MiniTAO/MAX38 first light: 30-micron band observations from the ground-based telescope

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ABSTRACT

We successfully carried out 30-micron observations from the ground-based telescope for the first time with our newly developed mid-infrared instrument, MAX38, which is mounted on the University of Tokyo Atacama 1.0-m telescope (miniTAO telescope). Thanks to the high altitude of the miniTAO (5,640m) and dry weather condition of the Atacama site, we can access the 30-micron wavelength region from ground-based telescopes. To achieve the observation at 30-micron wavelength, remarkable devices are employed in MAX38. First, a Si:Sb 128x128 array detector is installed which can detect long mid-infrared light up to 38-micron. Second, we developed metal mesh filters for 30-micron region band-pass filter, which are composed of several gold thin-films with cross-shaped holes. Third, a cold chopper, a 6-cm square plane mirror controlled by a piezoelectric actuator, is built into the MAX38 optics for canceling out the atmospheric turbulence noise. It enables square-wave chopping with a 50-arcsecound throw at a frequency more than 5-Hz. Finally, a low-dispersion grism spectrometer (R~50) will provide information on the transmission spectrum of the terrestrial atmosphere in 20 to 40 micron. In this observation, we clearly demonstrated that the atmospheric windows around 30-micron can be used for the astronomical observations at the miniTAO site.

Keywords: mid-infrared, 30-micron band, ground-based observations, Si:Sb, metal mesh filter, cold chopper, Atacama, TAO

1. INTRODUCTION

Long mid-infrared (25-40 micron) observation is one of the frontiers of astronomy. This wavelength is suitable to observe dusty astronomical objects, such as star forming regions, planetary disks, asymptotic giant branch stars and massive mass-losing stars, because dust around the stars typically has a temperature of ~100K. Although high spatial resolution is needed for investigating details of disks and envelopes, it has been difficult to achieve sufficient resolution observations from space or airborne telescopes so far.

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Institute of Astronomy, The University of Tokyo constructed the 1.0-m telescope, called miniTAO telescope, at the summit of Cerro (Co.) Chajnantor in Atacama, Chile[1, 2]. This is a prior project of the Tokyo Atacama Observatory (TAO; P.I. Y. Yoshii), which is a project to build a 6.5-m infrared-optimized telescope at the same place[3, 4]. The miniTAO telescope is now the world's highest ground-based telescope. The weather is so dry that perceptible water vapor (PWV) predicted by the satellite data is 0.56 mm at 25%-tile at this site[5]. Thanks to this low PWV, we can carry out observations with wavelengths such as Paschen-alpha line (1.875 micron) and the 30-micron wavelength region, which had never been observed from the ground-based telescopes[6] (see Figure 1).

For the long mid-infrared observations with the miniTAO telescope, we developed a new camera MAX38 (Mid-infrared Astronomical eXplorer) [7]. Table 1 summarizes the specifications of MAX38. A Si:Sb blocked impurity band (BIB) array detector is installed, which has sensitivity at near infrared to 38-micron. Grism spectroscopic observations at N-band are also capable.

Previously, test observations at the N-band were successfully conducted at Higashi Hiroshima Observatory (Hiroshima, Japan) in June 2007 and March 2008. In November 2009, we carried out MAX38 first light observation with the miniTAO telescope.

