

# PFS Commissioning Work Flow

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# 1 Overview

## 1.1 Work-flow overview

The ultimate goal of the PFS 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 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 processes 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 of 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.
- Fiber-reconfiguration.
- Performance verification:
  - Flux calibration
  - Sky subtraction

- 
- Total throughput
  - Maximum exposure time of one frame, and stacking for long time ( $> 10$  hours) exposure
  - Quality Assurance procedure
  - Beam-switching mode
  - 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), and quality-assurance (QA) process and so on.

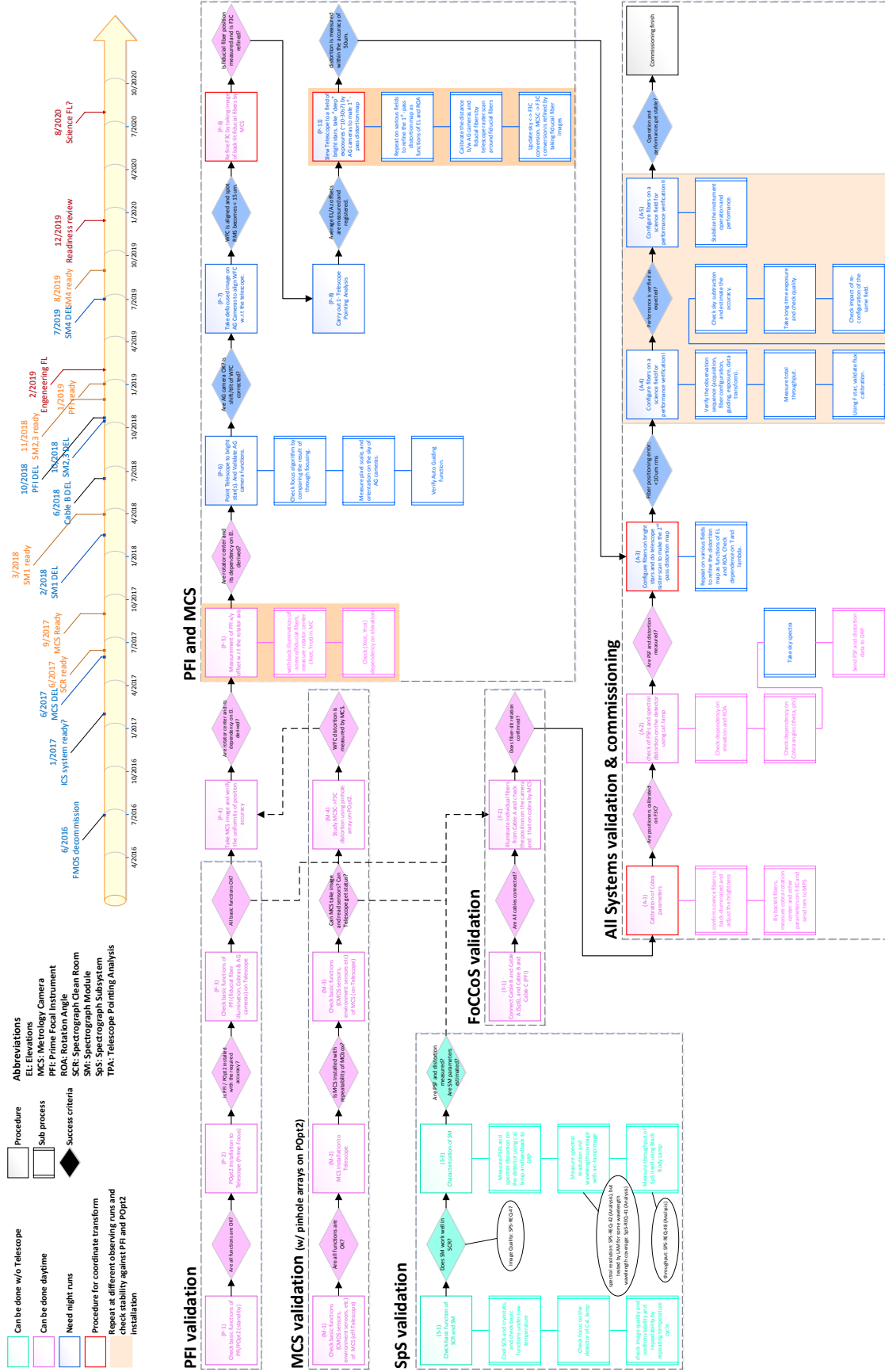


Figure 1: Flowchart of Validation & Commissioning. Larger one is available on the PBworks:

<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 9. The file named `PFS_AIT_Subaru.pptx`<sup>1</sup> summarizes The required sources, layout of working space and other configurations of I&T process in Hawaii

Table 1: Subsystem I&T time and place. In column 1 is listed subsystem. In column 2 is described the latest schedule (June 2019) of A&I in Hawaii. In columns 3 and 4 are listed working place at Hilo base and at the summit, respectively.

Subsystem	Year/Month	I&T Place (Hilo)	I&T Place (Summit)
PFI	2021/06–2021/07	–	Instrument Lab. & Observation floor
MCS	2018/04–2018/05	Simulator lab.	Observation floor
SpS-SM1 (B+R)	2019/12	–	IR4 (SCR)
SpS-SM1 (N)	2022/02	–	IR4 (SCR)
SpS-SM2 (B+R)	2021/12	–	IR4 (SCR)
SpS-SM2 (N)	2022/04	–	IR4 (SCR)
SpS-SM3	2022/03	–	IR4 (SCR)
SpS-SM4 (B+R)	2022/05	–	IR4 (SCR)
SpS-SM4 (N)	2022/08	–	IR4 (SCR)
Cable B1	2021/01–2021/02	Simulator lab.	Observation floor & SCR
Cable B2–4	2022	Simulator lab.	Observation floor & SCR

**PFI** PFI will be shipped after assembled at ASIAA/ASRD, so it doesn't need to be re-assembled at Subaru, except for the field element. The field element will be disassembled for protection, so that it will be integrated again at the Summit. Although the I&T story board at the summit is in preparation, 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

<sup>1</sup>[http://sumire.pbworks.com/w/file/111633073/PFS\\_AIT\\_Subaru.pptx](http://sumire.pbworks.com/w/file/111633073/PFS_AIT_Subaru.pptx)

7. Cobra convergence test with dummy MCS
8. AG camera test for dark and noise
9. Integration of Field Element and calibration lamp
10. Fitting test with POpt2

These tests 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 same tests are repeated, except for the cobra circular motion test and integration.

Software modules controlling PFI will be also integrated on-site ICS. Not only communication among ICS individual modules, but also communication among ICS Actors and MLP1 will be tested. Also, telemetry system, communication among PFI software actors, SAS, and STS will be validated.

**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, the achromatic lens will be installed, and MCS will be installed MCBBox. 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-4).

Because MCS is the first subsystem delivered to Subaru, the ICS infrastructure will be prepared to accommodate MHS and ICS actors. MCS software modules are hooked up to the MHS running on the summit infrastructure.

**SpS** After AIT at LAM, four modules are shipped to Subaru separately. Individual 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 and stability
- Characterization of spectrograph (optional: TBD)

SpS software modules are also integrated and tested.

**Cable B** After shipped to Subaru, the light-path will be tested firstly. FRD is measured before and after installation on the telescope, and in the middle of it in order to check extra stress have induced to the fibers during installation process. Uniformity test using USB microscope is carried out. Besides, spectral transmission are tested for a set of fibers. To test the cables on the telescope, the dedicated connector making loops on Tower connector side is used.

For Fiber Monitoring System, only low-level command is available, so software integration is needed.

### 1.2.2 Complementarity between subsystem I& T and the commissioning

To be written.

### 1.3 Achieved PFS Functions during the Commissioning (TBD)

Table 2 shows achieved PFS functions and related commissioning sequences (compliance matrix). Column 1 lists the ID of the functions. Column 2 lists the priority of the functions (TBC). In column 3 and 4 are described the functions, and detailed success criteria respectively. Columns 5 lists the process where the functions will be validated. In columns 6, a checked-mark will be put when the the functions will be validated. Columns 7 describes other notes.



Table 2: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
<b>Fiber Allocation</b>						
1	A	Initial check of subsystems	MCS can communicate with MHS	M-1, M-3	✓(Run 1)	
2	A		MCS can take image with required performance (dark, noise, etc.)	M-1, M-3	✓(Run 1)	
3	A		All mechanical and environmental sensors of MCS can be read	M-1, M-3	✓(Run 1)	
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 $-270^\circ$ to $+270^\circ$	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 $< 45\text{mm}$ in x,y each)	M-2		
12	A		PFI is installed in POpt2 meeting required repeatability ( $< 200\mu\text{m}$ in lateral, $< 100\mu\text{m}$ 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 $\mu\text{m}$	P-2		Specification of Mit-subishi
14	A		Cable B is connected with PFI and SpS correctly (fiber ID, throughput?)	F-1, F-2		

Table 2: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
15	A	Pre-study of coordinate transformation	Algorithm of coordinate transformation works (accuracy: 50 um)	M-4		
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 $< 10$ um (TBD)	A-3		

Table 2: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
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		
<b>Spectrograph</b>						
37	A	Initial check of subsystems	SCR and SpS can communicate with MHS	S-1		
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		

Table 2: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
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. ( $30^\circ - 90^\circ$ ) and RoA ( $-270^\circ - +270^\circ$ )	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 lamp turns on/off	P- 1		
61	A		Calibration sources are bright enough on the detectors (XXX count)	S- 2		
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		
<b>Total Performance</b>						
65	A	Long-term exposure	S/N is proportional to $\sqrt{t}$ during long-term exposures ( $\sim 10$ hours)	A- 5		

Table 2: The list of achieved functions during the commissioning.

No	Pri.	Functions	Success Criteria	#Sq.	Succ.?	Notes
66	A	Data archive	All Spectrograph images (including up-the ramp), MCS image and AG image as well as fiber configuration data are archived to STARS.	A- 4		
67	?	Beam-switching mode	TBD	A- 4		

## 1.4 Expected Number of Nights for Validation & Commissioning (TBC)

The PFS commissioning requires several “engineering observation runs”, during which a few processes will be executed step by step. We estimate the number of required runs and working-days for the PFS commissioning procedure. For most of the tests the night time (sky) is essential, but for some tests, day-time is acceptable. 14-day works require dark night in later phase of the commissioning, where we shall validate the total instrument performance. We arrange the working process to use the telescope time as effectively as possible. In total, **10 runs of 45 working days** will be required for the commissioning. Here, we take account into the weather factor of 70 % uniformly for nighttime processes. We also include the uniform 20 % technical margin into each process for unseen situations.

At the first run when PFS observes the sky, 3 nights will be required for Mitsubishi to test the updated software to control the telescope. Also, to check the performance the algorithm for PFI alignment (P- 7) and study the distortion, 7 nights were used with HSC from the S17B to the S21A semester. Combined with these numbers, **52 working days** will be required for the PFS commissioning.

