Prime Focus Spectrograph: The Metrology Camera System

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Abstract

The metrology camera system (MCS) of the Prime Focus Spectrograph serves as the optical encoder of the COBRA fiber motors for configuring fibers. It is located at the Cassegrain focus of Subaru telescope to cover the whole focal plane with one 50M pixel CMOS sensor. The metrology camera is designed to provide fiber position information within a 5μm error over the 45cm focal plane. MCS was delivered to Subaru Observatory in Apr 2018. The engineering run result shows the MCS overall position accuracy is better than 4μm and image processing time is less than 4 seconds. The MCS is ready for the integration with other PFS components.

MCS Overview

The aperture size of MCS is **380mm** which is the maximum value that Subaru Cassegrain flange can afford while minimizing the beam deviation caused by wide field corrector (WFC) surface irregularity. The optical layout of MCS is shown below (magnification 0.037, f/2.2 Schmidt reflector design). The main MCS optics consists of a Schmidt corrector lens, a spherical primary mirror and a field flattener lens. The achromatic lens set before the Schmidt lens can retain the centroid accuracy given the potential wavelength shift of the fiber illuminating light source. MCS can deliver PSFs with FWHM of ~ 10μm across the entire field. The simulated as-built PSFs (center & field edge) and the constructed MCS are shown in figure 1. As an optical encoder of PFS fibers, MCS shall provide a position accuracy better than 5μm over the 45cm prime focal plane. The potential error sources of the MCS position accuracy include the PSF centroid error, the WFC surface error, the chromatic error and the dome seeing effect.

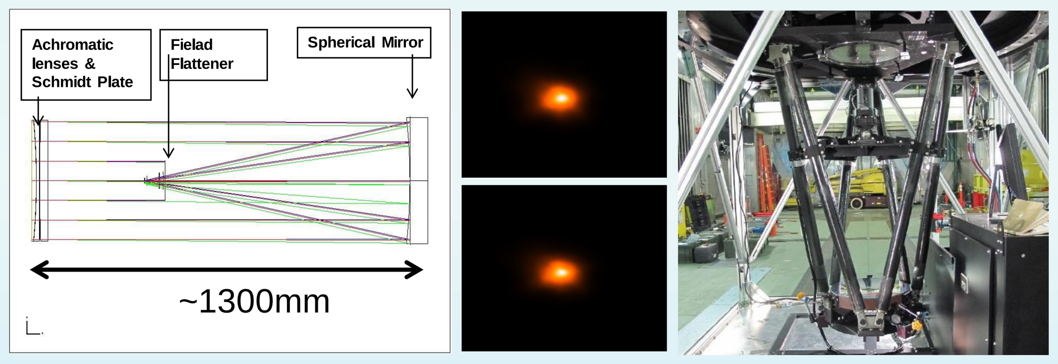

Fig. 1: Left panel shows the optical layout of MCS. Middle panels shows the as-built PSF at field center and edge. Right: MCS installed on the telescope flange.

Engineering Run 1

MCS was delivered to the observatory in April, 2018 followed by the alignment procedure and the 1st engineering run in Oct. A backlit pinhole mask with 3576 holes was placed at the telescope prime focal plane to simulate the fiber spots. The size of the pinholes is the same as the PFS fiber and the precision of the hole locations is better than 2 μm so that the pinholes can be used to calibrate the accuracy of the MCS. This mask is positioned off the MCS center so that it can cover from the center to the edge of the MCS FoV as shown in the picture below. The bottom corners are vignetted by the WFC. During the engineering run, we found that the image quality was not stable when the temperature and elevation angle changed. The PSF shape is also not spherical and shows several tail like structure as shown in figure 2. This affects the centroid accuracy greatly and needs to be improved. After some analysis, we concluded that the mirror support over constraint the primary mirror and caused the problem in the 1st engineering run.

