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Prime Focus Spectrograph (PFS) for the Subaru telescope: Its start of the last development phase

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ABSTRACT

PFS (Prime Focus Spectrograph), a next generation facility instrument on the Subaru telescope, is now being tested on the telescope. The instrument is equipped with very wide (1.3 degrees in diameter) field of view on the Subaru's prime focus, high multiplexity by 2394 reconfigurable fibers, and wide waveband spectrograph that covers from 380nm to 1260nm simultaneously in one exposure. Currently engineering observations are ongoing with Prime Focus Instrument (PFI), Metrology Camera System (MCS), the first spectrpgraph module (SM1) with visible cameras and the first fiber cable providing optical link between PFI and SM1. Among the rest of the hardware, the second fiber cable has been already installed on the telescope and in the dome building since April 2022, and the two others were also delivered in June 2022. The integration and test of next SMs including near-infrared cameras are ongoing for timely deliveries. The progress in the software development is also worth noting. The instrument control software delivered with the subsystems is being well integrated with its system-level layer, the telescope system, observation planning software and associated databases. The data reduction pipelines are also rapidly progressing especially since sky spectra started being taken in early 2021 using Subaru Nigh Sky Spectrograph (SuNSS), and more recently using PFI during the engineering observations. In parallel to these instrumentation activities, the PFS science team in the collaboration is timely formulating a plan of large-sky survey observation to be proposed and conducted as a Subaru Strategic Program (SSP) from 2024. In this article, we report these recent progresses, ongoing developments and future perspectives of the PFS instrumentation.

Keywords: Subaru Telescope, future instrument under commissioning, wide-field instrument, multi-object spectroscopy, optical and near-infrared spectroscopy, optical fibers, large sky survey, international collaboration

1. INTRODUCTION

The wide-field capability of the Subaru telescope at its prime focus is one of the unique strengths that was exploited from the beginning of the telescope operation with the former generation instruments (i.e. Suprime-Cam[1] and FMOS[2,3]). Subsequently, since several years ago, Hyper Suprime-Cam (HSC)[4] has been continuously delivering superb imaging data over a very wide area of the sky.[5–7] Then obviously conducting a follow-up spectroscopic survey for objects detected on HSC images is a natural path forward. In particular, a systematic survey is desired to complete a large census of the universe with spectroscopic information to address various unresolved

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questions in modern cosmology and astrophysics. This clearly requires a spectrometer that is powerful in multiple aspects such as field of view, multiplicity, and wavelength coverage that maximize observation efficiency, and motivated the Subaru Measurement of Images and Redshifts (SuMIRe) project (PI: H. Murayama) aiming to conduct deep and wide surveys using the same telescope (i.e. 8.2m Subaru telescope) on the same patches of the sky in imaging by HSC and in spectroscopy by Prime Focus Spectrograph (PFS).

PFS is a very wide-field, massively multiplexed, optical and near-infrared (NIR) spectrometer.[8–10] The focal plane at the prime focus of the telescope will be populated with 2394 reconfigurable fibers distributed in the 1.3-degree wide hexagonal field of view. The fiber configuration will be completed relatively quickly (2 minutes or shorter is the plan) with the dedicated camera system at the Subaru Cassegrain focus to measure the positions of all the science and fiducial fibers at the prime focus in one exposure. The spectrograph has been designed to cover a wide range of wavelengths simultaneously from 380nm to 1260nm in one exposure. The development of this instrument has been undertaken by an international collaboration managed by the project office hosted by Kavli IPMU, with work packages for subsystem and subcomponent developments assigned to various institutes in the collaboration.

The instrumentation is now in its last phase. The system-level test on the telescope has been underway since September 2021 with Prime Focus Instrument (PFI), Metrology Camera System (MCS), the first on-telescope fiber cable, and the first spectrograph module (SM1) with visible cameras. The software development is rapidly progressing through the engineering observations. The development of the fiber system is now complete[11] and all the hardware components have been either implemented in the other subsystems or delivered for next-level integration. The integration and test of the spectrograph system are also moving forward to deliveries to the observatory. Currently the project is aiming to complete the engineering observations so that the operations for scientific use can be started in 2024. In parallel to the instrumentation, the science working groups in the collaboration are trying to timely develop a plan of large-sky survey observation to be proposed and conducted in the framework of Subaru Strategic Program (SSP). The basic structure of the planned survey still consists of the three main components: cosmology, galaxy & AGN evolution, and Galactic archaeology.[12] But the details have been greatly updated and advanced since then[13] and optimization is still actively under discussion with the actual instrument characteristics considered as they are better understood. The goal is to address key questions in the modern cosmology and astrophysics by employing multiple independent approaches over multiple scales of dark matter density structure, which we believe will ultimately lead us to comprehensive challenges to the Λ-CDM cosmology.

In what follows, the recent developments in the integration at the Subaru telescope observation are provided in § 2, ongoing hardware and software developments at the PFS institutes are described in § 3, progresses in the on-telescope tests and engineering observations are reported in § 4, and finally this article is summarized in § 5 with a timeline of the instrumentation and science operation, and some future perspectives.

2. INTEGRATION AT THE SUBARU TELESCOPE OBSERVATORY

In the last proceeding article in Dec 2020,[10] we reported that the reassembly and test of MCS[14] and SM1 with visible cameras[10,15] were completed at the Subaru telescope observatory on the summit of Maunakea following their deliveries in 2018 and 2019, respectively. We also reported the progresses of integration and test of PFI and the on-telescope fiber cables (so-called Cable B) in Taiwan and Brazil, respectively. In this section, we provide updates on the integration at the Subaru telescope observation from 2021 to June 2022.

2.1 On-Telescope Fiber Cable "Cable B"

This fiber cable is to provide the optical link between PFI and Spectrograph System (SpS). The 2394 fibers are grouped into four cables corresponding to the number of the spectrograph modules (SM), and the two cables out of the four have been installed on the telescope so far (see Fig. 1). The assembly and test of the first and second production cables (Cable B1 and B2) were completed in 2020 and 2021 at LNA in Brazil, respectively. Then the cables passed the pre-shipment reviews, and they arrived in Hawaii a few months after. The two fiber cables were then installed on the telescope in February 2021 and April 2022, respectively as follows. After visual inspections and basic tests in Hilo to confirm the good conditions of the cable after the shipment mechanically and optically (by a simple continuity check), the cable was transported to the observatory on the summit of

Maunakea, and two optical tests were performed on the so-called observation floor in the dome enclosing the telescope:

(1) The Focal Ratio Degradation (FRD) of a subset of the fibers in the cable: We employed the collimated beam method[16] where we input a collimated beam at a specific angle to the fiber optical axis corresponding to the focal ratio in question. Then an image of the beam coming out of the other end of the fiber is taken by a detector at an appropriate distance from the fiber tip. The image forms a ring and its width (or thickness) represents the FRD with respect to the input focal ratio. We connected a loopback connector to the Tower connector of the cable[10] to connect the specific pairs of two fibers in the cable on that end. This way, when we input a collimated beam from the Gang connector side (i.e. SpS side)[10] of one fiber, then the output beam comes back to the same Gang/SpS side but from the other fiber through the loopback on the Tower connector side. This ends up being a double-path measurement but greatly eases designing and building the test setup. We measured FRD in this method not only at this time at Subaru but also at the few earlier stages in the cable integration process at the PPC Broadband factory in the UK[16] and LNA[*] in Brazil using the same fibers as much as possible to see how FRD evolved as the integration progressed. We confirmed a good match in FRD between the two data sets before and after the shipment from LNA to Subaru.

