International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Development of compact integral field unit for spaceborne solar spectro-polarimeter

Y. Suematsu

M. Koyama

T. Sukegawa

Y. Enokida

et al.

DEVELOPMENT OF COMPACT INTEGRAL FIELD UNIT FOR SPACEBORNE SOLAR SPECTRO-POLARIMETER

Y. Suematsu[1], M. Koyama[2], T. Sukegawa[2], Y. Enokida[2], K. Saito[2], Y. Okura[2], T. Nakayasu[2], S. Ozaki[1], S. Tsuneta[3]

[1]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; [2]Canon Inc., 30-2, Shimomaruko 3-chome, Ohta-ku, Tokyo 146-8501, Japan; [3]ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

I. INTRODUCTION

A 1.5-m class aperture Solar Ultra-violet Visible and IR telescope (SUVIT) and its instruments for the Japanese next space solar mission SOLAR-C [1] are under study to obtain critical physical parameters in the lower solar atmosphere. For the precise magnetic field measurements covering field-of-view of 3 arcmin x3 acmin, a full stokes polarimetry at three magnetic sensitive lines in wavelength range of 525 nm to 1083 nm with a four-slit spectrograph of two dinesional image scanning mechanism is proposed: one is a true slit and the other three are pseudo-slits from integral field unit (IFU). To suit this configuration, besides a fiber bundle IFU, a compact mirror slicer IFU is designed and being developed.

Integral field spectroscopy (IFS), which is realized with IFU, is a two dimensional spectroscopy, providing spectra simultaneously for each spatial direction of an extended two-dimensional field. The scientific advantages of the IFS for studies of localized and transient solar surface phenomena are obvious. There are in general three methods [2][3] to realize the IFS depending on image slicing devices such as a micro-lenslet array, an optical fiber bundle and a narrow rectangular image slicer array.

So far, there exist many applications of the IFS for ground-based astronomical observations [4]. Regarding solar instrumentations, the IFS of micro-lenslet array was done by Suematsu et al. [5], the IFS of densely packed rectangular fiber bundle with thin clads was realized [6] and being developed for 4-m aperture solar telescope DKIST by Lin [7] and being considered for space solar telescope SOLAR-C by Katsukawa et al. [8], and the IFS with mirror slicer array was presented by Ren et al. [9] and under study for up-coming large-aperture solar telescope in Europe by Calcines et al. [10]

From the view point of a high efficiency spectroscopy, a wide wavelength coverage, a precision spectro-polarimetry and space application, the image slicer consisting of all reflective optics is the best option among the three. However, the image slicers are presently limited either by their risk in the case of classical glass polishing techniques (see Vivès et al. [11] for recent development) or by their optical performances when constituted by metallic mirrors. For space instruments, small sized units are much advantageous and demands that width of each slicer mirror is as narrow as an optimal slit width (< 100 micron) of spectrograph which is usually hard to manufacture with glass polishing techniques. On the other hand, Canon is developing a novel technique for such as high performance gratings which can be applicable for manufacturing high optical performance metallic mirrors of small dimensions.

For the space-borne spectrograph of SUVIT to be aboard SOLAR-C, we designed the IFS made of a micro image slicer of 45 arrayed 30-micron-thick metal mirrors and a pseudo-pupil metal mirror array re-formatting three pseudo-slits; the design is feasible for optical configuration sharing a spectrograph with a conventional real slit. According to the optical deign, Canon manufactured a prototype IFU for evaluation, demonstrating high performances of micro image slicer and pupil mirrors; enough small micro roughness for visible light spectrographs, sharp edges for efficient image slices, surface figure for high image quality, etc. In the following, we describe the optical design of IFU feasible for space-borne spectrograph, manufacturing method to attain high optical performance of metal mirrors developed by Canon, and resulted performance of prototype IFU in detail.