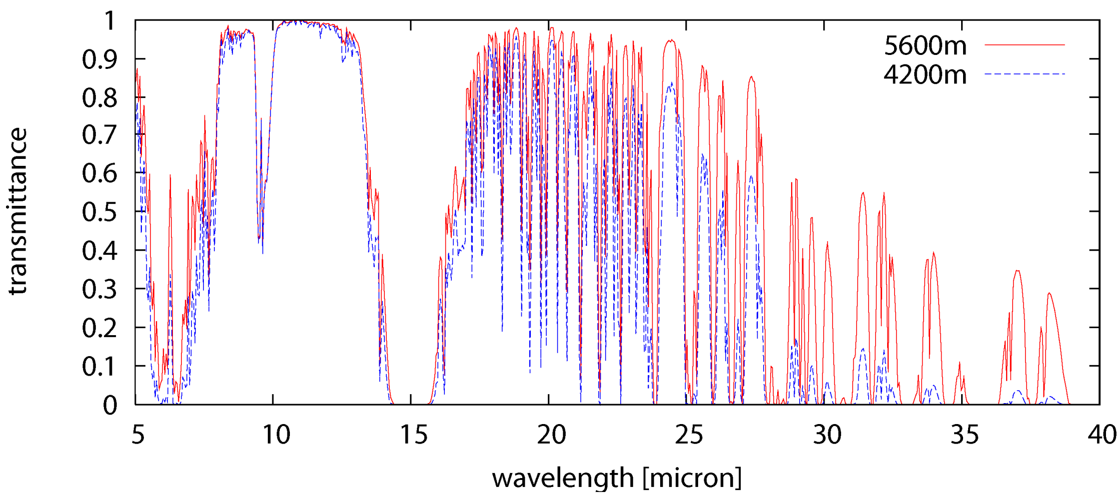

Figure 1. A plot of atmospheric transmittance calculated with ATRAN[8]. The solid line shows the transmittance of best 25% at the summit of Chajnantor (5,640m; PWV 0.56 mm), and the dashed line shows that at Mauna Kea (4,200m; PWV 1.32 mm).

Table 1. MAX38 specifications on the Atacama 1.0-m telescope

Parameters	Value	Notes
Detector	Si:Sb BIB array	manufactured by DRS
Array format	128x128	
Pixel scale	1.26 arcsec/pix	
Field of View	161arcsec x 79arcsec	for imaging
Wavelength coverage	8-38 micron	
Grism Spectroscopy mode (for measurements of atmosphere)		
Resolving power	~50	
Wavelength Coverage	19.0 – 38.0 micron	
N-band Spectroscopy mode		
Resolving power ($\lambda / \Delta \lambda$)	~100	
Wavelength Coverage	7.5 – 13.5 micron	

Table 2. Specifications of Metal Mesh Filters.

Name	Center [micron]	FWHM [micron]	Peak Transmittance
MMF-31	31.7	2.2	78%
MMF-37	37.3	2.4	80%

Figure 2. A Metal Mesh Filter. It is composed of four gold thin-films. The diameter of the films is about 10-mm, and the thickness of each film is 2-micron.

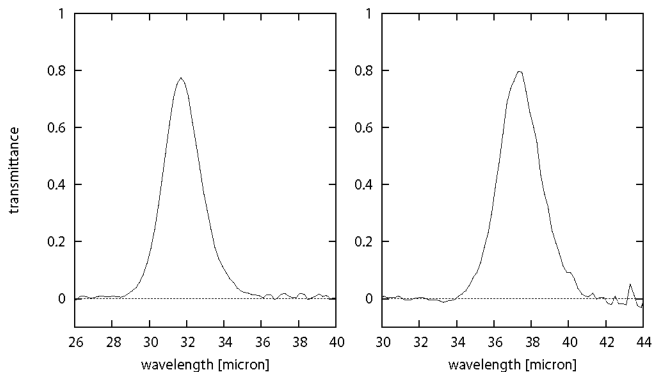

Figure 3. Transmission curves of MMFs, MMF-31 (*left*) and MMF-37 (*right*). Both of them consists of stacked four films and achieve about 80% of the peak transmittance and R~15.

In section 2, we describe new devices installed in MAX38 for observations at the long mid-infrared wavelengths. In section 3, we report the result of the first light observations and discuss the feasibility of 30-micron observations from the miniTAO site.

2. NEW COMPONENTS FOR 30-MICRON OBSERVATIONS

For the 30-micron region observations, we developed new devices and installed them in MAX38. In this section, we make a brief introduction of newly developed components.

2.1 Metal Mesh filters

It is difficult to produce narrow band filters for long mid-infrared region because most materials are obscure at this wavelength. To conduct 30-micron band observations with MAX38, we developed Metal Mesh Filters (MMFs) exploiting the band-pass characteristics of gold thin-films with cross-shaped holes[9].

We have developed the MMFs which has peaks at 31-micron (MMF-31) and 37-micron (MMF-37), respectively. Table 2 summarizes the specifications of MMFs. These were designed with finite-difference time-domain (FDTD) method. The thickness of the films is 2-micron. We measured the transmittance of the film at the peak is measured as 85%, while the predicted transmittance is over 95%. This difference is considered to be due to manufacturing processes such as wrinkles on the films and inaccuracy of the holes. To prevent transmission at the shorter wavelength, we install four films stacked with the gaps of a few mm in the MAX38 filter wheel (see Figure 2). Figure 3 shows the transmission curves of the MMFs. The stacked MMFs have about 80% transparency at the peak with a blocking of 10^{-5} at the shorter wavelength. The width of the MMFs is R~15. The MMFs can survive a number of vacuuming and thermal cycles. Therefore, these MMFs are sufficient for 30-micron band observation.

