26) P. Su, et al., “Swing-arm optical coordinate measuring machine: modal estimation of systematic errors from dual probe shear measurements”, Opt. Eng., 51(4), 043604 (2012)

To align the dual probe system, probe locations on the SOC are adjusted with a laser tracker so that the tips of the probes swing the same trajectory in the space of the tracker coordinate system. The probe tip coordinates are located with a point source microscope (PSM)[14] and a laser tracker[15] as shown in Fig. 7. The probe tip is first imaged with a PSM, then the arm is swung out of the way, and a tracker ball is located so its center is at the PSM focus. This way the center of the ball is coincident with the original probe tip position. The tracker ball coordinates positioned at the probe tip and the coordinates of the three other balls mounted around the probe when the arm was in the original position are recorded. In this way, the probe tip information is incorporated into the tracker coordinate system along with the arm coordinates. As shown in Fig. 6(a), three tracker balls are mounted around each probe.

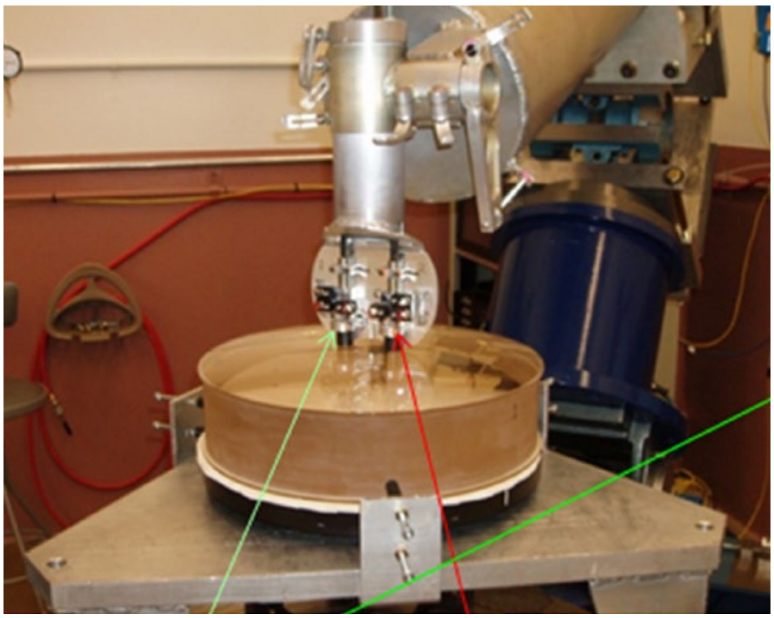

Fig. 6 (a) An experimental setup using the dual probe SOC to measure a 350 mm-diameter convex aspheric surface

28) M. Gao, et. al, "Research on the relationship of the probe system for the swing arm profilometer based on the point source microscope", Proc. SPIE 9623, 2015 International Conference on Optical Instruments and Technology: Optoelectronic Measurement Technology and Systems, 96230N (7 August 2015) (Institute of Optics and Electronics, Chengdu, China)

As shown in Figure 4, the structure and position of the probe system that is installed on the multifunctional measuring microscope. The coordinate ***xyzo*** is the multifunction measuring microscope coordinate system. In the process of experiment, we need the measurement software supporting the *PSM*. As shown in Figure 5, the bright spot is the imaging on the *CCD* camera . Based on the imaging on the *CCD* camera, the measurement software processes the bright spot, we can get the relationship between the center of the bright spot and the center of the *CCD* center. In Figure 5, "+" is the center of the *CCD* camera, the coordinate system ***xyo*** is established. A pixel unit in the software is equivalent to 0.5 *μm* in the actual coordinate, the relationship can be expressed as n=0.5 *μm/pixel*.

