

Development of a new mid-infrared instrument for the TAO 6.5-m telescope.

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ABSTRACT

Ground-based mid-infrared observations have two distinct advantages over space observations despite relatively lower sensitivity. One is the high spatial resolution and the other is the monitoring capability. These advantages can be emphasized particularly for the next coming ground-based infrared project University of Tokyo Atacama Observatory (TAO). Thanks to the low water vapor of the TAO site (5,640m) and the large aperture of the telescope (6.5meter), we can observe at 30 micron with a spatial resolution of 1 arcsec. It is about ten times higher than that of current space telescopes. The TAO is also useful for monitoring observations because of the ample observing time.

To take these advantages we are now developing a new mid-infrared infrared instrument for the TAO 6.5-meter telescope. This covers a wide wavelength range from 2 to 38 micron with three detectors (Si:As, Si:Sb, and InSb). Diffraction limited spatial resolution can be achieved at wavelengths longer than 7 micron. Low-resolution spectroscopy can also be carried out with gratings. This instrument equips a newly invented "field stacker" for monitoring observations. It is an optical system that consists of two movable pick-up mirrors and a triangle shaped mirror, and combine two discrete fields of the telescope into camera's field of view. It will enable us to apply a differential photometry method and dramatically improve the accuracy and increase the feasibility of the monitoring observations at the mid-infrared wavelengths.

Keywords: mid-infrared, imager, spectrograph, monitoring observations, Atacama

1. INTRODUCTION

Mid-infrared region is one of the key wavelengths for studying dusty astronomical objects such as star forming regions, planetary/debris disks, mass losing stars, and nuclei of galaxies. It includes a number of dust features in addition to the peak of blackbody radiation of 100-300K, at which temperature most dusty shells/disks emit. So far many observations at these wavelengths have been carried out from space telescopes such as IRAS, ISO, Spitzer, and AKARI, and remarkable discoveries have been obtained. However detailed structures of dust shells/disks remain still unclear because of insufficient spatial resolution of space telescopes. Higher spatial resolution by larger (ground-based) telescopes is strongly needed.

Our group led by Institute of Astronomy, the University of Tokyo is now urging a ground-based infrared project named University of Tokyo Atacama Observatory (TAO, P.I. Y. Yoshii^{1,2}). It is a project to build a 6.5-meter infrared telescope at the world's highest site (5,640m) on the summit of Co. Chajnantor, Atacama, Chile. The perceptible water vapor amount at the TAO site of 0.4 to 1.3 mm is much lower than at Mauna Kea, Hawaii of 0.9 to 2.8 mm and the site

provides excellent atmospheric transmission especially at the mid-infrared. A modeled transmission curve of the atmosphere at 5,640m is shown in Figure-1. The 20 micron “Q-band” window is much clearer than that of the other astronomical sites, and new atmospheric windows appear at wavelengths longer than 25 micron. These windows are only accessible from the TAO site. In fact we have carried out test observations through these 30 micron windows with our new 30 micron instrument MAX38⁴ attached to the pilot 1.0-m telescope called miniTAO at the TAO site, which clearly demonstrates that the 30 micron window can be used for astronomical observations under low water vapor conditions⁵.

Another important advantage of ground-based telescopes is the monitoring capability of variable objects. Since most of dust supplying objects such as AGB stars, LBVs, novae, and supernovae are variables, monitoring observations are obviously essential for the understanding of the nature of these objects. Recently time variations of young planetary disks at mid-infrared wavelengths have also been reported. They have provided unique information about disk structures and components of dust grains. However few systematic studies of time variations at mid-infrared wavelengths have so far been carried out, because the observing time of mid-infrared instruments is very competitive. The TAO project will change this situation. Ample observing time and stable weather condition of the TAO enable us to carry out a systematic survey or monitoring of the time variation at mid-infrared wavelengths for the first time.

