FOCAS: Faint Object Camera and Spectrograph for the Subaru Telescope

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ABSTRACT

Faint object camera and spectrograph, FOCAS, is a Cassegrain optical instrument of Subaru telescope. It has a capability of 6 arcmin FOV direst imaging, low resolution spectroscopy ($R = 500 - 3000$ with 0.2arcsec slitwidth) , multi-slit spectroscopy as well as polarimetry. Only the imaging mode has been available so far. The overall design, the observing functions, and the preliminary performance verifications of FOCAS will be presented.

Keywords: Instrumentation, Optical imaging, Optical spectroscopy

1. INTRODUCTION

The **F**aint **O**bject **C**amera **A**nd **S**pectrograph, FOCAS, is a Cassegrain optical instrument of Subaru telescope. It has direct imaging mode, long slit spectroscopy mode, multi-slit spectroscopy mode and will have capabilities of polarimetric imaging and spectropolarimetry modes. These modes are easily exchanged by disposing several optical elements onto the collimated beam. The main optic train is all-refractive which allows high throughput optimized for the wavelength coverage of $365 - 900$nm. Characteristics of FOCAS are summarized in Table 1 and overall structure of FOCAS is shown in Figure 1.

FOCAS is one of the 1st generation instruments for Subaru telescope (Iye 2000[1]). In designing FOCAS, the basic requirements for the instruments are;

1. having a capability of no less than three observational modes, imaging, spectroscopy, and polarimetry for multilateral studies of extremely faint objects.
2. achieving high throughput with an all-refractive optics and reducing flares and ghosts that might hinder observation of faint objects with broad-band anti-reflection coating.
3. taking full advantage of the entire FOV of the Subaru Cassegrain focus for multi-object observations.

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4. sampling the image at pixel scale compatible with the best seeing size at the summit of Mauna-Kea.
5. minimizing the image distortion and image motion caused by the flexure of the instrument.
6. achieving high observing efficiency with the aid of highly automatic instrument control and data acquisition system, quick change of observing mode among the available modes, and accurate positioning of objects on slits.

The most important requirement for FOCAS on the Subaru project is to develop a standard optical instrument which enables basic imaging and spectroscopic observations with high stability and high efficiency for the study of distant galaxies, cluster of galaxies, quasars, AGNs, nearby galaxies, and the solar system.

FOCAS was first proposed as the 1st generation instrument for Subaru in 1989. There have been some version-ups[2] and concept changes from its primitive design (Sasaki et al. 1994[3]), and the final design is determined in 1997(Iye 1997[4]). FOCAS has been developed and assembled in Japan and was shipped to Hilo in September 1999. Action/control tests, adjustments and optimizations have been carried out for the instrument with the common use telescope simulators installed at the Mitaka campus and at the Hilo base facility of NAOJ. Now FOCAS is fully integrated and starts observation on Subaru for the functional test and the performance evaluation. In this paper, we will report the current status of this instrument and preliminary performances verified during the first functional observation run.

Table 1. Characteristics of FOCAS

Observation modes	imaging, long-slit spectroscopy, multi-slit spectroscopy, imaging polarimetry, spectro-polarimetry
Scale	2m(d)×2m(h)
Weight	2.1*t*
Optics	all-refractive optics: 8 groups 14 lenses
Optimized wavelength	365 – 900nm
FOV	6 arcminϕ
Transmission	$\sim$ 80% (420 – 900nm: designed value)
Pupil diameter	90mm
f(collimeter)	1097.7mm
f(camera)	329.4mm
Minification factor	3/10
RMS spot diameter (white)	16μm(on axis), 21μm(edge of the FOV)
Coatings	reflection rate $<$ 1%
Maximum number of mountable grisms	7
Maximum number of mountable filters	21
Maximum number of slit-mask plates	10
Minimum exposure time	0.5sec
CCD format	4K×2K 3-side buttable CCD × 2 mosaic
CCD type	Thinned, back-illuminated
CCD Readout time	200sec
Pix size	15μm
Image scale	0.103 arcsec/pix
Slit cutting method	diode-pumped YAG laser

