PFS Commissioning & Operation Work Flow

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1 Overview

1.1 Work-flow overview

The ultimate goal of the PFS validation & commissioning work-flow is to optimize the PFS performance and validate the goodness for scientific use. To achieve this goal, we proceed the PFS commissioning following this outline:

1. Integrate PFS subsystems of which the performances have been validated by the PFS collaborators.
2. Operate the system and confirm their functions on the telescope.
3. Characterize the system, e.g. by calibrating the coordinate systems to put the fibers on the targets with required accuracy.
4. Evaluate the on-sky performance and validate it.
   Firstly we focus on verifying the performances at given telescope positions, rotation angles even if we cannot confirm the same performance at all positions.
5. Finally, stabilize the instrument performances.
   We optimize software, re-configuration sequence, calibration and so on. We validate the performance at any telescope pointing or time.

The latest top-level requirements are described on the following page:
`http://sumire.pbworks.com/w/page/76118150/System%20level%20requirements`
See also the compliance matrix in section 1.3.

The work-flow of the PFS commissioning (Fig. 1) consists of five parts:

1. Validation of MCS (labeled with M-#, see section 2.1)
   - Validation of MCS basic functions.
   - Pre-study of the coordinate transformation using pinhole array or FMOS/PIR or pinhole array on POpt2.

   This part requires only MCS.

2. Validation of PFI (labeled with P-#, see section 2.2), basically prior to SpS delivery at Subaru.
   - Alignment of WFC with the primary mirror.
   - Telescope pointing analysis.
   - AG camera validation.
   - Confirmation of PFI–MCS relation (registration of Fixed Fiducial Fibers in F3C).
   - Make the first-pass distortion map using AGCs (sky).

   This part requires only PFI basically, but some sequences need MCS, too.

3. Validation of SpS (labeled with S-#, see section 2.3)
   - Validation of image quality and stability in the SCR.
   - Characterization of SMs.

   This part requires SMs and SCR. We don't need the telescope to carry out this part.

4. Validation of FoCCoS–Cable B (labeled with F-#, see section 2.4)
   - Validation of cable connection.
   - Confirmation of fibers ID on MCS and SpS.

   This part requires all subsystems: MCS, PFI, Cable B and SpS.

5. Commissioning all systems (labeled with A-#, see section 2.5
   - Cobra calibration.
   - PSF characterization.
   - Make the second-pass distortion map using fibers (sky).
   - Validation of all observational sequence.
   - Performance verification.
   - Stabilization of the instrument performance and operation.

   This part requires all subsystems: MCS, PFI, Cable B and SpS.

During the commissioning procedure, we also verify the software sequence for observation (acquisition, fiber configuration, guiding, and exposure) at suitable commissioning sequences. We also verify the data reduction pipeline (DRP).

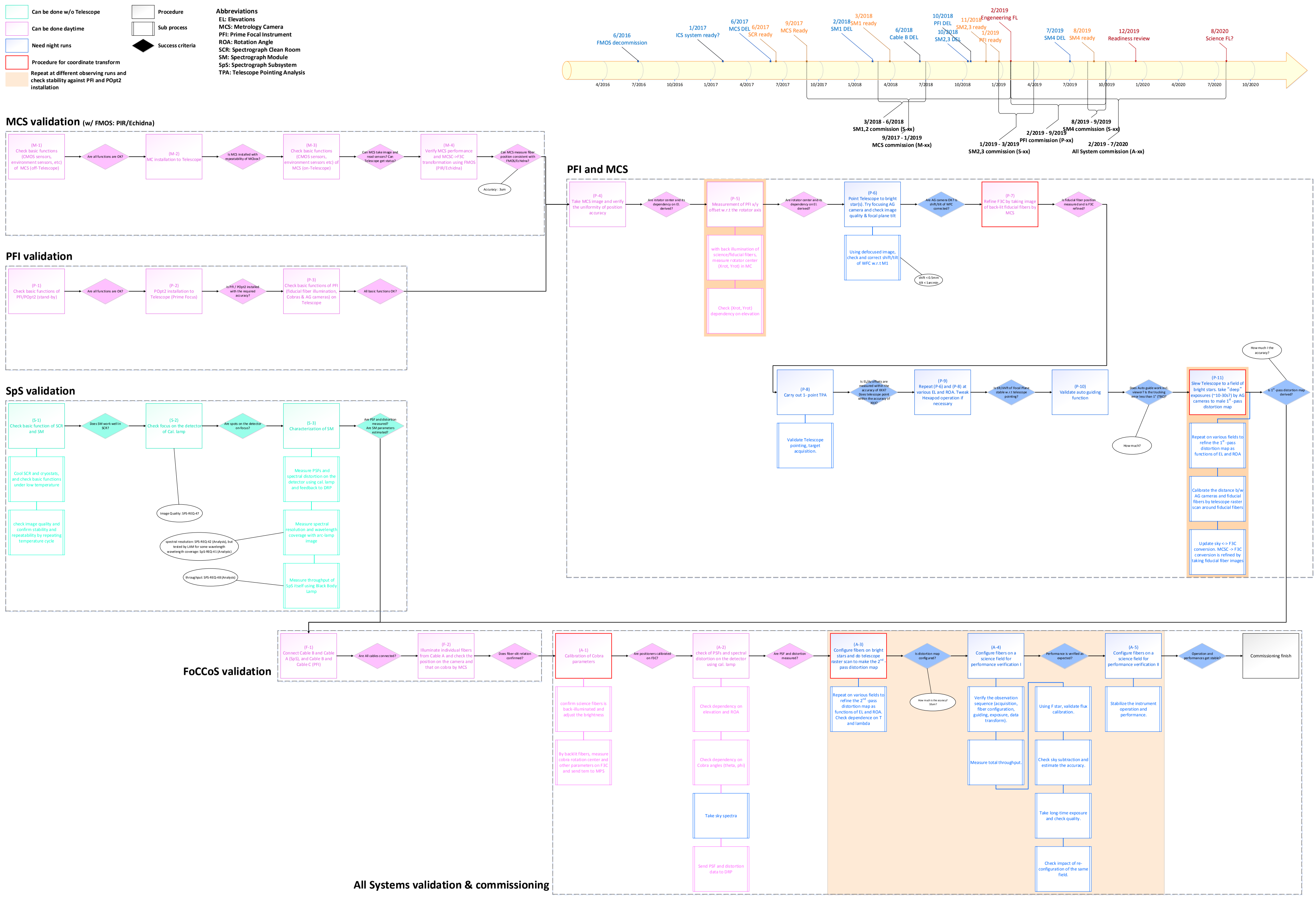

Figure 1: Flowchart of Validation & Commissioning. Larger one is available on the PBworks: http://sumire.pbworks.com/w/file/101350174/PFScommissioning.pdf

1.2 Subsystem I & T (TBD)

1.2.1 I & T at Subaru

Each subsystem is delivered to Subaru separately. After the delivery, collaborators will re-assemble modules (if needed) and test their performance. In this section, the brief summary of I&T of subsystems are described. See the documents by collaborators (TBA) for detailed procedure of I&T.

Table 1 summarizes schedule and place of I&T of subsystems. The validated functions before shipping (or before commissioning) is listed in table 2. The file named `PFS_AIT_Subaru.pptx`[1] summarizes The required source, layout of working space and other configurations of I&T process in Hawaii

Table 1: Subsystem I&T time and place.

Subsystem	Year/Month	I&T Place (Hilo)	I&T Place (Summit)
PFI	2018/10–2019/01	Simulator lab.	Instrument Lab. & Observation floor
MCS	2017/07–2017/09	Simulator lab.	Observation floor
SpS-SM1	2018/02–2018/03		IR4 (SCR)
SpS-SM2	2018/11–2018/12		IR4 (SCR)
SpS-SM3	2018/11–2018/12		IR4 (SCR)
SpS-SM4	2019/07–2019/08		IR4 (SCR)
Cable B	2018/06–2018/08	TBD	TBD

PFI PFI is shipped after assembled at ASIAA, so it doesn't need to be re-assembled at Subaru. However, field element will be disassembled for protection, so that it will be integrated again at the Summit. The I&T story board at the summit is in preparation but the currently assumed test items are as follows:

1. Fiber transparency tests
2. Rotational test for Cable Wrapper
3. Power on/off test (fiducial fiber illuminator etc.)
4. Image acquisition (central camera, fiducial fiber viewing cameras, and AG cameras)
5. Cobra circular motion test
6. Dot position check
7. Cobra convergence test with dummy MCS
8. AG camera test for dark and noise
9. Integration of Field Element

These test are carried out using test stand on which PFI will be shipped, and dummy MCS. Because the tilt mechanism is not assumed to be delivered so far, the test should be limited compared to AIT phase at ASIAA.

After the above tests are passed, PFI will be installed to POpt2, and the the same tests are repeated, except for the cobra circular motion test.

Test items for software — control individual modules, telemetry, communicate with MLP1/STS etc.

[1] http://sumire.pbworks.com/w/file/111633073/PFS_AIT_Subaru.pptx

MCS After AIT at ASIAA, MCS will be shipped to Subaru without disassembling. The optical alignment of the subsystem will be checked using laser at Hilo base, then the subsystem will be transported to the Summit.

At the Summit, the image quality will be checked with the pinhole array. ASIAA will also adjust the alignment of MCS with respect to the prime focus, because MCS will be mounted to CsBox only "mechanically". Such a test enables us to use time efficiently before PFI arrival, and to save time after PFI arrival, which is expected one year later than MCS arrival, because we should align MCS with the prime focus firstly. After the alignment, the image quality will be also checked under the more realistic observational condition (e.g. dome seeing). This test will be performed using the pinhole array can be equipped on POpt2. Note that the I&T process using Popt2 with pinhole array will be done combining to MCS commissioning process (M- 3).

Test items for software — control individual modules, telemetry, communicate with STS etc.

SpS After AIT at LAM, four modules are shipped to Subaru two by two. The modules are re-assembled in SCR on the IR4 floor, and the following test will be carried out (TBC):

- Thermal function (cooling down /warming up)
- Image quality
- Characterization of spectrograph (optional: TBD)

Test items for software — control individual modules, telemetry, communicate with STS etc.

Cable B After shipped to Subaru, the light-path will be tested firstly. It is still to be discussed, but we will also execute FRD measurement with simple equipment for some fibers as aliveness test. Then the cable is installed to the telescope, while the fiber connection monitoring system is installed to the IR3 floor. It is desirable to measure FRD on the telescope, but details are to be discussed. The details is TBC.

Test items for software?

1.2.2 Complementarity between subsystem I& T and the commissioning

To be written.

Table 2: The list of validated functions before the commissioning.

No	Functions	No. of Table 3	Succ.?	Req.	Notes
PFI (including Cable C)					
P01	Instrument rotator moves from $-278°$ to $+278°$.	8			
P02	Positioning error of A&C camera is ~ 2.8 um.	25			CDR
P03	PFI has 97 fiducial fibers.			`REQ-FOC-L3-267`	CDR
P04	All fiducial fibers can be back-illuminated.	28, 30		`REQ-L3-PFI-008`	
P05	Science fibers home position is measured in the accuracy of 50 um PTV.	34, 35			Relative position to a fiducial fiber near the center.
P06	Science fibers rotation center is measured in the accuracy of 50 um PTV.	34, 35			Relative position to a fiducial fiber near the center.
P07	Perimeter fiducial fibers position is measured in the accuracy of 50 um PTV.	34, 26			Relative position to a fiducial fiber near the center.
P08	Field element dots position is measured in the accuracy of 50 um PTV.	34, 35			Relative position to a fiducial fiber near the center.
P09	The position of AG camera fiducial fibers is measured in the accuracy of 10 um PTV.	26			Relative to nearest perimeter fiducial fiber.
P10	The position of AG camera sensors is measured in the accuracy of 10 um PTV.				Relative to nearest perimeter fiducial fiber.
P11	The focus position of science fibers is measured in the accuracy of 12 um PTV.				Relative to designed focus position.
P12	The focus position of perimeter fiducial fibers is measured in the accuracy of 12 um PTV.				Relative to designed focus position.
P13	The focus position of AG camera sensors is measured in the accuracy of 12 um PTV.				Relative to designed focus position.
P14	The tilt of science fibers is measured in the accuracy of 0.17° PTV.				Relative to a fiducial fiber near the center.
P15	The tilt of perimeter fiducial fibers is measured in the accuracy of 0.17° PTV.				Relative to a fiducial fiber near the center.
P16	The tilt of AG camera sensors is measured in the accuracy of 0.17° PTV.				Relative to a COB rear surface.
P17	P05–P16 are achieved with rotation angle of $0, \pm 60°$ and El. $90, 60, 30°$				CDR
P18	The cobra positioner converge to requested x/y position in the accuracy of 10 um PTV.	34, 35			

Table 2: The list of validated functions before the commissioning.

No	Functions	No. of Table 3	Succ.?	Req.	Notes
P19	P19 is achieved with rotation angle of $0, \pm 60°$ and El. $90, 60, 30°$				CDR
P21	AG camera shall acquire image.				
P21	Fiducial fiber viewing cameras shall acquire image.	6			
P22	Center camera shall acquire image.	7			
P21	PFI shall be operated remotely via MHS.	4, 10			
...	...	...	...	...	
MCS					
M01	The FoV is large enough to see all science and fiducial fibers at a time.	16, 17		`REQ-MET-2`	MCS covers 462mm in diameter at the focal plane (CDR).
M02	The fiber centroid cam be measured within the error of 5 um (RMS) for all fibers.	15, 16, 17, 26		`REQ-MET-6`	$<$ 4.46um RMS (CDR)
M03	MCS completes one cycle of image acquisition, data read, and measurement within 5 seconds in average.	18		`REQ-MET-7`	$<$ 3 seconds (CDR)
M04	MCS shall be operated remotely via MHS.	1,3			
...	...	...	...	...	...
SpS (including Cable A)					
S01	The blue detector shall be cooled down to operating temperature (173 ± 0.5 K)			`SPS-REQ-307`, `SPS-REQ-202`, `SPS-REQ-95`	
S02	The red detector shall be cooled down to operating temperature (173 ± 0.5 K)			`SPS-REQ-307`, `SPS-REQ-203`, `SPS-REQ-95`	
S03	The nir detector shall be cooled down to operating temperature (110 ± 0.5 K)			`SPS-REQ-307`, `SPS-REQ-204`, `SPS-REQ-95`	
S04	All camera units cover 2394 science fibers in their readable area.				
S05	SpS shall back-illuminate science fibers.	29, 30			
...	...	...	...	...	...
Cable B					
F01	Cable shall deliver 2394 light source from PFI to SpS.	14		`REQ-FOC-L3-267`	

Table 2: The list of validated functions before the commissioning.