II. OPTICAL DESIGN OF INTEGRAL FIELD UNIT WITH IMAGE SLICER

Optical design of the IFU with an image slicer employing only reflective optics can be flexible [12]. Here we follow requirements for the IFU to be equipped with the spectrograph (Fig. 1) of SUVIT/SOLAR-C. They are to achieve scientific requirements on the spatial (better than 0.2 arcsec) and spectral resolution (resolving power of 10^5) for chromospheric lines at 854 nm and 1083nm, to share with conventional slit spectrograph for higher spatial and spectral resolution for the photospheric line at 525 nm (4 slits configuration; one from real slit and three from IFU pseudo-slits), and to realize the unit within a reasonably small dimension for space application.
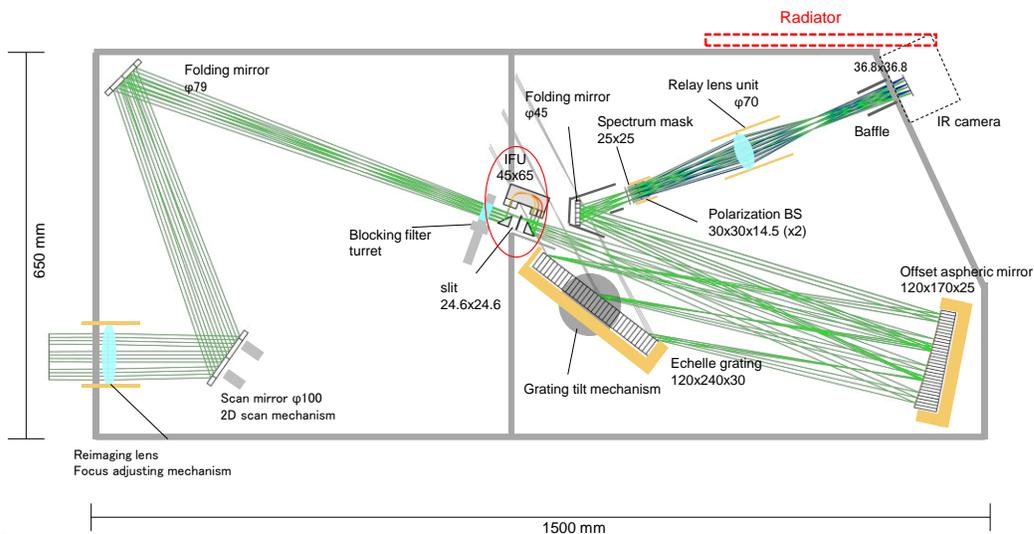
Fig. 1 Optical layout of SUVIT spectrograph with fiber bundle IFU.
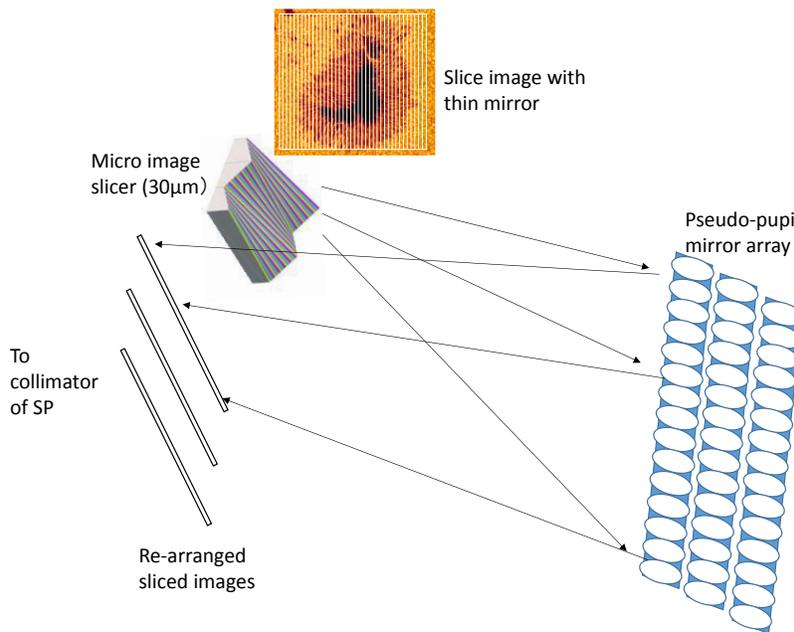
Fig. 2 Conceptual optical layout of IFU with image slicer for SOLAR-C.
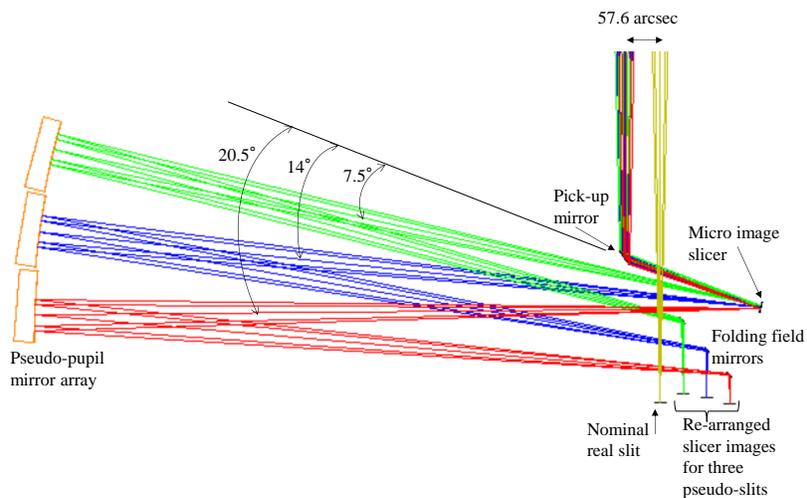
Fig. 3 Possible optical configuration of IFU for spectrograph of SOLAR-C/SUVIT

The solar image formed on the slit plane by the telescope of beam F/24 with image scale of 0.18 arcsec per 30 μm. Then as a rough guideline, we tried to design the IFU in which a slicing mirror is 30 μm wide and a pupil mirror refocus the slicer without changing the image scale. The real slit is 24 mm (143 arcec) high which corresponds to a stack of 15 slicers of 1.58 mm (9.5 arcsec) long. As a result, we come to a stack of 45 narrow slicers of 30μm wide and 1.56 mm long; each 15 set of slicers is re-focused as three set of pseudo-slits (Fig. 2). Each flat mirror slice is set at a different angle so that the diverging beam from each slice exits in three columns of pupil mirror array. Each beam is then reflected by pupil mirror which is offset in the direction parallel to the long axis of each slice. The overall effect is to rearrange the rectangular field of 9.5 x 8.1 arcsec^2 into three sets of a long thin field made up of all the slices arranged end to end, which forms three entrance slits of the spectrograph.