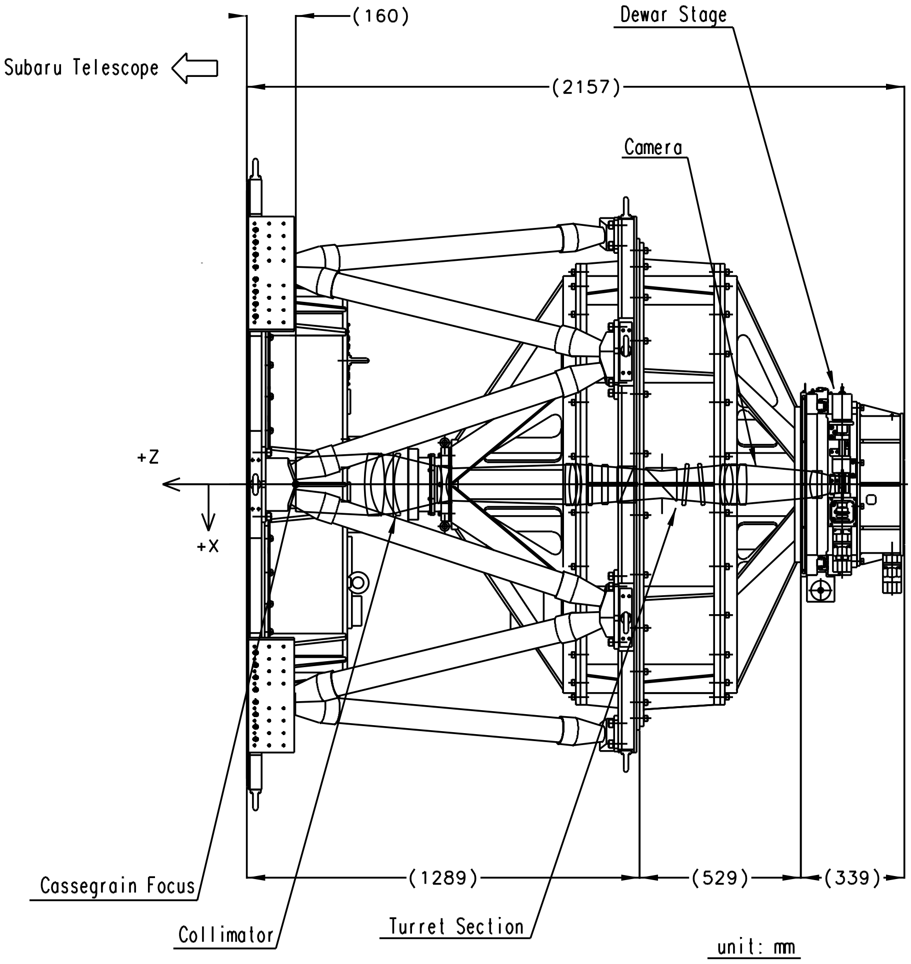

Figure 1. Overview of FOCAS. Left to Subaru telescope.

2. OPTICS

The optical train of FOCAS consists of 14 lens elements in 8 groups (see Figure 2). It consists of two parts, one is the collimator part (f= 1097.7mm) of 8 elements in 4 groups and the other is the camera part (f= 329.4mm) of 6 elements in 4 groups. The minification factor of the collimator to the camera is about 3/10. The resulting image scale of 0.103arcsec/pixel on the detector matches the high resolution observation under good seeing condition. The length of collimated beam is 451mm which is long enough to insert several optical elements such as grisms, filters, and polarizers. This realizes various observational modes for FOCAS. A field of view of 6 arcmin in diameter is available at the F/12.2 Cassegrain focus of Subaru telescope at a scale of 2.06 arcsec/mm. FOCAS takes full coverage of this 6 arcmin FOV. The estimated RMS spot diameter for white light (365 – 900nm) is 16μm at the optical axis, and 21μm at the edge of the FOV.

Fully transmitting optics will be treated with broad-band anti-reflection (AR) coating. This AR coating has a reflection rate less than 1% over 365 – 900nm. The optical throughput of the entire optics is expected to be about 80% or better at 420 – 900nm.

