Invited Paper

Prime Focus Spectrograph (PFS) for the Subaru telescope: Progressing final steps to science operation

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ABSTRACT

The instrumentation of the Prime Focus Spectrograph (PFS), a next generation facility instrument on the Subaru telescope, is now in the final phase of its commissioning process and its general, open-use operations for sciences will provisionally start in 2025. The instrument enables simultaneous spectroscopy with 2386 individual fibers distributed over a very wide (∼1.3 degrees in diameter) field of view on the Subaru's prime focus. The spectra cover a wide range of wavelengths from 380nm to 1260nm in one exposure in the Low-Resolution (LR) mode (while the visible red channel has the Medium-Resolution (MR) mode as well that covers $710-885$nm). The system integration activities at the observatory on Maunakea in Hawaii have been continuing since the arrival of the Metrology Camera System in 2018. On-sky engineering tests and observations have also been carried out continually since September 2021 and, despite various difficulties in interlacing commissioning processes with development activities on the schedule and addressing some major issues on hardware and software, the team successfully observed many targeted stars as intended over the entire field of view (Engineering First Light) in September 2022. Then in parallel to the arrival, integration and commissioning of more hardware components, validations and optimizations of the performance and

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operation of the instrument are ongoing. The accuracy of the fiber positioning process and the speed of the fiber reconfiguration process have been recently confirmed to be $\sim 20-30\mu$m for 95% of allocated fibers, and ∼130 seconds, respectively. While precise quantitative analyses are still in progress, the measured throughput has been confirmed to be consistent with the model where the information from various sub-components and sub-assemblies is integrated. Long integration of relatively faint objects are being taken to validate an expected increase of signal-to-noise ratio as more exposures are taken and co-added without any serious systematic errors from, e.g., sky subtraction process. The PFS science operation will be carried out in a queue mode by default and various developments, implementations and validations have been underway accordingly in parallel to the instrument commissioning activities. Meetings and sessions are arranged continually with the communities of potential PFS users on multiple scales, and discussions are iterated for mutual understanding and possible optimization of the rules and procedures over a wide range of processes such as proposal submission, observation planning, data acquisition and data delivery. The end-to-end processes of queue observations including successive exposures with updated plans based on assessed qualities of the data from past observations are being tested during engineering observations, and further optimizations are being undertaken. In this contribution, a top-level summary of these achievements and ongoing progresses and future perspectives will be provided.

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 (Kimura et al. 2010,[2] Tamura et al. 2012[3]). Subsequently, since 2013, Hyper Suprime-Cam (HSC)[4] has been continuously delivering superb images over large areas of the sky from the Subaru's prime focus and leading researchers to various exciting results (e.g. Sugiyama et al. 2023[5]). Now a powerful, next-generation spectrometer is upcoming on the Subaru prime focus. It is the Prime Focus Spectrograph (PFS) with a very wide field of view (∼1.3 degrees in diameter) comparable to HSC, high multiplexity by ∼2400 individual fibers, and a wide spectral coverage from visible to near-infrared (NIR) wavelengths (380–1260nm). HSC and PFS will be a unique suite of instruments as they are very wide-field imager and spectrometer on the same telescope with a large light-gathering power by the 8.2m primary mirror.

The development of this instrument has been undertaken by an international collaboration managed by the project office which was hosted by the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo[*] with work packages for subsystem and subcomponent developments assigned to various institutes in the collaboration. The PFS instrument consists of four major subsystems: the **Prime Focus Instrument (PFI)** receives the light from astronomical objects through the telescope and the Wide Field Corrector lens system, and then **the on-telescope fiber cable system** transmits the lights from PFI to the **Spectrograph System (SpS)**. Meanwhile, the **Metrology Camera System** that is installed on the Cassegrain focus takes an image of the entire focal plane at the prime focus in one exposure and measures the positions of the back-lit fiber tip images very accurately for fiber configuration. These subsystems started being delivered from the PFS partner institutes outside Hawaii and being integrated on the telescope since MCS first arrived in 2018. In parallel to continual hardware deliveries since then, on-sky engineering tests and observations started in September 2021. The commissioning process since then was not smooth due to some major hardware and software challenges, but the collaboration accomplished Engineering First Light (EFL) in September 2022 based on the successful feeds of photons into the instrument from many targeted stars over the entire focal plane as intended, although the fiber positioning accuracy was still preliminary. In this article, the progresses of instrument

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[*] The project office was recently migrated to the Subaru telescope observatory, National Astronomical Observatory of Japan (NAOJ) as some of the key members moved from Kavli IPMU to Subaru as the instrument was getting assembled at Subaru.