No	Functions	No. of Table 3	Succ.?	Req.	Notes
F02	Cable connection should be monitored remotely.	14		`REQ-FOC-L3-043`	
...	...	...	...	...	...

1.3 Achieved PFS Functions during the Commissioning (TBD)

Table 3 shows achieved PFS functions and related commissioning sequences (compliance matrix). Column 1 lists the priority of the functions (TBD).

Table 3: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
	Fiber Allocation					
1	A	Initial check of subsystems	MCS can communicate with MHS	M- 1, M- 3		
2	A		MCS can take image with required performance (dark, noise,etc.)	M- 1, M- 3		
3	A		All mechanical and environmental sensors of MCS can be read	M- 1, M- 3		
4	A		PFI can communicate with MHS	P- 1, P- 3		
5	A		AG cameras can take image with required performance (noise, dark, etc.)	P- 1, P- 3		
6	A		Fixed fiducial cameras can take image with required performance (noise, dark, etc.)	P- 1, P- 3		
7	A		Center camera can take image with required performance (noise, dark, etc.)	P- 1, P- 3		
8	A		Instrument rotator moves from $-270°$ to $+270°$	P- 1, P- 3		
9	A		Cooling system works	P- 1, P- 3		
10	A		All mechanical and environmental sensors of PFI can be read	P- 1, P- 3		
11	A	Installation of subsystems	MCS is installed on the Cs focus meeting required accuracy (tilt $<$ 0.14 degree, decenter of optical axis $<$ 45mm in x,y each)	M- 2		
12	A		PFI is installed in POpt2 meeting required repeatability ($<$ 200um in lateral, $<$ 100um in focus, $<$ 15 arcsec in tilt)	P- 1, P- 5		repeatability of focus and tilt is not measured in P- 5
13	A		POpt2 is installed on the prime focus with accuracy of 10 um	P- 2		Specification of Mitsubishi
14	A		Cable B is connected with PFI and SpS correctly (fiber ID, throughput?)	F- 1, F- 2		
15	A	Pre-study of coordinate transformation	Algorithm of coordinate transformation works (accuracy: 50 um)	M- 4		

Table 3: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
16	A	Measurement of fibers centroids	Spot size is $\sim$2.6 pix on entire FoV at various Elevations and rotator angles	P- 4		
17	A		Centroids can be measured within the accuracy of 5 um (1.5 pixel)	P- 4		
18	A		Measurement process is done within 5 seconds	P- 4		
19	A	Telescope pointing and tracing	Telescope can be focused with error of 10 um	P- 7		
21	A		WFC is aligned to Primary Mirror within the shift of 0.5mm and tilt of 1 arcmin	P- 7		
23	A		Telescope Pointing Analysis can be done with error of XXX	P- 9		
24	A		PFS can acquire field and start auto guiding within 15 seconds	P- 6		
25	A		Telescope can track a field with error of $\lesssim$ 0.1 arcsec in both RA and DEC directions using A&G camera	P- 6		
26	A	Registration of fixed fiducial fibers	Positions of the fixed fiducial fibers measured on F3C within the accuracy of 5 um (TBD)	P- 8		P- 7 is needed prior to P- 8
27	A	First-pass sky-PFI distortion map	Fiber allocation error is <50 um	P- 10		
28	A	Back illumination of fibers	Fixed fiducial fibers are back-illuminated	P- 1		
29	A		Science fibers are back-illuminated	A- 1		
30	A		Brightness of science and fixed fiducial fibers is the same on MCS	A- 1		
31	A	Cobra initial movement	Cobra can move anyhow	P- 3		
32	A	Calibration of Cobra	Cobra parameters are calibrated	A- 1		
33	A	Cobra movement	Cobra can move everywhere in their patrol area	A- 1		
34	A	Second-pass sky-PFI distortion map	Fiber allocation error is <$\sim$10 um (TBD)	A- 3		
35	A	Fiber configuration	95% of 2394 fibers can be allocated to their targeted position within 105 seconds	A- 4		
36	A	Fiber re-configuration	Fibers are reconfigured within 105 seconds with the accuracy of 10um (TBD)	A- 5		
Spectrograph						
37	A	Initial check of subsystems	SCR and SpS can communicate with MHS	S- 1		

Table 3: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
38	A		The temperature of SCR is controlled stably (3–5 degC)	S- 1		
39	A		SCR ans SpS Can recover from power failure mode	S- 1		
40	A		All 12 detectors can take images within expected noise.	S- 1		
41	A		SpS can change LR/MR mode in RED arms	S- 1		
42	A		SpS can open/close shutters	S- 1		
43	A		All mechanical and environmental sensors of SMs can be read	S- 1		
44	A		The input light can be focused on the detectors (EE is 50% in 3 x 3 pixels and 90 % in 5 x 5 pixels in 90% of detector area)	S- 1		
45	A	Characterization	Wavelength coverage is 380–650 nm in BLUE arms	S- 2		
46	A		Wavelength coverage is 630–970 nm in RED(LR) arms	S- 2		
47	A		Wavelength coverage is 710–885 nm in RED(MR) arms	S- 2		
48	A		Wavelength coverage is 940–1260 nm in NIR arms	S- 2		
49	A		Spectral resolution is >2300 at 520 nm (BLUE)	S- 2		
50	A		Spectral resolution is >2800 at 810 nm (RED, LR)	S- 2		
51	A		Spectral resolution is >5000 at 810 nm (RED, MR)	S- 2		
52	A		Spectral resolution is >4100 at 1100 nm (NIR)	S- 2		
53	A		Throughput of SpS (TBD)	S- 2		
54	A		PSF and spectral distribution of SpS are characterized	S- 2		
55	A		PSF and spectral distribution through the entire system are characterized at various El. (30°–90°) and RoA (−270° – +270°)	A- 2		
56	A		Total throughput of BLUE arm is $\gtrsim$12% (380–450 nm), $\gtrsim$21% (450–550 nm) and $\gtrsim$24% (550–650 nm)	A- 4		
57	A		Total throughput of RED (LR) arm is $\gtrsim$30% (630–750 nm), $\gtrsim$29% (750–850 nm) and $\gtrsim$27% (850–970 nm)	A- 4		
58	A		Total throughput of RED (MR) arm is $\gtrsim$26% (710–875 nm), $\gtrsim$28% (775–825 nm) and $\gtrsim$27% (725–885 nm)	A- 4		
59	A		Total throughput of NIR arm is $\gtrsim$17% (940–1050 nm), $\gtrsim$19% (1050–1150 nm), and $\gtrsim$17% (1150–1260 nm)	A- 4		
60	A	Calibration	Calibration lamp turns on/off	P- 1		
61	A		Calibration sources are bright enough on the detectors (XXX count)	S- 2		

Table 3: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
62	A		Dots shall obscure fibers during taking calibration data	A- 1		
63	A		Sky background can be corrected within the accuracy of $\lesssim$ 0.5 %	A- 5		
64	A		Flux can be calibrated within the accuracy of 5 %	A- 5		
Total Performance						
65	A	Long-term exposure	S/N is proportional to $\sqrt{t}$ during long-term exposures (∼10 hours)	A- 5		
?	?	Beam-switching mode	TBD			Current plan doesn't include validation for BS mode

1.4 Expected Number of Nights for Validation & Commissioning (TBD)

The PFS commissioning requires several "engineering observation runs", during which a few sequences are executed step by step. We estimate the number of required runs and working-days for the PFS validation & commissioning procedure. There are 15-day works for which night time is not required, and 35-day works for which the night time is essential. Among the latter, 22-day works require dark night, in later phase of the commissioning. We arranges the working process to use the telescope time as effectively as possible. In total, **8 runs of 38 working-days** will be required for the commissioning. Here, we take account into the weather factor of 70 % uniformly for nighttime sequences. We also include the uniform 20 % technical margin into each sequence for unseen situations.

The expected numbers of working-days for each run and its breakdown is as below. Figures 2 – 8 display the rough schedule of each run, from installation of subsystems before the engineering observation to uninstallation of them after the run. Here, sequences which requires dark night-sky are colored by navy, while ones requiring night-sky even bright/grey by blue. Sequences we can carry out even in the daytime are colored by pink. Table 4 summarizes these numbers with schedule on the assumption of the current timeline of the project.

Note that we don't count the required days for validation of SpS (seq. S-#) for the above estimation, because the telescope time is not occupied with PFS during its validation.

Breakdown of individual runs are as follows.

Run 1: 3 (4) days (Figure 2)

- 1 day (daytime) for M-1 – M-3: (1) check MCS functions standing by, (2) install MCS to the Cassegrain focus, and (3) check MCS functions on telescope
- 3 days (daytime) for M-4 : (1) pre-study the coordinate transformation system

Note that telescope can be used for other Ns/PF instruments on the night when MCS is installed (seq. M-1 – M-3). Note also that this run has AIT work by ASIAA — alignment the MCS to the prime focus and image quality test, although the exact number of working day is TBD.

	pre-run	Day 1	Day 2	Day 3	post-run
Telescope work	MCS install = M1—M3	FMOS/PIR or pinhole install			FMOS/PIR or pinhole uninstall
Daytime	M1—M3	AISAA AIT (alignment)	AISAA AIT (IQ), M4	M4	inspection
Nighttime		AISAA AIT (IQ)	AISAA AIT (IQ), M4	M4	

Figure 2: Time table of Run 1.

Run 2 : 7 days (Figure 3)

- 1 day (daytime) for P-1 – P-3, P-5 : (1) check PFI/Popt2 standing by, (2) install POpt2 to the prime focus, (3) check PFI functions, and (4) measure x/y offset of PFI rotation center on MCS
- 0.5 day (daytime) for P-4 : (1) verify MCS performance
- 1.5 days (nighttime) for P-6 : (1) verification of A&G camera functions
- 2.5 days (nighttime) for P-7 : (1) correct WFC shift/tilt with respect to the primary mirror
- 1.5 days (daytime) for P-8 : (1) confirm fixed fiducial fiber positions on F3C (refine the PFI-MCS relation)
- 1.5 days (nighttime) for P-9 : (1) Telescope Pointing Analysis
- 0.7 day (daytime) for F-1 : (1) connect Cable B to PFI and SpS (SM1/2/3)
- 1.8 day (daytime) for F-2 : (1) confirm the fiber identifications (SM1/2/3)
- 1.5 days (daytime) for A-1 : (1) calibration of Cobras (SM1/2)
- 1.5 days (1.5-day nighttime) for A-2 : (1) PSF measurement through the entire system (SM1/2/3)

	pre-run	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	post-run
Telescope work	MCS install	PFI install =P1—P3,P5							PFI uninstall
Daytime		P1—P3,P5 preparation	P4 ,F1 (Trouble shooting)	F1, F2 (Trouble shooting)	F2 (Trouble shooting)	A1 (Trouble shooting)	A1, P8 (Trouble shooting)	P8 (Trouble shooting)	inspection
Nighttime		P6	P6,P7	P7	P7	P9	P9,A2	A2	

Figure 3: Time table of Run 2.

Run 3 : 4 days (Figure 4)

- 4 days (nighttime) for P-10 : (1) 1st-pass distortion map
- 1.5 days (daytime) for A-1 : (1) calibration of Cobras (SM3/4)
- 1.5 days (1.5-day daytime) for A-2 : (1) PSF measurement through the entire system (SM1/2/3)

	pre-run	Day 1	Day 2	Day 3	Day 4	post-run
Telescope work	MCS install	PFI install				PFI uninstall
Daytime		A1 preparation	A1,A2 (Trouble shooting)	A2 (Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		P10	P10	P10	P10	

Figure 4: Time table of Run 3.

Run 4 : 6 days (Figure 5)

- 2 days (nighttime) for P-10 : (1) 1st-pass distortion map
- 0.4 day (daytime) for F-1 : (1) connecting Cable B to PFI and SpS (SM4)
- 0.6 day (daytime) for F-2 : (1) confirmation of the fiber identifications (SM4)
- 1.5 days (1.0-day daytime and 0.5-day nighttime) for A-2: (1) PSF measurement through the entire system (all SMs)
- 3.5 days (nighttime) for A-3: (1) 2nd-pass distortion map

	pre-run	Day 1	Day 2	Day 3	Day 4	Day5	Day 6	post-run
Telescope work	MCS install	PFI install						PFI uninstall
Daytime		F1,F2 preparation	A2 (Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)		inspection
Nighttime		P10	P10	A2,A3	A3	A3	A3	

Figure 5: Time table of Run 4.

Run 5 : 6 days (Figure 6)

- 3 days (nighttime) for A-3: (1) 2nd-pass distortion map
- 3 day (dark-night) for A-4 : (1) performance verification I

	pre-run	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	post-run
Telescope work	MCS install	PFI install						PFI uninstall
Daytime		preparation	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		A3	A3	A3	A4	A4	A4	

Figure 6: Time table of Run 5.

Run 6 : 4 days (Figure 7)

- 2 days (dark-night) for A-4 : (1) performance verification I
- 2 days (dark-night) for A-5 : (1) performance verification II (stabilization)

	pre-run	Day 1	Day 2	Day 3	Day 4	post-run
Telescope work	MCS install	PFI install				PFI uninstall
Daytime		preparation	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		A4,5	A4,A5	A4,A5	A4,A5	

Figure 7: Time table of Run 6.