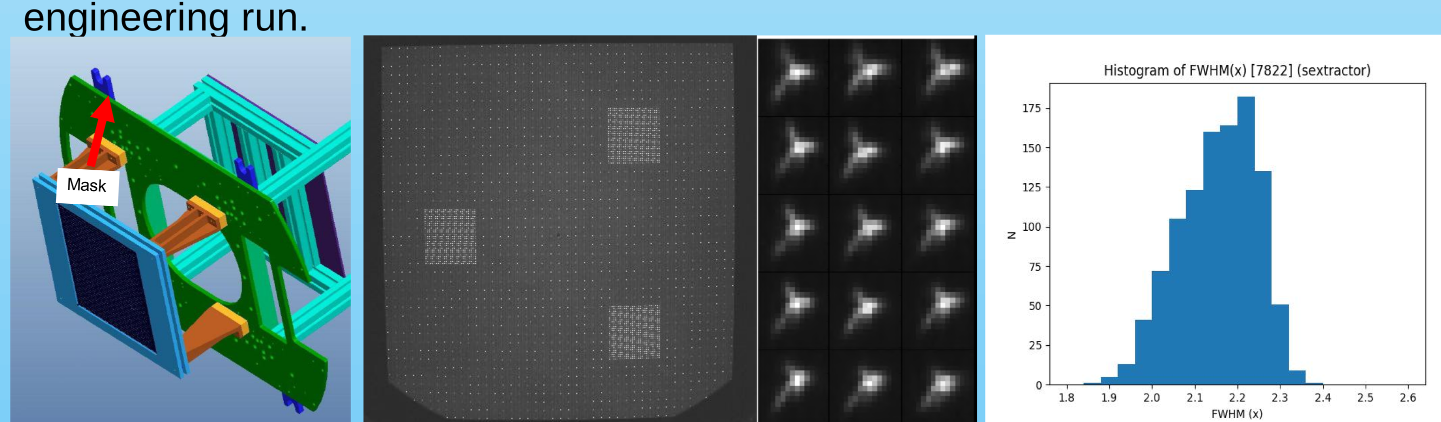

Fig. 2: Left panel shows the design of the pin hole mask structure. Middle left: full view of the pinhole mask. Middle right: PSF samples with 1s exposure time taken during the 1st engineering run. Right panel: histogram of the PSF FWHM in X-direction.

Mirror Support Replacement & Optical Alignment

To solve the mirror support problem, a newly designed mirror support adopts a micrometer for mirror tilt/height adjustment and a ball head with a V groove support for the reduction of the constraint on the mirror. Figure 3 shows the details of the mirror support schematics. The pictures taken at different steps during the mirror support replacement and the re-alignment procedure as also shown: a. three lifting jigs was used to hold the MCS mirror and the original mirror support was removed. b: installing the new mirror support. c: rotating the micrometer to adjust mirror tilt/height to optimize the image quality. d: adjusting the tilt/height of the camera module to fine tune the image quality. After the adjustment and alignment, the MCS image center is (-9,-16) pixels away from the telescope optical axis and well within the expected tolerances.

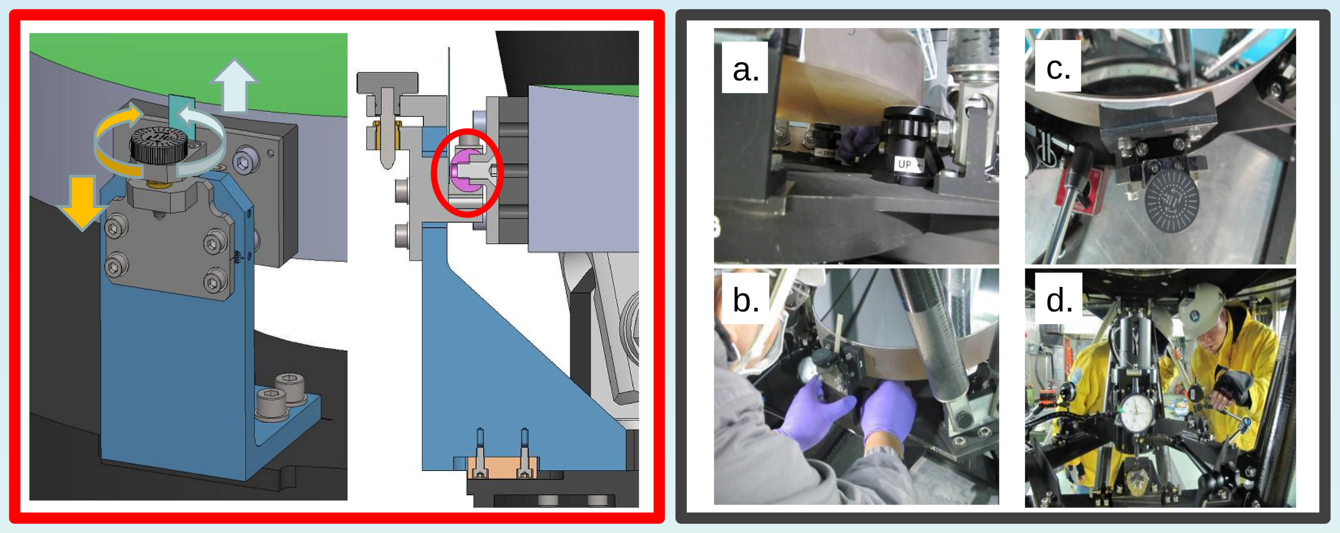

Fig. 3: Left panel shows the design of the new MCS mirror support. Right panel shows the pictures taken from important stages during the mirror support replacement and the following optical alignment.