Fig. 3 gives the optical layout of IFU for SOLAR-C, and Tables 1 and 2 give specification of optical parameters for mirror slicer (see Figure 4 for its 3D structure) and pupil mirrors, respectively. Note that the ratio of the distances pupil-mirror-to-slicing mirror (200 mm) and pupil-mirror-to-image-of-slice (200 mm) set unity so that the slicer and the image-of-slicer have the same size and that the pupil mirrors are oversized in the direction of diffraction to pick up a main lobe of diffracted beam in the longest observation wavelength of 1083 nm, reducing amount of the light vignetted by the pupil-mirrors. The distance between the pupil mirror and the slicing mirror was determined so that each 15 pupil mirror in a column can have the same off-axis conic asphere. The tilts of pupil mirrors are set so that the re-arranged slicer images make a line with an accuracy of 30μm and with a gap of 30μm each other. The pupil images do not need to be exactly on the pupil mirrors, as long as the beam size is sufficiently small on them and this is why we here call them pseudo-pupil mirrors. Fig. 4 gives 3D view of ray paths from the slicers to the pseudo-slits and simulated pseudo-slit image using non-sequential ray tracing tool of Zemax.
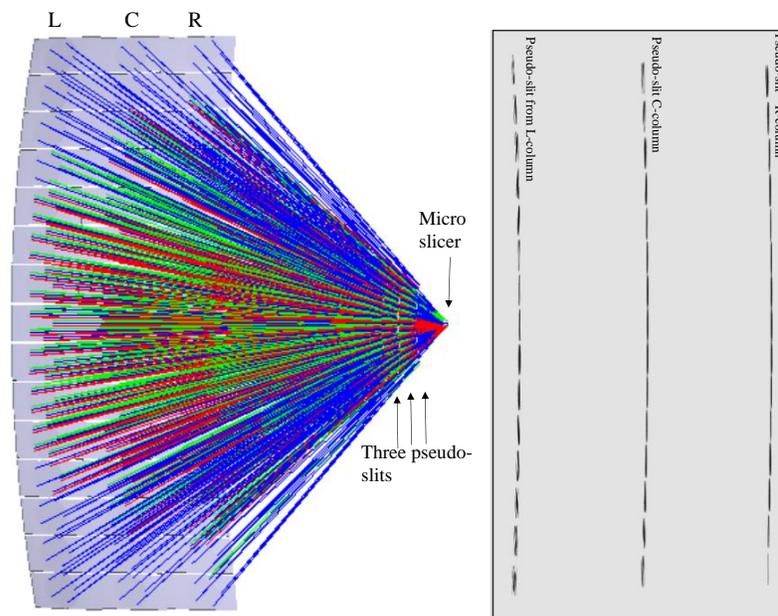

Fig. 4 3D view of ray paths from the slicers to the pseudo-slits and simulated pseudo-slit image using non-sequential ray tracing tool of Zemax

III. MANUFACRURING METHOD AND RESULTS

In accordance with the specifications given in section II, we made a prototype image slicer IFU. We here describe the method and manufacturing accuracies of the IFU optical components.

A. Micro slicer mirrors

The micro slicer mirrors consist of three units, each unit consists of 15 plane mirrors as shown in Table 1. Each mirror is 1.58mm in length and 30μm in width together the micro slicer mirrors are 1.58mm in length and 1.35mm in width. Each mirror tilts 1.55 degrees toward θx in a unit. Two outside units tilt 3.25 degrees compared to the center unit. This metal mirrors were cut using a high precision free form cutting machine developed by Canon (Fig. 8 right) [15].

Table 1. Specification of micro imaging slicer mirror. The slicer mirrors are divided into three sets each which has 15 slicers. Each set corresponds to each column of pseudo pupil mirror array: R, C and L-column (see Figure 3). Each column has 15 sub-mirrors numbered in row with n (= -7,-6,…,6,7 in order of +y-direction).

