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The University of Tokyo Atacama Observatory 6.5m telescope : On-sky performance of the near-infrared instrument SWIMS on the Subaru telescope

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ABSTRACT

The Simultaneous-color Wide-field Infrared Multi-object Spectrograph (SWIMS) is one of the 1st generation facility instruments for the University of Tokyo Atacama Observatory (TAO) 6.5 m telescope currently being constructed at the summit of Cerro Chajnantor (5,640 m altitude) in northern Chile. SWIMS has two optical arms, the *blue* arm covering 0.9–1.4 μm and the *red* 1.4–2.5 μm, by inserting a dichroic mirror into the collimated

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beam, and thus is capable of taking images in two filter-bands simultaneously in imaging mode, or whole near-infrared (0.9–2.5 μm) low-to-medium resolution multi-object spectra in spectroscopy (MOS) mode, both with a single exposure. SWIMS was carried into Subaru Telescope in 2017 for performance evaluation prior to completion of the construction of the 6.5 m telescope, and successfully saw the imaging first light in May 2018 and MOS first light in Jan 2019. After three engineering runs including the first light observations, SWIMS has been accepted as a new PI instrument for Subaru Telescope from the semester S21A until S22B. In this paper, we report on details of on-sky performance of the instrument evaluated during the engineering observations for a total of 7.5 nights.

Keywords: near infrared, multi-object spectroscopy, wide-field imager, integral field unit, TAO

1. INTRODUCTION

The University of Tokyo Atacama Observatory (TAO) project (PI: Yuzuru Yoshii), promoted by Institute of Astronomy, the University of Tokyo, is currently constructing a 6.5 m infrared-optimized telescope at the world highest site (altitude of 5640 m above sea level) on Cerro Chajnantor in the Atacama desert in northern Chile.[1–6] Thanks to the extremely high altitude of the site with dry climate, very low precipitable water vapor (PWV) less than 1mm can be easily achieved.[7–12] As a result, it provides us an almost continuous atmospheric window in the near-infrared (NIR) wavelength of 0.9–2.5 μm which even enables ground-based observations of the hydrogen Paschen-α line at 1.8751 μm originated from Galactic objects and nearby galaxies in the local Universe.[13,14]

In order to efficiently utilize the continuous NIR window, Simultaneous-color Wide-field Infrared Multi-object Spectrograph (SWIMS, PI: Kentaro Motohara)[15–19] has been developed as one of the first-generation facility instruments for the 6.5 m telescope. The instrument covers the whole NIR wavelength of 0.9–2.5 μm with two optical arms (a *blue* arm: 0.9–1.4 μm and *red*: 1.4–2.5 μm) and is capable of two-color simultaneous imaging or $\lambda/\Delta\lambda \sim 1000$ multi-object spectroscopy (MOS) at 0.9–2.5 μm wavelength range, both with a single exposure. As a module that can be handled by a MOS mask exchanger unit, an image-slicer integral-field spectroscopy unit (IFU) is under development.[20–23] Detailed information on the current status of the IFU module is reported elsewhere in this conference.[24] The instrument was carried into Subaru Telescope at Maunakea, Hawaii in 2017 for evaluating and optimizing its observing performance prior to the completion of the construction of the 6.5 m telescope, and successfully saw the imaging first light in May 2018 and the MOS first light in Jan 2019 on the Subaru Telescope.

In this paper, we present updates on the status of the instrument in Section 2 and report on the on-sky performance evaluated during the engineering observations on the Subaru Telescope conducted between 2018 and 2020 in Section 3.

2. UPDATES ON THE INSTRUMENT

SWIMS has two 2048 × 2048 pixels HAWAII-2RG (H2RG) focal-plane arrays manufactured by Teledyne Imaging Sensors for each arm. Heavily degraded science-grade arrays in the *blue* arm were replaced with 1.7 μm cut-off engineering-grade arrays in 2017, which give better cosmetics but lower quantum efficiency. To operate with better performance in open-use programs on the Subaru Telescope, we replaced one of those engineering-grade arrays (#17086) which has a large defect with a science-grade array (#16321) in Mar 2020. Figure 1 shows a dark current map of the new array obtained with 1000s integration time using *Up-the-Ramp* readout mode*. We see a large defect region similar to that seen on #17086. An observer may avoid overlap of spectra with the defect by placing slits to the left on a MOS slit mask. In addition, there is a hot-pixel region where the dark current reaches up to ~ 0.3 e$^-$ s^{-1} pixel^{-1} that is higher than the requirement for background-limited (narrow-band imaging and spectroscopic) observation (0.21 e$^-$ s^{-1} pixel^{-1}). That results in 0.17 e$^-$ s^{-1} pixel^{-1} at 95th percentile while most (90th percentile) of the pixels have lower ($<$ 0.1 e$^-$ s^{-1} pixel^{-1}). A deep spectroscopic observation is needed to further investigate its impact on sensitivity to faint signals. Table 1 summarizes performances of all the four arrays evaluated on the telescope.

* *Up-the-Ramp* mode is not supported in open-use observations on Subaru Telescope since an on-site (on-instrument) calculation of the count rate (ADU s^{-1}) per pixel is difficult due to limited on-instrument machine resource and therefore any final science image to be archived is not produced.

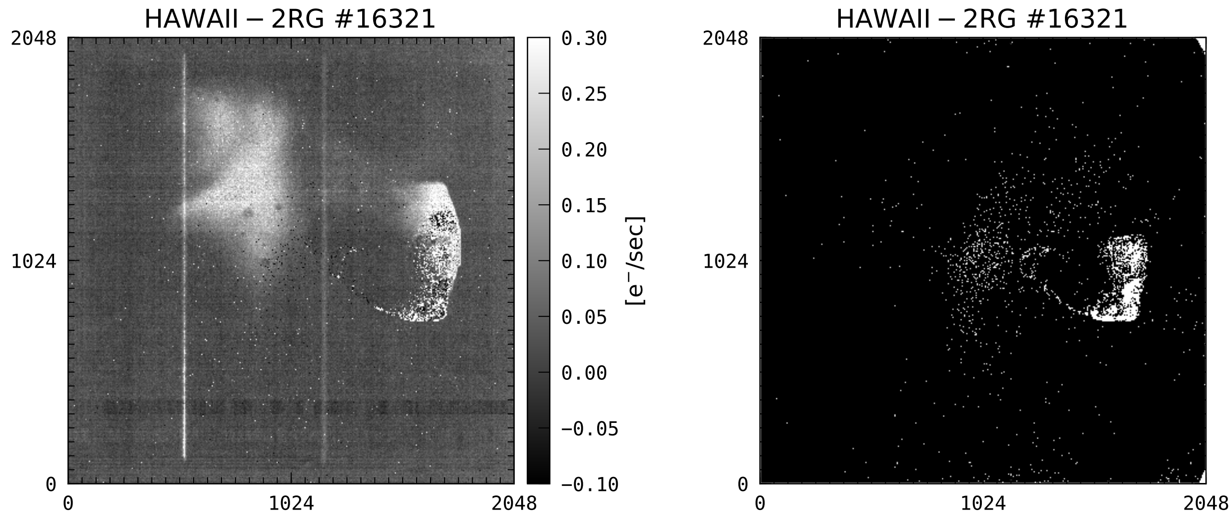

Figure 1. Dark current characteristics of the new science-grade array #16321 installed in the *blue* arm. *Left*: a dark current map evaluated with $\sim$ 1000s integration at 88K. There is a high dark-current (~ 0.3 e$^-$ s^{-1} pixel^{-1}) region around the top-left quadrant and a bad-pixel cluster at middle-right area, as identified in the *right* panel which is a bad-pixel map where bad pixels are marked in white.

Table 1. Detector performances evaluated on the Subaru Telescope.