Image Processing Time

The image readout time for 1s exposure takes 3.36s due to the rolling shutter operation of the CMOS camera. It takes three frames to be saved and co-added. The centroid calculation time using a 16 core computer is 0.35s. It also takes 0.2s for database insertion. This process needs to insert all the fiber positions and measured parameters into the database. Therefore, the total image processing time needed is **3.36 + 0.35 + 0.2 = 3.91sec**.

Engineering Run 2 – Image Quality

MCS had 2nd engineering run after the optical alignment process was completed in Aug. 2019. The test setup is the same as the engineering run 1. Figure 4 shows one of the example of the images taken. The left panel shows the full view of the image, the derived magnification of **0.037** is consistent with the ZEMAX simulation. The middle left panel shows the averaged PSFs taken from various corners of the pinhole image. The PSF is not a perfect round shape but it is quite stable under different elevation angle of temperatures. The centroid algorithm can deliver good accuracy without problems. The PSF FWHM distributions in X and Y direction are close to Gaussian with its peak at 2.3 pixels in X and 2.7 pixels in Y. This shows the modification of the mirror support is effective and the data taken during the whole engineering run could be used for the MCS performance evaluation.

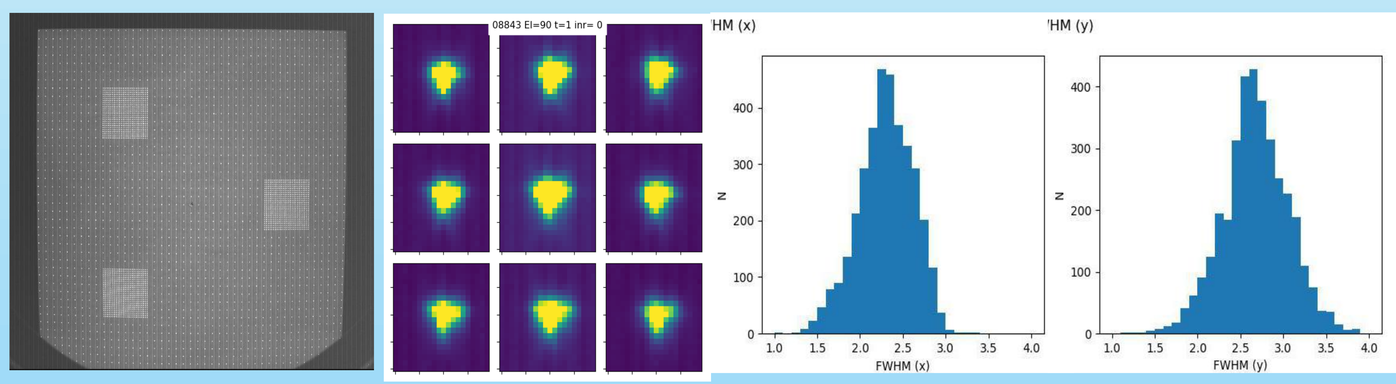

Fig. 4: Left panel shows a full image taken from 2nd engineering run. Middle left: PSF samples with 1s exposure from various corners of the image. Middle right and right: histograms of the PSF FWHM in x and y directions.

Engineering Run 2 - Dome Seeing Measurements & Results

One major task for the 2nd engineering run is to measure the dome seeing effect, which is crucial to the MCS positioning accuracy. During the 2nd engineering run, the weather condition was good so we were able to test MCS under different dome conditions. The variation of the pinhole locations taken by the MCS system was used to investigate the dome seeing. The result for the three nights are presented in the figure below. Different shapes and colors of the symbols indicate various telescope elevation angles and exposure times. The green horizontal dashed line indicates the allocated error budget for the pure centroid accuracy; while the blue horizontal dashed line indicates the overall MCS centroid error. The vertical blue dashed line shows when telescope dome was open and the vertical solid line means we closed the dome. The green vertical dashed and solid lines indicate when the air purge inside MCS cage is on and off. The test result are summarized below:

1. Generally the dome seeing becomes better as night went on. The best seeing tend to happen by the end of the night.
2. The dome seeing decreases when exposure time increases. It seems to settle down when the exposure time longer than 2s. The seeing dependence to the elevation angle is relatively low.
3. The seeing settled in relatively short time (~10mins) after the telescope dome is opened.
4. In most cases, 1s exposure time can deliver dome seeing within the required MCS accuracy value of 0.04 pixels.
5. The centroid error (based on the best seeing obtained) is less than 0.01 pixels.
6. Overall the image quality is stable under various conditions (temperatures, elevation angles and air purge) and can satisfy the operation requirements.