To take the advantages of the high spatial resolution and the monitoring capability of the TAO 6.5-meter telescope, we are developing a new mid-infrared camera. It has capabilities of imaging and spectroscopy from 2 to 38 micron. To cover the wide wavelength range three array detectors of Si:As, Si:Sb, and InSb are employed. Diffraction limited spatial resolution can be achieved at wavelengths longer than 7 micron for both imaging and spectroscopic modes. To improve the photometric accuracy and carry out reliable monitoring observations at the mid-infrared, a new “field stacker” system is invented. We note that the TAO mid-infrared camera can be attached to the Subaru 8.2-meter telescope because of the compatibility of the Subaru and the TAO.

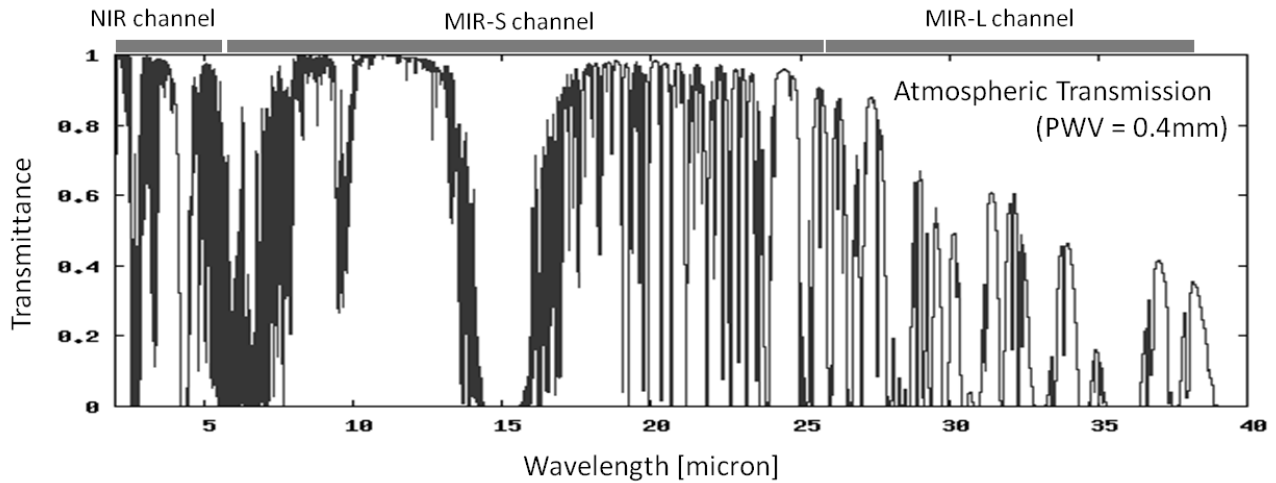


Figure 1. A plot of atmospheric transmission calculated with ATRAN³. The transmission is calculated with the PWV of 0.4mm, which is comparable to the best 10% at the TAO site. The bars above the plot show the wavelength coverage of the NIR, the MIR-S, and the MIR-L channels.

2. DESIGN

The designed specification of the TAO mid-infrared camera is summarized in Table-1.

Table 1. Specifications of the TAO mid-infrared camera

	MIR-S	MIR-L	NIR	Note
Detector	Si:As BIB	Si:Sb BIB	InSb	
Array format	1024x1024	128x128	1024x1024	
Wavelength coverage	6-26 micron	25-38 micron	2-5.6 micron	
Pixel scale	0.11"/pix	0.46"/pix	0.11"/pix	at TAO 6.5m telescope
Field of view	2'x2'	1'x1'	2'x2'	w/o Field stacker
	1'x2' x2	1'x1' x2	1'x2' x2	w/ Field stacker
Number of filters	max 16	max 17	max 16	
Spectroscopy	long slit	long slit	long slit	
Spectral Resolution	7.5-13.5 / R~200	26-38 / R~50	2.8-4.2 / R~200	
	16.5-26.5 / R~150		4.5-5.5 / R~400	

