

# PFS Coordinates and Calibrations in Commissioning Procedure

Reference ID: PFS-GEN-IPM004015-01

Yuki Moritani, Atsushi Shimono (PFS Project Office, Kavli IPMU),  
James E. Gunn (Princeton)

Issue 01, ver. 1: July 19, 2020

## Contents

<a href="#">1 Definitions of Coordinates</a>	<a href="#">1</a>
<a href="#">2 Observational Sequence and Definitions of Coordinate Transformations</a>	<a href="#">2</a>
<a href="#">3 Format of Coordinate Transform Function</a>	<a href="#">4</a>
<a href="#">4 Calibrations of Coordinate Transformation during the Commissioning</a>	<a href="#">5</a>
<a href="#">5 Failure Modes</a>	<a href="#">7</a>

## 1 Definitions of Coordinates

PFS has four coordinates used for fiber positioning: Sky Catalogue, Fixed Fiducial Fiber Coordinate (F3C), Cobra Coordinate, and Meteorology Camera System Coordinate (MCSC).

The definitions of each coordinates are as follows.

**Sky Catalogue** The sky targets such as galaxies and stars as well as sky backgrounds lie on this coordinates. We describe the target positions using the equatorial coordinates  $\mathbf{S} = (\alpha, \delta)$  in the unit of degree. In the operation, we slew the telescope to a given field centered at  $\mathbf{S} = (\alpha[^\circ], \delta[^\circ])$ . In this Field of View, the sky targets have a position on Sky Catalogue as the differential from the center:  $\mathbf{S}_k = (\Delta\alpha_k[^\circ], \Delta\delta_k[^\circ])$ .

**Fixed Fiducial Fiber Coordinate (F3C)** In order to calculate fiber positions at each exposures, 97 fixed fiducial fibers are used. F3C is the coordinate from the viewpoint of these fibers. In this coordinate, sky targets and fiber positions are described in the unit of mm:  $\mathbf{X}_k = (x_k[\text{mm}], y_k[\text{mm}])$ . In practical, F3C is roughly defined as mean plane of the top surface of the fixed fiducial fibers. F3C resembles physical metrics of PFI (Prime Focal Instrument), but in fact it is *different* because the orientation between each fiducial fiber is constant in F3C. For example, consider the case where the Focal Plane expands along with the increase of the temperature. In such a case, the separation of the two fiducial fibers gets larger, whilst the separation in F3C doesn't change at all (see [Figure 1](#)).

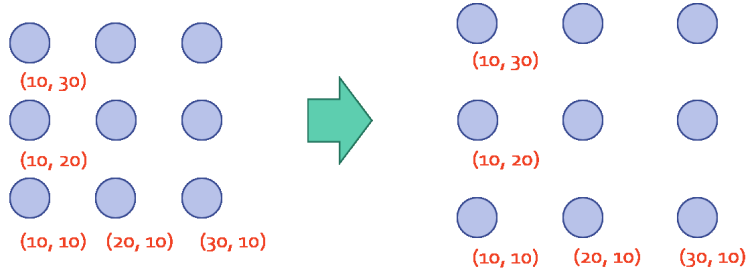


Figure 1: An example of the change in physical metrics of fiducial fibers (blue circles). The fiber positions in F3C are described in red letters.

Another example explaining the difference between F3C and the physical metrics of PFI is the case where one of the fixed fiducial fibers happens to shift from the original position (Figure 2). In such case, the positions of all fixed fiducial fibers are constant again. Measure for this case is described in section 5.

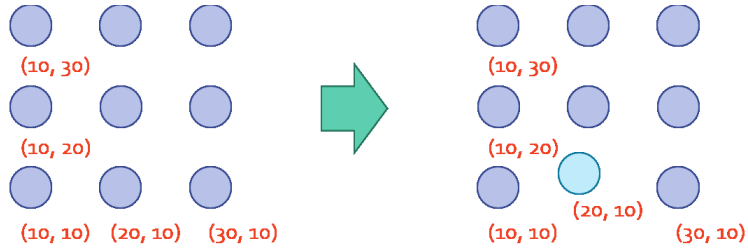


Figure 2: Another example of the change in physical positions of fiducial fibers (blue and light-blue circles). The fiber positions in F3C is described in red letters.

**Cobra Coordinates** The fiber positioner “cobra” is a two-axis motor;  $\theta$  stage and  $\phi$  stage. The motion of each cobra is controlled by FPS and ics.CobraCharmer with the two angles of these stage in degree. We call the two angle as the Cobra Coordinates:  $\mathbf{C}_k = (\theta_k[^\circ], \phi_k[^\circ])$ ,  $[k = 1, 2, \dots, 2394]$ .

