Subaru Prime Focus Spectrograph (PFS) Operational Plan

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Contents

1 Background

PFS is an open use instrument of the Subaru Telescope starting its commissioning from 2018 and the scientific operation from 2019. In this document, we describe the operation concept of PFS system during the commissioning phase and after the scientific operation starts. One of the aims of writing this document is not only to define the overall concept of the operation but also to check the possibility of the discontinuity between the operational concept and the telescope system in the Subaru Telescope (including Gen2 and archival system such as STARS/MSTARS) through conversations between the observatory and the PFS project team to mitigate the risk after the commissioning starts. Therefore, some descriptions in this document is of course subject to be updated in the future.

2 PFS System Description

Here, we briefly summarize PFS instrument system, which is described in the technical documents in more detail(e.g. [1]).

PFS is a fiber-fed type spectrograph mounted on the prime focus of the Subaru Telescope. The distinctive features are a wide area of FoV of $\sim$ 1.3 deg^2, a large multiplicity of $\sim$ 2400 fibers, and a wide range of wavelength coverage from 380 nm to 1260 nm. PFS comprises several instruments: Prime Focus Instrument (PFI), Fiber system, Spectrograph System (SpS), and Metrology Camera System (MCS). These components are driven independently and sparsely connected in software controlled on the Messaging Hub System (MHS). In the following subsections, a brief summary of each component is described.

2.1 Prime Focus Instrument (PFI)

At the Subaru prime focus, HSC has already been in science operation with the wide field of view and the reasonably flat focal plane provided by the new Wide-Field Corrector lens system (WFC). The WFC will be used for PFS as well. Mechanically, the new prime focus housing unit "POpt2" is integrated with WFC and accommodates the HSC instrument inside. When PFS is in operation, the HSC instrument will be taken out and our **Prime Focus Instrument (PFI)** will be installed in POpt2.

PFI has been developed by the collaboration of California Institute of Technology (CIT) & NASA Jet Propulsion Laboratory (JPL), Laboratório Nacional de Astrofísica (LNA, in Brazil), and Academia Sinica Institute of Astronomy and Astrophysics (ASIAA, in Taiwan), accommodating key subcomponents such as the fiber positioner system, science & fiducial fiber system, Acquisition & Guide (AG) cameras, and calibration system[2]. The fiber positioner system consists of 42 modules each of which accommodates 57 "Cobra" rotary actuators populated with science fibers. The tip of each science fiber is equipped with a plano-concave microlens to increase the focal ratio of the input beam to the fiber to 2.8[3]. The Cobra engineering model actuators have been assembled to a prototype module and tested. The results show satisfactory target convergence performance in the patrol field of each fiber[4]. These subcomponents will be integrated into PFI and be fully tested at ASIAA before delivery to

2.2 Metrology Camera System (MCS)

Metrology Camera System (MCS) is under development at ASIAA[5]. It will be installed at the Cassegrain focus of the telescope. Because the fiber positioners have no encoders, an external system is required to drive them to the proper position. MCS corresponds to this external system which takes images of the science and fiducial fibers back-lit from the other side of prime focus, and then measures the fiber positions, enabling closed-loop operation of the positioners. MCS is capable of taking an image of all the back-lit science and fiducial fibers on the prime focus in one exposure. The fiber configuration time is significantly shorter than FMOS for which a small CCD camera needs to scan the field of view to measure all the fibers. The 380mm aperture system is designed to minimize the impacts of the dome seeing effect and small-scale figure errors of the WFC lens surface shapes.

2.3 Spectrograph System (SpS)

Spectrograph System (SpS) will be integrated at Laboratoire d'Astrophysique de Marseille (LAM)[6], with the fiber system delivered by LNA and the camera dewars & detectors developed by Princeton University (PU)[7] and Johns Hopkins University (JHU)[8, 9]. The divergent beams from the science fibers on the pseudo slit are collimated and then split into blue, red and NIR channels by two dichroic mirrors. After this, the beam is dispersed by the VPH grating and spectral images are formed on the detectors. A grating exchange mechanism allows a higher dispersion VPH grism to be accommodated in the system and deliver medium resolution spectra in the red channel with no changes in the other parts of SpS. SpS consists of four spectrograph modules (SM) each of which is identically designed to deliver ∼600 spectral images on the detectors.

2.4 Fiber system

Fiber system "FOCCoS" to be delivered by LNA[**?**] consists of three parts: Two short-fiber systems accommodated in PFI and SpS, and a long cable system between them routed on the telescope. The route of this long one is still being finalized, but the total fiber length will be approximately 65m. These three parts are connected together by two sets of fiber connectors. One is needed at the telescope top end to make POpt2 detachable from the telescope, and the other is in front of SpS to ease the delivery and integration of SpS at Subaru and to make the operation and maintenance activities independent of the other PFS subsystems.