	Blue arm		*Red* arm	
	Left (b2)	Right (b1)	Left (r1)	Right (r2)
Array SN	#17285[a]	#16321	#196	#206
Dark current (e$^-$ s^{-1} pixel^{-1})	< 0.11	< 0.17	< 0.03	< 0.06
Readout Noise (NDR[b]=1) (e$^-$ rms)	~ 22	~ 18	~ 20	~ 20
Readout Noise (NDR[b]=32) (e$^-$ rms)	~ 7	~ 4	~ 4	~ 5
Operating temperature (K)	90	90	80	80

[a] an engineering-grade array with a cut-off wavelength of 1.7 μm.

[b] Non-Destructive Readout. A sampling with NDR=1 is also called as Correlated Double Sampling (CDS) which is the default configuration of the SWIMS array control system.

During the run #3, we have optimized performance of the array #17285 as well as #16321, resulting in increase of the gain (and the throughput). We take it into account in the following sections when showing data of the array #17285 obtained before the run #3.

3. ENGINEERING OBSERVATIONS ON THE SUBARU TELESCOPE

In this section, we report on the on-sky instrument performance evaluated on the Cassegrain focus of the Subaru Telescope during the three engineering runs. Table 2 overviews the observation schedule and major engineering items.

3.1 Imaging performance

Figure 2 shows dome flat images in the J- and H-band to roughly show the cosmetics of the arrays. The right-side array of the *blue* arm (the top-right panel of the figure) is the new array #16321. For the both arms, left corners of the left arrays and right corners of the right arrays are slightly vignetted by the collimator optics of the instrument which corresponds to the edge of the FoV of $\phi 7\rlap{.}'2$.

Image qualities of all the filters are evaluated using a photometric standard star FS12 and surrounding point sources within the FoV. The average full width at half maximum (FWHM) of the sources shows no significant

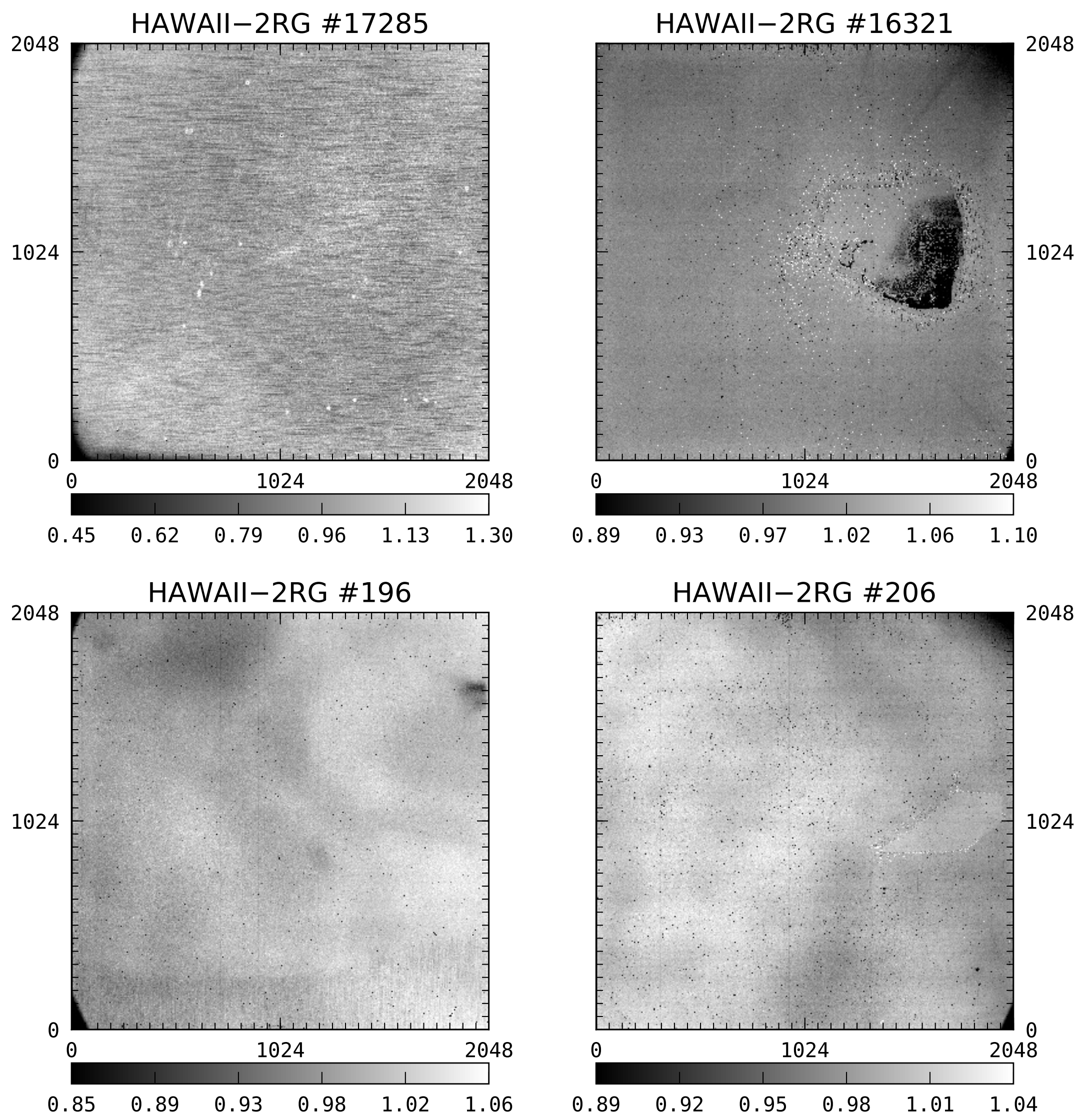

Figure 2. Dome flat images in the J-band (*top-left*: #17285 and *top-right*: #16321) and in the H-band (*bottom-left*: #196 and *bottom-right*: #206) obtained in the engineering run #3. Left corners of the *left* images and right corners of the *right* images are vignetted by the collimator optics of the instrument, as designed.

Table 2. Summary of the engineering runs on Subaru Telescope.

#	Observing date	Weather condition	Major engineering items
1	May 29[b], 2018	Clouded out	Software tests
	May 30[b]	Clear to cloudy	*Imaging first light*, basic functional tests, efficiency check of narrow-band filters
	May 31[c]	Thick cirrus	deep (∼ 2 hr) imaging
	June 1[c]	Heavy cloud	*Long-slit spectroscopy first light*
2	Jan 22[a], 2019	Clear	Efficiency measurement of all filters
	Jan 23[a]	Clear to cloudy	Software test for Multi-object spectroscopy
	Jan 24[c]	Clear	*Multi-object spectroscopy first light*, medium-band deep (∼ 2 hr) imaging
	Jan 26[c]	Thick cirrus	Multi-object spectroscopy, medium-band deep (∼ 2 hr) imaging
–	May 6[b] and 7[b], 2020	–	(Cancelled due to COVID-19 pandemic)
3	Oct 3[a], 2020	Partially cirrus	Performance evaluation of a new detector array, long-slit spectroscopy
	Oct 4[a]	Partially cirrus	Performance evaluation of the new array, multi-object spectroscopy

[a] Allocation of first-half nights.
[b] Allocation of second-half nights.
[c] Allocation of full nights.

variation between filters (∼ 5.0–6.5 pixels) except for two narrow-band filters in the *red* arm (NB1875 and NB1945) which have relatively larger FWHMs (> 10 pixels) due to off-focus. The cause of the focus shift is not clear at the moment but one possibility is that surfaces of those filters are not parallel, and that either surface might have a slight power (under cryogenic environment). The image quality of those filters can be improved by adjusting the telescope focus, but in that case, simultaneous two-color imaging would be difficult since no focus adjustment mechanism between two arms is equipped and therefore the *blue* arm gets significantly defocused instead.

