Multi-object spectroscopy of FOCAS: Software and its Performance

Yoshihiko Saito[a], Youichi Ohyama[b], Nobunari Kashikawa[a], Michitoshi Yoshida[c], Toshiyuki Sasaki[b], George Kosugi[b], Tadafumi Takata[b], Yasuhiro Shimizu[c], Motoko Inata[c], Kiichi Okita[c], Kentaro Aoki[b], Kaz Sekiguchi[b], Koji S. Kawabata[a], Ryo Asai[d], Hiroko Taguchi[e], Noboru Ebizuka[f], Yasushi Yadoumaru[g], Tomohiko Ozawa[g], and Masanori Iye[a]

[a] Optical Infrared Astronomy Division,
National Astronomocal Observatory of Japan,
2-21-1 Osawa, Mitaka, Tokyo, 181-8588 Japan
[b] Subaru Telescope, National Astronomical Observatory of Japan,
650 North A'ohoku Place, Hilo, Hawaii, 96720 USA
[c] Okayama Astrophysical Observatory, National Astronomical Observatory of Japan,
Kamogata, Okayama, 719-0232 Japan
[d]Systems Engineering Consultants, Co., LTD., Shibuya-ku, Tokyo, 150-0031 Japan
[e]Waseda Jitsugyo, 1-2-1 Honcho, Kokubunji, Tokyo, 185-8505 Japan
[f]The Institute of Physical and Chemical Research, Wako, Saitama 351-0198 Japan
[g]Misato Observatory, 180 Matsugamine, Misato, Wakayama, 640-1366 Japan

ABSTRACT

Faint Object Camera and Spectrograph, FOCAS, is a Cassegrain versatile optical instrument of Subaru telescope. Among various observing modes of FOCAS, the multi-object spectroscopy (MOS) requires dedicated software suite which enables accurate positioning of masks which have over fifty slitlets on faint targets over 6 arcminutes diameter field-of-view (FOV). We have been developing three kinds of software: the image processing software performing combining mosaic CCD images and optics distortion correction, mask designing program (MDP) for the slit arrangement, and pointing offset calculator (POC) for the target acquisition on slits. MDP and POC provide observers a graphical user interface (GUI) for efficient and quick mask designing and target acquisition. Our test has shown that the slit positioning accuracy on targets is about 0.2 arcsec RMS over entire FOV, and is accurate enough for typical observations with 0.4 arcsec slits or wider. We briefly describe our software as well as the pointing accuracy and the required time for the MOS target acquisition with FOCAS.

Keywords: Instrumentation, Subaru Telescope, Multi-Object Spectroscopy, Software

1. INTRODUCTION

Faint Object Camera and Spectrograph, FOCAS, is an optical versatile Cassegrain instrument of the Subaru telescope, and the following observing modes are available: direct imaging, long slit spectroscopy, multi-object spectroscopy (MOS), polarimetric imaging, and spectro-polarimetry (Kashikawa et al. 2000).[1] It has been designed especially for the deep spectroscopy of faint objects, e.g., distant galaxies, quasars, faint objects around extra-galaxies, outer asteroids of Solar system, and so on. The MOS mode is very powerful since it fully utilizes the large photon-collecting power and the high image quality of the Subaru 8.2m telescope as well as the wide field-of-view (FOV) available at the Cassegrain focus. The "fixed slit mask" method has been adopted for

Further author information:
Yoshihiko Saito: E-mail: saitoys@optik.mtk.nao.ac.jp

the FOCAS MOS system. For this purpose, the slit mask changing system is installed at the Cassegrain focal plane atop of FOCAS, and the slit mask fabricating system is installed at the summit facility of the Subaru telescope (Kashikawa et al. 2000; Yoshida et al. 2000)[1].[2] Table 1 summarizes the properties of FOCAS optics and camera, mask changing system, and the mask fabricating system.