integration and commissioning observations at Subaru over the last couple of years are summarized. According to the advancement of the commissioning process, more activities are being accommodated to develop, implement and validate the instrument operation for scientific use in the framework of general open-use observations, A summary of this work is given later in one specific section, too. In parallel to these instrumentation activities, the science working groups in the collaboration have been trying to timely develop and consolidate a plan of large-sky survey observations to be conducted in the framework of the Subaru Strategic Program (SSP). The three main survey components (cosmology, galaxy & AGN evolution, and Galactic archaeology)[6] will enable independent approaches and investigations of dark matter density structures over a wide range of spatial scales at different epochs of the Universe, which we believe will ultimately lead us to a comprehensive understanding of and challenges to the Λ-CDM cosmology. Recently, the details of the survey plan have been greatly updated and advanced as the actual instrument performance and characteristics are being better understood, and all these persistent efforts have led to the submission of a formal proposal to SSP.

In what follows, the recent progresses and achievements in the instrument system integration at the Subaru telescope observatory are described in § 2. Then in § 3, the instrument performance measured during the engineering observations is explained. The data reduction pipelines, actual data processing and data analyses for quality assessments are introduced in § 4, and the development and implementation for the PFS science operation are described in § 5. Finally, a summary of this contribution with some future perspectives is given in § 6.

2. INSTRUMENT SYSTEM INTEGRATION AT SUBARU

Since the last report,[7] the hardware delivery and integration have proceeded significantly. As of the middle of June 2024, all hardware components (except for the Near Infrared (NIR) camera of Spectrograph Module 1 (SM1)) have been integrated at the Subaru Telescope. A few components were upgraded to improve the instrument performance following the results from the engineering observations.

The installation of the second, third and fourth unit of the fiber cable system on the telescope was carried out in April 2022, January 2023 and May 2023, respectively. The installation was done in a two-stage manner: routing the cable on telescope and routing the cable along with the telescope dome wall. Based on the procedure significatly improved and consolidated with feedback from the installation work of the first cable in 2021, the installation work of the three cable units went smoothly with great support by Day Crews of the Subaru Telescope. The FRD (Focal Ratio Degradation) of ~ 30 pairs of fibers was monitored during the installation work, and no significant degradation was observed in the middle of the installation process and afterwards for each cable unit. Readers should refer to Koshida et al. for this meeting[8] for a detailed report on the performance including long-term monitoring.

Besides, the three other SMs as well as two NIR cameras (9 cameras in total) were delivered from Laboratoire d'Astrophysique de Marseille (LAM) and Johns Hopkins University (JHU) respectively. The details of these processes are well described in the papers by Madec et al.[9] and Rousselle et al.[10] for this meeting. Accordingly the engineering runs since November 2022 were carried out with new cameras and modules, which increased the number of spectra and/or extension of the spectral wavelength range: In November 2022, with SM3 integrated, the number of sky spectra doubled to be ~ 1200. The engineering first light of the NIR spectra was achieved in April 2023 with the SM1 NIR camera, followed by the SM3 NIR camera in July 2023. In November 2023, the remaining two SMs, one full module and the other one with the visible cameras, were delivered and integrated by LAM and Subaru members. In the same period, modification of the Volume Phase Holographic Grating (VPHG) assembly was also carried out because the throughput measurement with spectro-photometric standards revealed a significantly lower throughput than predicted and this turned out to be due to the wrong orientation of the VPHG. The details are provided by Dohlen et al.[11] for this meeting. The orientations of the blue, red (LR) and NIR VPHG were corrected for SM1, SM2 and SM3, which had been already shipped from LAM to Subaru, by rolling the assembly by 180 deg. As a result, ~ 2400 spectra were obtained and sufficicent throughput recovery was confirmed during the on-telescope test in December 2023. The modification of the MR-mode VPHG assembly was carried out in February 2024, by flipping the ~ 60 kg assembly. The work was done by LAM and Subaru members, and the jigs were designed and produced by JHU and Princeton University (PU).

In addition, the electrical box to control PFI was upgraded to run the instrument more stably, because previously the communication to the AG (Acquisition & Guide) cameras was lost frequently on the telescope. Originally, 2 single-mode fibers and fiber-USB converters were used for communications between the AG cameras in PFI on the telescope and control server computer in the control building. However, the fiber-USB converter occasionally showed voltage drops which caused communication losses. By replacing the converters with a small computer and an industrial-standard USB hub, PFI operation has improved much, and been stable since July 2023. From the engineering observation, it was found that the AG focus position was shifted by $\sim 500\ \mu$m from the science fibers focus position. A 3mm-thick glass plate was therefore installed on each AG camera, in front of its field element, to compensate for the focus shift in February 2023 whose details are reported by Wang et al.[12] for this meeting. As a result, the focus position between the AG cameras and fibers now matches within $\sim 50\ \mu$m.