The expected numbers of working-days for each run and its breakdown is as below. Figures 2 – 10 display the rough schedule of runs 1–9, from installation of subsystems before the engineering observation to their uninstallation after the run. Here, commissioning processes which require dark night-sky are colored by navy, while ones requiring night-sky even bright/grey by blue. Processes we can carry out even in the daytime are colored by pink. Table 3 summarizes these numbers with schedule on the assumption of the current timeline of the project (as of April 2018).

Note that we do not 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. Note also that we do not count working days for MCS on-telescope test in June 2018, before the run 1, because the telescope will not be occupied on nights.

Breakdown of individual engineering runs are as follows.

**Run 0: 7 days used “HSC”** Since the S17B semester, 7 days have been allocated for the engineering runs using “HSC” to test the following items. In addition, there were a couple of nights used for SuNSS.

- $\sim 4$  days to check if the algorithm for PFI alignment (P- 7) work or not.
- 1 day to test the algorithm further and field acquisition procedure, and to demonstrate the PFI alignment.
- $\sim 2$  days to study distortion of WFC.

**Run 1: 3 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
- 2 days (nighttime) for M-4 : (1) pre-study the coordinate transformation system

Run 1 also has AIT work by ASIAA:

- 1 day (daytime) for alignment the MCS to the prime focus
- 2 days (nighttime) for image quality test, study of dome seeing under observational configuration.

Note that we shared nighttime (and data) to carry out ASIAA's tests and M-4.

	pre-run	Day 1	Day 2	Day 3	post-run
Telescope work	MCS install = M1–M3	pinhole/POpt2 install			pinhole/POpt2 uninstall
Daytime	M1–M3	preparation	alignment, analysis	analysis	inspection
Nighttime		ASIAA AIT (alignment)	ASIAA AIT (IQ), M4	ASIAA AIT (IQ), M4	

Figure 2: Time table of Run 1.

**Run 2: 5 days (Figure 3)** This run was done for upgrading MCS primary mirror support. Before the run, ASIAA had summit work to replace the mirror support. As AIT work y ASIAA,

- 3 days (nighttime) for alignment, image quality test, study of dome seeing under observational configuration.

As a commissioning,

- 2 day (nighttime) for M-3 and M-4: (1) check ICS command dataflow including operation database (2) pre-study the coordinate transformation system

	pre-run	Day A1	Day A2	Day A3		Day B1	Day B2	post-run
Telescope work	MCS, pinhole/POpt 2 install							pinhole/POpt2 uninstall
Daytime	(M1–M3)	preparation	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)		(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		ASIAA AIT (IQ) / M4	ASIAA AIT (IQ) / M4	ASIAA AIT (IQ) / M4		ASIAA AIT (IQ) / M4	ASIAA AIT (IQ) / M4	

Figure 3: Time table of Run 2.

**Run 3 : 10 days (Figure 4)** During the telescope down-time for Mitsubishi's test using PFS, we will use the nights to test Cobra using MCS.

- 1 day (daytime) for P-1 – P-3, and F-1: (1) check PFI/POpt2 standing by, (2) install POpt2 to the prime focus, (3) check PFI functions, and (4) connect Cable B to PFI and SpS (SM1)
- 0.5 day (nighttime) for P-4 : (1) verify MCS performance at zenith
- $\sim 5$  days (nighttime) for A-1 : (1) calibration of Cobras (all)
- $\sim 2$  days (1.0-day nighttime) for A-2 : (1) PSF measurement through the entire system (SM1)
- 1 day (nighttime) for P-4 and P-5 (after telescope can be moved): (1) measure x/y offset of PFI rotation center on MCS, and (2) verify MCS performance at different elevation angle

We also plan to take arc and flat images.

	pre-run	Day 1	Day 2, 3, 4	Day 5	Day 6	Day 7, 8	Day 9	Day 10	post-run
Telescope work	MCS install	PFI install =P1—P3							PFI uninstall
Daytime		P1,-3, F1 Mitsubishi	Mitsubishi	Mitsubishi	Mitsubishi	Mitsubishi	Mitsubishi	Mitsubishi	inspection
Nighttime		P4*, A1	A1	A2 (analysis)	P5, P4**, arc, flat	(A1,) A2	A2, F2	F2	

Figure 4: Time table of Run 3.



**Run 4 : 7 days (Figure 5)**

- 1.2 + 1.5 days (nighttime) for P-6 : (1) verification of A&G camera functions (1.5 days is done with Mitsubishi)
- 1.0 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 (w/ith Mitsubishi)
- 0.5 days (daytime and/or nighttime) for A-1 : (1) Test fiber allocation
- 1.0 days (1.0-day nighttime) for A-2 : (1) PSF measurement through the entire system (SM1,2,3)

The run 4 has 3-night work by/with Mitsubishi for test of software of the telescope control. Note that we assume that we can coordinate with Mitsubishi to proceed some test items in parallel. Note also that some test items such as AG functionality test and TPA will be done with Mitsubishi. The below is test items when we apply the engineering time in the S21B semester:

- [a] P0pt2 alignment, measure InR center using AG camera. [1 night]
- [b] AG camera test and characterization [1.2 nights]
  - AG camera centroiding test (0.3 nights)
  - AG camera Orientation and pixel scale measurement (0.3 night)
  - Check focus position of AG focal plane and focusing test (0.4 night)
  - Field acquisition (0.2 night)
- [c] Mitsubishi's test for AG [1.5 nights]
- [d] Mitsubishi's test for PA [1.5 nights]
- [e] Fiber allocation test [0.5 nights]
- [f] PSF characterization for development of data reduction pipeline [1 night]
  - Sky spectra acquisition at different El and InR (0.5 nights x 2 sets).  
(2 sets of images are needed to study time dependency)

Note: In addition to night-time observation, the following tests need to be done at the daytime.

- Measurement of PFI rotation center on MCS and check the repeatability of installation. (0.1 day)
- Check and refine the fixed fiducial fibers position on focal plane. (1 day)
- Study effect of the Cobra position on PSF (0.5 day x 4 sets)

	pre-run	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	post-run
Telescope work	MCS install	PFI install							PFI uninstall
Daytime		preparation (Cobra cal.)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	A2	(Analysis & Trouble shooting)	P8 (Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		Mitsubishi (A2?, P6,g)	Mitsubishi (A2?, P6,g)	Mitsubishi (A2?, P6,g)	P6	P6, P7	P7,P9	A2	

Figure 5: Time table of Run 4.

**Run 5 : 5 days (Figure 6)**

- 0.2 days (nighttime) for P-6 : (1) check AG focus comparing with the focus of the science fibers.
- 0.3 days (nighttime) for P-7 : (1) correct WFC shift/tilt with respect to the primary mirror (confirmation)
- 0.1 days (nighttime) for P-9 : (1) Telescope Pointing Analysis (confirmation)
- 2 days (nighttime) for P-10 : (1) 1st-pass distortion map
- 2.5 days (1.0-day daytime and 1-day nighttime) for A-2 : (1) PSF measurement through the entire system (SM1)
- 1 day (nighttime) for A-3 : (1) 2nd-pass distortion map

The below is test items when we apply the engineering time in the S21B semester. Since 5 nights are allocated whereas 7 nights were applied, 1 nights are reduced for A-10 and A-3, respectively:

- [a] P0pt2 alignment and InR center confirmation (repeatability) [0.3 nights]
- [b] Confirm telescope pointing [0.1 nights]
- [c] Determine the AG camera coordinate system w.r.t. the fiducial fibers [1.5 nights]
  - dithering around the AG fiducial fibers (2 fibers for each camera).
  - El dependency confirmation
- [d] Distortion study using astrometry data on AG camera [3 nights]
  - Study dependency of the instrument rotator
  - Study dependency on elevation
  - Study dependency on ADC position
  - In total, ~50 set of data (1 set ~0.05 nights)
- [e] Distortion study by taking star spectra (dithering around the allocated position) [2 nights]
  - Do dithering (raster-scan) for ~20 fields at different El, N/S and InR and refine fiber allocation. (0.1 nights per field)
- [f] AG focus position measurement to compare with the science fibers focal plane [0.2 nights]
- [g] Take reference star spectra (radial velocity standard, telluric, abundance) for data reduction pipeline [0.5 night]
- [h] PSF characterization for development of data reduction pipeline [1 night]
  - Sky spectra acquisition at different El and InR (0.5 nights x 2 sets)

Note: In addition to night-time observation, the following tests need to be done at the daytime.

- Study effect of the Cobra position on PSF (repeatability) (0.25 day x 4 sets)

	pre-run	Day 1	Day 2	Day 3	Day 4	Day 5	post-run
Telescope work	MCS install	PFI install					PFI uninstall
Daytime		preparation	A2 (Trouble shooting)	A2 (Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		P7, P9, A6	P10	P10	A2	A3	

Figure 6: Time table of Run 5.

**Run 6 : 6 days (Figure 7)**

- 2 days (nighttime) for P-10 : (1) 1st-pass distortion map
- 0.5 day (daytime) for F-1 : (1) connecting Cable B to PFI and SpS (SM2,3,4)
- 1.0 day (daytime) for F-2 : (1) confirmation of the fiber identifications (SM2,3,4)
- 1.5 days (1.0-day daytime and 0.5-day nighttime) for A-2: (1) PSF measurement through the entire system (all but SM4-NIR)
- 3.5 days (nighttime) for A-3: (1) 2nd-pass distortion map

	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		F1, F2 preparation	F2, A2 (Analysis & Trouble shooting)	A2 (Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		P10	P10	A2, A3	A3	A3	A3	

Figure 7: Time table of Run 6.

**Run 7 : 6 days (Figure 8)**

- 4 days (nighttime) for A-3: (1) 2nd-pass distortion map
- 2 days (dark-night) for A-4 : (1) performance verification I (all but SM4-NIR)

	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	A3	A4	A4	

Figure 8: Time table of Run 7.

**Run 8 : 5 days (Figure 9)**

- 2.0 days (1.0-day daytime and 1.0-day nighttime) for A-2: (1) PSF measurement through the entire system (all SMs)
- 4 days (dark-night) for A-4 and A-5 : (1) performance verification I (SM1/2/3), and (2) performance verification II (stabilization, using SM1/2/3)

	pre-run	Day 1	Day 2	Day 3	Day 4	Day 5	post-run
Telescope work	MCS install	PFI install					PFI uninstall
Daytime		preparation	A2 (Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	(Analysis & Trouble shooting)	inspection
Nighttime		A2	A4	A4	A5	A5	

Figure 9: Time table of Run 8.

**Runs 9 and 10 : 4 days (Figure 10)**

- 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 10: Time table of Runs 9 and 10.