	Dimension of each slicer mirror (mm)	Surface figure	Surface normal tilt angle θ x	Surface normal tilt angle θ y	
Slicers for pupil mirrors in R- column			1.55 n (deg)	-3.25 (deg)	
Slicers for pupil mirrors in C- column	0.03W x 1.58 L	flat	-1.55 n (deg)	0 (deg)	
Slicers for pupil mirrors in L- column			1.55 n (deg)	3.25 (deg)	
accuracy	Edge sharpness < 1µm	Figure error < 1 λ (630 nm) PV Roughness < 1 nm rms	< 0.003 (deg) (10 arcsec)	< 0.003 (deg) (10 arcsec)	

Table 2. Specification of pseudo pupil mirror array. The array consists of three column: R, C and L (see Figure 3). Each column has 15 sub-mirrors numbered in row with n (= -7,-6,…,6, 7 in order of +y-direction). Each sub-mirror in the column has the same rectangular size and surface figure parameters, where R is the radius of curvature, k the conic const. and $\triangle$x is the mirror center offset from the vertex. Each sub-mirror is placed at the radial distance 200 mm from corresponding slicer mirror.

Column	Surface figure	Tilt θ x from the radial direction from the each slicer center to pupil mirror center	Tilt θ y from the radial direction from the each slicer center to pupil mirror center	
R	R=-200 (mm) k=-0.8351 $\triangle$x=-4.260 (mm)	-0.23 n (deg)	-2.5+0.0043 n (deg)	
C	R=-200 (mm) k=-1.220 $\triangle$x=-6.102 (mm)	-0.23 n (deg)	-3.8-0.0043 n (deg)	
L	R=-200 (mm) k=-1.4602 $\triangle$x=-7.897 (mm)	-0.23 n (deg)	-5.1+0.0043 n (deg)	
accuracy	Figure error < λ /8 (80 nm) PV Roughness < 1nm rms	< 0.00215 (deg) (7.7 arcsec)	< 0.00215 (deg) (7.7 arcsec)	
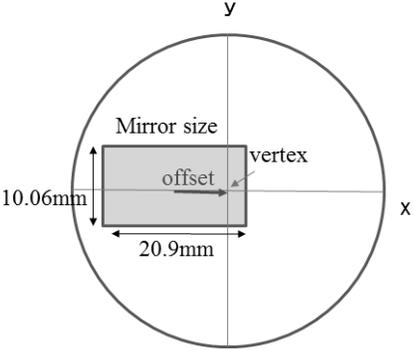
A rectangular diamond tool whose width is 30µm was set on the B-axis of the cutting machine, the work of the micro slicer mirrors was set on the C-axis table, and shaper cutting was conducted using single point of diamond tool by controlling XYZBC-axes. By using cutting method instead of polishing, it is possible to make the micro slicer mirrors as monolithic module. Compared to polishing, Cutting can make a flexible shape, and decrease geometric form error by cutting units together. In addition, cutting has advantages of making micro planes of 30 µm width which have different directions, and ensuring a shape which has sharp edge. However, there is a drawback in cutting. It is difficult to obtain low surface roughness. To overcome this drawback, Canon has a high precision free form cutting machine and ultra-precision cutting process technology. Our high precision free form cutting machine has three liner axes (X-axis, Y-axis, and Z-axis) and two rotation axes (B-axis, C-axis) on a highly rigid frame with air mount to suppress vibration and has a high quality control system which enables positioning resolutions of control axes which is less than 1nm [15]. Moreover, Canon has ultra-precision cutting

technology which can control and optimize cutting conditions such as feed speed, cutting depth, rake angle, etc. and other conditions such as crystal orientation, cutting force, temperature, etc. [16]

Fig. 5 shows the picture and the scanning electron microscope (SEM) images(X50, X200) of the micro slicer mirrors. It is found that the micro slicer mirrors of flip grating shape were cut as expected as shown in Fig. 5. Fig. 6 (left) shows the surface roughness of one of the micro slicer mirrors in 0.02mm X 0.02mm measured by Zygo NewView 3D Optical Surface Profiler; the surface roughness is 0.61 nm (rms). The average of the surface roughness of any 9 surfaces is 0.93nm rms and has achieved the requirement of less than 1nm rms. By using Canon's high precision cutting machine and cutting process technology, it is confirmed that cutting can obtain low surface roughness equivalent to polishing. The width of this micro slicer mirrors is 30 μm, it is too small to be constructed from separated mirrors and also reduce tilt errors. However, the cutting does not require re-configuration because it can make monolithic module and is able to satisfy strict requirement of tilt error (10 arcsec). Fig. 6 (right) shows the SEM image (X50000) of an edge quality of the micro slicer mirrors. The edge quality is less than 0.1μm. A sharp figure of diamond tool used makes a sharp edge by cutting.Tilts of each mirror's surface were measured from profiles by Zygo NewView 3D Optical Surface Profiler. Tilt errors were calculated by subtracting tilts between two consecutive mirrors from design values. Fig. 7 shows an example of the tilt errors between design value and tilts formed by profiles of longitudinal direction of one surface of the micro slicer mirrors (B) and adjacent surfaces (A,C). It is clear that tilt errors are both less than 6 arcsec.