Runs 7 and 8 : 4 days (Figure 8)

- 4 days (dark-night) for A-5 : (1) performance verification II (stabilization)

	pre-run	Day 1	Day 2	Day 3	Day 4	post-run
Telescope work	MCS install	PFI install				PFI uninstall
Daytime		preparation	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		A5	A5	A5	A5	

Figure 8: Time table of Runs 7 and 8.

Table 4: Expected days for commissioning. Note that Year/Month in column 2 are just roughly set assuming the latest schedule of each subsystems and that scientific operation will start in the S20B semester.

Run	Year/ Month	#days	seq.	daytime is OK	night-sky is needed	dark-sky is needed
1	2017/08	3*	M1–3	(1*)	0	0
	–2019/02		M4	3	0	0
2	2019/02	7 (14**)	P1–P3,P5	1	0	0
			P4	0.5	0	0
			P6	0	1.5	0
			P7	0	2.5	0
			P8	1.5	0	0
			P9	0	1.5	0
			F1 (SM1,2)	0.7	0	0
			F2 (SM1,2)	1.8	0	0
			A1 (SM1,2)	1.5	0	0
			A2 (SM1,2)	0	1.5	0
3	2019/06	4 (7**)	P11	0	4	0
			A1 (SM3,4)	1.5	0	0
			A2 (SM1,2)	1.5	0	0
4	2019/09	6 (8**)	P10	0	2	0
			F1 (SM3,4)	0.4	0	0
			F2 (SM3,4)	0.6	0	0
			A2 (all SMs)	1.0	0.5	0
			A3	0	3.5	0
5	2019/10	6	A3	0	3	0
			A4	0	0	3
6	2019/12	4	A4	0	0	2
			A5	0	0	2
7	2020/04	4	A5	0	0	4
8	2020/07	4	A5	0	0	4
	in total	38 (50**)				

* telescope can be used for other instruments
** day-time and night-time works are counted independently

1.5 Relationship among Individual Sequence

Some sequences can be carried out in parallel, but some should in series. Table 5 shows the relationship among the individual sequences. The rows are commissioning sequences related to each sequence in the columns. "X" means required sequences. For example, prior to the sequence M–3, M–2 (and hence M–1) should be succeeded.

Table 5: The relation of commissioning sequences.

	M1	M2	M3	M4	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	S1	S2	F1	F2	A1	A2	A3	A4	A5
M1																							
M2	X																						
M3	X	X																					
M4	X	X	X																				
P1																							
P2					X																		
P3					X	X																	
P4	X	X	X		X	X	X																
P5	X	X	X		X	X	X																
P6					X	X	X		X														
P7					X	X	X		X	X													
P8					X	X	X		X	X	X												
P9					X	X	X		X	X	X												
P10					X	X	X		X	X	X		X										
S1																							
S2															X								
F1					X	X	X																
F2	X	X	X		X	X	X								X		X						
A1					X	X	X		X	X	X				X		X	X					
A2	X	X	X		X	X	X								X		X	X	X				
A3	X	X	X		X	X	X		X	X	X	X	X	X	X	X				X			
A4	X	X	X		X	X	X		X	X	X	X	X	X	X	X				X	X		
A5	X	X	X		X	X	X		X	X	X	X	X	X	X	X				X	X		

2 Details of Work Flow

2.1 Validation of MCS

M- 1 Off-Telescope (stand-by) characterization of MCS [Daytime]

In this step, the basic functions of MCS are checked before installation to the telescope.

Firstly, we turn on the power of MCS computer and electronic chassis. Then we check the following functions:

- MCS can read CMOS sensor with expected performance.
  - dark level: No detectable dark current at 20–25 [decC] with 1.1 sec. exposure time
  - noise level: $6.4e^{-}$
  - background level: how much??

- shutter: We take several images changing the exposure time to confirm the mechanical shutter works properly.

These values are cited from the CDR slides (`MCS camera system.pdf`).

- MCS can read environmental and mechanical (?) sensors.
  - 7 temperature sensors (where)?
  - flow meter?

Because every command is sent vis MHS, we can confirm communication via MHS in this sequence. That is we also validate that MHS can send commands to read CMOS sensors and environmental sensors, and then receive proper results and status.

Note that once MCS is powered on, it will be connected to the power supply and Subaru network. Then telemetry is monitored during stand-by. Considering this fact, we can skip this sequence from the second and more times for commissioning run.

Success Criteria

All MCS basic functions are verified — power, CMOS sensor, telemetry.
Required long time to analyze the data?: No.
—We can check the functions in real time.

M- 2 MCS installation to the Telescope [Daytime]

In this sequence, MCS is installed to the Cassegrain (Cs) Focus of the Subaru telescope. MCS is attached to MCBox, which is installed to the flange of the Cs focus. This means that the MCS position is determined by how accurate MCBox is attached to the Cs focus. The requirement `REQ-MET-9` demands the accuracy of the MCS position with respect to the optical axis; decenter within 45mm (x/y each), and tilt within 0.14 degree. The Subaru demonstrated the repeatability of mounting MCBox in 2015 (report by Y. Minowa: `NDTN-20150714`[2]), resulting in the following performance:

- Tilt: < 10 arcsec
- Shift(X,Y): < 50um
- Shift(Z): < 0.5mm
- Rot. : 0.0015 degree (shift by 0.24 um at the edge of MCS FoV)

This result implies the MCS will be installed well with the required accuracy, if it is installed in the normal way. Note that we don't measure the repeatability indeed in the commissioning sequence.

Success Criteria

MCS is mounted to Cassegrain focus with the required accuracy ($\leq$ 45mm offset in x/y direction, and $\leq$ 0.14 degree tilt).
Required long time to analyze the data?: No.

[2] MCBox_repeatability_report.pdf

M- 3 Check of Basic Functions of MCS on the Telescope [Daytime]

— MCS is operated on the telescope for the first time. —

After installation to the telescope, basic functions of MCS are checked again, but on-telescope condition in this sequence. During installing operation, the power of MCS will be off, so we should turn on the MCS electric devices again.

Then we check the following functions (the same as M- 1):

- MCS can read CMOS sensor with expected performance.
  - dark level: No detectable dark current at 20–25 [decC] with 1.1 sec. exposure time
  - noise level: $6.4e^{-}$
  - background level: how much??
  - shutter: We take several images changing the exposure time to confirm the mechanical shutter works properly.

  These values are cited from the CDR slides (`MCS camera system.pdf`).

- MCS can read environmental and mechanical (?) sensors.
  - 7 temperature sensors (where)?
  - flow meter?

After the basic functions are confirmed to work, the calibration data (flat, bias and, dark?:TBC) of CMOS sensor shall be obtained. The stability of calibration data can be examined using the data in multiple runs.

By sending command from gen2, we will also confirm communication between MCS and Gen2.

According to the MCS delta-CDR, the flat screen is attached MCS flange for obtaining flat-fielding, and 3–4 LEDs are attached near MCS-M1 module. On the other hand, because the Cassegrain stand-by flange has a space for light source on the top, the calibration data can be obtained during stand-by (TBD).

Success Criteria

All MCS basic functions are verified — power, CMOS sensor, telemetry.
The calibration data (bias, flat, and dark?) of CMOS are acquired.
Required long time to analyze the data?: No.
— We can check the functions in real-time

M- 4 Verify MCS performance [Daytime]

In this sequence, we verify MCS performance to measure the fiber positions on focal plane. We also check validity the PFS coordinate-transfer system. This sequence is to use time efficiently after the PFI arrival, because, according to the current schedule (as of October 2016), MCS will be delivered to the Subaru telescope a half year earlier the PFI.

In this sequence [3], we will:

1. Align MCS on MCBox with respect to the WFC
2. Verify image quality
3. Demonstrate MCS-PFI coordinate transformation, and
4. Study distortion map in detail

[3] Some test are also proposed in MCS CDR document by ASIAA: MCS_I&T.pdf, and PFS MCS Delta CDR.pdf

Regarding the image quality, the same test will be done in seq. P- 4. Hence, if the image quality will be validated well enough in this sequence, we can skip P- 4.

Since PFI will not available, we have two options as an alternative. One is Echidna positioner system of FMOS/PIR, and the other is pinhole array equipped to POpt2. Table 6 summarize the specifications of Echidna on FMOS/PIR and pinhole on POpt2 as well as their usefulness for tests in this sequence.

In the case of FMOS/PIR The field of view of FMOS/PIR ($\sim$ 150mm $\times$ $\sim$ 150mm, corresponding to $\sim$ 30 arcmin in diameter) is much smaller than that of PFS, and their optics and mechanics are different from each other. Besides, only 32 fibers out of 400 can be back-illuminated simultaneously. These facts imply that Echidna on FMOS/PIR is not suitable for the MCS alignment and image quality test. Nonetheless, the procedure of coordinate transformation shall be studied well.

MCS measures fiber positions somewhat converted to MCS frame, and then positions are transferred to them on focal plane. On the other hand, FMOS fiber positioner (Echidna) measures fiber positions on the focal plane. By comparing measured fiber positions by MCS and the coordinate transformation system, with those by Echidna, MCS function of measuring the fiber positions is verified. At present, Echidna can position fibers with the accuracy of $\sim$ 35 um[4]. We set the goal in accuracy of fiber positioning 50 um for pre-study, the same as 1-st pass distortion map (P- 10).

The procedure of the measurement is as follows:

1. Decide which fibers to move and which fibers not to move (like fixed fiducial fibers). Figure 9 shows an example.

2. Built distortion map of PIR from the MCS viewpoint (the form of D_2 for FMOS/PIR). With all fibers back-illuminated, we take the fiber image at home position by MCS. We also have the physical positions of FMOS fibers. Using these positions, we will determine the form of the distortion map.

3. Define F3C for FMOS. In order to distinguish with F3C for PFS, we name the defined coordinate "F3C(PIR)". "F3C(PIR)" is practically the same as the positions measured with the spine camera of Echidna. With fixed fibers back-illuminated, we take fibers image by both MCS and Echidna, and then the positions of fixed fiducial fibers on F3C are measured.

4. Take all fibers image by MCS and calculate their position
   (a) Using image of fixed fibers, determine the transformation from MCS coordinate to F3C(PIR) coordinates, that is, the parameters of D_2 for FMOS/PIR).
   (b) Using images of the rest fibers, calculate the positions on above coordinate frame.

5. Measure fiber positions of FMOS/PIR, and compare with those derived on F3C(PIR)

6. Executing the above procedures for several fiber configurations at a various Elevation (EL) and Rotator angle (ROA), study the stability of the measurements. We may be able to study the effect of local surface error of corrector lens for coordinate transform by changing fiber configurations. Here the error due to temperature and dome seeing is included. We also examine these effect.

Because the corrector lens are different between PIR and WFC, we cannot study a effect of WFC surface figure error itself if we use FMOS. However, similar study will be performed by changing the fiber configurations (TBC).

[4]Originally the fiber allocation was achieved with the accuracy of $\sim$ 10um. Recently the encoder of X position of sky camera was broken, which have added $\sim$ 25 um for fiber positions.

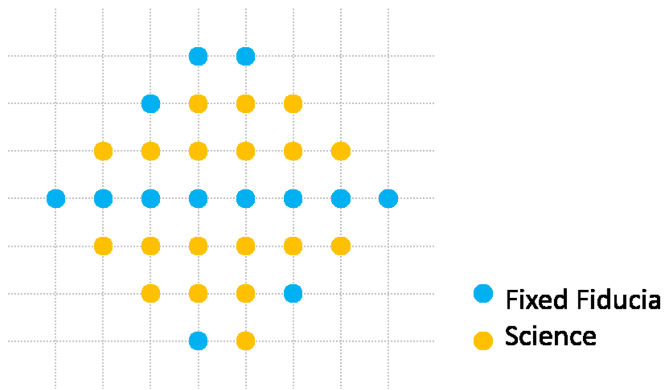

Figure 9: Example of the arrangement of FMOS/Echidna back-lit fibers. 32 fibers can be back-illuminated at a time.

In the case of pinhole array on POpt2 If pinhole array can be attached on the POpt2, we can of course align MCS and test image quality. Also we can study transfer coordinate system in the similar procedure above. WFC has a ring-patterned local surface error with a pitch of 6mm, we can study the effect of the local surface error on WFC distortion by using pinholes with the smaller pitch, or rotating pinholes slightly.

Supposing that we will have designated pinhole mask with holes arranged at fiducial fiber position and hexagonal position of 4 mm (half of the pitch of Cobras), we will study the the coordinate transform in the following procedure.

1. Distortion map is determined with WFC as-built model.
2. Take pin holes array images by MCS. Choose one of the holes in the patrol areas and calculate their position on F3C.
3. Compare the calculated positions with the design.
4. Choosing the another holes, repeat 2.
5. Executing the above procedures at a various Elevation (EL) and Rotator angle (ROA), study the stability of the measurements.

Although the pinhole, which ASIAA has prepared for testing image quality of MCS, has the 8mm pitch (partly 2mm), we can use the ASIAA pinhole by rotating the instrument slightly. The movement accuracy of the instrument rotator of POpt2 is 8 arcsec, enough smaller than angle corresponds to 8 mm at the field edge (at 250 mm radius, $\sim 1.8^\circ$). This pinhole size is $\sim$ 356mm $\times \sim$ 356mm, which covers $\sim$ 75% of FoV of WFC, so that distortion shall studied well.

Back-up plan If MCS would deliver at Subaru just before the arrival of PFI, we will not have enough time to practice the procedure of the coordinate transformation. As back-up plan, we will use the camera which was used to measure dome seeing in 2012.

According to the report (http://sumire.pbworks.com/w/file/70195197/domeseeing3v1.pdf), the camera was equipped to the Caseggrain focus with NexStar4SE telescope. In this configuration, the camera covers 100 mm $\times$ 120 mm of FMOS focal plane, which is large enough to illuminate 32 fibers, because neighboring fibers have 7mm separation. The FWHM of the spot size on the camera will be 2.6 pixel, which is the same as that of the PFS fibers on MCS.