Table 3: Expected number of working days for commissioning (as of June 2021). Column 1 lists the run number. Year/Month in column 2 are just roughly set for the Run 6 and later assuming the latest schedule of each subsystems and that scientific operation will start in the S23B semester. The required days for each run are listed in column 3. Required days for individual processes at each run are listed in column 5 (daytime) or 6 (night-time). The numbers in parentheses in column 6 is required dark nights.

Run	Year/Month	#days	process	daytime	night (dark)
0	S17B-S21A	4.5***	P7(*) etc.	0	7.0 (2.5)
–	2018/06	–	M1	–	–
1	2018/10	3	M1–3	(1**)	0 (0)
			M4, ASIAA	0	3 (0)
2	2019/08	5	M4, M3, ASIAA	0	5 (0)
–	2019/12–2020/01	–	S1,S2 (SM1:B+R)	–	–
3	2021/09	10****	P1–P3,F1 (SM1)		0.5 (0)
			P4,P5	0	1.5 (0)
			A1	0	5.0 (0)
			A2 (SM1B+R)	0	2.0 (0)
4	2021/10	7***	P6	0	2.7*** (0)
			P7	0	1.0 (0)
			P8	1.5	0 (0)
			P9	0	1.5*** (0)
			A1	0.5	0 (0)
			A2 (SM1,2,3)	0	1.0 (0)
5	2021/11	5	P6	0	0.2 (0)
			P7	0	0.3 (0)
			P9	0	0.1 (0)
			P10	0	2 (0)
			A2 (SM1)	1	1 (0)
			A3	0	1 (0)
–	2022/early	–	S1,S2 (SM2:B+R)	–	–
–	2022/early	–	S1,S2 (SM3)	–	–
–	2022/early	–	S1,S2 (SM4:B+R)	–	–
–	2022/middle	–	S1,S2 (SM1:N)	–	–
6	2022/05	6	P10	0	2 (0)
			A2 (SM1,2,3)	1	0.5 (0)
			A3	0	3.5 (0)
–	2022/middle	–	S1,S2 (SM2:N)	–	–
7	2022/07	6	A3	0	4 (0)
			A4	0	0 (2)
–	2022/07	–	S1,S2 (SM4:N)	–	–
–	2022/middle	–	S1,S2 (SM4:N)	–	–
8	2022/10	5	A2 (all SMs)	1	1 (0)
			A4	0	0 (2)
			A5	0	0 (2)
9	2022/12	4	A5	0	0 (4)
19	2023/02	4	A5	0	0 (4)
in total		45 (52****)			

\* Check algorithm at HSC engineering run.

\*\* Telescope can be used for other instruments

\*\*\* The number combined with run 0 and Mitsubishi's work

\*\*\*\* During telescope downtime for Mitsubishi's test (the number of used night is not counted)

## 1.5 Relationship among Individual Sequence

Some processes can be carried out in parallel, but some should in series. Table 4 shows the relationship among the individual sequences. Each row displays commissioning processes related to each process in the columns. “X” means required process. For example, prior to the process M-3, M-2 (and hence M-1) should be succeeded.

Table 4: The relation of commissioning processes.

	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 process, 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] in one 0.8s frame
- noise level:  $6.4e^-$
- background level: **how much??**
- shutter: We take several images opening and closing the mechanical shutter to confirm it works properly.

These values are based on the CDR slides (`MCS_camera_system.pdf`).

- MCS can read environmental and sensors.
  - 7 temperature sensors on optics, mechanical structure, coolant lines, MCBox and electrical rack (**where exactly?**)
  - flow meter
  - microphone

In addition, we will send command on Subaru side (Gen2), so that we can validate ICS performance as follows:

- MHS communicates with between Gen2
- IIC interprets Gen2 commands and send MCS proper commands through MHS
- Subaru (STS and Gen2) refers MCS status
- Subaru (Gen2) receives MCS image

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

After validating the above performance, we will take calibration data (bias, dark, and flat) of CMOS sensor. Note that this process will be skipped in this step, and be carried out in the step [M- 3](#) instead.

**Designated Tool for This Process** We will prepare commands to check MCS functions. This will be used as health check of the subsystem.

#### Success Criteria

All MCS basic functions are verified — power, CMOS sensor, telemetry.  
 ICS can control the instrument communicating with Gen2.  
 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 process, 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. Subaru demonstrated the repeatability of mounting MCBox in 2015 (report by Y. Minowa: NDTN-20150714<sup>2</sup>), 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 within the required accuracy, if it is installed in the normal way. Note that we don't measure the repeatability indeed in the commissioning processes. We will, however, have to check this process later, when a problem will happen; e.g. the center of PFI on MCS are quite different in individual runs.

### Success Criteria

MCS is mounted to Cassegrain focus with the required accuracy ( $\leq 45\text{mm}$  offset in x/y direction, and  $\leq 0.14$  degree tilt).

Required long time to analyze the data?: No.

## 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 process. During installing operation, the power of MCS will be kept on (TBC<sup>3</sup>), so we should turn on the MCS electric devices (or reconnect to the network) 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 [degC] in one 0.8s frame
  - noise level:  $6.4e^-$
  - background level: how much??
  - shutter: We take several images opening and closing the mechanical shutter to confirm it works properly.

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

<sup>2</sup>MCBox\_repeatability\_report.pdf

<sup>3</sup>Having UPS, MCS computer can be kept on. Still, the network will be disconnected



- MCS can read environmental sensors.
  - 7 temperature sensors on optics, mechanical structure, coolant lines, MCBox and electrical rack (where exactly?)
  - flow meter
  - microphone

After the basic functions are confirmed to work, the calibration data (flat, bias and, dark?:TBC) of CMOS sensor shall be obtained, if they are not taken in the step of M- 1. The stability of calibration data can be examined using the data in multiple runs.

From the viewpoint of software, this process opportunity to demonstrate the “callback” function, with which the IIC sends a signal to Gen2 to move the telescope at a given condition. For instance, we execute the following sequence by a single command:

1. Take MCS exposure,
2. After MCS exposure done, IIC sends a signal Gen2 to move the telescope Az, and MCS to take another exposure simultaneously.

**Designated Tool for This Process** We will prepare Gen2 commands to check MCS functions, the same as M- 1.

#### 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 Study Focal Plane using MCS [Daytime]

In this process, we study the distortion of the focal plane using MCS, and check validity the PFS coordinate-transfer system. This process is planned to use time efficiently after the PFI arrival, because, according to the current schedule (as of January 2017), MCS will be delivered to the Subaru telescope a year earlier PFI.

In this process , we will:

1. Align MCS on MCBox with respect to the Prime Focus (POpt2). [ASIAA work]
2. Verify image quality. [ASIAA work]
3. Study dome seeing effect. [ASIAA work]
4. Demonstrate fiber configuration process command and dataflow, namely
  - centroiding,
  - MCS-F3C coordinate transformation, and
  - data input and output with operation database
  - visualization of fiber position difference.

## 5. Study WFC distortion map in detail

Note that the first three items is proposed by ASIAA in MCS CDR document : (MCS\_I&T.pdf, and PFS MCS Delta CDR.pdf),

Regarding the image quality, the similar test will be done in the process P- 4, where science and fiducial fibers are used. Hence, if the image quality will be validated well enough in this process, we may skip P- 4. but note that it is still worth validating the image quality with real fibers.

Since PFI will not available for this process, 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 5 summarizes the specifications of Echidna on FMOS/PIR and pinhole on POpt2 as well as their usefulness for tests in this sequence. **At discussion on AIT work in October 2016, it was decided that we will use pinhole array on POpt2.**

**In the case of FMOS/PIR** The field of view of FMOS/PIR ( $\sim 150\text{mm} \times \sim 150\text{mm}$ , 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  $\sim 35 \mu\text{m}$ <sup>4</sup>. We set the goal in accuracy of fiber positioning 50  $\mu\text{m}$  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 11 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.

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<sup>4</sup>Originally the fiber allocation was achieved with the accuracy of  $\sim 10\mu\text{m}$ . Recently the encoder of X position of sky camera was broken, which have added  $\sim 25 \mu\text{m}$  for fiber positions.

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.

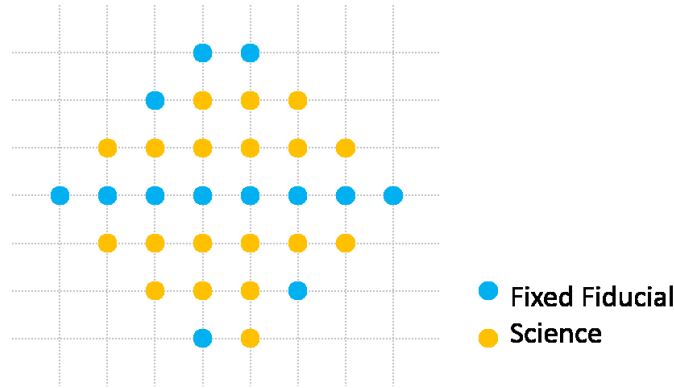


Figure 11: Example of the arrangement of FMOS/Echidna back-lit fibers. 32 fibers can be back-illuminated at a time.

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).

**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 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 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. Since the existing as-build models are at only three elevations (EL=90°, 60°, and 30°), we will modify the distortion map using the data at other elevations.

Although the pinhole array prepared by ASIAA has the 8mm pitch (partly 2mm), we can use the ASIAA pinhole for the above 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  $\sim 356\text{mm} \times \sim 356\text{mm}$ , which covers  $\sim 75\%$  of FoV of WFC. The diagonal length 497.84 mm is larger than the circumcircle of AG cameras (496 mm in diameter). Therefore, distortion shall be studied well.

To minimize (and measure) the effect of dome seeing, we will take 100 frames for a given position. Assuming that it takes  $\sim 10$  seconds, it will take about 20 minutes to obtain the data at a given position. For study of distortion map, we will take data at 7 elevation angles (with  $10^\circ$  step from EL= $90^\circ$  to  $30^\circ$ ). To cover the entire FoV, we have to arrange the pinhole array at three azimuth angles. It will, therefore, take 7 hours to obtain the data. To study the effect of WFC surface figure error on the coordinate transformation, we will take 5 sets of 100 frames by moving the instrument rotator slightly. If we will study this at 5 elevations (with  $15^\circ$  step from EL= $90^\circ$  to  $30^\circ$ ), it will take about 8.3 hours. In total, 2-day are required for this step.

Table 5: Specifications of Echidna on FMOS/PIR and pinhole on POpt2, and their usefulness.

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

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

**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 Casagrain focus with NexStar4SE telescope. In this configuration, the camera covers  $100 \text{ mm} \times 120 \text{ mm}$  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.

**Designated Tool for This Process** For function of MCS-PFI coordinate transformation, we will use the first version for the scientific operation. For measurement of spot measurement, we will use MCS software itself. To check coordinate transformation algorithm, we will prepare a software to choose the fiducial spots and science spots.

### Success Criteria

MCS measures the fiber position consistent with pinhole array spacing at various telescope positions. The accuracy is less than 50  $\mu\text{m}$ .

Required long time to analyze the data?: Yes.