B. Pseudo Pupil Mirrors

Fig. 8 shows the model of the pseudo pupil mirror. The pseudo pupil mirror also consists of three units and each unit has 15 mirrors. All mirrors are off-axis conic asphere as defined in Table 2. The metal pseudo pupil mirror was cut using a high precision free form cutting machine developed by Canon as well as the micro slicer mirrors. A diamond tool which has curvature on this tip was set on the B-axis of the cutting machine, the work of the pseudo pupil mirror was set on the C-axis table, and shaper cutting was conducted using single point of diamond tool by controlling XYZB-axes. Pseudo pupil mirror also has tight requirement in tilt error (7.7 arcsec) so that cutting which does not need re-alignments of separated mirrors is very useful compared to polishing which needs alignments of separated mirrors and control tilt of each mirror's surface.
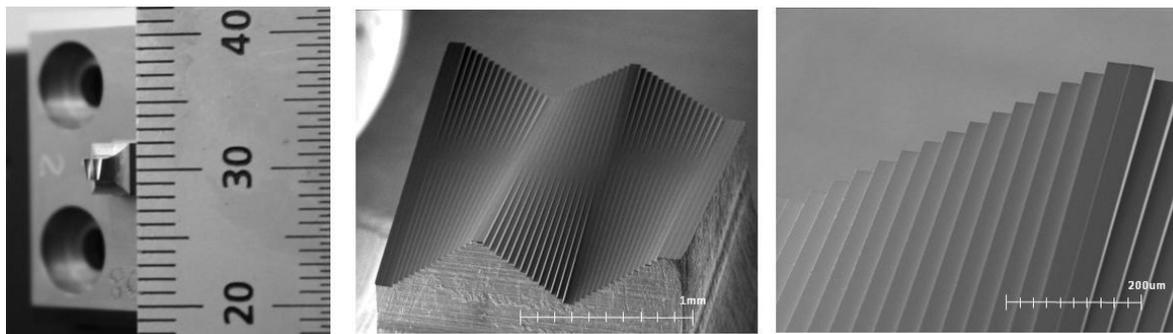

Fig. 5 Picture and the scanning electron microscope (SEM) images(X50, X200) of the micro slicer mirrors.
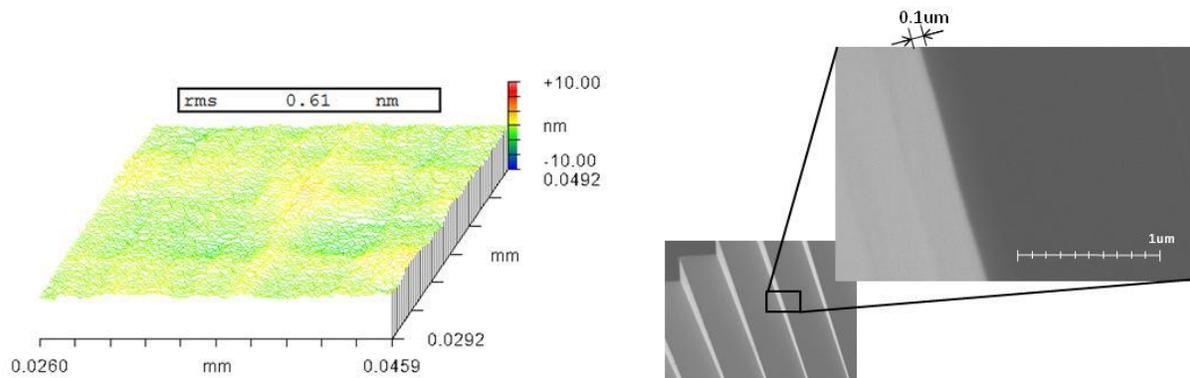

Fig. 6 Surface roughness of the micro slicer mirrors (left) and SEM image (X50000) of an edge quality of the micro slicer mirrors (right).
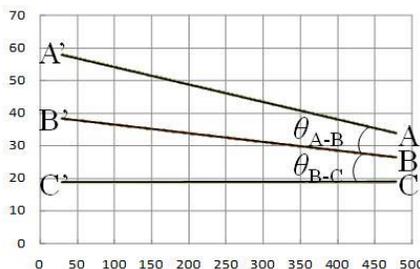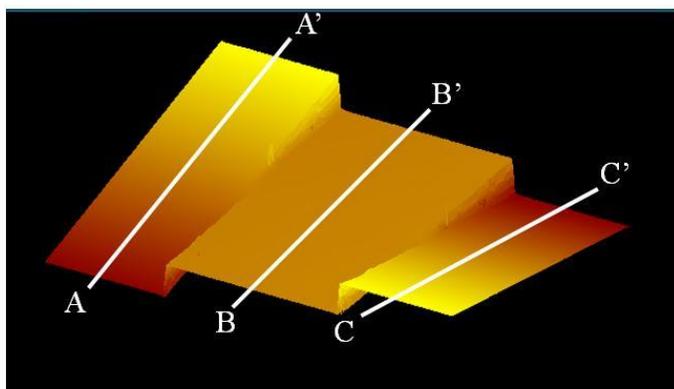
|	Tilt (Tilt Error)
$\theta_{A\text{-}B}$	1° 32'55'' ($\triangle$0° 00'05'')
$\theta_{B\text{-}C}$	1° 32'54'' ($\triangle$0° 00'06'')