(2) The relative uniformity of the throughput among all the fibers in the cable: This was measured by diffusely illuminating the fiber array on the individual MTP ferrule in the GANG connector approximately with a focal ratio of 2.8, taking the image of the fiber array on the other side of the cable and then measuring the flux of each spot from the individual fiber. Like the FRD measurement, this is the same test as having been done at LNA, so a simple comparison of the data at Subaru with those at LNA is possible, and again we confirmed a good match between the two data sets.

The results of these two tests were good for both Cable B1 and B2 in the senses that they meet the specifications[†] and also are consistent with those from the measurements at LNA in Brazil before the cable was shipped. So we concluded the condition of the fiber cable was good to proceed with the installation on the telescope and in the telescope dome.

The installation work was performed on February 8, 9 and 10 in 2021 for Cable B1 (Fig. 2) and April 12, 13 and 14 in 2022 for Cable B2. It was quite a labor-intensive process. Unfortunately there were strong restrictions in traveling to Hawaii, visiting the observatory and working at the summit facility due to COVID-19, but we managed to form a team of approximately 15 people with two persons from Kavli IPMU and the rest from the Subaru telescope observatory. Initially one end of the cable was lifted by the 80t crane and installed on the telescope spider and down to the elevation wrap along the ladder on the so-called "infrared" side of the telescope, and then the other end of the cable was sent beyond the so-called Great wall (see the photos from 1 to 5 in Fig. 2). At this point, we measured the double-path FRD of several fiber pairs in the cable by the collimated beam method (see above), and monitored the FRD of one fiber pair during the night observation. Then we confirmed that no significant additional FRD was seen, and also the FRD was stable against telescope elevation movement. Based on these results, we decided to go to the next process which was to route the cable inside Great Wall up to the third floor, then eventually fourth floor in the dome where the PFS spectrograph system is implemented and operated (see the photos from 6 to 8 in Fig. 2). The FRD measurement was again carried out in the same way after all these installation processes finished, and we found no sign of significant FRD degradation and no sign of instability against telescope elevation change. For Cable B1, later we continued to monitor the double-path FRD of a single fiber pair using the same test configuration for two periods of a few weeks, and found a good stability against not only the telescope elevation movement but also temperature change as expected by the

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[†]The specification for FRD is that 95% or more of measured fibers (typically several tens of fibers were measured) shall have an FRD of 20 milli-Radians (mRad) or better. There is no formal specification to the relative throughput uniformity, but the uniformity has to be good enough for the specification of the throughput itself (95% or more of measured fibers shall have a throughput of 75% or better) to be met. So the consistency of relative throughput uniformity before and after a major event like a shipment is useful evidence for no deterioration.

glass-rod core in the tensile element along the axis of the cable (which was a detailed but important update from the prototype cable[10, 16]).

We have been testing the FRD stability over more than 100 days so far using the Cable B2. The FRD stability against temperature change as well as telescope elevation change is important to understand, and then a monitoring over a long period such as months is required to capture not only daily & nightly variation but also seasonal change to a possible extent. In Fig. 3, some early results from Cable B2 are presented. These plots are based on the data sets over about a month in April and May 2022. The telescope was operated normally during daytime and nighttime, so the telescope elevation (and azimuth) changed a lot upon observational demands as shown in the middle panel. Also, as shown in the top panel, the temperatures in the telescope dome varied by several degrees during a day and night, and also the averages slowly varied over a longer time scale. The temperature inside the PFS spectrograph clean room was stable around 5.5°C because it is actively controlled and maintained. Under this circumstance, the FRD of Cable B2 was very stable as indicated by the green line in the bottom panel: The variation is only at a level of ∼0.1 (∼0.4) milli-Radians (mRad) in standard deviation (peak to valley), respectively. We will keep collecting data to better quantify the stability and look into correlations of small variations with various parameters.

We will continue this FRD monitoring not only on Cable B2 but also some or all of the other three cables, and will consider publishing the results in the future.

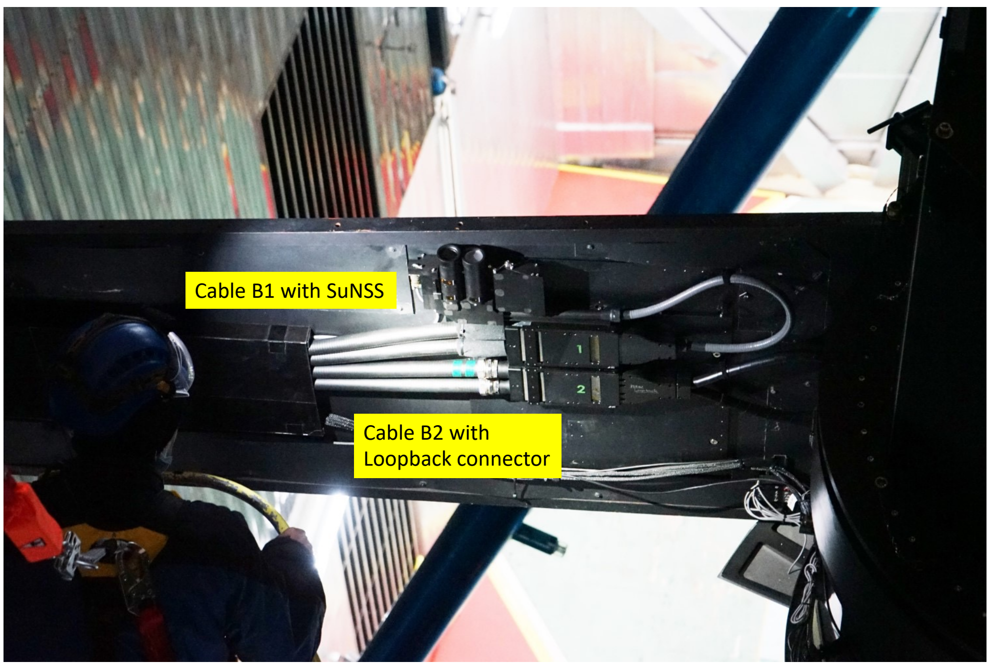

Figure 1. Cable B1 and Cable B2 on the telescope spider, after the Cable B2 installation in April 2022. At that time, we connected Cable B1 with SuNSS for sky observation, and Cable B2 with the loopback connector for the FRD measurement.

2.2 Subaru Night Sky Spectrograph (SuNSS)

On the next day after the Cable B1 installation, the installation of Subaru Night Sky Spectrograph (SuNSS) was also completed. SuNSS was developed by the collaboration of Princeton University and LNA, and the technical details will be explained in the other article,[17] so here only an overview is given. SuNSS is a system of two small-aperture (∼36mm diameter) telescopes that permanently stay on the Subaru telescope spider on its top end and enables to take sky spectra with PFS on-telescope fiber cable and PFS SpS when PFI is off the telescope. The two telescopes have been designed to deliver sky emission to their focal planes with the focal ratio of 2.8 but in two different ways: One is to generate an image with a lens, and the other is to just provide an aperture

