"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

Project (Grant) Number:	824135
Project Acronym:	SOLARNET
Project Title:	Integrating High Resolution Solar Physics

Document Details	
Document Title:	Report on the ability to manufacture thin metallic slices
Prepared by (Institution's Name):	National Institute of Natural Sciences - National Astronomical Observatory of Japan (NINS-NAOJ)
Work Package (WP) Number & Title:	WP6 - Advanced Instrumentation Development
Deliverable Number & Title:	D6.3 - Report on the ability to manufacture thin metallic slicers
Serial Number of Deliverable:	D57
Document Code: (inserted by project office)	D6.3_Version 2.0
File Name: (inserted by project office)	SOLARNET_D6.3_V2.0_TMS_Public_20200306
Date of First Submission (V1.0): (inserted by project office)	Feb 26th, 2020
Date Second Submission (V2.0): (inserted by project office)	March 6th, 2020

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

AUTHORS/ CONTRIBUTORS LIST

Name	Function	Organization
Yoshinori Suematsu	Researcher/ Task leader	NINS-NAOJ
Carlos Dominguez	Postdoc / Sub-WP leader	Instituto de Astrofisica de Canarias (IAC)
Angel Mato	Mechanical Engineer/ Task contributor	IAC

APPROVAL CONTROL FROM SUB-WP & WP LEAD

Control	Name	Organization	Function	Date
Prepared	Yoshinori Suematsu	NINS-NAOJ	Researcher	Feb 23rd, 2020
Revised	Carlos Dominguez	IAC	Postdoc / Sub-WP leader	Feb 26th, 2020
Approved	Carlos Dominguez	IAC	Postdoc / Sub-WP leader	Feb 26th, 2020
Approved	Manuel Collados	IAC	WP6 leader	Feb 27th, 2020

APPROVAL CONTROL FROM PROJECT OFFICE

Control	Name	Organization	Function	Date
Approved	Tirtha Som	Leibniz-Institute for Solar Physics (KIS)	Project Manager	Feb 27th, 2020
Approved	Rolf Schlichenmaier	KIS	Project Coordinator	Feb 27th, 2020
Authorized	Markus Roth	KIS	Project Scientist	Feb 27th, 2020

HISTORY OF DOCUMENT CHANGES

Issue	Date	Change Description
Version 1.0	Feb 26th, 2020	Initial Issue
Version 2.0	March 6th, 2020	2nd Issue

Table of Contents

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

List of Abbreviations

GRIS	GREGOR Infrared Spectrograph
IFU	Integral Field Unit
IAC	Instituto de Astrofísica de Canarias
NAOJ	National Astronomical Observatory of Japan
NINS	National Institutes of Natural Sciences
PV	Peak-to-valley

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

“This project has received funding from the European Union’s Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)”

Introduction

The ability of manufacturing thin metallic mirror slicers is evaluated during the manufacturing of the metallic image slicer described in RD1. The manufacturing is done ahead the milestone date thanks to the collaboration with Canon Inc. (RD2) and a grant obtained for the fabrication of the slicer unit. Image slicers whose width is less than 100 µm are presently limited, either by their risk in the case of classical polishing techniques or by their optical performances when constituted by metallic mirrors. In this report, we demonstrate an ability of manufacturing thin metallic mirror slicers as narrow as 35 µm and of high optical performances. The following sections describes the applicable design, done in collaboration with IAC, the manufacturing methods and the measurements summary to the metallic mirror slicers.

Design and Specification of Thin Image Slicer for IFU of GRIS

The optical design of the IFU with an image slicer employing only reflective optics was made (RD1) for GRIS (GREGOR Infrared Spectrograph; RD3) at GREGOR. A diffraction-limited resolution of GREGOR at the wavelength 1.56 µm is 0.26 arcsec and the solar image formed on the slit plane with image scale of 0.13 arcsec per 35 µm. Then as a guideline, we tried to design the IFU in which a slicing mirror is 35 µm wide and a collimator and camera mirror refocus the slicer without changing the image scale. As a result, we come to a stack of 16 narrow slicers of 35 µm wide and 1.176 mm long; each 8 set of slicers is re-focused as two set of pseudo-slits (Figure 1). Each flat mirror slicer is set at a different angle so that the diverging beam from each slicer exits in two columns of collimator mirror array. Each beam is then reflected to a corresponding camera mirror and a following folding mirror. The overall effect is to rearrange the rectangular field of 2.1 x 4.4 arcsec^2 into two sets of a long thin field made up of all the slices arranged end to end, which forms two entrance slits of the spectrograph. Note that the collimator and camera mirrors are oversized in the direction of diffraction to pick up a main lobe of diffracted beam in the longest observation wavelength of 1.56 µm, reducing amount of the light vignetted by the collimator and camera mirrors. The specification of the thin metallic mirror slicers are given in Table 1.