Fig. 7 Tilt errors between design value and tilts formed by profiles of longitudinal direction of one surface of the micro slicer mirrors (B) and adjacent surfaces (A, C)

Fig. 9 (top left) shows the surface roughness of one of the pseudo pupil mirror in 0.14 mm x 0.105 mm measured by Zygo NewView 3D Optical Surface Profiler. The surface roughness is 0.94 nm rms. The requirement which is 1nm rms is achieved and it is confirmed that cutting can obtain low surface roughness even if work is freeform surface as a result of this surface roughness. In order to measure a surfacee accuracy, A-Ruler developed by Canon was used. A-Ruler is one of the measurement machine using a contact probe, and it is possible to measure aspherical surfaces accurately [17][18]. After measuring all surfaces' shape, surface accuracy was calculated using all the surfaces simultaneous best fitting so that surface errors are minimized. Fig. 9 (top right) shows the surface accuracy of one of the pseudo pupil mirrors. It is found that the surface accuracy is 17 nm PV and high quality surface is obtained so the surface accuracy is enough excellent compared with the requirement. A-Ruler was also used for measuring tilt errors. Tilt errors between design value and tilts around X-axis and Y-axis were calculated after all the surfaces simultaneous best fitting. Fig. 9 (bottom) shows the result of tilt errors. Tilt errors around X-axis of all surfaces are less than 4.7 arcsec and tilt errors around Y-axis of all surfaces are less than 3.3 arcsec which are less than requirement (7.7 arcsec). This means that by using cutting method, tilt errors can be reduced even if a surface is freeform.

III. OPTICAL PERFORMANCE

Since the prototype IFU components were made of metal mirrors of very small micro roughness, they have reflectivity high enough to simulate the optical examination without a reflective coating on them. To optically evaluate the image slicer IFU, the prototype micro image slicer and pseudo pupil mirror array was set up as designed, using a halogen lamp focused on the micro slicer with focal ratio of F/24. We confirmed that the pseudo pupils are projected as designed and re-arranged slicer images are focused by the pseudo pupil mirrors as three pseudo slits at the distance 200 mm away (Fig. 10).

We also simulated a spectrograph configuration with the IFU, simply using a collimator lens and a camera lens, to re-focus the pseudo slits on a camera and evaluate their optical quality. The collimator was not of a high quality, showing internal reflection, and as a result giving ghost pseudo slits aside of the real ones. Other than this, we confirmed very sharp slicer images and low level (in the order of 10^{-4}) of scattered light in the wavelength 430 nm, that is, very small errors in the surface figure of pseudo pupil mirrors and very small micro roughness of both mirrors as mentioned above in section II.

IV. SUMMARY

We have presented an innovative optical design for image slicer IFU and manufacturing method to attain high performances of micro image slicer; accurate roughness, sharp edges, surface form, etc., using a novel technique developed by Canon. Our IFU is small-sized and consists of micro image slicer of 45 arrayed 30-micron-thick metal mirrors and a pseudo pupil mirror array for forming three pseudo-slits, providing possible optical configuration for a multi-slit spectrograph: coexistence of a real slit and pseudo slits from the IFU, which is suitable for space-borne spectrograph. Using a prototype IFU, we confirmed high optical performances of metal-made micro image slicer mirrors and pseudo pupil mirrors, such as the micro roughness less than 1 nm rms, edge sharpness less than 0.1μm, mirror tilt errors less than required accuracies, etc. We plan to put a

reflective coating on both of metal mirrors and will examine their optical performance after the coating and carry out their space qualification tests.
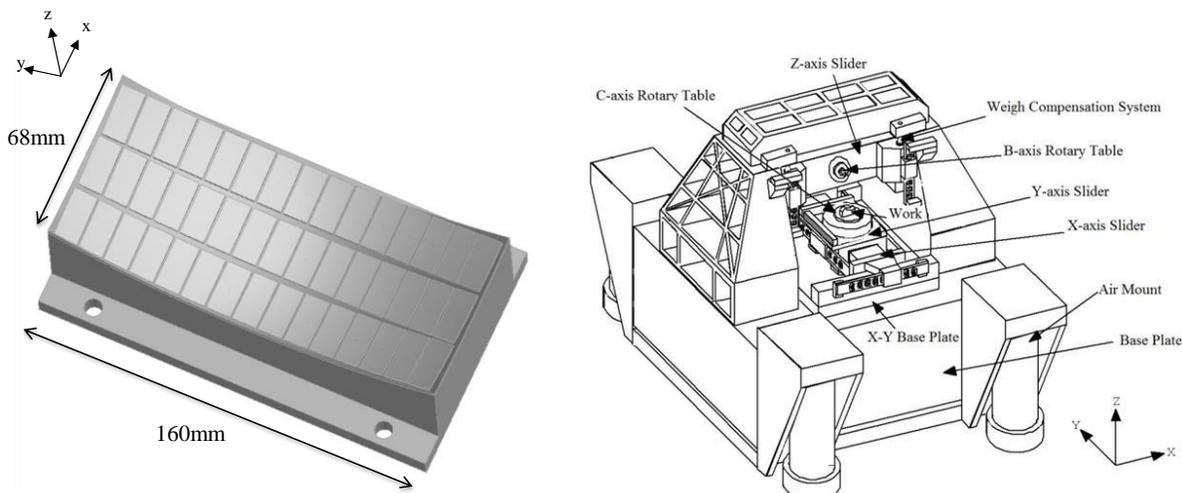