3 PFS Operation Concept

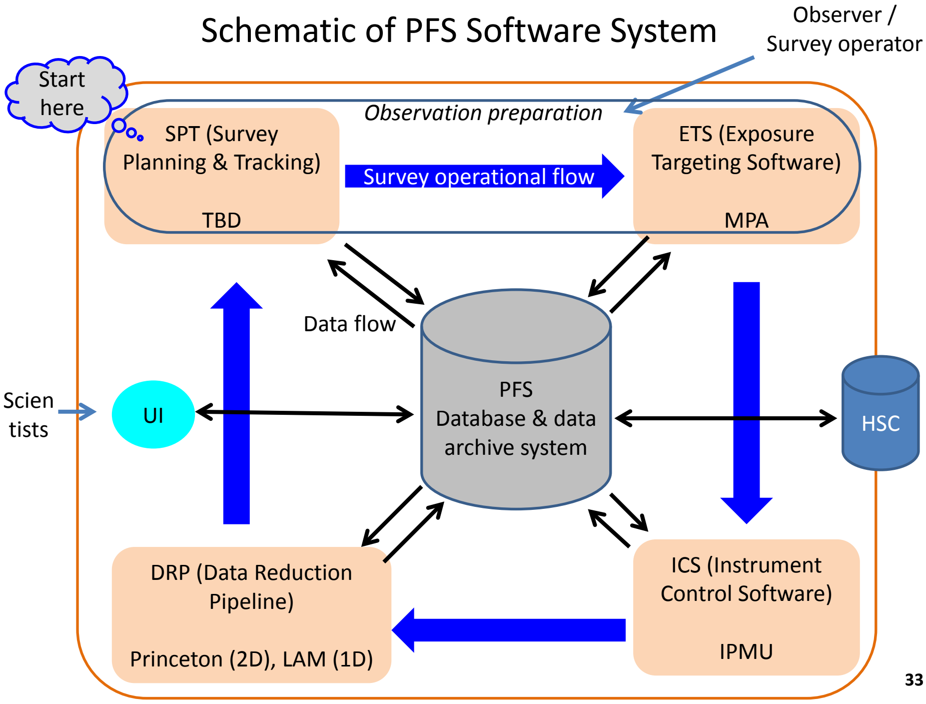

Figure 1: A schematic diagram of PFS survey operation concept with the four software packages and database/data archive system responsible for key processes (to be updated).

For the operation of the PFS instrument and the large survey program it will carry out, coordination not only between the hardware and software but also between different software packages is crucial. Four software components are under development for this, with different sets of functions packaged and therefore designed to be only loosely coupled to each other. The detailed definitions of these four packages have been evolving as the instrument and survey operation concepts are being updated to maximally accommodate the distinct features of the planned survey for PFS SSP such as: (1) A much fainter limit than previous legacy surveys such as SDSS is pursued, exploiting the large light-gathering power of the Subaru Telescope, (2) given the wide variety of scientific goals, a wide variety of objects are targeted for observation and therefore a variety of definitions of success need to be encompassed, (3) PFS allows dynamic fiber reallocation even on an individual exposure basis, unlike the static integration in case of classical multi-slit and multi-fiber spectroscopy using machined plates. In addition, since PFS will be a facility instrument at the Subaru Telescope observatory and will be operated in the framework of general open-use observation, we are continually discussing all aspects of operations with the observatory and are trying to adapt our plans accordingly. Below an overview is given of the current operation concepts and the main bodies of the software definitions which is sketched out in Figure 1.

3.1 Observation preparation

The observation process starts with preparing an input target catalog which includes not only science targets but also stars for field acquisition, auto-guiding & focusing, and flux calibration. Then telescope pointings, position angles, and fiber allocations to science targets at each pointing are defined for a given time of observation (statements about the dot should be here). This planning task is performed by a software package called **"ETS" (Exposure Targeting Software)** being developed by Max-Planck-Institut für Astrophysik (MPA). This observation configuration is prepared by scientists at sites off the observatory, and the prepared configuration is then uploaded to a **database** system. At the actual time of observation, which may be different from the one in the plan, the details in the mapping between the science targets and allocated fibers are recalculated before the fiber configuration starts. Observers should assign a fraction of fibers to observe blank sky regions and another fraction to observe flux calibration stars simultaneously with the science targets. The optimal numbers and distributions of these fibers for sky and calibration targets will be determined in the course of on-sky engineering observations.

3.2 Instrument operation & data acquisition

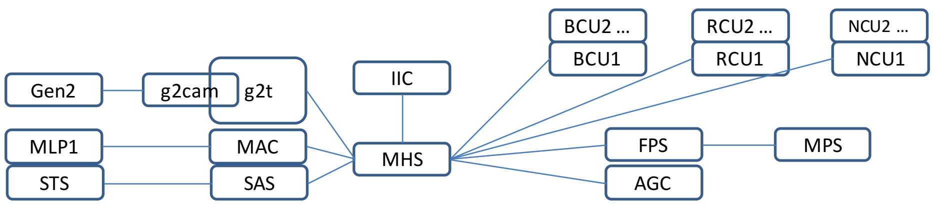

Figure 2: A diagram showing the connections of software components around MHS (Messaging Hub System) which is the key to organizing distributed processes.

"ICS" (Instrument Control Software) is the software package that orchestrates the PFS subsystems and subcomponents for instrument operation in coordination with the telescope system. The key component for the integration and coordination is a messaging hub system (MHS). Figure 2 shows a schematic diagram of the distributed PFS software components and the telescope control system connected via MHS. As has been demonstrated in the SDSS operations at Apache Point Observatory, it efficiently organizes distributed processes providing uniform communication interfaces between subcomponents. MHS is being used for the operation of the CHARIS instrument[11] (a high contrast integral field spectrograph for studying disks and extrasolar planets around stars) which is now in the commissioning phase at the Subaru Telescope, so we will take advantages of this experience in advance of the PFS commissioning process.

Details of the telescope and PFS instrument operation will be explained later in § **??**, but after various setup processes such as telescope pointing, instrument rotator rotation, focusing, and fiber configuration, auto-guiding starts and the spectrograph system starts taking exposures. The data format from each exposure are two 4K $\times$ 2K CCDs from the blue and red cameras, and one 4K $\times$ 4K H4RG detector from the NIR camera. At the end of each exposure, the data are read out and passed on to the Data Reduction Pipeline (DRP) for on-site data reduction, data quality assessment & assurance, and data archival.

3.3 Data reduction & spectral calibration strategy

"DRP" (Data Reduction Pipeline) comprises the "2D" part (2D-DRP) and the "1D" part (1D-DRP). The 2D-DRP, which is under development by PU, receives two-dimensional raw spectral FITS images read out from the detectors and produces one-dimensional, sky-subtracted, flux- and wavelength-calibrated spectra ready for scientific analyses. The 1D-DRP being developed by LAM then receives these 1D spectra and measures various parameters of spectroscopic features such as redshifts and emission line fluxes. After each exposure of the spectrograph detectors, the data will be processed by on-site DRP with calibration data sets taken in advance. 1D-DRP is applied to the reduced and calibrated 1D spectra and measured parameters are added to the database. As successive exposures are taken for the same objects at different nights and observation runs, deeper and higher quality spectra will be produced from from full, batch processing of all available data.