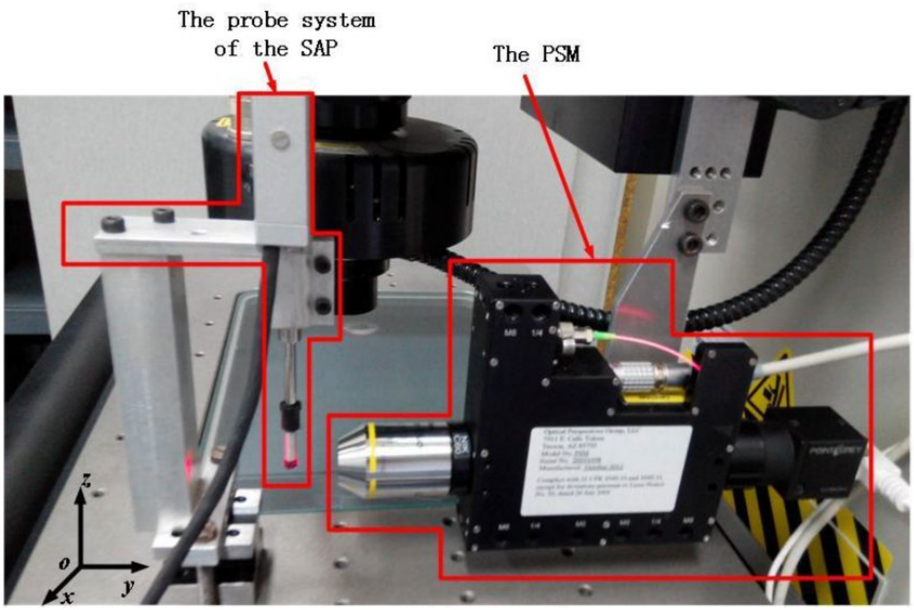

Figure 4 The experiment of the *PSM* calibrate the probe

29) Q. An, et. al, “Alignment for sparse aperture telescope with serial robot arm”, *Infrared and Laser Engineering*, 2018, 47(8): 818002-0818002(6) (Changchun Institute of Optics, Fine Mechanics and Physics, Changchun, China)

将 PSM 安装于机械臂之上，驱动机械臂，将 PSM 的焦点对准相同的靶球，将靶面上的光斑调节至最小后记录若干幅图像。通过统计靶面像点光斑大小的变化，可以评价机械臂的夹持是否满足实际工程试验中的稳定性要求。串联机械臂及 PSM 如图 4 所示。

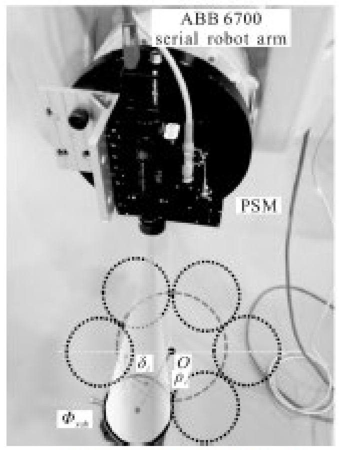

图 4 串联机械臂以及 PSM

Fig.4 Sketch of serial robot arm and PSM

31) M. Häberle, "Validating the local volume mapper acquisition and guiding hardware", Proc. SPIE 12184, Ground-based and Airborne Instrumentation for Astronomy IX, 121846U (29 August 2022) (Max-Planck-Institut für Astronomie, Heidelberg, Germany)

Hybrid measurements on camera sensors After the stages have been fixed on the table, we remove the target from the focal plane and install the guide cameras. Then, we measure multiple positions on each of the 2 camera sensors. We identify which pixel is illuminated by the PSM by reading out the cameras. At the same time, we log the positions measured with the digital micrometers that move the stages. In principle, 3 measurements would be enough to fully determine the spatial position of each sensor, but to test the precision of our method and improve statistics, we take 9 measurements at different locations on each sensor.

The coordinates and transformations determined with the PSM measurements were used to accurately calculate the required adjustments to the shims used to align the A&G cameras to the reference focal plane. This proved to be very effective - in 2 iterations of re-shimming we reduced the RMS of the focus deviations from initial ~0.6-0.7 mm to to d0.005 mm (see Table 3), clearly matching our focus requirement of 0.05 mm.

