Fibre Multi-Object Spectrograph (FMOS) for the Subaru Telescope

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Abstract

Fibre Multi-Object Spectrograph (FMOS) is the first near-infrared instrument with a wide field of view capable of acquiring spectra simultaneously from up to 400 objects. It has been developed as a common-use instrument for the F/2 prime-focus of the Subaru Telescope. The field coverage of 30’ diameter is achieved using a new 3-element corrector optimized in the near-infrared (0.9–1.8 μm) wavelength range. Due to limited space at the prime-focus, we have had to develop a novel fibre positioner, called “Echidna”, together with two OH-airglow suppressed spectrographs. FMOS consists of three subsystems: the prime focus unit for IR, the fibre positioning system/connector units, and the two spectrographs. After full systems integration, FMOS was installed on the telescope in late 2007. Many aspects of the performance were checked through various test and engineering observations. In this paper, we present the optical and mechanical components of FMOS, and show the results of our on-sky engineering observations to date.

Key words: cosmology: observations — instrumentation: spectrographs — surveys — telescopes: Subaru

1. Introduction

In recent years, multi-object spectroscopy surveys on large telescopes have proven to be an essential technique to investigate galaxy formation and other statistical parameters of the Universe. Consequently, most large telescopes now have some kind of multi-object spectrograph. Statistical observations using near-infrared spectrographs have played an important role in the study of galaxy evolution for years. This is largely because the results can be directly compared with studies of local galaxies at optical wavelength. These observations, however, require a considerable amount of telescope time. The multi-object spectrograph in the near-infrared (NIR) wavelength range is the key instrument to make such a study possible.

Using the MOIRCS (Multi-Object InfraRed Camera and Spectrograph) instrument (Suzuki et al. 2008) on the Subaru telescope, it is already possible to obtain spectra from 30–50 objects within a 4’ × 7’ field of view using cold slit masks. The FMOS instrument, however, is capable of acquiring ~10-times more objects within an ~25-times wider field of view. Such a large increase in objects and wide field of view is useful not only for studying galaxy evolution and variation with the galaxy environment, but also for investigating star-forming regions, cluster formation, cosmology, and so on.

2. Design of the Instrument

2.1. Overview

FMOS is a fibre-fed NIR spectrograph of Subaru Telescope (Kimura et al. 2003; Maihara et al. 2000). FMOS has a capability to acquire spectra from 400 targets simultaneously in a 0.9–1.8 μm wavelength range with a field coverage of 30’ diameter at the prime-focus of the telescope (figure 1). FMOS consists of three subsystems: (1) the Prime focus unit for...
InfraRed (PIR), (2) fibre positioning system/connector units, called Echidna, and (3) two cooled infrared spectrographs (IRS1 and IRS2).

The PIR containing an Echidna fibre positioner is mounted at the centre of the top-ring of the telescope. It has an attachment mechanism, an optical alignment mechanism, and a corrector lens system (figure 2).

Echidna is a novel fibre positioning system collecting light from the 15 cm diameter focal plane at the prime-focus of the Subaru Telescope. Tilting fibres are attached to a carbon-fibre “spine”, and are moved using a quadrant tube piezo actuator (Brzeski et al. 2004; Gillingham et al. 2000, 2003; Moore et al. 2003). In front of the array of fibres, the Focal Plane Imager (FPI) is located on an XY gantry. The FPI is a dual imaging system capable of measuring the fibre positions for instrument calibration as well as acquiring sky images for field acquisition. Using several iterations with FPI, Echidna completes a field reconfiguration in less than 15 min. The 400 science fibres are divided equally and fed to two cooled spectrographs installed on the fourth floor of the telescope dome (Murray et al. 2003, 2004, 2008). The interconnecting optical feed is a fibre-optic downlink with a length of ~70 m.
The two cooled spectrographs have the capability of eliminating strong OH-airglow lines in the \( J \)- and \( H \)-bands, which are the major sources of background radiation at NIR wavelengths (Dalton et al. 2006, 2008; Iwamuro et al. 2006, 2008; Lewis et al. 2003, 2004). The suppression system provides a substantial \( S/N \) gain for observations at low spectral resolution, thus allowing large simultaneous spectral coverage from a single 2k \( \times \) 2k detector (Iwamuro et al. 1994, 2001; Maihara et al. 1993, 1994). To reduce the thermal background in the spectrographs, all of the optics are assembled in a large refrigerator and cooled to below \(-50^\circ\)C. Each spectrograph has two modes of spectral resolutions: a high-resolution mode with \( \lambda/\Delta \lambda = 2200 \) and a low-resolution mode with \( \lambda/\Delta \lambda = 500 \). The low-resolution mode is realized by using a VPH (Volume Phase Holographic) grating as an anti-disperser. The NIR detector uses a HAWAII-2 HgCdTe detector. It covers the entire \( J \)- and \( H \)-bands, which are sensitive to wavelengths of 0.9, 1.1, 1.35, 1.6, and 1.8 \( \mu \)m. The typical gain for observations at low spectral resolution is \( \Delta S/\Delta N \approx 2200 \) and a low-resolution mode with \( \Delta S/\Delta N \approx 500 \).