Table 6: Specifications of Echidna on FMOS/PIR and pinhole on POpt2, and their usefulness. Note that we assume that pinhole mask is the same type as ASIAA.

Specifications	Echidna on FMOS/PIR	Pinhole on POpt2	Requiring Test Items
Size at focal plane	∼150 mm × ∼150 mm (at field center)	∼356 mm × ∼356 mm (∼ 75% PFI FoV)	distortion
Optical and mechanics	FMOS specific	WFC + POpt2 itself	alignment, image quality, distortion, MCS-PFI coordinate transformation
Expected focal-plane spatial sampling rate	∼ 35 um	∼ 10um (at field edge)	distortion
RMS spot radius on MCS detector(*)	∼10 um at field center, ∼20um at field edge	∼ 9um	image quality

* : MCS CDR document ("PFS MCS Delta CDR.pdf" by S.-Y. Wang.)

Success Criteria

MCS measures the fiber position consistent with that by Echidna at various telescope positions. The accuracy is less than 50 um.
Required long time to analyze the data?: Yes.
—It should take time to compare the positions derived with MCS with that by Echidna, and mature the coordinate transfer algorithm. Once we obtained the data, we can use the same data to mature the algorithm.

2.2 Validation of PFI

Because MCS will be delivered to the Subaru telescope one year before PFI delivery, we can install MCS to the Cassecrain focus during the PFI validation.

P- 1 Check of basic functions of PFI / OPot2 on off-Telescope (stand-by) condition [Day-time]

In this sequence, we check basic functions of PFI and Popt2 before installation to the telescope. Firstly we check basic functions of PFI prior to installation to Popt2. Namely,

- fiducial fiber illuminator: turn on/off
- calibration lamp: turn on/off (it can be turned on /off by local computer)
- AG cameras: read image (bias/dark) with expected noise level. We also check that the images is sent to VLAN and Gen2.
- fiducial cameras can read image (bias/dark) with expected noise level
- Center camera can read image (bias/dark) with expected noise level
- sensors can be read
- network connection
- cooling system
- telemetry

The above functions of PFI, except for the turning on/off calibration lamp, are controlled from Gen2 through MHS

After the basic functions are checked, we install PFI to POpt2. When PFI is installed to POpt2, `REQ-SYS-648` claims PFI should be set within the accuracy of $\pm$20 um. This requirement is flowed down to `L3-PFI-042`, claiming the requirement for installation alignment accuracy with respect to the rotator coordinate:

- within 200um in radial translation
- within 100um accuracy in focus
- within 15 arcsec tilt (80 um @ outer ring of positioner frame w/ diameter of 1108 mm)

These requirements are for absolute positions. In addition to them, the repeatability within $\pm$ 20 um is required, and we lay weight on the repeatability.

The repeatability of the installation is determined by the tolerance of POpt2 gear support and PFI positioner frame. According to the HSC experience, the repeatability of installation of the camera dewar is quite well (less than 30 um with 0.21 mm gap between the dewar and the gear support). If we take the same procedure[5], we will be able to achieve the same repeatability.

After the installation of PFI to Popt2, then the following functions are checked.

- rotator: can mechanically rotate from -270 [deg] to + 270 [deg]

At this point, most of functions controlled by PFICS, MPS, so that these modules and their communication with Gen2 via MHS are validated. Name them. how about Cal. lamp?

Refer the requirement for pre-installation check-out to `L3-PFI-037`.

Success Criteria

All PFI basic functions are available and characterized.
PFI is installed to POpt2 within the required accuracy.
Required long time to analyze the data?: No.
—We can check the functions in real time.

P- 2 POpt 2 installation to Telescope [Daytime]

In this sequence, POpt2 is installed to the Prime Focus of the telescope.

According to `TM-N5143 (section 3.1.6)`, the accuracy in installing POpt2 to the top ring (and hence optical axis of the primary mirror) are determined by repeatability in engaging of curvic coupling. The repeatability is within 10 um in X,Y,Z direction, and 3.4 arcsec tilt. This is small enough, compared to the required repeatability in setting PFI to POpt2 (see P- 1).

We also install MCS to the Cassegrain Focus, basically one (or more) day before installation of POpt2.

Success Criteria

POpt2 is installed to the telescope.
Required long time to analyze the data?: No.

[5] some explanation is described here: NDTN-20150925-NTakato-Inner_diameter_of_PFI_interface_of_POpt2.pdf

P- 3 Check of basic function of PFI on the Telescope [Daytime]

— PFI is operated on the telescope for the first time. —

In this sequence, we check the functions of PFI again but on-telescope condition. Basically we repeat the same items as those in P- 1. Namely.

- Calibration lamp can be turned on/off.
- AG cameras: read image (bias/dark) with expected noise level. We also check that the images is sent to VLAN and Gen2.
- Fiducial fiber cameras can read image (bias/dark) with expected noise level.
- Center camera can read image (bias/dark) with expected noise level.
- Rotator can rotate from -270 [deg] to + 270 [deg].
- All telemetry sensors can sent proper status.
- Cooling system works.
- Network connection.

The following functions of PFI are validated using MCS by taking the fiber image.

- Fiducial fiber illuminator can be turned on/off [6]
- MPS can move fiber positioners (Cobras) move and read their status. At this point, because Cobras parameters are not calibrated (A- 1), we should move them slightly to avoid collision.

When the basic function of AG cameras, fixed fiducial cameras, center camera and Calibration lamp are verified, the calibration data (flat and bias) shall be obtained. (Acquiring the calibration data probably doesn't needed so frequently — at the beginning of each run is enough?)

Success Criteria

PFI basic functions above are checked on Telescope.
Required long time to analyze the data?: No.
— We can check the functions in real-time.

P- 4 Validation of MCS performance [Daytime]

— MCS reads fiducial/science fiber image for the first time. —

After the PFI and MCS are installed to the Prime Focus and the Cassegrain Focus, respectively, the image quality of the MCS is validated, because at this point MCS can take the image of fibers in the entire field of view for the first time. We check the intensity of the spots of fiducial fibers, and confirm the S/N meets the requirement (> several hundreds, according to CDR). We validate the MCS exposure and centroid measurement sequence; taking image and calculating the positions of fibers with expected time (< 5 seconds, according to CDR). Here, we need to somehow illuminate the science fibers if SpS and Cable B is not ready[7].

When we confirm MCS can take fibers image, we validate the MCS performance. MCS is designed to have uniform PSF with FWHM of 8.5um, or 2.6 pixel, in the entire field of view of PFI. In this step, we take the image of back-illuminated fiducial and science fibers, and check the FWHM of the PSFs. We also

[6] If SpS and Cable B are ready, we can also check back-illumination of science fibers.

[7] According to the latest schedule, Cable B and SM1,2 will be delivered before the PFI arrival. We then shall back-illuminate science fibers at the other end of Cable B (on IR4 floor).

check that the accuracy of the position of the spots is less than 5um (0.08 pixel) rms, by taking several image of the fibers and calculating the positions at a given Elevation. Taking fibers image at various Elevations and rotator angles, we also test the stability of the image quality and derived centroids.

Success Criteria

MCS can take fiber image and measure fiber positions.
The spot size is $\sim$ 8.5um (2.6 pixel) in the entire field of view.
Position of all fibers is estimated within the accuracy of 5um.
Required long time to analyze the data?: No.
— We can analyze FWHM and and centroid accuracy on relatively short-timescale.

P- 5 Measurement of PFI x/y offset [Daytime]

In this step, we measure offset of PFI in x/y direction by deriving its rotator center on MCS. By measuring in several runs, the repeatability of installing PFI to Popt2 (and then PFI positions w.r.t. rotator axis) are verified, taking account into the expected repeatability of decenter of MCS ($<$ 50um, see M- 2) and installing Popt2 to the top ring ($\leq$ 10um, see P- 2)

The measurement is carried out in the following procedure:

1. Firstly, we take several back-illuminated fiducial fibers images at a given rotator angle at aiming Elevation and Azimuth in order to measure the stability of the centroid.
2. Then we take fiducial fibers images at various instrument rotator angles. The series of spots of individual fibers is fit to concentric circles centered at the rotator axis. In other words, the position of rotator axis on the MCS (x_{rot}, y_{rot}) can be measured from the circles.
3. (x_{rot}, y_{rot}) with respect to the center of MCS is compared with the prediction or the value at the last PFI installation. If the new (x_{rot}, y_{rot}) is quite different from the previous value, we might have to adjust PFI to POpt2.
4. We also check dependence of (x_{rot}, y_{rot}) on telescope Elevation.

The first (x_{rot}, y_{rot}) is possibly different from that measured later, because we will align the WFC w.r.t the primary mirror in P- 7. In the current commissioning plan, the repeatability in z direction is not be measured.

Success Criteria

PFI x/y offset is measured and confirmed offset from the previous operation is smaller than 20 um.
Required long time to analyze the data?: No.
— We should measure x/y offset in short time scale for operation.

P- 6 Validation of Auto Guide Cameras [Nighttime]

— AGCs acquire star image for the first time, and the telescope is guided using AGCs for the first time. —

Six Auto Guide cameras on the edge of FoV are used for many purposes:

1. Acquisition and Guidance of the field
2. Auto Guiding
3. Focusing

4. Telescope Pointing analysis

5. Alignment of WFC+PFI with the prime mirror

To enable these functions, in this phase we validate basic functions of AG cameras — (1) focusing, (2) pixel scale and orientation of each sensor on the sky, and (3) auto guiding, that is, measuring the centroid and sending position error to the telescope.

Focusing Firstly, we seek on-focus position. We slew telescope to a bright stars and let them into the AG camera FoV. The we take AG camera image and seek on-focus position. AG cameras has step of 300um, with which they can take in-focus/ out-focus image simultaneously. By measuring the size of these spots, seek focus position. The focusing procedure is proposed by Jim Gunn (PFI:336), to derive α parameter. The parameter shall be calculated using simulated data (TBC), and in the commissioning sequence, we shall optimize the parameter α. If 4 out of 6 AGC can take pair of stars (in/out), the error of estimation of focus seems $\sim$10um (Jim's document: PFI:336)

Pixel scale and orientation on the sky Secondary, we measure pixel scale and orientation of the AGCs. We slew the telescope to the star clusters, and measure the pixel scale by the astrometry of stars on sensors. We then check the orientation of the x/y direction, putting slight offset on the telescope in R.A and Dec. direction individually. (And we can also check pixel scale by comparing two shifted images.) The derived pixel scale and orientations are implemented to the software module for acquisition and guidance.

Assuming that it takes 5 min for one exposure from slewing telescope to acquiring images, it takes 5 x 3 (position) x 6 (sets) = 90 min in total. Here, 3 positions are needed to measure the x/y direction: one is the origin and the others are with offset of either R.A or Dec.. To measure the direction easily, we will move InR so a given AGC as to have PA of 0 degree. therefore 6 sets are needed. If there are any fields for the two opposite AG cameras to have enough number of stars, we can reduce to 3 sets. Including the time to execute astrometry and calibration, 120min=2hours are needed to this test.

Auto guiding Finally, we validate the AGC functions as the guiding and confirm that the tracking error meets the requirement (How much?). For auto guiding, one or two AG camera are used to measure the position error of the telescope, and another camera is used to measure focusing.

We slew telescope to a given field, and execute Acquisition and Guidance sequence — measure the position of the star on Ag cameras, calculate position error (dRA, dDec) and d(InR), send telescope these errors, and correct the position. Then we start auto guiding — measure the position of the star on Ag cameras, calculate position error (dRA, dDec) [and d(InR)], send telescope these errors. At the same time, some AG camera measures focus position. Focus should be corrected if it gets out-focus, but threshold and frequency is optimized during the commissioning. We measure the guiding error.

We check these functions at several telescope positions. Assuming that it takes 15 min including optimizing the parameters for calculation of the pointing errors, 2 hours are required for this test. Note that we can also validate auto guiding in later phases and as mentioned above, parameters for correcting focus will be optimized during the commissioning.

Because in this sequence we have star image on AGCs and control the telescope accordingly, we can validate communication between Gen2/MLP1 and MHS/AGCC.

Success Criteria

Acquisition and Guidance, focusing, and Auto Guiding can be executed using AGCs.
Pixel scale and orientation of the x/y pixel direction on the sly are measured.
Required long time to analyze the data?: No.
— We shall analyze the data in real-time.

P- 7 Check focal plane shift/tilt [Night-time]

To have good image quality on the focal plane, WFC (and hence the instrument) need to be aligned in x/y/z and tilt with respect to the telescope primary mirror. The misalignment of WFC with the primary mirror in x/y causes coma aberration across the field. That in z defocuses images. A tilt error induces coma aberration and focal plane tilt. So it is important to minimize these errors to keep good image quality during observation. This alignment is carried out by Hexapod on POpt2 that can adjust the x/y/z and tilt of the assembly of WFC and PFI (see section B).

We slew the telescope to bright stars again, but defocused. Using defocused (ΔD5=0.5mm) image of AGCs, measure shift/tilt of WFC with respect to M1 and correct them. The goal of correction is that shift is less than 0.5mm, and that tilt is less than 1 arcmin, with which the spot size (RMS) is less than 15 um. [See Yoko Tanaka's report detailed procedure (WFC_position.pdf: Japanese)]

To measure tilt and shift of WFC, 6 defocused image are needed on every AG camera. As we use bright stars, we acquire such image by rotating the instrument. Assuming it takes about 3min including positioning, one iteration needs about 20 min. According to Yoko Tanaka's study, four iterations on average are needed to alignment. Therefore, it takes 80min for one position.

The parameters of Hexapod for alignment is registered as a function or table with respect to the elevation. Therefore, we measure the Hexapd parameters at several elevations. Given we measure them 5 positions (e.g., EL=30, 40, 50, 60, 75) and repeat three times at each elevation, 800 minutes, or 20 hours are needed for the correction.

Success Criteria

The focus is measured with the accuracy of ∼10 um
Misalignment of WFC and M1 is corrected (shift: 0.5mm and tilt 1 arcmin)
Hexapod position at several elevation are measured and registered as correction parameters.
Required long time to analyze the data?: No.
— We shall analyze the data in real-time to align WFC.