—It should take time to compare the positions derived with MCS with pinhole array, 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

MCS will be delivered to the Subaru telescope one year before PFI delivery. Hence, working process for PFI validation are considered assuming that we can install MCS to the Cassegrain focus.

### P- 1 Check of basic functions of PFI / OPot2 on stand-by condition [Daytime]

In this process, 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 viewing cameras can read image (bias/dark) with expected noise level
- Field center camera can read image (bias/dark) with expected noise level
- Telemetry sensors can be read
- Cooling system

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  $\pm 20 \mu\text{m}$ . This requirement is flowed down to L3-PFI-042, claiming the requirement for installation alignment accuracy with respect to the rotator coordinate:

- within 200 $\mu\text{m}$  in radial translation
- within 100 $\mu\text{m}$  accuracy in focus
- within 15 arcsec tilt ( 80  $\mu\text{m}$  @ outer ring of positioner frame w/ diameter of 1108 mm)

These requirements are for absolute positions. In addition to them, the repeatability within  $\pm 20 \mu\text{m}$  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  $\mu\text{m}$  with 0.21 mm gap between the dewar and the gear support). If we take the same procedure<sup>5</sup>, we will be able to achieve the same repeatability.

After the installation of PFI to POpt2, then the following functions are checked.

- Rotator: PFI can rotate from  $-270^\circ$  to  $+270^\circ$

At this point, the functions are controlled by `agccActor`, `fccActor`, `fvccActor` and `pebActor`, that these modules (actors) and their communication with Gen2 via MHS are also validated. **How about Cal. lamp?**

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

**Designated Tool for This Process** We will prepare a command sequence to check the basic functions. This sequence will be used as PFI health check.

#### 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 process, 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  $\mu\text{m}$  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 won't check how accurately PFI+POpt2 is installed, but will check repeatability by measuring the FoV center of PFI on MCS camera in the process P- 5. Once the repeatability will be found insufficient, we will have to check installation procedure of both PFI and MCS.

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

**Designated Tool for This Process** Nothing.

#### Success Criteria

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

<sup>5</sup>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 process, 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 again.
- Fiducial fiber cameras can read image (bias/dark) with expected noise level.
- Field center camera can read image (bias/dark) with expected noise level.
- Rotator can rotate PFI from  $-270^\circ$  to  $+270^\circ$ .
- All telemetry sensors can send proper status.
- Cooling system works.

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

- Fiducial fiber illuminator can be turned on/off
- Check back-illumination of science fibers (If SpS and Cable B are ready<sup>6</sup>)
- 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) fiber viewing cameras, center camera and calibration lamp are verified, the calibration data (flat and bias) for these cameras shall be obtained. (We probably don't have to acquire the calibration data so frequently — at the beginning of each run is enough?)

**Designated Tool for This Process** We will prepare a command sequence for checking basic functions, as P- 1. Also, we will prepare a command sequence for acquiring calibration data.

#### 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.

<sup>6</sup>As of January 2017, three Spectrograph Modules and Cable B will be ready before PFI delivery. Therefore, back-illumination function of these three SMs are checked at run 2. The function of the last SM will be tested at run 5 after its delivery. Besides, if we have time, we can regulate the brightness of fiducial fibers and science fibers, which will be done in the step A- 1.

## P- 4 Validation of MCS performance [Daytime]

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

After PFI and MCS are installed to the Prime Focus and the Cassegrain Focus, respectively, the image quality of the MCS is validated finally, 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 the fiducial fibers and the science fibers, and confirm the S/N meets the requirement ( $>$  several hundreds, according to CDR). We assume the science fibers, even though partly, can be back-illuminated, that is, the Back Illumination Assembly in the SpS subsystem does work (see P- 3, where we can do this step alternatively) <sup>7</sup>.

At the beginning, 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 ( $1 \text{ [W m}^{-2} \text{ sr}^{-1}] \pm 20\%$ ). 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 we confirm MCS can take fibers image with required S/N, 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. For the accuracy of the position of the spots, the requirement is less than 5um (0.08 pixel) rms, The validation will be processed as follows:

1. Take the image of back-illuminated fiducial and science fibers, and measure the FWHM of the PSFs.
2. Take several fiber images and calculate the positions errors at a given Elevation.
3. Repeating 1. and 2. at various elevations and rotator angles, test the stability of the image quality and derived centroids.

If we take 50 frames for a given elevation and rotator angle, it will take  $\sim 10$  minutes (see also M- 4). Assuming we test at 6 rotator angles (with  $60^\circ$  step from InR=  $-180^\circ$  to  $180^\circ$ ) for every 5 elevation (with  $15^\circ$  step from EL=  $30^\circ$  to  $90^\circ$ ), 5 hours are required for this test. Hence, 0.5 day is enough for this process, including the time for verifying the S/N of the spots.

Engineering run using the pin-hole mask showed a possibility that spot brightness may affect measured centroids, although it is small<sup>8</sup>. The images of different brightness can check this effect.

**Designated Tool for This Process** Nothing except for statistics of the measured values. For measurement of centroid and FWHM, we will use MCS software.

### Success Criteria

MCS can take fiber image and measure fiber positions.

The spot size is  $\sim 8.5\text{um}$  (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.

<sup>7</sup>According to the latest schedule (as of December 2019), Cable B1 and SM1,2, will be delivered before the PFI arrival. We will use B1 and SM1 for this process.

<sup>8</sup>PFS-MCS-ASI000115-03\_MCSCentroidAlgorithmReport.pdf



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

In this process, we measure offset of PFI in x/y direction by deriving its rotator center on MCS. By measuring this at 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 ( $< 50\mu\text{m}$ , see M- 2) and installing POpt2 to the top ring ( $\leq 10\mu\text{m}$ , see P- 2)

MCS has a function to measure rotation center given that rotation angle. Using this, at the run 2 we have developed a Gen2 command to rotate the InR, register centroids, and measure the rotation center on MCS camera. We shall use similar command.

The measurement is carried out in the following procedure:

1. Illuminate the fiducial fibers and/or science fibers. Measure the rotation center on MCS ( $x_{rot}, y_{rot}$ ) at zenith.
2. Compare ( $x_{rot}, y_{rot}$ ) 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, and/or MCS to Cs.
3. 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 offset in z direction and its repeatability will not be measured.

**Designated Tool for This Process** Nothing.

### Success Criteria

PFI x/y offset is measured and confirmed offset from the previous operation is smaller than 20  $\mu\text{m}$ .

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 process 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. The focusing procedure is proposed by Jim Gunn (PFI:336)<sup>9</sup>. With a glass plate covering half area of the detector, AG camera has two focus positions. Hence, the cameras can take out-focus/ in-focus image simultaneously, when the PFI is at focus. Measuring the spot size of stars at the area with and without glass plate,  $s_+$  and  $s_-$ , we calculate focus positions. Namely,  $\delta f = (s_+^2 - s_-^2)/(4\alpha\Delta)$ , where  $\Delta$  is 150  $\mu\text{m}$  from the current design. The parameter  $\alpha$  shall be calculated using simulated data (TBC), and in the commissioning sequence, we shall optimize the parameter  $\alpha$ . If 4 out of 6 cameras can take pair of stars (in/out), the error of estimation of focus seems  $\sim 10\mu\text{m}$  (Jim's document: PFI:336).

To determine  $\alpha$ , we

1. Slew the telescope to a given field.
2. Seek on-focus position changing  $z$  direction. Here either area with or without position is used.
3. Move focus position by 1.40 mm, then measure spot sizes ( $s_+$  and  $s_-$ ). In the current design, AG camera detectors locate 1.40mm back-ward from the best position of scientific fibers (see reference for REQ-SYS-1390).
4. Repeating step 1.–3. at a various telescope position, derive  $\alpha$ .
5. After deriving  $\alpha$ , slew telescope to a given field, configure fibers to stars somehow, and seek focus position using AG camera. Changing the focus position around on-focus position, estimate position accuracy. By taking spectra, check the consistency of the on-focus position between the science fibers and the AG cameras.

Assuming 10-sec exposure, it will take  $\sim 10$  minutes to execute step 1.–3. for a given field. Here we set 7 different focus positions. The same number is used to measuring the focusing accuracy (step 4.). If we visit three fields every  $15^\circ$  from El.= $30^\circ$  to El.= $75^\circ$  to derive  $\alpha$ , it will take 120 minutes. Another 40 minutes are needed to measure focusing accuracy. Therefore,  $\sim 3$  hours are required for this step, including time for analysis.

**Focal plane characterization**  $z$ -position of each AG camera needs to be checked to make sure every AG camera makes the same plane when we rotate the instrument rotator. The procedure is:

1. Slew the telescope to a given field.
2. Check focus position on each camera.
3. Rotate the instrument rotator and check focus on each camera.
4. Repeat item 3. and compare the planes which each AG camera travels.

Note that this test can be done with data taken below (“Pixel scale and orientation on the sky”).

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<sup>9</sup>As of February 2020, Satoshi Kawanomoto from NAOJ is thinking algorithm too. This process may change following to discussion in the future

**Pixel scale and orientation on the sky** Secondary, we measure pixel scale and orientation of the AGCs in the following steps. Because AG cameras locate every  $60^\circ$ , we have to measure the orientation individually (see below).

1. Slew the telescope to the star clusters, and measure the pixel scale by the astrometry of stars on sensors.
2. Put slight offset on the telescope in R.A and Dec. direction individually, and check the orientation of the x/y direction. (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  $5 \times 4$  (position)  $\times 6$  (sets) = 120 min in total. Here, 4 positions are needed to measure the x/y direction: the origin and 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  $0^\circ$ . Therefore 6 sets are needed. Note that if there are any fields for the two diagonal AG cameras to have enough number of stars, we can reduce to 3 sets. Including the time to execute astrometry and calibration, 150 minutes = 2.5 hours 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.

Validation is done following standard procedure for Acquisition and Guidance and Auto Guide:

1. Slew telescope to a given field.
2. 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.
3. 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.
4. Keeping guiding for a couple of minutes, 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.

**Designated Tool for This Process** Spot size and spot position are measured by ICS module (Auto Guide Camera Controller). Using these values, a script is needed for seeking on-focus position using either in-focus or out-focus area. Also, a script to measure the orientation of the camera and an analyzer for brightness of spectra are needed. Astrometry should be done using specified script.

#### Success Criteria

Acquisition and Guidance, focusing, and Auto Guiding can be executed using AGCs. The focus is measured with the accuracy of  $\sim 10$   $\mu\text{m}$

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 defocused 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. In this process we optimize the Hexapod position for PFS.

We use out-focused ( $\Delta D5=0.5\text{mm}$ ) image of the bright star on AGCs to measure shift and tilt of WFC with respect to M1 and correct them. Yoko Tanaka (Subaru) and Satoshi Kawanomoto (Mitaka) from NAOJ have developed to measure shift and tilt of Hexapod. [See Tanaka's report (WFC\_position.pdf: in Japanese), and Kawanomoto's report (20190719.pdf: in Japanese) for detailed procedures.]