MCS accidentally fell by ~ 10 cm during the instrument exchange in December 2023, which resulted in $\sim 35\ \mu$m focus shift on the MCS image plane, corresponding to ~ 14 mm on the PFI focal plane. During the downtime in January 2024 when PFI was still on the telescope after the on-telescope test, realignment of the MCS camera assembly was performed by the team from Academia Sinica, Institute of Astronomy and Astrophysics (ASIAA). The tilt of the image plane, which had been found from the initial engineering run data, was also corrected in the same period.

During the integration and test of the last NIR camera at Johns Hopkins University (JHU) in late 2023, we found the Quantum Efficiencies (QE) of the NIR detectors (Teledyne H4RG-15) had degraded to at least half of the originally measured value. One of the detectors was returned to Teledyne for failure analysis and the root cause was determined by Teledyne, who then developed a rework procedure to remove contamination. This procedure was applied to the unit and ultimately the original performance was achieved. The investigation, analysis and rework caused a delay of several months to restart the integration and test of the camera. Subsequently, the camera has been completed successfully and arrived at the Subaru summit in May 2024 for its integration on the fourth SM (SM4), which is planned this summer. In fact, upon thorough review of all NIR detectors, one of the NIR cameras that was already in operation at Subaru turned out to host a detector with a factor of two lower QE than originally tested, according to the data obtained from engineering runs. The group decided to extract the detector, ship it back to JHU, and finally return it to Teledyne to apply the same rework procedure. The reintegration and testing of this camera was complete, and is now being shipped to Subaru.

3. INSTRUMENT PERFORMANCE AND VALIDATIONS FROM ENGINEERING OBSERVATIONS

Since the MCS delivery in 2018, 18 engineering runs[†] with 117 nights in total have been scheduled, among which 79 nights have been carried out. 38 nights (32% of the scheduled nights) were cancelled due to instrument troubles (14 nights), telescope troubles (14 nights) and bad weathers (10 nights). The engineering observations are continuing over years, mainly because hardware development and delivery are accommodated intermittently. We started on-sky tests without waiting for completion of all the hardware components because the test items in the early phase of engineering observations could be executed with part of the instrument (i.e., PFI, MCS and one on-telescope fiber cable unit and one SM).

The processes of the engineering observations are to (1) verify the instrument operation on the telescope, (2) calibrate/verify the instruments to put the science fibers on the celestial objects on the PFI focal plane accurately, and (3) verify the instrument performance such as throughput, sky-subtraction accuracy and flux-calibration accuracy, and (4) stabilize the performance and operation. Currently we are on the stage of finalizing (2), and in the middle of (3). In this section, we pick up the major achievements from the engineering observations.

[†] This includes one 14-night on-telescope test in September 2021 during a downtime for telescope maintenance.

3.1 Guiding Performance

Six AG cameras are installed at the edge of PFI's Field of View (FoV) to lock the instrument onto a targeting sky field. Performance tests of software on both the PFS and telescope sides were carried out in April 2023 with the telescope manufacturer. From the test in the several fields across the sky, it was validated the software uses correct logic. Typically, the accuracy of field acquisition and guiding is of the order of $0''.1$ in both R.A. and Dec. (Alt. and Az.) directions, corresponding to 10% of the fiber core size in each axis. In some fields, the instrument rotator does not seem to catch up with the rotation of sky. The drift speed is of the order of 10^{-6} deg/sec, so the targets around the edge of the FoV go off by a few μm for 900-sec exposure.

The focus position (i.e. the z-position of POpt2 Hexapod) was compared between the AG cameras and the science fibers in November 2022 by comparing the fiber flux at different focus positions around the position where AG cameras are in-focus. The measurement showed that the focus position was different between the two by ~ 500 μm. The correction was done for all the AG cameras (§ 2, and also by Wang et al.[12] for this meeting). We roughly confirmed the focus offset was improved in observations in 2023, and comparison was done in March 2024 with more fibers to have better statistics. The result showed that the focus position was the same within ~ 50 μm.

3.2 Fiber Configuration

To position the fibers at the targets on the PFI focal plane, we move the fiber positioners "Cobra" after measuring their centroids using MCS and iterate this several times. Since the Cobra convergence performance on the telescope became well-understood, we have been optimising the convergence speed by eliminating the redundant and unnecessary processes and modifying the software. As a result, the convergence speed is typically ~ 130 sec with 8 iterations (and the best record is ~ 120 sec. See the details on the paper by Wang et al. for this meeting[12]). Cobra convergence rate is typically several μm as a 75 percentile of the assigned fibers.