Table 1. Summary of FOCAS optics and camera, mask changing system, and the mask fabricating system

FOCAS Optics and Camera	
Plate scale	2 arcsec / mm
CCDs	two 2K×4K CCD mosaic
Pixel scale	0.1 arcsec / pixel
Field of view	Circular, 6 arcminutes diameter
Mask Changing System	
Mask placing accuracy on focal plane	~ 0.005 deg.
Max. number of masks per night	10 in total. 2-3 are reserved for long slits and Hartmann mask
Time for replacing masks	~30–60 sec, depending on the mask position in the mask stocker
Mask Fabrication	
Mask material	four-multi-layered carbon fiber sheet (100 μm thick)
Mask cutter	diode-pumped YAG laser
Slit figure	rectangle or hole. Tilted slit is available.
Minimum slit width	100 μm = 0.2 arcsec
Parallelism error of slit edges	~ 0.002 deg.
Straightness of slit edges	$< 3\mu$m RMS
Accuracy of slit cutting positions	$< 1\mu$m
Typical slit number per mask	30–100 depending on grism/order-sorting filters used

In addition to the hardware system shown above, various kinds of software are required to support the MOS observation. We have been developing three kinds of software for MOS: the image processing software performing combining mosaic CCD images and optics distortion correction, mask designing software providing interactive graphical interface for easy and efficient arrangement of the slits, and the pointing offset calculator for quick target acquisition on slits. The MOS mode of FOCAS has been used by common-use observers since Oct. 2001, and the software has been used since then. In this paper, we briefly describe our software and mention the pointing accuracy and the required time for the MOS target acquisition.

2. OVERVIEW OF THE MOS OBSERVING SEQUENCE AND THE RELEVANT SOFTWARE

The MOS observation sequence is shown in figure 1. Before the MOS run, observers need to design their masks based on the image taken with the FOCAS direct imaging mode. The FOCAS image itself is currently required for the slit positioning with high accuracy. This pre-imaging will be done about a month before the MOS run by observatory staffs, and the images will be sent to the observers. Observers reduce the data with so-called "bigimage" program, which combines two images of mosaic CCDs and apply the optics distortion correction. Observers make a "target list" which contains target positions measured on the distortion-corrected FOCAS images and the slit shape parameters (width/length/tilt angle), and the list will be used as an initial set of slits for the mask designing program (MDP). The slit positions and shapes can be examined on the graphical display of MDP, and observers do the interactive designing of slits, e.g., deleting/appending slits and modifying slit shape. Some small holes for brighter stars will be created with MDP and are used for alignment of the

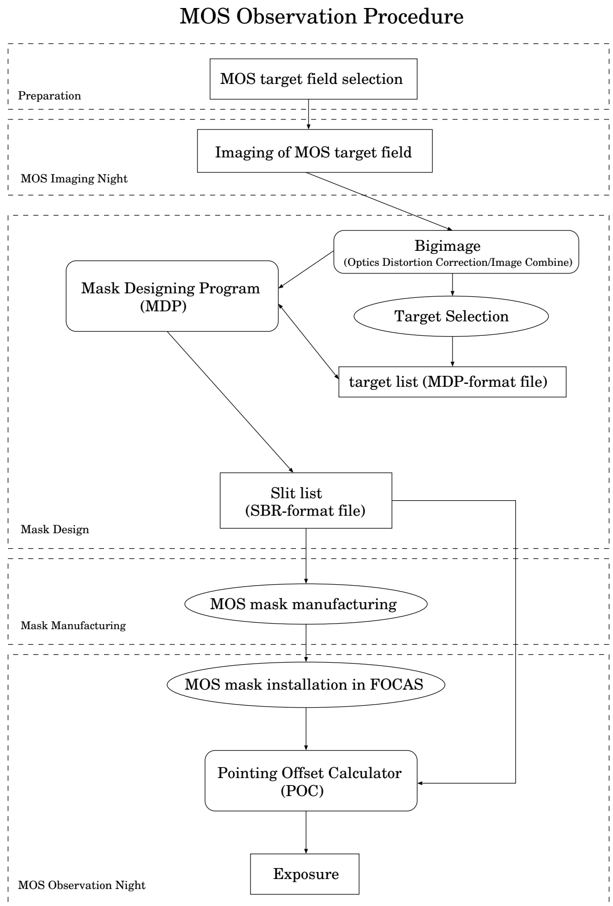

Figure 1. A schematic outline of MOS observation sequence

mask onto the targets at the time of target acquisition. The MDP creates a "slit list" which is used in the CAD system of the laser cutter for fabricating the slit. At the night of MOS observation, the pointing offset calculator (POC) is used to calculate the telescope-pointing offset while considering the optics distortion and image combining parameters.

