistent measurement program, though it introduces the risk of a less accurate measurement by ignoring any concentricity error between the buffer material and fiber core. Both methods were trialed, and it was ultimately decided that backlighting the fibers was the way to go. Three main reasons factored into this decision:

1. Circularity error was much smaller for the fiber core measurement than the buffer measurement.
2. Measuring the fiber core revealed concentricity error within the buffer on order of 10 microns.
3. It was not as difficult as originally assumed to prevent CCD saturation.

The difference between the circularity error of the two measurement methods was what drove home the notion the back-illumination was the superior method. A comparison in circularity error can be seen in Figure 11:



No Back-Illumination | Back-Illumination

Figure 11. View of Hexagon software attempting to centroid a fiducial fiber core while back-illuminated and not back-illuminated

The edge finding algorithm of the optical probe software was much more reliable at finding a circle to fit the fiber core than it was for the buffer. Because of the three reasons listed above, it was conclusive that back-illuminating the fibers provided a higher quality and more accurate measurement.

Figure 12. View of optical probe while measuring a fiducial fiber core. Fiber is illuminated center inside black buffer

The back-illumination was done by LED panels placed around the CMM several feet away from the connector panels. Connectors where the fiducial fibers were attached were exposed to the light from the panels.

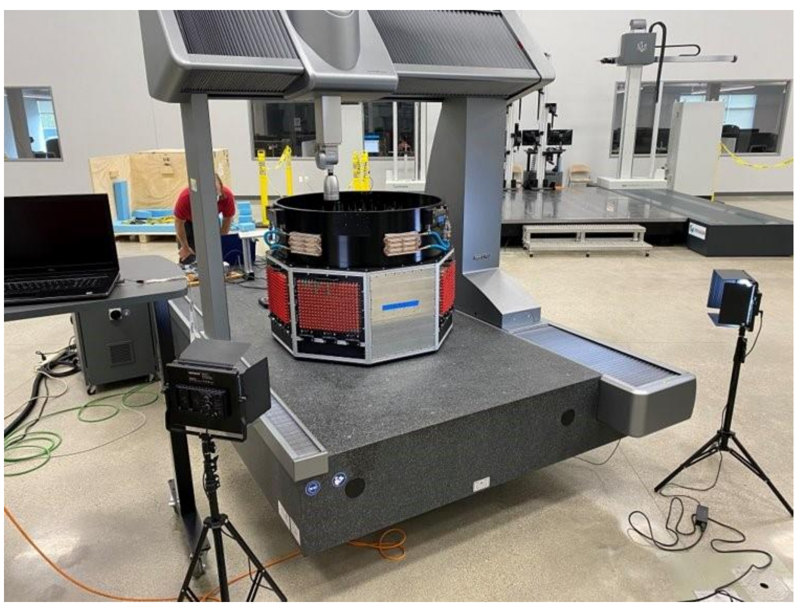


Figure 13. FPS on Hexagon CMM, FIF fibers illuminated with LED panels shining light on exposed ST connectors

The brightness of the panels had to constantly be tweaked depending on the location of the connector to which a given fiducial fiber was attached. The appropriate light intensity was decided by two factors – the reported fiber diameter value of the optical probe software and the circularity error.

The fibers have nominal diameters of 120 microns. The brightness of the LED panels was tuned so that the software of the probe would report a measured diameter near this value. This was done to prevent saturation of the CCD in the optical probe. When CCDs saturate, photons from the source object often “spill over” into nearby pixels on the detector, creating an apparently larger point spread function. This intentional biasing of the diameter measurement was deemed acceptable because it created a high level of confidence in knowing that the LED panels were not saturating the CCD, and because the critical measurement was of the fiber center, not the reported diameter. This procedure also routinely gave very little circularity error, which was critical for accurately identifying the centers of the fiber cores. The image below shows a table that reports the fiber coordinates, diameter, and a graphic that shows circularity error based upon the circle the software was able to fit around the fiber.

Figure 14. Hexagon software readout for measuring fiducial fibers. Readout shows X, Y coordinates, diameter, and circularity error

This optical measurement process was repeated for all 48 wok-mounted fiducials in both FPS units, and this concluded the wok-mounted fiducial metrology program.

Moving forward, the following dimensions are adopted to define the field of fiducials against which to compare the robot positions:

- XY coordinates of fiber core as measured by optical probe
- Z coordinates of fiber tip as projected by tactile probe data
- Cosine terms against X, Y, and Z axes found by tactile probe to define fiducial axes

Subsequent analysis is based on these data.

3.4 CMM Metrology Results

After receiving the FIF measurement data from Hexagon, an analysis was done to assure its quality and usability as a basis for robot performance validation. This analysis was conducted using Python, and several components of the data were checked, including:

1. A comparison between measured and nominal CAD data
2. A linear transform data fit to minimize residual errors between measured and CAD data
3. A residual analysis between projected Z positions of FIF fibers and the nominal focal surfaces of both FPS instruments
4. A residual analysis between optical and tactile CMM probes

3.4.1 Measured CMM vs Nominal CAD Fiber Illuminated Fiducial Positions

Hexagon provided Microsoft Excel files and CSV files of all the measured and nominal CAD data for analysis purposes. Python scripts were created, and one of the first checks done on the measured data was to compare it to the CAD models. The following figures and tables show the residual error between the two data sets for both FPS units. The points represent the nominal positions of the FIFs in CAD, while the tails represent the difference in position between the two data sets. The tails are also magnified to read the plot more easily. A scaling bar is provided in the bottom left corner of each plot.