One important challenge for this project is to achieve the goal of sky subtraction accuracy (down to $\sim$0.5% in the faint sky continuum between the lines). This means, given that we are not doing beam-switching operations, that the sky spectrum of an object fiber needs to be accurately modeled from the spectra of other fibers looking at the sky, and for this, the two-dimensional fiber PSF needs to be well characterized as functions of x and y on the detectors (corresponding to fibers and wavelengths approximately). In other words, the conditions during the calibration data acquisition need to closely mimic the observing conditions at night. We have the following plans for this:

- We have a calibration lamp system on top of PFI for both flat-fielding and wavelength calibration. This lamp illuminates a quasi-Lambertian (TBC) screen on the ceiling of the telescope enclosure and the illumination reflects back to the telescope primary mirror. In this way, the telescope pupil can be diffusely illuminated for calibration mimicking the illumination by the sky in real observations at night.

- Even if the pupil illumination is managed as above, differences of the fiber status between observations and calibration may cause some errors in the PSF modeling due to e.g. variation of Focal Ratio Degradation (FRD) in the fibers. There are three cases where such errors may be introduced: (1) Fiber moves (mainly twists) as the Cobras move, (2) coils/uncoils of fiber bundles with the rotation of the instrument by the rotator, and (3) bending/unbending of the fiber cable due to telescope elevation changes. We currently think that (1) has the most significant impact, so the procedure is likely to take the calibration data for every fiber configuration taken in a given night. Detailed studies are underway. If (2) is also significant, the rotator angle should also be reproduced in this data acquisition but the amount of calibration data required could be huge and it may not be realistic to take them all during a night. If (2) and/or (3) are significant, we will plan to have another calibration lamp system to take data in the daytime as functions of telescope elevation and rotator angle and characterize the impacts.

- A significant number of fibers should be assigned as sky fibers and should be roughly uniformly distributed over the focal plane. The required number is still TBD, and will be clarified in commissioning observations.

3.4 Data quality assessment and assurance for long-term survey processing

The procedure of data quality assessment and assurance (QA) is still being actively discussed in detail, but we are aiming to accommodate a data QA on an object-by-object basis: Data quality assessment procedure and success criteria are set for each object so that, once a particular object is considered "done", the fiber(s) assigned to the object can be allocated to a different target and be reconfigured accordingly. Also, discussions of a data QA in a short time scale (much shorter than one night) are underway, for which "on-site" (i.e. at the telescope) quick data reduction is needed in addition to "off-site" full reduction. In particular for faint objects, one of the key processes is full analysis of sky fibers even in the quick on-site data QA to understand the noise characteristics and subsequently limiting fluxes as a function of wavelength. The database is then updated with such information, revisions are applied to the field definitions and/or fiber configurations accordingly, and observations are performed using such updated fields and fiber configurations. This routine is repeated until the survey is considered "done". **"SPT" (Survey Planning and Tracking software)** is the software package for the survey management responsible for data QA.

4 Telescope & Instrument Operation Details

Below is a list of processes that are carried out in a typical observing "night", including the evening before and morning after the night.

- Instrument exchange
- Startup of the PFS system
- Telescope & instrument pre-check
- Telescope pointing and field acquisition
- Start of the telescope and instrument rotator operation in the siderial tracking mode
- Focusing
- Fiber (re-)configuration
- Start of telesecope auto guiding
- "Science" exposures of sky
- "Calibration" exposures of domeflat and arc
- Shutdown of the PFS system

These are processed roughly sequentially in the order they appear, but some of them run in parallel and there are a set of those that are repeated e.g. every time when the telescope points to a different field. In what follows, some details of individual processes are described with such concurrent and iterative processing into account. These are also visualized and exemplified in the forms of flowchart and timing chart in Figures 3 and 4.

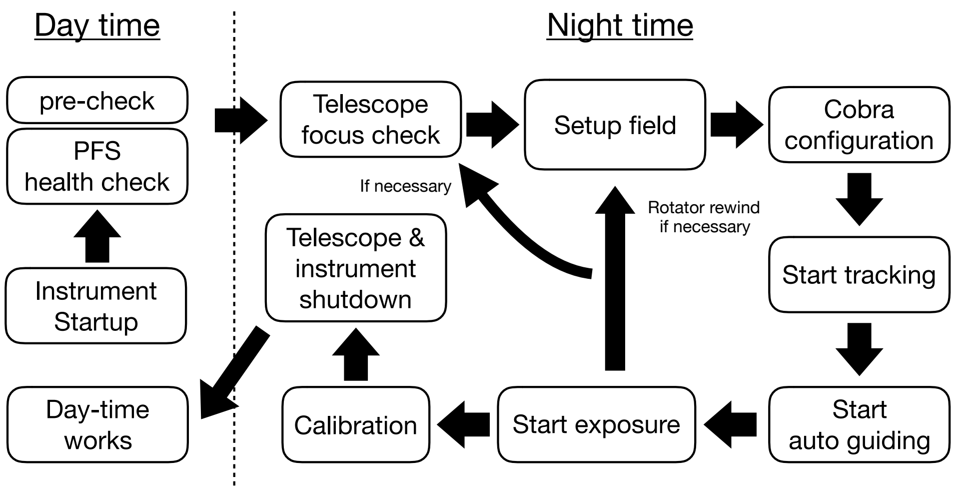

Figure 3: An example of the rough operational sequence of the normal scientific observing run.