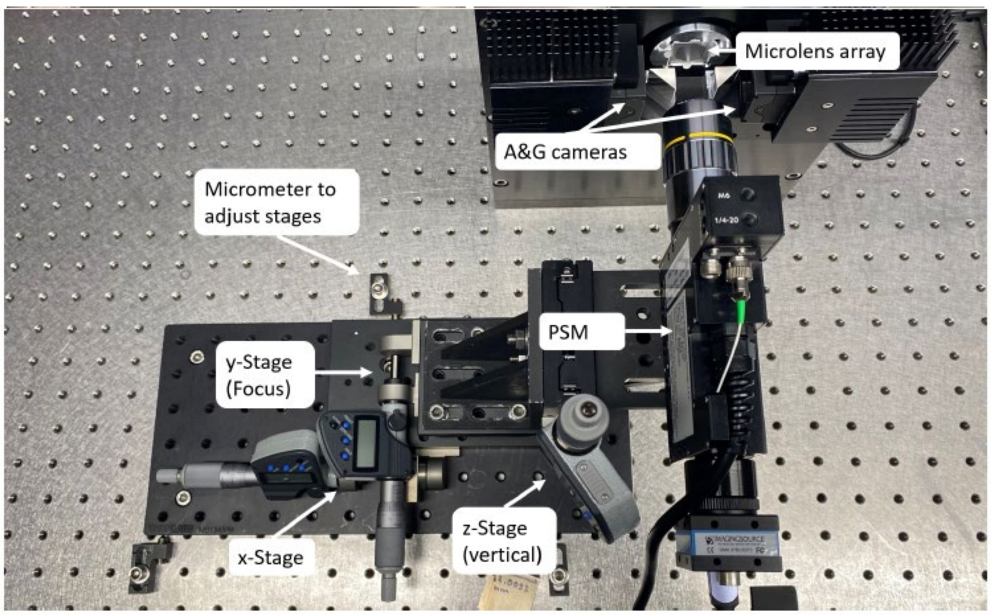

Figure 11. Top left: Backside of the focal plane alignment target. Top right: Front of the focal plane alignment target. One can also see the objective lens of the PSM. Bottom: Top-view of the focal plane metrology setup.

32) T. Herbst, "Construction, testing, and commissioning of the SDSS-V Local Volume Mapper telescope system", Proc. SPIE 12182, Ground-based and Airborne Telescopes IX, 121821Q (29 August 2022) (Max Planck Institute for Astronomy, Heidelberg, Germany)

As mentioned in Step 7, the fundamental position and tip-tilt reference now resides in the Point Source Microscope. We use the measured 3-dimensional location of the IFU microlenses and the AG camera pixels to adjust their position and tiptilt to coincide with this reference. In the case of the IFU, we measure several points around the periphery of a number of microlenses to locate their centers and hence the overall orientation of the IFU. Push bolts on the x-y-q stage allow adjustment of the location and rotation in the focal plane, while shimming of three precision pins in the connector provide tip-tilt correction. Measuring and adjusting the AG cameras follows a similar procedure, although in this case, we illuminate individual pixels with the PSM's point source and read out the sensors to derive the 3D location. The mounting brackets of the AG cameras have 3 attachment points with pre-sized shims. Modification of these shims allows tip-tilt and focus adjustment.

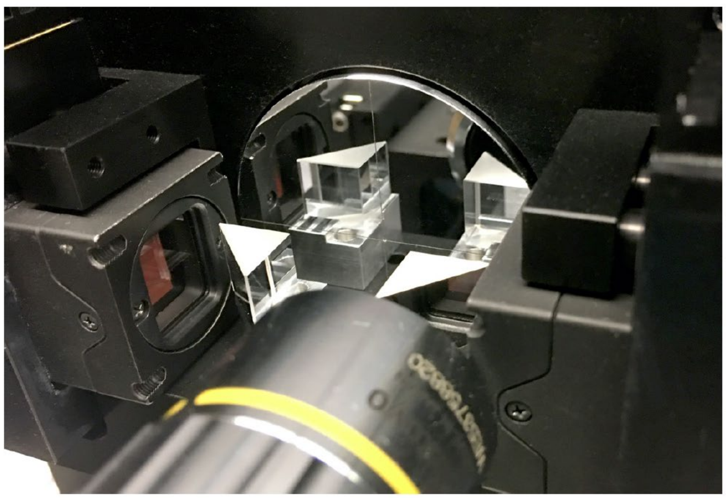

Figure 8: Scanning the surface of the reflecting target to transfer the fundamental reference to the Point Source Microscope (Step 7). Note that these prism mirrors and their mounts are temporary. The final versions will be blackened to minimize scattered light.

33) M. Engelman, "SDSS-V focal plane system high-precision metrology", Proc. SPIE 12184, Ground-based and Airborne Instrumentation for Astronomy IX, 121847J (29 August 2022) (The Ohio State University, Columbus, OH)

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.