3. DESCRIPTION OF EACH SOFTWARE

3.1. Image Processing

A pair of images is obtained per single exposure for FOCAS observation, and the images must be combined to be a single "big" image for designing the masks. The `bigimage` program performs image combination and applies the optics distortion correction. This software can also perform simple image processing procedures such as overscan subtraction, bias subtraction, and flat-field correction if observers wish to use these options. The software is written in IDL.

Combining two images and correcting the optics distortion should be done as accurate as possible. We have investigated the optics distortion pattern and the combining parameters very carefully by using a grid mask. A grid pattern at Cassegrain focus is projected onto the CCD surface after distorted through the FOCAS optical train, and we mapped the displacement from the original grid to the observed one. We found that the displacement can be characterized as a simple radial pattern after carefully adjusting the CCD combining parameters (Fig.2 left), and one-dimensional distortion function can represent the FOCAS optics distortion

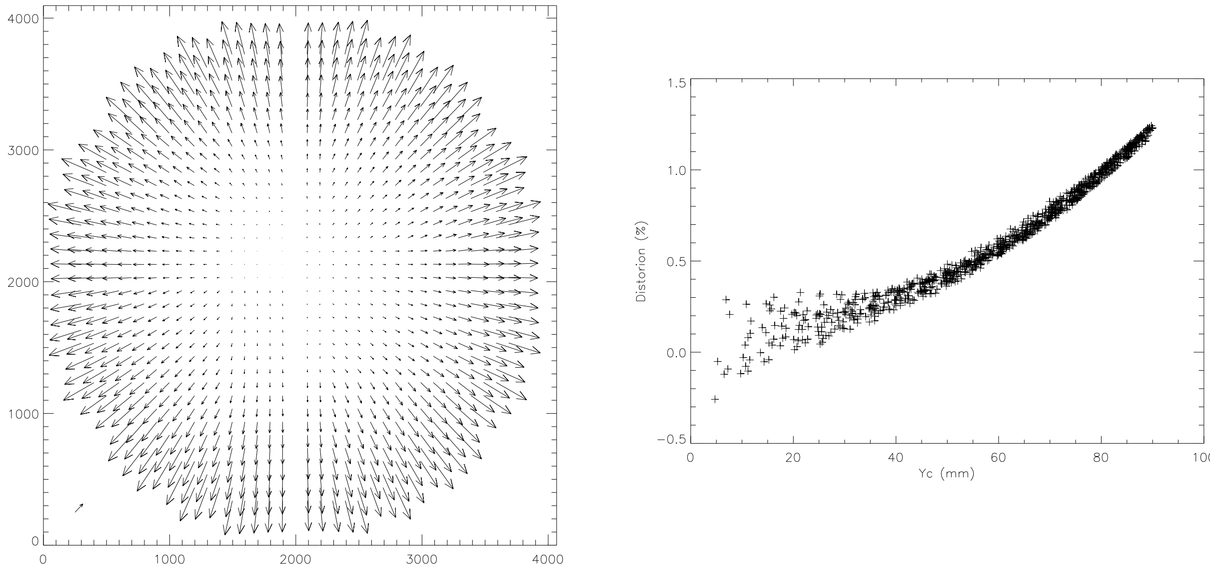

Figure 2. (left) Two-dimensional vector plot showing the image displacement from the original grid points on Cassegrain focus to the projected points on the CCD surface over the entire FOV (4000 pixel by 4000 pixel). No data are available around X=2000 because of a gap between two CCDs. A lower left vector is a reference vector showing a shift of 5 pixel by 5 pixel. (right) One-dimensional distortion plot showing the distortion percentage as a function of distance from the center of the distortion on the Cassegrain focus (in millimeters units). The maximum distortion is about 1.2% which corresponds to 24 pixel of displacement on the CCDs near outer edge of the FOV (2000 pixel away from the center of FOV).

characteristics very well (Fig.2 right). Similar distortion mapping has been done at various telescope elevation angle and instrument rotator positions. After correcting for the parallel movement of the pattern caused by the flexure of the FOCAS body ($\sim$ 6 pixel shift from EL=0 deg to 80 deg), we found that the displacement from one pattern to another is very small ($<$ 1 pixel RMS) and does not show any systematic patterns. Therefore we do not have to take care of the instrument orientation in designing/fabricating the masks. We parameterized the one-dimensional distortion function (Fig.2 right) and the parameters derived are stored as a database which is referred by all pieces of software described in this paper. The estimated error of the distortion correction (including errors of the distortion mapping, parameterizing the distortion function, and the error in the determination of the relative positions of the two mosaic CCDs) is 2 pixel or less at the edge of FOV ($\sim$ 0.1%).