2.1 Detectors

The TAO mid-infrared camera employs three detectors. For the short side of the mid-infrared wavelengths (6-26micron) we use a state-of-the-art Si:As BIB detector AQUARIOUS manufactured by Raytheon Company. It has a 1kx1k array format with a pixel size of 30 micron. The pixel scale is set as 0.11 arcsec/pix, which is comparable to 3 pixel sampling of the diffraction limited image at 9 micron. For the longer mid-infrared (26-38micron), a Si:Sb 128x128 array detector manufactured by DRS sensor and targeting system, Inc. will be used. Since the format is smaller but the pixel size is larger (75micron) than the AQUARIOUS, the Si:Sb detector covers approximately a half of the field of view of the AQUARIOUS. The pixel scale matches with the Nyquist sample of the diffraction limited images at 26 micron (0.46 arcsec/pix). For the near-infrared, the InSb array Aladdin II is used. The format is 1kx1k, and the pixel scale is the same as the AQUARIOUS. All of the detectors are driven by our own developed control system (TAO array controller: TAC⁷) which has been successfully used for the infrared cameras MAX38 and ANIR of the miniTAO telescope⁶.

2.2 Optics

Figure-2 shows a conceptual diagram of the optics. The optics consists of two blocks, fore-optics and rear-optics. The fore-optics is used as a relay optics, which converts the incident light from the telescope into a collimated beam and makes a re-image at the slit position. At the pupil position in the collimated beam we install a cold chopper, which is a wobbling mirror system operated below 20K to enable chopping observations. A prototype of the cold chopper has been developed and successfully operated in the MAX38 camera⁷.

The rear optics is designed for each detector. The ray passed through the slit goes into the MIR-S (Si:As) optics. When we use the MIR-L (Si:Sb) optics, a flat flip-flop mirror is inserted just after the slit. On the contrary the ray reflected by the slit enters to the NIR (InSb) optics. At the slit position we have a slit wheel to exchange observing modes. If a long slit is installed, the MIR-S or the MIR-L channel can be used as spectrograph, while the NIR channel is used as a slit viewer. On the contrary, the NIR can be used for spectroscopy and the MIR-S or the MIR-L for slit viewing when a reflecting slit is installed. For imaging observations a hole (for the MIR-S and the MIR-L) or a mirror (for the NIR) is inserted at the slit position. The filter wheels are installed at the pupil position of each of the rear-optics. We use our own developed metal mesh filters in the MIR-L channel for the 30 micron observations⁸ in addition to usual interference filters. Grisms for spectroscopy are also installed in the filter wheels.

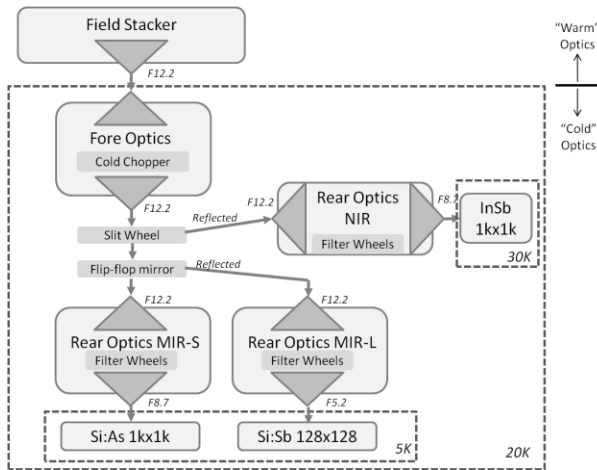


Figure 2. Conceptual diagram of the optics of the TAO mid-infrared camera.

Figure-3 shows the ray-tracing diagram of the cold optics. To achieve the wide wavelength coverage over 4 octaves, reflective optics is adopted. Each of the collimators and the cameras consists of two off-axis conic mirrors. The optical design is based on the linear astigmatism theory of confocal off-axis reflective imaging system developed by Chang et al. 2006⁹.

The ray-tracing shows that the optics achieves the diffraction limited performance (the Strehl ratio of larger than 0.84 is achieved for all field stacker positions at 8 micron) at the MIR-S and the MIR-L channels. At the NIR channel, the geometrical spot diameter of 0.3" is larger than the diffraction size, but smaller than the seeing size at the TAO site, which is typically 0.8 arcsec at the K-band¹⁰. Hence we conclude that the camera can achieve the seeing limited or the diffraction limited spatial resolution at all the wavelengths.