The alignment procedure is as follows:

1. Check focus, and defocus by  $\Delta D5=0.5\text{mm}$ .
2. Slew the telescope to a field where we have a few stars on AG.
3. Acquire the image (120 sec and a couple of frames). To measure tilt and shift of WFC, 6 defocused image are needed on every AG camera.
4. Measure Hexapod shift and tilt and apply correction.
5. Repeat 3 and 4 a few times until shift and tilt meets the requirement.

These algorithm have been tested using HSC. At te HSC run in May 2020, it took 20–30min to align WFC in a few iterations with Kawanomoto method.

The parameters of Hexapod for alignment is registered as a function or table with respect to the elevation. Therefore, we measure the Hexapod 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, 450 minutes, or 7.5 hours are needed for the correction. In the current plan, we will derive the function of Hexapod parameters with 2 sets of measurement at the runs 3. At the next run, we will execute

the other 1 set to check the registered function, and modify if needed. Note that it will be fine visit apart of 5 positions above to check the alignment, but it will be better to modify the functions with measurement at all 5 positions.

**Designated Tools for This Process** This process needs designated scripts (1) to measure shift and tilt and correct them, and (2) to determine the function of Hexapod parameters with respect to the elevation, or create tables.

#### Success Criteria

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]

Once the alignment of WFC with the primary mirror is confirmed at a given telescope position (P- 7), we can confirm and refine PFI–MCS relation using fiducial fibers in this process (see also PFS-GEN-IPM004015-01.PFScoordinates.pdf).

Prior to the integration, the focal plane from the viewpoint of MCS (F3C–MCSC relation) has been calculated with ZEMAX, using the WFC as-built model. (the function form: TBD) Using this formula, we calculate the positions of fixed fiducial fibers on F3C.

The physical positions of fixed fiducial fibers on focal plane, on the other hand, will be measured during the PFI I&T process at ASIAA before shipment. By comparing derived positions with the physical positions, we refine the position of the fixed fiducial fibers on F3C.

We will carry out this process as follows:

1. Take the images of back-lit fixed fiducial fibers with MCS, and transform the centroid on MCSC to F3C.
2. Compare measured fixed fiducial fiber positions with physical positions. Here, we aim at getting these positions consistent with each other by 10 um RMS (TBC). If the positions of fixed fiducial fibers are consistent between F3C and physical position, the position on F3C are registered. The firer positions with terrible discrepancy shall be excluded from F3C.
3. Check dependency of the offset of fiducial fiber positions at various RoA and El, although the offset is negligible given that PFI should be solid. If the displacement of given fiducial fibers is quite large and randomly, we should exclude those fibers from F3C.

At this point, the transforming function from the MCS coordinate to the F3C coordinate is defined. If we take  $\sim 10$ – $20$  images to measure fixed fiducial fiber position on F3C,  $\sim 15$  minutes is quite enough. Including comparing positions, updating the coordinate transformation (and hence softwares), 1 day is enough for this process.

Once MCS-F3C transformation is confirmed, one 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.

**Designated Tool for This Process** A tool for plotting physical positions and F3C positions, to compare them easily. Centroids on F3C will be derived in the standard way for coordinates transformation (by Fiber Positioner Sequencer).

#### Success Criteria

PFI–MCS relation is calibrated and MCSC–F3C transformation is confirmed.  
 Fixed fiducial fibers position on F3C is consistent with physical position by 10  $\mu\text{m}$  RMS (TBC),  
 Required long time to analyze the data?: No.  
 — We shall analyze the data in real-time.

## P- 9 Telescope Pointing Analysis [Night-time]

Although there are originally 1-, 5-, 32-points Telescope Pointing Analysis (TPA) functions on the Subaru telescope, PFS can execute only 1- TPA<sup>10</sup>. 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 executes TPA. (Note that 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. Calculate the Az/El offset, by measuring offset of the star from where it should be.
4. Repeat step 1.–3. for different stars. We will visit every  $30^\circ$  in the azimuth direction and every  $15^\circ$  from  $30 - 75^\circ$  in elevation. 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 efficiencies, as the additional parameter.

Assuming it will take 300 sec to obtain the data in a given field, 4 hours ( $300 \times 48$  seconds) are required. We derive mount correction efficiencies in a run, and check them in another run. In total, it will take 8 hours to complete this process.

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

**Designated Tool for This Process** It depends on ICS software (MAC: MLP1 AGCC Converter) has this function (TBC).

#### Success Criteria

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

<sup>10</sup>It is noted that 1-TPA for PFS doesn't seem Subaru standard manner.

## 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<sup>th</sup>-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 process, we calibrate the distortion map purely by the AGCs with no fibers involved (First pass distortion map). This process comprises two major sequences: calibration of the sky scale, and astrometry on AGCs.

**Calibration of the Sky Scale** Firstly, we calibrate the sky scale on F3C (focal plane). For this calibration we measure the position of A&G camera relative to their two fixed fiducial fibers.

We proceed this sequence as follows:

1. Slew the telescope to have a star in the center of either half area of a given A&G camera. To proceed step 2. easily, rotate PFI for the target camera to locate PA=0. Note that the center of the A&G camera cannot be used because of the shade of the glass plate.
2. Move the telescope to have the AG fixed fiducial fiber pointed to the star. Then execute the raster scan around the fixed fiducial fiber and calibrate the distance between A&G camera and the fiber.
3. Repeat 1. and 2. for the other half area of the AG camera.
4. Repeat 1.–3. for all fixed fiducial fiber of all 6 A&G cameras.

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.

Assuming that we take 9 images for each AG fixed fiducial fiber ( $3'' \times 3''$  grid), it will take 10 minutes to take a set of raster scan images, including the moving telescope, readout, etc. Therefore,  $10 \times 2$  (areas)  $\times 2$  (fibers)  $\times 6$  (cameras) = 240 minutes (6 hours) is requires for this sequence.

**Typical exposure time of fiducial fiber viewing camera.**

**Astrometry** Secondary, we make distortion map by images from the 6 AG cameras. The total field of view of the A&G camera is  $5.5 \text{ arcmin}^2 \times 6 = 33 \text{ arcmin}^2$ . AG camera is lightly out of focus when we focus the telescope; a half region of camera is inside, while the other half outside. However, the accuracy in calculation centroids of a spot is  $\sim 3\mu\text{m}$ , referring estimation by Jim Gunn: **Focus Offsets, Sensitivity, and Star Counts for AG Cameras** (ver. 2015.05.18), is small enough to make the distortion map (accuracy:  $\sim 50\mu\text{m}$ ).

We proceed this sequence as follows:

1. Take deep images ( $\sim 60$  sec exposure: TBD) of bright stars with good astrometry. We take 3–5 images for statistics.
2. Derive distortion of AG cameras by measuring the positions of stars on camera and comparing with catalogue. Update the distortion map of the entire FoV by interpolating with the new A&G distortion map.



3. Repeat 1.–2. at various elevation and azimuth and refine the map as a function of El, Az, and ROA. At present, we will visit from EL=30, 45, 60 and 80deg, and 2–4 Az positions at every elevation (TBD).

Using the calibrated data, the transformation from Sky Catalogue to F3C is refined. The new distortion map is called “1<sup>st</sup>-pass” distortion map.

Assuming it will take  $\sim 15$  minutes for a given field, 80 fields will be visited in 20 hours. We will execute this process at two turns. At the first run, we will calibrate sky scale and do astrometry using  $\sim 50$  fields to make the first distortion map. Using the first distortion map, we visit the several fields to check this map and update it if needed.

At this point, we can configure the science fibers and take spectra to demonstrate the instrument performance. So we take fiber spectra for a couple of fields.

**Designated Tool for This Process** A method is needed to analyze AG camera images for astrometry, and analyze raster scan data of the five viewing cameras. **To do: Check output from fvcactor. If it outputs intensity of the fiber spot, the method will be simple..**

#### Success Criteria

The “1<sup>st</sup>-pass” distortion map is obtained with the accuracy of 50 $\mu$ m

Required long time to analyze the data?: Yes.

— It shall take 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 in the designated room called SCR (Spectrograph Clean Room) on the IR4 floor, where the temperature is controlled from 3 degC to 5 degC. The Camera Assemblies are cooled down in the cryostat. On the below floor (IR3), the compressors will be used during the operations. Under such a condition, the following functions of SpS assemblies as well as SCR functions should be verified:

- The temperature in SCR can be controlled stably in the range from 3 degC to 5 degC.
- All SMs can switch Medium-Resolution mode and Low-Resolution mode (red arm).
- All SMs can open and close blue and red shutters.
- All SMs can move all other mechanical part. **Name**
- All SMs can back-illuminate the fibers (by looking from GANG connectors of cable A?)
- All SMs can read telemetry sensors
- All SMs can read their all detectors within expected noise – dark, bias.
- 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 test that the SMs can be operated stably (with good thermal and optical performance) for longer time scale ( $\sim 10$  days and longer).
- We demonstrate power failure mode
- The exposure sequence works.

**Designated Tool for This Process** We will prepare commands to check SpS functions. This might be used as health check of the subsystems (TBD).

#### Success Criteria

All basic function of SCR and SpS is verified.

## S- 2 Characterization of SpS [Daytime]

In this process, we characterize the SMs using arc lamps and continuum lamp. 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<sup>11</sup>. Note that LAM also has a plan to characterize each SM during their AIT work<sup>12</sup>. Compared to SM AIT work, we aim to characterize spectra in wider range both spatially and spectrally. According to the document by Sandrine Pascal (LAM; `PFS-DummyCableB_V1.0.pdf`), Dummy Cable B has 4 sets of 7 fibers and 8 sets of single fibers. We can use 5 out of 8 sets at a time.

**PSF and spectral distribution measurement** We take arc-lamp image and continuum lamp image, and measure PSF and spectral distribution of various fibers on the detectors, respectively. These images are sent to DRP development team, who will analyze them in detail. **Fiber configurations for measurement is TBD.**

**Spectral resolution** We take the arc-lamp images, and measure FWHM of the spots. Then we estimate spectral resolution including wavelength dependence, and compare with specifications. The requirement for the spectral resolution (**REQ-SpS-42 (Analysis)**) is:

- $>2300$  @ 520 nm (blue)
- $>2800$  @ 810 nm (red, LR),  $>5000$  @ 810 nm (red, MR)

<sup>11</sup>To achieve characterization well, lamps with large wavelength coverage would be ideal. We need black body lamp for throughput measurement, but should input the light from slit or GANG connector.

<sup>12</sup>See their document for validation roadmap (`LAM.PJT.SUM.DS.1024.1-4.VerificationRequirements.pdf`);  $\lambda$  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?).

- >4100 @ 1110 um (nir)

We will characterize at least 4 fibers at the outer-most and inner-most of up and down areas, and all 3 sets of 7 fibers.