PFS uses four coordinate systems to configure the fibers — sky (α, δ) [deg], PFI (X_{PFI}, Y_{PFI}) [mm], MCS (i_{MCS}, j_{MCS}) [pixels] and the Cobra motor axes (θ, ϕ) [rad]. To calculate the command (θ, ϕ) angles to Cobras, the celestial object (target) position on the sky coordinate and the fiber position on the MCS coordinate are transformed to the PFI coordinate, respectively. Through the engineering observations, we have been optimizing these transformation functions. We adopted a "raster-scan" method to measure the offset between the configured fiber positions and the actual target positions. The concrete procedure is as follows: (1) Configure the fibers to the targets, and acquire the field using the AG cameras. Here, the target positions are updated just before fiber configuration with actual observing time. (2) Take spectra at the position set in (1) and then at the surrounding positions by dithering the telescope. (3) Measure the actual positions of target objects based on the centroid of the flux map generated by each fiber in (2). We utilized partial readout of SpS CCD (20 sec instead of 60 sec) to reduce the impact of change in sky condition as well as to obtain the data more efficiently. We dithered the telescope to draw a hexagon with a $1''.5$ pitch in an early phase, and later reduced the pitch to $1''.0$, which corresponds to the fiber core size. The targeted stars for the raster scan were selected from the Gaia DR2 or DR3 catalogue in the open cluster regions and a few arbitrary sky regions. Comparing the results among the several fields at different telescope positions as well as different instrument rotator angles, we compensated systematic error and higher-order pattern $[O(x^5)]$ from the distortion of Wide Field Corrector[13] step by step. So far, the configuration accuracy is $< 20 - 30$ μm for 95 % of the assigned fibers. Note that the fiber configuration accuracy includes the error of field acquisition and that of the Cobra convergence (see above).

3.3 Total throughput

The evaluation of the system throughput is underway using data taken during the on-sky engineering observations. We observed flux standard stars including Calspec spectrophotometric standards and faint DA white dwarfs. We also observed flux calibration stars, which were assigned into fibers with sky fibers and science fibers. In order to evaluate the system throughput, flux loss by the fiber aperture needs to be estimated by considering the seeing and the fiber offset properly. The seeing size is estimated by using the size measurements of guide stars during the observation. The fiber offset is also estimated using the result of raster scanning. The measurement of the total throughput includes typical atmospheric transmission, telescope primary mirror reflectivity and WFC, PFS system throughput from the micro-lens to detector QE. Although there is still uncertainty, the preliminary analysis shows that the total system throughput is basically consistent with what we expected in the compilation of measurements of each sub-system component and some assumptions, which are ∼0.18 (at 500 nm in b-arm), ∼0.24 (at 800 nm in r-arm), and ∼0.18 (at 1100 nm in n-arm).

4. DATA REDUCTION PIPELINES AND QUALITY ASSESSMENTS

The PFS Data Reduction Pipeline (DRP) processes obtained data to extracted and calibrated spectra and derives the physical information of the observed objects from the spectra. The 2D DRP reduces raw 2-Dimensional (2D) images from SpS and generates 1D spectra which are calibrated for wavelength and flux. The 1D DRP then processes the obtained 1D extracted spectra to derive physical quantities such as radial velocities of stars and redshifts & spectral line fluxes of galaxies. The basic framework and functionality of the DRPs have been implemented and verified by the end-to-end processing of real data obtained in the on-sky engineering observations. Quality Assessment (QA) of processed data is one of the current major activities to improve the quality of the pipeline products. Currently the QA process checks the accuracy of wavelength calibration, extraction, and flux calibration, and it automatically starts after each product is generated.