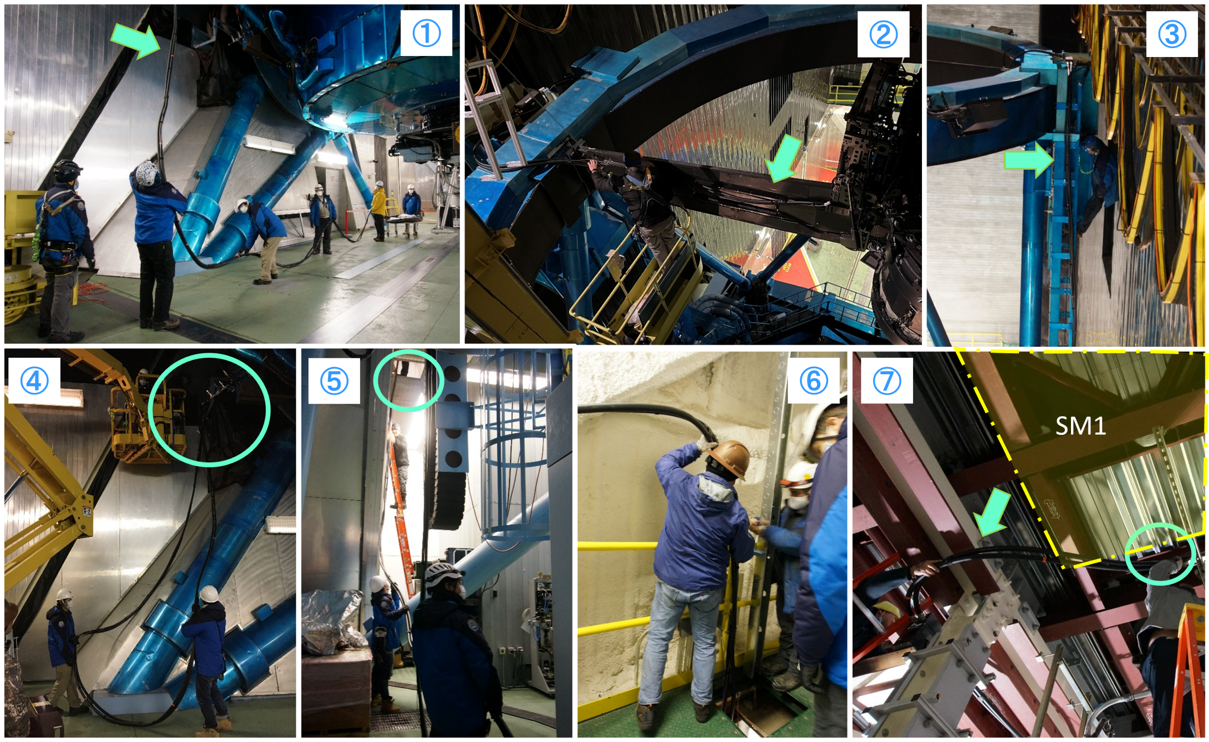

Figure 2. Snapshots of Cable B1 installation process.

stop with a diffuser. The sky emission is fed to the short (∼1m) fiber cable from each small telescope with the hexagonal fiber array at the focal plane, and with the Tower connector on the other side that is mated with the Tower connector of Cable B. As of June 2022, ∼ 700 hours of SuNSS data have been taken and are being analyzed for the development of 2D Data Reduction Pipeline in particular the algorithm for accurate sky subtraction,[18] and also for characterization of Cable B1 and SM1 by looking into correlations with various parameters. So far we are seeing growing evidence from these data for an extremely good stability of Cable B1 and SM1.

Having Cable B1 ready on the telescope as well as MCS and SM1, then PFI was the only missing piece at Subaru to start an engineering observation. At that time, unfortunately, the delivery of PFI to Subaru was expected to take some more time such as a few months at least. The successful SuNSS installation and start of its data acquisition operation were also good to collect and analyze sky spectra taken with the real PFS hardware and make the best use of time for developments before the PFI arrival.

2.3 Prime Focus Instrument (PFI)

The commissioning of PFI and its characteristics are described in the other article[19] in detail, so in this section we will focus on a high-level overview of the commissioning process. After the integration of all the fiber positioner modules and the fiber cables were completed,[10] next several months were spent for a campaign of mainly PFI - level tests in Taiwan. Then PFI passed the pre-shipment review in May 2021, and it arrived at the Subaru summit facility in June 2021. Again due to COVID-19 and subsequent unfortunate restrictions, the team members in Taiwan could not come to Hawaii with PFI and could only provide remote supports. To mitigate risks due to this difficult circumstance in the commissioning of PFI at Subaru, the several members from Kavli IPMU and Subaru observatory visited Taiwan for 2 months from March 2021 to participate in the test campaign and related engineering works to be familiar with various details of PFI. Accordingly, the reassemblies of PFI and the test bench system were successfully completed at Subaru and the commissioning of PFI as a stand-alone subsystem was started in the clean booth temporally built on the observation floor. This configuration of testing PFI on

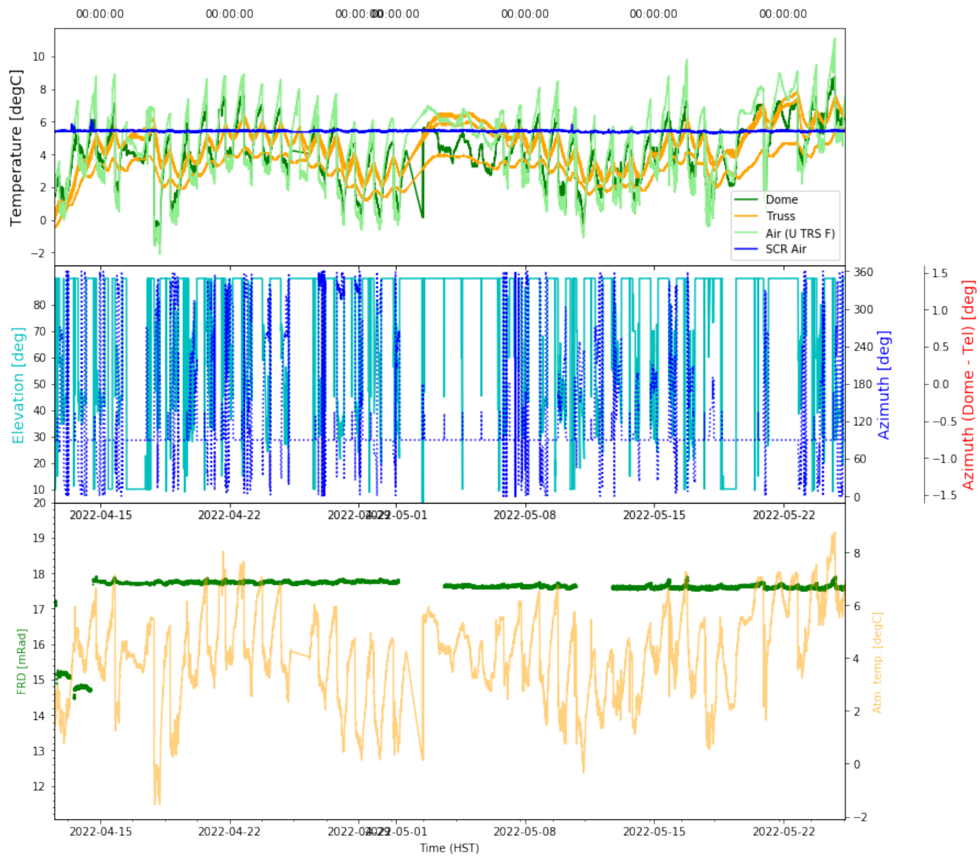

Figure 3. (Top) The temperatures of the telescope dome, telescope truss, and PFS spectrograph clean room are plotted with the noted color code. (Middle) The telescope elevation and azimuth are plotted in angle. (Bottom) The measured FRD is plotted in milli-Radians (mRad) with the telescope truss temperature (same as that in the top panel) overlaid for reference.

the test bench system is exactly how PFI was tested in Taiwan[‡]. The test bench system equips a short focal length, wide-field camera with which all the back-lit fibers on the PFI focal plane can be imaged in one exposure. Namely, this camera works essentially as MCS on the telescope, and therefore enables various characterizations of Cobras and tests for software developments on this test bench even when PFI is off the telescope.