P- 8 Refine of the PFI – MCS relation [Daytime]

After the alignment of WFC with the primary mirror is confirmed at a given telescope position, we confirm and refine PFI–MCS relation using fiducial fibers in this sequence (see also section 4.3).

Prior to the integration, the Focal Plane from the viewpoint of MCS (PFI–MCS relation) has been calculated with ZEMAX, using the WFC as-built model. Using the ZEMAX calculation, we derive the form of relation in advance. (the function form: TBD)

In this sequence, we refine the position of the fixed fiducial fibers on F3C. We take the images of back-lit fixed fiducial fibers with MCS, and transform the centroid on MCSC to F3C. The physical positions of fixed fiducial fibers on focal plane, on the other hand, are measured during I&T at ASIAA before shipment. We compare those two positions and check the consistency.

If the positions of fixed fiducial fibers are consistent between F3C and physical position, the position on F3C are registered. The positions with terrible discrepancy shall be excluded from F3C. At this point, the transforming function from the MCS coordinate to the F3C coordinate is defined.

Once MCS-F3C transformation is confirmed, MPS can send command for moving the Cobras to dot position. We verify this command, by taking the images with the fibers on-/off- dots after the Cobra calibration A- 1.

Success Criteria

PFI–MCS relation is calibrated and MCSC–F3C transformation is confirmed.

Required long time to analyze the data?: No.
— We shall analyze the data in real-time.

P- 9 Telescope Pointing Analysis [Night-time]

— PFS send Az/El offset measured using AGC to the telescope for the first time. —

Although there are originally 1-, 5-, 32-points Telescope Pointing Analysis (TPA) functions on the Subaru telescope, PFS can execute only 1- TPA. Here, the number shows the numbers of stars to be observed at a given field. PFS uses the same mount correction coefficients as HSC, and they are updated when HSC executed TPA. (Operator can decide whether to update for PFS.)

By executing 1- TPA, offset angles for Az/EL are estimated. These offset are used the additional parameters for mount correction coefficients for PFS.

For 1- TPA, the telescope control system drives the sequence as below:

1. Slew the telescope to set a certain star on the one of the AG camera.
2. Take its image by AG camera.
3. Measure the Az/El offset, by measuring offset of the star from where it should be.
4. repeat [1-3] for different stars. We will visit every 30 degree in the azimuth direction and every 15 degree in elevation from 30 − 75 degree. In total , Az/El offsets are measured at $12 \times 4 = 48$ field of view.
5. Average offset measured at sequence [3]. Update Az/El offset value of mount correction efficients, as the additional parameter.

Assuming it will tale 900sec to obtain the data in a given field, 12 hours (900×48 seconds) are required.

How much does the difference of the scale b/w FoV center and edge effect??

Success Criteria

Obtain Az/El offset value of mount correction efficients.
Required long time to analyze the data?: No.
— We shall analyze the data in real-time.

P- 10 First Pass Distortion Map [Night-time]

In the PFS operation we need to convert sky coordinate (Sky Catalogue) to another convenient to position fibers (F3C). For this coordinate transformation we have a "0^{th}-pass" distortion map from the optical model with the as-built WFC & model of atmospheric refraction (including the differential effect), prior to the commissioning.

In this step, we calibrate the distortion map purely by the AGCs with no fibers involved (First pass distortion map). The sequence is as follows:

1. Make distortion map by images from the 6 AG cameras;
   Take deep images ($\sim 10-30$ sec exposure) of bright stars with good astrometry and derive distortion map. Derive distortion of AG camera by measuring the positions of stars on camera and comparing

with catalogue. Here, we need special method to analyze the A&G images. We update the distortion map of the entire FoV by interpolating with the new A&G distortion map. The total field of view of the A&G camera is (5.5 arcmin^2 $\times$ 6)/2 = 16.5 arcmin^2. The division by 2 is because of the step of the A&G cameras, half region of which has the same focal plane. Note that the registration of images $\sim$ 1.4 deg apart from the field center, should be possible thanks to the off-telescope calibration of A&G camera positions on F3C. This should be useful to give constraints to the models.

2. We make the map at various elevation and azimuth and refine it as a function of El, Az, and ROA

3. Measure the sky scale on F3C;
   We calibrate the position of the A&G cameras relative to their fixed fiducial fibers. Firstly, we slew the telescope to have a star in the center of an A&G camera. Then we move the telescope to have the AG fixed fiducial fiber pointed to the star. We execute the raster scan around the fixed fiducial fiber and calibrate the distance between A&G camera and the fiber. Because one A&G camera has two fiducial fibers on both sides in the azimuth direction, the raster scan should be carried out using both fibers. Therefore, we shall do $12 \times n$ raster scan in total.

Using the calibrated data, the transformation from Sky Catalogue ti F3C is refined. The new distortion map is called “1$^{\text{st}}$-pass” distortion map.

Success Criteria

The “1$^{\text{st}}$-pass” distortion map is obtained with the accuracy of 50um
Required long time to analyze the data?: Yes.
— It shall takes time (one month?) to astrometry of A&G Camera, derive distortion map, measure sky scale on F3C.

2.3 Validation of SpS

S- 1 Validation of the Basic function of SCR and SpS [Daytime]

SpS modules (SM1, 2, 3,and 4) are operated on the IR4 floor in the designated room called SCR, where the temperature is controlled from 3 degC to 5 degC. The Camera Assemblies are cooled down in the cryostat. On the below floor, the compressors will be used during the operations. Under such a condition, the following functions of SpS assemblies should be verified: We also check the functions of SCR in this sequence.

- The temperature in SCR can be controlled stably in the range from 3 degC to 5 degC.
- SpS can read cameras within expected noise – dark, bias.
- SpS can switch MR/LR mode (red arm).
- SpS can open/close shutters.
- SpS can move all other mechanical part. Name
- SpS can back-illuminate the fibers (by looking from GANG connectors of cable A?)
- SpS can read sensors
- The spots are on-focus in the detector.
- We check the image quality and stability at a certain temperature and vibration [cf. Validation Roadmap by LAM: tests stability (2.5.8)]. Repeat temperature cycle and check repeatability. The image quality is defined in the requirements `REQ-SpS-47 (Test)`, which declares that the Ensquared

Energy in more than 90% detector area should be (1) 50% within 3 x 3 pixels, and (2) 90% within 5 x 5 pixels.

- We demonstrate power failure mode
- The exposure sequence works.

Success Criteria

All basic function of SCR and SpS is verified.

S- 2 Characterization of SpS [Daytime]

Using arc lamps and continuum lamps, we characterize the SMs. Here we will use Dummy Cable B module [see DummyCableB-MainDocument.pptx (PFS-SpS:01680) for details] which is used for the integration by LAM[8].

PSF and spectral distribution measurement With arc-lamp image and continuum lamp image, we measure PSF and spectral distribution of various fibers on the detectors, respectively. These information of the fiber image is feedbacked to DRP development. Configuration of measured fibers is TBD[9].

wavelength coverage, spectral resolution, and throughput Using the arc-lamp image, we estimate wavelength coverage and spectral resolution (including wavelength dependence), and compare with specifications, by measuring the FWHMs of the spots. Note that the wavelength coverage and the spectral resolution will be partly measured by LAM[10].

The requirement for the wavelength coverage (`REQ-SpS-41 (Analysis)`) is 380–650 nm (blue), 630–970 nm (red), and 940–1260 nm (nir).

The requirement for the spectral resolution, on the other hand, (`REQ-SpS-42 (Analysis)`) is >2300 @ 520 nm (blue), > 2800 @ 810 nm (red, LR), > 5000 @ 810 nm (red, MR), and > 4100 @ 1110 um (nir).

Using a black body lamp, we will measure throughput of the SpS itself and compare with specifications, which is estimated by combining the performance of each element (LAM). If measured throughput is inconsistent with analysed one, consider possible causes (vignetting, background etc.) The stability of the black body lamp (TBD) is needed.

The requirement for the throughput of SpS (`REQ-SpS-48 (Analysis)`) is in Table **??**:

Success Criteria

SpS is characterized. These characters is consistent with expected by specification.

[8] To achieve characterization well, we need lamps with large wavelength coverage. We also need black body lamp, but should input the light from slit or GANG connector.

[9] LAM will use 4 fibers with the option of extra 7 fibers sparsely arranged in the detectors, but is it acceptable for DRP development? It seems some room for fiber configurations. 1–2 fibers per block, for instance, are too much? At least, the PSFs and spectral distribution both centre and edge seems required. Besides, how many spots is needed in wavelength direction?

[10] Validation Roadmap; λ coverage — 2.5.3: checked by centring the image. R — 2.5.4: extrapolated by FWHM of the spot for testing image quality (maybe only center?).

Table 7

wavelength	Throughput [%] requirement	goal
380	14	19
440	38	49
550	39	50
650	33	50
790	42	56
980	36	47
1260	35	45

2.4 Validation of FoCCos

F- 1 Connection of Cables [Daytime]

In this step, we connect Cable C–B (PFI) and Cable B–A (SpS)[11]. We check the connection of of the Cables with the fiber monitoring system. Alternatively, we can also confirm the connection of the Cables by taking the calibration lamp image.

Success Criteria

Cable B is connected to PFI (Cable C) and SpS (Cable A) correctly.

F- 2 Confirmation of Fibre-Slit Relationship [Daytime]

In this step, we check fibre-slit relationship. It is defined in e.g.
http://sumire.pbworks.com/w/file/76743299/FiberMapping.pdf .

Firstly, we move all fibers to be obscured by the dots. Then move each fiber out of the dot, take back-illuminated fiber image using MCS and identify it. We identify position on the spectrograph, on the other hand, by taking a spectra of continuum lamp (or dome light).

Note that we will move cobra to dots before calibration, but it should be safe considering that the position will have been calibrated during I&T at ASIAA[12].

If the relationship is different than the expected one, update the relationship. It seems simpler to modify the position on the camera, fixing the positioner ID.

Success Criteria

Fibre position on Cobra and PFI is confirmed

2.5 Commissioning of All Systems

A- 1 Measurement of Cobra Center Positions and Other Parameters [Daytime]

In this step, we measure the center position and other parameters of the fiber positioner "Cobras". In order for MPS to send commands for moving Cobras, MPS should should obtain firstly the following parameters (Figure 10):

[11] The connection of Cable B–A may be not off so often once it has connected.

[12] If the accuracy of calibration will be poor and is risky to move positioners before calibration, we disconnect the Cable B and A, and check identification by illuminating each holes.

- $\boldsymbol{X_{c,k}} = (x_{c,k}, y_{c,k})$: center position of the positioner
- $a_{1,k}$: arm lengths of θ stage
- $a_{2,k}$: arm lengths of ϕ stage
- $\boldsymbol{\theta_{\mathrm{CW},k}}$: CW limit of θ stage (angle or position)
- $\boldsymbol{\phi_{\mathrm{CW},k}}$: CW limit of ϕ stage (angle or position)
- $\boldsymbol{\theta_{\mathrm{CCW},k}}$: CCW limit of θ stage (angle or position), and
- $\boldsymbol{\phi_{\mathrm{CCW},k}}$: CCW limit of ϕ stage (angle or position).

Note that these parameters are calculated in F3C. We shall derive these parameters in this phase using back-illuminated fibers.

Prior to the measurement, we should confirm that the science fibers can be back-illuminated, that is, the Back Illumination Assembly in the SpS subsystem does work (see P- 3). At this point, we regulate the brightness of back-illumination. The brightness of back-illuminated fibers are set based on that of the science fibers illuminated in the strobe mode, whose brightness is fixed (1 [W m^{-2} sr^{-1}] $\pm$ 20%). Firstly, we shall regulate the brightness the brightness of the fiducial fibers comparing with that of science fibers illuminated in the strobe mode. Secondary, we shall adjust the brightness of science fibers back-lit in the normal mode to that of fiducial fibers.

After tuning the brightness of the light sources, we shall back-illuminate the science fibers in the strobe mode, with which the fibers blink. We shall take blinking fibers image using MCS with "Cobra" rotating. Then we shall measure the centroid of the positioner, arm lengths, and minimum and maximum positions of each stage, by fitting the spots with a circle on F3C. Here, we move θ and ϕ stage individually to determine these parameters. The detailed procedure is presented in `SSN-00021-001+-MPSconfiguration.pptx` (by Atsushi Shimono). Strobe mode is not used. How high is frequency of the pulse in strobe mode? Also, Tuning can be done at P-3.

We also check dependency of the offset of fiducial fibre positions at various RoA and El, although the offset is negligible given that PFI should be solid. If the displacement of the fiducial fibers is quite large and randomly, we should improve MCS–PFI relation, which is determined in the P- 8 process.

Derived parameters are sent to MPS, which can move cobras at this point. Then, we also validate the following items:

- If the SpS and Cable B are installed, the science fibers are moved to the home position several times to test good repeatability (∼1um)
- Dots can be obscure the Fibers. We move the fibers to the dot positions and turn on the calibration lamp. Take fibers image by MCS and compare with that of home position, where the fibers are not obscured. If dots work, the spots in MCS is fainter than those with the fibers at home position.

NOTE: This sequence will be carried out only when ALL science fibers can be back illuminated to avoid collisions. Although SM3,4 will be delivered one year later than SM1,2, we shall back-illuminate all fibers and then save Cobra positions for SM3,4.

Success Criteria

The brightness of back-lit fibers are regulated.
Parameters of each Cobra $(x_{c,k}, y_{c,k}, a_{1,k}, a_{2,k}, \boldsymbol{\theta_{0,k}}, \boldsymbol{\theta_{m,k}}, \boldsymbol{\phi_{0,k}}, \boldsymbol{\phi_{m,k}})$ are measured and stored to MPS.
Required long time to analyze the data?: No.
— We shall analyze the data in real-time. In addition, cobra parameters will be stored in short time scale.

