Design and status of a near-infrared multi-object spectrograph for the TAO 6.5-m Telescope

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ABSTRACT

We describe the design and current status of a near-infrared multi-object spectrograph for the University of Tokyo Atacama Observatory (TAO) project, which is to construct a 6.5m infrared telescope on the summit of Co. Chajnantor (altitude of 5,460m) in the northern Chile. The instrument, named SWIMS (Simultaneous-color Wide-field Infrared Multi-object Spectrograph), covers a wavelength range from 0.9 to 2.5 μm with a field of view of $9'.6$ in diameter using 4096×4096 pixels with a pixel scale of $0''.13$ pixel^{-1}. It has two observation modes: a wide-field imager and a multi-object spectrograph (MOS). The MOS mode adopts cooled multi-slit masks with 30 slits at a maximum, and achieves a spectral resolution of $\lambda/\Delta\lambda \sim 1000$. Up to 20 masks can be installed in a mask storage dewar. In both modes, two wavelength ranges of 0.9–1.4 μm and 1.4–2.5 μm are observed simultaneously with a dichroic mirror placed in the collimated beam. This will provide us data covering the wide spectral range under same conditions such as weather, telescope pointing, and so on. Such data are important not only for redshift surveys of distant galaxies but also for rapidly time-variable events such as gamma-ray bursts. As SWIMS is expected to be completed before the construction of the 6.5m telescope, we plan to carry out performance verification and early scientific observations on the Subaru Telescope at Hawaii.

Keywords: near-infrared, wide-field imaging, multi-object spectroscopy, simultaneous color, Atacama

1. INTRODUCTION

SWIMS (Simultaneous-color Wide-field Infrared Multi-object Spectrograph) is a near-infrared (NIR) instrument to be installed on the Nasmyth focus of the University of Tokyo Atacama Observatory (TAO, P.I.: Yuzuru Yoshii)[1,2] 6.5m telescope, which is an infrared-optimized telescope planned to be constructed on the summit of Co. Chajnantor at Atacama Desert in northern Chile, the world's highest site of 5,640m (18,000 feet) altitude. As Co. Chajnantor is one of the best sites for the infrared astronomy thanks to the dry climate and the high altitude[3,4] , it provides us almost continuous atmospheric window in the NIR wavelength range from 0.9 to 2.5 μm, which is covered by SWIMS.

SWIMS has capabilities of wide field imaging and multi-object spectroscopy (MOS) with cooled multi-slit masks. A unique feature of the instrument is to observe two bands (*blue* channel: 0.9–1.4 μm and *red* channel: 1.4–2.5 μm) simultaneously with a dichroic mirror placed at the collimated beam. Combined with the advantages

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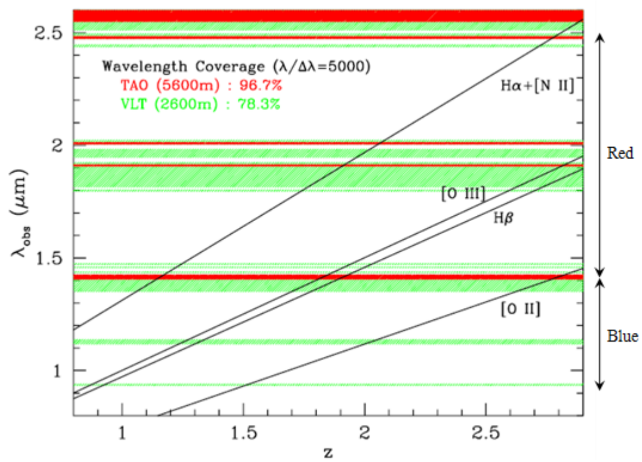

Figure 1. Observed-frame wavelength of optical emission lines as a function of redshift. *Red* and *green* hatched regions represent wavelength ranges with low atmospheric transmittance (<50%) at the TAO site (Co. Chajnantor) and the VLT site (Co. Paranal, altitude of 2,600m), respectively. Solid lines show the wavelength of Hα ($\lambda_{\rm rest}$ = 6563Å), [OIII] ($\lambda_{\rm rest}$ = 4959, 5007Å), Hβ ($\lambda_{\rm rest}$ = 4861Å), and [OII] ($\lambda_{\rm rest}$ = 3727Å).