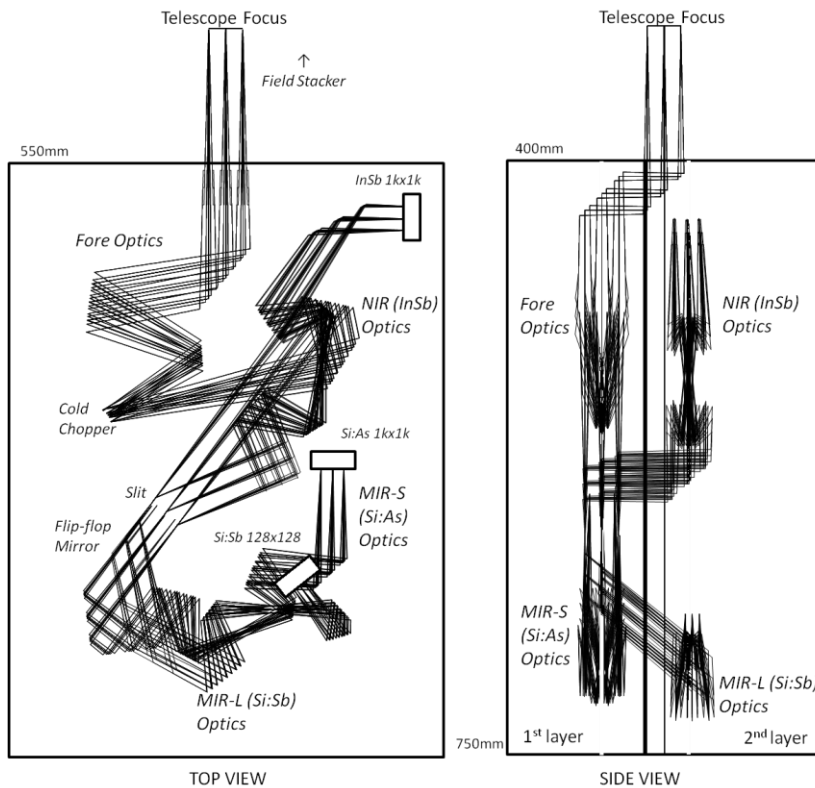


Figure 3. The ray-tracing and configuration of the cold-optics. The boxes show a cold worksurface of 75cm x 55cm x 40cm. The optical components are placed on two layers: The first layer includes the fore-optics and the MIR-S optics, and the second includes the NIR optics and the MIR-L optics. Each collimator / camera consists of a pair of conical off-axis mirrors.

2.3 Field Stacker

Since the sky condition is not always stable, accurate absolute photometry is quite difficult for ground-based telescopes. At the optical or the near-infrared wavelengths, a differential photometric method, in which star fluxes simultaneously measured around a target are used for the standard of the photometry, is widely used for monitoring observations. The accuracy is limited by uncertainties in the flat-fielding, and it is possible to achieve accuracy of 1% or better, which is several times better than the absolute photometry. However, the differential photometry cannot be applied for mid-infrared observations so far because that the number of stars is very small at mid-infrared wavelengths. It is not possible to observe more than one stars in the same field in most cases.

The field stacker is a newly invented optical unit to achieve the differential photometry in the mid-infrared. The concept is shown in Figure-4. It consists of two pick-up mirrors and a triangular-prism shape mirror on a rotatable table. The pick-up mirrors can move along the radial direction of the rotatable table, and pick up two separate fields in the telescope field of view. The picked-up beams are brought to the triangular-prism shape mirror, combined (or stacked) into the single beam, and then led to the cold optics. Thus the field stacker enables us to observe two arbitrary fields of view, i.e. two or more stars simultaneously. The field of view of each field is $1' \times 2'$ and the combined field is $2' \times 2'$. The triangular-prism shape mirror can be retracted out when the field stacker unit is not used. At that time the camera can be used as a simple imager with a wide field of view of $2' \times 2'$.