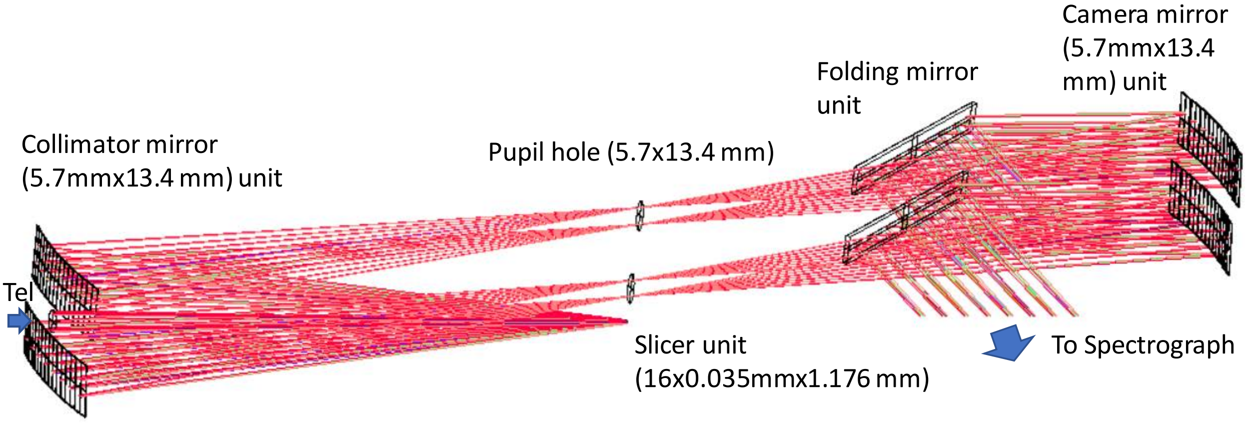

Figure 1. Optical design of IFU for the GRIS of GREGOR

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

Table 1. Specification of micro imaging slicer mirror.

	Slicer Unit
Substrate	Zero-invar IC-ZX (SHINHOKOKU Steel CO.) CTE=0.05 ppm
Array	10x2 (outer 4 slicers are for an alignment)
Slicer surface figure	Flat
One slicer size (mm)	0.035x1.4 (clear length is a central 1.176 mm)
Tilt in θ_y in the order of slicer no. =10, 9, .. -9, -10	6.3261, 5.1096, 3.8931, 2.7766, 1.6643, 0.5545, -0.5545, -1.6643, -2.7767, -3.8933, -3.8933, -2.7767, -1.6643, -0.5545, 0.5545, 1.6643, 2.7766, 3.8931, 5.1096, 6.3261
Tilt in θ_x in the order of slicer no. =10, 9, .. -9, -10	1.8600, 1.8622, 1.8652, 1.8698, 1.8751, 1.8811, 1.8878, 1.8953, 1.9034, 1.9123, -1.923, -1.9034, -1.8953, -1.8878, -1.8811, -1.8751, -1.8698, -1.8652, -1.8622, -1.8600
Accuracy of width	±1 µm
Edge sharpness	≦1 µm
Flatness	≦20 nm PV (y-direction), ≦55 nm PV (x-direction)
Tilt accuracy	≦ ±0.01°
Micro-roughness	≦1.3 nm RMS

Manufacturing method of thin metallic slicer mirrors

Figure 2 shows the model of the slicer mirrors. The slicer mirrors consist of two units, each unit consists of 10 flat mirrors; outer 2 mirrors are for an alignment purpose and not used for spectroscopy. There are total of 20 mirrors. Each mirror is 1.4 mm in length and 35 µm in width, and together the slicer mirrors are 1.4 mm in length and 0.7 mm in width. Each mirror has a tilt as specified in Table 1. We selected an ultra-low expansion metal (Zero-invar IC-ZX of SHINHOKOKU Steel CO.) as a substrate of the slicer mirror unit.