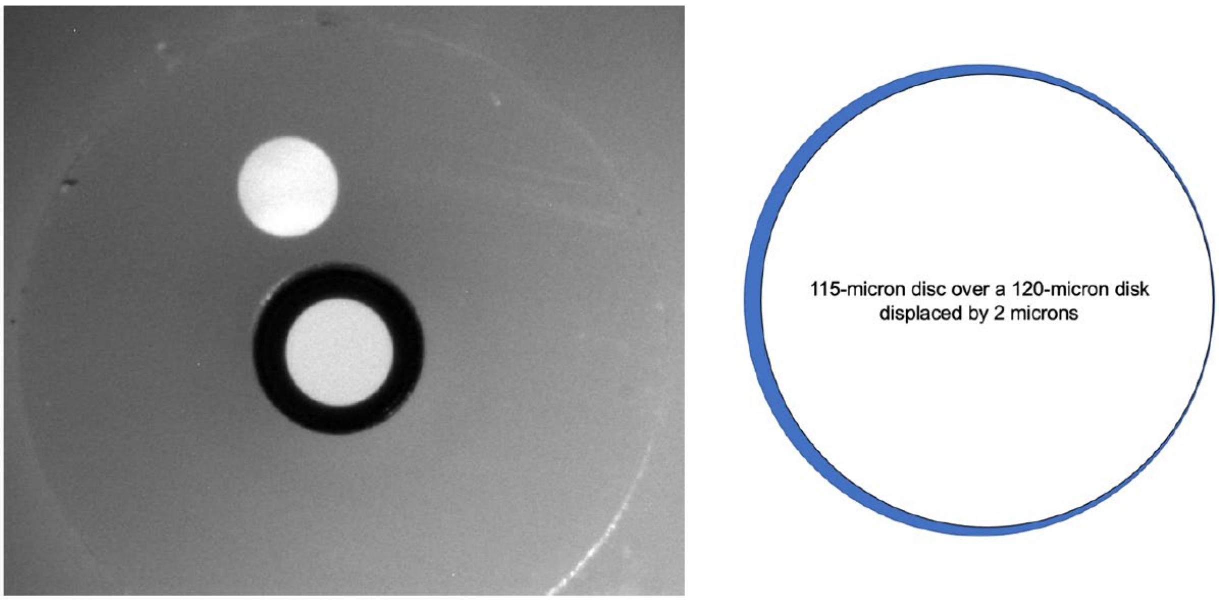

Figure 24. Left: PSM image of a 115-micron spot projected on an FIF fiber face at 11-o’clock next to a back-lit 120-micron fiber core (ringed in black). Right: Simulation of a 115-micron disk (white) over a 120-micron disk (blue) decentered by 2-microns.

36) J. Burge, et. al., “Use of a commercial laser tracker for optical alignment”, Proc SPIE, 6676, 66760E (2007) (College of Optical Sciences, University of Arizona)

The SMRs can be used as optical references in the same way that precision tooling balls are used. An optical system such as an interferometer or point source microscope can be set up so that the spherical wavefront is well aligned with the optical surface or system. Then the SMR can be inserted so that the converging wavefront is concentric with the spherical surface of the ball, as determined by the interferometer or point source microscope (PSM). The position of the SMR can be measured by the laser tracker.

(This paper does not show why the SMRs and solid balls behave the same way when viewed by a PSM or interferometer, but the paper “Evaluating SMR Positioning with an Autostigmatic Microscope”, by Karrfelt, Parks and Kim in the Bibliography does as shown below)

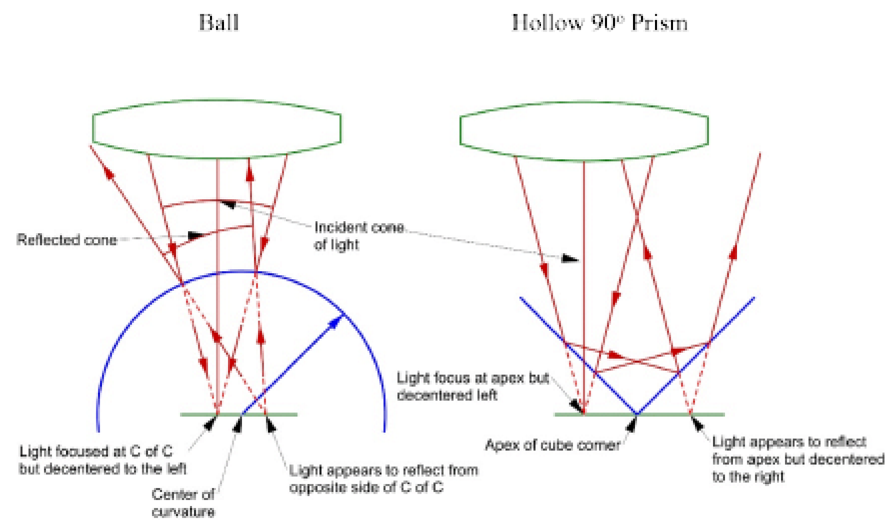

Figure 2. The effect of decentered cones of light incident on a ball or hollow 90° prism on the reflected cones.