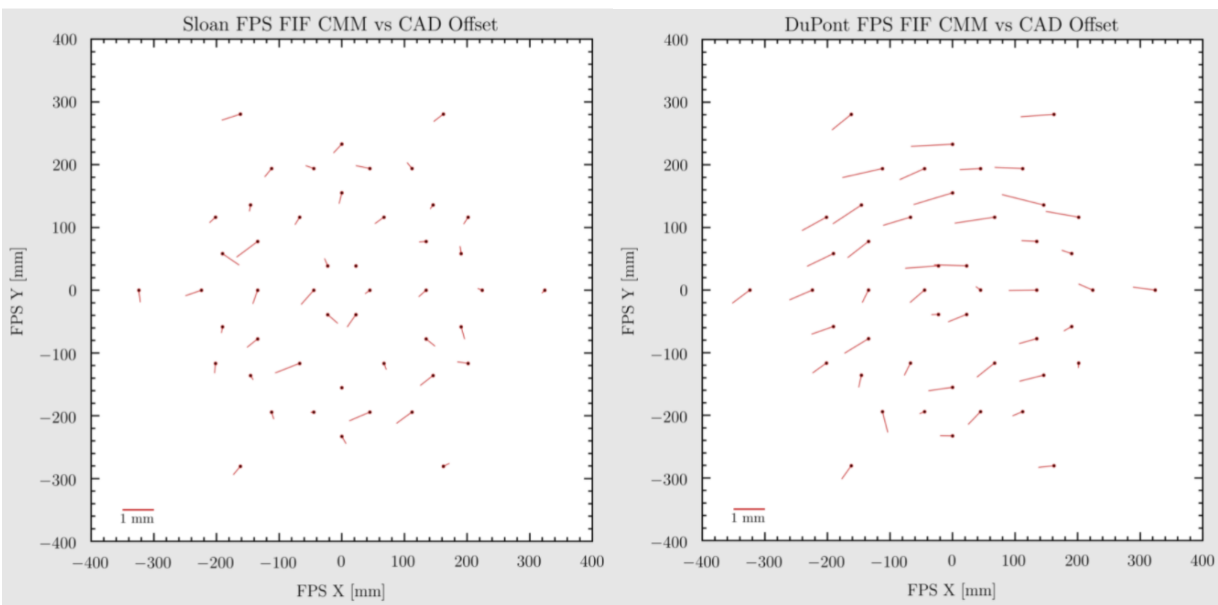


Figure 15. FIF positions as measured by CMM vs FIF positions in CAD models. Left: Sloan FPS. Right: du Pont FPS

Table 3. FIF position residuals between CAD and CMM measurements

FPS	Minimum (mm)	Median (mm)	Maximum (mm)
Sloan	0.0045	0.3215	0.8303
du Pont	0.1471	0.7085	1.3626

Linear transforms were then calculated to minimize the residual errors between the measured and nominal data. This was done to eliminate any sources of systematic error that may have been captured in the measurements, such as the imperfection of tooling balls used to define the CMM coordinate system. These linear transforms were calculated using the skimage package from the Python open-source library. Table 4 and Figure 16 describe the transforms for each FPS unit.

Table 4. Linear transforms for FIF residuals

FPS	ΔX (mm)	ΔY (mm)	Rotation (°)
Sloan	-0.1579	-0.1740	0.022
Du Pont	-0.6266	-0.1978	0.080

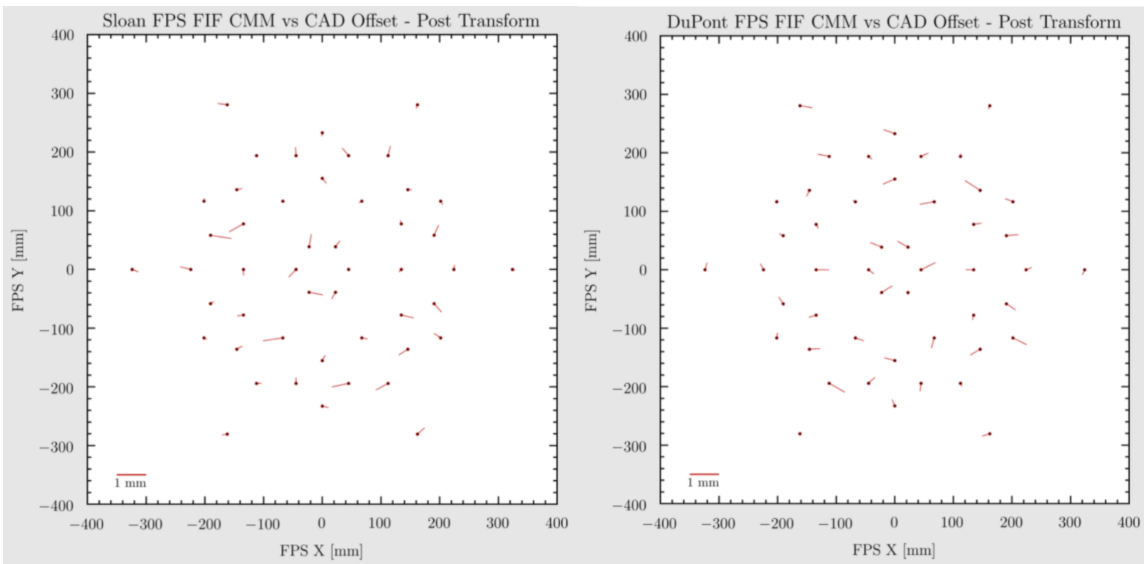


Figure 16. CMM-measured FIF positions vs CAD positions, after applying linear transform to eliminate systematic measurement errors. Left: Sloan. Right: du Pont

From a visual inspection, the residuals decreased in magnitude and became more random in direction following the application of the transforms as shown in Table 5.

Table 5. Mean measurement deviations from CAD with one standard deviation

FPS	Before Transform (mm)	After Transform (mm)
Sloan	0.3404 ± 0.1863	0.2535 ± 0.1584
du Pont	0.7146 ± 0.3206	0.2851 ± 0.1417

The systematic errors of the residuals were also eliminated by the transforms, as the mean values of the X and Y components of the deviations both became zero, whereas before the transform they were nonzero, as shown in Table 6.

Table 6. X and Y average offsets pre- and post- transform application

FPS	Direction	Before Transform (mm)	After Transform (mm)
Sloan	X	-0.1579 ± 0.2542	0.0000 ± 0.2506
	Y	-0.1740 ± 0.1753	0.0000 ± 0.1630
du Pont	X	-0.6266 ± 0.3631	0.0000 ± 0.2757
	Y	-0.1978 ± 0.2231	0.0000 ± 0.1593

3.4.2 Projected Z Position Validation

The Z positions of the FIF fiber tips are critical to make sure that the FPS instruments achieve good optical focus on their respective telescopes, however they could not be measured directly on the CMM due to fear of damage or degradation of quality while using the touch probe or difficulty of measurement using optical probe. Instead, using the FPS CAD model as a reference, a point was projected by the CMM software to the nominal height of the FIFs along the axis established for each fiducial using the touch probe. The coordinates of these points were reported by the CMM. This was considered a good approximation since the heights of the fiber tips were finely controlled by OSU during the manufacturing process.