The slicer mirrors were manufactured using a high precision free form cutting machine developed by Canon Inc. (RD2). A rectangular diamond tool whose width is 35 µm 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 35 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, we applied ultra-precision cutting process technology. The 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). It is fixed on a highly rigid frame with air mount to suppress vibrations and has a high quality control system which

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

enables positioning resolutions of control axes which is less than 1 nm. It uses ultra-precision cutting technology, which controls and optimizes the cutting conditions such as feed speed, cutting depth, rake angle, etc. and other conditions such as cutting force and operation temperature.

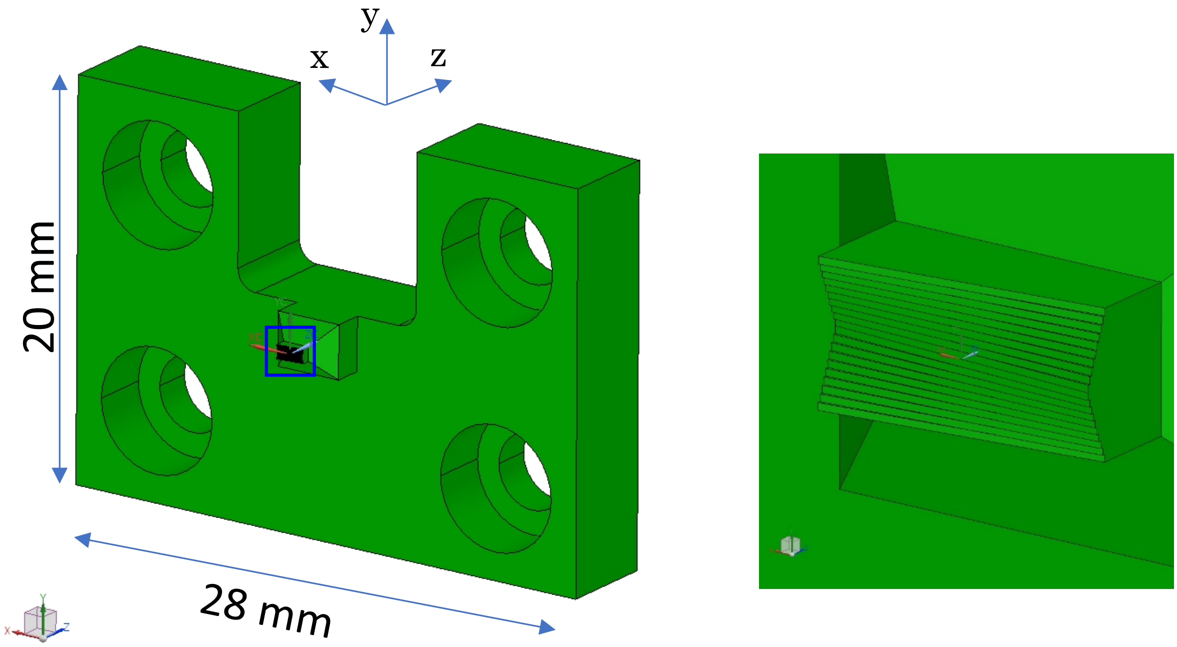

Figure 2. CAD Model of the micro slicer mirrors

Manufacturing Results

Figure 3 shows the picture and the scanning electron microscope (SEM) images (X100) of the slicer mirrors as manufactured, showing a flip grating shape as designed. Evaluations of the edge quality, tilt error, surface figure error (flatness) and surface roughness are given in the following.