2.2 Cold Chopper

The cold chopper is a newly developed oscillating mirror system under cryogenic temperature (below 10K) [10], which enables chopping observations as a substitution of chopping secondaries. Chopping technique is vital to reduce the noises caused by atmospheric turbulence and detect signals from targets for mid-infrared observations, especially 30-micron observations. The chopper on the MAX38 optical bench is cooled to about 7 K. It enables square-wave chopping with a 50-arcsecound throw on the sky at a frequency more than 5 Hz. A piezoelectric actuator (PZT) drives the chopping mirror to switch the field of view of the MAX38 detector. Gap sensors monitor the position of the chopping mirror to drive the PZT with closed-loop feedback control.

We also developed a new PZT actuator optimized for cryogenics. The PZT actuators are usually made for using at room temperature, while some PZTs are available at cryogenic temperature. However, these PZTs are very fragile against heating and cooling cycles. These typically cause short circuits and damages within a few ten cycles. By the better quality control and the use of harder ceramics, we achieved to make PZTs with a high reliability and a high stroke length in cryogenics. We tested the new PZTs for endurance and found that they are proof against at least 60 thermal cycles. Furthermore, the stroke of the new PZTs at cryogenic temperature is 2.4 micron, that is three times as long as the old PZTs with the same physical length of 30 mm. As a result, the stroke of the cold chopping system has been wide enough to carry out mid-infrared chopping observations for most of the astronomical objects.

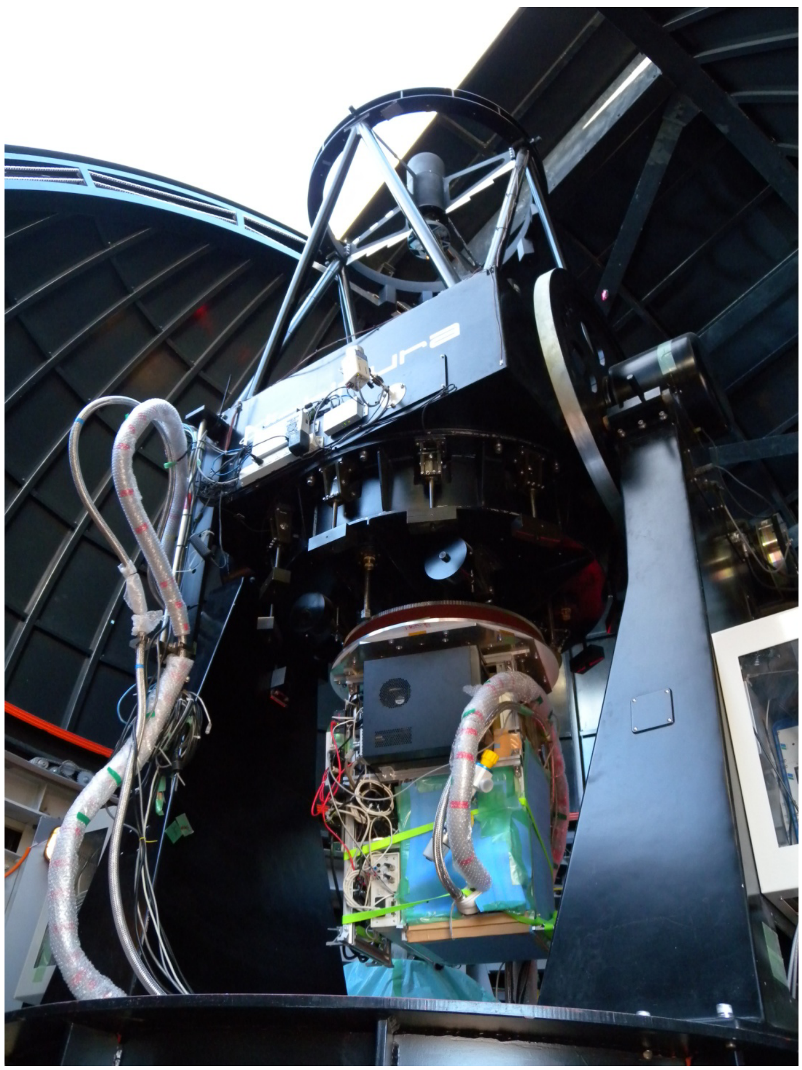

Figure 4. MAX38 on the miniTAO telescope.