The conceptual design of FMOS started in 1998, and all of the mechanical components were assembled and mounted on the telescope in late 2007. Intensive commissioning observations started in 2007 December, and first light was accomplished in 2008 May. FMOS is expected to explore various scientific frontiers from nearby substellar objects to the large-scale structure of the distant universe.

2.2. PIR: Prime Focus Unit for IR

2.2.1. Interface mechanism

The Subaru Telescope has two prime-focus units, and three secondary mirrors exchangeable semi-automatically in about six hours in the daytime. One prime-focus unit is optimized for visible light, and the other (i.e., PIR) is for the NIR wavelength region. The PIR is developed as the front-end unit for FMOS, attached to the centre of the top ring. The Echidna fibre positioner with FPI, and the Shack–Hartmann camera are installed in the instrument bay, which is supported by an outer shell structure with the Focus-Adjustment Mechanism (FAM) and the instrument rotator (figure 2). The corrector lens system is fixed on the bottom of the outer shell structure via the Corrector-Movement Mechanism (CMM) to compensate for the offset of the corrector lens system from the optical axis of the primary mirror with the rotation/tilt of the telescope. A computer, cable wrapping system and fibre connector are also attached to this outer-shell structure.

We can make an optical alignment between the corrector axis and the telescope axis by CMM and FAM using a defocused star image taken by the sky camera of FPI (see sub-subsection 2.3.1). We can also measure the optical aberration of the telescope, including the corrector lenses in detail using the Shack–Hartmann camera at the centre of the field. The results of the Shack–Hartmann camera are analysed in a series of Zernike’s coefficients by the mirror analysis software of the Subaru Telescope. On the basis of these measurement and corrections, the best XY position of CMM and the best Z position of FAM can be determined as a function of the telescope elevation-angle.

2.2.2. Prime focus corrector

Faint galaxies are considered to be main targets of FMOS. The measured intrinsic half-light radius of a faint galaxy is typically 0.3 at \( H = 20.5 \) (Yan et al. 1998). The typical atmospheric seeing is FWHM = 0.6 on the summit of Mauna Kea, yielding about 0.9 diameter for an 80% energy circle of faint galaxies. Thus, we selected the aperture diameter of the fibre core to 1" on the sky. This aperture diameter corresponds to about 100 \( \mu \)m on the F/2.1 focal plane of the Subaru Telescope.

A telecentric focal surface has been chosen to decrease any misalignment between an object and its fibre aperture over the whole field. The three (BSM51Y) spherical lenses of the corrector system allow acquisition over its 30" diameter field of view in the NIR wavelength range. The first corrector element has a diameter of 590 mm.

The optical aberration of this corrector system is less than 0.2" (15 \( \mu \)m) in FWHM, small enough compared to the fibre core diameter of 1.24 (100 \( \mu \)m). The 80% encircled energy diameter is 0.7" at the edge of the field of view including the chromatic aberration of magnification (figure 3). In the NIR wavelength range of 0.9–1.8 \( \mu \)m, the atmospheric dispersion is 0.1" and 0.3" at zenith distance of 30° and 60°, respectively. Since these dispersion displacements are considerably smaller than the diameter of the science fibre, we do not use an Atmospheric Dispersion Corrector (ADC).