of the site, SWIMS enables us to obtain NIR spectra from 0.9 to 2.5 μm simultaneously. A major scientific target of SWIMS is galaxies at redshift $z = 1$–3, which is the most important era for the stellar mass assembly of galaxies, formation of galaxy clusters, and build-up of super-massive blackholes in the universe. Because most rest-frame optical spectral features such as emission lines ([OII], Hβ, [OIII], and Hα) and continuum breaks from those distant objects are observed in NIR wavelength as shown in Figure 1, the simultaneous observation with SWIMS is very useful not only to perform a redshift survey for those objects efficiently in statistically meaningful sample size, but also to obtain line ratios precisely thanks to same observational conditions (weather, telescope, and the instrument) over the wide spectral range. Such wide spectral data are also efficient for studies in time-variable astronomical events such as gamma-ray bursts.

The development of SWIMS will be completed before the construction of the TAO 6.5m telescope, and we plan to carry out performance verification and early scientific observations on the Cassegrain focus of the Subaru Telescope. Therefore, the initial design of SWIMS optics is optimized for the Subaru Telescope and when moved to the 6.5m telescope, it will be re-optimized by replacing only 3 collimator lenses.

In this paper, we describe current status of the development of SWIMS. In Section 2, the overall specifications are presented. In Section 3, we review the optics and its performances. In Section 4, detector arrays and electronics are described. In Section 5, we describe the mechanics of the SWIMS MOS unit.

2. SPECIFICATIONS

Figure 2 shows schematic drawings of SWIMS. The SWIMS cryostat consists of three components: i) main dewar in which optics and detectors are installed, ii) focal plane dewar located at the telescope focus, where a slit mask is placed in the MOS mode, and iii) mask dewar which stores slit masks in cryogenic environment ($\sim$ 100K). The main dewar and the mask dewar are equipped with a Gifford-McMahon (GM) closed cycle cryocooler.

Table 1 summarizes the specifications of SWIMS. Since the instrument is planned to be mounted on both the Subaru Telescope and the TAO 6.5m telescope, some specifications are described for each telescope. SWIMS has the wide-field imaging mode and the MOS mode. As will be described in detail in Section 3, a dichroic mirror is used to split the collimated beam into two channels at $\lambda = 1.4$ μm (*blue*: 0.9–1.4 μm, *red*: 1.4–2.5 μm). The field of view (FoV) at the Nasmyth focus of the TAO 6.5m telescope is $\phi 9\farcm 6$, and it is covered by 4096 $\times$ 4096 pixels of four HAWAII-2RG arrays with $0\farcs 13$ pixel^{-1} sampling. Thus, the image size is $8\farcm 8 \times 8\farcm 8$ on a side, and edge of the image is vignetted. During the commissioning and early science phase at the Subaru Telescope,