A quick analysis was done to make sure that this projection was applied correctly and would indeed be a reliable reference. This involved taking the reported Z coordinates of the fiducials and comparing them to a radial profile of the equation-driven focal surface of each FPS. Each focal surface is driven by the equation:

$$z(r) = \left(\frac{1}{2R_r} + \alpha_1\right) r^2 \qquad (2)$$

Where z represents the focal surface as a function of radius, Rc represents the radius of curvature of the surface, and $\alpha 1$ is a term that represents the departure from a perfect sphere. The values of these terms for each FPS can be seen in Table 7.

Table 7. Focal plane equation parameters

FPS	R_c (mm)	α_1 (mm^{-1})
Sloan	9199.3225	0
du Pont	8800	1.23363×10^{-6}

The radial position for each fiducial is calculated from their measured X and Y coordinates. The projected Z coordinate for each fiducial fiber is then plotted against the radial profile of each focal surface. The plots below show this radial profile as well the Z residuals.

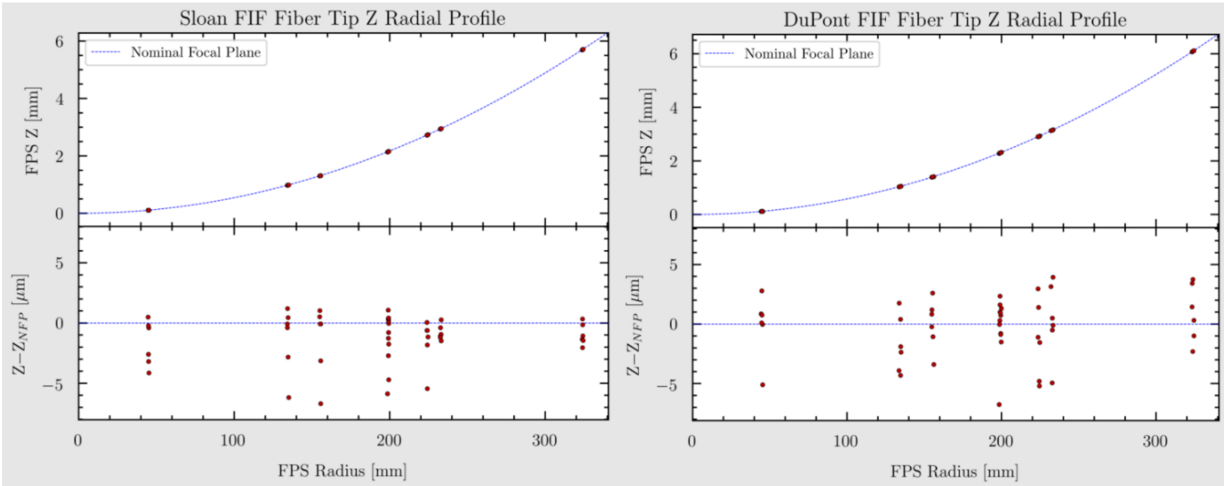


Figure 17. Residual errors between projected height of fiducials and theoretical, equation-driven focal surface. Left: Sloan. Right: du Pont

With residuals within ±5 microns from the nominal focal surfaces of both FPS units, it is safe to conclude that the projected Z coordinates have a satisfactory level of accuracy and precision.

3.4.3 Tactile Probe vs Optical Probe Offset

The X and Y coordinates that are used to represent the fiducial fibers were found using the optical probe. As shown in section 4.1, the error margin for the optical probe was more than double that of the touch probe. To get a good sense of performance of the optical probe, a comparison was done between the two probes.

This is possible because the center position of the stainless-steel sleeve of each FIF was measure by both probes. However, some analytical steps needed to be taken before a direct comparison could be made. The optical probe reported a Z position that was lower than the tactile probe. This is because the tip of the fiducial fiber extends above the top of the sleeve. Because all the fiducials have some degree of tilt relative to the Z axis, this carries implications on the reported XY coordinates.

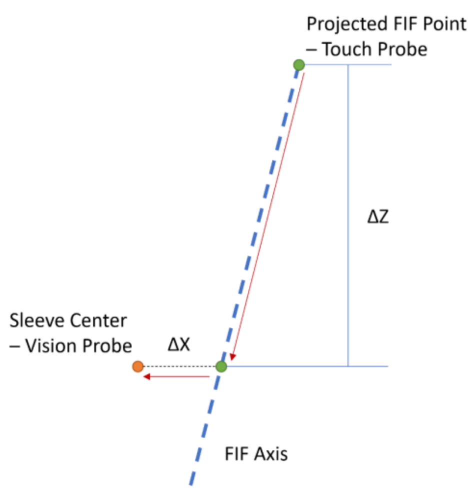


Figure 18. FIF point correction for probe comparison

To correct for this, either the sleeve center or the fiber center must be projected to be at the same Z coordinate as the other. In this case, the fiber center was projected down to the sleeve height. The projection was done using the cosine values reported by the CMM that define each FIF axis. The equations for this projection were identical between X and Y. The X projection is shown below.

$$x_{off} = x_{tactile} - dx - x_{sleeve} \tag{3}$$

$$dx = (z_{tactile} - z_{sleeve})\tan(sin^{-1}(X_{cosine})) \approx (z_{tactile} - z_{sleeve})\,X_{cosine} \tag{4}$$

The small angle approximation is valid for the projection since the maximum tilt of all fiducials is less than 2 degrees relative to the Z axis.

The last step before analysis of the probe residuals was to compute a linear transform between the optical and tactile data sets for each FPS. Doing this eliminates the potential for error in the probe calibration to influence the residuals. Table 8 shows the computed offsets between the probe linear transforms in translation and rotation for each data set. They also represent the probe calibration error between the optical and tactile probes for each FPS unit.

Table 8. Probe calibration offsets

FPS	ΔX (microns)	ΔY (microns)	Rotation (º)
Sloan	3.61	0.32	0
Du Pont	-3.69	-1.87	0

Finally, the residuals can be calculated. The results for each FPS unit are shown in the histograms below.