3.2. Mask Design

The observers make a target list as an initial set of slits used in the mask designing program, MDP. In most cases, the candidates should be selected according to the observers' interest based on, e.g., their colors, morphologies, velocities, and so on, and the MDP helps observers to choose a subset of observable slits from the candidates. Since slits can be appended/deleted interactively from MDP, one does not have to consider the mask design carefully while making a target list. The list should be in so-called "MDP-format" which is a simple space-separated ASCII table containing target positions (X-Y pixel coordinates of the target), slit width/length/tilt angle, priorities of the slits, and some notes. Observers can use any kinds of software to measure the target coordinates, i.e., one may use an automatic target finding software like `SExtractor`, or any FITS image viewers like `SAOimage` or `Skycat`.

MDP provides a graphical and an interactive interface for designing the custom slit mask (figure 3). This program is written in IDL. MDP reads both the FITS image and the target list, and it draws various kinds of marks showing slit positions, regions occupied by spectra of each slit expected in the spectroscopy mode, and

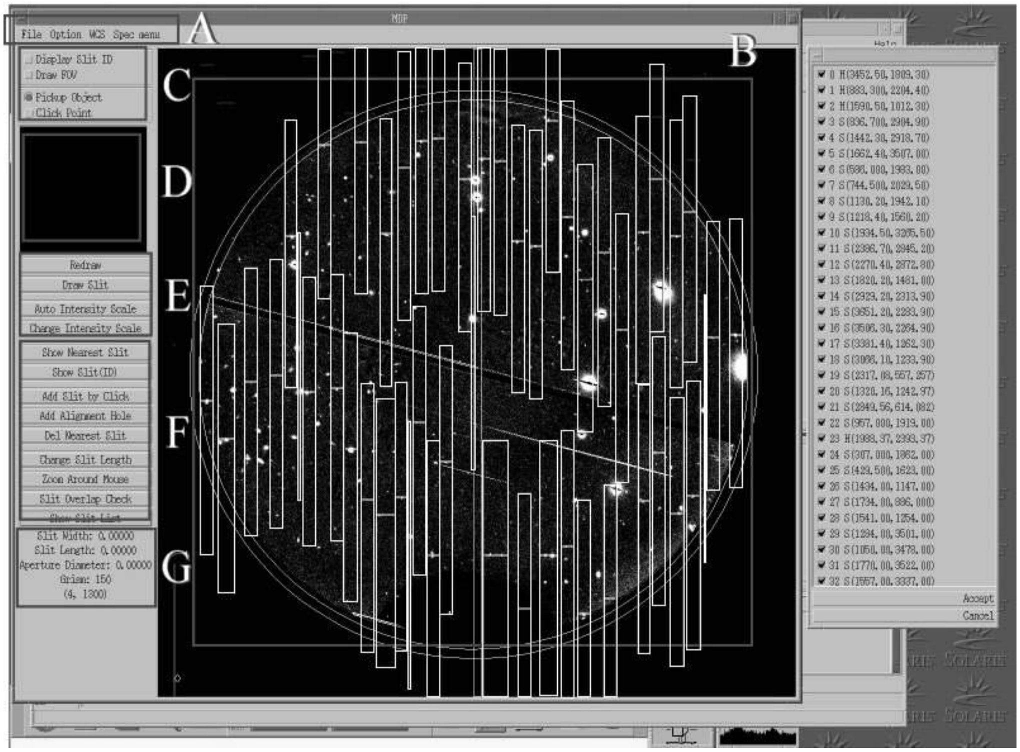

Figure 3. A Snapshot of the mask designing program (MDP). (A): Pull-down menus. Reading/saving the MDP-format file, and saving the SBR-format file can be selected from these menus. (B): Main window showing a FITS image and marks for the slit/spectrum regions. (C): Mode selection switches. (D): Zoom image display. (E): Buttons for controlling the image display. (F): Buttons for slit editing. (G): Information panel. Right sub-panel shows a list of slits with check boxes for selecting the slits.