The calibration of the spectra is being tested continuously against data taken during the engineering runs so far. The confirmation of wavelength calibration accuracy is performed using a calibration product called `detectorMap`, which contains the trace position of each fiber and the mappings between the detector position in pixel coordinates and the wavelength. `detectorMap`s are generated using quartz (Halogen) and arc (Ar, HgCd, Kr, Ne, and Xe) lamp data. This `detectorMap` is adjusted during the on-sky observation using sky lines to correct small differences from the original `detectorMaps`. The current achievement of the wavelength calibration is < 0.1 pix in both spatial and wavelength[‡] directions for all arms and SMs. 1D spectra are extracted optimally from the 2D image using the information of the fiber traces and profiles in the spatial direction which is called `fiberProfiles`. The `fiberProfiles` are generated using quartz data but the data are taken by illuminating every 4 fibers and hiding others in-between behind the black dots printed on the Field Element in front of the PFI focal plane. Thanks to this illumination arrangement, the wings of the fiber profiles are accurately measured out to distances reasonably far from the profile center. We take 4 sets of this data in different fiber configurations to derive the profiles of all fibers. Improvements are still possible in the `fiberProfiles`, e.g., by modeling the faint, diffuse backgrounds on the SpS detectors due to the scattered light inside the cameras. The extraction is made for each arm (`pfsArm`), which are merged into a spectrum with the full wavelength coverage (`pfsMerged`). In this stage, the sky subtraction is performed in 1D. A study on the quality of the sky-subtraction will be mentioned later. The flux calibration is performed using the data of flux calibration stars observed on the same field and at the same time as science objects. Firstly, the determination of stellar type is carried out by measuring absorption features of the flux calibration stars from their whitened spectra as well as the broad band photometry in the original catalog, which generates a calibration product called `pfsFluxReference`. The vector of conversion between observed count and physical unit is calculated for other fibers observing science objects by interpolating the information over the focal plane, which generates another calibration product called `fluxCal`. The quality of the flux calibration is checked by comparing the measured magnitudes and colors to the catalog values of the flux calibration stars. The wavelength- and flux-calibrated 1D spectra are then stored in output products called `pfsSingle`, which are co-added for an individual object and are saved as a product called `pfsObject`.

The final `pfsObject` from the processes in the 2D DRP is fed to the 1D DRP. The 1D DRP is developed based on Algorithm for Massive Automated Z Evaluation and Determination (AMAZED),[14] which is an instrumental

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[‡] Accordingly, the current wavelength calibration accuracy is 0.01nm or better and work is still ongoing for further improvements.

adaptable Bayesian object classification and redshift measurement code. The code is calibrated using the heritage of previous large spectroscopic surveys. The adaptation of the codes and interfaces to PFS is being undertaken and now tested using simulated and real PFS spectra. The code classifies spectra to galaxies, QSOs and stars and infers the probability distribution function of redshift (for galaxies and QSOs) and radial velocity (for stars). It also measures the line fluxes and equivalent widths for galaxies and QSOs. In addition, there is a separate 1D DRP for the measurement of radial velocities[15] and chemical abundances of stars targeted by the PFS Galactic Archaeology program. The velocities will be fit by maximizing the statistical significance in each individual exposure. The chemical abundances will be measured by comparing observed spectra to a custom grid of model spectra, with special attention paid to molecules like TiO, which are especially important for the cool red giants PFS will observe in M31. The resulting quantities are stored into `pfsZCandidate`. All processed data from the 2D and 1D DRPs will be delivered to users via the PFS Science Platform mentioned in § 5.

While the developments and testing of these pipelines and associated frameworks are progressing well overall, it is also true that there are ongoing challenges such as those highlighted here: (1) Modeling of `fiberProfiles` and subsequent extraction of individual spectra taking into consideration the effect of scattered light. Once these are better dealt with, faint object spectra with those from bright targets nearby on the same SpS images can be better extracted. But there are a few difficulties, e.g., the scattered light depends on input source spectra, and it is not straightforward to develop a robust enough kernel for scattered light modeling and subtraction. (2) Performance of the flux calibration over the entire wavelength range. Better understanding requirements to the number of flux calibration stars and their spatial distribution on the focal plane would be necessary for optimizing observation planning. (3) Processing of the H4RG data taken in the up-the-ramps mode. This is one of the important remaining tasks based on high demands for sciences of high-redshift galaxies. (4) Speeding up processing times in the 2D and 1D DRPs for efficient overall PFS operation. (5) Accurate sky subtraction. To characterize its performance, we sometimes intentionally put all the fibers on blank sky areas, and see how well the sky spectra can be modelled using a subset of them and subtracted from the other fibers. The distribution of residuals in each arm after sky subtraction looks quite close to a Gaussian with a peak around zero.[16] This is a good sign, but investigations should continue for detailed understandings and improvements which may also come from precise understandings of the OH lines and subsequently more accurate wavelength calibrations.[17] The challenge in the sky subtraction process is to accurately model the sky on any fiber using a limited subset of fibers looking purely at sky. To address this, we are trying to model a 2D Point Spread Function at each detector position and characterize this fiber spectrum as a successive integration of 2D PSFs. Our approach to do this is some sort of a physical forward modeling that models the instrument from the pupil image in the spectrograph and simulate the corresponding in-focus image. We are still in the middle of studies but we do have a partial success, and efforts are continuing.[18] The team will continue to tackle these with processing data from future engineering observations as well as reprocessing those from the past ones.