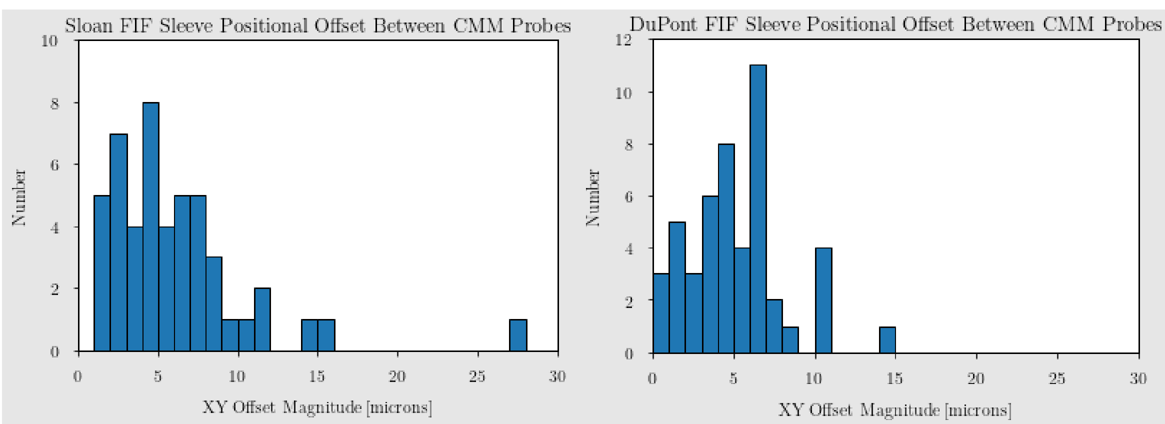


Figure 19. Probe offset magnitudes. Left: Sloan. Right: du Pont

It can be seen in the histograms that there is a clear outlier in the Sloan data set. After removing this outlier, the average offsets between the visual and tactile probes can be calculated. These values are seen in Table 9.

Table 9. Mean probe offset magnitudes

FPS	Mean Offset
Sloan	5.11 microns
Du Pont	5.27 microns
Total Average	**5.19 microns**

The total average offset between the two probes across the two FPS units was found to be 5.19 microns. This outperforms the expected offset of 6 microns as told by Hexagon's nominal error margins and establishes a high degree of confidence in the XY fiber coordinates reported by the optical probe.

It also justifies the use of the optical probe measurements as reference values for future metrology purposes because the optical probe offset is less than the measured decentering of the fiber core with the sleeve. The mean concentricity error of fibers within their fiducials was 7.3 microns. This analysis can be seen in the histogram in Figure 20.

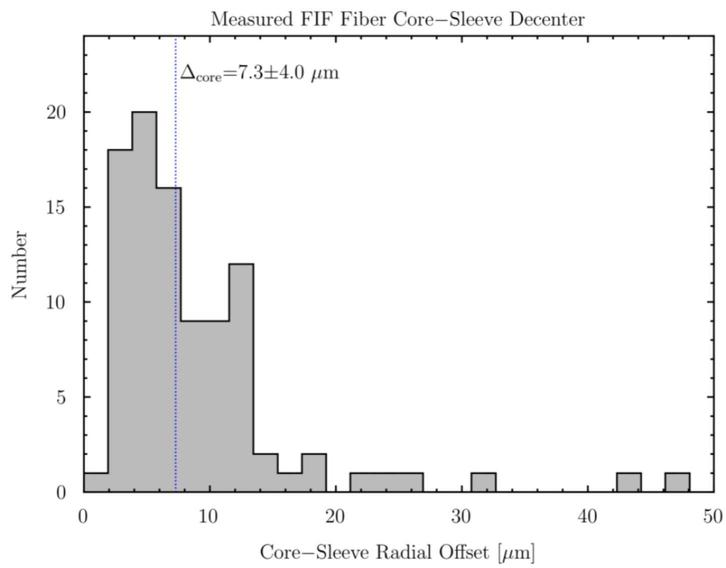


Figure 20. Histogram of fiber-sleeve concentricity error

3.4.4 Total CMM Metrology Error

While the measurements conducted by the optical probe were able to be standardized to the touch probe, the touch probe measurements, and their errors, could not be validated since there were no true values to begin with that could be compared. Because of this, the CMM error must be taken at face value as described in Equation 1. Even so, the total observed error from the CMM metrology can be tabulated as a sum of the probe offset findings in Table 9 with the RMS values of the inherent CMM and touch probe uncertainty from Table 2. This overall metrology error can be seen in Table 10.

Table 10. Total CMM metrology error

Error Source	**Du Pont FPS**	**Sloan FPS**
CMM RMS Error [microns]	2.6	2.6
Observed Optical Probe Offset from Touch Probe [microns]	5.3	5.1
Total Metrology Error [microns]	**7.8**	**7.7**

4. GFA CAMERA CCD AND FIDUCIAL METROLOGY

Metrology for the GFA camera CCDs and attached fiducials was done in-house at OSU using a Haas CNC Mini-Mill as a pseudo CMM. A point-source microscope (PSM) was attached to the mill's tool holder and used for optical metrology. A custom mount was also made for the GFA camera to accommodate the power and ethernet cables, glycol plumbing, and fiducial optical fibers while in the Mini-Mill. The PSM is the black cylindrical device mounted in the CNC chuck hovering over the reference fiducial (FIF with blue masking tape).

The Mini-Mill proved to be a good stand in for a CMM for the much smaller GFA subassemblies. Testing was done prior to metrology to assess the machine's accuracy and precision by making repeated measurements of different NIST gauge blocks with an edge finder. For a sample size of 24 test measurements, it was found that the Mini-Mill could make measurements with an **RMS accuracy error of 9 microns** and **RMS precision of 1 micron**.