regions of the zero-th order light on the FITS image. Position marks for these regions are calculated according to the grisms and order-sorting filters selected in MDP. These marks help the observers to find overlapping spectra and to think how to modify the slit arrangement for maximizing the number of targets and the scientific output. One may shorten the length of the slit to give room to the neighbor slit, and/or one may have to delete the slit. To make this procedure easy and efficient, one can select a slit by clicking the mouse around the slit, and edit the parameters in the sub-window, and then check the updated mask image. Also one can add new slits interactively on the MDP display by clicking around the target. The target position can be determined either by performing two-dimensional Gaussian profile fitting on the sub-region around the clicked position, or by just reading the mouse position at the click. This method may be useful to add slits for extra objects after arranging observers' first-priority objects. Alignment holes should be added by selecting a star by click and the Gaussian fitting method.

MDP provides some other useful features. First, it can automatically search for any overlapping spectra. If observers have provided priorities ranking of each target in the MDP-format file, the MDP automatically rejects slits with lower priority in case of overlapping. Second, MDP shows some warning messages if some slits are located near the edge of the FOV or on the gap between the CCDs. One can shift the center of the mask or rotate the FITS image to avoid such slit arrangement difficulties. Third, the slit length can be automatically expanded to fill in the region without any slit images between the neighbor slits.

After designing the masks, MDP creates a text file in which the positions and shapes of slits (slit or hole) are written in a comma-separated ASCII table. The positions are in coordinates of the telescope Cassegrain focal plane in millimeters and we call the file "SBR-format" file (meaning format in the "Subaru" coordinates).

Figure 4. The laser cutting equipment: **Left**: A computer running the mask-fabricating CAD system (PowerCAM), **Center**: Main body of the laser cutting machine (ML-7040A), **Right**: Controller of the laser cutter (LD YAGSCAN).

The file is sent to the observatory staff for fabricating the mask.

3.3. Mask Fabrication

The laser cutting machine is used to fabricate the MDP-designed mask based on the SBR file (Figure 4). Customized commercial CAD software, PowerCAM (KURAKI Co., LTD.), is used to read the SBR-format file and to control the laser cutting machine. It translates the SBR format into the commands for controlling the laser cutting machine, and it actually control both a diode-pumped YAG laser ML-7040A (Miyachi-Technos, Co.) and the XY stage on which a holder of the carbon fiber sheet is attached. The XY stage moves at an accuracy of $< 1\mu$m or < 0.002 arcsec. The parameters used to cut the mask are the cutting speed (s_l) and intensity (I_l) of the laser. We searched for the best parameters to achieve the most smooth edge of slits, and determined the best parameter set as $s_l = 20$mm/min and $I_l = 19$A. The roughness of the slit edges is $\sim 3\mu$m RMS with the best parameter set, which corresponds to 3% of the minimum slit width available in the system (100 μm or 0.2 arcsec), being accurate enough for the purpose of MOS observation. It will take about 30-60 minutes to make a mask, and the time depends on the number of slits. MOS masks are normally installed at the evening of the MOS observing night.

3.4. Target acquisition on the slit masks

The pointing offset calculator (POC) is used to calculate the pointing offset by comparing the positions of alignment holes with those of alignment stars at the night of observation. This program is also written in IDL. A typical sequence of the MOS mask pointing is as follows: First an image of nearby blank sky is taken through the mask to know the positions of the alignment holes. Then, a direct image of the target field is taken without the mask. These two images are sent to the POC. No filter is used to obtain more sky counts within a short exposure time of $\sim$ 30 seconds. The recommended magnitude range of the alignment stars is $17 \sim 19$ in R or I, and the range is determined to avoid the saturation of brighter stars while to obtain large number of counts which is enough to measure the positions of fainter stars in 30 seconds exposure. The