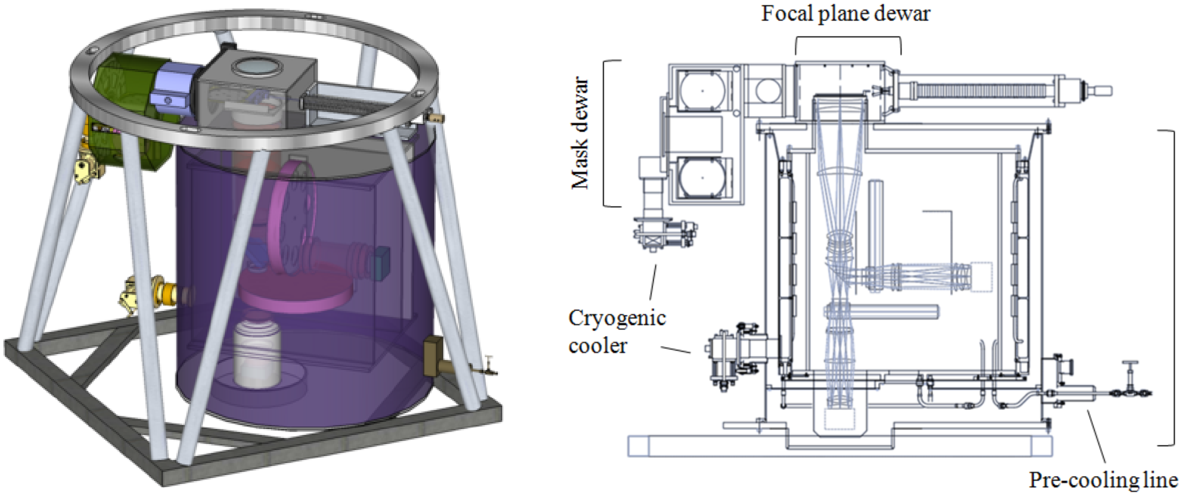

Figure 2. 3D (*left*) and 2D cross-sectional (*right*) schematic drawings of SWIMS. The interface and support structures for the Cassegrain focus of the Subaru Telescope are also shown in the *left* panel. Dimension and weight of SWIMS are approximately $2 \times 2 \times 2$ m^3 and 2 tons.

Table 1. Specifications of SWIMS

	TAO 6.5m	Subaru 8.2m
Observation Modes	Imaging and Multi-Object Spectroscopy (MOS)	
Field of View	$8'.8 \times 4'.4$ ($\phi 9'.6^a$)	$6'.8 \times 3'.4$
Pixel Scale	$0''.13$ pixel^{-1}	$0''.10$ pixel^{-1}
Wavelength Coverage	0.9–1.4 μm (*blue* channel) and 1.4–2.5 μm (*red* channel)	
Detector	2048×2048 pixel HAWAII-2RG	
Filters[b]	Y (1.02 μm), J (1.25 μm), H (1.64 μm), K_s (2.15 μm)	
Spectral Resolution	$\lambda/\Delta\lambda \sim 1000$	
Slit Mask Capacity	20 masks	
MOS Multiplicity	$\sim$ 30 objects per mask	
Estimated Total Throughput	Imaging: 31%, Spectroscopy: 20%	
Estimated Limiting Magnitudes (in AB)[c]		
Imaging (1hr, S/N=5):	Y=25.0 mag, J=24.2 mag, H=23.5 mag, K_s=23.8 mag,	Y=25.3 mag, J=24.5 mag, H=23.7 mag, K_s=24.0 mag,
Spectroscopy (1hr, S/N=5, R=1000):	Y=23.3 mag, J=22.4 mag, H=22.2 mag, K_s=21.9 mag,	Y=23.6 mag, J=22.7 mag, H=22.5 mag, K_s=22.2mag,

[a]The full field of view at the Cassegrain focus of the TAO 6.5m telescope is covered with four detector arrays (4096 $\times$ 4096 pixels).
[b]Narrow-band filters are under consideration.
[c]Magnitudes for TAO are estimated from those for Subaru by only considering the difference of the telescope diameter between TAO (6.5m) and Subaru (8.2m).

Table 2. Specifications of SWIMS Optics

	Blue channel	*Red* channel
Optimized Wavelength	0.9–1.5 μm	1.4–2.5 μm
Collimator Unit	Common (7 lenses including an aspherical lens made of Fused Silica)	
Camera Unit	6 spherical lenses	7 spherical lenses
Image Quality (RMS Spot size)	$<$ 1.3 pixel ($<$ 1.2 pixel on TAO)	$<$ 1.2 pixel ($<$ 1.0 pixel on TAO)
Image Distortion	$<$ 1% across the field of view	
Pupil Size	70 mm in diameter	
Overall Length	$\sim$ 1600 mm	
Operation Temperature	90 $\pm$10 K	