**Wavelength coverage** We take continuum and measure the effective area for signal, and take arc-lamp image and derive pixel-wavelength relation. Then we estimate wavelength coverage using the relation, and compare with specifications. The requirement for the wavelength coverage (REQ-SpS-41 (Analysis)) is:

- 380–650 nm (blue)
- 630–970 nm (red, LR), 710 - 885 nm (red, MR)
- 940–1260 nm (nir).

As spectral resolution, we will characterize at least 4 fibers at the outer-most and inner-most of up and down areas, and all 3 sets of 7 fibers.

**Throughput** Given that throughput will be measured at LAM before shipping to Subaru (discussion in the 8th collaboration meeting in December 2016), this measurement is probably optional. For the condition of experiment at laboratory is more stable than at the summit.

Nevertheless, in this paragraph the procedure is described for throughput measurement. We illuminate GANG connector with a black body lamp, and take fiber images. We count the intensity of the detector, and measure throughput of the SpS itself. We compare the measured values with specifications, which is estimated by combining the performance of each element (LAM). If measured throughput is inconsistent with analyzed one, consider possible causes (vignetting, background etc.) For this measurement, the stability of the black body lamp (TBD) is needed.

The requirement for the throughput of SpS (REQ-SpS-48 (Analysis)) is in Table 6:

Table 6

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

**Designated Tool for This Process** A tool for FWHM measurement is needed. For throughput measurement, illuminating system including light source is needed.

**Success Criteria**

SpS is characterized. These characters is consistent with expected by specification. **Required long time to analyze the data?: Yes.**  
 — No, but we don't need to analyze on real time for this process. This process doesn't require the telescope, either.

**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)<sup>13</sup>. 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 process, we check fibre-slit relationship. It is defined in e.g.

<http://sumire.pbworks.com/w/file/76743299/FiberMapping.pdf>. There are four cables connecting PFI and SpS (Cable B), each of which deliver lights to four spectrograph module.

The ID of Cobra positioner and position on the Spectrograph detectors is checked by hiding a given fiber by the field element dot. The detailed procedure is as follows:

1. Move all fibers out of the dots.
2. Back-illuminate fibers by each Spectrograph Module, and take the MCS image. At this point, we check the fiber mapping in unit of Spectrograph Module. On the other hand, take flat image. In this step, we have four MCS image and four SpS images with all fibers illuminated (Images set A).
3. Move given two fibers  $(i, j)$  to be obscured by dots, and take MCS image and SpS image (Images set B).
4. Move one of these two fibers  $(j)$  out of the dot and another fiber  $(k)$  onto the dot. Take MCS image and SpS image (Images set C).
5. Comparing image sets A, B, and C, identify three fibers. Fiber  $i$  is hidden for both B and C,  $j$  is hidden for B, and  $k$  is hidden for C.
6. Repeat 3.–5. for other three fibers  $(i', j', k')$ .

<sup>13</sup>The connection of Cable B–A may be not off so often once it has connected.

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.

There are 2394 fibers in total, among which 600 fibers are assigned to SM 1 and 2 each, and 597 fibers to SM 3 and 4. Hence, 200 or 199 series of the image sets B,C are required. (Image set A is shared for all fibers.) We can check fibers for different modules, once we confirmed their IDs in unit of SMs (in step 2.).

Assuming that it will take  $\sim 3$  minutes to get a series of image sets, 1 day is required for this process. Because SMs other than SM4 will be available at run 2, another 1 day will be needed at run 5.

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<sup>14</sup>.

**Designated Tool for This Process** Nothing. At present, it is planned to simply subtract the images to find which fiber is hidden.

#### Success Criteria

Fiber positions on PFI and SpS are confirmed.

## 2.5 Commissioning of All Systems

### A- 1 Measurement of Cobra Geometry Parameters and Motor Map [Daytime]

In this process, we measure The “Cobra” geometry parameters such as the center position, arm length, hard stops. In order to move Cobras, FPS (and its libraries) should obtain firstly the following parameters (Figure 12):

- $\mathbf{X}_{c,k} = (x_{c,k}, y_{c,k})$  : center position of the positioner
- $a_{1,k}$ : arm lengths of  $\theta$  stage
- $a_{2,k}$ : arm lengths of  $\phi$  stage
- $\theta_{CW,k}$ : CW limit of  $\theta$  stage (angle or position)
- $\phi_{CW,k}$ : CW limit of  $\phi$  stage (angle or position)
- $\theta_{CCW,k}$ : CCW limit of  $\theta$  stage (angle or position), and
- $\phi_{CCW,k}$ : CCW limit of  $\phi$  stage (angle or position).
- Motor map

Note that these parameters are calculated in F3C [mm]. We shall derive these parameters in this phase using back-illuminated fibers (BIA or alternative light sources).

We shall back-illuminate the science fibers in the normal mode. We shall take fibers image using MCS in both short-exposure and long-exposure mode ( $\sim 1$  second) with “Cobra” rotating. Because

<sup>14</sup>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.

one MCS image has arcs of illuminated fibers, we combine the images, or use the spot positions which MCS measures. 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  $\theta$  and  $\phi$  stage individually to determine these parameters. To void the collision, the calibration of  $\phi$  motor is done at first. Then  $\theta$  motor is calibrated by setting the Cobras at “the safe position”. The detailed procedure is presented in `PFISoftwarePreship_20210514.CHYan.pdf` (by Chi-Hung Yan).

Derived parameters are stored in the xml file. Then, we also validate the following items:

- Target convergence.
- Home position repeatability.
- Dots can be obscure the Fibers. We move the fibers to the dot positions and turn on the calibration lamp. Take SpS image and check if the fibers are obscured or not.

Because only SM1 is ready by the run 3 (September 2021), when Cobra calibration is scheduled, we will back-illuminate fibers using a dedicated illuminator attached to the Tower I/F plate.

We estimate 1–2 days for calibration of all the cobra parameters and motor map.

**Designated Tool for This Process** Nothing. FPS can take care the calibration.

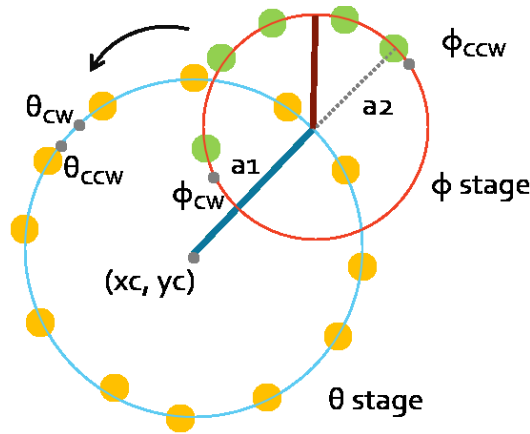


Figure 12: Schematic picture of Cobra parameters. Orange and green spots imply the positions of blinking fiber in F3C. Light-blue and red circles indicate fitted circles for fiber spots.

### Success Criteria

The brightness of back-lit fibers are regulated.

Parameters of each Cobra  $(x_{c,k}, y_{c,k}, a_{1,k}, a_{2,k}, \theta_{0,k}, \theta_{m,k}, \phi_{0,k}, \phi_{m,k})$  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.

## A- 2 Characterization of PSF and Spectral Distribution [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. Check wavelength resolution, wavelength coverage for all fibers.

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<sup>15</sup> 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 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.).

<sup>15</sup>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.

**Characterization according to Cobra Movement** In this sequence, we also examine PSF variance with respect to the Cobra rotation angles ( $\theta$ ,  $\phi$ ). 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, 2, and 3 will be delivered ahead of the delivery of PFI. Therefore, we can repeat the same test for the first three SMs when SM4 will be tested. Alternatively, if we can characterize PSF well for the first SMs, we can limit the PSF test for the last SM, 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.

**Designated Tool for This Process** Detailed analysis will be done by 2D-DRP team (Princeton). For PFS commissioning, a tool for measure FWHM is needed.

#### 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]

After the process [P- 10](#), the science fibers should be pointed to the targets with the accuracy of  $\sim 50$   $\mu\text{m}$  (at least less than 100  $\mu\text{m}$ ). In this step, we will do raster scan to improve the distortion map and achieve the fiber pointing accuracy of  $\sim 10$   $\mu\text{m}$  RMS.

The process is as follows:

1. Slew the telescope to the field where enough bright stars is cataloged with good astrometry (see section [3](#)).
2. Put these bright stars on the science fibers and take fiber spectra with the telescope moving in  $3'' \times 3''$  grid, approximately three time as large as the fiber core diameters. Note that the raster with 5 position of hexagonal pattern provide denser scan than the grid (TBD).
3. Calculate the brightest position by comparing the intensity of these spectra.

4. Repeat 1.–3. for several fields at various telescope positions, and calibrate the distortion map.
5. Check the dependency of the map on wavelength, and check if ADC works correctly, by comparing the observed positions with predicted ones by ADC.

Calibrations will include the following factors:

- 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)

Assuming we take 120- –150-second exposure for a given position, it will take  $\sim 30$  minutes including slewing, fiber configuration, and acquiring sky frames. We will take 2 sets of  $4 \text{ El} \times 4 \text{ RoA}$  positions ( $\sim 8$  hours) to study the dependence of the above parameters. We repeat 2 times of these sets using SMs 1–3 (runs. 4 and 5). Note that fibers of each SM are arranged on the focal plane to cover entire field of view, we can study distortion without SM4. However, we will check and finalize the distortion map using all SMs at run 6. In total, 5 nights are required in this process.

When the second distortion map is made, update ETS using this map, and/or update the repository for coordinate transformation (TBC).

**Designated Tool for This Process** A tool for measuring the brightest position from raster scan data.

#### Success Criteria

Second distortion map is obtained with error less than 10 $\mu\text{m}$ .

Required long time to analyze the data?: Yes.

— It takes time ( $\sim$  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  $\mu\text{m}$ . 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. At this stage, we will obtain the following data set:

- Set I). A field with only blank fibers
- Set II). A field with bright stars whose absolute flux is well estimated.
- Set III). A field with faint galaxies and/or stars, accommodating a variety of exposure times up to  $\sim 10$  hours.

Using the above data set, we will verify the following performances (it indicated which data set to use for each item):

- Verification of the observation sequence (Set I, II, III)
- Measurement of the total throughput (Set II)
- Verification of the absolute flux calibration (Set II)
- Verification of sky background subtraction (Set I)
- Verification of the limit of exposure time in each frame (Set I, II, III)
- Verification of observations with a long total exposure time (Set III)
- Verification of re-configuration of cobra during scientific observations (Set III)
- Verification of beam-switching mode (Set III)
- Verification of Quality Assurance procedure (Set III)
- etc.. (TBD)

Hereafter, the detailed process is described for each performance.