Fig. 8 CAD model of pseudo pupil mirror array (left) and Canon's high precision free form cutting machine (right).
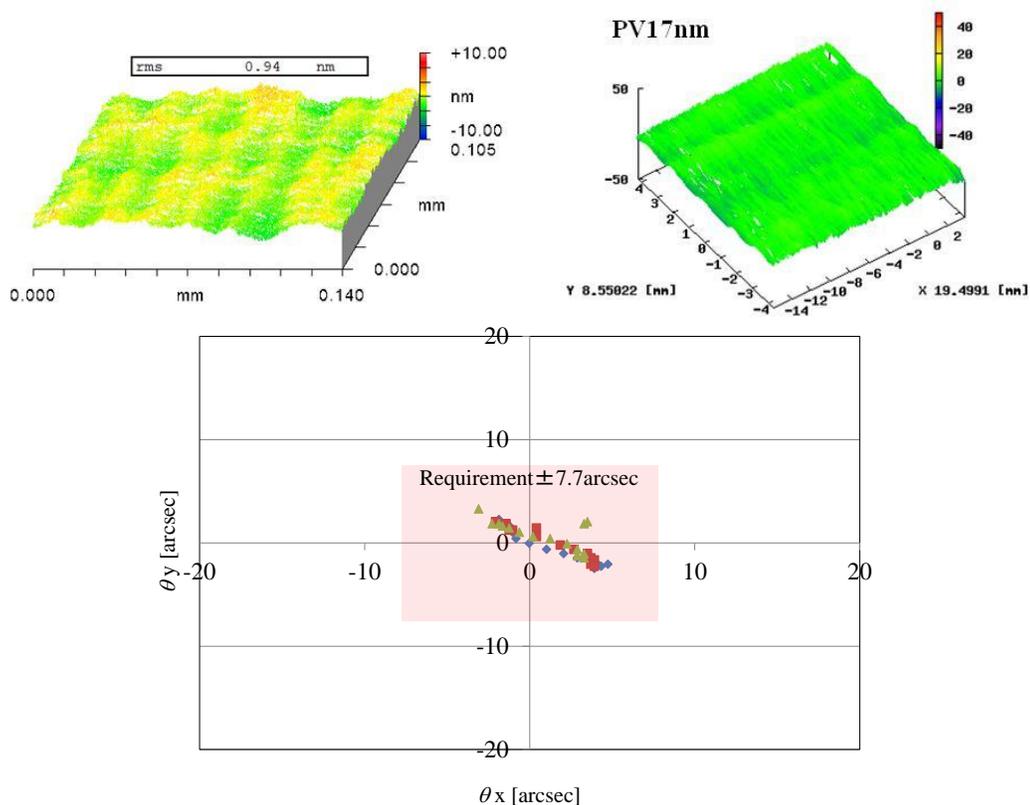
Fig. 9 Surface roughness of the pseudo pupil mirror (top left), Surface accuracy of the pseudo pupil mirror (top right) and tilt errors of the pseudo pupil mirror (bottom).

REFERENCES

[1] Suematsu, Y.; Katsukawa, Y.; Shimizu, T.; Ichimoto, K. "Instrument Design of 1.5-m Aperture Solar Optical Telescope for the SOLAR-C Mission", International Conference on Space Optics, , Ajaccio, Corse, 9-12 October 2012.

[2] Allington-Smith, J. and Content, R., "Sampling and Background Subtraction in Fiber-Lenslet Integral Field Spectrograph", PASP 110, pp.1216-1234, 1998.

[3] Allington-Smith, J., "3D Instrumentation", Science Perspectives for 3D Spectroscopy, Proc. ESO Workshop, Eds. by M. Kissler-Patig, J. R. Walsh and M. M. Roth, Springer, pp. 3-13, 2007.

[4] Bershady, M. A. "3D Spectroscopic Instrumentation", 3D Spectroscopy in Astronomy, XVII Canary Island Winter School of Astrophysics, eds. E. Mediavilla, S. Arribas, M. Roth, J. Cepa-Nogue, and F. Sanchez, Cambridge Univ. Press, 2009.

[5] Suematsu, Y., Imai, H., Yoshimura, K., Ishigaki, T., Ueno, S., Hayashi, T., Ohtani, H., "Tridimensional Spectroscopic Observations of the Sun with a Microlens-Array Spectrograph", High Resolution Solar Physics: Theory, Observations, and Techniques, ASP Conf. Ser. 183. Eds. T. R. Rimmele, K. S. Balasubramaniam, and R. R. Radick, pp.303-310, 1999.