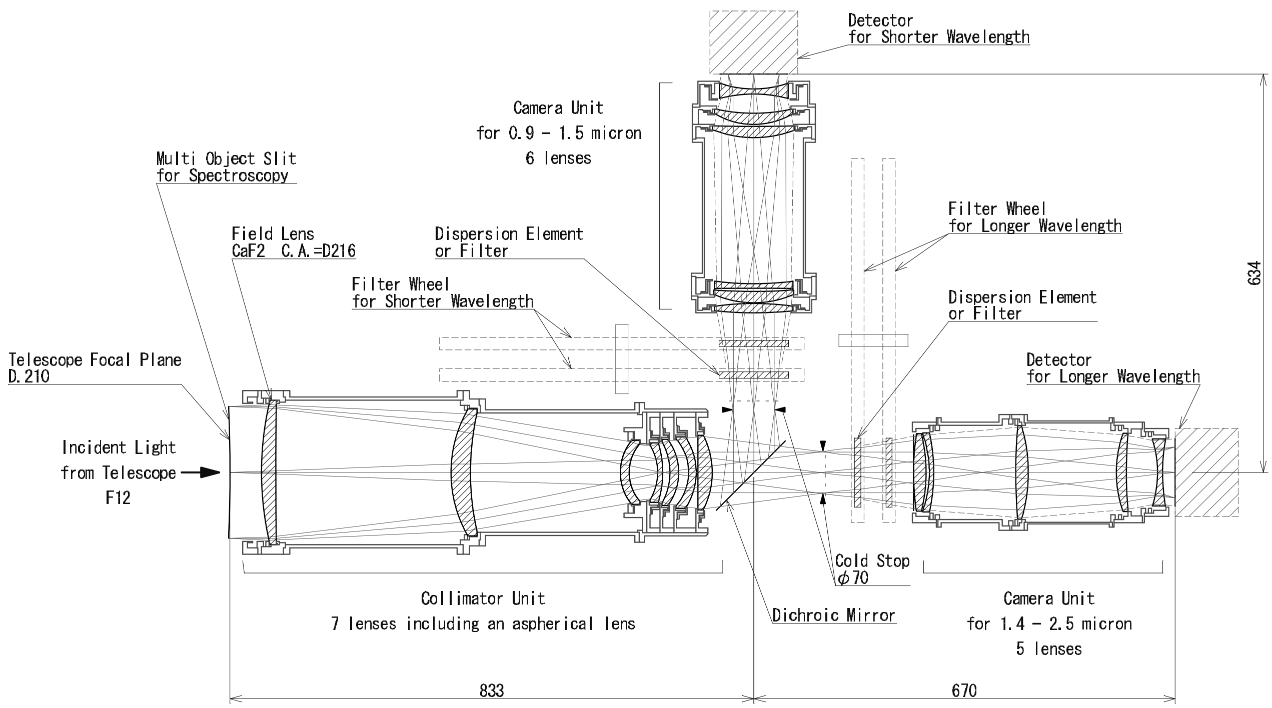

Figure 3. A schematic of the layout of the optics inside the SWIMS cryostat optimized for the Subaru Telescope.

only two arrays are installed on each channel, which cover $6'.8 \times 3'.4$ with a pixel scale of $0''.10$ pixel^{-1}. The MOS mode allows us to observe up to 30 objects with one slit mask, and 20 masks are stored in the mask dewar. Total throughputs are estimated to be 31% for the imaging mode and 21% for the MOS mode, assuming reflectivities of the primary and secondary mirrors of the telescope (96%), transmission of optics (lenses: 95%, dichroic mirror: 95%, filters: 90%, and dispersive element: 60%), and a quantum efficiency of the detector (70%). Limiting magnitudes are calculated with typical sky brightnesses at Mauna Kea, Hawaii.