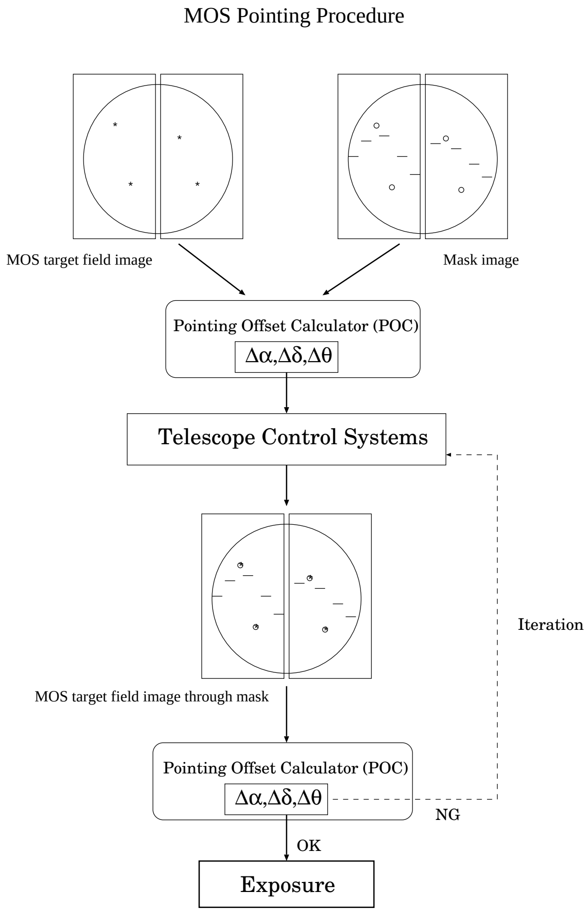

Figure 5. A schematic outline of the MOS pointing procedure

POC also reads the SBR-format file and automatically searches for the image area of alignment stars/holes, and then two-dimensional Gaussian fittings are applied for determining their positions. The POC calculates the offsets in X-Y CCD coordinates and the field rotation to minimize the displacement between alignment star/hole positions. The optical distortion and the image combining parameters are taken into account in the calculation. Those offsets are transformed to the celestial coordinates (ΔRA, ΔDec, and ΔPA), and the results are sent to the telescope control systems. After correcting the offset, another target image will be obtained through the mask. All alignment stars should be found in the holes on the new image. This image is further utilized to calculate the star/hole position offset, and the telescope offset is calculated again. The second step can be repeated until the calculated offsets become sufficiently small for all alignment holes (e.g., $\Delta\alpha \sim 0.1$ arcsec, $\Delta\delta \sim 0.1$ arcsec, and $\Delta\theta \sim 0.01$ deg). Currently at least four alignment holes are recommended to be used although two holes should be enough in principle to measure the telescope positioning offset in RA, DEC, and θ directions. Third and fourth stars/holes are used to estimate the pointing error in POC and that is why stars should be scattered evenly within the FOV as shown in Figure 5.

We have investigated the accuracy of the target positioning in the following way. 1) Take an image of bright stellar fields and perform the distortion correction and image combination. 2) Choose some stellar objects from the field. 3) Make a mask with $20 - 50$ alignment holes corresponding to the objects. 4) Take an image of this alignment hole pattern by using dome flat light. 5) Measure the displacement between the hole/star positions. We found that the typical positioning error of the slits is about 0.2 arcsec RMS. In addition, we have been checking the accuracy every time we do the MOS pointing by using alignment hole/slit pairs. Although the