Astrometry is performed using images of an open cluster Kronberger 60 to evaluate pixel scale and image distortion for the individual arrays. We adopt Pan-STARRS[25] (PS1) DR2 catalog coordinates for reference. By linearly fitting the PS1 coordinates with those measured on images obtained by SWIMS, we obtain the pixel scale of $\sim 0.''095$ pixel^{-1} and the fitting residuals of $0.''01$–$0.''02$ in both the *blue* and the *red* arms, as shown in Figure 3. Some fraction of the residual may come from the systematic uncertainty of the astrometry in the PS1 catalog ($\sim 0.''005$).[26] Note that no systematic distortion pattern is found over the full FoV in the both arms. As the result of astrometry, we obtain detector gaps and relative orientation between the detector arrays to be ∼ 133 pixels and 0.112 deg for the *blue* arm and ∼ 126 pixels and 0.028 deg for *red*, leading to a FoV including the detector gap of $\sim 6.'7 \times 3.'3$.

A total imaging throughput of all the filters is evaluated using photometric standard stars (FS12 in the run #2 and FS34 in #3) and surrounding point sources within the FoV. As reference magnitudes, we adopt the Two Micron All Sky Survey (2MASS)[27] point-source catalog magnitudes except for the Y-band for which the PS1 DR2 catalog magnitude is used. To account for difference in central wavelength of filters between the references and ours, we linearly interpolate magnitudes of a star at shorter and longer wavelengths and obtain a magnitude at a wavelength of interest. Figure 4 shows the throughputs including the telescope reflectivity and the atmospheric transmittance. No correction for airmass is taken into account at the moment due to poor statistics of data. Note that for the FS12 data of the *blue* arm, we only plot those taken with #17285 array, as the other array at that time (#17086) has been replaced with the science-grade array (#16321) after the run (Section 2). The array #17285 shows lower throughputs at shorter wavelengths which are partly due to low telescope reflectivity, as a report on the recoating campaign of the secondary mirror of the telescope shows

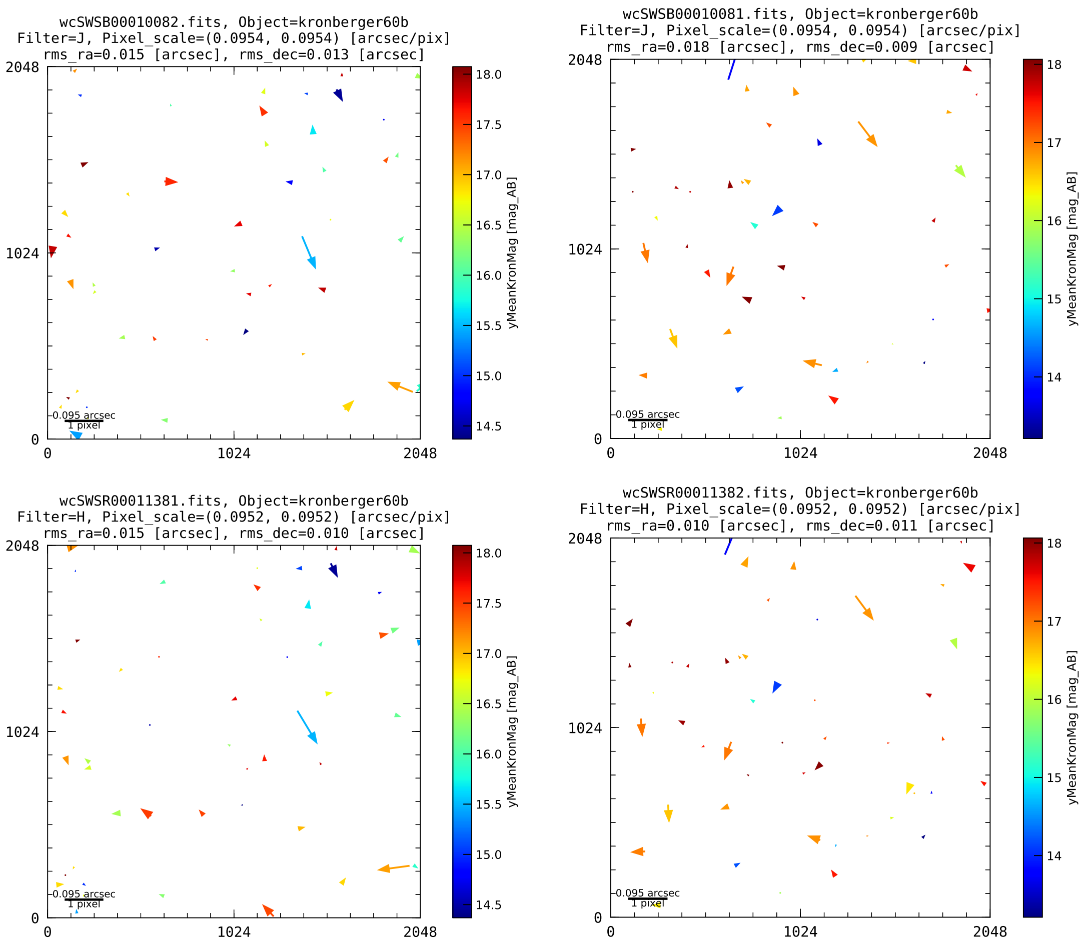

Figure 3. An example of the astrometric residual maps evaluated with a open cluster Kronberger 60 taken in the engineering run #2 (*top* for *blue* and *bottom* for *red* arm) after performing linear astrometry (i.e., xshift, yshift, xscale, yscale, and rotation) with Pan-STARRS DR2 catalog. The residual vectors are color-coded by catalog magnitude. Note that the *top-right* map (i.e., the right-side array in the *blue* arm) is taken with the array #17086 before the replacement with #16321.

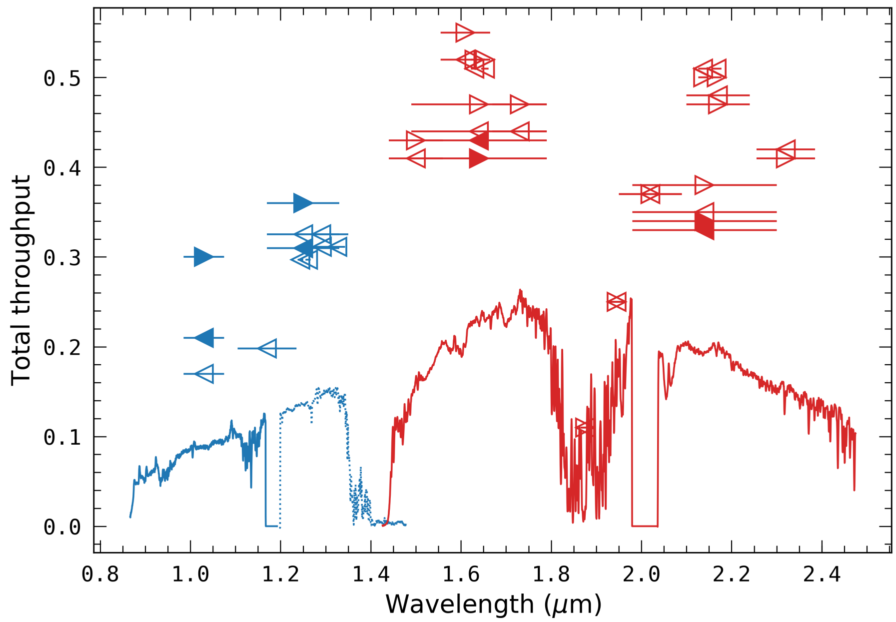

Figure 4. Total throughput of SWIMS as a function of wavelength evaluated using standard stars. The throughputs include the reflectivity of the telescope mirrors and the atmospheric transmittance. Triangles (left-pointing triangles for the left-side arrays while right-pointing for the right-side arrays) represent results for imaging data (open symbols for the FS12 field obtained in the run #2 and filled for FS34 in the run #3) while solid lines for spectroscopic data (HIP48106) obtained in the run #2. Error bars represent the width of the filters. For values obtained with the array #17285 both in the imaging and spectroscopic modes, we take into account the effect of the performance optimization. For the imaging result in the run #2 for the *blue* arm, only those on the left-side array (#17285) is shown since the right-side array (#17086) was replaced. The imaging result of the array #17285 in the run #2 and the spectroscopic result at shorter ($\lambda \lesssim 1.2$ μm) wavelengths are obtained before the recoating of the secondary mirror of the telescope, at which considerable improvement is expected. The *blue* spectrum longer than 1.2 μm is shown with dotted line to represent that it has been obtained with the array #17086 which was replaced with #16321 after taking data. Missing spectral data around wavelengths of $\sim$ 1.2 and 2.0 μm are due to the detector gaps.