3. OPTICAL DESIGN

A schematic layout of the SWIMS optics is shown in Figure 3, where the collimator unit is optimized to the Subaru Telescope. When mounted on the TAO 6.5m telescope, the collimator unit will be replaced in order to

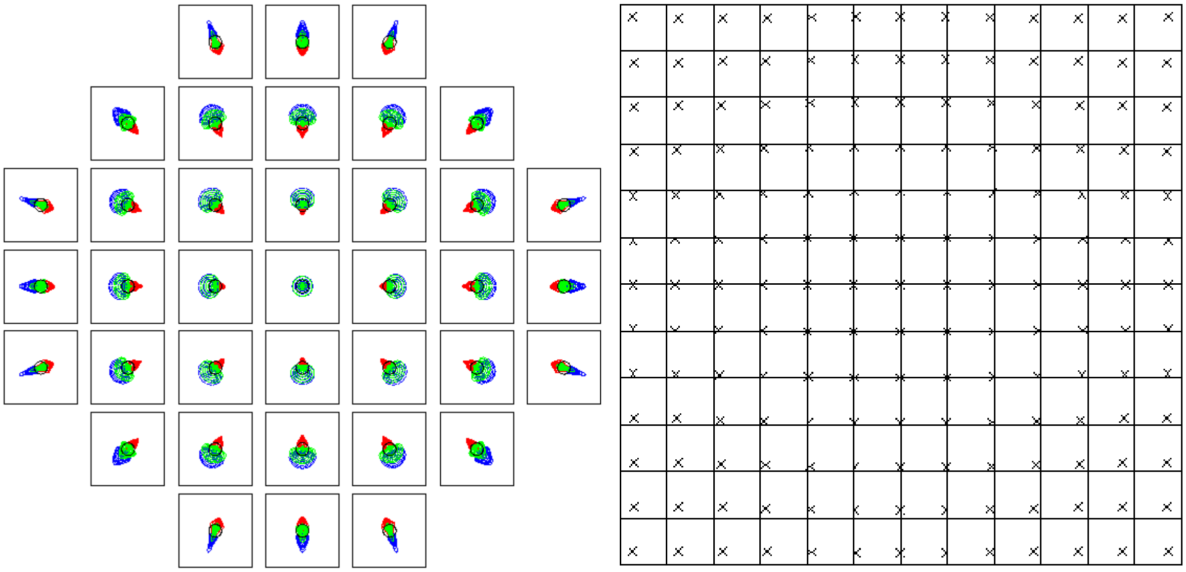

Figure 4. Image qualities of the *blue* channel of the imaging mode optimized for the Subaru Telescope. *Left*: spot diagrams for the center of the FoV and the positions $\pm 1'\!.1$, $\pm 2'\!.2$, $\pm 3'\!.3$ apart from the center is shown. The box shows 5.4 pixel (~ 100 μm with a pixel pitch of 18.5 μm) on a side. For each diagram, the red, blue, and green spots correspond to wavelengths of $\lambda = 0.9$, 1.25, and 1.50 μm, respectively. The Airy disk at $\lambda = 1.5$ μm is also shown as a circle in each diagram. *Right*: distortion map for $6'\!.6 \times 6'\!.6$ field is shown as a distance between the grid point (ideal position) and cross (position predicted from the design) across the field. Note that the map is exaggerated by a factor of 50.