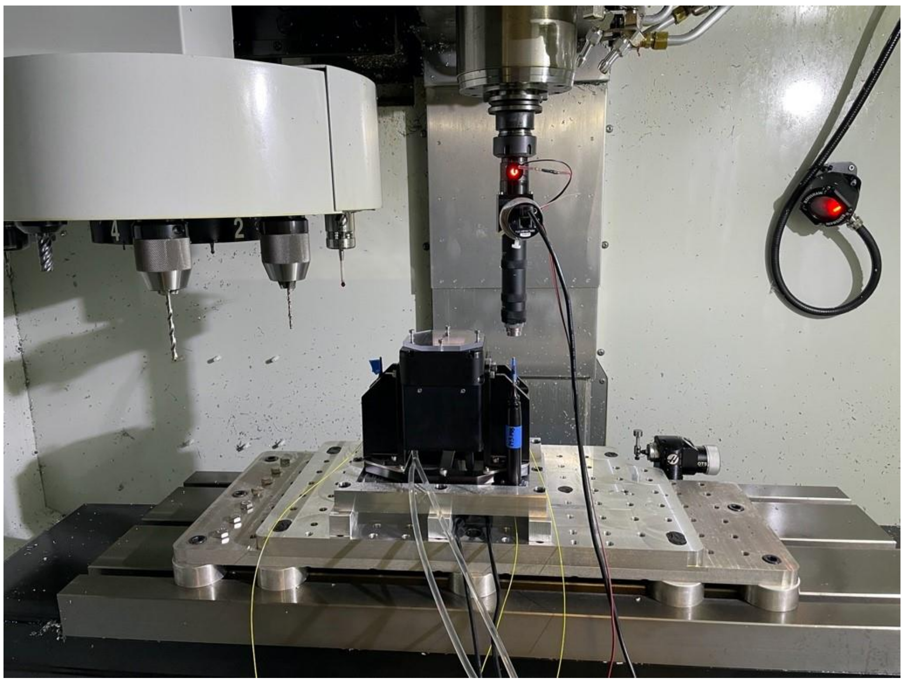


Figure 21. GFA metrology setup using Haas Mini-Mill at OSU

4.1 GFA Metrology Objectives

- Measure the vertical (local Z/"focus") location of the GFA CCD detector relative to the GFA mount base at 5 locations on the CCD using optical CMM. This will yield the initial mean focus and measure any detector tilt relative to plane perpendicular to this Z/focus axis. Adjust the focus and tilt with precision shims that are inserted between the GFA mount baseplate and the camera mounts to out the CCD into focus when installed on the wok with a 5 mm SDSS-r filter (the CCD will be in *optical* focus, including the optical paths through the filter and fused-silica CCD window).
- Install the GFA-mounted FIFs then set their focus heights set to 143.10 mm above the GFA mount pads (point of contact with the wok surface) using a precision height gauge. These put the GFA-mounted FIFs into the telescope focal plane when the GFA unit is installed on the wok.
- The integrated, in-focus GFA unit is returned to the CMM to measure the XY locations of centers of the two GFA-mounted Fiber-Illuminated Fiducuals (FIFs) relative to the CCD. The latter includes making a 5´5 2D grid scan of spots on the CCD to measure the position and rotation of the CCD.
- Results are measurements of the XY positions of the center and corners of the CCD relative to the two GFA-mounted FIFs and the positions of the FIFs relative to each other.

Upon completion, the integrated GFA unit (mount, camera, filters, and FIFs) is ready to install in an FPS unit. These measurements are done for the 12 "flight" GFA units (6 per FPS) and 2 spares GFA units. When mounted on the FPS wok, the positions of back-illuminated GFA-mounted FIFs are measured relative to the positions of the 48 back-illuminated fixed wok-mounted FIFs with the Fiber Viewing Camera, allowing us to GFA CCD pixels coordinates into the XY focal plane coordinate system defined by the wok-mounted FIFs.

4.2 GFA Metrology Equipment

- A Haas Mini-Mill with fully programmable move sequences in XYZ.
- A PSM (Point Source Microscope) to place a well illuminated circular pinhole image onto the CCD and FIF fiber faces.
- A small CCD camera connected to a beam-splitter port on the PSM for viewing the PSM projection plane (projection plane camera).
- A custom mount interface to attach the PSM to the Haas spindle.
- A custom stand for the GFA mount to provide clearance for CCD power, USB, and liquid cooling connections.
- A lab chiller to circulate water/glycol coolant to the CCD when operated.
- A computer with GFA camera control software for collecting GFA images for the focus and 2d grid scan data with the Haas and PSM

4.3 GFA Metrology Procedure

As outlined by the objectives listed in section 3.1, several different parts made up the entire GFA metrology procedure. Those are detailed in the following subsections.

4.3.1 Determining GFA Focus

With the PSM mounted in the Haas tool holder, a gauge block stack with a height of 143.10 mm is focus reference. The PSM is then scanned in the z-direction (perpendicular to CCD face) to generate a focus curve. A representative focus curve is shown in Figure 22.

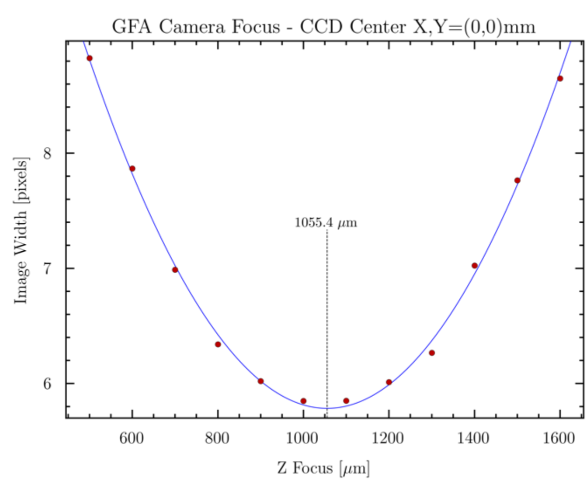


Figure 22. GFA camera focus curve measured at CCD center. Parabolic fit with minimum image width representing best focus

The focus value precision depends upon how shallow the focus curve is for a single measurement. Using repeated focus runs, focus repeatability of ±10 microns from run to run was achieved.

We also tried to measure detector tilt by measuring the focus at the center and off-center positions in an L-pattern and near the 4 corner locations. The Z offset was found to be about 5 microns from point to point for 3 cameras, suggesting that the manufacturer's detector tilt was below our ability to measure easily, and is below the level of field curvature across the CCDs due to their placement at the tangent of the curved focal surfaces. Therefore, focus was only measured at the center of each CCD.