On this test bench, the PFI functionalities were confirmed, and the performance and geometry of Cobra fiber positioners were validated to be the same as before shipping. The mechanical fitting test with POpt2 (see § 4) was carried out in July 2021 and no interference was found, although we found 90-degree offset between the rotation origins of PFI and POpt2, which ends up limiting the operation range of the instrument rotator. Aside from this finding, PFI was ready to the system-level commissioning with the telescope and the other PFS subsystems.

3. ONGOING DEVELOPMENTS AT THE PFS INSTITUTES

3.1 Cable B

The integration and test of the third and fourth Cable B cables (Cable B3 and B4) were carried out in parallel on the dual integration benches at LNA in Brazil, and both passed the pre-shipment review at the same time in

[‡]Except for the mechanism to tilt PFI. We decided not to ship it to Hawaii to simplify the shipping process because the PFI's performance when it was tilted by up to 60 degrees (corresponding to the situation with the telescope elevation angle of 30 degrees) were well tested and characterized in Taiwan.

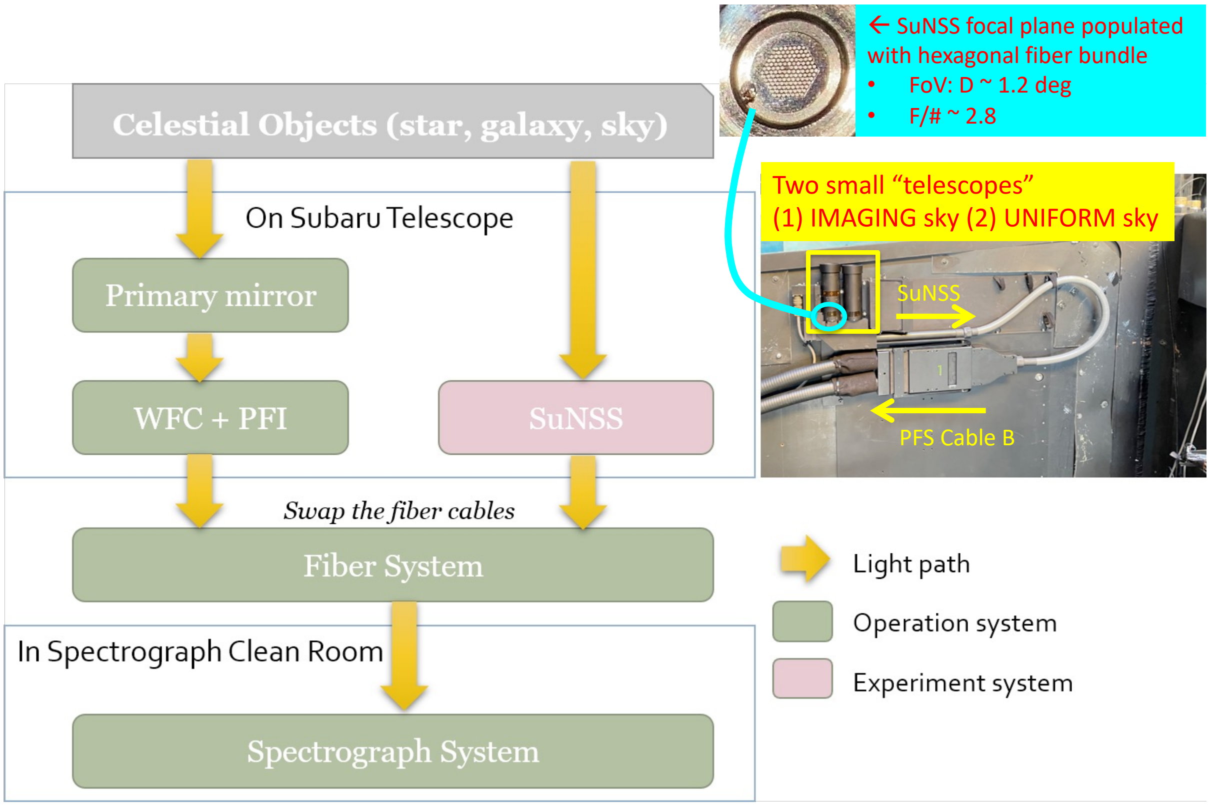

Figure 4. (Left) The block diagram of operation setup with PFI, and experimental setup with SuNSS. (Right) The actual hardware of SuNSS on the telescope spider together with Cable B1.

March 2022. The two cables then safely arrived at the Subaru Hilo base facility in June 2022. Now discussions are ongoing with the observatory for the engineering works on these cables to be scheduled at the Subaru summit. Having completed the production of all the four cables, we should stress that these cables have been validated to be very similar to each other in their mechanical and optical characteristics such as weight, length, FRD and throughput.

3.2 Spectrograph System

The development of spectrograph system has been slower than expected unfortunately since the team found two problems in the visible cameras for the second and third spectrograph modules (SM2 and SM3): Unexpectedly large offsets of the detector plane from the optical focal plane in tilt and focus, and the contamination on some of the optics. On SM1, such offset problems have not been found. No such contamination has been confirmed either based on the searches on the detector images for unexpected diffuse background and/or extended halos in continuum and emission line spectra as well as based on possible visual inspections. The team put a lot of efforts not only to find ways to fix these problems but also to prevent them from happening again. According to the results from a number of experiments the team carried out, the tilt and focus offsets were found to be stable against such processes as disassembling & reassembling, and warming up & cooling down the camera. Therefore we decided to fix those problems basically by shimming, and confirmed the offsets were successfully removed. In parallel, the team introduced additional metrology processes at multiple stages in the camera assembly process. Quality control and sensitivity to unexpected errors must have been improved with these although the assembly process now requires more time. The contamination could fortunately be cleaned up by wiping and then additional baking processes were applied as a preventive measure. The materials having condensed on the optics were studied by collaboration with a local company doing chemical analyses, and possible causes and potential risks of such contamination in the camera assembly process (in particular the procedure of baking processes) were carefully reviewed and discussed for optimization. Having accommodated these, the team has regained momentum, and is now aiming to deliver one more SM with the visible cameras from LAM[§] to Subaru later in 2022. In addition, they are trying to get another SM ready at LAM with the visible cameras to test the first NIR camera as part of the SM in the temperature controlled chamber once it arrives from JHU[¶].[20] This will enable us to confirm all the three cameras being simultaneously aligned and functioning, and to confirm the thermal background level in the NIR camera by setting up the temperature of the chamber to ∼5°C as in the spectrograph clean room at the Subaru summit. Once one of these two SMs departs from LAM to Subaru, the integration of SM4 (i.e. the last SM) will then be started at LAM.