2.3. Fibre Positioning System

2.3.1. Fibre positioner and focal plane imager

The prime focus of the Subaru Telescope has a fast F-ratio and a wide field of view; however, it is too small (about 150 mm in diameter) to use a fibre positioner with magnetic buttons, such as 2dF/AAT (Lewis et al. 2002). We have therefore developed a novel fibre positioning system, Echidna, capable of positioning up to 400 fibres at the prime focus (figure 2). It is based on the use of piezo tube actuators tilting the fibres by electric pulse trains of roughly saw-tooth shape. Each science fibre has a length of \( \sim 160 \) mm from the tip of the fibre to the pivot ball on the tube piezo actuator, covering a circular area of \( \sim 7 \) mm in radius by tilting by up to 2.5°. The optical loss caused by the tilt to the incident beam is less than 10%, even at the maximum tilt. To limit any coupling efficiency losses between a target and a fibre, the fibre is positioned within 10 \( \mu \)m of its target.
In order to achieve the required positioning accuracy, we utilise the FPI for spine position feedback (figure 4). The FPI has two cameras: the sky camera and the fibre camera, mounted on the XY stage.

The sky camera checks the telescope pointing by measuring the positions of several bright stars \((R \leq 15\) AB mag). The fibre camera, which divides the focal plane into 59 small subfields, checks each fibre’s position using a back-illumination system. After measuring the positioning error of each fibre from an image taken by the fibre camera, the positioner moves each spine (in parallel) to correct for the error. To achieve a desired positioning accuracy of less than \(10\) \(\mu\)m, this process is repeated \(\approx 7\) times.

Echidna has 14 guide-fibre bundles for auto guiding; they are located on each side of the field (figure 5). Each guide-fibre bundle consists of \(7 \times 50\) \(\mu\)m diameter fibres. These bundles are imaged onto a cooled CCD camera through an OG570 filter, where stars with \(R = 16.5\) mag, or brighter are usable for auto guiding.

2.3.2. Fibre cable and fibre connector

The fibre connector is required to allow the PIR to be removed from the telescope and replaced with other instruments. The connector box is attached to the side surface of the PIR, while the conjugated plug is usually parked at the junction between the centre of the top ring and the spiders. Additionally, the connector has two more roles apart from detaching the PIR unit: (1) conversion of the F-ratio from F/2 fibres of Echidna into F/5 fibres of the bundle fed by IRS1 and IRS2, (2) back-illumination of F/2 fibres to flash their tips at the prime focus during exposure of the fibre camera (Murray et al. 2003, 2004). The incident light at the focal plane has a focal ratio of F/2, which is not optimal when light is to be transmitted through a long fibre. Furthermore, at the spectrograph, such a divergent exit beam would present significant challenges for the design of the spectrograph collimator optics. The expected efficiency of a plano-convex lens coupling in the connector is more than 95% over the wavelength range. The F/2 fibres are 7.6 m long, to cover the routing distance from the focal plane of Echidna to the site of the connector. The F/5 fibres are 62 m long, from the connector to the spectrographs.

The back-illumination has a movable coupling prism and LEDs, which are necessary to measure the exact position of each spine with each exposure on the sky.

2.4. Cooled Spectrograph

2.4.1. Overview

FMOS has two spectrographs; IRS1 was developed by Kyoto University and IRS2 was developed by University of Oxford and Rutherford Appleton Laboratory, to obtain \(2 \times 200\) spectra simultaneously in the NIR wavelength range (Dalton et al. 2006; Iwamuro et al. 2006; Kimura et al. 2003; Tosh et al. 2004). Although the mechanical components are completely different, all of the optical components and parameters of these spectrographs are identical. Each spectrograph has two spectral resolution modes: the low-resolution mode covers the whole wavelength range of 0.9–1.8 \(\mu\)m with one exposure, while the high-resolution mode requires four exposures at different camera positions to cover the full wavelength range.

The sky background in the NIR region is dominated by many narrow emission lines by OH-airglow. During the night, the OH-airglow lines vary in brightness by 5–10% on a timescale...
The secondary spectra are obtained by the \( 2048 \times 2048 \) infrared array detector HAWAII-2 installed in the camera dewar. The length of the incident fibre slit is 12 cm, which is reduced to \( \approx 4 \) cm on the detector.

Although the typical spectral resolution of the primary spectra is \( \lambda/\Delta \lambda = 2200 \), we can choose the spectral resolution of the secondary spectra to be \( \lambda/\Delta \lambda = 500 \) in the low-resolution mode \( \lambda/\Delta \lambda = 2200 \) in the high-resolution mode with (without) the VPH grating, respectively, into the optical path at the secondary pupil position to reduce any dispersion given by the first grating. Spectra with the full wavelength range (0.9–1.8 \( \mu \)m) are obtained by a single exposure in the low-resolution mode, while four exposures at different camera positions are required to cover the same wavelength range in the high-resolution mode (figure 8).