Table 3. Predicted limiting magnitudes in imaging mode, assuming a point source, S/N=5, on-source integration time of 3600s, 1.″0 aperture, and 0.″5 seeing.

Filter	AB mag	Filter	AB mag
Y	25.2	H	24.2
J	24.9	K_s	24.4

improvements on the reflectivity by $\sim$ 22% at 0.9 μm and $\sim$ 3% at 1.3 μm between data obtained before (January 31, 2019) and after (November 27, 2019) the recoating (November 7, 2019)[†]. W refer to Reference 28 for details on a methodology for measuring and monitoring reflectivity of mirrors of the Subaru Telescope. Taking the improvement into account, we especially expect an improvement for the throughput at the Y-band up to $\sim$ 0.21. The other cause of the lower throughputs at shorter wavelengths would be insufficient thinning of CdTe substrate (as it is engineering-grade) that causes lower response at shorter wavelengths.

Finally, we calculate the limiting magnitudes using the throughputs and measured background brightness. Table 3 gives the predicted limiting magnitudes for the broad-band filters. We refer to a paper for an actual deep imaging performance, which uses long ($\sim$ 2 hr) integration data taken in the run #2.[29]

[†]https://www.naoj.org/Observing/Telescope/Parameters/Reflectivity/#irm2

Table 4. Predicted continuum (emission) sensitivities in spectroscopy mode, assuming a point source, S/N=5, on-source integration time of 3600s, slit width of 0.″4 and 0.″6 (0.″5) seeing.

Filter	Continuum AB mag	Emission line erg s^{-1} cm^{-2}	Filter	Continuum AB mag	Emission line erg s^{-1} cm^{-2}
Y	20.1	1×10^{-16}	H	20.5	6×10^{-17}
J	20.5	5×10^{-17}	K_s	20.4	6×10^{-17}

3.2 Spectroscopic performance

Here we evaluate the spectroscopic performance using data obtained during the run #2. As the latest example to show spectral extent, we show in Figure 5 MOS images taken in the run #3. A MOS mask contains several holes for alignment purposes and a number of slits for science targets. As mentioned in Section 2, some slits are placed to the left to avoid overlap of *blue* spectra with the defect. The both *blue* and *red* spectra have a lack of data due to the detector gap. The location (i.e., wavelength ranges) of the missing part depends on the position of a slit. An observer thus requires carefully designing a MOS mask pattern (i.e., choosing a slit position along spatial direction) so that spectral features of interest do not fall in the gap.

In the run #2, we have taken spectra of a spectroscopic standard star HIP48106 (spectral type of A3V) with a MOS mask with a slit width of 0.″4 to evaluate the spectroscopic performance. Performing wavelength calibration using a thorium-argon (ThAr) lamp and atmospheric OH airglow emission lines, we obtain spectral sampling of the resolution element to be ~ 2.40 Å pixel^{-1} (*blue*) and ~ 4.57 Å pixel^{-1} (*red*), which correspond to a spectral resolving power ($R \equiv \lambda/\Delta\lambda$) with a slit width of 0.″5 of about 810 (Y), 990 (J), 680 (H), and 890 (K_s). Comparing the wavelength-calibrated spectra of the standard star with stellar atmosphere models,[30] the spectroscopic throughput is evaluated to be $\sim$ 9%, (Y), 11% (J), 21%(H), and 15% (K_s). The whole throughput curves from 0.9 to 2.5 μm are shown with solid lines in Figure 4. As mentioned above, we correct those results obtained with the array #17285, as the performance optimization yields the increase in throughput (Section 2). Similar to the imaging throughputs reported in Section 3.1, lower throughputs at shorter wavelengths may be partly due to the low telescope reflectivity and the low response of the engineering-grade array (#17285). We have no results around wavelengths of $\sim$ 1.2 and 2.0 μm due to the detector gaps. To fill them, we need more spectra obtained with slits located at various positions along spatial direction.

Figure 6 shows the MOS target acquisition sequence using our interactive software which is a plugin of Ginga image viewer;[31,32] at first we take a target frame before inserting a MOS mask. To securely detect and measure coordinates of alignment stars later, we also take a sky frame which is slightly off-centered from the target coordinate. Then, after inserting the MOS mask on the focal plane, we take an image of the mask frame. Using these three frames, we measure detector coordinates of the stars and the alignment holes, and calculate a transformation matrix on Ginga to align the stars with the holes. The telescope pointing and rotation angle of the instrument are then adjusted with the matrix and a mask image is taken again to recalculate the matrix. This process is iterated until the transformation becomes sufficiently small. It is usually converged with two iterations down to pointing accuracy of $\sim$ 1 pixel ($\sim$ 0.″1) and rotation of $\sim$ 0.05 deg. The acquisition sequence including all the mechanical motions typically takes $\sim$ 15 min to complete.

To demonstrate the spectroscopic sensitivity, we show in Figure 7 spectra of a star-forming galaxy ($K_s \sim$ 14 ABmag) at redshift $z \sim 0.15$ observed with on-source exposure time of 2400s and slit width of 0.″4. Clearly, we obtain various emission lines and absorption lines with high signal-to-noise ratio (> 50) simultaneously from 0.9 to 2.5 μm. Similar to Figure 4, no spectral data exist around wavelengths of $\sim$ 1.2 and 2.0 μm due to the detector gap. Based on the analysis of the spectra of the galaxy, we summarize in Table 4 predicted continuum and emission-line sensitivities for a point source.

4. SUMMARY AND FUTURE SCHEDULE

We have presented the on-sky performance of SWIMS, which is the first-generation near-infrared imager and multi-object spectrograph for the TAO 6.5 m telescope being constructed at the summit of Cerro Chajnantor (an altitude of 5640 m) in northern Chile, evaluated during the engineering observations on Subaru Telescope.