After determining best focus, precision shims are installed in the 3-point GFA camera mount, and the unit is returned to the Haas to verify focus is now at the design location. A further test was made after mounting the focus-shimmed GFA unit in the curved 1st article wok and latch ring installed on a large Haas CNC mill, also at OSU, and focus checked for a subset of cameras. This confirmed the direction of the shimming and corrections for being mounted on the tilted wok surface, and once verified, bestowed confidence in the procedure to go into production for all 14 GFA camera units (6 flight plus 1 spare for each FPS unit).

4.3.2 GFA CCD Center and Rotation

The next step after finding focus and shimming the camera was to define an origin (0,0) on the CCD from which the FIF locations will be measured. This was done by translating the PSM in the Haas tool holder to multiple x/y-positions at the focus position above the CCD surface. The PSM is then scanned in a 5´5 grid pattern relative to the center of the CCD and covering the detector (out to within 10% of the edges to conservatively avoid filter/shutter vignetting), taking an image at each location. A serpentine scanning pattern was used to minimize systematic run-out error in the CNC stage. The 5´5 grid data was evaluated and compared to 3x3 grids that used every other point and it was found that the 3´3 grid gave the same results as the 5x5 grid to within errors. In all cases the RMS deviations of the XY scan spots (observed-fit) were typically ±1 micron, or less than 10% of a pixel. Figure 23 is an example comparing 5´5 and 3´3 results. 5´5 had median 0.8-micron RMS, 3´3 had median 0.9-micron RMS.

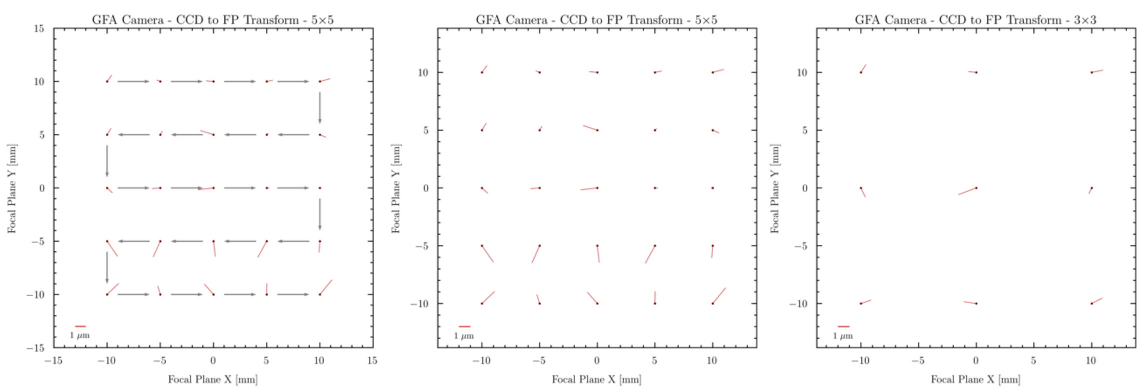


Figure 23. Example of grid scanning results: Left: 5x5 grid scan pattern and fit residuals; Middle: 5x5-grid fit residual tadpole plot; Right: 3x3 subset fit residual tadpole plot

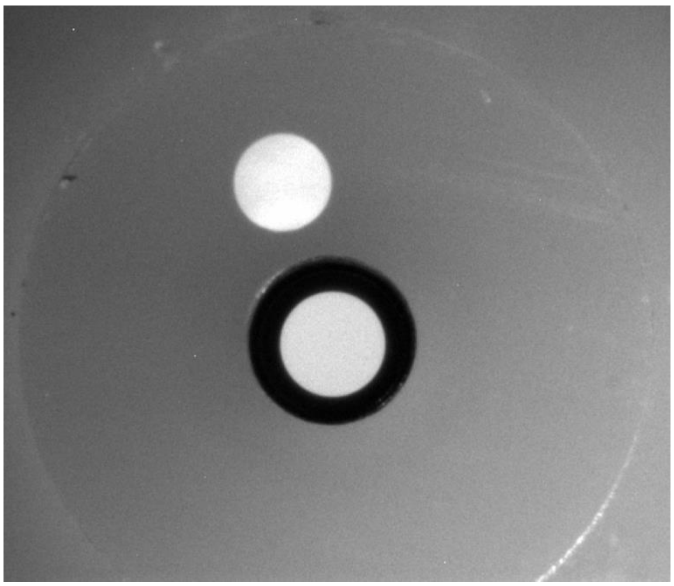
In analysis, linear transformation between the XY CCD centroids of the spots and the XY stage coordinates are computed and used to derive the location of the CCD geometric center (pixel 1024,1024), the pixel coordinates of each of the CCD corners, and the rotation of the CCD detector about the Z (focus) axis. As an extra check, the best fit linear scale factor should recover the pixel pitch of the device (13.5 microns) and be the same in both dimensions, giving an additional estimate of measurement fidelity and precision.

In experiments before doing the full GFA camera production metrology, repeatable sub-pixel precision was achieved with the serpentine pattern and the 3x3 grid scan was adopted as standard methods for this measurement. This saved a lot of time in measurement and analysis and made it possible to complete 3 or 4 GFA calibrations in a single day session of about 4 to 5 hours.

The accuracy of this measurement is a stack-up of the small-move precision of the Haas XY stage (about 1-2 microns), and the accuracy of the centroiding algorithm (a tiny fraction of a 13.5-micron pixel for bright, well-sampled spots).

4.3.3 Locating the GFA-Mounted FIFs

After measuring the grid spot grid, the GFA unit is left on the Haas and the locations of the GFA-mounted FIFs are optically measured using the PSM projector and the Haas stage to project light onto each fiber face using a pinhole that projects a 120-micron spot, the same diameter as the fiber core. Viewing the spot on the fiber face through the PSM in testing, the spot could be centered on the fiber to a precision of ~2 microns as any de-centering of the spot produces a distinctive "crescent moon" pattern, as shown in Figure 24.