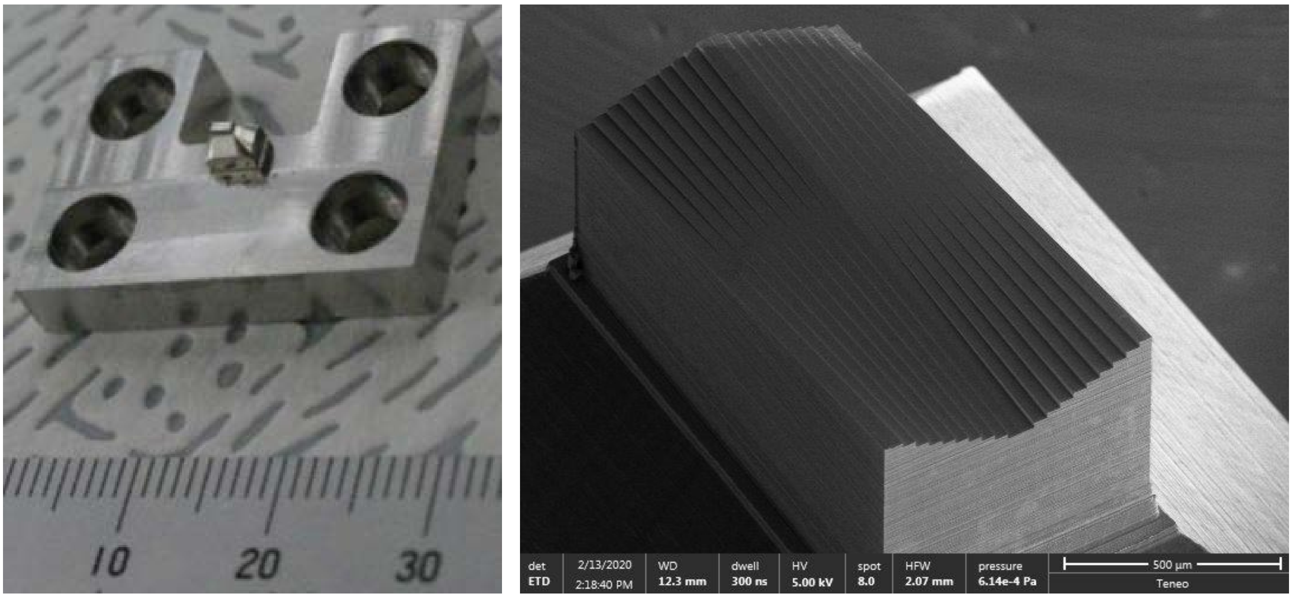

Figure 3. Picture and the scanning electron microscope (SEM) images (X100) of the micro slicer mirrors

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

Edge quality

Figure 4 shows the SEM image (X2000) of an edge quality of the micro slicer mirrors. The edge quality is less than 0.1 µm. A contour of sharp diamond tool makes a sharp edge by cutting.

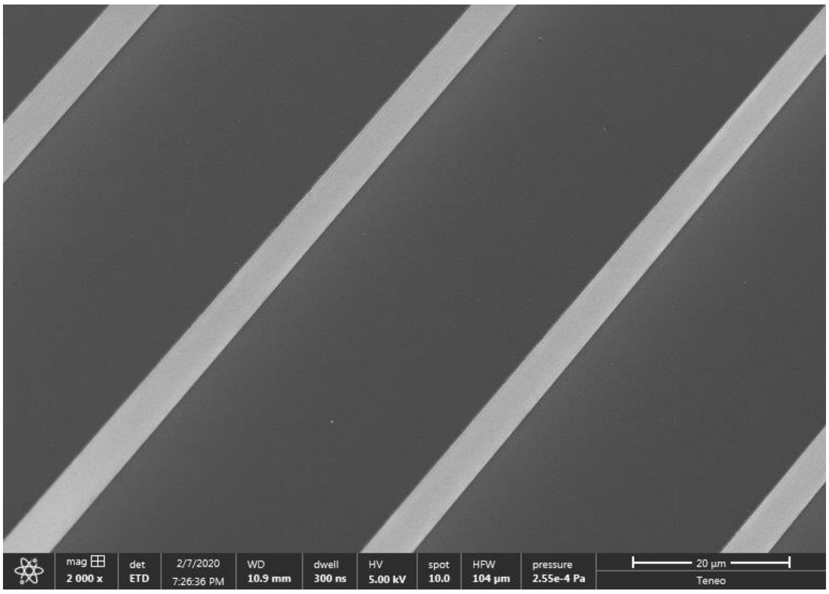

Figure 4. SEM image (X2000) of an edge quality of the micro slicer mirrors

Tilt error

Tilts of each mirror's surface were measured using profiles by Zygo NewView 3D Optical Surface Profiler. Tilt errors were calculated by subtracting tilts between two consecutive mirrors from the designed values. We confirmed that tilt errors are as small as 0.003 degrees. The width of this micro slicer mirrors is 35 µm, it is too small to be constructed from separated mirrors and reduce tilt errors. However, cutting does not require tilt alignment because cutting can make monolithic module and cutting is able to satisfy strict requirement (smaller than 0.01 degrees) of tilt error.