3. FIRST LIGHT OBSERVATIONS AT MINITAO TELESCOPE

On November 8, 2009, we achieved the first-light observations of MAX38 on the miniTAO telescope. Figure 4 shows MAX38 mounted on the Cassegrain focus of the miniTAO telescope. Commissioning observations are carried out for two weeks in November.

3.1 30-micron band imaging

Figure 5 displays images of IK Tau, a Mira variable, at 31 micron (left) and 37 micron (right). These images are taken by using Chop-and-nod mode, so that two positive and two negative images are shown in an image. The plate scale of the 31-micron image is 1.26 arcsec/pixel. The 2x2 pixel binning is used for the 38-micron image, so that the plate scale is 2.52 arcsec/pixel.

Vignettings are seen in the upper left of each panel. In addition stellar images are slightly elongated. Full width half maximum (FWHM) of the image along to the major-axis is 10.6 arcsecond while the FWHM along the minor-axis almost corresponds to the diffraction limited resolution of 9.3 arcsecond. These could be caused by minor misalignment of the MAX38 optics. We are planning the alignment of the optics before the next observation.

Figure 6 displays a mid-infrared image of the Galactic center region with the 12.2-micron filter (left) and the 31-micron filter (right). The exposure time of each image is 50 seconds. Extended structures from the Galactic center to the north direction can be seen. This seems more extended and more prominent in the 31-micron image. This corresponds to a cold (~100K) dust cloud associated with the mini spiral structure around the Galactic center. Deeper and wider image will be obtained in the near future.

3.2 Image quality and system efficiency

The image quality of MAX38 was verified with N-band filters. The FWHM of an image of a point source object is 2.5 arcseconds at 8.9 micron filter (Figure 7), which agrees with the diffraction limit of the telescope. Although the images should be affected by the misalignment of the optics discussed in Section 3.1, the differential between the longitudinal and transverse length corresponds to 0.4 arcsecond, which is too small to discern. Nearly diffraction-limited images also indicate that displacements caused by the cold chopping system and the telescope pointing are negligible.

We examined the system efficiencies of the instrument with observations of bright standard stars. In the N-band, the measured system efficiencies are 2.5% at 8.9 micron and 3.9% at 12.2 micron. These values include the atmospheric transmittance, the optics throughput, and the quantum efficiency of the Si:Sb detector. Assuming that the quantum efficiencies are 6.0% at 8.9-micron and 9.0% at 12.2-micron, these are reasonable results. Measurements of the efficiencies in the 30-micron band are difficult because of poor number of bright standard stars. We estimated that the system efficiencies from the extrapolation of the quantum efficiency of the detector at 31 micron and 37 micron are 10% and 5%, respectively. These values are consistent with the measured flux of IK Tau at 31 micron and 37 micron mentioned in previous section, while there remains the uncertainty because of the variability of IK Tau in a few magnitudes.

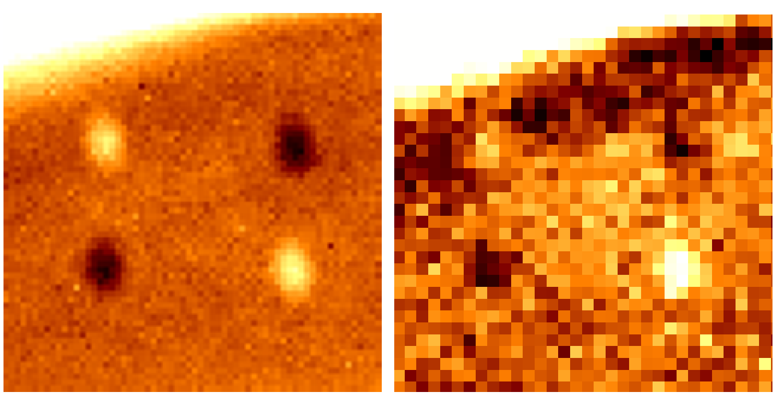

Figure 5. 30-micron band images of IK Tau with (*left*) MMF-31 and (*right*) MMF-37. The field of view of each image is 80 arcseconds square. Although vignettings are seen in the upper light of each image, we are considered to be able to realignment the optics and remove it before the next observation.