Each fibre slit contains 200 fibres with a centre-to-centre spacing of 600 \( \mu \)m (almost twice the 280 \( \mu \)m fibre diameter), which consists of 10 subsets of 20 fibres separated with an additional small spacing between them. The fibres in this fibre slit are arranged in a fan shape along the curvature of the focal sphere of the Schmidt optical system. The output beam is nominally \( F = 5 \), with up to 10% of the light emerging into \( F = 4.2 \), which is controlled back to \( F = 4.7 \) using field lenses on the output of the slit blocks (Murray et al. 2003).

The spherical camera mirror is a honeycomb light-weight mirror with a diameter of 1.4 m and a weight of 137 kg. The radius of curvature is 1940 mm. The slit is placed 951 mm in front of the collimator to produce a single-beam diameter of \( \approx 200 \) mm. The reflective surface is silver with a sapphire over-coating.

The off-axis Schmidt plate with dimensions of 280 mm \( \times 236 \) mm (\( \times 33 \) mm in thickness) was manufactured using a high-accuracy grinding process (without polishing). The accuracy of the total shape is 0.3 \( \mu \)m, and the local roughness is 80 nm rms. The material is fused silica with anti-reflection coatings on both sides.

The grating at the primary pupil position is composed of a \( 2 \times 2 \) mosaic of usual reflective gratings with a groove density of 500 g mm\(^{-1} \) blazed at 1.35 \( \mu \)m for an incident angle of 20°, because diffraction-limited performance is not required, and the cost is reduced considerably. This \( 2 \times 2 \) mosaic grating is controlled by using 8 pieces of picomotor actuators for adjusting the direction of the four gratings under the...
Fig. 9. Mask mirror in IRS1(top) and IRS2(bottom). These masks have patterns of the airglow lines in the J-band and the H-band. The airglow mask of IRS1 is made of a thin (0.2 mm in thickness) stain- less-steel plate at the positions of the strong OH-airglow lines, and blackened to absorb the OH light (Iwamuro et al. 2006). The airglow mask of IRS2 is printed directly on the surface of the mirror by photochemically etching away the reflective gold coating of the mirror so that the OH light is absorbed in the substrate and the mount of the mirror (Lewis et al. 2004).

Fig. 10. Spot diagram on the detector in the low-resolution mode. Spots at wavelengths of 0.9, 1.1, 1.35, 1.6, and 1.8 μm vs. the positions of +60 mm (top of the fibre slit), 0 mm, −60 mm (bottom of the fibre slit) are plotted. The box represents 4 pixels of the detector.

The mask mirror consists of the two spherical-convex mirrors with a curvature radius of 993 mm (figure 9). Each mirror has dimensions of 280 mm × 140 mm, arranged at both sides of the entrance fibre slit. The gap between these two mirrors corresponds to the atmospheric absorption band at ~1.4 μm in the primary spectra focused onto these mirrors. The methods of masking strong OH-airglow lines are different between IRS1 and IRS2. The airglow mask of IRS1 is made of a thin (0.2 mm in thickness) stainless-steel plate, which is processed by photochemical etching to leave material only at the positions of the strong OH-airglow lines, and blackened to absorb the OH light (Iwamuro et al. 2006). On the other hand, the airglow mask of IRS2 is printed directly on the surface of the mirror by photochemically etching away the reflective gold coating of the mirror so that the OH light is absorbed in the substrate and the mount of the mirror (Lewis et al. 2004). A total of 283 OH and O₂ air-glow lines are rejected on the mask mirror, and thus the effective opening area is 78.8%. The width of each mask element is 0.4 mm, which is a factor of 1.4-times the width of the fibre core diameter of 280 μm on the fibre slit in IRS1. The suppression factor of the OH-airglow line is about 10, and the estimated gain is 1 mag, if observations are sky-background limited.

The special Schmidt plate has two aspherical concave/convex surfaces with dimensions of 315 mm × 251 mm (× ~90 mm in thickness), which are achieved using a combination of two elements having concave-flat and flat-convex shape (figure 7). Both aspherical surfaces are processed by the “ELID” (ELectrolytic In-process Dressing) grinding method. The accuracy of the total shape is 3 μm and the local roughness is 100 nm rms. The material is fused silica with an anti-reflection coating on both sides of each element.