**Meteorology Camera System Coordinate (MCSC)** The subsystem Meteorology Camera System calculates centroids of back-illuminated fibers. Here, the centroids are determined as the position on CMOS sensor in the unit of pixels, equivalent to MCSC. The centroids of the fibers, therefore, is determined in MCSC as  $\mathbf{F}_k = (i_k[\text{pixel}], j_k[\text{pixel}])$ .

## 2 Observational Sequence and Definitions of Coordinate Transformations

Figure 3 shows observational sequence in particular during positioning fibers, and transformations of the above coordinates. The procedure of fiber positioning is as follows:

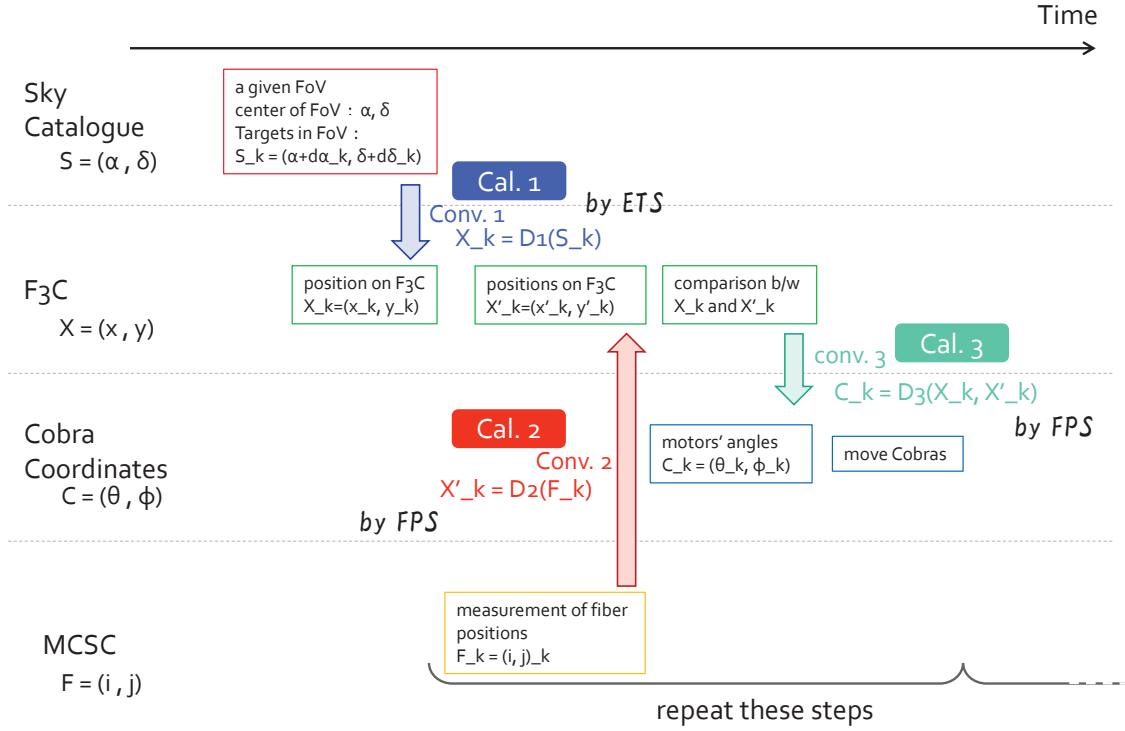


Figure 3: PFS observational sequence and coordinates transformations.

1. ETS (Exposure Time Sequencer) calculate the target positions  $\mathbf{S}_k = (\Delta\alpha_k[^\circ], \Delta\delta_k[^\circ])$  in the observed field centered at  $\mathbf{S} = (\alpha[^\circ], \delta[^\circ])$ .
2. ETS transforms the target positions in Sky Catalogue to those in F3C using the telescope parameters at that moment ( $Az, El, InR, T$ ). We define this transformation as  $D_1$ . That is,

$$\begin{aligned} \mathbf{S}_k = (\alpha_k[^\circ], \delta_k[^\circ]) &\rightarrow \mathbf{X}_k = (x_k[\text{mm}], y_k[\text{mm}]), \\ &D_1 \\ \text{or} \quad \mathbf{X}_k &= D_1(\mathbf{S}_k). \end{aligned} \quad (1)$$