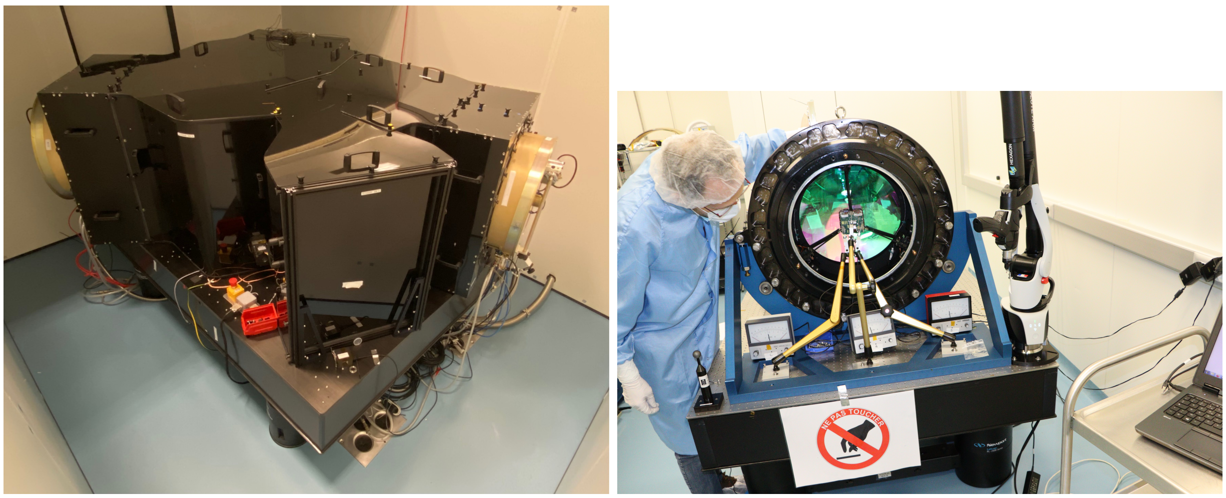

Figure 5. (Left) A spectrograph module assembled in the temperature controlled chamber. (Right) A metrology process for the visible camera focal plane geometry.

We have not been able to ship any NIR cameras yet, but the progress is catching up. As described in detail in the other article,[20] the first NIR Camera Unit (NCU) SN1 has been fully assembled and operated for testings for quite some time. We had an internal review in July 2022 to assess the readiness of the camera for its shipment from JHU to LAM. The only major open question turned out to be the compliance of the image quality, and now this is being reconfirmed by additional data and model analyses. Also, it has been pointed out that some contributions to the measured image sizes were missed to consider when the camera-level image quality specification was defined, so this is also being double checked. In parallel, the second camera (NCU SN2) has also been fully assembled, and is ready to be pumped and cooled for testings, so the performances of this camera will also be understood soon. The cryostat for NCU SN3 has already been tested and validated, so once SN1 is shipped out of JHU to LAM, then the integration of SN3 with the optics will be started on the bench. Once SN1 is tested and validated as part of an SM at LAM, it will be shipped to Subaru from LAM. Meanwhile, SN2, SN3 and SN4 are supposed to be shipped directly from JHU to Subaru and integrated to the SMs implemented already at the Subaru summit.

The procurement of the special coating to suppress the thermal background radiation reaching the detector was an outstanding difficulty for several years, but recently all the coating processes were completed successfully and the coated optics were delivered to JHU. The spectral transmission data having been taken by the vendor look all good, and indeed the thermal background level actually measured in the SN1 camera is low enough as expected from the model prediction with the measured coating performances considered.

For both visible cameras and NIR cameras, the detectors (Hamamatsu CCD and Teledyne H4RG) are tested and characterized at JHU in the test dewars before they are integrated in the cameras. Data acquisitions and

[§]Laboratoire d'Astrophysique de Marseille
[¶]Johns Hopkins University (JHU)

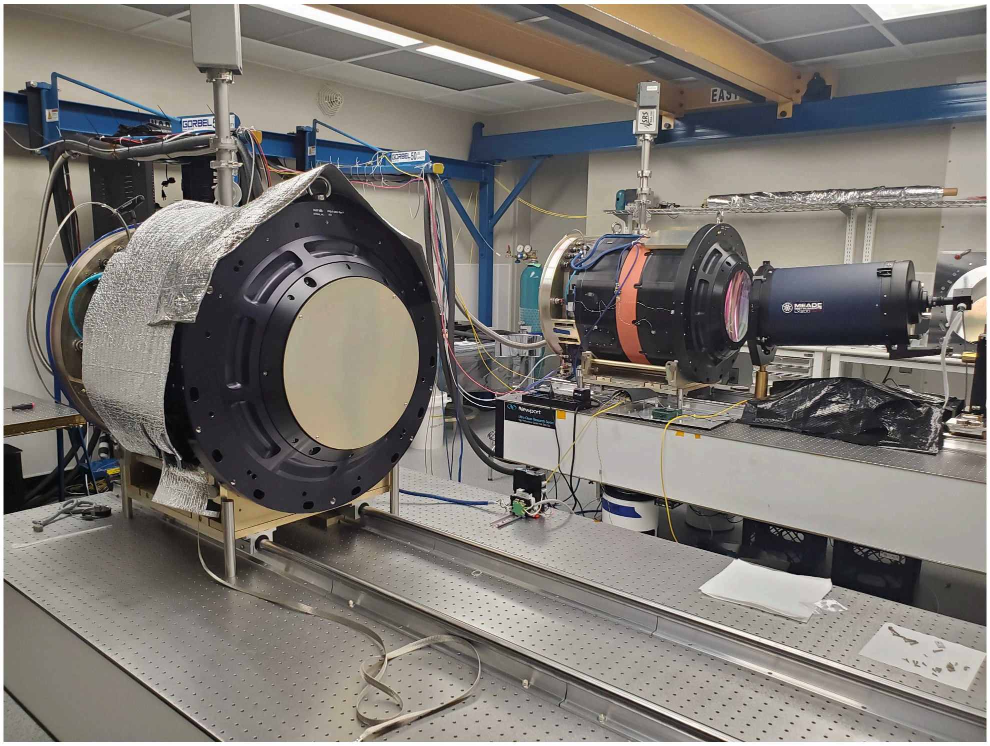

Figure 6. Two NIR cameras on the dual integration benches in the clean room at JHU. The first NIR Camera Unit (NCU SN1) with the fore-optics for the image quality investigation is shown on the far side (or on the right of this photo), while the second camera (NCU SN2) is in front of it (or on the left of this photo).

analyses are being performed by collaboration of the teams from JHU, Princeton University, NAOJ[‖] and STScI[**]. Only one more set of CCDs for the SM4 blue camera remains to be tested, and two more H4RG devices for NCU SN3 and SN4 need to be tested from now.

3.3 Instrument control software and fiber allocation software

Various software modules and databases need to communicate with each other for PFS operation (Fig 7). Among them, the software packages for instrument control were delivered when individual subsystems were delivered. The software was used while the subsystems were integrated and tested as a stand-alone subsystem at Subaru to validate that the functions and performances are the same as before the shipment. After this confirmation, the software integration was carried out, which includes such processes as sending telemetry statuses to Subaru Telemetry System (STS), reading from/writing to PFS operation database "opDB", and so on. GUI for instrument operation, which was developed for SpS first, has also been updated to provide contents from PFI and MCS. Visualization tools for fiber positioning process have also been implemented to the GUI so that one can check the progress and result of the convergence, image quality of MCS, and so on, during/after the operation.

During the commissioning activities, the schema of opDB has been updated continually, in particular for fiber positioning and field acquisition to be successful and efficient since the PFI delivery. Top-level commands from IIC (Instrument Interface and Controller) actor have been also implemented to orchestrate multiple subsystems either concurrently or sequentially upon demands as well as to carry out specific test processes. The scripts on

[‖]National Astronomical Observatory of Japan

[**]Space Telescope Science Institute. An expert of infrared detector (Eddie Bergeron) is working with us on the best effort basis but is giving substantial contributions which we all appreciate greatly.