A total of 283 OH and O₂ air-glow lines are rejected on the mask mirror, and thus the effective opening area is 78.8%. The width of each mask element is 0.4 mm, which is a factor of 1.4-times the width of the fibre core diameter of 280 μm on the fibre slit in IRS1. The suppression factor of the OH-airglow line is about 10, and the estimated gain is 1 mag, if observations are sky-background limited.

The VPH grating with a diameter of 262 mm and 10 mm in thickness is used at the secondary pupil to reduce the dispersion power in the low-resolution mode. The line density is 385 g mm⁻¹ and the peak of diffraction efficiency is around 1.3 μm under the Bragg condition (Tamura et al. 2003). The material of all the camera elements is fused silica with the maximum diameter of 250 mm. The first order of the axial chromatic aberration of this system is corrected by tilting the detector along the dispersion axis. The focus position and this tilt angle are adjusted to the best position of the selected observation mode.

The designed spot images in the low-resolution mode are shown in figure 10. The 80% encircled energy diameter is less than 50 μm (2.5 pixels) in this mode as well as in the high-resolution mode, smaller than the real image size of a single fibre core of 80 μm (4 pixels).

2.5. Control System

The FMOS control system is designed as a network of subsystem controller PCs. The central PC, called FMOS OBCP (OBservation Control Processor), interfaces with the telescope computer system, and also supervises all of the FMOS subsystems through the network. The OBCP links to two PIR-dedicated PCs, IRS-dedicated PCs, and Subaru computers. One PIR-PC controls FAM, CMM, and the stage...
of the Shack–Hartmann system. Another PIR-PC takes part in controlling the Echidna positioner as well as the auto guiding signal and the FPI system. The IRS-PCs control all parts of the spectrograph: many cooled optical stages and the dewar stage, the cooling system of refrigerator, and the data acquisition and transfer (Eto et al. 2004; Dipper et al. 2004).

We use two HAWAII-2 array detectors for IRS1 and IRS2, developed by different institutes. The readout electronics of the IRS2 camera is a SDSU IR controller system (Leach et al. 2000) using a software interface developed for WFCam by UKATC (Hirst et al. 2006), while that for IRS1 is a newly developed one, which adopts a similar front-end circuit of MOIRCS (Ichikawa et al. 2003) combined with the Messia-V system (Nakaya 2004). The Messia-V provides a package of the “Clock Sequencer” and the “Frame Grabber”, which has been incorporated in the CCD data-acquisition system of the optical instruments of the Subaru Telescope.

3. Performance

3.1. Engineering Observation

The conceptual design started in 1998, and all of the mechanical components were assembled and mounted on the telescope in late 2007. Since 2008 May, engineering observations have been carried out several times to check the basic performance of FMOS. After measuring the image quality at the prime focus, the total system efficiency from the corrector lenses to the detector was estimated from the results of these observations, as well as from tests using a blackbody source. The positioning accuracy of Echidna was calibrated using several observations of a part of the galactic plane or open clusters under various conditions. The guiding stability using the guide-fibre bundles was also examined from the dispersion of the error signal during the observations.

3.2. Optical Performance of the PIR

In the first stage of our engineering run, we made a rough adjustment of the corrector axis (CMM axis) and the telescope optical axis using a defocused bright-star image taken by the sky camera of FPI. The position of the focus is adjusted by FAM using a star image taken by the same camera. The typical FWHM of the point source is 0.6 at the optical wavelength. After rough positioning, we measured the optical aberration of the telescope, including the corrector lenses in detail using the Shack–Hartmann camera at the centre of the field. In this camera, the wave-front error was measured as the position shifts of multiple-images of a single star divided by a micro lens array at the pupil position. The results were expanded in a series of Zernike’s coefficients by mirror analysis software of the Subaru Telescope. On the basis of these measurements and corrections, the best XY position of CMM could be determined as a function of the telescope elevation angle. The Coma aberration term in the calculated Zernike’s coefficients is sensitive to the XY position of CMM, while the defocus term corresponds to the position of FAM. We found that active control of the CMM as a function of the elevation angle of the telescope is not necessary at an elevation angle larger than 40°. The aberration coefficient indicates that the spherical and the coma aberration is small enough, while the astigmatism component contributes to the image size of ~0.4, even at the centre of the field (Kimura et al. 2008).