4.1 Instrument exchange

In the beginning of the PFS observing runs, the PFS instrument needs to be set up at the right place on the telescope system. While the spectrograph system and most of the fiber system are static, PFI and MCS need to be re-installed every time. Since PFI shares the Popt2 unit with HSC, HSC unit should firstly be removed from the Popt2 if it is used before the PFS run, and then PFI is installed. MCS is an

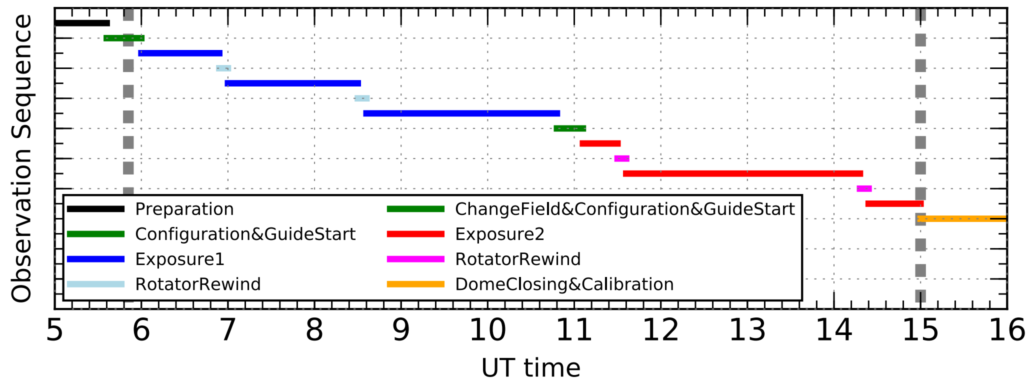

Figure 4: An example of the time sequence of the normal scientific operation. Here, we assume that moderately long exposures (several hours) are done in two different fields.

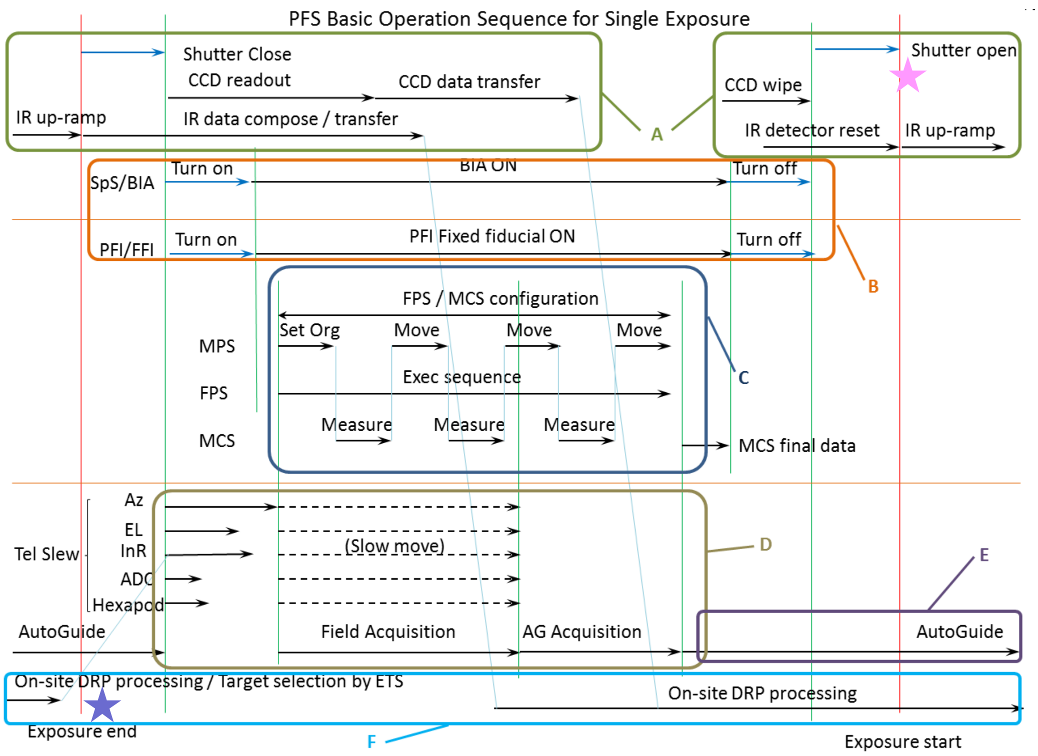

Figure 5: A schematic view of the operational sequence of instruments as a function of time. (To Be Updated)

assembly as an independent Cassegrain instrument, so it is attached directly to the Cassegrain port after another Cassegrain instrument is removed. These installation processes should be described somewhere else TBD in detail.

4.2 Startup of the PFS system

The basic procedure of this startup is supposed to be the following.

- Power ON each sub-system

- Run an initialization process on each sub-system and confirm its operation.
- Establish the communication between the sub-systems via ICS
- Leave them in a stand-by/ready state for the next process

Note that the spectrograph system is static (i.e. no need of something like instrument exchange), so it can be left in a ready status for a long time between PFS runs. Meanwhile, PFI and MCS are reinstalled at the beginning of every run. So they can be turned on at the stand-by positions for initialization and test/maintenance processes, but they are supposed to be turned off before the installation processes and the startup sequence is applied again after they get on the telescope.

The details of each process in this startup procedure should be developed and written down with a step-by-step procedure. A preliminary one will be developed at a sub-system level by the time of its delivery to the observatory, and it will be further developed by the collaboration with the observatory staffs in the process of re-integration and commissioning at Subaru.

4.3 Telescope & instrument pre-check

Once the instrument exchange is completed, the pre-check is performed before the night operation starts. This pre-check covers the health and readiness check of not only the telescope system but also the PFS instrument. The pre-check of PFS should be developed in detail in the future by collaboration with the observatory staffs, but will likely be composed of a subset of subsystem check processes and those to check the system operation on the telescope.