2.1. Grisms, Filters, and Polarizers

A set of FOCAS standard grisms with dispersions of 550 – 3000 Å/pix (slit width of 0.2 arcsec) are available. The effective diameter of a grism is larger than 102mmϕ which covers the whole FOV of FOCAS, and the maximum height is 110 mm. Table 2 summarizes the parameters of present available grism set for FOCAS. In addition, higher dispersion grisms ($R \sim 5000$) is now under fabrication (Ebizuka et al. 1998[5]). A set of standard FOCAS filters are also available for broad-band filters (Johnson's UBVRI), narrow-band filters, and order-cut filters. A Wollaston prism and a quarter-wave retarder can be inserted to the collimated beam. A half-wave retarder for linear polarization will be available in near future.

Table 2. A set of present grisms for FOCAS

grisms	R	λ_c(nm)	gr/mm	glass	α(deg)
very low resolution	555	650	75	FK-5	5.75
low resolution	1126	650	150	FK-5	11.55
middle resolution(blue)	1984	550	300	FK-5	19.72
middle resolution(red)	2836	750	300	BK-7	26.10

R: spectral resolution for 0.2 arcsec slit width,
λ_c: central wavelength,
α: vertical angle of a prism.

3. MECHANICS

A schematic view of the structure of FOCAS is shown in Figure 1. The entire of the FOCAS has a size 2m diameter and 2m height, and the weight is approximately 2.1t. The center of gravity of the FOCAS locates on the turret section which contains some moving parts such as a grism turret, three filter turrets, and two polarizer slides. This turret section is supported by the truss structure from the Cassegrain flange section. This truss support structure is designed to give small flexure, which will be described below.

FOCAS is attached to the Subaru telescope by 16 bolts that go through 16 holes at a circular ring on the Cassegrain flange surface by the automatic instrument exchanger (CIAX). The flange section of FOCAS contains the multi-slit unit inside and seven electronical drive units outside. The 12 torrus are made by the CFRP (Carbon Fiber Reinforced Plastic) which is light (relative density 1.8) and at the same time as strong (Young's modulus $E = 1.4 \times 10^4$kg/mm^2) as Invar. Each has an 80mm diameter and the weight is about 10kg. The collimator lenses and the camera lenses are integrated in a cell which is made by brass respectively. These cells are mainly suspended from the turret section by several limbs at their center of gravity. The lens cells are estimated to be stiff enough to give the maximum displacement by self gravity as small as 0.254μm for a collimator cell and 1.11 μm for the camera cell.

In the collimated beam section of 451mm long between the collimator lenses and the camera lenses, various optical elements such as grisms, filters, and polarizers can be inserted with three turrets or two slides. Figure 2 shows the inside of the turret section, the left is to the Cassegrain focus, and right is to the CCD. The auxiliary filter turret holds ND filters, hartman shutters, and calibration filters for polarimetry. A quarter-retarder plate and a Wollaston prism are on the slide respectively. On the retarder plate slide, both a half-retarder plate and a quater-retarder plate can be mounted. Each can go round on it. Seven of eight positions are available for grisms and filters on each turrets. To avoid ghosts, filters are tilted by 10 degrees on this turret. We have a large turning shutter at the end of the collimated beam. The minimum exposure time is set to be 0.5 seconds with 10% accuracy. We have some access windows on the body surface of the turret section for exchange and maintenance of these optical elements. The entire dewar is mounted on the XYZ-stage which is fixed on the turret section. The focus of the FOCAS itself is adjusted with 3μm accuracy by this Z-stage.

3.1. The Multi-slit Assembly

The Multi Object Spectroscopy (MOS) mode aims to increase the observational efficiency of spectroscopy especially for high-z galaxies whose redshifts are between 1 and 1.5. First of all, we have to take a direct image in order to get spectroscopic targets. Based on the imaging data, the slit pattern is designed. It remains to be seen in future to create the slit pattern based on any astrometric catalog provided the positions of all the targets are known. Then slit masks are manufactured by Slit-Mask Making Machine (SMMM) which will be described below. At the beginning of spectroscopic night, the field should be confirmed with bright alignment stars which should be found at least 2 or 3 per a field. During this plate alignment procedure, we have to slightly move the telescope or rotate the plate,