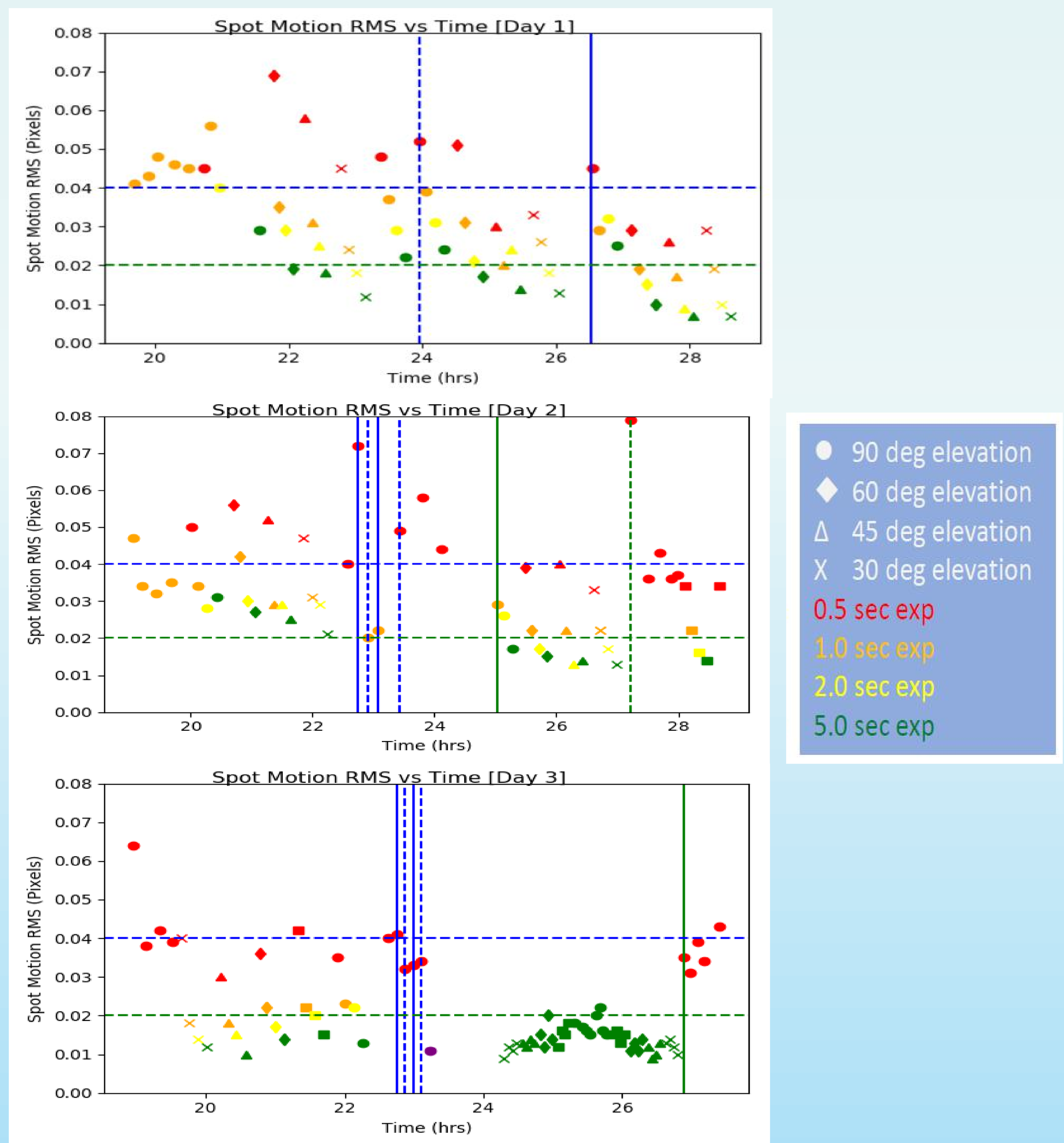

Fig. 5: Left to right panels show spot RMS value in pixels versus time for day 1 to day 3 of the 2nd engineering run. Different symbols and colors indicate various telescope elevation angles and exposure times as indicated on the right hand size.

Summary & Conclusions

- **MCS can deliver stable images with the new mirror supports under various elevation angles and temperatures.**
- **MCS can provide the positioning accuracy better than 4 μm on the PFI focal plane, and the image process time is less than 4 seconds.**
- **The MCS center is aligned with prime focus InR center.**
- **The above summaries shows that MCS satisfies the expected requirements and is ready for the PFS operation.**