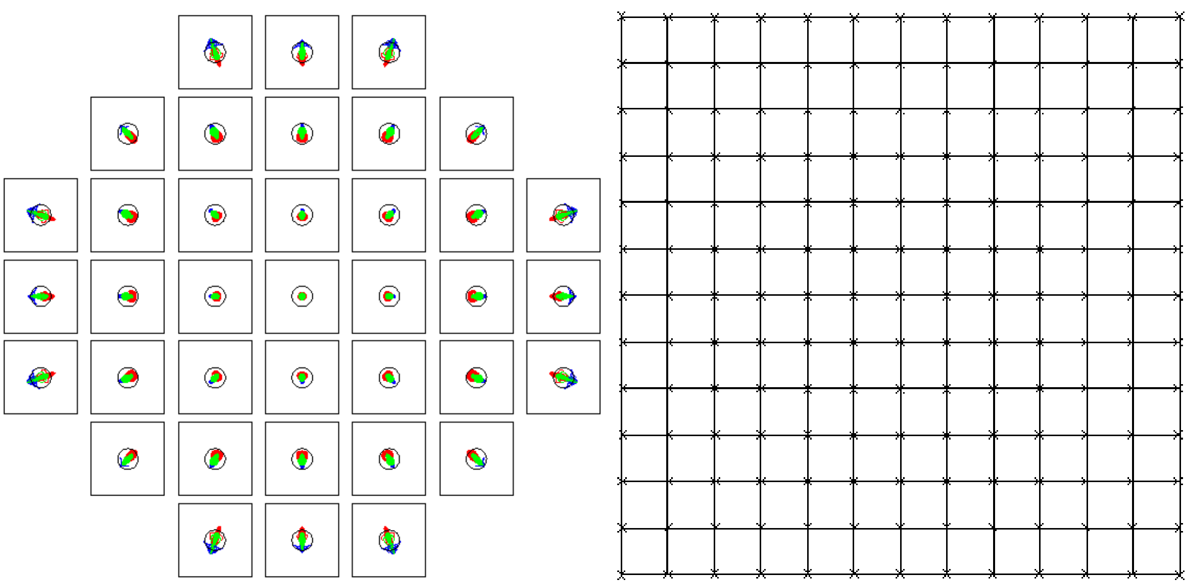

Figure 5. Similar to Figure 4, but for the *red* channel. For each diagram in the *left* panel, the red, blue, and green spots correspond to wavelengths of $\lambda = 1.4$, 1.8, and 2.4 μm, respectively, and the circle represents the Airy disk at $\lambda = 2.4$ μm.

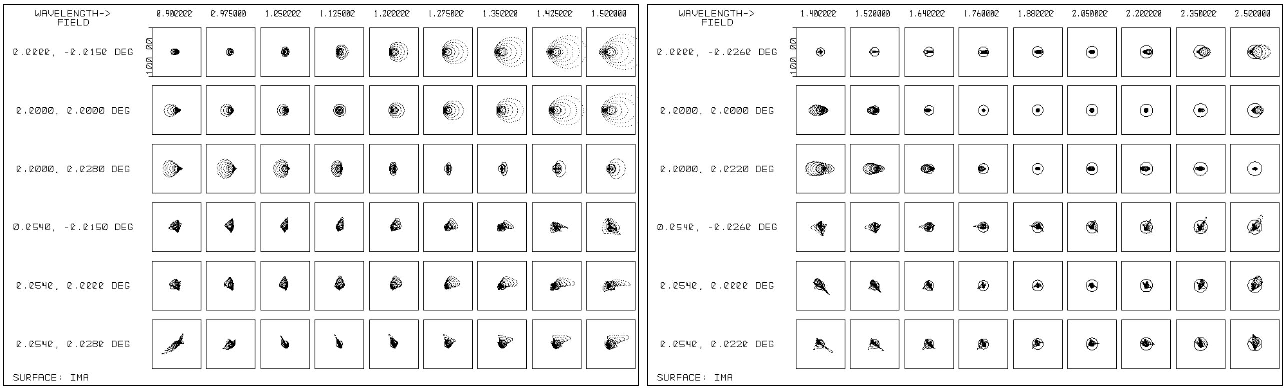

Figure 6. Spot diagrams of the spectroscopy mode optimized for the Subaru Telescope (*left* for the *blue* channel and *right* for the *red* channel). Positions (in degree from the center) and wavelength (in μm) for each diagram are shown on the left and top, respectively. The Airy disk at each wavelength is also shown as a circle. The box shows 5.4 pixel (~ 100 μm with a pixel pitch of 18.5 μm) on a side. A transmission grating (grism) with a blaze angle of 30 (27) degrees and 200 (100) grooves/mm is assumed for the *blue* (*red*) channel.

compensate different optical parameters between TAO and Subaru. Optical specifications are summarized in Table 2.

The collimator unit consists of 7 lenses, including an aspherical lens made of Fused Silica. The field lens (the first collimator lens) is made of CaF_2 and has a diameter of 216mm. Note that the collimator unit will be re-optimized by replacing three lenses when mounted on the TAO 6.5m telescope. A dichroic mirror with 150mm $\times$ 120mm is placed at the collimated beam for the two-band simultaneous observations. There are two re-imaging camera units after the dichroic mirror: one for the *blue* channel (λ = 0.9–1.4 μm) and another for the *red* channel (λ = 1.4–2.5 μm). Note that the *blue* channel is optimized for slightly wider wavelength range: λ = 0.9–1.5 μm. There are a cold stop and two filter wheels between the dichroic mirror and each camera unit. All of the optical components and the opto-mechanics are placed on an optical bench of 1400mm $\times$ 920mm, and cooled down below 90K to suppress thermal radiation.