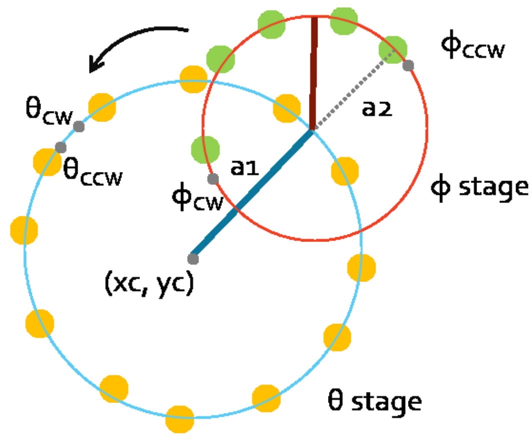

Figure 10: Schematic picture of Cobra parameters. Orange and green spots imply the positions of blinking fiber in F3C. Light-blue and red circles indicate fitted circles for fiber spots.

A- 2 Characterization of PSF and Spectral Distribution on the detectors [Daytime/Nighttime]

— The light is delivered from the primary mirror to the detectors for the first time. —

In this step, we measure PSFs and the spectral distribution on the detectors. As twist of fiber changes, PSF depends on telescope positions as well as Cobra position in its patrol area. This step is similar to step S- 2, but the data includes all optics and systems; namely, Primary Mirror — WFC, — Field Element — Cable C — Cable B — Cable A — SpS, and all connectors between them.

PSF/spectral distribution image will be sent to 2D DRP team of Princeton University, who will characterize them in detail. We will check basic properties of PSFs such as FWHM etc., though.

This sequence consist of three step: (1) principal characterization, (2) measurement of sky spectra, and (3) characterization according to Cobra movement. The arc/flat lamp on PFI is used to measure PSFs/spectral distribution of all fibers. We therefore also check the uniformity of the calibration lamps, and validate the calibration sequence.

Principal Characterization As soon as PFS can deliver light from the primary mirror to the Spectrograph detector, we will take arc and flat. As of the writing (June 2016), it can be done during PFI check on Telescope (P- 3), because PFI, Cable B and two SMs will be delivered. In order to look into the PSF, we shall dithered flat as well. Dark and bias data is needed for calibration.

Once Cobra calibration is carried out, sparse arc and flat shall be taken in order to look into the PSF wing. How sparse is TBD, but we can estimate AIT data at LAM. Current plan[13] by Robert Lupton from Princeton University (2D-DRP team) is every other fibers and every 10th fibers with shorter and longer integrations.

Measurement of Sky Spectra We will take arc and continuum image with changing telescope elevation and/or RoA. For example,

- RoA $= -270, -180, -90, -60, 0, +60, +90, +180, +270$ (9 positions)
- Elevation $= 30, 45, 60, 75$ (4 positions)

If we take 3 types fiber configuration (e.g. full, a little sparse, very sparse), there are $3 \times 4 \times 9 = 108$ configurations in total. Assuming that it takes 5 minutes to configure, and acquire a couple of images, it will take 9 hours for a series of either arc or continuum images. As time will be limited, we will

[13] In his draft, he requested to observe semi-crowded fields before we can target objects for demonstration and PR. May be it can be done during later phase of P- 10, if it is acceptable accurate fiber positioning is crucial.

firstly characterize PSFs in operation RoAs at every elevation angles, and then study other RoAs. If we take images at 9 RoA positions at El=60 degree, and 3 RoA operational positions at other elevations (18 telescope positions in total), it will take 4.5 hours. In the current plan, required time is estimated assuming measurement at 18 positions. Ideally, as sky condition changes during a night, we shall revisit to a given elevation and RoA every hour or so.

By comparing the properties of PSF such as FWHM, we examine dependency and repeatability of the spots on telescope pointing. In the PFS operation RoA is limited from −60 deg to +60 deg, considering that impact of twisted fibers on FRD. During the commissioning, however, we shall check the PSFs in wider range of RoA. If the impact is enough low at wider RoA, we can have more flexibility of operation (e.g. constraint due to dots.).

Characterization according to Cobra Movement In this sequence, we also examine PSF variance with respect to the Cobra rotation angles (θ, ϕ). Here, we use calibration lamps with the telescope pointing at zenith. If we change Cobra positions by 60 degrees, namely

- $\theta = 0, +60, +120, +180, +240, +300, +360$ (0, +360 mean limit angles)
- $\phi = 0, +60, +120, +180$ (0, +180 mean limit angles)

We will take $3 \times 7 \times 4 = 84$ sets of data, for 3 fiber configurations. We will take $3 \times 7 \times 4 = 84$ sets of data, for 3 fiber configurations. It will take 7 hours to acquire a series of arc data. We shall take images while Cobras are moving.

During the commissioning phase, SMs 1 and 2 will be delivered ahead of the rest SMs. Then we can repeat the same test for the first two SMs. Alternatively, if we can characterize PSF well for the first SMs, we can limit the PSF test for the last SMs, in order to minimize the telescope time.

In either case, the test using sky shall be limited, for example

- RoA $= -60, 0, +60$ (3 positions)
- Elevation $= 30, 60$ (2 positions)

In this case, it will take 0.5 hours for either arc or continuum data.

Measure wavelength resolution, wavelength coverage. Sequence A- 2 can be skipped at least wavelength resolution and coverage for SM3,4, which will be ready in August 2018.

Success Criteria

The dependency of PSF and spectral distribution on Telescope elevation and RoA is measured.
Required long time to analyze the data?: No.
— Detailed PSF characterization is mainly carried out by 2D-DRP team, and we will proceed to the next sequence in parallel with analysis.

A- 3 Second-Pass Distortion Map [Night-time]

At this step, the science fibers should be pointed to the targets with the accuracy of ~ 50 um (at least less than 100 um).

The goal of the accuracy of pointing of the fibers is ~ 10 um, which is achieved by raster scan observation in this step.

We slew the telescope to the field where enough stars is catalogued with good astrometry (see section 3). We put these bright stars on the science fibers and do telescope raster scan observation by $3'' \times 3''$ grid, approximately three time as large as the fiber core diameters. It is suggested that raster with hexagonal pattern provide denser scan than grid.

Calibrations in the previous sequences shall include the following errors:

- Telescope elevation, and azimuth
- Temperature
- Focus
- ROA
- Error in the relative position of A&G cameras to fiber positioner.
- Error in Cobras' position measured prior to integration at Subaru
- Error in Catalogue
- ADC
- etc······ (TBD)

We also check the dependency of the map on wavelength, and check if ADC works correctly, by comparing the observed positions with predicted ones by ADC.

When the second distortion map is made, update ETS using this map.

Success Criteria

Second distortion map is obtained with error less than 10um.
Required long time to analyze the data?: Yes.
— It takes time (∼ one month) to improve distortion map, by analyzing raster scan data in various condition. Also it needed more than one run to check dependency of temperature and so on.

When this step is completed, the fibers shall point to the target within the accuracy of 10 um. Then, we verify the instrument performance in the following steps.

A- 4 Performance Verification I [Night-time]

— We operate full observation sequence for 900-sec exposure for the first time. —
— PFS acquire faint galaxies/stars spectra for the first time. —

The goal of this commissioning stage is to verify the performance of the integrated PFS system. Specifically, after we confirm that the observational sequence in order to carry out scientific observations can be made, we measure the total throughput from end to end, i.e., from the primary mirror of the telescope to the detectors, with actual celestial objects.

- Verification of the observation sequence

  The following points, which correspond to the sequence itself that is supposed to be carried out in normal science observations, will be verified:

  1. Acquisition of the target field
  2. Confirmation of the guiding
  3. The cobra configuration for target objects
  4. Start exposure
  5. Acquisition of the next target, if any

  At this sequence, we test that all commands can be sent correctly. We have requirements for overheads, assuming typical exposure time of 900 seconds. According to `REQ-SYS-520 (Test)`, the taken time from field acquisition to starting auto guiding is within 105 seconds, which this shall be confirmed in P- 6. By selecting a field where all science fibers should be allocated objects, we test whether 95 % of 2394 fibers (2275 fibers) moves to the their targets within 105 seconds `REQ-SYS-517 (Test)`, with accuracy of < 10um. We shall take 900-sec exposure, during which the tracking error should be ~ 0.2 arcsec rms by auto guiding (0.2 arcsec rms for 10 minites and 0.6 arcsec rms for 30 minites: `REQ-SYS-888 (Test)`). (It seems the first time to track a field for longer period, > 10 minutes, because we execute short exposures in the previous sequences.) After exposure, it should take less than 35 seconds to readout detectors, archive the fits (including MCS data for finally configured fiber image) data and telemetry data to STARS, Subaru archiving system (`REQ-SYS-519`).

Success Criteria

Confirm that the normal observation sequence can be carried out.

- 95 % of science fibers can be allocated to their objects within 105 seconds, and allocation error should be less than 10 um.
- Tracking error for 10 minutes and 30 minutes is 0.2 arcsec rms and 0.6 arcsec rms.
- Reading out the detectors and archiving data are completed for less than 35 seconds.

- Measurement of the total throughput

The throughput is estimated using measured transmissions / reflection curve for each optical components (e.g. the primary mirror, fibers, optics for Spectrographs). The expected PFS performance is shown on the web.

http://pfs.ipmu.jp/research/performance.html

In this test, we measure the throughput of the entire system and compare with the prediction.

The process of the total throughput measure will be carried out as the following way:

1. Observe stars with known spectral types
   This process requires a substantial number of stars whose spectral types and absolute flux are known. The spectra should have as less spectral feature in the observed wavelength range as possible, therefore F-type dwarf stars will be a suitable candidate for this measurement. The number of stars in the observations should be ideally equal to the number of fibers per one FoV. Star clusters will be a good candidates.
2. Comparison of the observed counts to the given flux density as a function of wavelength
   We will compare the obtained spectra to the given spectra of the observed stars. From the given spectra, the expected counts as a function of wavelength can be calculated by assuming atmospheric transmission. By comparing the obtained counts and expected counts, the total throughput can be estimated.
3. Repeat this measurement and comparison in various conditions
   The total throughput measurement should be carried out in different conditions (e.g., weather including different seeing, cobra configuration, telescope EL, and ROA, etc.). The average value will be the representative measured value of the total throughput.
4. Comparison of the obtained throughput to the expected one
   If the measured value is significantly different from the expected total throughput, we might need to verify the input source. In FMOS engineering observations, they checked the total throughput measurement with celestial objects by using a black body furnace. In this case, the optimization of the set up of the blackbody furnace, such as position, incident angle, and the calibration of absolute flux, would need to be considered.

The time duration of this commissioning stage will be about 1 engineering run, i.e., about 2–3 engineering nights, taking into consideration of a weather factor.

Success Criteria

Confirm that the total throughput of PFS is as expected:
BLUE arm — ∼12% (380–450 nm), ∼21% (450–550 nm) and ∼24% (550–650 nm)
RED arm (LR) — ∼30% (630–750 nm), ∼29% (750–850 nm) and ∼27% (850–970 nm)
RED arm (MR) — ∼26% (710–875 nm), ∼28% (775–825 nm) and ∼27% (725–885 nm)
NIR arm — ∼17% (940–1050 nm), ∼19% (1050–1150 nm), and ∼17% (1150–1260 nm)

- Verification of the absolute flux calibration

  One of the important tasks is the establishment of the absolute flux calibration process. In the normal observations of faint objects such as distant galaxies, we suppose that a certain fraction of fibers is used for flux calibration stars, for which F-type stars are desirable. By using the flux calibration stars, the spectra of all other fibers will be calibrated. In this measurement, we verify whether the absolute flux calibration process can be made at the expected level, with the accuracy of 5 % (`REQ-SYS-656 (Test)`). The measurement process will be done as follows:

  1. The process is closely related to the measurement of the total throughput described in the previous subsection. In this measurement, we observe a substantial number of stars whose spectral types and absolute flux are known, including flux calibration stars. The data reduction is done following the normal procedure.
  2. The calibrated spectra can be compared to the given spectra. The deviation from the expected spectra can be calculated as a function of wavelength. If necessary, this measurement will be done in various different condition such as ones listed in the previous subsection, and the deviation of the flux calibration as a function of these quantities.
  3. The cross-correlation to the external catalogue will be useful especially for faint galaxies. In this measurements, targets selected from the external catalogue (e.g., SDSS) will be observed and the data processing will be done in the normal procedure. We check the obtained spectra and the deviation from the external SDSS spectra.
  4. Verify the following items:
     – that absolute flux calibration can be done at the desired level of accuracy (5 %)
     – the number of objects that should be used for the calibration
     – the spectral type of stars that is optimal and acceptable for the desired flux calibration
     – the optimal spatial distribution of the calibration stars on the FoV

Success Criteria

Confirm that the absolute flux calibration can be done with the accuracy of 5 %.
The number of fibers for flux calibration is determined (100–200 ? TBC).

- Verification of sky background subtraction

  The subtraction of the sky background in the data analysis is one of the most critical tasks in the PFS projects. In this verification process, we allocate all fibers on the sky, among which we choose some of them as the sky fibers. Then we test sky subtraction by checking the reduced data of the rest fibers, selected as “scientific object”. If the sky background is subtracted perfectly, the reduced spectra should be “flat”. We also observe a substantial number of faint objects that is supposed to be observed in the actual scientific operations. In the normal and expected observations, a certain fraction of total fibers will be used for the sky background subtraction. We will estimate the residual of the sky subtraction as a function of:

  1. exposure or observing time

2. airmass
3. other weather condition such as seeing
4. cobra configuration and ROA?

We verify whether the sub subtraction residual is in the range of the expected level (0.5 % accuracy`REQ-SYS-679 (Analysis)`) or not. Another important items to be verified is the number of the sky fibers that is required for the desired sky subtraction.

Success Criteria

Confirm that the sky background can be subtracted within the accuracy of 0.5 %.