The tilt and distortion of the focal plane is also checked by the sky camera. We observed the field, including an open cluster by tilting the sky camera to determine the direction of the XY axes of the FPI coordinate, the pixel scale, and the distortion map of the field. At the edge of the field (15° off-centre position), the position of the star shifted about 10° outward because of the distortion. We could identify the optical axis of the telescope, including the corrector lenses as the centre position of this distortion pattern. As a result of the distortion measurement, we found that the position difference between the rotator axis and the distortion centre is 0.89 (4.3 mm); in other words, the distortion pattern moves along a circle during an observation. This movement causes a 0.24 shift at the outer-edge region of the field for a 13° rotation of the instrument rotator. Since neither the optical axis of the telescope nor the rotator axis can be adjusted, we have to readjust (“tweak”) a part of the outer fibres blindly between long exposures. No tilt of the focal plane was detected during this measurement.

3.3. Positioning Accuracy of Echidna

We measured the displacements of the tips of the fibres while changing the elevation angle from zenith to 30°. Almost all of the measured displacements were distributed within the range of 50 ± 10 μm, including the displacements of the guide-fibre bundles. Here, the average offset of 50 μm has no effect on the positioning accuracy, because the average flexure of the fibres will be cancelled by auto-guiding the telescope using the guide-fibre bundles. The measured scatter is sufficiently small to keep the targets to within 10 μm (0.12′′) accuracy during a long exposure. Both the stability of the fibre positions in two hours and the measurement accuracy of the fibre camera in FPI are ~2 μm, negligible compared with the flexure variation of the fibres. A sufficient configuration accuracy can be achieved with 7 iterations of readjustment using FPI (Akiyama et al. 2008); on average 98% of the fibres reach the target positions within 10 μm at above the zenith distance of 60°. In each configuration, about 10 fibres cannot reach the target positions due to collisions etc. Since 100 s are needed to measure the positions of 400 fibres with the FPI, Echidna takes about 15 min to complete 7 iterations.

The guide-fibre bundle consists of 7 fibres with a core diameter of 50 μm arranged in a hexagonal shape with 80 μm spacing, which corresponds to 0.96 at the focal plane. There are 14 guide-fibre bundles located at both edges of the field of view, marked with circles, indicating a covering area of ~3′ in figure 5. Images of bright stars acquired by these guide-fibre bundles are shown in figure 11.

The position error for the telescope pointing was calculated by the weighted average of the position offsets of these stars, which is typically less than 0.18 under the typical sky condition (figure 12). We can expect at least a few guide stars brighter than \( R = 16.5 \text{mag} \), even in the high galactic-latitude area.

The position error for each fibre is estimated by “rastering” of the telescope in a grid pattern around the target position. The map of the observed flux of each object on all grids of the raster pattern represents the position offset of
Fig. 11. Image of the guide-fibre bundles. There are 14 bundles, each of which consists of 7 × 50 μm diameter fibres. All fibres are illuminated by sky emission, and two bundles indicated with large circles are aligned to guide stars and used for auto-guiding.

Fig. 12. Distribution of the position error during the auto-guide in the fixed coordinate (XY) to Echidna. The fibre diameter of 1′′/2 is indicated by the circle at the centre. Almost all of the points located at the outside of the circle are sampled before auto-guiding is started. The size of the symbols corresponds to the averaged brightness of the guide stars. The median auto-guiding error is 0′′.067, and typically less than 0′′.18.

Fig. 13. Position offsets between the targets and science fibres measured by rastering observation in an open cluster field (NGC 6633). The big circle indicates the science field of view of FMOS, and each arrow indicates an offset measured with one science fibre. The length of the arrows is exaggerated, and the left-bottom arrow represents a 1′′.0 offset. The rms of the offsets is 0′′.15. The offsets are random, and there is no systematic offsets due to incorrect distortion pattern modelling.

3.4. Characteristics of the Spectrographs

First, we describe the results of the readout system on the detector. We then describe the thermal noise from the optics of the spectrograph.

The typical exposure time of FMOS is expected to be ~5–15 min to observe faint targets. Since very fast readout of the detector compared with the expected exposure time is not required, we operate the HAWAII-2 array with the four-channel readout mode, taking 17 s to make a single read with IRS1, and taking 15 s with IRS2. We use the “ramp sampling mode” (iteration of a single read without resetting the detector) in the usual scientific exposure to reduce the contribution of the read-noise of the electronics, and also to enable the acquisition of bright objects among faint targets.