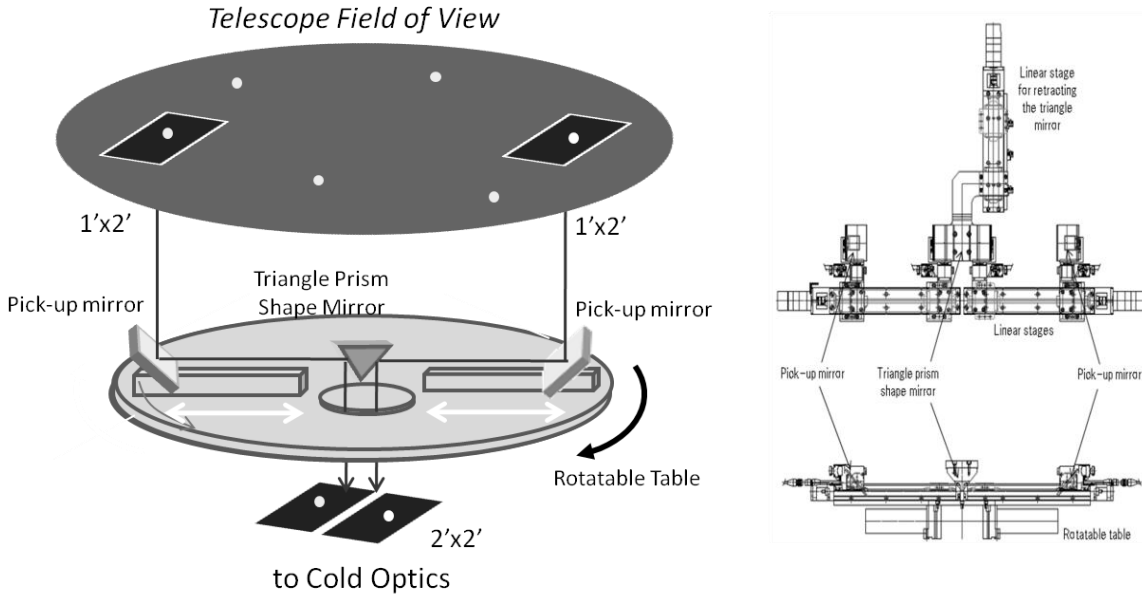


Figure 4. The conceptual drawing of the field stacker (left) and the current mechanical design (right). See text for details.

To investigate the efficiency of the field stacker, conceptual studies have been carried out. One of most critical issues about the concept of the field stacker is if the number density of stars at mid-infrared wavelengths is enough for the differential photometry. To answer this question, we counted the 9 and the 18 micron sources in the AKARI all-sky survey and calculated how many AKARI sources can be simultaneously observed with other sources with the field stacker. The detection limit of the AKARI survey¹¹ is almost comparable to, or slightly better than the 1σ -1seconds the sensitivity of the TAO mid-infrared camera (50mJy at 9 micron and 180mJy at 18 micron). Table-2 summarizes the result of the calculation. An observable counterpart(s) can be found for ~50% of the AKARI 9 and the 18 micron sources in the field of view of $25'$ at the TAO telescope. The fraction of the 18 micron sources decreases to 40% when the field of view is $5'$ at the Subaru telescope, but still high enough. These sources strongly concentrate in the galactic plane, therefore we conclude that the field stacker can be used for galactic mid-infrared sources effectively.

Table 2. Fraction of the AKARI 9 micron and the 18 micron sources to which a counterpart star(s) can be found.

Telescope	FOV of the telescope	9 micron sources		18um sources	
		>50mJy	>300mJy	>130mJy	>1000mJy
TAO 6.5m	ϕ 25arcmin	55%	51%	51%	15%
Subaru 8.2m	ϕ 5arcmin	51%	10%	41%	0.3%

The field stacker will improve the accuracy of the photometry to a few percent, which is similar to the accuracy achieved at optical and near-infrared wavelengths. This system will be also useful for spectroscopic observations. Calibration of the atmospheric absorptions is one of critical problems for ground-based mid-infrared spectroscopy. Simultaneous observations of two or more stars will enable us to cancel out the atmospheric absorptions with a high accuracy. It will be especially effective around 10 micron, which is close to strong absorption features of telluric ozone, the Q-band, and the 30 micron windows, in which there are a lot of water vapor absorptions.