- Verification of the limit of exposure time in each frame

  According to `REQ-SYS-732 (Demonstration)`, the exposure time for one frame shall range 10 sec – 1800 sec. The maximum exposure time is determined not to have too many cosmic rays, nor saturated sky emission lines. In this verification process, we will determine the maximum exposure time for one frame by taking a substantial number of frames with longer exposure (> 150 sec. TBC). The purpose of this verification is as follows:

  – Check the fiber loss as a function of time
  – Effects on the sky subtraction
  – Check the saturation of OH emission lines
  – Effects by cosmic ray on obtained spectra and data reduction process
  – Check the instrument stability (c.f. FMOS instability problem during engineering observation)

Success Criteria

Confirm that the maximum limit of long exposure time (< 1800 sec) in each frame can be verified.

- Verification of observations with a long total exposure time

  In the observations targeting very faint objects such as high-redshift galaxies, very long exposure time in total will be supposed. The signal-to-noise ratio of the obtained spectra should, ideally, increase with exposure time just as expected. In this verification process, we will carried out observations with very long exposure time in total (∼10-20 hours). The target is supposed to be both bright and faint galaxies. In the measurement, we will check the following points:

  – The obtained signal-to-noise ratio grows as a function of exposure time following $\propto \sqrt{t_{exp}}$.
  – The effect of very long exposure on the sky subtraction.

  The time duration of this commissioning stage will be about 2 engineering runs, i.e., about 5–7 engineering nights, taking into consideration of a weather factor.

Success Criteria

Confirm that the expected growth of Signal-to-Noise ratio of faint targets for long exposure time

- Verification of re-configuration of cobra during scientific observations

Success Criteria

Confirm weather the re-configuration of cobra during observations with long total exposure time and how often the re-configuration is needed

- Verification of beam-switching mode (TBD)

A- 5 Performance Verification II [Night-time]

By the previous commissioning sequences, the instrument performance shall be verified at given telescope position. In this this commissioning phase, we stabilize the operation and performance at any telescope positions for long-term surveys.

We repeat the same procedure as A- 5, optimizing the software and operation.

3 Selection of Raster Fields [TBD]

In this section, we describe the preparation of target stars in order to carry out the raster scan during the engineering observations. The stars should be sufficiently bright and the number density should be matched to the number of fibers in the PFS FoV. The most plausible candidate is an open cluster. Here, we describe the selection of the raster field and the possible target stars.

3.1 Open Clusters as the Raster Targets

Open clusters in the Galaxy are possible target of stars for the raster observations. The open clusters are selected from DAML02 catalogue (Dias et al. 2002, A&A, 389, 871), which includes information on fundamental parameters (distance, apparent diameter, proper motion, age, reddening, metallicity, and so on) of ~ 2000 open clusters.

Figure 11 and Figure 12 show the spatial distribution of the open clusters with the apparent diameter (d [deg.]) of > 30. There exist ~ 130, ~ 50, ~ 30 open clusters with the apparent diameter of $30 < d < 60$, $60 < d < 120$, and $d > 120$, respectively. The typical number of member stars is ~ 1000.

3.2 Field Stars

As Figure 11 and Figure 12 show, the spatial location of the available open clusters with sufficient apparent diameter for the PFS FoV is very limited. We thus consider the possibility of using normal field stars as raster scan targets in this subsection. In Figure 11 and Figure 12, the density map of stars with $f < 16.0$ mag. selected from the UCAC4 catalogue (Zacharias et al. 2013, AJ, 145, 44), which contains 113 million stars down to $R \sim 16$ mag for which the positions determined with the accuracy of < 100 mas. Although the number of available stars in one PFS FoV is limited in the high galactic latitude (b), there exist sufficient available stars of < 16 mag in $b < 60$ deg.

3.3 Detailed Procedure of Raster Scan

TBW

3.4 List of Candidate Raster Fields

TBW

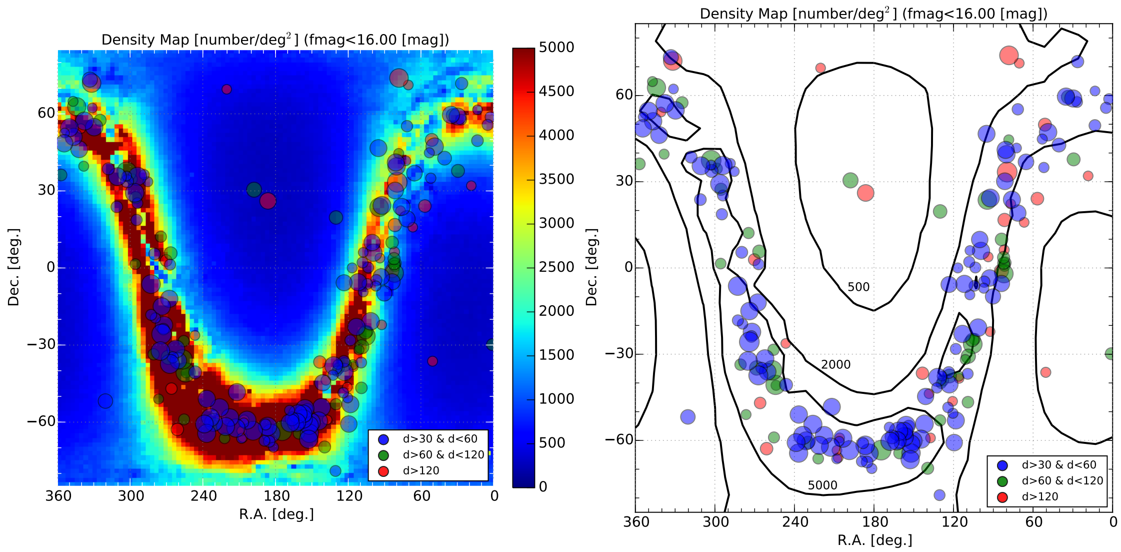

Figure 11: Stellar density with objects $f < 16.0$ mag taken from UCAC4 catalog in color map (left) and contour (right). The spatial distribution of open clusters with the apparent diameter (d [deg.]) of $d > 30$. from DAML02 catalogue is also plotted in both panels. Open clusters with $30 < d < 60$, $60 < d < 120$, and $d > 120$ are shown by *blue*, *green*, and *red circles*, respectively. The size of symbols represents the number of member stars.

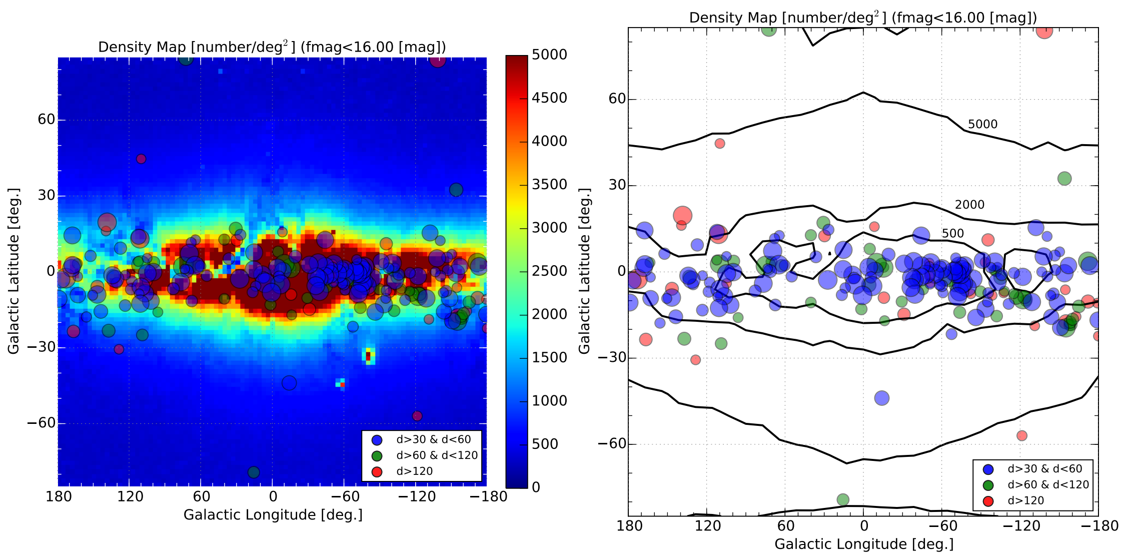

Figure 12: Similar to Figure 11, but on the Galactic longitude and latitude.

4 PFS Coordinates and Calibrations in Commissioning Procedure

4.1 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.

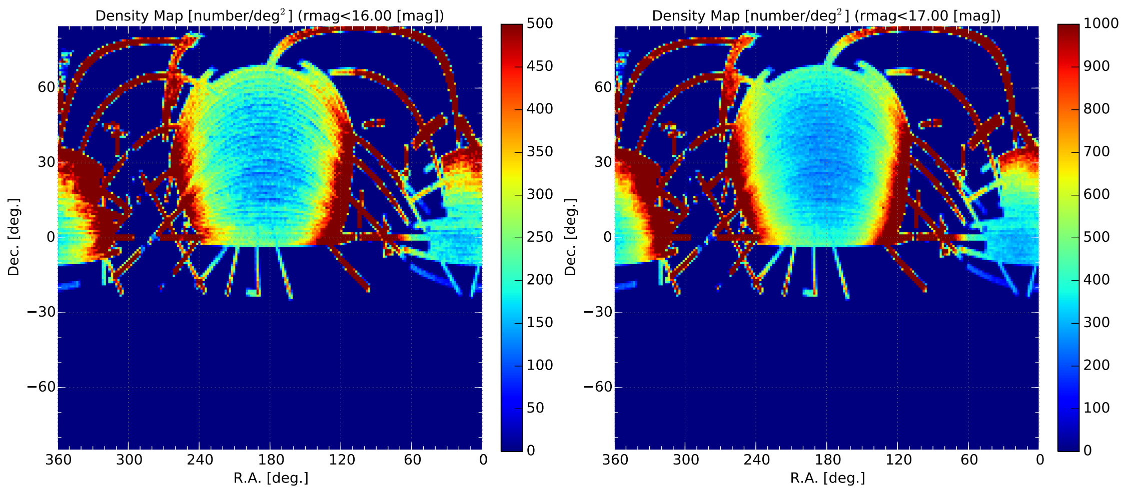

Figure 13: Stellar density with objects $r < 16.0$ mag (left) and $r < 17.0$ mag taken from SDSS DR12 catalog in color map.

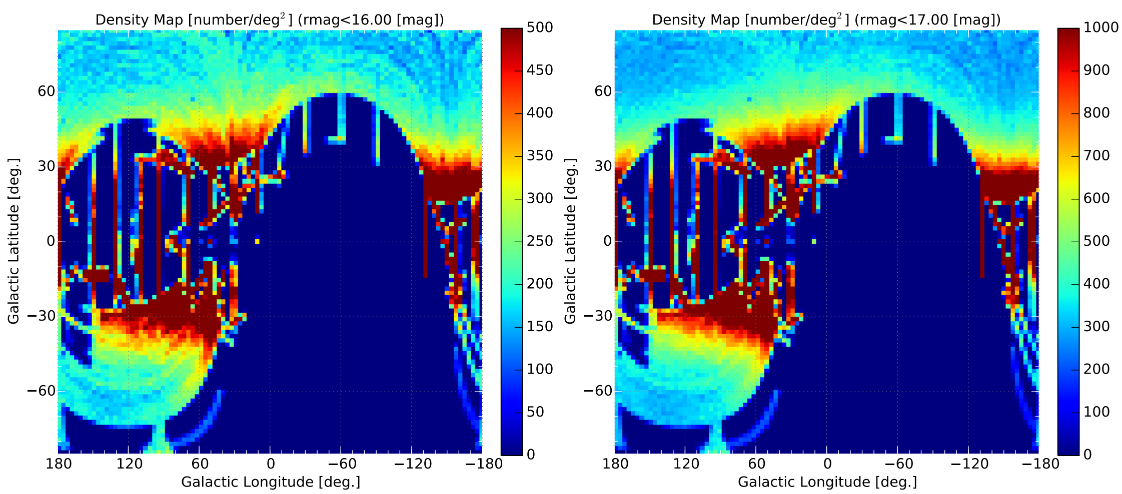

Figure 14: Similar to Figure 13, but on the Galactic longitude and latitude.

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 $\boldsymbol{S} = (\alpha, \delta)$ in the unit of degree. In the operation, we slew the telescope to a given field centered at $\boldsymbol{S} = (\alpha[^\circ], \delta[^\circ])$. In this Field of View, the sky targets have a position on Sky Catalogue as the differential from the center: $\boldsymbol{S_k} = (\Delta\alpha_k[^\circ], \Delta\delta_k[^\circ])$.

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: $\boldsymbol{X_k} = (x_k[\mathrm{mm}], y_k[\mathrm{mm}])$. 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 15).

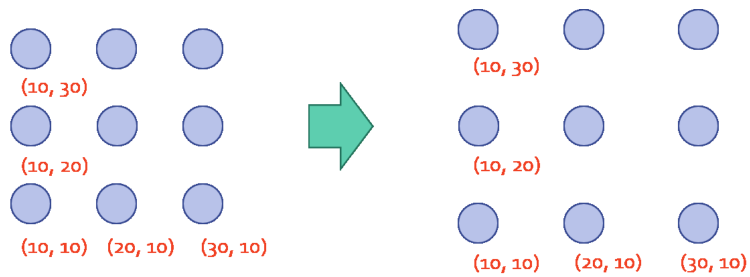

Figure 15: An example of the change in physical metrics of fiducial fibers (blue circles). The fiber positions in F3C are described in red letters.

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 16). In such case, the positions of all fixed fiducial fibers are constant again. Measure for this case is described in section 4.4.

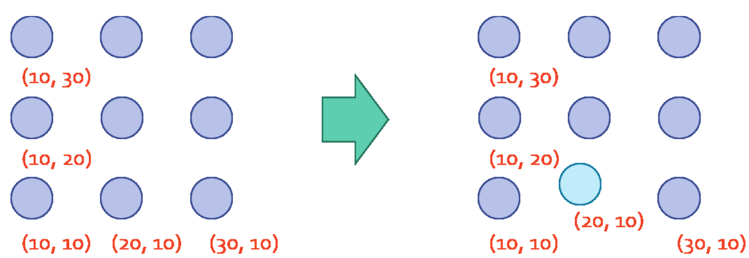

Figure 16: Another example of the change in physical positions of fiducial fibers (blue and light-blue circles). The fiber positions in F3C is described in red letters.