The conversion factor and the read-noise of the detector can be estimated from the count-noise diagram derived from many sets of ramp sampling data with a cover attached to the entrance window of the camera dewar. The conversion factor estimated for IRS1 from the diagram is ~2.0 electrons ADU−1 and the readout noise is ~22 electrons for a single read (figure 14). The slope of the dashed line is 1/2, which is consistent with the shot noise.

Since the maximum ADU count of 216 = 65536, corresponding to ~1.3 × 106 electrons, is about half of the full electron capacity of the detector, the non-linearity of the detector is very small, even when the count is high. The measured non-linearity is typically less than 1% up to 40000 ADU at IRS1.

When very bright objects are included in the targets, we have to consider two effects on the image: crosstalk and latent images. The crosstalk is identified as “negative” images...
Fig. 14. Conversion factor measurement. The broken line indicates the least-squares estimation between the count and the noise. The measured conversion factor is $2.0 \, (e^{-} \text{ADU}^{-1})$. The readout noise is $22 \, (e^{-} \text{rms})$ at IRS1. The dashed line is a least-squares fit to high count data.

on the other quadrant of the detector, where the counts are sampled at the same timing as the region with very high counts. The contribution of the crosstalk is about $-0.15\%$ of the count of the bright region, correctable in the later data-reduction process (figure 15).

The latent images are “positive” patterns remaining after an exposure including a highly saturated region, caused by released charges into the conduction band of the detector array. It is difficult to correct the latent images because they depend on various parameters, such as the incident flux during a previous exposure, the elapsed time, temperature, and so on. It takes about 7 min until the latent image decays.

The rejection capability of the thermal background of the IRS1 camera part was estimated from the correlation between the background count rate on the detector and the temperature of the refrigerator. In IRS1, we use a normal large refrigerator with pressurised dry air. In IRS2, cooling is performed with a dry chilled air enclosure by a Polycold chiller and ducted into the enclosure. Figure 16 shows the measured background flux for various temperatures of the refrigerator plotted with the expected correlation calculated from the transmission curve of the lens materials and the thermal-blocking filter multiplied by the quantum efficiency of the detector. The measured background flux is consistent with the expected flux, indicating that the thermal-blocking filter works effectively.

3.5. Total Performance

At first, a black-body source with a temperature of $1095^\circ\text{C}$ was attached to the Cassegrain focus to measure the system efficiency. Figure 17 shows the spectra of the blackbody source obtained by IRS1 in the $J$-long and $H$-short bands. The typical FWHM of the vertical width of each spectrum is 5 pixels.

Fig. 15. Correction of crosstalk. The effect of the corrections is presented, comparing the image before a correction (top) with that after (bottom). The positions of the crosstalk images are indicated by arrows.

Fig. 16. Background flux as a function of temperature. Points show the measured background count (ADU pixel$^{-1}$ s$^{-1}$). The dashed line is the expected thermal background flux.
Fig. 17. Spectra of a blackbody emission with a temperature of 1095°C in the J-long (left) and H-short (right) bands.

Fig. 18. Closeup view of the figure 17 (left). The right panel shows the count (horizontal axis) to pixels (vertical axis, 10 pixel lines−1) along the vertical line in the left figure.

including the optical aberration of 2 pixels, with a pitch of 10 pixels between the spectra (figure 18).

Figure 19 shows the measured efficiencies with the low- and high-resolution mode in the full wavelength range. The typical system efficiency for the high-resolution mode is 6% in J and 10% in H from the prime-focus corrector to the detector, almost consistent with the expected value at the high-resolution mode. The decreases of the efficiency in the shorter wavelength side is due to the grating, which has the peak of the diffraction efficiency around 1.35 μm. On the other hand, the decreases in the longer wavelength edge is due to the thermal cut-off filter in the camera dewar. Furthermore, the gradual absorption feature from 1.3 μm to 1.4 μm is due to attenuation of the fibre and other silica material used in almost all of the lenses. The 1.35–1.40 μm part has to be blocked by the fibre
slit. Furthermore, these measured efficiencies have about 30% of the fibre-to-fibre variabilities. These are caused by grime on fibre edges as well as the throughput variety of the fibres, including a misalignment of the connectors. We also found that the focal ratio degradation effect is not negligible, the factor of \( \sim 0.8 \) estimated from the relative efficiency map for various positions of the black body source on the primary mirror cover.