[6] Lin, H., and Versteegh, A., "VisIRIS: a visible/IR imaging spectropolarimeter based on a birefringent fiber-optic image slicer", Proc. SPIE, Volume 6269, 62690K, 2006.

[7] Lin, H., "SPIES: the spectropolarimetric imager for the energetic sun", Proc. SPIE 8446, 84461D (2012).

[8] Katsukawa, Y., Ichimoto, K., Suematsu, Y., Hara, H., Kano, R., Shimizu, T., Matsuzaki, K., "Design progress of the solar UV-Vis-IR telescope (SUVIT) aboard SOLAR-C", Proc. SPIE, Volume 8862, article id. 88620S, 2013.

[9] Ren, D., Keller, C., Plymate, C., "An IFU for diffraction-limited 3D spectroscopic imaging: laboratory and on-site tests", Proc. SPIE, Volume 7438, article id. 743818, 6 pp., 2009.

[10] Calcines, A., López, R. L., Collados, M., "MuSICa: The Multi-Slit Image Slicer for the EST Spctrograph", Journal of Astronomical Instrumentation, Vol. 2, No. 1, id. 1350009, 2013.

[11] Vivès, S., Prieto, E., Salaun, Y., Godefroy, P., "New technological developments in integral field spectroscopy", Proc. SPIE, Volume 7018, article id. 70182N, 10 pp., 2008.

[12] Content, R. "Advanced Image Slicers for Integral Field pectroscopy with UKIRT and GEMINI", Proc. SPIE, Volume 3354, pp. 187-200, 1998.

[13] Suematsu, Y., Katsukawa, Y., Hara, H., Shimizu, T., Ichimoto, K., "Design of large aperture solar optical telescope for the SOLAR-C mission", Proc. SPIE, Volume 8442, article id. 844225, 8 pp., 2012.

[14] Suematsu, Y., Katsukawa, Y., Shimizu, T., Ichimoto, K., Takeyama, N., "Instrument Design of the Large Aperture Solar UV Visible and IR Observing Telescope (SUVIT) for the SOLAR-C Mission", the Second ATST-EAST Meeting: Magnetic Fields from the Photosphere to the Corona, ASP Conf. Proc. 463. Eds. by T. Rimmele, A. Tritschler, F. Wöger, V. Collados, H. Socos-Navarro, R. Schlichenmaier, M. Carlsson, T. Berger, A. Cadavid, P. Gilbert, P. Goode, and M. Knölker, pp.439-444, 2012.

[15] Yokomatsu, T., Takizawa, N., Deguchi, A., Saito, T., Kumai, K., "Development of High Precision Free Form Cutting Machine", Proc.JSPE, in Japanese, 1999.

[16] Sukegawa, T., Sugiyama, S., Kitamura, T., Okura, Y., Koyama, M., "High-performance astronomical gratings by Canon", Proc. SPIE, 8450, 2012.

[17] Negishi, M., Watanabe, K., Matsushita, K., Kasahara, T., and Hosaka, K., "A High-Precision Coordinate Measurement Machine for Aspherical Optics", Proc.9th ICPS, 354-359, 1999.

[18] Negishi, M., Matsushita, K., Hosaka, K. and Iwakura, N., "A Double-Sided Contour Measurement Machine for Aspherical Lenses", Proc. International Euspen Conference, 63-66, 2002.
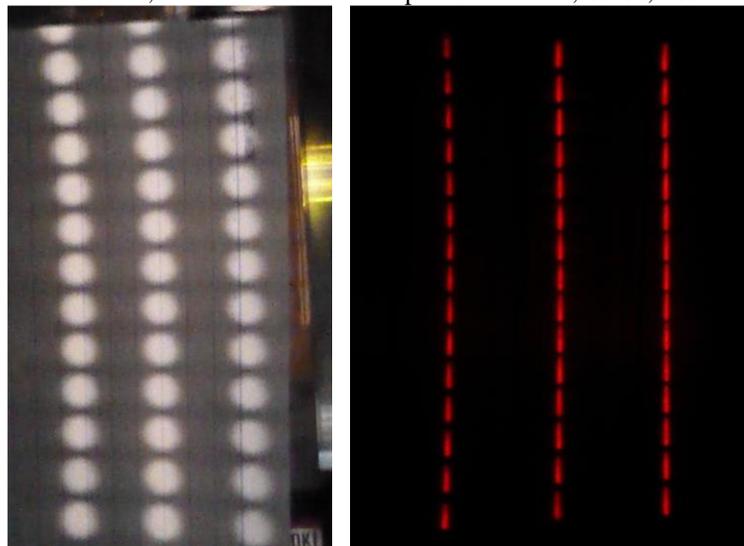
Fig. 10 Pseudo pupil array by the micro image slicer (left panel), and re-arranges slicer image (three pseudo slits) focused by the pseudo pupil mirror array (right panel).