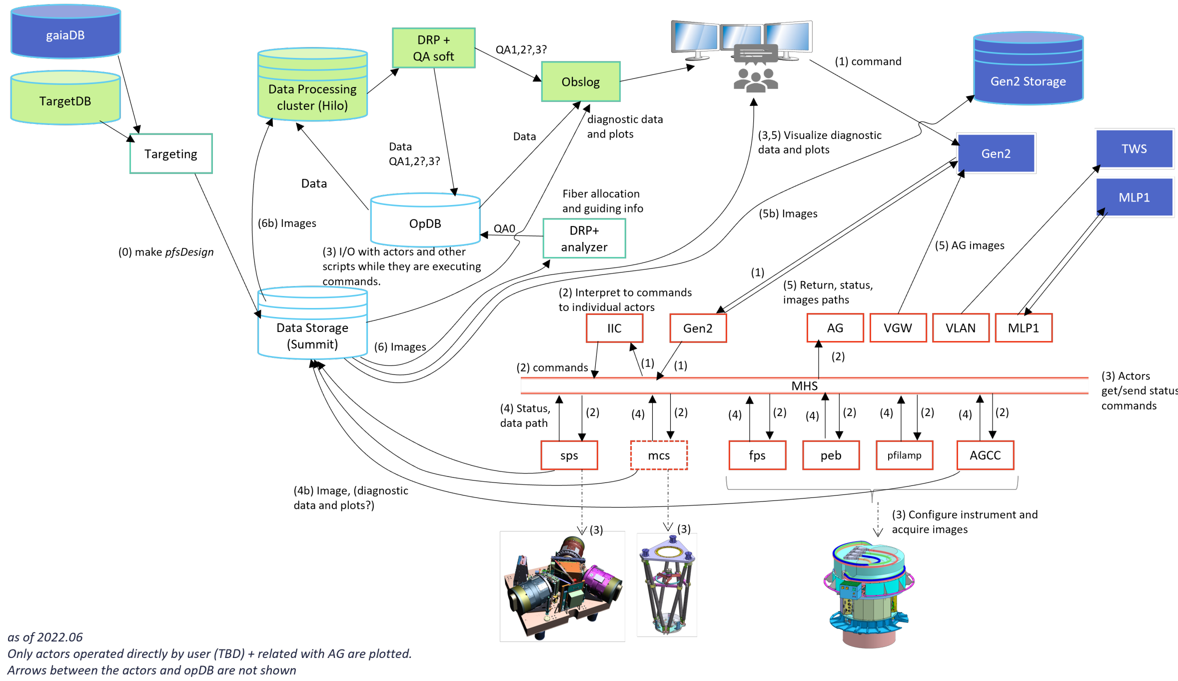

Figure 7. Schematic diagram of various software components and databases required for PFS operation.

the telescope side (so-called SOSS Gen2[21] commands including SETUPFIELD (see § 4)) have been developed to operate the telescope and the PFS instrument in coordinated manners for engineering observations.

In order to observe a given field of sky with a given fiber configuration, firstly a pfsDesign file is generated. This file contains the information of the field itself (field center in RA & Dec and position angle) and the information of fiber allocation to astronomical objects which are possibly observed for science and calibration (flux standards and blank sky). A pfsDesign file also contains a list of guide stars that can be used for field acquisition and auto guiding. For allocating the fibers and searching for guide stars, the members from MPA[††] and MPE[‡‡] have developed specific software modules. One recent development on them is the implementation of a functionality to more or less uniformly distribute the calibration sources across the field of view and/or the fiber slit.

The database called "targetDB" was developed to store the catalogs of science and calibration sources. The schema was already designed to a sufficient level for engineering runs, and the database was populated with not only targets for engineering purposes such as testing and characterizing the instrument but also F-type stars for flux calibration, and pseudo objects for "blank sky" represented by positions where there are apparently no objects down to a certain limiting magnitude identified in the HSC catalogue and the Pan-STARRS1 catalogue, for sky spectrum acquisition and then sky subtraction. NAOJ developed software code to generate pfsDesign files by retrieving the information of various objects from targetDB and Gaia database locally maintained at Subaru, and calling the software modules for fiber allocation and guide star selection.

3.4 Data reduction pipelines

Data processing is performed in two stages: 2D Data Reduction Pipeline (2D DRP) developed by Princeton University, Kavli IPMU, NAOJ and California Institute of Technology processes SpS detector images and delivers

[††]Max-Planck-Institut für Astrophysik
[‡‡]Max-Planck-Institut für extraterrestrische Physik

fully calibrated one-dimensional (1D) spectra. Then 1D Data Reduction Pipeline (1D DRP) developed by LAM performs various measurements on the 1D spectra delivered from 2D DRP. There have been a few major progresses on 2D DRP recently in particular because, after SuNSS was installed, ~ 700 hours of sky data (more than $280,000$ spectra) were taken. At the moment, the wavelength solution reaches an accuracy approximately of 0.05 pixels, corresponding to a radial velocity of ~ 1.5 km s^{-1}. So far the sky subtraction can be carried out only with partial understandings of Point Spread Function (PSF) in 2D, but the residual after subtracting the modeled sky implies only a little (<1%) systematic error. The pipeline will be optimized and the performances will be improved as more sky spectra are taken with PFI instead of SuNSS. The team is also developing a routine for flux calibration. Currently the routine is being tested against simulated spectra, but real stellar spectra will start being used once data become available from future engineering observations.

As reported above, NCU SN1 will be integrated on an SM at LAM soon and spectral images will be taken for alignment and other tests on the H4RG detector. For this upcoming phase, the team is accelerating the developments of routines required for NIR data reduction. One of them is to process up-the-ramp exposures from the H4RG detector, remove specific instrument features from the camera and detector, and generate an image that is similar enough to a CCD image from the visible cameras and therefore can be analyzed in similar ways to those for the CCD images. An algorithm of minimizing the noise using interleave reference pixels is also being developed.

1D DRP has been improved steadily. Its functionalities and performances to various types of galaxy spectra are being developed and tested against simulated spectra. Capabilities of measuring stellar spectra are also being strengthened. In both 2D DRP and 1D DRP, updated versions have been released quite regularly at a reasonably short cadence and become deployable automatically. Also, a release of 2D DRP comes with simulated spectra and products after reduction processes. Hence it is worth giving the outputs from 2D DRP to 1D DRP for verifying the entire data processing. From such a motivation, a regular end-to-end test has been in operation at Kavli IPMU since 2020 and has been very useful to discover unexpected problems and issues and steer team's efforts to resolutions and improvements.

3.5 Other key software components for PFS operation

For PFS operation over a timescale of several months (e.g. six months in one single Subaru semester), an appropriate operation workflow is required, and it is one item being actively discussed mainly by the member at NAOJ and Kavli IPMU. In order to design and schedule PFS observations with various targets from multiple different observation programs coexisting in individual PFS pointings, a software module called PFS Pointing Planner (PPP) is being developed. PPP is supposed to be open online for users to simulate expected completeness of observations for their programs. Studies of simulated observation plannings and executions using PPP suggest that dealing with multiple programs simultaneously actually makes observations more efficient after all and the completeness can be as high as ∼80–90% even when the targets are clustered in small areas. Online platform for PPP will be developed in the near future.

The web-based observation log system "Obslog" has also been developed based on good communications to opDB. Obslog has been intensively used thanks to its rich user interfaces since the first engineering observation in September 2021. Recently visualization of the designed observations in `pfsDesign` files was implemented and it has indeed eased making judgements & decisions for planning night operations.