5. DEVELOPMENTS AND END-TO-END IMPLEMENTATION OF FORMAL OPERATION PROCEDURES

5.1 Science Operation Scheme

PFS is the most complicated instrument ever developed for the Subaru Telescope. In order to make the best use of it and maximize the science outputs, it is crucial to develop and establish an efficient science operation scheme. The Subaru Telescope observatory has discussed with the Subaru community over the last several years, and the science operation policies are defined in the most part, although there are details that need to be worked upon. The policies summarized here are as of this writing.

Due to the wide field coverage and high multiplexity of the instrument, we cannot always expect an observer to use all the fibers in all exposures. In addition, the precursor survey, Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP), imaged over $\sim$1,000 square degrees of the sky down to unprecedented depths, and we expect many of the PFS targets will be drawn from HSC-SSP with a significant spatial overlap between different observing programs.

For these reasons, we will quite likely execute multiple observing programs when the targets fall in the same field of view. In order to efficiently share fibers between multiple programs, queue observation has to be the default observing mode.

We collect targets from phase 1. The Time Allocation Committee (TAC) reviews the proposals and grants time in units of fiber hours. The fiber hour is a new concept but simple; if a proposal has 1,000 targets with 2 hours each, then the program has $1000 \times 2 = 2,000$ fiber hours. We use targets from approved programs to define PFS observing pointings taking into account the TAC grade of each program so that higher grade programs are given higher priorities for observation. We then run a custom-designed code to optimally assign fibers to targets in each pointing, taking into account the overlap between the pointings. Calibration objects such as sky fibers and flux standards are also assigned fibers at this time, and care is taken so that they are reasonably uniformly distributed within the field of view. Details of these procedures can be found in He et al. for this conference.[19]

Each exposure (or visit) is processed onsite and the quality of each exposure is evaluated in terms of Effective Exposure Time (EET), which is an S/N-based measure of exposure time with respect to a hypothetical exposure taken under typical observing conditions. If a 15min exposure is taken under poor conditions, it can be counted as, e.g., 5min. If the conditions are better than average, it can be, e.g., 20min. Once a target reaches the allocated fiber hour, the target is considered done. When a program executes all the allocated fiber hours, then the program is considered complete.

There is also classical observing mode, where an observer joins the observation either onsite or online. Classical mode is for programs that cannot be executed in queue mode. An example case would be to run a program that requires a sequence of short exposures at the same pointing. There will be other (unexpected) cases. We also accept Target of Opportunity (ToO) programs for timely follow-up observations of transient sources.

While we try to use the fibers as efficiently as possible, we cannot always assume that all of the fibers are fed to science targets; we may not have sufficient targets in some parts of the sky and a fraction of fibers may be left unassigned. To utilize these unassigned fibers, we prepare two types of filler targets: community filler and observatory filler. The community filler is collected from the community and the details are being discussed. Targets from the community filler programs are likely heterogeneous and may not provide sufficient targets across the entire sky. To make sure that we always have something to observe, we prepare the observatory filler, which is likely a magnitude limited sample drawn from the PanSTARRS 1 survey.

Our current plan is that the observatory processes the data and deliver fully calibrated spectra to the users. NAOJ is developing the PFS Science Platform, where the users can login and analyze the data without retrieving those over the network. We plan to deliver the calibrated data there as well.

We emphasize that the policies and plans here are developed through close discussions with the Subaru community. This is important because PFS will be a facility instrument of Subaru and will be used by the community for years to come.

5.2 Implementation of the End-to-End Procedures

The goal of the PFS science operation described above is to maximize the scientific outputs making the most of all the available fibers within a limited amount of open-use observing time. To achieve this goal under the default queue observing mode, we implement a semi-automated end-to-end queue operation scheme detailed below. We have conducted a dedicated end-to-end test run to validate and optimize this scheme during the past PFS commissioning observations.

First, we created mock open-use programs based on targets selected for the science verification of the commissioning observations. To mimic the process at the TAC, relative scores and fiber hours are assigned to each mock program. The targets (coordinates, exposure times, priorities, etc.) and program information (scores, fiber hours, etc.) are then ingested to dedicated databases. During the daytime, the observatory creates a queue by generating an optimal set of pointing coordinates, fiber assignments, and nightly schedule of the observation taking into account all the programs and assuming a nominal overhead. During a given night, the queue observation is carried out following the schedule created in the daytime. At the end of each night, an initial quality assessment of taken data is performed by calculating the EET (see previous section) for each visit. The completion of each target is evaluated by the sum of EET relative to the requested exposure time for a given target. The completion of the program is judged by the achieved fiber hours compared to the requested fiber hours. The information on the observation progress and completion status of individual objects is then stored in relevant databases and queried during the planning for the next night.