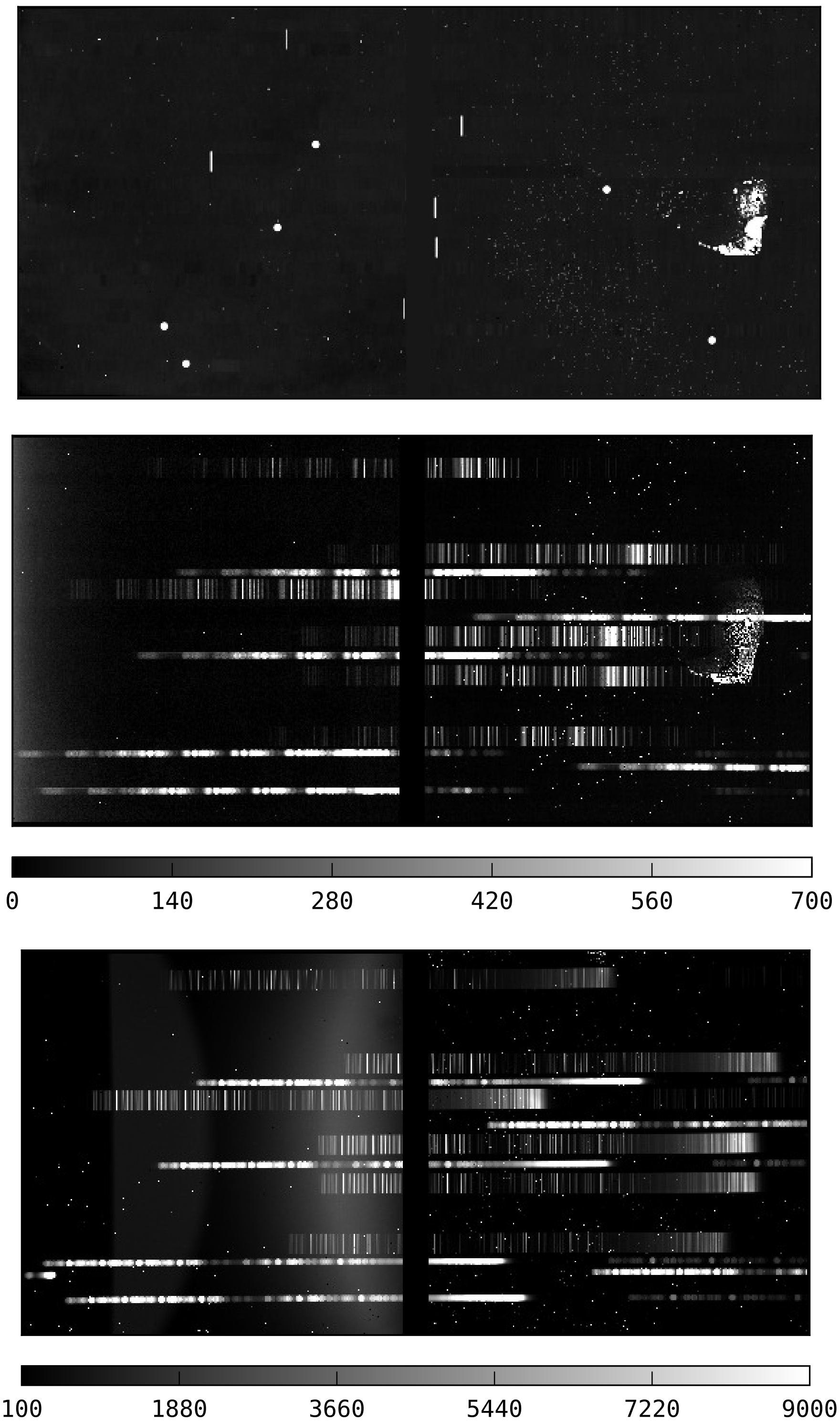

Figure 5. An example of a MOS mask image (*top*) and raw MOS 2D spectral images (*middle* for the *blue* arm and *bottom* for the *red*) taken with an exposure time of 300s each in the engineering run #3 . Arc-like diffuse patterns are seen in the left-side image of the *red* arm which are thought to be stray light contamination from a focal-plane structure equipped right above the field lens to hold a slit mask.

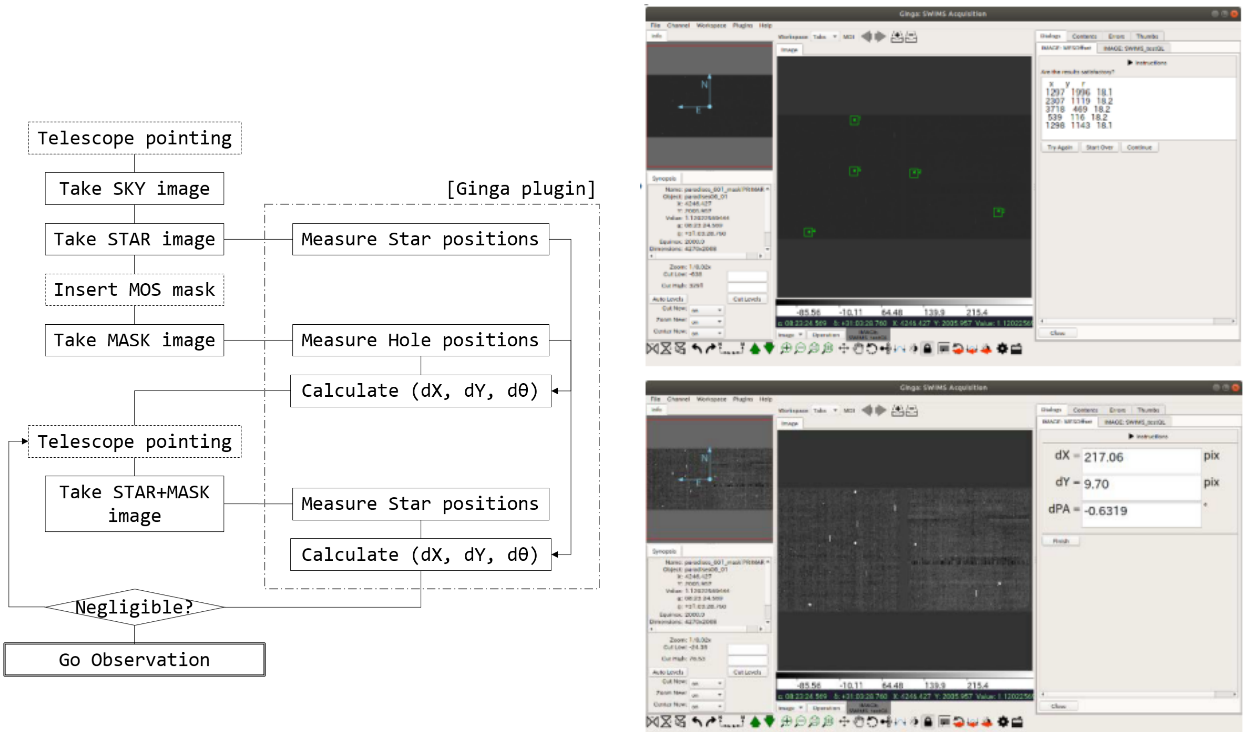

Figure 6. *Left*: A flow-chart of the target acquisition sequence in the multi-object spectroscopy mode. *Right*: Snapshots of the acquisition sequence. The acquisition software runs as a plugin on Ginga scientific image viewer. In the *upper* panel center coordinates of stars seen in acquisition holes are measured. In the *lower* panel, comparing coordinates of the stars with those of the holes, a linear transformation matrix (dX, dY, dθ) is calculated. The matrix is applied as a feedback to adjust the telescope pointing.

The instrument provides a field of view of $6'.7 \times 3'.3$ with a pixel scale of $0''.095$ pixel^{-1} and negligible image distortion ($\ll 1$ pixel). The measured image quality shows no significant variation between filters except for two narrow-band filters in the *red* arm which have poorer quality (FWHM $>$ 10 pixels) due to off-focus. Those filters can deliver better quality by adjusting the telescope focus, but in that case the *blue* arm will be blurred instead. The imaging throughputs including the telescope reflectivity and the atmospheric transmittance are measured to range from $\sim$ 15–35% with a peak at the J-band in the *blue* arm and $\sim$ 30–55% with a peak at the H-band in the *red* arm. For the spectroscopy mode, the spectral sampling of the resolution element is measured to be 2.40 and 4.57 Å pixel^{-1} for the *blue* and *red* arms, respectively, which corresponds to the spectral resolving power of R ($\equiv \lambda/\Delta\lambda$) $\sim$ 710–1150 (*blue*) and 600–1040 (*red*) with a slit width of $0''.5$. The spectroscopic throughputs show $\sim$ 10–20% on average with a peak at the H-band.

The instrument has been accepted as a new PI instrument for Subaru Telescope to be used for open-use programs on shared-risk basis from the semester S21A until S22B. It will be then transported to Chile and is planned to start science operation on the 6.5 m telescope in 2023.