We also measured the total efficiency with an on-sky observation. There is some difference between the on-sky observation and the blackbody test. One part is the throughput before the corrector, the reflectivity of the primary mirror and the sky transmittance; the other part is loss at the input surface of the fibres: the position error of the fibre, a mis-match of the input light for the spine-tilt effect, a flux loss for the effect of seeing fluctuation, and the focal ratio degradation effect.

Initially we measured the observational efficiency of the system using an image of a defocused bright star. The measured efficiency is 8% in the \( H \)-bands, almost consistent with the result of a blackbody test assuming the throughput. On the other hand, the total system efficiency based on the observation of an open cluster is 7% \( \pm 3\% \) in the \( H \)-bands, which is a factor of 0.9 lower than the measured value using the defocused bright star. Therefore, the loss at the input surface of fibres is not negligible during observations.

The airglow rejection capability of the spectrograph can be tested by scanning the fibre slit along the dispersion direction slightly. Figure 20 shows the variation of the airglow intensity for various offsets of the slit positions, indicating that the mask configuration is not yet perfect. The expected rejection factor of the OH-airglow lines is \( \sim 10 \) after we make a little more improvement in the mask to obtain the maximum performance of the spectrograph.

Some scientific exposures have been carried out during the engineering observation. Figure 21 shows the reduced spectral image taken in the SXDF (Subaru/XMM-Newton Deep Survey) field from six sets of 15 min on- and off-source exposure (total 180 min exposure time) in the low-resolution mode. The magnitudes of the four bright stars in this image are around 17 mag. in the \( K \)-band. The centre gaps in the spectra correspond to the gap between the two mask mirrors where the fibre slit is located.

Although the sky and instrument conditions were not ideal, the estimated limiting magnitudes of the continuum flux for an hour exposure with \( S/N = 5 \) are \( J = 20.1 \) mag and \( H = 19.8 \) AB mag in the low-resolution mode. Furthermore, an emission line flux of \( 1 \times 10^{-16} \) erg cm\(^{-2}\) s\(^{-1}\) is detected with \( S/N = 5 \) by 1 hr integration in both \( J \) and \( H \).

4. Conclusions

FMOS is a second-generation common-use instrument for the Subaru Telescope, having the capability to simultaneously acquire NIR spectra from up to 400 targets within a 30’ field.
of view. After all of the components were installed on the telescope in late 2007, the total performance was checked through various tests and engineering observations. The major results are as follows:

1. A sufficient configuration accuracy can be achieved with 7 iterations using FPI; on average, 98% of the fibres reach the target positions within 10 μm at above the zenith distance of 60°. Echidna takes about 15 min to complete 7 iterations.

2. The configuration accuracy of fibres measured by the raster sampling method is less than 0′.15. The accuracy of auto-guiding using guide-fibre bundles is typically less than 0′.18.

3. The typical system efficiency of 10% from the prime-focus corrector to the detector is consistent with the expected value. The total system efficiency of 7% based on real observations is somewhat lower than expected.

4. The rejection capability of the thermal background of IRS1 almost approaches the ideal value, indicating the refrigerator system and the thermal-blocking filter are working well. Although the blocking capability of the OH-airglow mask is currently sub-optimal, a blocking factor of ~10 is expected after a little more improvement in the mask.

5. Currently, the limiting magnitudes for a 1 hour exposure with S/N = 5 are \( J = 20.1 \) mag and \( H = 19.8 \) mag in the low-resolution modes. The emission-line flux of \( 1 \times 10^{16} \) erg cm\(^{-2}\) s\(^{-1}\) was detected with \( S/N = 5 \) by 1 hr integration both in \( J \) and \( H \). These values were measured from the results of short observations in the SXDS field.

Although IRS1 has almost been completed, it still has scope for improvement. The blaze-wavelength of the mosaic grating, the cut-off wavelength of the thermal-blocking filter and the deterioration of the total efficiency in low-resolution mode (due to a mis-match of the line density of the VPH grating) can all be improved.

If we use gratings having a shorter blaze-wavelength as well as the thermal-blocking filter with a shorter cut-off wavelength, the limiting magnitude in the \( J \)-band will be improved considerably.

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