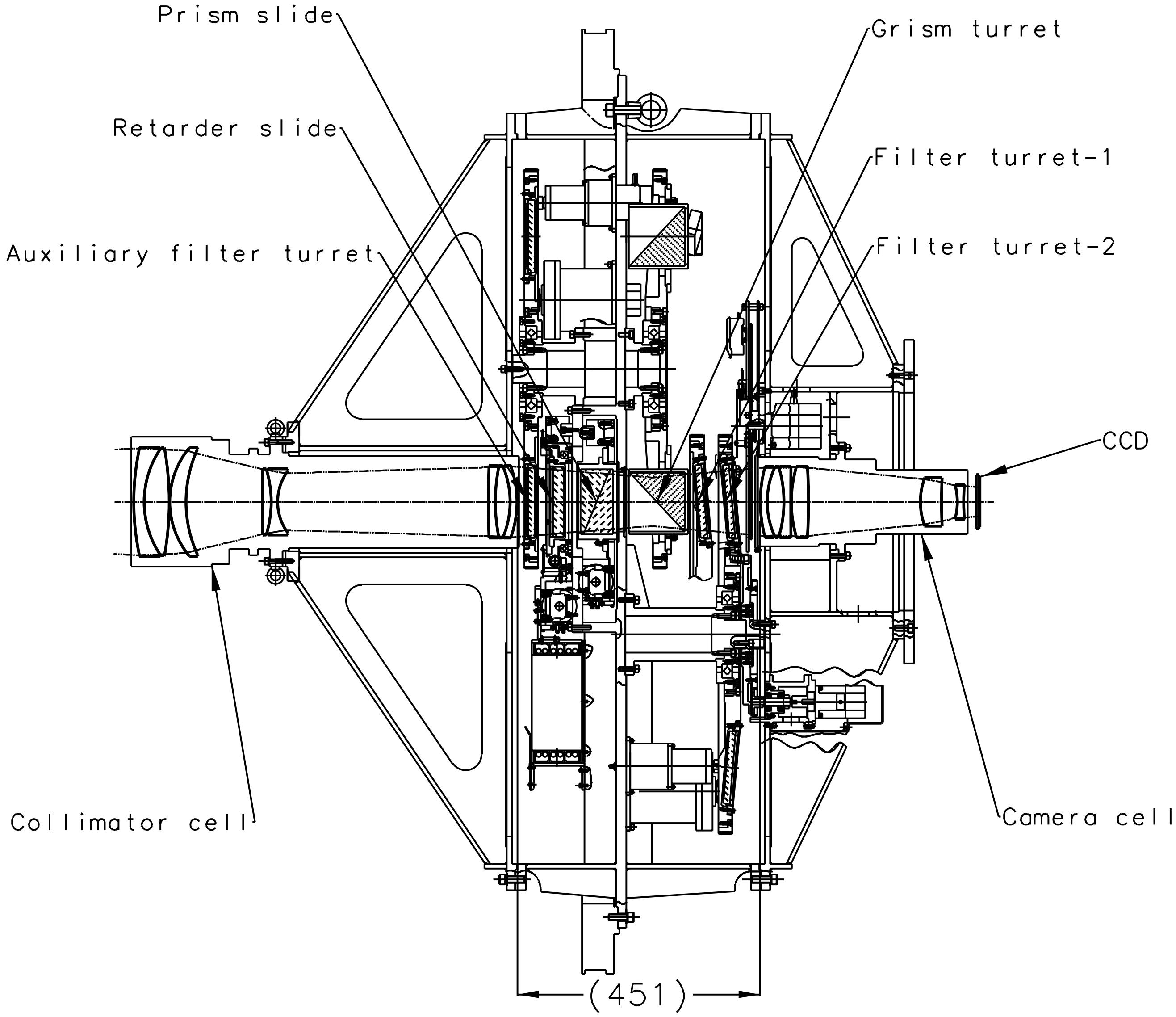

Figure 2. Inside view of FOCAS turret section.Left to the Cassegrain focus and right to the CCD. Optical train of FOCAS consists of two parts, the collimator part in 4 groups and the camera part of 6 elements in 4 groups. The turret section contains various optical elements.

and after that we should start guiding. If the spectroscopic exposure is ready, we can start an exposure. In this MOS procedure, we have three main investigations. One is to determine precisely slit positions, second is the fine processing of slit with high accuracy, and third is to exchange slit-masks quickly and smoothly.