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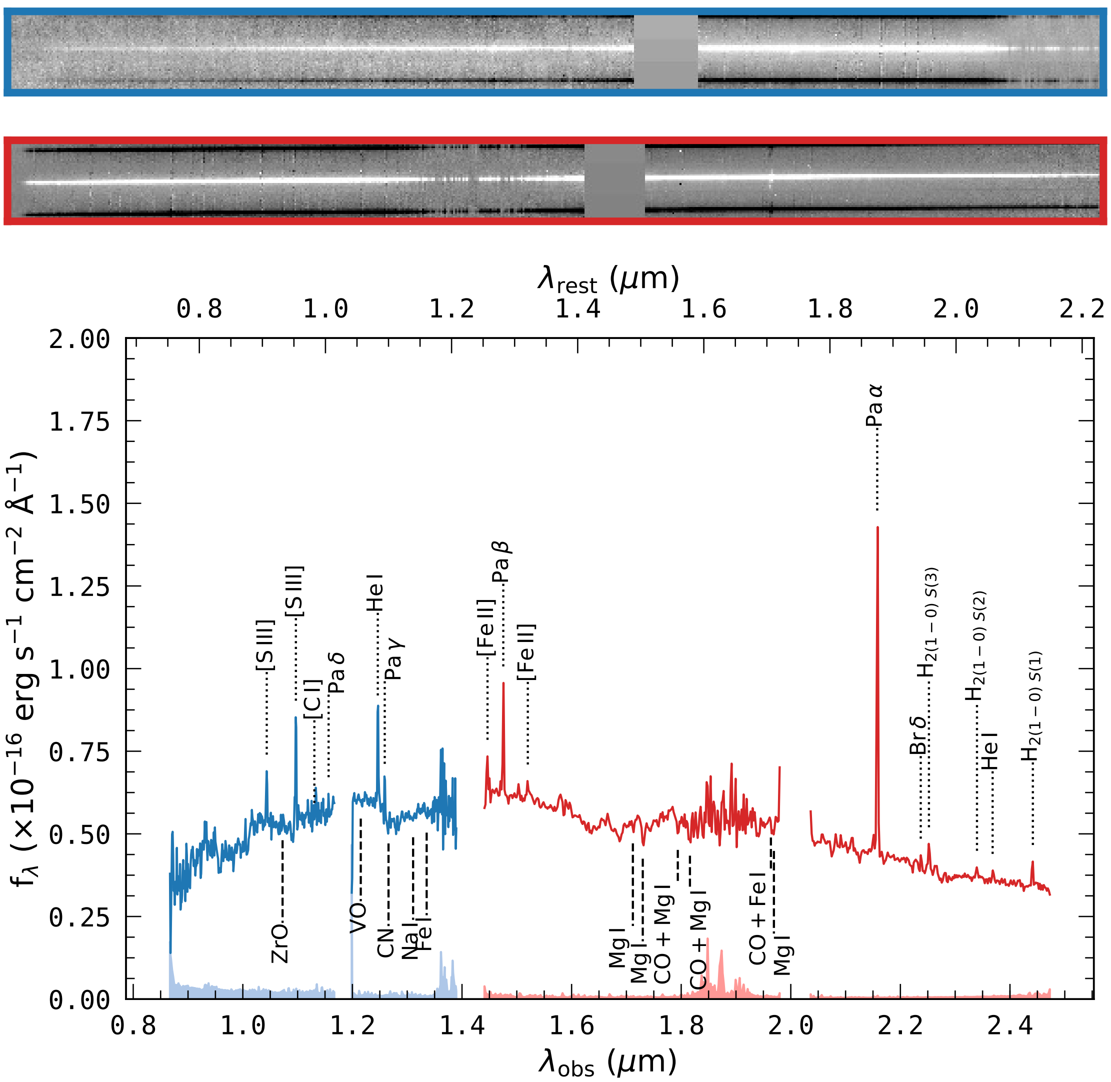

Figure 7. The full-extracted near-infrared spectrum of a star-forming galaxy ($K_s \sim 14$ ABmag) at $z \sim 0.15$ observed with on-source integration time of 2400s in the engineering run #2. *Top*: wavelength-calibrated 2D spectra using atmospheric OH airglow emission lines (*upper* for the *blue* spectrum while *lower* for *red*). In both spectra, a detector gap is seen at which no pixel data is obtained. *Bottom*: wavelength- and flux-calibrated 1D spectra. 4-pixel binning along the spectral direction is applied for visual clarity. Visually-identified line features are also denoted. At the bottom of the figure, the 1σ flux uncertainties are shown. The detector gap around 1.2 μm and 2.0 μm has no spectral data, as shown in the 2D spectra.

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REFERENCES

[1] Yoshii, Y., Doi, M., Miyata, T., Kohno, K., Tanaka, M., Minezaki, T., Sako, S., Morokuma, T., Tanabe, T., Hatsukade, B., Konishi, M., Kamizuka, T., Asano, K., Sameshima, H., Kato, N., Numata, M., Takahashi, H., Aoki, T., Soyano, T., Tarusawa, K., Yoshikawa, K., Motohara, K., Tamura, Y., Koshida, S., Handa, T., Bronfman, L., Ruiz, M., Hamuy, M., Mendez, R., and Escala, A., "The university of tokyo atacama observatory 6.5m telescope : Overview and construction status," in [*Ground-based and Airborne Telescopes VIII*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11445**, in this conference (2020).

[2] Doi, M., Miyata, T., Yoshii, Y., Kohno, K., Motohara, K., Kawara, K., Tanaka, M., Minezaki, T., Sako, S., Morokuma, T., Tamura, Y., Tanabe, T. Hatsukade, B., Takahashi, H., Konishi, M., Kamizuka, T., Kato, N., Aoki, T., Soyano, T., Tarusawa, K., Handa, T., Koshida, S., Bronfman, L., Ruiz, M. T., Hamuy, M., and Garay, G., "The University of Tokyo Atacama Observatory 6.5m telescope: project overview and current status," in [*Ground-based and Airborne Telescopes VII*], Marshall, H. K. and Spyromilio, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10700**, 107000W (July 2018).

[3] Yoshii, Y., Doi, M., Kohno, K., Miyata, T., Motohara, K., Kawara, K., Tanaka, M., Minezaki, T., Sako, S., Morokuma, T., Tamura, Y., Tanabe, T., Takahashi, H., Konishi, M., Kamizuka, T., Kato, N., Aoki, T., Soyano, T., Tarusawa, K., Handa, T., Koshida, S., Bronfman, L., Ruiz, M. T., Hamuy, M., and Garay, G., "The University of Tokyo Atacama Observatory 6.5m telescope: project overview and current status," in [*Ground-based and Airborne Telescopes VI*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9906**, 99060R (July 2016).

[4] Yoshii, Y., Doi, M., Kohno, K., Miyata, T., Motohara, K., Kawara, K., Tanaka, M., Minezaki, T., Sako, S., Morokuma, T., Tamura, Y., Tanabe, T., Takahashi, H., Konishi, M., Kamizuka, T., Koshida, S., Kato, N., Aoki, T., Soyano, T., Tarusawa, K., Handa, T., Bronfman, L., Ruiz, M. T., Hamuy, M., and Mendez, R., "Overview of University of Tokyo Atacama Observatory 6.5m telescope project," in [*Ground-based and Airborne Telescopes V*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9145**, 914507 (July 2014).

[5] Yoshii, Y., Aoki, T., Doi, M., Handa, T., Kawara, K., Kato, D., Kohno, K., Konishi, M., Koshida, S., Minezaki, T., Mitani, N., Miyata, T., Motohara, K., Sako, S., Soyano, T., Tanabe, T., Tanaka, M., Tarusawa, K., Bronfman, L., Ruiz, M. T., and Hamuy, M., "The University of Tokyo Atacama Observatory 6.5m telescope project," in [*Ground-based and Airborne Telescopes III*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7733**, 773308 (July 2010).