27) C. Peng, et. al, "Calibration method of shear amount based on the optical layout of point source microscope for lateral shearing interferometric wavefront sensor," *Optical Engineering* 59(9), 094106 (26 September 2020). (Shanghai Institute of Optics and Fine Mechanics, Shanghai, China)

First, an alignment step is required to ensure that the optical axis is perpendicular to the sensitivity plane of the sensor. In this step, the objective lens is removed and the PSM is in the autocollimator mode. (It is worth noting that the PSM works as an electronic autocollimator when the objective lens is removed because the microscope is based on infinite conjugate optics.[28]) A collimated beam exits the PSM and is reflected by the sensitivity plane of the sensor. Then the reflected beams are focused by the lens before the PSM camera, depicted in green dashed lines in Fig. 12(a). Adjust the tilt of the wavefront sensor so that the reflected image is focused on the center of the PSM camera and is centrosymmetric to the crosshairs of the PSM camera. By now, the precalibration alignment step is finished and the sensitivity plane of the sensor is considered as being perpendicular to the optical axis.

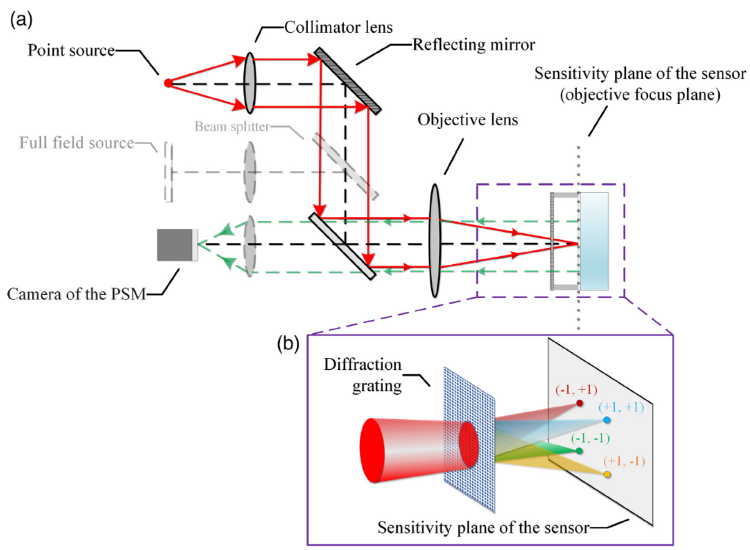

Fig. 12 The principle of the calibration method based on the optical layout of PSM. (a) The overall optical layout. (b) Detailed illustration when the convergent beam enters the wavefront sensor.

38) D. Keyes, et. al., "Optomechanical design and tolerance of a microscope objective at 121.6 nm", Proc SPIE, 9575, 95750E (2015)

In order to maintain diffraction limited performance over the 160μm full field, the optomechanical system must be precisely aligned with tight tolerances on the centration of the secondary mirror. To precisely control the centration of the optical elements, the optomechanical system is designed around the ability to control certain datum surface positions to micrometers using a Point Source Microscope (PSM) on an air bearing rotary table for alignment.

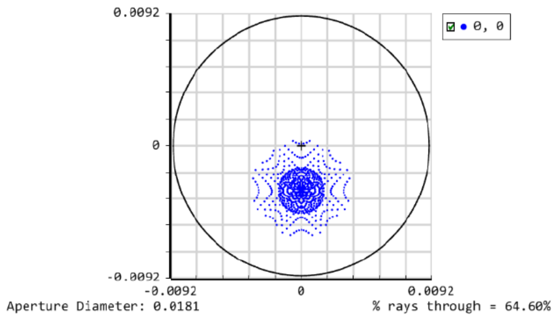

Figure 4. 3 micrometer offset of centroid on PSM camera due to a 1 micrometer decenter of the secondary mirror