In the past commissioning observations, we verified that the basic queue-mode operation scheme described above can be executed smoothly. Specifically, we confirmed that (1) the pointing center determination,[19] fiber assignments, and nightly schedules are reasonably optimized to complete high science rank programs efficiently, (2) the assumed overhead in the scheduling is consistent with actual overhead, (3) the initial quality assessment can be completed on time so that the results are incorporated to the daytime planning of the next night, and (4) the contents of the relevant databases can handle all necessary information to close this queue-mode operation loop. Further optimization of the queue-mode operation, as well as the classical-mode scheme and ToO operation are in progress and will be tested in the upcoming engineering observation.

6. SUMMARY AND FUTURE PERSPECTIVES

The PFS instrumentation developments are finally about to be complete thanks to great efforts especially those by its international collaboration for more than a decade after the project was formally launched. The team is continuing commissioning activities to aim at starting general, open-use operations for sciences in 2025.

PFS is a very wide-field, massively multiplexed, optical and NIR spectrograph. The prime focus is equipped with 2386 fibers (out of which ∼2355 are reconfigurable) 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 in the LR mode while there is the MR mode selectable on the visible red channel which covers $710 - 885$nm. Over the last couple of years, the fiber cable system on the telescope was integrated into its complete shape, and SpS was also fully integrated except for one NIR camera that was dismantled for detector refurbishment and will be re-installed hopefully in August 2024. According to the persistent efforts of validation and optimization during engineering observations, the instrument performance has been found to be quite as good as expected: the accuracy and speed of the fiber reconfiguration process have been recently confirmed to be $\sim 20 - 30\mu$m for 95% of allocated fibers, and ∼130 seconds, respectively. While precise quantitative analyses are still being carried out, the measured throughput has been confirmed to be consistent with what is expected from the model integrating the information from the lower-level assemblies and components. Long integration of relatively faint objects are being taken to validate the expected increase of signal-to-noise ratio as more exposures are taken and co-added without any serious systematic errors from, e.g., sky subtraction process. The PFS science operation will be carried out in a queue mode by default and various developments, implementations and validations have been underway accordingly in parallel to the instrument commissioning activities. Meetings and sessions are arranged continually with the communities of potential PFS users on multiple scales, and iterative discussions are conducted for mutual understanding and possible optimization of the rules and procedures over a wide range of processes such as proposal submission, observation planning, data acquisition and data delivery. The end-to-end processes of queue observations including successive exposures with updated plans based on assessed qualities of the data from past observations are being tested during engineering observations, and further optimizations are being attempted. The information on the instrument, collaboration and survey strategy are 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/`.

PFS and HSC are a unique suite of powerful survey instruments exploiting the prime focus of the Subaru Telescope and will be crucial strategic pieces in the next decades from their complementarities to new generation ground-based and space facilities such as Rubin Observatory, Thirty-Meter Telescope (TMT), Nancy Grace Roman

Space Telescope, and James-Webb Space Telescope (JWST). From the coming years, PFS on the Subaru telescope will continue to be a world-leading astronomical facility from its wide-field, wide-waveband spectroscopic capability to further advance our understandings of the physics of the Universe as the “multiplest” part of the Subaru’s wide-field tripod with HSC for the deepest and ULTIMATE-Subaru[20] for the sharpest.

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REFERENCES

[1] Miyazaki, S., Komiyama, Y., Sekiguchi, M., Okamura, S., and Doi, M. *et al.*., “Subaru Prime Focus Camera – Suprime-Cam,” *PASJ* **54**, 833–853 (2002).

[2] Kimura, M., Maihara, T., Iwamuro, F., Akiyama, M., and Tamura, N. *et al.*, “Fibre Multi-Object Spectrograph (FMOS) for the Subaru Telescope,” *PASJ* **62**, 1135–1147 (2010).

[3] Tamura, N., Takato, N., Iwamuro, F., Akiyama, M., and Kimura, M. *et al.*, “Subaru FMOS now and future,” in [*Ground-based and Airborne Instrumentation for Astronomy IV*], Ian S. McLean, Suzanne K. Ramsay, H. T., ed., *Proc. SPIE* **8446**, 8446M0 (2012).

[4] Miyazaki, S., Komiyama, Y., Nakaya, H., Kamata, Y., and Doi, Y. *et al.*, “Hyper Suprime Cam,” in [*Ground-based Instrumentation for Astronomy*], Moorwood, A. F. M. and Masanori, I., eds., *Proc. SPIE* **5492**, 1228–1242 (2012).