4.4 Focusing

There are three foci important for the PFS operation: The prime focus, MCS focus, and SpS focus. The prime focus is checked by the images of bright stars on the PFS AG cameras after the sun sets and the dome opens. There are six AG cameras surrounding the PFS science field of view where the fibers are populated. In front of each AG camera sensor, there is a setup by which the half area of camera sensor is covered by a slightly different optical path length from the other half, so that by looking at the stellar images and comparing those in one area with the other, one can determine which way the focus should be shifted. The focus is adjusted by the Hexapod which can change the distance from the telescope primary mirror to the assembly of WFC and PFI. We intend to implement this focus adjustment in parallel to running field acquisition and auto guiding. Since the focus should vary during a night, we shoud monitor it and apply correction if needed. The frequency of the focus check is not clear at this moment, but we probably need to do a few focus checks during a night.

Meanwhile, we assume the other two foci will have already been set to the optimal positions before the evening of a PFS observing night. The focus position of the detector in MCS will be optimized in the commissioning phase looking at the back-illuminated fibers at the prime focus. Opto-mechanically MCS is reasonablly thermalized within a temparature range typically expected during a night, so we expect only occasionally to have to adjust the focus position. Note that the image quality on the MCS detector is quite insensitive to the distance between the prime focus and MCS as a bulk.

The SpS focus will also be optimized in the integration and commissioning phase using the hexapod mechanism under the fiber slit assembly and the detector focus mechanism in each camera. This process can be done independent of the status of the other PFS subsystems and the telescope using the internal illumination source of SpS. Since SpS is locaetd in the temperature-controlled Spectrograph Clean Room (SCR), once the focus is optimized, we expect only occasionally to have to check and adjust it again. One exception may be when the configuration of the red camera is changed to the medium-resolution mode from the low-resolution mode or vice versa in the middle of a night: Although the spectrograph has been designed in such a way that no focus adjustment is needed between these two setups with different gratings, we will have to confirm this in the commissioning phase.

4.5 Telescope pointing and field acquisition

The first step in actual observations is to point the telescope to the target field and set the instrument rotator to a requested angle. In parallel, the Hexapod, ADC, and telescope primary mirror active support

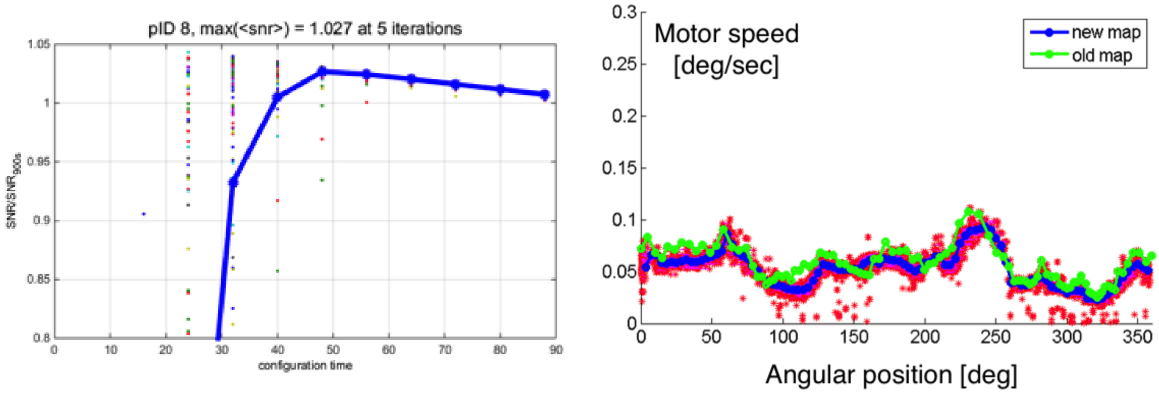

Figure 6: On the left, the level of convergence of Cobras to requested positions is plotted against measure of the signal-to-noise ratio relative to a fiducial value, which increases to the maximum at the fourth iterations and slowly decreases at later iterations. These data were taken at the target convergence tests on the engineering model Cobra positioners module. On the right, the data points indicate the Cobra motor speeds as a function of angular position. The relationship is so-called a motor map. As two curves are shown in the graph, a motor map can be updated as more data are collected.

are adjusted by the telescope control system for this new field. Once the telescope and rotator stop slewing and start operating in the tracking mode, exposures of acquisition stars are taken by the AG cameras, errors in the telescope pointing and rotator angle are calculated, and feedback is sent to the telescope control system for corrections. This process is iterated continuously until the errors are small enough to start auto-guiding. A focusing operation can be executed at some point in this course of field acquisition and auto-guiding.

4.6 Fiber (re-)configuration

While the telescope is slewing, the fiber positioner system can start configuring the science fibers at least coarsely to the expected positions of the science targets on the focal plane. When the process of fiber configuration starts, SpS closes the shutters and starts reading out the detectors. It also turns on the LEDs to illuminate the surfaces of the shutters (the other sides from the cameras are illuminated, so there is no interference to the detector readouts). The diffuse reflection of the LED lights illuminates the collimator mirror and is focused by the collimator mirror back onto the fiber slit. In this way, the fiber tips at the prime focus are back-illuminated. Meanwhile, the fixed fiducial fibers are illuminated by the fiducial illuminator accommodated in PFI. MCS then takes images of the back-lit science and fiducial fibers, measures the current positions of them and calculate the errors from the requested positions of the science fibers. Based on this information the fiber positions are updated and the errors get smaller as successive iterations are applied. Once the telescope and rotator start operating in the siderial tracking mode, the rotator operation and auto-guiding are temporarily stopped[1] for fine positioning of the fibers (the telescope can still be moving in the tracking mode). Apart from the time for telescope slewing and rotator operation, one iteration of fiber configuration is expected to take $\sim$10$-$15sec, including both the time of Cobra moves and exposure time of MCS. We expect $\sim$6 iterations will be required, so one fiber configuration will be completed in $\sim$90sec given several iterations are needed, but more studies are on-going to fully understand the timing budget.