The multi-slit assembly is composed of three units, the Mask-Stocker, the Mask-Changer, and the Mask-Stage. This Mask-Stocker carries up to 10 slit-mask plates at a time. One of the stocked plates is taken from the Mask-Stocker with vertically moving elevator and transported to the focal plane by horizontal linear guide of the Mask-Changer. The Mask-Stage is the precise θ-stage that sets mask plate with several μm position accuracy. When we have just to shift the mask plate, we will move the telescope which has a 0.07 arcsec resolution for pointing accuracy. It takes almost 15 seconds to complete the mask exchange. The long slit mask plates with various slit width, 0.2, 0.4, 0.6, 2.0 according to the seeing size or the target size are also installed with this multi-slit assembly.

4. THE CCD CAMERA

FOCAS CCD Camera consists of a pair of abuttable CCDs of 2048 × 4096 pixels with 15μm square pixel size. The CCD chips are SITe ST-002A (see Miyazaki et al. 1998[6]). These CCDs cover whole the Subaru Cassegrain 6 arcminϕ FOV, and the pixel scale is 0.103arcsec/pix.

The CCDs are put in a dewar of the size 200mmϕ × 100mm(h). The AlN mother-board on which the CCD chips are mounted is supported by four polycarbonate posts and is thermally isolated. The CCDs are cooled down to $-100°$C with a stirling cycle cooler WE-1000A manufactured by DAIKIN, Co. The mother board is connected to the head of the cooler by the so called cold fingers made of copper straps.

The method of CCD mosaicing is basically the same as that of Sekiguchi et al. 1992[7] and Miyazaki et al. 1998.[6] Each chip is mounted on a fine machined spacer of Invar which is matched with the CCD package material. We glue each CCD chip on the spacer under a microscope with a laser displacement meter to measure x-y positions and height. The glue was Ag-based conductive epoxy. Thin metal sims are inserted between the chips and the spacer to make the thickness of glue even. Then we screw the CCD chip and the spacer on a AlN mother-board with the help of a microscope. The gap size between two CCD chips was 70.45 pix. The alignment accuracy we can get with such set-up procedures is an order of 16μm in the horizontal direction and also 14μm in the vertical direction. The tilt angle of a chip in regard to another chip was 0.°021 which corresponds to 1 pix deviance along the 4000pix.

We use a system called MESSIA3 (Modularized Expandable SyStem for Image Acquisition: Sekiguchi et al. 1996[8]) and MFront(Mosaic CCD Front-end Electronics) for CCD control and data acquisition. These are the standard optical-CCD controller for Subaru telescope. MESSIA3 is based on VME bus and is originally designed for a single chip operation. A pair of CCDs are read simultaneously. The front-end electronics inside the dewar has both channel switches which generates the clock and FET amplifiers. Amplified analog signals are sent to 16 bit A/D converters which are located outside the dewar as close as possible to the CCDs. It takes about 200 sec to read all the effective pixels. The conversion factor of CCD chips was $2.8e^-$/ADU. The CCD operation and data acquisition softwares are included in FALCON.[9]

5. THE SLIT-MASK MAKING MACHINE

The slit-masks are manufactured as an off-line process. The requirement for this Slit-Mask Making Machine (SMMM) is to cut slits whose width is as fine as 100μm corresponding to the 0.2 arcsec. The most adequate laser of all that we have investigated so far is the diode-pumped YAG laser ML-7040A which is made by Miyachi-Technos, Co. This is a compact system and is cooled only by the circulation of primary coolant. The laser itself works on multi-mode of Q-switch pulse oscillation at the wavelengh 1064μm and has a power as high as 15W. The SMMM also has a precise XY-stage to carry the slit mask plate. This system is designed to cut slits with 8μm accuracy. To avoid flexure and thermal expansion, the slit mask sheet is made of four-multi-layered carbon fiber sheet with 100μm thick. Determination of the precise positions of the slits from the imaging data is realized by the dedicated software which is described in Yoshida et al. 2000.[9]