Alternatively, firstly ETS calculates ( $Az, El, InR$ ) at a given time for the field centered at  $\mathbf{S}$ , or receives them from the telescope. Then ETS calculates ( $\Delta Az_k[^\circ], \Delta El_k[^\circ]$ ) of each target  $\mathbf{S}_k$ , as the offset of the field center. This offset is transformed to the position on F3C using  $D_1$ . That is,

$$\mathbf{S}_k = (\alpha_k[^\circ], \delta_k[^\circ]) \rightarrow (\Delta Az_k[^\circ], \Delta El_k[^\circ]) \rightarrow \mathbf{X}_k = (x_k[\text{mm}], y_k[\text{mm}]), \quad (2)$$

$$D_1$$

3. Take fiber image with MCS and measure fiber positions  $\mathbf{F}_k = (i_k[\text{pixel}], j_k[\text{pixel}])$ . Then FPS (Fiber Positioning Sequencer) transforms the fiber positions in MCSC to those in F3C. We define this transform as  $D_2$ . That is,

$$\begin{aligned} \mathbf{F}_k = (i_k[\text{pixel}], j_k[\text{pixel}]) &\rightarrow \mathbf{X}'_k = (x'_k[\text{mm}], y'_k[\text{mm}]), \\ &D_2 \\ \text{or} \quad \mathbf{X}'_k &= D_2(\mathbf{F}_k). \end{aligned} \quad (3)$$

4. FPS calculates Cobra Coordinates to be commanded, by comparing the position of fibers  $\mathbf{X}'_k$  and targets  $\mathbf{X}_k$ . We call this transformation  $D_3$ .

$$\begin{aligned} \mathbf{X}_k = (x_k[\text{mm}], y_k[\text{mm}]), \mathbf{X}'_k = (x'_k[\text{mm}], y'_k[\text{mm}]) &\xrightarrow{D_3} \mathbf{C}_k = (\theta_k[^\circ], \phi_k[^\circ]), \\ \text{or} \quad \mathbf{C}_k &= D_3(\mathbf{X}_k, \mathbf{X}'_k). \end{aligned} \quad (4)$$

Then move Cobras following the derived angles  $\mathbf{C}_k$ .

5. Repeat 3 and 4 until the differential between the target and the fiber positions meets the required accuracy;  $\Delta r_k = \sqrt{\Delta x_k^2 + \Delta y_k^2} \leq 10$  [um] (TBC; REQ-SYS-553). FPS judges which fibers should be moved, and sends  $\mathbf{C}_k$  to the relevant Cobras.

As of July 2020, main part of the formation of  $D_1$  and  $D_2$  is determined by IPMU/Princeton and stored to a designated repository `pfs_utils`, while  $D_3$  is determined by ASIAA/Princeton. During the commissioning, the transformation functions  $D_1$ ,  $D_2$ , and defined and/or calibrated, and calibration for  $D_3$  are executed. In the following section, these process are described.

### 3 Format of Coordinate Transform Function

Fig 4 shows Process flow of the coordinate transformation of  $D_1$  and  $D_2$ . The coordinate transformation includes the distortion of WFC,  $D'_1$ , and  $D'_2$  in the figure. We studied the format of the distortion map for each coordinate transformation using spot calculation with WFC as-built model, and found it is described with the same format.

The transformation from one coordinate  $(i, j)$  to another  $(X, Y)$  is described as follows:

$$\begin{aligned} X &= R(r) \cos \phi + dX \\ Y &= R(r) \sin \phi + dY \end{aligned} \quad (5)$$

Gravity exists in the  $Y(j)$  axis. The first term of scaling factor (axi-symmetric component) and the second term is deviation from scaling (axi-asymmetric component).  $r$  is distance of  $(i, j)$  from the center, and  $\phi$  is argument (i.e.,  $i = r \cos \phi$ ,  $j = r \sin \phi$ ).

The scaling factor, which is represented by one at zenith, is broken down into the polynomial terms and residual.

$$R(r) = \sum_{n=1}^{3 \text{ or } 4} r^{(2n-1)} + \langle \delta r \rangle \quad (6)$$

Polynomial is an 5th or 7th-order odd function. The residual  $\delta r$  is interpolated.