Below are a few details to be highlighted regarding the fiber (re-)configuration process:

- The formulae to match the fiber positions on the focal plane with the positions of astronomical objects on the sky will be understood in advance and stored in the database. We expect not to have to update them often, but we should confirm this by monitoring the stability in a longer

[1] When observations are carried out using the prime focus, the prime focus instrument can be rotated, but the Cassegrain instrument cannot be operated because the focus is not in use. Accordingly, the MCS cannot be rotated synchronously with PFI and therefore the images of back-illuminated fibers on MCS are elongated if PFI is rotated and could worsen the centroiding error.

term (we will record the errors of fiber positioning at each configuration process). We should likely request engineering nights to confirm/update the formulae of coordinate transformation because quite a few fiber configuration processes on several fields will probably be required and therefore it will take a while for data acquisition and subsequent analyses.

- It is not trivial to determine that the Cobras are aligned well enough to the target positions. Actual criteria for convergence and procedure of assessment are still under discussions, but we consider that the concept of a signal-to-noise ratio can be useful as a measure of optimality, rather than the residual distances of the fibers from their targets. Starting from a situation in which all the fibers are remote from their target positions (except for chance coincidence), in the first few iterations, all the fibers get closer to the targets, so the signal in terms of fluxes from the objects to the fibers increases quickly. However, the gain of the signal after each move of the Cobras gets smaller at later iterations because most of the fibers are already reasonably close to the targets, and then the gain becomes less than the loss due to the loss of the observing time for integration on the detectors. Therefore the number of iterations giving the optimal signal-to-noise ratio must be somewhere in the middle (Fig. 6). In reality, since the time for one iteration is rather short in particular at later iterations, some more iterations to pursue better positions of more fibers may be worth at relatively small expenses of observing time, so we will leave such flexibility in the choice.

- The response of each motor in the Cobra actuator to a drive signal is known to depend on angular position (Fig. 6). Characterizing this so-called "motor map" and operating the Cobras taking it into account are considered key to achieve efficient convergence.

- Although observation strategies and data quality success criteria are different among the three main science areas in the plan of PFS SSP survey[12], all are planning to acquire data with no beam-switching to blank sky. (The instrument control system will however accommodate the beam switching capability as an option.) This will maximize the on-source integration time over the observing time and minimize the geometric constraints in the allocation of science fibers to science targets[2].

- Due to the large field of view, the differential atmospheric refraction effect is severe over most of the sky. Accordingly, the science fibers need to be reconfigured e.g. every ∼30 minutes (TBC).

4.7 Start of telescope auto guiding and "science" exposures

Once the fiber configuration is complete, the rotator operation is restarted, the field acquisition process is redone and the auto-guiding operation is restarted. In parallel, SpS turns off the LEDs for science fiber back-illumination and PFI turns off the fiducial illuminator. Then SpS opens the shutters and starts exposing the detectors to the sky.

4.8 When should the fibers be reconfigured?

In most cases of the PFS survey observation, multiple exposures for the same targets and fiber configuration are expected, but we should likely repeat exposures with often updating the fiber configuration. There are a few reasons for this:

- Due to the large field of view, the differential atmospheric refraction effect is severe over most of the sky. Accordingly, the science fibers need to be reconfigured e.g. every ∼30 minutes (TBC).

- In the current plan, the data quality assessment and assurance are carried out on an individual object basis. So, even if the same area of sky is integrated, the fiber configuration should partially change from exposure to exposure as integrated data of some targets show e.g. high enough signal-to-noise ratio.

[2] In cross-beam switching observations, two fibers are assigned to one science target and the telescope pointing is dithered between one exposure and another so that in the first exposure one of the fibers is placed on the target and the other observes blank sky, and in the next exposure, they switch the role. This way, 100% of the exposure time can be used for on-source integration, but the fibers can be significantly less flexibly allocated to targets.

4.9 Rewinding the instrument rotator

In the PFS operation, the range of instrument rotator angle is intentionally restricted by the software to that from −60 deg to +60 deg (mechanically it can rotate from −270 deg to +270 deg with no damage to the instrument). This is to minimize any variation of the fiber status by instrument rotation (possibly important for stable Point Spread Function (PSF) on the spectrograph detectors and therefore for good sky subtraction), exploiting the hexagonal symmetry on the PFS focal plane. This means that we need to rewind the rotator by 60 or 120 deg when the rotator angle hits the limit (see A.3). Figure 4 shows an example of the operation over night for a case that observations with multiple exposures in two different fields. In this case, we need to rewind the rotator two times in each field.

4.10 Calibration exposures

In the current plan, calibration exposures (i.e. domeflat frames and arc frames) are taken only at the beginning and end of a night (i.e. in the evening and morning) when the dome is closed and the telescope points to the zenith. The PFS instrument is equipped with its own calibration lamp system on top of PFI for flat-fielding and wavelength calibration. These lamps will be turned on, and exposures are taken. The mirror cover should be left open in this data acquisition for the light come into the instrument as similarly as possible to the case of observing the sky. Also, to reproduce the fiber status in the observing conditions as much as possible, we consider to configure the science fibers in the same way as observing the sky. We believe fine positioning is not needed, so a small number of iterative moves should be enough for the fiber configuration. However, if science exposures are taken with different fiber configurasions during a night, subsequently a set of calibration frames for each configuration need to be taken as in the case of FMOS calibration data acquisition. As mentioned in § 3.3, if we find additinal variation for some reasons with the telescope elevation angle, time, environmental conditions, and so on, we may need to take calibration exposures more frequently. We will clarify needs in the engineering observations.