Flatness

Figure 5 shows the flatness in the x-direction of one of the micro slicer mirrors in 0.02 mm x 1 mm measured by Zygo NewView 3D Optical Surface Profiler. The surface flatness is 21 nm PV. The flatness of the surface is ranging from 20 nm PV to 37 nm PV and has achieved the requirement of less than 55 nm PV. It should be noted that the flatness in the y-direction is typically 8 nm PV and is much smaller than the requirement of 20 nm PV.

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

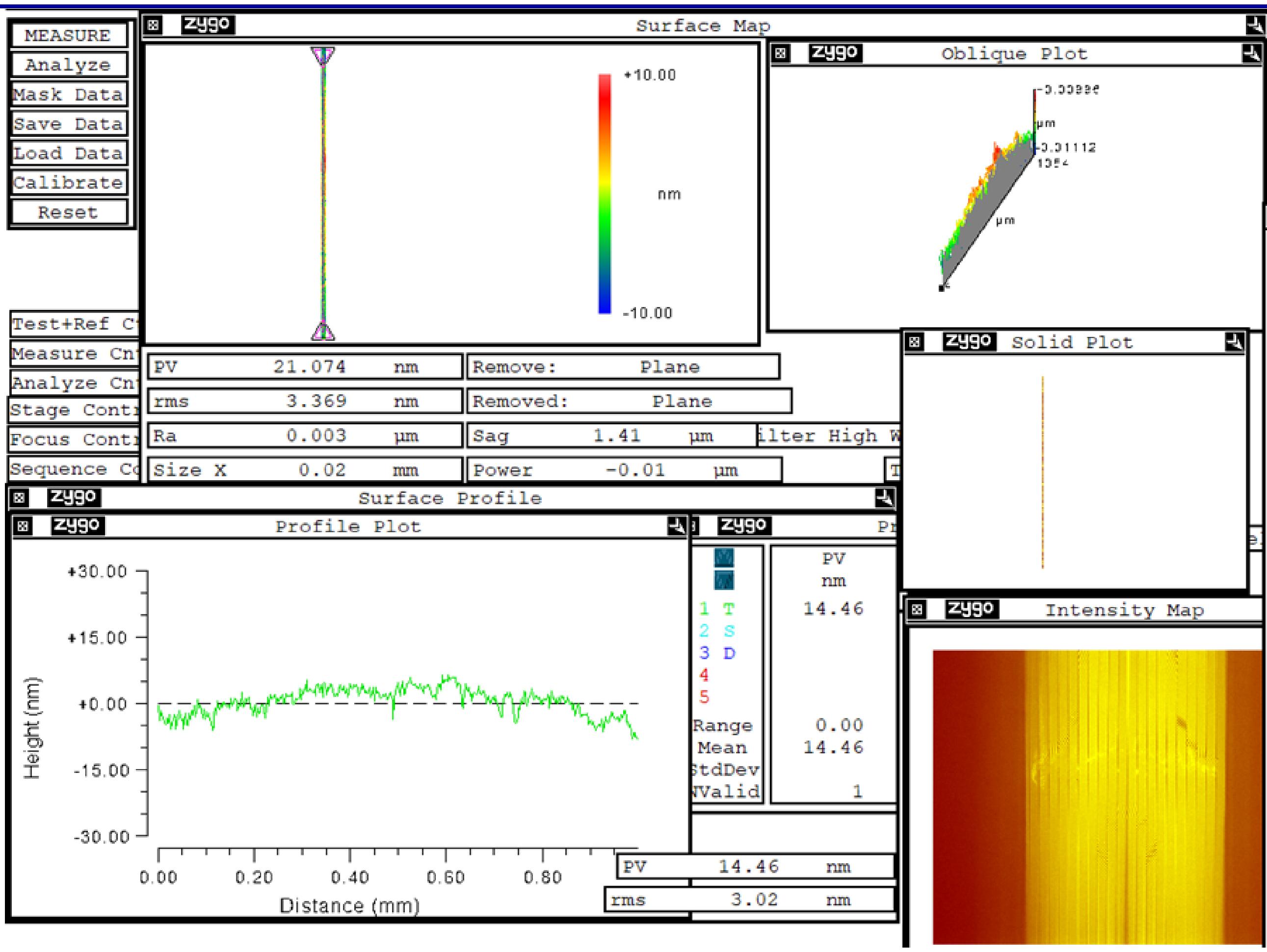

Figure 5. The flatness of micro slicer in the y-direction.