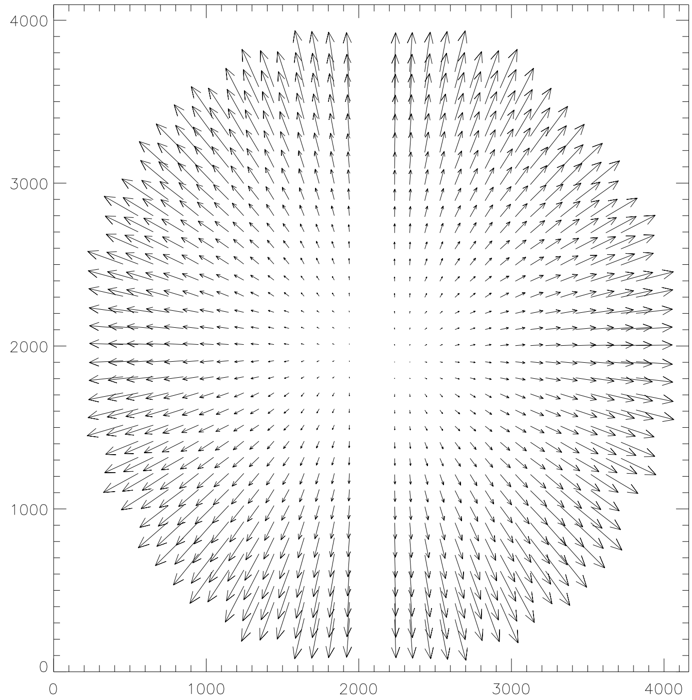

Figure 3. The vector plot for the image shifts from the original points on Cassegrain focus to the projected points on the CCD surface over the entire FOV.

6. CONTROLS

Each moving part of FOCAS is individually controlled by each dedicated drive unit and all of the drive units are integrated by the VME based CPU board through multi-channel serial communication. The drive unit has many functions such as driving motors, acquiring a status from encoders or limitters, controling communications with CPU board, monitoring voltages, measuring temperatures inside a drive unit, and so on. These functions are locally operated by a versatile one-chip microprocessor HITACHI H8/3048F CPU. This local control system for each drive units is of benefit during debugging or maintenance keeping out of other drive units.

The VME/CPU board plays a part in functions such as monitoring the status of each drive unit, monitoring interlocks among drive units, checking the control command from the observational computer (OBCP) and decoding it to local commands, expanding macro-commands and sequential executing, transfer the acquired data and the control logs, and so on,

All the drive units as well as CPU boards on VME rack are installed on the thermal insulator boxes. These insulator boxes have pipelaying of coolant which is supplied from Subaru telescope. To avoid any thermal over drive, We have 34 temperature sensors which is distributed whole wide of the instruments. The species of grisms, filters, and slit-masks are discriminated remotely with bar code readers.

The detail of the control software for FOCAS (FALCON; Focas ALlround CONtrol software) is presented in Yoshida et al. 2000.[9] The software system consists of several processes; a network interface process, a user interface process, a central control engine process, a command dispatcher process, local control units, and a data acquisition system. Each process is communicated to other processes and controlled by passing messages of commands and its status. A control flow and generalized command messages are defined following the software guideline for the Subaru instruments.

Figure 4. FOCAS mounted on the Subaru telescope.

7. PRELIMINARY PERFORMANCE

While testing with telescope simulator, we have measured the flexure of FOCAS. The flexure of the instrument is crucial for the fixed slit-position mask plate for multi-slit spectroscopy. The total image shift amounts to 5.5 pix while the telescopes points from the zenith to 80°. However, a typical exposure time would be less than one hour because of the contamination of cosmic rays. In order to obtain a good image quality, the image shift should be small enough whithin this one hour exposure corresponding 15°ZD change, The maxmum image shift within this 15°ZD change is 1.3pix which is acceptable. We have made it sure that the image shift to orthogonal direction to gravity is negligible.

We have also evaluated the image distortion caused by our optics. The grid mask which has a lot of holes alligned in regular grid was put on the MOS. Figure 3 is a vector plot for the image shifts from these original point on Cassegrain focus to the projected point on the CCD surface over the entire FOV. The coordinates are CCD XY-pixels and the vector on lower left shows the 5pix by 5pix image shift length. The distortion increases with the distance from the center of FOV. The radial distortion seems to be symmetrical and the maximum image shift is 15pix length at the edge of FOV. Almost no distortion is found on tangential direction. What is most important is that this distortion pattern does NOT depend on ZD with an accuracy of less than 1 pix. That is, the flexure of FOCAS causes only the image shift. These distortions should be corrected in the case of the MOS modes on which the transformation between Cassegrain focus and CCD coordinates is essential.