[6] Yoshii, Y., Doi, M., Handa, T., Kawara, K., Kohno, K., Minezaki, T., Mitsuda, K., Miyata, T., Motohara, K., and Tanaka, M., "Tokyo Atacama Observatory Project," in [*8th Asian-Pacific Regional Meeting, Volume II*], Ikeuchi, S., Hearnshaw, J., and Hanawa, T., eds., 35–36 (Jan. 2002).

[7] Erasmus, D. A. and Peterson, R., "The Feasibility of Forecasting Cirrus Cloud Cover and Water Vapor Above Telescope Sites in Northern Chile," *Publications of the Astronomical Society of the Pacific* **109**, 208–214 (Feb. 1997).

[8] Erasmus, D. A. and van Staden, C. A., [*A Satellite Survey of Cloud Cover and Water Vapor in Northern Chile*], A study conducted for Cerro Tololo Inter-American Observatory and University of Tokyo (2001).

[9] Erasmus, D. A. and Sarazin, M. S., "Forecasting precipitable water vapor and cirrus cloud cover for astronomical observatories: satellite image processing guided by synoptic model dissemination data," in [*Remote Sensing of Clouds and the Atmosphere V*], Russell, J. E., Schaefer, K., and Lado-Bordowsky, O., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4168**, 317–328 (Jan. 2001).

[10] Konishi, M., Motohara, K., Tateuchi, K., Takahashi, H., Kitagawa, Y., Kato, N., Sako, S., Uchimoto, Y. K., Toshikawa, K., Ohsawa, R., Yamamuro, T., Asano, K., Ita, Y., Kamizuka, T., Komugi, S., Koshida, S., Manabe, S., Matsunaga, N., Minezaki, T., Morokuma, T., Nakashima, A., Takagi, T., Tanabé, T., Uchiyama, M., Aoki, T., Doi, M., Handa, T., Kato, D., Kawara, K., Kohno, K., Miyata, T., Nakamura, T., Okada, K., Soyano, T., Tamura, Y., Tanaka, M., Tarusawa, K., and Yoshii, Y., "ANIR: Atacama near-infrared camera for the 1.0 m miniTAO telescope," *Publications of the Astronomical Society of Japan* **67**, 4 (Feb. 2015).

[11] Miyata, T., Motohara, K., Sako, S., Tanaka, M., Minezaki, T., Aoki, T., Soyano, T., Tanabe, T., Kawara, K., Kohno, K., Tarusawa, K., Handa, T., Doi, M., Yoshii, Y., Ezawa, H., Bronfman, L., and Ruiz, M. T., "Site evaluations of the summit of Co. Chajnantor for infrared observations," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7012**, 701243–701243–8 (2008).

[12] Motohara, K., Aoki, T., Sako, S., Soyano, T., Doi, M., Tanaka, M., Tanabe, T., Handa, T., Mitani, N., Minezaki, T., Miyata, T., Kawara, K., Kohno, K., Tarusawa, K., Yoshii, Y., Bronfman, L., and Ruiz, M. T., "Seeing environment at a 5640m altitude of Co. Chajnantor in northern Chile," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7012**, 701244–701244–10 (2008).

[13] Motohara, K., Konishi, M., Toshikawa, K., Mitani, N., Sako, S., Uchimoto, Y. K., Yamamuro, T., Minezaki, T., Tanabe, T., Miyata, T., Koshida, S., Kato, D., Ohsawa, R., Nakamura, T., Asano, K., Yoshii, Y., Doi, M., Kohno, K., Tanaka, M., Kawara, K., Handa, T., Aoki, T., Soyano, T., Tarusawa, K., and Ita, Y., "First Paschen alpha imaging from the ground: the first light of Atacama Near-Infrared Camera on the miniTAO 1m telescope," in [*Ground-based and Airborne Instrumentation for Astronomy III*], McLean, I. S., Ramsay, S. K., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7735**, 77353K (July 2010).

[14] Tanabé, T., Motohara, K., Tateuchi, K., Matsunaga, N., Ita, Y., Toshikawa, K., Konishi, M., Kato, N., and Yoshii, Y., "Paschen α Observations of Be Stars Toward the SMC Cluster NGC 330," *Publications of the Astronomical Society of Japan* **65**, 55 (June 2013).

[15] Konishi, M., Motohara, K., Takahashi, H., Kato, N., Terao, Y., Ohashi, H., Kono, Y., Kushibiki, K., Kodama, T., Hayashi, M., Tanaka, I., Tadaki, K.-i., Toshikawa, J., Koyama, Y., Shimakawa, R., Suzuki, T., Tateuchi, K., Kitagawa, Y., Kobayakawa, Y., Todo, S., Aoki, T., Doi, M., Hatsukade, B., Kamizuka, T., Kohno, K., Minezaki, T., Miyata, T., Morokuma, T., Sako, S., Soyano, T., Tanabé, T., Tanaka, M., Tarusawa, K., Tamura, Y., Koshida, S., Ohsawa, R., Uchiyama, M., Mori, T., Yamaguchi, J., Yoshida, Y., and Yoshii, Y., "Development status of the simultaneous two-color near-infrared multi-object spectrograph SWIMS for the TAO 6.5m telescope," in [*Ground-based and Airborne Instrumentation for Astronomy VII*], Evans, C. J., Simard, L., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10702**, 1070226 (July 2018).

[16] Motohara, K., Konishi, M., Takahashi, H., Kato, N. M., Kitagawa, Y., Kobayakawa, Y., Terao, Y., Ohashi, H., Aoki, T., Doi, M., Kamizuka, T., Kohno, K., Minezaki, T., Miyata, T., Morokuma, T., Mori, K., Ohsawa, R., Okada, K., Sako, S., Soyano, T., Tamura, Y., Tanabe, T., Tanaka, M., Tarusawa, K., Uchiyama, M. S., Koshida, S., Asano, K., Tateuchi, K., Uchiyama, M., Todo, S., and Yoshii, Y., "NIR camera and spectrograph SWIMS for TAO 6.5m telescope: overview and development status," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9908**, 99083U (Aug. 2016).

[17] Motohara, K., Konishi, M., Takahashi, H., Tateuchi, K., Kitagawa, Y., Todo, S., Kato, N. M., Ohsawa, R., Aoki, T., Asano, K., Doi, M., Kamizuka, T., Kawara, K., Kohno, K., Koshida, S., Minezaki, T., Miyata, T., Morokuma, T., Okada, K., Sako, S., Soyano, T., Tamura, Y., Tanabe, T., Tanaka, M., Tarusawa, K., Uchiyama, M., and Yoshii, Y., "Development of a simultaneous two-color near-infrared multi-object spectrograph SWIMS for the TAO 6.5-m telescope," in [*Ground-based and Airborne Instrumentation for Astronomy V*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9147**, 91476K (July 2014).

[18] Konishi, M., Motohara, K., Takahashi, H., Tateuchi, K., Kitagawa, Y., Kato, N., Aoki, T., Doi, M., Handa, T., Kamizuka, T., Kawara, K., Kohno, K., Koshida, S., Minezaki, T., Miyata, T., Morokuma, T., Sako, S., Soyano, T., Tamura, Y., Tanabe, T., Tanaka, M., Tarusawa, K., and Yoshii, Y., "Design and development of SWIMS: a near-infrared multi-object spectrograph for the University of Tokyo Atacama Observatory," in [*Ground-based and Airborne Instrumentation for Astronomy IV*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446**, 84467P (Sept. 2012).