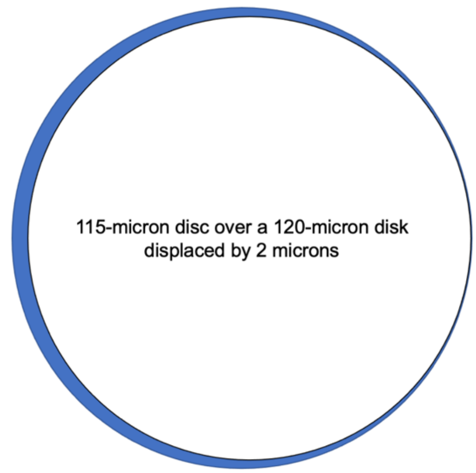


Figure 24. Left: PSM image of a 115-micron spot projected on an FIF fiber face at 11-o'clock next to a back-lit 120-micron fiber core (ringed in black). Right: Simulation of a 115-micron disk (white) over a 120-micron disk (blue) decentered by 2-microns.

Centroid measurement was also attempted by scanning a spot across the fiber face and measuring the output with a NIST-calibrated photometer and a Thorlabs power meter, but it was found that the fiber-transmitted spot intensity was not bright enough and the method very imprecise and laborious because neither system had good data logging.

In the end, the by-eye estimate of the spot-on-fiber center delivered superior results and was far faster and more repeatable to execute. Figuring out this method was important to the success in the subsequent metrology of 14 cameras, and crucial for being able to complete the work in a finite time.

4.4 GFA Metrology Results

The 14 GFA cameras (12 flight and 2 spare) were measured using the methods above in the OSU Astronomy machine shop over multiple days at the end of June 2021.

To analyze the CCD spot images Source Extractor was used to derive the centroids from the X_IMAGE and Y_IMAGE measurements, and the image widths from the X and Y 2nd moments of the spot images (X2_IMAGE and Y2_IMAGE) measurements. The 2nd moment measurements were more reliable estimates of the spot widths than 2d Gaussian or other profile fits because the spots are actually flat-topped, especially close to focus. Source Extractor output was analyzed using two Jupyter python notebooks for focus and XY scan analysis.

4.4.1 CCD Camera Focus

For the focus data, focus precision of ±10 microns RMS was routinely with excellent repeatability. Target focus (which is corrected for the optical thickness of an 5mm SDSS r filter and the fused silica CCD window) is 142.390 microns, for the cameras a median focus after installing focus shims of 142.391 microns was measured with a standard deviation of 12 microns, with a maximum deviation of -18 microns from the target value. Focus was re-measured when installed on the 1st article wok, and the median focus offset was under 10 microns with a standard deviation of 15 microns.

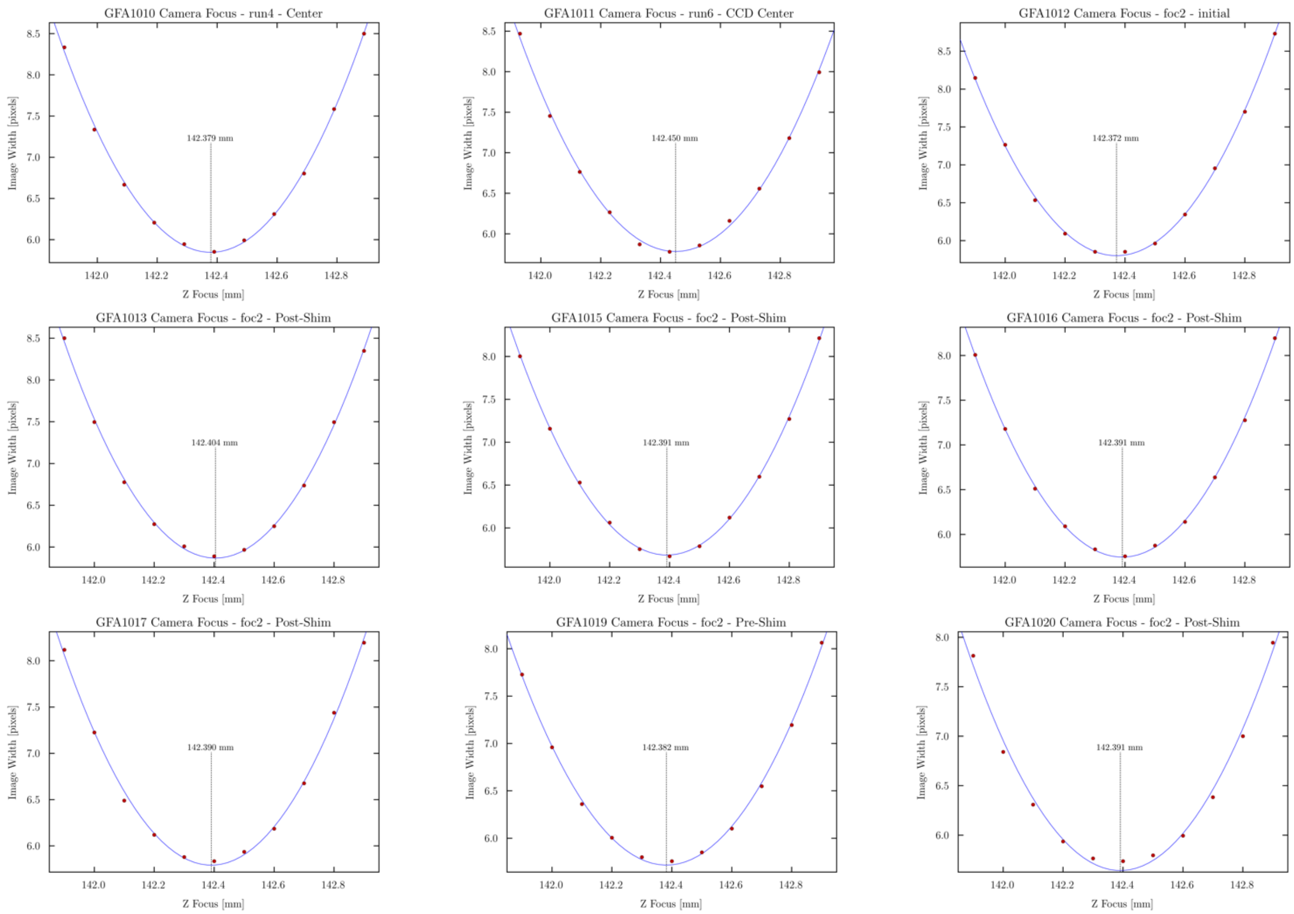


Figure 25. Selection of focus curves for the GFA cameras

4.4.2 CCD Position and Rotation

The 3x3 grid XY scans of the cameras had typical RMS fit residuals to the 9 grid points of 1-2 microns. Rotation of the CCD relative to the CMM stage was <1° for all cameras, ranging from -0.13° to +0.73°, averaging 0.25°.