Spot diagrams and distortion maps of the imaging mode for the optics optimized for the Subaru Telescope are shown in Figure 4 and 5 for the *blue* and *red* channel, respectively. Note that we exaggerate the distortion maps by a factor of 50 to clearly show the distortion. Good image qualities are achieved (RMS spot size < 1.3 pixel) across the field for both channels. Figure 6 shows spot diagrams for the spectroscopic mode as functions of field position and wavelength when transmission grating (grism) with a blaze angle of 30 and 27 degrees and 200 and 100 grooves/mm is adopted as a dispersive element for the *blue* and *red* channel, respectively. The largest aberration seen at the position of (0.0000deg, -0.0320deg) and the wavelength of 1.5 μm of the *blue* channel has the RMS spot size of 1.8 pixel, which is sufficiently small compared to typical seeing size of $0.''7$ at Mauna Kea or Co. Chajnantor.

4. DETECTORS

We adopt 2048 $\times$ 2048 pixel Liquid Phase Epitaxy (LPE)-grown HgCdTe focal plane arrays, HAWAII-2RG, manufactured by Teledyne Technologies, Inc. The full field of view ($\phi 9.'6$) of each channel at the Nasmyth focus of the TAO 6.5m telescope is planned to be covered with four arrays with a pixel scale of $0.''13$ pixel^{-1}. During the first stage of performance verification and scientific observations at the Subaru Telescope, two arrays covering $8.'8 \times 4.'4$ for each channel are procured. The arrays are driven by SIDECAR ASICs working at the cryogenic temperature. The JADE cards to operate the SIDECAR ASIC will be placed at a room temperature environment inside the dewar.

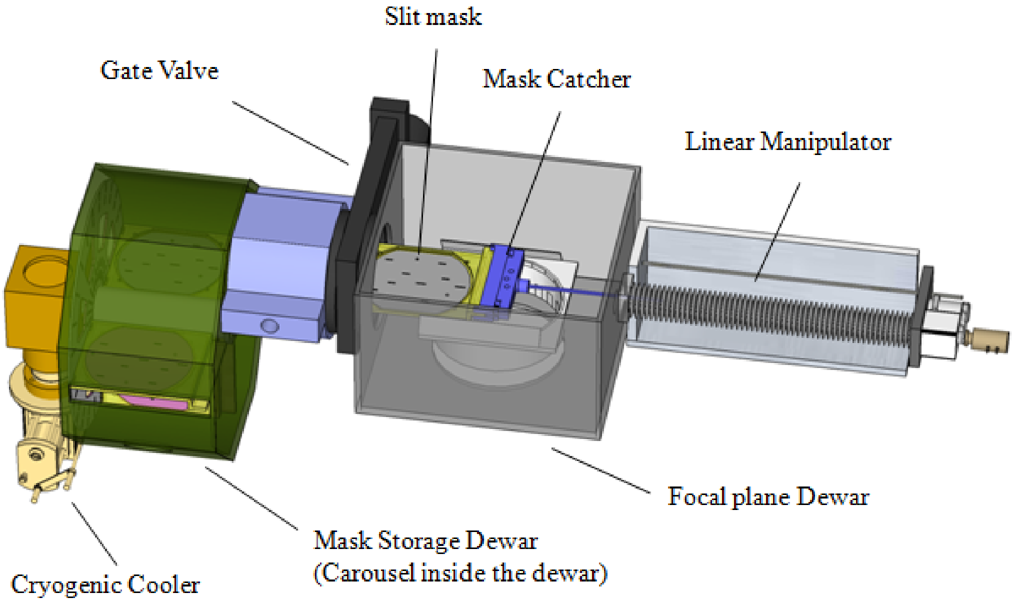

Figure 7. 3D schematic view of the MOS unit. The overall length of the unit is about 2400mm. The telescope focus is located in the focal plane dewar, where a slit mask is set.