4. PROGRESSES IN THE ON-TELESCOPE TESTS AND ENGINEERING OBSERVATIONS

After PFI was tested substantially and its functions and performances were confirmed to be consistent with those in Taiwan before the shipment, we had opportunities to test the PFS instrument system on the telescope. As of June 2022, we had four periods of on-telescope test and engineering observation: (1) September 13-26 2021, (2) November 17-21 2021, (3) May 13-19 2022, and (4) June 15-21 2022, although we had to cancel several nights and spend some other nights inefficiently in November 2021 and May 2022 due to some PFS hardware troubles before and/or during the runs. In what follows, the major achievements through these four engineering runs are summarized with some future works. On top of these highlights, we should emphasize that the operations of MCS and SM1 were overall stable and as expected, and these were essential for important progresses as highlighted below:

(1) **PFS installation to and removal from the telescope:** In order operate the PFS instrument on the telescope, PFI and MCS need to be installed on the prime focus and Cassegrain focus, respectively. Exchanging an equipment at two foci to operate one instrument is a unique requirement of PFS in the Subaru instrument operation, and scheduling these exchanges in a timely manner for PFS operation is not trivial at all. In addition, while the MCS installation is relatively straightforward, PFI installation is complicated: A prime focus instrument is firstly installed into Prime Focus Unit (PFU) which is a mechanical housing with a wide-field corrector lens system integrated, and then this PFU is installed on the telescope. In case of HSC and PFS, the same PFU so-called POpt2 having the Wide Field Corrector lens system (WFC) is shared, and therefore in order to install PFI in POpt2, in most cases the HSC instrument needs to be removed first. The critical mechanical interface to POpt2 is essentially the same between HSC and PFI, but there are various differences in detailed configurations and thus logistics for the installation. The situation is similar also in the installation of POpt2 on the telescope. Since the first attempt of PFI installation to and removal from POpt2, the PFS team and Subaru daycrews have been working closely together, and the installation and removal processes for the engineering runs went reasonably well. We will continue collaborative efforts of optimization and routinization.

(2) **Alignment of the assembly of WFC and PFI against the telescope primary mirror:** Inside POpt2, WFC and an prime focus instrument (either HSC or PFI) are fixed to each other as a single assembly, and its position along XYZ axes and tilt around XYZ axes can be adjusted by the POpt2's Hexapod mechanism. To generate sharp images on the prime focus focal plane and maximize the flux delivered on a fiber tip, the assembly of WFC and PFI should be well aligned against the telescope primary mirror, especially with respect to their optical axes. We developed an algorithm to measure offsets from the well-aligned configuration by taking defocused stellar images on the PFI AG cameras located at $\sim$0.7 degrees away from the field center, and fitting them with a linear combination of model images that represent changes of a defocused stellar image due to a different type of misalignment such as tilt and shift. The algorithm, which was tested using HSC beforehand, works well and stably converges to Hexapod positions consistent with those that are typical in the HSC operation.

(3) **Field acquisition and auto guiding:** The telescope pointing is typically offset from the requested position by several arcseconds just after its slewing, and this needs to be corrected to align the fibers onto targeted astronomical objects on the focal plane. This field acquisition process is carried out by taking stellar images on the AG cameras, calculating a systematic offset of stars from their expected positions, and applying that to the telescope pointing. During the observation in June 2022, this process was successfully validated. The telescope auto guiding is essentially the same process although a pointing offset calculated on the AG cameras needs to be sent the telescope control system in a different manner. We are ready to test this too and will be able to validate it in a near-future run.

(4) **Implementation of sequential observation operation:** Given multiple `pfsDesign` files are prepared for different observations, one of them is picked out for an upcoming exposure during a night. Then the information required for telescope pointing is retrieved from the `pfsDesign` file, transferred to the Subaru side, and ingested to opDB. Accordingly, when the specific command so-called `SETUPFIELD` is issued, the telescope starts slewing to the field as specified, and the fiber configuration process follows it. A spectrograph exposure is started once the fiber configuration is completed, and finally initial data reduction process is applied to make the images ready for further reductions and analyses once the readout of the spectrograph detectors is completed and file generation is finished. This sequence of multiple processes from observation preparation to spectrograph exposure & initial data reduction managed to be carried out smoothly during the run in June 2022. In future runs, we will start spending more efforts to minimize overheads by e.g. parallelizing fiber configuration with telescope slewing, parallelizing spectrograph detector readout with telescope slewing to a next field, and so on. Impacts and risks against instrument performances need to be carefully minimized, though. For example, some complex operation of the instrument rotator at the prime focus is needed at least in the final phase of fiber configuration: Since MCS does not look

at the sky and therefore does not rotate for tracking field rotation, the images of back-lit fibers on MCS would be elongated as the PFI rotates. The fiber position measurement would then become less accurate, and the accuracy of fiber positioning would eventually get deteriorated. To avoid this, the PFI rotation should be suspended temporarily for the last few (TBC) iterative moves of Cobras and be restarted after the fiber configuration is completed, and field re-acquisition and start of auto-guiding should follow that. Automation to minimize human intervention in such complex operation is one way to minimize overheads and risks of mis-operations.

(5) **Fiber configuration:** While we have not fully validated the capability of aligning the fibers onto astronomical objects yet, we manage to converge the fibers to requested target positions in XY on the PFI focal plane to 10μm accuracy for more than 95% of the Cobras (after excluding about 40 disabled Cobras)[19]). We had already reached similar performances during the tests in Taiwan, and those at Subaru summit on the test bench system, and it was an important milestone to confirm the same on the telescope with the real MCS, WFC, and the presence of significant dome seeing between PFI and MCS.

Here we briefly put two comments about the fiber convergence:

- **Dome seeing:** Earlier we demonstrated by the on-telescope tests[14] and confirmed during the recent engineering runs that the MCS centroiding accuracy in measuring the fiber positions on PFI is within the budget of 5μm on the PFI focal plane, as long as an individual MCS exposure time of 1 second or longer is employed. This is as expected from the design study with which we implemented the large aperture (380mm) for MCS. But still a few-micron dancing of the back-lit fiber images on MCS exists, and this fluctuates the statuses of some Cobras in the later iterations between converged and non-converged given the convergence is judged simply with the nominal criteria of 10μm offset from the target positions, and subsequently makes the statistical estimate of Cobra convergence performance somewhat inaccurate. The team is discussing how to deal with this impact of dome seeing and find a more robust way to judge convergence.
- **Required time for Cobra convergence:** Currently we apply 13 iterative moves as a single run of Cobra convergence and it takes about 4 minutes for completion. The 13 iterations are probably more than necessary because little improvement is seen in the statistics of the residual distances to the targets beyond 6th or 7th iteration. The team will discuss how to stop the iterations in conjunction with a robust judgement of each Cobra's convergence. In addition, although we have not done a detailed profiling of how time is spent in each process during the convergence, there appear to be some processes that currently require longer times than expected. So we believe, given a reasonable amount of efforts will be applied to optimization in the near future, there are good prospects for being able to complete each convergence run as quickly as within 2 minutes as we are aiming.