**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  $< 10\mu\text{m}$ . We shall take 900-sec exposure, during which the tracking error should be  $\sim 0.2$  arcsec rms by auto guiding (0.2 arcsec rms for 10 minutes and 0.6 arcsec rms for 30 minutes: 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  $\mu\text{m}$ .
- 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 —  $\sim 12\%$  (380–450 nm),  $\sim 21\%$  (450–550 nm) and  $\sim 24\%$  (550–650 nm)

RED arm (LR) —  $\sim 30\%$  (630–750 nm),  $\sim 29\%$  (750–850 nm) and  $\sim 27\%$  (850–970 nm)

RED arm (MR) —  $\sim 26\%$  (710–875 nm),  $\sim 28\%$  (775–825 nm) and  $\sim 27\%$  (725–885 nm)

NIR arm —  $\sim 17\%$  (940–1050 nm),  $\sim 19\%$  (1050–1150 nm), and  $\sim 17\%$  (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 % accuracyREQ-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 ( $\sim 10$ -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** TBW.

#### 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]

In the previous commissioning process (A- 4), basic instrument parameters and performance will be revealed. After this phase, a normal observational sequence can be done properly using almost the same software interface used in actual survey observations including data reduction pipeline.

In this this commissioning phase, we will stabilize the instrument operation and the performance optimizing the softwares and the operation processes for long-term survey observations. Specifically, we will conduct the following verifications:

- Long exposure of faint galaxies and stars
- DRP optimization using a wide variety of galaxies and stars
- Confirmation that there is no time change of the performance

#### Success Criteria

- Confirm that observation process can be done properly and stably
- Confirm that there is no time change of the instrument performance
- Confirm that a sufficient number of galaxies and stars was observed to optimize the 1D-DRP using a machine learning technique

## A- 6 Data acquisition of standard stars [Nighttime]

During the commissioning, the data acquisition of the following standard stars are necessary:

- Flux standard stars
- Radial velocity standard stars
- Telluric line standard stars
- (Abundance standard stars)
- ( $\log g$  standards stars)

for DRPs development. Note that abundance and  $\log g$  measurements are out of scope of the DRP performance since they are not measured by 1D-DRP.

Assuming that the fibers don't need to be configured so precisely, we may take these standards by selecting the fields for processes [P- 10](#) and [A- 3](#).

**Designated Tool for This Process** Nothing, as this is data acquisition by setting the targets for other tests. DRP team will develop their tools using the data.

### Success Criteria

Acquire enough data of the standard stars.

Required long time to analyze the data?: No.

— DRP team will develop their tools using the data.

## 2.6 Required Tools

As shown the above, a various tools are requires, some of which is used for scientific operation and other of which is designated for the commissioning (or engineering). Table [7](#) summarizes input and output of individual tools.

Table 7: The list of tools used for PFS commissioning (TBW). Column 4 describes a method to see if the success criteria (column 3) is satisfied. The tools in the blue row are designated only for the PFS commissioning.

M- 1 and M- 3: Initial check of MCS				
Inputs	Outputs	Success Criteria	Method	Notes
Gen2 command to acquire MCS image.	Shutter moves (if needed) and MCS image is saved.	Image is acquired with name and headers along with datamodel, and is archived.	Check if the file exist in target place. Check the filename and header.	
Gen2 command to open/close MCS shutter.	Shutter moves and its status returns.	Shutter movement and status are consistent.	Take image after moving shutter. Alternatively, hear shutter moving using microphone.	
Gen2 command to read MCS temperatures.	Values of the temperature sensors return.	The temperature values are correct.	See if the sensor value is reasonable by compare the dome temperature and/or history.	
Gen2 command to read MCS coolant flow.	Value of the flow meter returns.	The flow value is correct.	See if the sensor value is reasonable.	
Gen2 command to listen (Gen2 command to listen microphone?)	Sound from microphone.	Sound is transferred correctly.	Make some sound around the microphone and listen to it.	How to transfer audio is under discussion.
Gen 2 command to execute the above in sequence.	Outputs of individual commands.	Individual commands succeeded.		
Gen2 command “for IIC” to change the telescope Az. after taking image.	Images are taken before and while telescope moves.	Az. moves after an MCS exposure.	Check telescope status and/or MCS image and if the telescope moves.	Demonstration of “callback” function.
M- 4 : Study of the prime focal plane				
Inputs	Outputs	Success Criteria	Method	Notes
Gen2 command to acquire a series of MCS images ( $\sim 10$ or 20 frames).	MCS images are saved.	Images are acquired and archived.	See if the images exist in target place.	

Table 7: The list of tools used for PFS commissioning (TBW). Column 4 describes a method to see if the success criteria (column 3) is satisfied. The tools in the blue row are designated only for the PFS commissioning.

(Gen2) command to measure the spot centroids.	Spots are identified and their centroids are measured.	Centroids are measured and saved with IDs.	Check the database.	(ICS/MCS)	
Gen2 command to change telescope El. and InR.	Telescope moves and its status returns.	N/A	N/A		The telescope movement itself is out of the scope of the PFS commissioning.
A series of ( $\sim 100$ frames) measured centroids.	Average of the centroids.	Averages are obtained.	Compare individual data and average for one or two spots.		
Position on MCS.	Position on F3C.	Coordinates are transformed within accuracy of TBC um (on prime focal plane).	Compare calculated positions to hole positions as designed.		Coordinates transformation function will be developed in analyzing the data.



### 3 Selection of Observing Fields [TBD]

In this section, we describe the preparation of target objects for the on-sky commissioning and the performance verification. We suppose three cases of target fields, 1. a field with many bright stars such as an open cluster for the raster scan, 2. a field with a sufficient number of bright stars such as an SDSS field at high galactic latitude for the throughput measurement and the verification of the flux calibration, 3. a field with faint galaxies and stars for the verification of long exposure. We briefly describe each case and possible candidate targets below.

#### 3.1 Open Clusters as the Raster Targets

For the raster scan process, targets should be sufficiently bright and point sources for the accurate evaluation in the analysis. In addition, they should cover the entire PFS FoV and the number density should be matched to the PFS fiber density. Open clusters with sufficient bright member stars in the Galaxy are plausible targets for the raster scan.

The candidate 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  $\sim 2000$  open clusters. Figure 13 and Figure 14 show the spatial distribution of the open clusters with the apparent diameter ( $d$  [deg.]) of  $> 30$ . There exist  $\sim 130$ ,  $\sim 50$ ,  $\sim 30$  open clusters with the apparent diameter of  $30 < d < 60$ ,  $60 < d < 120$ , and  $d > 120$ , respectively. The typical number of member stars is  $\sim 1000$ .

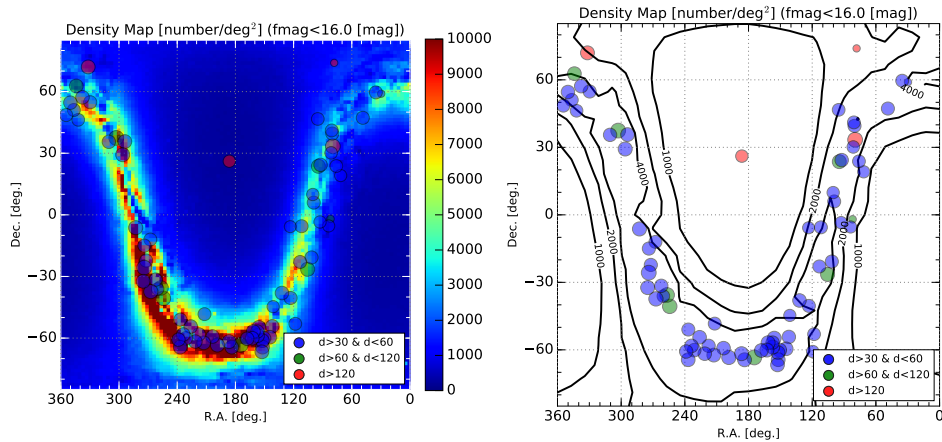


Figure 13: Stellar density with objects  $f < 16.0$  mag taken from UCAC4 catalog in color map (left) and contour (right). The spatial distribution of open clusters with the apparent diameter ( $d$  [deg.]) of  $d > 30$ . from DAML02 catalogue is also plotted in both panels. Open clusters with  $30 < d < 60$ ,  $60 < d < 120$ , and  $d > 120$  are shown by *blue*, *green*, and *red circles*, respectively. The size of symbols represents the number of member stars.

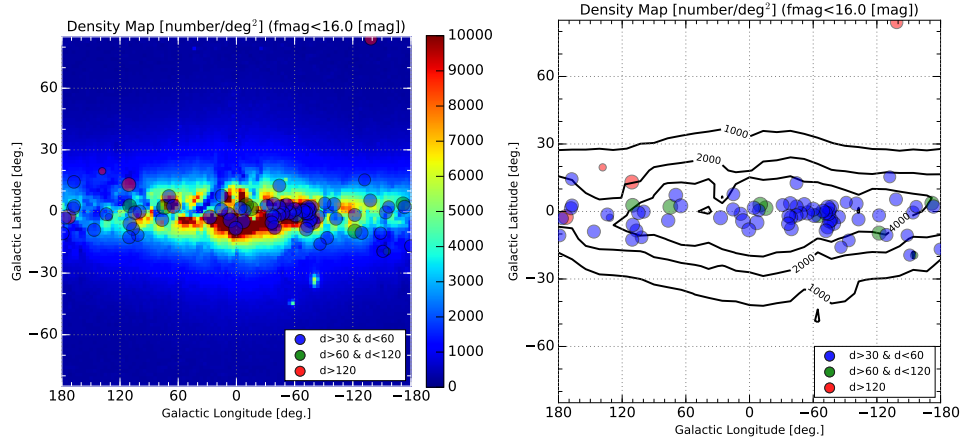


Figure 14: Similar to Figure 13, but on the Galactic longitude and latitude.

Table 8

Name	R.A. [hh:mm:ss]	Dec. [dd:mm:ss]	Diameter [arcmin]	# of members	Mag. limit [mag]
Collinder 464	05:12:39	+73:58:29	120.0	5212	TBC
Melotte 31	05:18:10	+33:22:25	135.0	14341	TBC
Melotte 111	12:25:06	+26:06:00	120.0	863	TBC
Collinder 471	22:07:06	+72:00:00	130.0	4573	TBC
ASCC 19	05:27:47	-01:58:48	96.0	2412	TBC
Collinder 89	06:18:00	+23:38:00	60.0	2971	TBC
Alessi 33	07:01:59	-26:30:12	60.0	3371	TBC
IC 2944*	11:38:20	-63:22:22	65.0	8860	TBC
Trumpler 24*	16:57:00	-40:40:00	60.0	5720	TBC
ASCC 88*	17:06:47	-35:36:00	66.0	6501	TBC
ASCC 111	20:11:13	+37:27:00	66.0	8004	TBC
ASCC 125	22:56:17	+62:45:00	66.0	2332	TBC

\*: These targets cannot be observed with a good visibility.

### 3.2 Field Bright Stars

As Figure 13 and Figure 14 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 13 and Figure 14, 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  $f < 16$  mag in  $b < 60$  deg.