The recovered pixel size was 13.4988±0.0005 microns in X, 13.5002±0.0010 microns in Y, for a merged pixel size of 13.4995±0.0011 microns, compared to the design pixel size of 13.500 microns (e2v did not respond to a request for an estimate of the rms of the pixel size of the CCD42-40 detectors).

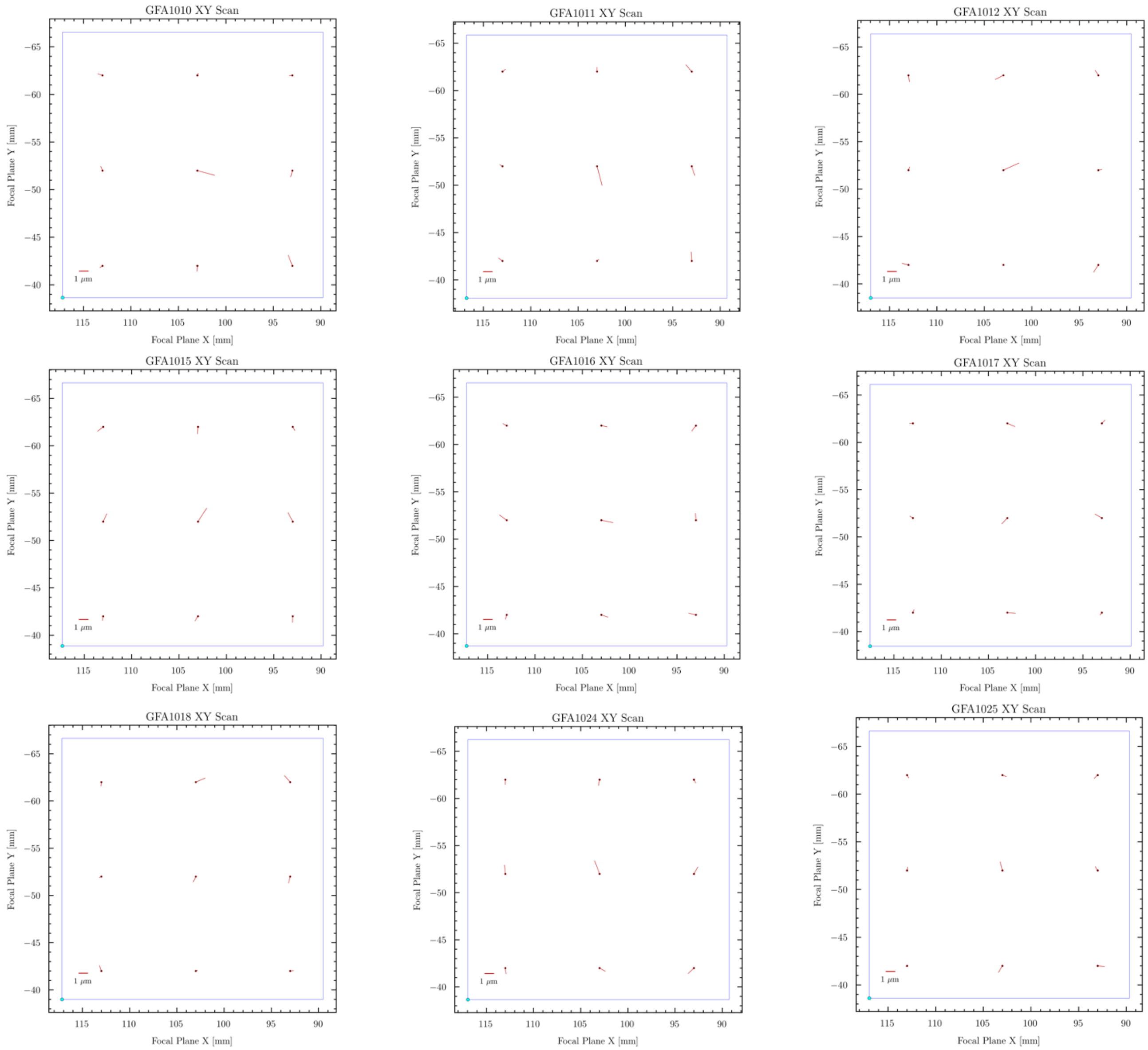


Figure 26. Selection of XY Scan fit residuals for GFA CCDs

ACKNOWLEDGEMENTS

Funding for the Sloan Digital Sky Survey V has been provided by the Alfred P. Sloan Foundation, the Heising-Simons Foundation, and the Participating Institutions. SDSS acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss5.org.

SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration, including the Carnegie Institution for Science, Chilean National Time Allocation Committee (CNTAC) ratified researchers, the Gotham Participation Group, Harvard University, The Johns Hopkins University, L'Ecole polytechnique fédérale de Lausanne (EPFL), Leibniz-Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Extraterrestrische Physik (MPE), Nanjing University, National Astronomical Observatories of China (NAOC), New Mexico State University, The Ohio State University, Pennsylvania State University, Smithsonian Astrophysical Observatory, Space Telescope Science Institute (STScI), the Stellar Astrophysics Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Illinois at Urbana-Champaign, University of Toronto, University of Utah, University of Virginia, Yale University, and Yunnan University.

REFERENCES

[1] Pogge, R., et al., “A robotic Focal Plane System (FPS) for the Sloan Digital Sky Survey V,” Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 1144781 (2020)

[2] Jurgenson, C., et al., "SDSS-V focal plane robot positioning metrology", Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 1144780 (2020)

[3] Sayres, C. et al., “SDSS-V Robotic Focal Plane System: Overview of Coordinate Systems and Transforms,” Proc. SPIE 12184, Ground-based and Airborne Instrumentation for Astronomy IX, 12184286 (2022)

[4] Engelman, M., “Pre-Commissioning of SDSS-V Focal Plane Instruments with Optical Measurement and Analysis,” Master’s thesis, Ohio State University (2021). http://rave.ohiolink.edu/etdc/view?acc_num=osu1637667814104858