In February 2000, FOCAS was completely integrated and installed to the Subaru telescope (Figure 4). During the first test observation run, we have confirmed all the functions working well, and measured the optical performance,

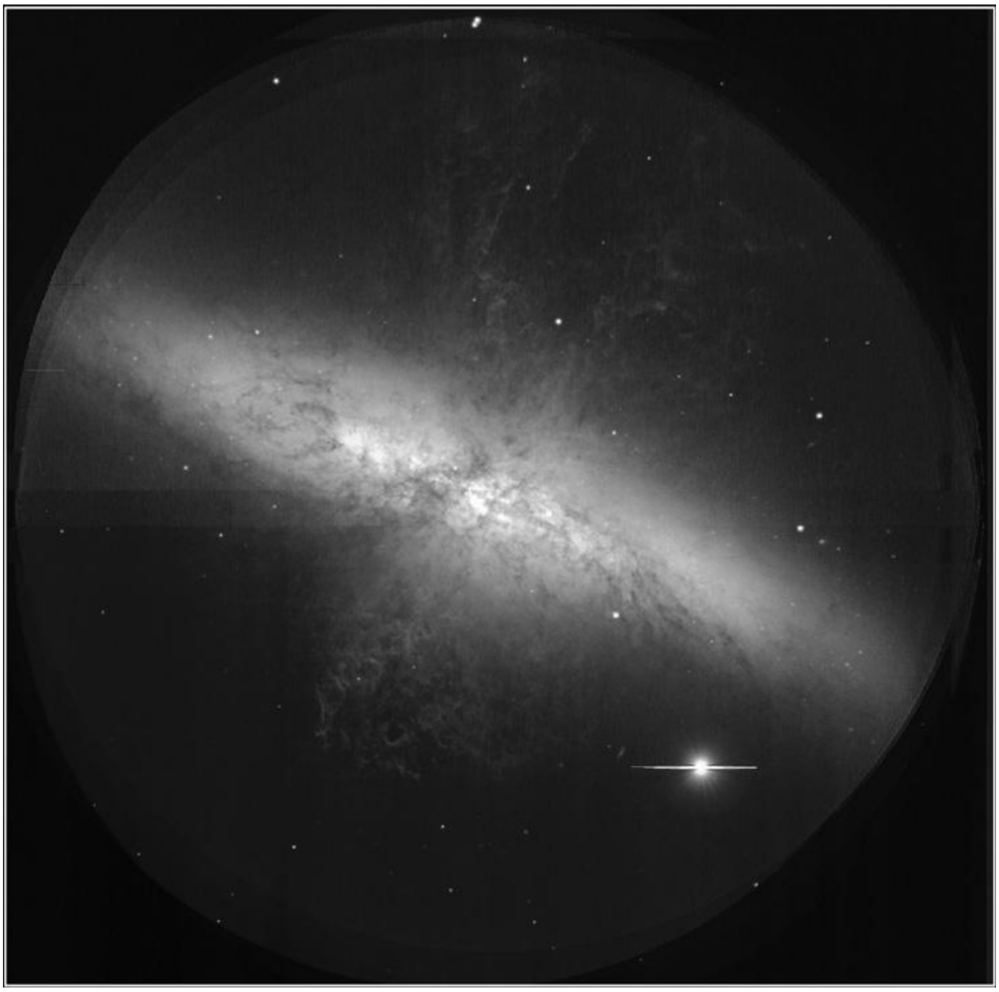

Figure 5. A demonstration picure of M82 with FOCAS 120sec exposure. North is up and east is to the left. 4000pix square covers the whole 6arcminϕ FOV(circular feature) of Subaru cassegrain focus.

image motion due to flexure. It is still in the function test observing phase. Although the spectroscopy mode is not yet available, the imaging mode is almost completely up and run. Figure 5 shows the demonstration image of M82 taken with FOCAS. The picure was taken in 2000 February 2 under moderate seeing condition. Star images have a FWHM of 0.9arcsec. The best seeing size we have obtained during the test run was 0.35arcsec.

A systematic analysis for image quality, system transmission, ghost, CCD evaluations, image motion and focus shift due to flexure and estimate of limiting magnitudes is currently being undertaken.

Further information is available on WWW: http://sds.mtk.nao.ac.jp.

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