5. MULTI-OBJECT SLIT UNIT

The MOS unit of SWIMS shown in Figure 7 is designed based on MOIRCS[5,6] on the Subaru Telescope, which has a carousel (turret-like) slit mask storage in the mask storage dewar, a robotic mask catcher, and an independent cryogenic cooler independent from the main dewar. In order to make the unit operative with high reliability at the Nasmyth focus of the TAO 6.5m telescope as well as at the Cassegrain focus of the Subaru Telescope, we refine the design from that of MOIRCS. MOIRCS uses robotic hands driven by a pneumatic linear motion feedthrough to hold a slit mask at the focal plane, and uses neodymium magnets to stock a slit mask at the carousel. We replace the robotic hands to magnets (having sufficiently strong magnetic force), which can make the unit more simple and reduce mechanical troubles. A slit mask holder is designed to hold the cylindrically curved mask sheet to compensate for the curved focal plane of the telescopes, especially for the TAO 6.5m telescope. The unit has an overall length of about 2400mm. A schematic drawing of the mask holder and its prototype are shown in Figure 8. A mask is made of aluminum sheet, and its shape is a combination of a circle with 210mm in diameter and a rectangle with 150mm $\times$ 210mm.

Approximately 30 slits can be cut on the mask sheet, and a fixture ring fastens the sheet to the holder with screws. The slit mask is fixed on the focal plane by the neodymium magnets placed at each corner of the holder and a plate at the focal plane.

Mask exchanging procedure is almost same as that of MOIRCS: At first, an observer selects a slit mask stored by rotating the carousel and moves the selected mask to the position where the mask catcher grabs it. The mask catcher moves forward to grab the mask, and then moves back to the focal plane to set the mask. The mask can be returned back in the carousel in the inverse order. A gate valve placed between the mask dewar and the focal plane dewar is closed when the mask dewar is opened to replace slit masks with keeping the focal plane dewar and the main dewar under cryogenic environment.

6. DEVELOPMENT SCHEDULE

The detailed design of the opto-mechanics and the MOS unit will be completed by July 2010. All of the components (dewar, MOS, and detectors) will be manufactured and delivered in 2011, and their installation

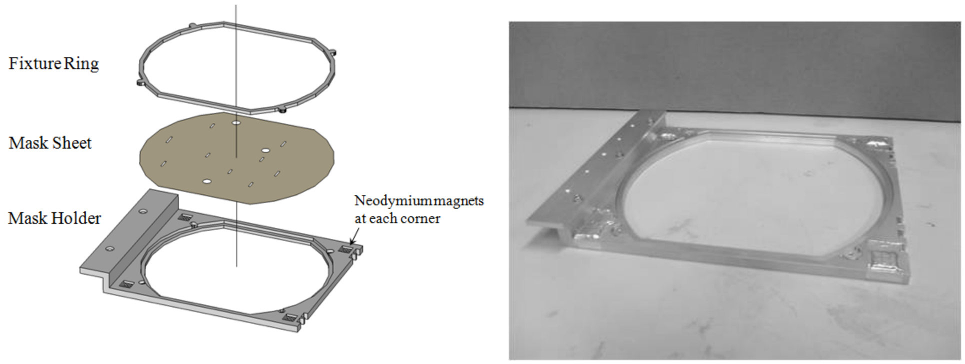

Figure 8. Schematic drawing of the slit mask (*left*) and a prototype for positioning tests using neodymium magnets (*right*). The mask sheet is made of aluminum sheet and its shape is a combination of a circle (210mm in diameter) and a rectangle (150mm $\times$ 210mm).

and assembly are expected to be completed by 2012. SWIMS is then planned to be transported to the Subaru Telescope by the end of 2012 for performance verification in 2013. It is expected to be operated as a PI-type instrument there until the construction of the TAO 6.5m telescope is completed.

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