(6) **Data acquisitions for focal plane characterization and data reduction pipeline development:** We successfully developed and validated two engineering routines to acquire data sets for specific measurement and characterization. A short overview is given here while readers should refer to the other article[19] for more details. The "dot-crossing" operation is to move Cobras so that the fibers move across the opaque dots on Field Element in front of the PFI focal plane. By taking images of back-lit fibers on MCS and analyzing the trajectories, the positions of the opaque dots can be measured accurately in the sense of where the fibers are hidden by them. Once the positions of the opaque dots are understood, then the "dot-roaching" operation is carried out to intentionally move a selected subset of the fibers or all of them upon demands behind the dots to hide them from any forward illumination. This operation consists of two parts: Firstly, Cobras are moved to place the fibers somewhere next to the dots, and then a set of small Cobra moves are given to push the fibers into the middle of the dots by monitoring the fluxes smeared from those fibers on the spectrograph detectors. The latter is some sort of a close-loop operation between PFI, SM1 and data reduction pipeline as well as MCS. To minimize the overheads while the detector readout and data processing are involved, a window read and subsequent data reduction have been implemented so that only a part of the wavelength coverage can be processed for flux measurement. This way, we can only sparsely illuminate the spectrograph detectors with forward illuminated fibers and therefore can analyze cleanly separated individual images of emission lines from the calibration lamps even when the

spectrograph is largely defocused to characterize the illumination and model the spectrograph. Or, in case the spectrograph is in focus, we can well study the individual emission line images out to their outskirts without any contamination from adjacent fibers that is crucial to characterize the PSF in 2D for accurate sky subtraction.[18]

5. SUMMARY AND FUTURE PERSPECTIVES

PFS, a next generation facility instrument on the Subaru Telescope, is a very wide-field, massively multiplexed, optical and NIR spectrograph: The prime focus will be equipped with 2394 reconfigurable fibers in the 1.3 degree diameter field of view, and the spectra simultaneously cover the wide range of wavelengths from 380nm to 1260nm in one exposure. This instrument is being developed by the international collaboration managed by the project office hosted by Kavli IPMU. Now the instrumentation is in its last phase. Following the successful deliveries and commissioning of PFI, MCS, Cable B1 and SM1 with visible cameras, we started engineering observations in Fall 2021 and managed to make various progresses during the four runs we carried out so far until June 2022. In parallel, in April 2022, we successfully installed Cable B2 on the telescope. Given subsequent timely arrivals and deployments of the remaining hardware, we are hoping to be able to complete the engineering observations in the next couple of years and start science operation including a ∼5-year PFS SSP survey and other general open-use programs from sometime in 2024. Information on the instrument development and survey strategy will be posted and updated on the PFS official website http://pfs.ipmu.jp/. In addition, milestones, achievements, events and other news are reported in the PFS official blog http://pfs.ipmu.jp/blog/ and instagram https://www.instagram.com/pfs_collaboration/. In parallel to these efforts of instrumentation, the science team in the PFS collaboration is developing a timely plan of large-sky survey observation to be proposed and conducted in the framework of SSP. Having the three main survey components labelled as cosmology, galaxy & AGN evolution, and Galactic archaeology, the team is aiming at addressing key questions in the modern cosmology and astrophysics by multiple approaches over multiple scales of dark matter density structure, leading to comprehensive challenges to the ΛCDM cosmology. The team has been continuously updating and refining the survey plan in detail with the instrument characteristics considered as they are better understood from the engineering observations.

PFS and HSC are a unique set of powerful survey instruments exploiting the prime focus of the Subaru Telescope and will be crucial strategic pieces in the next decades from their complementarity to new generation ground-based and space facilities. For example, the 6.5m effective-aperture telescope system of Rubin Observatory will enable an ultimate dedicated imaging survey of the universe, namely the ten-year Rubin Observatory Legacy Survey of Space and Time (LSST). Then complementing this with a large-sky spectroscopic follow-up observation will remain essential for accurate understandings about observed populations of stars and galaxies, and Subaru PFS is a promising candidate for a instrument suite that meets such a demand. Thirty-Meter Telescope (TMT) is an extremely large-aperture telescope project aiming to start its operation in 2030s in which the Japanese community is participating. The strength is clearly its huge light-gathering power while the field of view is small, implying that it will best suit a detailed spectroscopic observation of very interesting and/or rare astronomical objects. TMT is therefore complementary to HSC and PFS on Subaru in light of their roles, meaning that there must be good chances of synergy. From similar viewpoints, synergies with space facilities such as James Webb Space Telescope and Nancy Grace Roman Space Telescope are also exciting. Accordingly, PFS on the Subaru telescope will still be a world-leading astronomical facility not only in 2020s but also in 2030s to further advance our understanding of the physics of the Universe as the "multiplest" part of the Subaru's wide-field tripod with HSC for the deepest and ULTIMATE[22] for the sharpest.

ACKNOWLEDGMENTS

First of all, we would like to inscribe the names of two great colleagues we unfortunately lost recently. We are certain that neither of them could have been missed for the PFS project to have been off the ground and been elevated to what we are seeing today. We would like to express deep acknowledgements of their essential contributions.

- **Professor Olivier Le Févre** passed away on June 25 2020 at the age of 59, despite his courageous and persistent fights against a cancer for the few years. Prof. Le Févre was one of the key players who established

the PFS project, in particular by bringing LAM as a full partner institute to the collaboration with a wide range of great expertise under his leadership both in the survey science for cosmology and galaxy & AGN evolution, and in the instrumentation for the developments of spectrograph system and 1D data reduction pipeline. Prof. Le Févre always stimulated and promoted the collaboration with his clear visions about how hardware and software should be built, and how a survey observation program should be planned, in such a project of its size as PFS. But same time, he was very familiar with and was therefore caring about various difficulties one has to run into in the project. The last personal meeting with him was in June 2019 while I was visiting LAM to participate in the works of spectrograph integration and discussions about the 1D data reduction pipeline. Prof. Le Févre was active only intermittently for medical treatments but there was one day he was in and I was invited to his office to share updates. I had to explain various problems and issues as well as progresses, but then he said that he was glad to see I was still keeping a fighting pose. I remember very well that these words, together with his gentle, enveloping smiles, cleared stagnant mood in my mind and generated some power to move forward, which is an unforgettable moment. The official obituary from LAM can be found here https://www.lam.fr/les-actualites/article/olivier-le-fevre and the article from the PFS project can be found here https://pfs.ipmu.jp/blog/2020/07/p1667.

- **Professor Naruhisa Takato** passed away on May 14 2021 at the age of 56. He got suddenly sick on April 24 while he was staying in Taichung to participate in the final phase of PFI integration and test. Despite emergency operation and subsequent intensive care, he could not regain consciousness. Prof. Takato also had a long history with the PFS project. In January 2011, the PFS project was endorsed by the Subaru Advisory Committee representing the entire Subaru community. The PFS project was then officially established, and Prof. Takato became a member of the PFS project office immediately. He was from the Subaru telescope observatory, so his primary charge was to successfully accept the PFS instrument to the observatory when it was delivered. But he was very well aware that it would not happen successfully unless the observatory participated intensively in the instrument developments, so he always stayed together with us for building the PFS hardware & software and commissioning the system as perfectly as possible. Prof. Takato really knew how an instrument should be developed, and therefore what should be done at each time no matter what phase the project was at. He was impressively good at not only addressing specific details of the instrumentation but also understanding big pictures for strategic planning. Both of these are essential to accomplish the development of an instrument that works well, and because of them his inputs were always insightful. He was always the person for us to contact first and ask for advice anytime when we ran into difficulties. We were all counting on his sea of expertise, and also every one of us loved him from his great personality. The official obituary from NAOJ can be found here https://subarutelescope.org/en/news/topics/2021/06/02/2960.html and the article from the PFS project can be found here https://pfs.ipmu.jp/blog/2021/07/p1851.

We appreciate all the contributions from tne PFS science team to the instrument requirement definitions, the survey planning, and various supports based on patient understandings of the instrumentation activities. We also thank all the people having been involved with this PFS project in the past in various formats. We are grateful to the staffs (in addition to those on the author list) at NAOJ and the Subaru Telescope observatory for their contributions to the deployments of PFS hardware and software, preparations for PFS system integration and engineering observations, and various other engineering works. Our thanks should also be sent to the administrative staffs at Kavli IPMU, NAOJ, the Subaru telescope observatory, and all the other PFS institutes for kind supports in the financial and contractual aspects.

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