Deviation from scaling, the symmetric component, depends on zenith angle  $z$ . Study of spot position calculated with WFC as-built model shows that the pattern of the position shift is proportional to change in zenith angle. So the deviation is described:

$$\begin{aligned} dX &= F(z) * g(i, j, z) + dX_0 \\ dY &= F(z) * h(i, j, z) + dY_0 \end{aligned} \quad (7)$$

The first term of deviation “pattern” across the field of view, and the second term is residual from the pattern, or offset, at zenith angle. Here,  $F(z)$  is coefficient of the deviation “pattern” is:

$$F(z) = A[B \sin z + (1 - \cos z)] \quad (8)$$

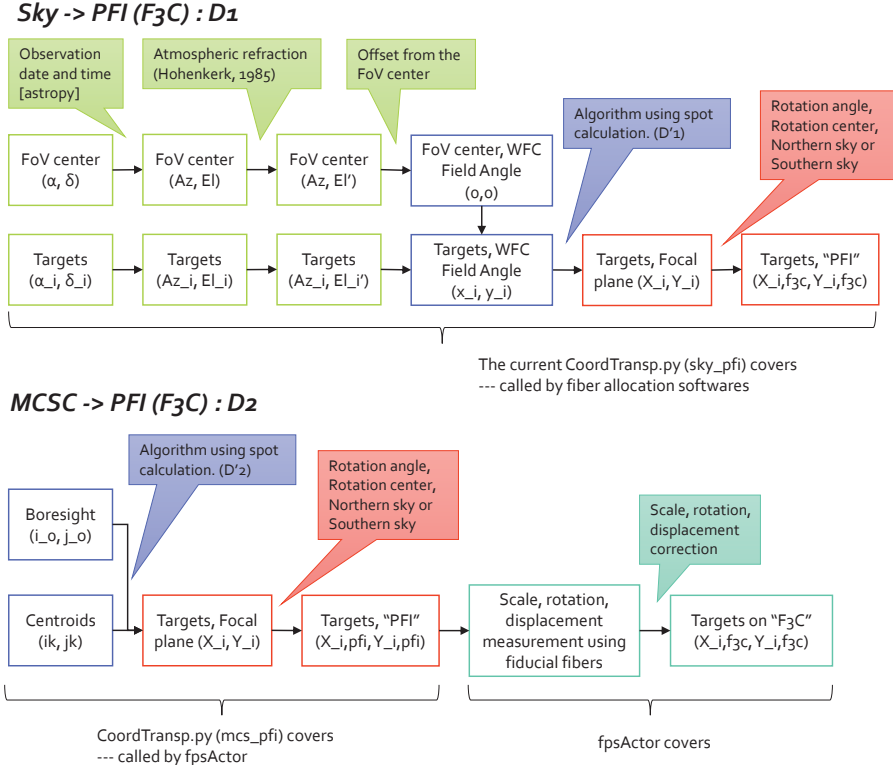


Figure 4: Process flow of the coordinate transformations  $D_1$ , and  $D_2$ . The main part of the transformation is determined by distortion map ( $D'_1$ , and  $D'_2$ ), which is based on WFC as-built model.

Deviation patterns are different between the two axes:

$$\begin{aligned} g(i, j, z) &= A_0 i^2 + A_1 j^2 + A_2 i j + A_3 i^3 j^3 + A_4 \\ h(i, j, z) &= B_0 i^2 + B_1 i^4 + B_2 j^2 + B_3 j^4 + B_4 i^2 j^2 + C(z) j + B_5 \end{aligned} \quad (9)$$

Pattern in Y axis depends on  $z$ . The offsets are interpolated in transformation code.

All the coefficients are derived from the spot position simulated using WFS as-built model at  $z = 0, 30, 60$ .

## 4 Calibrations of Coordinate Transformation during the Commissioning

Before shipping to the Subaru, the physical positions of all fixed fiducial fibers, science fibers and A&G Cameras are measured at a given temperature during the integration of PFI in Taiwan. We shall use the positions of fixed fiducial fibers at that time as their coordinates in F3C.

**Sky Catalogue to F3C transformation  $D_1$ :** In order to transform target coordinates in Sky Catalogue to those in F3C, we describe WFC distortion using as-built and spot position calculation

by Yoko Tanaka from Subaru Telescope as a first step  $D'_{1,0}$ . We call this distortion map “0<sup>th</sup>-pass distortion map” (see the section 3 for details). With “0<sup>th</sup>-pass distortion map” Sky – F3C transformation is described as follows:

$$\mathbf{X}_k = D'_{1,0}(\mathbf{S}_k; El, InR) \quad (10)$$

where  $x(\mathbf{S}_k)$ ,  $y(\mathbf{S}_k)$  is the distance from the center of FoV in the x, y direction, respectively, which corresponds to  $(\Delta Az[^\circ], \Delta El[^\circ])$  in the section 2.

Through the commissioning, we shall optimize  $D'_{1,0}$  by measuring the sky distortion and the sky scale in F3C. Note that the distortion map likely varies with respect to the telescope parameters (azimuth  $Az$ , elevation  $El$ , instrument rotator  $InR$ ), temperature  $T$  and so on.