[5] Sugiyama, S., Miyatake, H., More, S., Li, X., and Shirasaki, M. *et al.*, "Hyper suprime-cam year 3 results: Cosmology from galaxy clustering and weak lensing with hsc and sdss using the minimal bias model," *PhRvD* **108**, Issue 12, article id.123521 (2023).

[6] Takada, M., Ellis, R. S., Chiba, M., Greene, J. E., and Aihara, H. *et al.*, "Extragalactic science, cosmology, and Galactic archaeology with the Subaru Prime Focus Spectrograph," *PASJ* **66(1)**, id.R1 (2014).

[7] Tamura, N., Takato, N., Moritani, Y., Yabe, K., and Ishizuka, Y. *et al.*, "Prime Focus Spectrograph (PFS) for the Subaru telescope: A next-generation facility instrument of the subaru telescope has started coming," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], Christopher J. Evans, Julia J. Bryant, K. M., ed., *Proc. SPIE* **11447**, 1144713 (2021).

[8] Koshida, S., Moritani, Y., Rousselle, J. P., Wung, M., and Okita, H. e. a., "Prime Focus Spectrograph (PFS) for Subaru Telescope: performance verification of the science-grade fiber optics cable," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[9] Madec, F., Le Mignant, D., Dohlen, K., Barrette, R., and Blanchard, P. *et al.*., "Prime Focus Spectrograph (PFS) for Subaru Telescope: Spectrograph System final integration and performance at LAM and Subaru," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[10] Rousselle, J. P., Moritani, Y., Madec, F., Blanchard, P., and Le Mignant, D. *et al.*., "Prime Focus Spectrograph (PFS) for Subaru telescope: integration and test of the last spectrograph modules," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[11] Dohlen, K., Madec, F., Gunn, J. E., Moritani, Y., and Golebiowski, M. *et al.*., "Prime Focus Spectrograph (PFS) for Subaru Telescope: recovery of the VPHG efficiency," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[12] Wang, S.-Y., Yan, C.-H., Karr, J., Chou, R. C. Y., and Hsu, S-.F. Gunn, J. E. *et al.*., "Prime Focus Spectrograph (PFS) for Subaru telescope: the optimization of target convergence for Cobra positioners," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[13] S. Miyazaki and Y. Komiyama and S. Kawanomoto and Y. Doi and H. Furusawa *et al.*, "Hyper Suprime-Cam: System design and verification of image quality," *PASJ* **70**, S1 (Jan. 2018).

[14] Schmitt, A., Arnouts, S., Borges, R., Chabaud, P. Y., Fauchier, F., Jamal, S., Le Brun, V., Le Févre, O., Surace, C., Vibert, D., and Vidal, C., "AMAZED: Algorithm for Massive Automated Z Evaluation and Determination," in [*Astronomical Data Analysis Software and Systems XXVI*], Molinaro, M., Shortridge, K., and Pasian, F., eds., *Astronomical Society of the Pacific Conference Series* **521**, 398 (Oct. 2019).

[15] Dobos, L., Szalay, A. S., Budavári, T., Kirby, E. N., Lupton, R. H., and Wyse, R. F. G., "Uncertainty of line-of-sight velocity measurement of faint stars from low and medium resolution optical spectra," *ApJ accepted* , arxiv:2407.14943 (2024).

[16] Siegel, J., Strauss, M. A., Lupton, R. H., Price, P. A., and Yabe, K. *et al.*., "Sky subtraction for the Subaru Prime Focus Spectrograph," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[17] Jespersen, C. K., Lupton, R. H., Gunn, J. E., Price, P. A., and Moritani, Y. *et al.*., "Airglow and The Subaru Night Sky Spectrograph (SuNSS)," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[18] Hayashi, K., Caplar, N., Yabe, K., Lupton, R. H., and Gunn, J. E. *et al.*., "Prime Focus Spectrograph (PFS) for Subaru Telescope: modeling of the 2D point spread function using commissioning data," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[19] He, W., Ishigaki, M. N., Tanaka, M., Yabe, K., and Onodera, M. *et al.*., "Prime Focus Spectrograph (PFS) for Subaru Telescope: the algorithm to optimize pointing centers for open-use program," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).

[20] Minowa, Y., Koyama, Y., Motohara, K., Ono, Y., and Oya, S. *et al.*., "Project overview and update on ULTIMATE-Subaru: the next-generation wide-field adaptive optics instrument for the Subaru telescope," in [*Ground-based and Airborne Instrumentation for Astronomy X*], *Proc. SPIE* (2024).