### 3.3 Faint Galaxies and Stars

Basically, faint targets to verify the system performance will be selected from objects detected with HSC imaging data, which are candidate targets in the actual large survey with PFS. Inputs from 1D-DRP are appreciated as training/test set.

### 3.4 Detailed Procedure of Raster Scan

TBW

### 3.5 List of Candidate Raster Fields

TBW

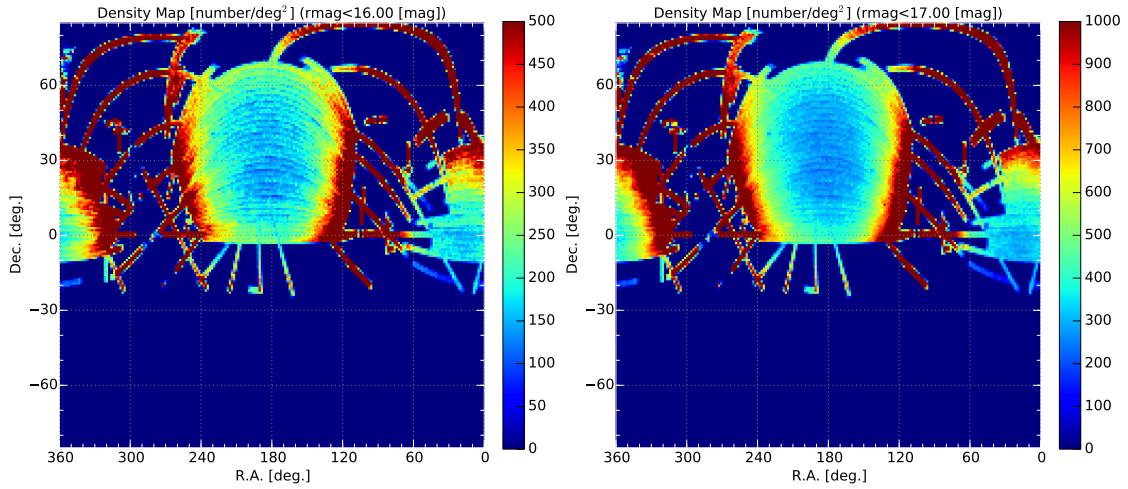


Figure 15: Stellar density with objects  $r < 16.0$  mag (left) and  $r < 17.0$  mag taken from SDSS DR12 catalog in color map.

### 3.6 List of Standard Star Catalogue

TBW: The data of the following standard stars are necessary for DRP/GA team:

- Flux standard stars
- Radial velocity standard stars
- Telluric line standard stars
- Abundance standard stars

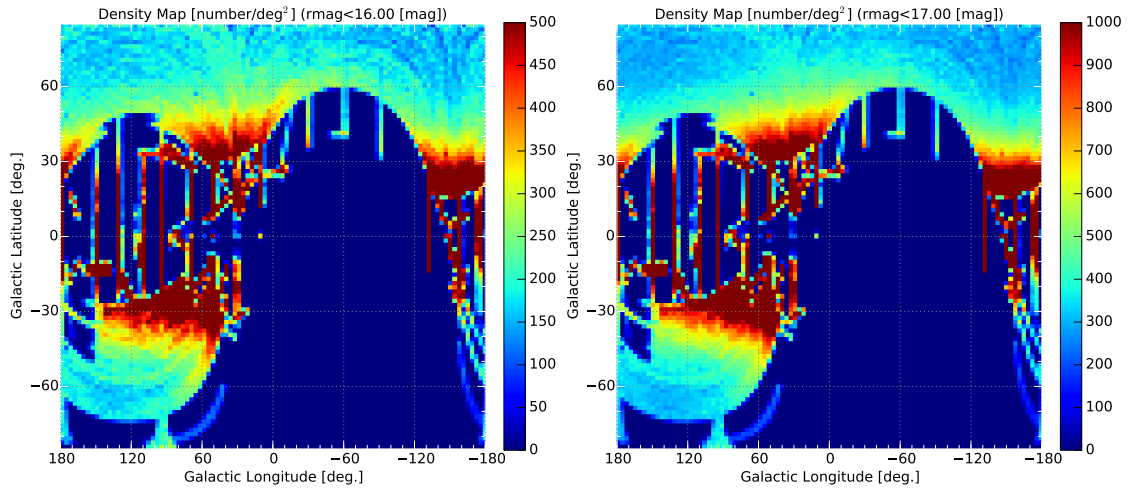


Figure 16: Similar to Figure 15, but on the Galactic longitude and latitude.

- $\log g$  standards stars

## 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 Summary of Fundamental Functions of Subsystems to be Achieved before PFS Commissioning.

Table 9 lists subsystems functions which should be validated before PFS commissioning. In column 1 is listed the ID of function. In column 2 is written brief description of the function. In column 3 are listed related items in compliance matrix of PFS commissioning (table 2). In column 4, checked-mark will be put when the function will be validated. In column 5 is listed reference in PFS requirements. In column 6 are written other notes.

Table 9: The list of fundamental functions validated before the commissioning.

No	Functions	No. of Table 2	Succ.?	Req.	Notes
<b>PFI (including Cable C)</b>					
P01	Instrument rotator moves from $-278^\circ$ to $+278^\circ$ .	8			
P02	Positioning error of A&C camera is $\sim 2.8$ um.	25			CDR
P03	PFI has 97 fiducial fibers.			REQ-F0C-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, 34			Relative to nearest perimeter fiducial fiber.
P10	The position of AG camera sensors is measured in the accuracy of 10 um PTV.	19, 21			Relative to nearest perimeter fiducial fiber.
P11	The focus position of science fibers is measured in the accuracy of 12 um PTV.	34			Relative to designed focus position.
P12	The focus position of perimeter fiducial fibers is measured in the accuracy of 12 um PTV.	26, 34			Relative to designed focus position.
P13	The focus position of AG camera sensors is measured in the accuracy of 12 um PTV.	19			Relative to designed focus position.
P14	The tilt of science fibers is measured in the accuracy of $0.17^\circ$ PTV.	34			Relative to a fiducial fiber near the center.
P15	The tilt of perimeter fiducial fibers is measured in the accuracy of $0.17^\circ$ PTV.	26, 34			Relative to a fiducial fiber near the center.
P16	The tilt of AG camera sensors is measured in the accuracy of $0.17^\circ$ PTV.	19, 21			Relative to a COB rear surface.
P17	P05-P16 are achieved with rotation angle of $0, \pm 60^\circ$ and El. $90, 60, 30^\circ$				CDR

Table 9: The list of fundamental functions validated before the commissioning.

No	Functions	No. of Table 2	Succ.?	Req.	Notes
P18	The cobra positioner converge to requested x/y position in the accuracy of 10 um PTV.	34, 35			
P19	P18 is achieved with rotation angle of $0, \pm 60^\circ$ and El. $90, 60, 30^\circ$				CDR
P21	AG camera shall acquire image.	19, 21, 23, 25			
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			
...	...	...	...	...	
<b>MCS</b>					
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 can 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			
...	...	...	...	...	...
<b>SpS (including Cable A)</b>					
S01	The blue detector shall be cooled down to operating temperature ( $173 \pm 0.5$ K)			SPS-REQ-307, SPS-REQ-202, SPS-REQ-95	
S02	The red detector shall be cooled down to operating temperature ( $173 \pm 0.5$ K)			SPS-REQ-307, SPS-REQ-203, SPS-REQ-95	
S03	The nir detector shall be cooled down to operating temperature ( $110 \pm 0.5$ K)			SPS-REQ-307, SPS-REQ-204, SPS-REQ-95	

Table 9: The list of fundamental functions validated before the commissioning.

No	Functions	No. of Table 2	Succ.?	Req.	Notes
S04	Each camera unit keeps operating pressure ( $1e-6$ Torr) for 400 days.			SPS-REQ-192	
S045	All camera units cover 2394 science fibers in total in their readable area. Dead fiber shall be less than 1%.			SPS-REQ-39, SPS-REQ-40, SPS-REQ-274	
S06	Visible-Blue camera units cover 380 – 650 nm.			SPS-REQ-41	45
S07	Visible-Red camera units cover 630 – 970 nm.			SPS-REQ-41	46, 47
S08	NIR camera units cover 940 – 1260 nm.	48		SPS-REQ-41	
S09	Visible-Blue camera have spectral resolution of >2300 at 520nm.	49		SPS-REQ-42	
S10	Visible-Red camera have spectral resolution of > 2800 (LR) and > 5000 (MR) at 810 nm.	50, 51		SPS-REQ-42	
S11	NIR camera units have spectral resolution of >4100 at 1110nm.	52		SPS-REQ-42	
S12	Spots in $\geq 95\%$ of detector area has Ensquared Energy $\geq 50\%$ within $3 \times 3$ pixels, and $\geq 90\%$ within $5 \times 5$ pixels, and its centroid is stable within 0.2pixel over 1 hour 1pixel over 16 hours.	41		SPS-REQ-47, SPS-REQ-45	
S13	The throughput of Spectrograph Modules is higher than 14% at 380nm, 38% at 440nm, 39% at 550nm, 33% at 650nm, 42% at 790nm, 36% at 980nm, and 25% at 1260nm.	53, 56-59		SPS-REQ-48	
S14	Image with exposure time from 2 sec. to 30 min. are acquired.	40		SPS-REQ-53	
S15	Red channel can exchange dispersers between LR-mode and MR-mode.	41		SPS-REQ-74	
S16	SpS shall back-illuminate science fibers.	29, 30			
S17	SpS shall be operated remotely via MHS.	37			
...	...	...	...	...	...
<b>Cable B</b>					



Table 9: The list of fundamental functions validated before the commissioning.

No	Functions	No. of Table 2	Succ.?	Req.	Notes
F01	Cable shall deliver 2394 light source from PFI to SpS.	14		REQ-F0C-L3-267	
F02	Cable connection should be monitored remotely.	14		REQ-F0C-L3-043	
...	...	...	...	...	...

## C 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

## Change log.

- ver. 1: 7 October, 2015
  - Released for informal meeting in Princeton.
- ver. 2: March 15, 2016
- ver. 3: 10 May, 2016 — Released for discussion with Subaru
- ver. 4: 5 October, 2016
  - Updates from informal meeting, and software collaboration meeting.
- ver. 5: 7 January, 2017
  - Update schedules of runs following the latest to-level schedule (as of Dec. 2016)
- ver. 6: 1 May, 2018
  - Update schedules of runs following discussion with Subaru in Jan. 2017., and the latest top-level schedule
  - Update following suggestion by J. Gunn in May 2017.
- ver. 7: December 2019
  - Change document structure
  - Update schedules based on project schedule as of 2019 July.
- ver. 8: 11 February 2020
  - Update process following the results of the Runs 0–2.
- ver. 9: 11 June 2021
  - Update process and schedule following allocated time in S21B.