Cobra Coordinates The fiber positioner "cobra" is a two-axis motor; θ stage and ϕ stage. The motion of each cobra is controlled by MPS (Movement Planning Software) with the two angles of these stage in degree. We call the two angle as the Cobra Coordinates: $\boldsymbol{C_k} = (\theta_k[°], \phi_k[°])$, $[k = 1, 2, ..., 2394]$.

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 $\boldsymbol{F_k} = (i_k[\text{pixel}], j_k[\text{pixel}])$.

4.2 Observational Sequence and Definitions of Coordinate Transformations

Figure 17 shows observational sequence in particular during positioning fibers, and transformations of the above coordinates. The procedure of fiber positioning is as follows:

1. ETS (Exposure Time Sequencer) calculate the target positions $\boldsymbol{S_k} = (\Delta\alpha_k[°], \Delta\delta_k[°])$ in the observed field centered at $\boldsymbol{S} = (\alpha[°], \delta[°])$.

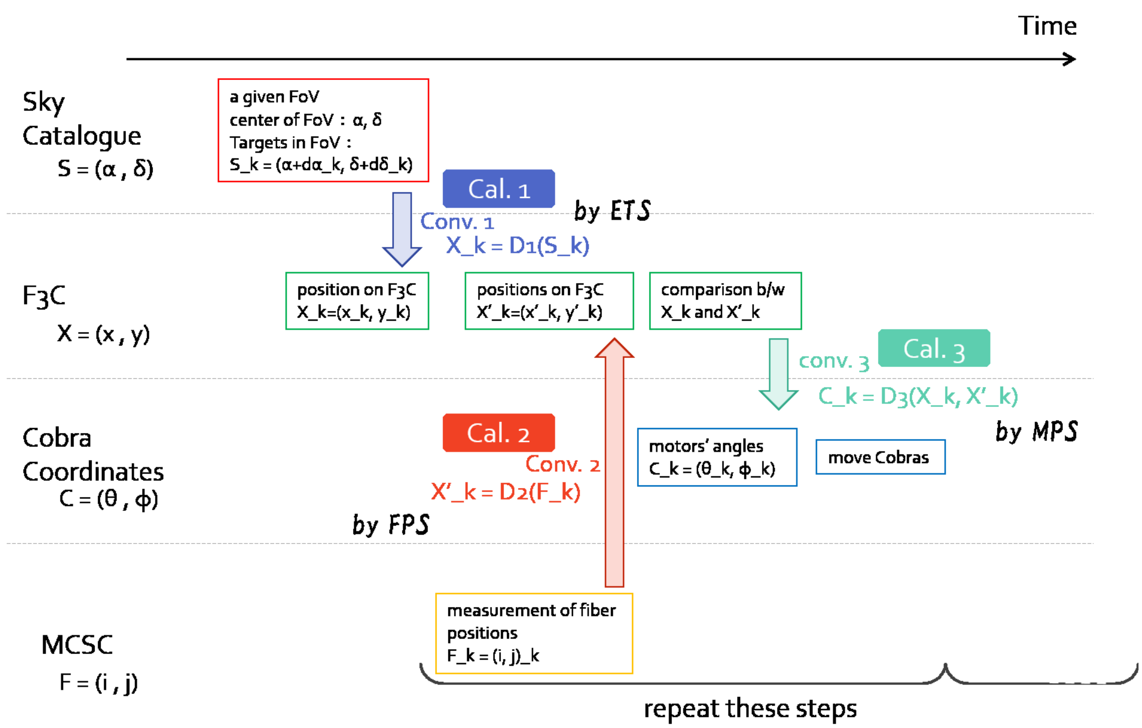

Figure 17: PFS observational sequence and coordinates transformations.

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,

$$\begin{aligned} \boldsymbol{S_k} = (\alpha_k[^\circ], \delta_k[^\circ]) \quad &\underset{D_1}{\rightarrow} \quad \boldsymbol{X_k} = (x_k[\mathrm{mm}], y_k[\mathrm{mm}]), \\ \text{or} \qquad \boldsymbol{X_k} \quad &= \quad D_1(\boldsymbol{S_k}). \end{aligned} \tag{1}$$

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

$$\boldsymbol{S_k} = (\alpha_k[^\circ], \delta_k[^\circ]) \;\rightarrow\; (\Delta Az[^\circ], \Delta El[^\circ]) \;\underset{D_1}{\rightarrow}\; \boldsymbol{X_k} = (x_k[\mathrm{mm}], y_k[\mathrm{mm}]), \tag{2}$$

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

$$\begin{aligned} \boldsymbol{F_k} = (i_k[\mathrm{pixel}], j_k[\mathrm{pixel}]) \quad &\underset{D_2}{\rightarrow} \quad \boldsymbol{X'_k} = (x'_k[\mathrm{mm}], y'_k[\mathrm{mm}]), \\ \text{or} \qquad \boldsymbol{X'_k} \quad &= \quad D_2(\boldsymbol{F_k}). \end{aligned} \tag{3}$$

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

$$\begin{aligned} \boldsymbol{X_k} = (x_k[\mathrm{mm}], y_k[\mathrm{mm}]), \boldsymbol{X'_k} = (x'_k[\mathrm{mm}], y'_k[\mathrm{mm}]) \quad &\underset{D_3}{\rightarrow} \quad \boldsymbol{C_k} = (\theta_k[^\circ], \phi_k[^\circ]), \\ \text{or} \qquad \boldsymbol{C_k} \quad &= \quad D_3(\boldsymbol{X_k}, \boldsymbol{X'_k}). \end{aligned} \tag{4}$$

Then move Cobras following the derived angles $\boldsymbol{C_k}$.

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 $\boldsymbol{X_k}$ and $\boldsymbol{X'_k}$ to MPS.

Formation of D_1 and D_2 is determined by the Project Office and stored to a designated repository (TBC), while D_3 is determined by JPL. 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.

4.3 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 use the WFC as-built model $D'_{1,0}$ as the first step. Using this model, the position on PFI is calculated by Yoko Tanaka from Subaru telescope. We call this distortion map "0^{th}-pass distortion map". The detail of the "0^{th}-pass distortion map" is under development. Given "0^{th}-pass distortion map" as a polynomial function, the Sky Catalogue – F3C transformation is described as follows:

$$\begin{aligned} \boldsymbol{X_k} &= D_{1,0}(\boldsymbol{S_k}) \\ &= \sum P_{ll',model} x^l(\boldsymbol{S_k}) y^{l'}(\boldsymbol{S_k}) \quad [l, l' = 0, 1, ..], \end{aligned} \tag{5}$$

where $x(\boldsymbol{S_k})$, $y(\boldsymbol{S_k})$ 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 4.2.

Through the commissioning, we shall optimize these coefficients for PFS by measuring the sky distortion and the sky scale in F3C. This means we shall derive $P_{ll',PFS}$, which expresses PFS distortion on the scale of 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. In other words, $P_{ll',PFS}$ has the dependency on them; $P_{ll',PFS} = P_{ll',PFS}(Az., El., InR., T, ...)$[14].

At first, in the commissioning phase 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 Galactic plane, we shall measure the positions of targets on A&G CCDs. The scale of of the sky in F3C is also measured in the P- 10 phase. The distance A&G camera and AG fiducial fibers in F3C is measured before 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 follows.

$$\begin{aligned} \boldsymbol{X_k} &= D_{1,1}(\boldsymbol{S_k}) \\ &= \sum P_{ll'} x^l(\boldsymbol{S_k}) y^{l'}(\boldsymbol{S_k}) \quad [l, l' = 0, 1, 2, ...]. \end{aligned} \tag{6}$$

The updated distortion map $D_{1,1}$ is called "1^{st}-pass distortion map".

In order to improve $D_{1,1}$, we shall do raster scan at commissioning phase A- 3, where "2^{nd}-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. $D_{1,2}$ is the final map for transformation from Sky Catalogue to F3C. That is,

$$\begin{aligned} \boldsymbol{X_k} &= D_{1,2}(\boldsymbol{S_k}) \\ &= \sum P_{ll',PFS}(Az., El., InR., T, ...) x^l(\boldsymbol{S_k}) y^{l'}(\boldsymbol{S_k}) \quad [l, l' = 0, 1, 2, ..]. \end{aligned} \tag{7}$$

[14] cf. The HSC distortion map ($P_{l,HSC}$) should also have such a dependency, but they use mean map. The dependency of these parameters will be checked.

MCS to F3C transformation D_2: In the observational sequence, PFS determines parameters of D_2 every time when MCS takes fibers image. The form of D_2 is determined in advance using ZEMAX calculation with WFC as-built model[15].

$$\begin{aligned} \boldsymbol{X} &= D_2(\boldsymbol{F}) \\ &= D_2(\boldsymbol{F}; P_2), \end{aligned} \tag{8}$$

where P_2 is parameters of D_2.

During the commissioning (P- 8), we shall refine the positions of fixed fiducial fibers in F3C. In this commissioning sequence, we compare the positions of fixed fiducial fibers in F3C expected by $D_2(\boldsymbol{F_k})$ and with those measured before shipment and check their consistency.

During the observations, P_2 is derived to minimize RMS:

$$D_2(\boldsymbol{F_l}; P_2) \quad := \quad \min(\|\boldsymbol{X_l} - D_2(\boldsymbol{F_l}; P_2)\|), \tag{9}$$

where l indicates fixed fiducial fibers ($l = 1, 2, ..., 97$). Note that we don't adopt the least mean square method because this method weights on error in spacial map. Using derived parameters P_2, the science fibers position is transformed to those in F3C;

$$\boldsymbol{X_k} \quad = \quad D_2(\boldsymbol{F_k}; P_2). \tag{10}$$

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 $\boldsymbol{F_k}$ 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 phase 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 $\boldsymbol{X_{c,k}} = (x_{c,k}, y_{c,k})$, arm lengths of θ stage $a_{1,k}$ and ϕ stage $a_{2,k}$, minimum positions of θ angle $\boldsymbol{\theta_{0,k}}$ and ϕ angle $\boldsymbol{\phi_{0,k}}$, and maximum positions of θ angle $\boldsymbol{\theta_{m,k}}$ and ϕ angle $\boldsymbol{\phi_{m,k}}$. Note that these parameters are calculated in F3C. In the commissioning phase of A- 1, we shall derive these parameters using back-illuminated science fibers (see A- 1 for details).

4.4 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.

[15] Going on.

A Effect of the Moonlight on the PFS Commissioning

TBW.

Effect on

1. limiting magnitude of guide star.
2. number of bright star for astrometry and raster scan.
3. WFC alignment.

B Hexapod Operation

The goal of Hexapod operation is to keep the x/y alignment, focus (z), and tilt of the WFC+HSC assembly with respect to the primary mirror. The Hexapod operation can depend on EL following a look-up table (see page 19). The z adjustment can also account for the effect depending on telescope truss temperature (Ttruss) via a simple model (details of the model TBC). The look-up table comes from a result of Mirror Analysis (MA) with HSC in POpt2 (see page 47), but the Hexapod operation can be optimized for PFS (see page 46). The instructions in the look-up table and those from the model with Ttruss can be imperfect, so probably an offset will need to be given based on a focusing operation from time to time during a night.

C Optimizing Hexapod Operation

A significant part of the Hexapod operation is determined by the investigations such as MA with HSC, so the result may not be optimal for PFS. However PFS can collect information to optimize it using the AG camera images: Image quality, focal plane tilt z & tilt Asymmetry in a defocused star image or coma features in a focused star image x/y (feasibility is under investigation, see a separate report) Initially PFS will have a look-up table copied from HSC, but this will be a different entity, so according to the information from the investigation using PFS, the PFS's look-up table can be edited to modify the Hexapod operation. It is also possible to apply offsets from a different command path.

D Mirror Analysis

PFS doesn't have capability of executing Mirror Analysis (MA). According to the document describing the mirror analysis and pointing analysis for PFS (`TM-N57208`), PFS uses the MA data of HSC. PFS uses the same coefficients of primary mirror as those for HSC, while adds differential parameter for coefficients of secondary mirror. When HSC updates the MA, operators can decide whether they also update the coefficients for PFS.

The best x/y/z position of WFC+HSC assembly with respect to the primary mirror is investigated by observing a bright star using a Shack-Hartmann system onboard HSC. The MA is performed at several EL to have the x/y/z positions as a function of EL. The operation of actuators for primary mirror support is also optimized as a function of EL via MA. The MA is performed only at the field center, so cannot investigate focal plane tilt. Instead HSC itself is used to check the focal plane by looking at stellar images across the field of view. This determines the optimal tilt operation of Hexapod. The optimization of x/y/z and tilt can be an iterative process: Once the tilt operation is determined, the MA is performed again to see if the best x/y/z position needs to be tweaked, and one may need to come back to tilt optimization.

E Abbreviation

General and Telescope:

Az: Azimuth

EL: Elevations

F3C: Fixed Fiducial Fibers Coordinate

IR4: IR-side forth floor in the Dome (TUE-IR floor in Subaru term)

ROA: Rotation Angle

TPA: Telescope Pointing Analysis

PFI / Popt2:

PFI: Prime Focal Instrument

AGC: Acquisition and Guidance Camera

AGCC: Acquisition and Guidance Camera Controller

COB: Cobra Optical Bench

WFC: Wide Field Corrector

MCS:

MCS: Meteorology Camera System

SpS:

SCR: Spectrograph Clean Room

SM: Spectrograph Module

SpS: Spectrograph Subsystem

Software:

DRP: Data Reduction Pipeline

ETS: Exposure Time Sequencer

FPS: Fiber Positioning Sequencer

MHS: Messaging Hub System

MPS: Movement Planning Software

PFICS: Prime Focus Instrument Control System