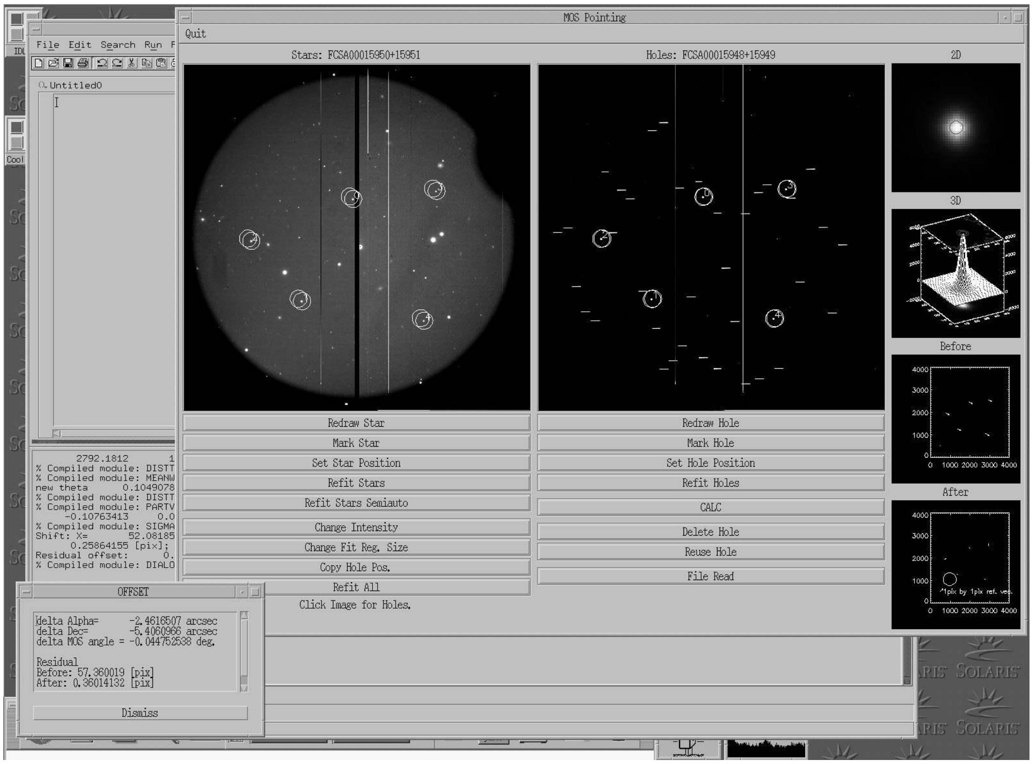

Figure 6. A snapshot of the MOS pointing offset calculator (POC). Big right panel shows the sky image taken through the mask, and the left panel shows the target image without the mask. Five alignment stars/holes are marked in each panel in this case. Buttons below these panels are used to tweak the fitting parameters, eliminating some pairs of stars/holes from the calculation in case of, e.g., big cosmic ray event near the stars/holes, and so on. Right panels show the position fitting results, and lower left sub-panel shows the calculation result.

number of the position measurement per field is very small (~ 4), our experience shows that the positioning accuracy is typically less than 0.2 arcsec for the alignment stars. This well satisfies the requirement of the MOS observation since the typical width is 0.4 arcsec or wider.

This level of accuracy can be achieved after one or two iterations of the telescope fine positioning. Since one offset calculation finishes in one minute, the most time-consuming part of the pointing procedure is the CCD read-out time. We need typically four images (including one iteration for fine positioning), and it typically takes two minutes in no-binning mode and 40 seconds in 2×2 binning mode. Note that 2×2 binning image can be used only for the first step of the comparison between the mask and target field images, and high-resolution 1×1 binning image is always required during the iteration for the fine pointing. Including exposure time of 30 seconds for each frame, it typically takes 15 minutes or more in total before starting the spectroscopic exposure.

4. SUMMARY AND FUTURE WORK

We have developed a dedicated software suite for MOS observation with FOCAS at the Subaru telescope to support the efficient MOS observation as well as the accurate positioning of the slits over the FOV. Number of FOCAS MOS observations has been made since Oct. 2001, and the software suite described in this paper has been used as a tool for observers.

Although FOCAS image itself is currently required to design the slits, we have been trying to establish a way to design the mask based on the images taken with other instruments like the Suprime-Cam (a wide field prime focus camera for Subaru telescope), or even on the celestial coordinates (RA, Dec). This method may be useful because we could save time for the pre-imaging if observers use rather wide slits (~ 1 arcsec) and the required positioning accuracy is not so high. Although some preliminary tests have been made successfully, we need to investigate more on the accuracy of the slit positioning.

As for the data reduction, we will develop data reduction tools (the MOS analysis program: MAP), which help observers to carry out the distortion correction, flat correction, and extracting each spectrum from the whole MOS images semi-automatically. Each spectrum will be extracted based on the information on the slit positions described in the MDP-format file. It will also perform a preliminary wavelength calibration for a quick look purpose. Subaru telescope provides "DASH" (Distributed Analysis System Hierarchy) data reduction support system and we plan to implement the MAP in DASH.

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