At first, in the commissioning process P-10, the distortion map shall be updated using 6 A&G Cameras attached at the edge FoV. Taking the A&G Camera image of the fields with enough numbers of stars such as star clusters or the Galactic Plane, we shall measure the positions of targets on A&G CCDs. The scale of the sky in F3C is also measured in the P-10 process: The distance A&G camera and AG fiducial fibers in F3C is measured before the PFI shipping. We shall measure their distance in sky with raster scan around AG fiducial fibers. When P-10 is succeeded, the distortion map shall be updated as “1<sup>st</sup>-pass distortion map”:

$$\mathbf{X}_k = D'_{1,1}(\mathbf{S}_k; El, InR) \quad (11)$$

In order to improve  $D'_{1,1}$ , we shall do raster scan in the commissioning process A-3, where “2<sup>nd</sup>-pass distortion map”  $D'_{1,2}$  shall be determined. Note that the A-3 sequence is carried out after  $D_2$  and  $D_3$  are determined/calibrated.  $D_{1,2}$  is the final map for transformation from Sky Catalogue to F3C. That is,

$$\mathbf{X}_k = D_{1,2}(\mathbf{S}_k; El, InR, \dots) \quad (12)$$

**MCS to F3C transformation  $D_2$ :** In the observational sequence, PFS determines parameters of  $D_2$  every time when MCS takes fibers image. The distortion for  $D_2$  is determined in advance using ZEMAX calculation with WFC as-built model ( $D'_2$ , section 3).

$$\begin{aligned} \mathbf{X} &= D_2(\mathbf{F}) \\ &= TD'_2(\mathbf{F}; El, InR), \end{aligned} \quad (13)$$

where  $T$  is affine transformation based on F3C by taken FPS.

During the commissioning, we shall refine the positions of fixed fiducial fibers in F3C (process P-8). In this commissioning sequence, we compare the positions of fixed fiducial fibers in F3C expected by  $D'_2(\mathbf{F}_k)$  and with those measured before shipment and check their consistency.

During the observations,  $T$  is derived to minimize RMS:

$$T := \min(\|\mathbf{X}_l - TD'_2(\mathbf{F}_l; El, InR)\|), \quad (14)$$

where  $l$  indicates fixed fiducial fibers ( $l = 1, 2, \dots, 96$ ). Note that we don't adopt the least mean square method because this method weights on error in spacial map. Using derived matrix  $T$ , the science fibers position is transformed to those in F3C;

$$\mathbf{X}_k = TD'_2(\mathbf{F}_k; El, InR). \quad (15)$$

Because the positions of fixed fiducial fibers on F3C contains the measurement error in physical position during integrations ( $\sim 10$  [um]), function  $D_2$  should take over this error even if the error of  $\mathbf{F}_k$  is small ( $\sim 3$  [um]). This error finally affects on total error in fiber positioning on targets. We shall optimize  $D'_{1,1}$  by doing raster scan (commissioning process A-3) and minimize this error.

**F3C to Cobra transformation  $D_3$ :** In order to move fiber positioner “cobra”, we should know the following parameters for each positioner: center position  $\mathbf{X}_{c,k} = (x_{c,k}, y_{c,k})$ , arm lengths of  $\theta$  stage  $a_{1,k}$  and  $\phi$  stage  $a_{2,k}$ , minimum positions of  $\theta$  angle  $\theta_{0,k}$  and  $\phi$  angle  $\phi_{0,k}$ , and maximum positions of  $\theta$  angle  $\theta_{m,k}$  and  $\phi$  angle  $\phi_{m,k}$ . Note that these parameters are calculated in F3C. In the commissioning phase of A-2, we shall derive these parameters using back-illuminated science fibers<sup>1</sup>.

## 5 Failure Modes

In this section, the expected failure modes in coordinates transformation are described. (*still updating...*)

**Unexpected displacement of the fixed fiducial fibers** The coordinate transformation system adopts some kind of function to estimate errors in the result of  $D_2$ , which is sensitive to the displacement of fixed fiducial fibers. If the conversion  $D_2$  has a large error and a proper fixed fiducial fiber is found to have the responsibility for the error, the fiber will be excluded from F3C.

**Discrepancy between the positions of fiducial fibers in F3C and those predicted by  $D_2$**  In the commissioning process P-8, we measure the positions of fixed fiducial fibers in F3C by converting with  $D_2$ , and compare with the original position in F3C. If there is large discrepancy between them, we can't transform from MCSC to F3C. One possibility of this error is that  $D_2$  is not suitable, so that we should improve its form.

## Change log.

- ver. 1: 31 January 2020 – modified on 19 July 2020

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<sup>1</sup>see PFS-GEN-IPM004000 for details.