[19] Konishi, M., Motohara, K., Doi, M., Sako, S., Toshikawa, K., Mitani, N., Aoki, T., Handa, T., Ita, Y., Kato, D., Kawara, K., Kohno, K., Koshida, S., Minezaki, T., Miyata, T., Soyano, T., Tanabe, T., Tanaka, M., Tarusawa, K., and Yoshii, Y., "Design and status of a near-infrared multi-object spectrograph for the TAO 6.5-m Telescope," in [*Ground-based and Airborne Instrumentation for Astronomy III*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7735**, 77356T (July 2010).

[20] Kono, Y., Yamagata, Y., Morita, S.-y., Motohara, K., Ozaki, S., Tsuzuki, T., Takahashi, H., Kitagawa, Y., Konishi, M., Kato, N. M., Terao, Y., Ohashi, H., and Kushibiki, K., "Design of an integral field unit for SWIMS and its milling process fabrication with an ultra-high precision machine tool," in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III*], Navarro, R. and Geyl, R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10706**, 107063F (July 2018).

[21] Kitagawa, Y., Yamagata, Y., Morita, S.-y., Motohara, K., Ozaki, S., Takahashi, H., Konishi, M., Kato, N. M., Kobayakawa, Y., Terao, Y., and Ohashi, H., "Fabrication of a wide-field NIR integral field unit for SWIMS using ultra-precision cutting," in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9912**, 991225 (July 2016).

[22] Kitagawa, Y., Ozaki, S., Motohara, K., Konishi, M., Takahashi, H., Tateuchi, K., Todo, S., Kato, N., and Yoshikawa, T., "Concept and optical design of the near-infrared integral field unit for SWIMS," in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9151**, 91514P (July 2014).

[23] Ozaki, S., Kitagawa, Y., Motohara, K., Konishi, M., Takahashi, H., Yoshikawa, T., Tateuchi, K., and Kato, N., "Development of an integral field unit for a near-infrared multi-object imaging spectrograph SWIMS," in [*Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8450**, 84503Y (Sept. 2012).

[24] Kushibiki, K., Hosobata, T., Takeda, M., Yamagata, Y., Morita, S., Motohara, K., Ozaki, S., Tsuzuki, T., Takahashi, H., Kono, Y., Konishi, M., Kato, N., Terao, Y., and Nakamura, H., "Fabrication of mirror arrays with an ultra-precision cutting technique for a near-infrared integral field unit swims-ifu," in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation IV*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11451**, in this conference (2020).

[25] Chambers, K. C., Magnier, E. A., Metcalfe, N., Flewelling, H. A., Huber, M. E., Waters, C. Z., Denneau, L., Draper, P. W., Farrow, D., Finkbeiner, D. P., Holmberg, C., Koppenhoefer, J., Price, P. A., Rest, A., Saglia, R. P., Schlafly, E. F., Smartt, S. J., Sweeney, W., Wainscoat, R. J., Burgett, W. S., Chastel, S., Grav, T., Heasley, J. N., Hodapp, K. W., Jedicke, R., Kaiser, N., Kudritzki, R. P., Luppino, G. A., Lupton, R. H., Monet, D. G., Morgan, J. S., Onaka, P. M., Shiao, B., Stubbs, C. W., Tonry, J. L., White, R., Bañados, E., Bell, E. F., Bender, R., Bernard, E. J., Boegner, M., Boffi, F., Botticella, M. T., Calamida, A., Casertano, S., Chen, W. P., Chen, X., Cole, S., Deacon, N., Frenk, C., Fitzsimmons, A., Gezari, S., Gibbs, V., Goessl, C., Goggia, T., Gourgue, R., Goldman, B., Grant, P., Grebel, E. K., Hambly, N. C., Hasinger, G., Heavens, A. F., Heckman, T. M., Henderson, R., Henning, T., Holman, M., Hopp, U., Ip, W. H., Isani, S., Jackson, M., Keyes, C. D., Koekemoer, A. M., Kotak, R., Le, D., Liska, D., Long, K. S., Lucey, J. R.,

Liu, M., Martin, N. F., Masci, G., McLean, B., Mindel, E., Misra, P., Morganson, E., Murphy, D. N. A., Obaika, A., Narayan, G., Nieto-Santisteban, M. A., Norberg, P., Peacock, J. A., Pier, E. A., Postman, M., Primak, N., Rae, C., Rai, A., Riess, A., Riffeser, A., Rix, H. W., Röser, S., Russel, R., Rutz, L., Schilbach, E., Schultz, A. S. B., Scolnic, D., Strolger, L., Szalay, A., Seitz, S., Small, E., Smith, K. W., Soderblom, D. R., Taylor, P., Thomson, R., Taylor, A. N., Thakar, A. R., Thiel, J., Thilker, D., Unger, D., Urata, Y., Valenti, J., Wagner, J., Walder, T., Walter, F., Watters, S. P., Werner, S., Wood-Vasey, W. M., and Wyse, R., "The Pan-STARRS1 Surveys," *arXiv e-prints* , arXiv:1612.05560 (Dec. 2016).

[26] Magnier, E. A., Schlafly, E. F., Finkbeiner, D. P., Tonry, J. L., Goldman, B., Röser, S., Schilbach, E., Casertano, S., Chambers, K. C., Flewelling, H. A., Huber, M. E., Price, P. A., Sweeney, W. E., Waters, C. Z., Denneau, L., Draper, P. W., Hodapp, K. W., Jedicke, R., Kaiser, N., Kudritzki, R.-P., Metcalfe, N., Stubbs, C. W., and Wainscoat, R. J., "Pan-STARRS photometric and astrometric calibration," *The Astrophysical Journal Supplement Series* **251**, 6 (oct 2020).

[27] Skrutskie, M. F., Cutri, R. M., Stiening, R., Weinberg, M. D., Schneider, S., Carpenter, J. M., Beichman, C., Capps, R., Chester, T., Elias, J., Huchra, J., Liebert, J., Lonsdale, C., Monet, D. G., Price, S., Seitzer, P., Jarrett, T., Kirkpatrick, J. D., Gizis, J. E., Howard, E., Evans, T., Fowler, J., Fullmer, L., Hurt, R., Light, R., Kopan, E. L., Marsh, K. A., McCallon, H. L., Tam, R., Van Dyk, S., and Wheelock, S., "The Two Micron All Sky Survey (2MASS)," *The Astronomical Journal* **131**, 1163–1183 (Feb. 2006).

[28] Okita, H., Takato, N., and Hayashi, S. S., "Subaru Portable Spectrophotometer: in-situ reflectivity measurement for large telescope mirror," *Journal of Astronomical Telescopes, Instruments, and Systems* **5**, 014002 (Jan. 2019).

[29] Asano, T., Kodama, T., Motohara, K., Lubin, L., Lemaux, B. C., Gal, R., Tomczak, A., Kocevski, D., Hayashi, M., Koyama, Y., Tanaka, I., Suzuki, T. L., Yamamoto, N., Kimura, D., Konishi, M., Takahashi, H., Terao, Y., Kushibiki, K., Kono, Y., Yoshii, Y., and Swims Team, "Environmental Impact on Star-forming Galaxies in a z $\sim$ 0.9 Cluster during the Course of Galaxy Accretion," *The Astrophysical Journal* **899**, 64 (Aug. 2020).

[30] Castelli, F. and Kurucz, R. L., "New Grids of ATLAS9 Model Atmospheres," in [*Modelling of Stellar Atmospheres*], Piskunov, N., Weiss, W. W., and Gray, D. F., eds., **210**, A20 (Jan. 2003).

[31] Jeschke, E., Inagaki, T., and Kackley, R., "A next-generation open-source toolkit for FITS file image viewing," in [*Software and Cyberinfrastructure for Astronomy II*], Radziwill, N. M. and Chiozzi, G., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8451**, 845102 (Sept. 2012).

[32] Jeschke, E., "Ginga: Flexible FITS viewer," (Mar. 2013).