Surface roughness

Figure 6 shows the surface roughness of one of the micro slicer mirrors in 0.02 mm x 0.02 mm measured by Zygo NewView 3D Optical Surface Profiler. The surface roughness is 0.798 nm rms. The average of the surface roughness of 9 surfaces is 0.818 nm RMS and has achieved the requirement of less than 1.3 nm RMS. We confirmed that the cutting can obtain low surface roughness equivalent to polishing.

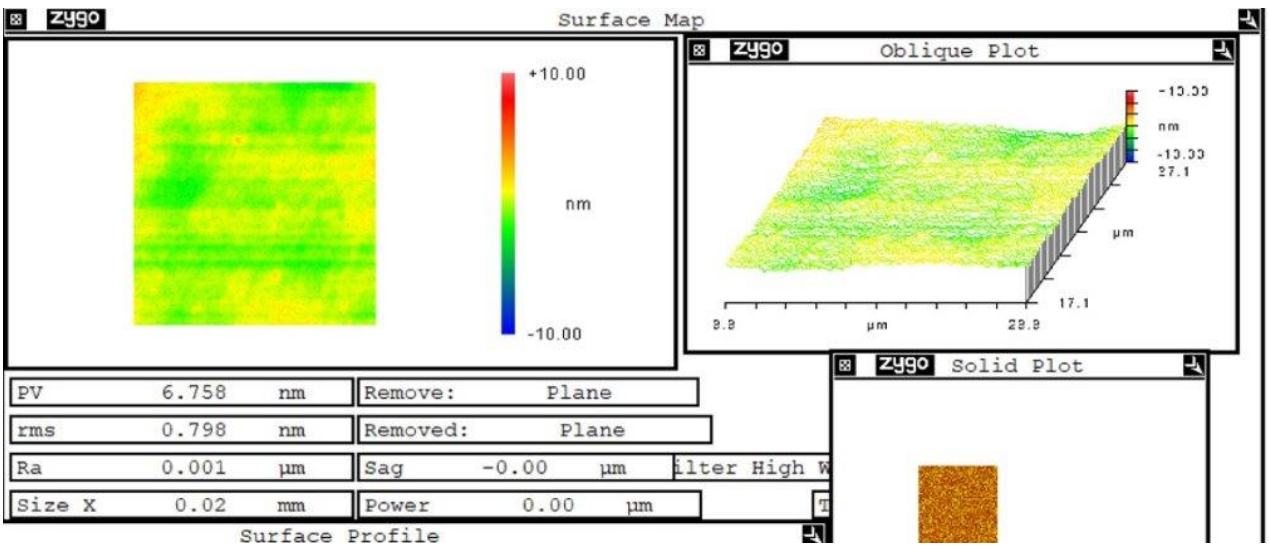

Figure 6. Surface micro-roughness of the slicer mirror measured by Zygo NewView

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

Summary

We have presented the ability of manufacturing thin metallic mirror slicers for the IFU of GRIS, which consists of 20 flat mirrors of 35-micron-width. We demonstrated the high optical quality of thin metallic mirror slicers such as edge sharpness less than 0.1 µm, slicer tilt errors less than 0.01 degrees, surface figure error less than 40 nm PV, and the surface micro-roughness less than 1 nm rms. The metallic mirror slicers are being deposited by a space-qualified, protected silver coating, which does not degrade the surface quality of slicers (RD2).

References

RD1	SOLARNET-H2020 Deliverable 6.1 Image slicer design
RD2	Suematsu, Y.; Saito, K.; Koyama, M.; et al., "Development of micro-mirror slicer integral field unit for space-borne solar spectrographs", 2017, CEAS Space Journal 9, 421-431
RD3	Collados, M., López, R., Páez, Hernández, E., Reyes, M., Calcines, A., Ballesteros, E.,Díaz, J. J., Denker, C., Lagg, A., Schlichenmaier, R., Schmidt, W., Solanki, S. K., Straameier, K. G., von der Lühe, O., Volkmer, R., "GRIS: The GREGOR Infrared Spectrograph", Astronomische Nachrichten, Vol. 333, Issue 9, p.872 (2012).

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de