2.4 Mechanics and Cryogenics

Figure-5 shows a current design of the cold chamber, the mechanical interface to the telescope, and a support system of the TAO mid-infrared camera. The size of the whole system is 2m x 2m x 2m, and the weight is 2 ton. The cold chamber has a diameter of 983mm and a height of 1390mm. The chamber can be lifted up and down with a maximum stroke of 265mm by an actuator fixed on the frame to compensate the increased light path when the field stacker is used.

All the optics except for the field stacker is cooled down to 20K to reduce thermal radiation from the optics. The operating temperatures of the Si:As and the Si:Sb detectors are 5K. A two 4K-1W GM cycle cooler are employed to cool the optics and the detectors. All of the cryogenics, the mechanics, and the support system are manufactured by Sumitomo Heavy Industries, Inc.

3. CURRENT STATUS AND PLAN

The design of the camera has almost been completed. In 2011 we will assemble all of the optics, the cryogenics, the detectors, and their electronics in our laboratory in Japan, and have the laboratory first light. After verifying the performances, the camera will be delivered to the Subaru telescope. The engineering first light is planned by the end of 2012.

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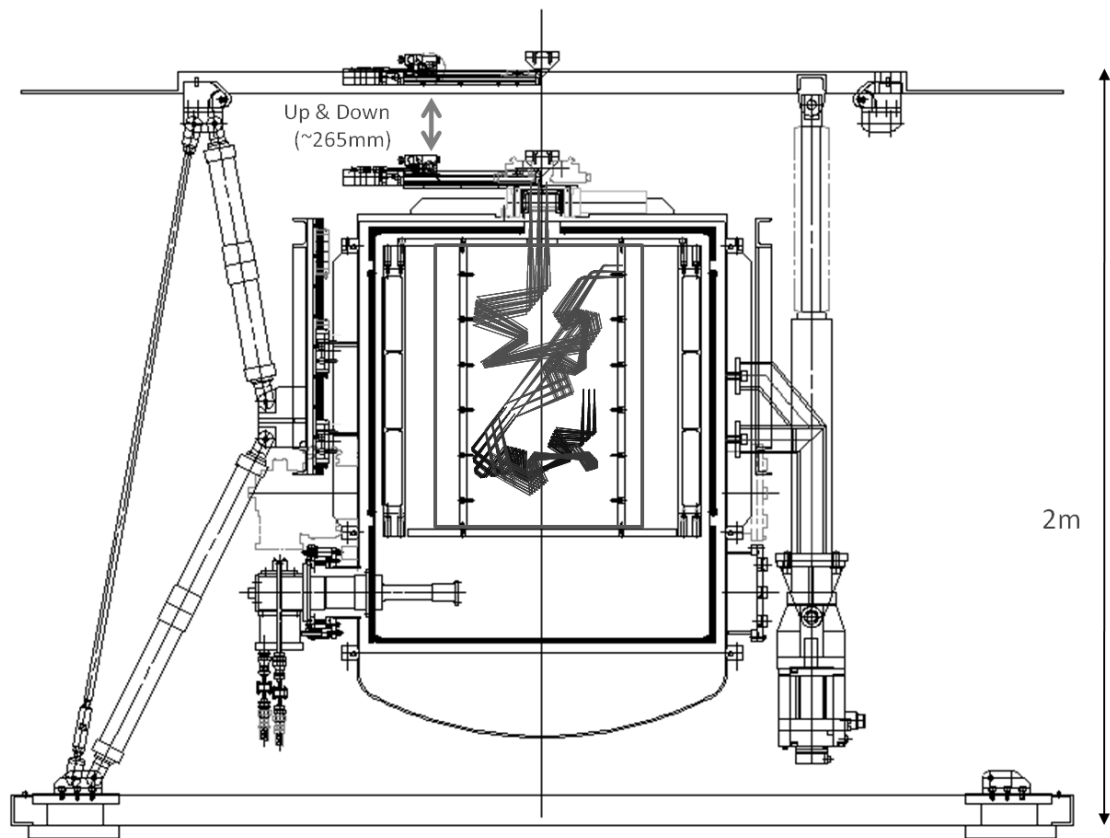


Figure 5 A drawing of the chamber, the telescope interface and the support system of the TAO mid-infrared camera. The chamber is lifted up and down to compensate the light path length in the field stacker unit.

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