4.11 Shutdown of the PFS system

This process is to terminate the PFS operation. Overall there are two cases: One is when a PFS observing run finishes (so this shutdown is done at the last morning before instrument exchange where PFS is removed from the telescope), and the other is when one night of PFS observation finishes but the run still continues (i.e. PFS observation is scheduled also on the next night). In the latter case, the instrument should be turned into a stand-by or sleep mode (to be defined, though) rather than shutdown completely so that it can be restarted efficiently at the beginning of next night.

The shutdown sequence is supposed to be roughly as follows, although many details should be developed through the collaboration with the observatory staffs.

- Stop the current procedure (probably calibration mode?) normally
- Check the system is in the safe state for shutdown process
- Turn the power systems OFF (especially PFI and MCS for removal from the telescope)

After the shutdown procedure is done, PFI and MCS should become ready for removal from the telescope in the day time.

As described in **??**, the entire instrument operation is done with sequences associated with each instrumental component. Here we described the detailed processes of each sequence and their relation between each other.

4.12 Special operations for commissioning, engineering, maintenance purposes

Operation details are to be written for individual processes like below needed in the commissioning phase.

- The xy and tilt alignment of the assembly of WFC and PFI against the telescope primary mirror by using defocused images of a bright star on the AG cameras

- Measuring the rotator center position relative to PFI focal plane using MCS
- Detailed characterization of PSF on the spectrograph detectors by masking quite a few fibers under the Field Element dots and making a sparse distribution of spectra on the detectors
- Initial characterization of Cobras: Arm lengths, phi and theta axes, etc.
- First-pass distortion map using the AG camera images
- Raster scan for 2nd-pass distortion map and its fine tunes
- Making formulae of relative flux calibration from observation of bright ∼F stars

5 Implementation plan (pretty much under development)

5.1 Connection between PFS and the telescope systems

The coordination of the telescope and the instruments at the summit is done by Gen2 system. In the operation of PFS system in the normal observing mode, ICS is required to communicate with Gen2 to receive the telescope status and also send the status of the instrument and requests for the movement to the telescope. The communication between the PFS system (MHS) and the telescope (Gen2) is done via an interface called “g2t” by using “g2cam” library in Python.

As we mentioned in section **??**, each sub-sequence can be processed in parallel. Since any commands in g2cam can be triggered only by Gen2, the sequence should be done in the following way:

- Gen2 prepares a command for callback
- Once the event occurs, PFS pushes the status with what should be done by Gen2 (such as rotate InR by 120 deg.) and ends the command
- The sequence running in Gen2 picks up the status value and execute the command
- Return to the 1st step (if necessary)

The detailed processing during the single exposure is described in the section **??**.

Another interface is between the status server called Subaru Telemetry System (STS) and the PFS internal Status Archival System (SAS). Various information on the instrument status is stored in SAS and some of them should also be stored in STS.

5.2 Checking the quality of the obtained data

5.2.1 Summit QA of the obtained data (inputs from Robert Lupton?)

Initial check of the obtained data:

A monitoring system of the obtained 2D images whether it is a scientific data or not would be helpful for the initial check of the obtained data. This is also useful for the health check of the instrument. The following items should be included in the monitoring system:

- A FITS viewer of the obtained 2D images
- Measurement of the count level at a given position on the image
- Zoom-in function for detailed inspections
- Scale and contrast change for detailed inspections

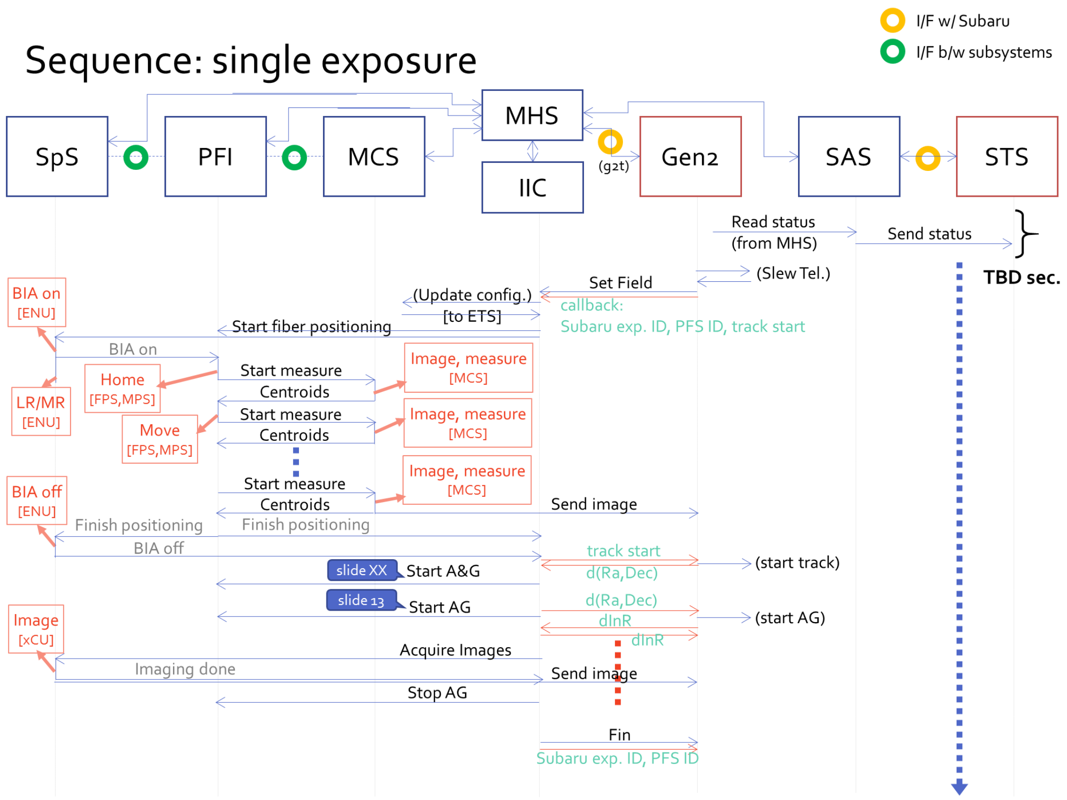

Figure 7: A schematic view of the communication between each sub-component during the operation. (To Be Updated)

Some functions are already implemented on the current Gen2 system.

Autoguiding monitoring:

The variation of the positional accuracy of assigned fibers to objects is critical to the signal-to-noise ratio of the obtained spectra. The statistical positional errors of the fibers is monitored by the centroids of bright stars in the A/G cameras. Again, bright (point source-like) galaxies can be used for this purpose. Not only the statistics but also a monitoring system with GUI may be useful to observers.

Sky condition monitoring:

The weather condition including seeing and transparency at a given time during the observation is essential to the precise measurements of fluxes of the obtained spectra. Bright stars in the A/G cameras are used for the monitoring of the weather condition. If we have too few stars in the FoVs of the A/G cameras, we alternatively use bright galaxies (as point source-like as possible) for these purposes. FWHM of the object image at a given time is at lease required to quantify the seeing size. The difference between the obtained fluxes and the catalogue values is used for the monitoring the sky transparency. Here, we expect precise photometry in HSC or SDSS and other catalogues.

Another possibility to monitor the sky condition during the night is to measure the flux level of the obtained spectra of e.g. standard stars in each arm. In particular, monitoring the continuum level of blue arm gives us information on the effect of the moon light, and the flux level of the red and/or NIR arm could be useful to the variation of OH sky lines. At least an interface to show the summary of the quality of the obtained spectra is desirable on the summit system (TBD).

5.2.2 Off-site QA of the obtained data (also inputs from Robert Lupton?)

TBW

5.3 PFS operation in queue mode

TBW

6 Possible troubles during the operation and tips for them

In this section, we describe possible troubles envisioned and the solutions during the operation.

6.1 Possible troubles in general

6.2 Possible troubles during the system startup/shutdown, the pre-check, and the instrument health check

6.3 Possible troubles during the scientific operation

6.4 Possible troubles during the calibration operation

References

[1] Tamura, N., et al., "Prime Focus Spectrograph (PFS) for the Subaru telescope: overview, recent progress, and future perspectives", Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 99081M (9 August 2016); doi: 10.1117/12.2232103

[2] Wang, S., et al., "The current status of prime focus instrument of Subaru prime focus spectrograph", Proc. SPIE AS105PS, Ground-based and Airborne Instrumentation for Astronomy VI Posters, 990882 (9 August 2016); doi: 10.1117/12.2232044

[3] Takato, N., et al., "Design and performance of a F/#-conversion microlens for prime focus spectrograph at Subaru Telescope", Proc. SPIE 9147, Ground-based and Airborne Instrumentation for Astronomy V, 914765 (31 July 2014); doi: 10.1117/12.2055051

[4] Fisher, C., et al., "Developing engineering model Cobra fiber positioners for the Subaru Telescopes prime focus spectrometer", Proc. SPIE 9151, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 91511Y (7 August 2014); doi: 10.1117/12.2054700

[5] Wang, S.. et al., "Metrology camera system of prime focus spectrograph for Suburu telescope", Proc. SPIE AS105PS, Ground-based and Airborne Instrumentation for Astronomy VI Posters, 990881 (9 August 2016); doi: 10.1117/12.2232035

[6] Madec, F., et al., "SUBARU prime focus spectrograph: integration, testing and performance for the first spectrograph", Proc. SPIE AS105PS, Ground-based and Airborne Instrumentation for Astronomy VI Posters, 99088U (9 August 2016); doi: 10.1117/12.2233057

[7] Gunn, J. E., et al., "Detector and control system design and performance for the SuMIRe prime focus spectrograph (PFS) cameras", Proc. SPIE AS105PS, Ground-based and Airborne Instrumentation for Astronomy VI Posters, 990893 (9 August 2016); doi: 10.1117/12.2233400

[8] Smee, S. A., et al., "Visible camera cryostat design and performance for the SuMIRe Prime Focus Spectrograph (PFS)", Proc. SPIE AS105PS, Ground-based and Airborne Instrumentation for Astronomy VI Posters, 99088Y (9 August 2016); doi: 10.1117/12.2233185

[9] Hart, M., et al., "A novel reflectometer for relative reflectance measurements of CCDs", Proc. SPIE 9915, High Energy, Optical, and Infrared Detectors for Astronomy VII, 99152D (27 July 2016); doi: 10.1117/12.2232943

[10] de Oliveira, A. C., et al., "Fiber optical cable and connector system (FOCCoS) for PFS/ Subaru", Proc. SPIE 9151, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 91514G (28 July 2014); doi: 10.1117/12.2056888

[11] Groff, T., et al., "Laboratory testing and performance verification of the CHARIS integral field spectrograph", Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 99080O (9 August 2016); doi: 10.1117/12.2233447

[12] Takada, M., et al., "Extragalactic science, cosmology, and Galactic archaeology with the Subaru Prime Focus Spectrograph", Publications of the Astronomical Society of Japan, Volume 66, Issue 1, id.R1 (2014)

A Pointers to technical documents

A.1 Documents by Atsushi Shimono

- SSN-00011-001 (Study on PFS Observation Sequence (I) Overall)
- SSN-00012-001 (Study on PFS Observation Sequence (II) From command next field to AutoGuide)
- SSN-00006-002 (Study on PFS A&G/AG communication)
- SSN-00016-001 (Connection from PFS ICS to Gen2)
-

A.2 Documents related to the commissioning by Yuki Moritani

- PFS commissioning plan

A.3 Documents related to various studies on PFS operation by Kiyoto Yabe

- material_pfs_operation_dots_20160629.pdf (Effects of instrument rotator angle on dot coverage on the focal plane)

B The operational process in FMOS

B.1