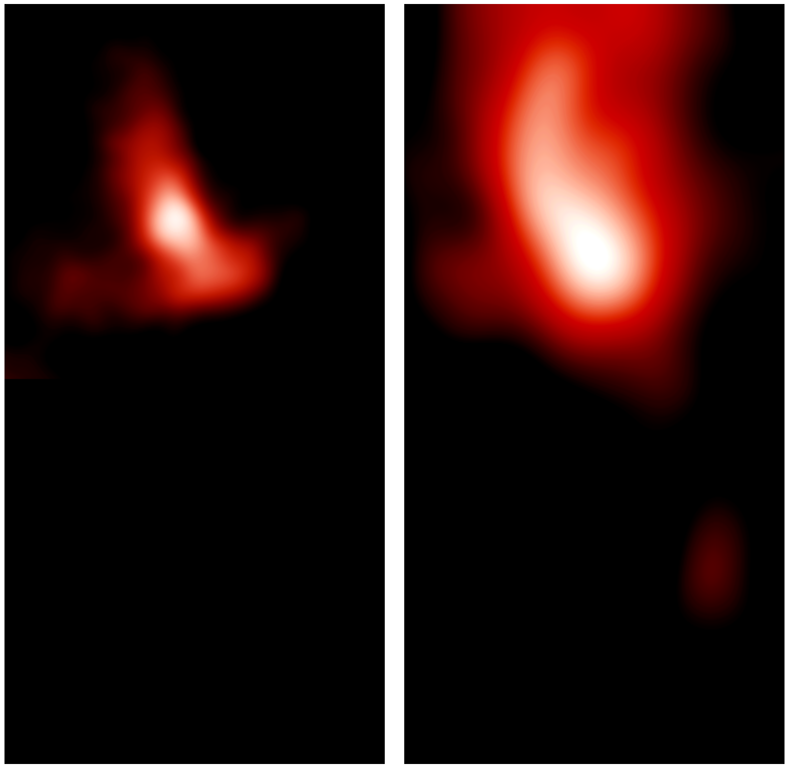

Figure 6. (*Left*) 12.2-micron and (*right*) 31-micron image of the Galactic center region. The field of view of each image is 40x80 arcseconds. The brightest part of the 31-micron image corresponds to the Galactic center. The 31-micron image can indicate the existence of the extended structure of cold dust.

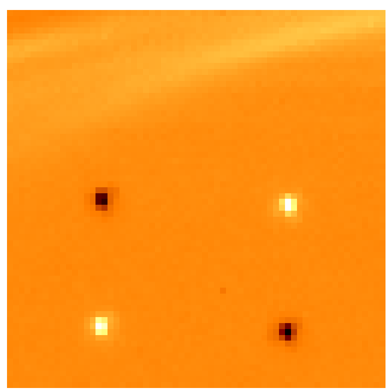

Figure 7. An 8.9-micron image of pi1Gru. FWHM of the images is 2.5 arcseconds, which agrees with the diffraction limit of the telescope.

3.3 Measurement of Atmospheric transmittance

For ensuring that there are atmospheric windows at 30-micron band at miniTAO site, we carried out spectrometric measurements of the atmospheric emission at the zenith with the low-dispersion grism spectroscopy mode. We also observed the emission from the mirror cover of the telescope as a greybody source. An atmospheric transmittance was calculated from these two spectra with estimating temperatures of the sky and the telescope from the miniTAO weather monitor and supposing that the throughput of the telescope mirrors is 90% at the mid-infrared wavelength. Figure 8 shows the measured atmospheric transmittances.

We investigated the variation of atmosphere with a precipitable water vapor (PWV). Table 3 summarizes the observing date of the spectroscopy and the measured PWV at the time. We utilized PWV data measured by a radiometer of Atacama Pathfinder Experiment (APEX) in the ALMA site at 5100m altitude, near Co. Chajnantor. While the measured transmittance on Nov 22 shows no atmospheric windows at the 30-micron wavelength, several windows appeared on Nov 17.

To compare the measured transmittance with a model calculation, we computed the atmospheric transmittance with PWV equal to 1.3mm, which is corresponded to the measured PWV value by APEX on Nov 17. Considering that the measured transmittance has an error of about 10%, it gives reasonable agreement with the model calculation. We note that the PWV of 1.3mm is above average of the PWV in 2009. The percentage of the time with the PWV < 1.3mm is approximately 60 % according to the APEX PWV monitoring. These clearly demonstrate that the atmospheric windows at the 30-micron wavelength range can be used for astronomical observations in more than half of the night.

Table 3. The list of the PWV values on selected days. We utilized PWV data measured by Atacama Pathfinder Experiment (APEX).

Date	PWV (mm)
Nov 17, 2009	2.1
Nov 22, 2009	1.3

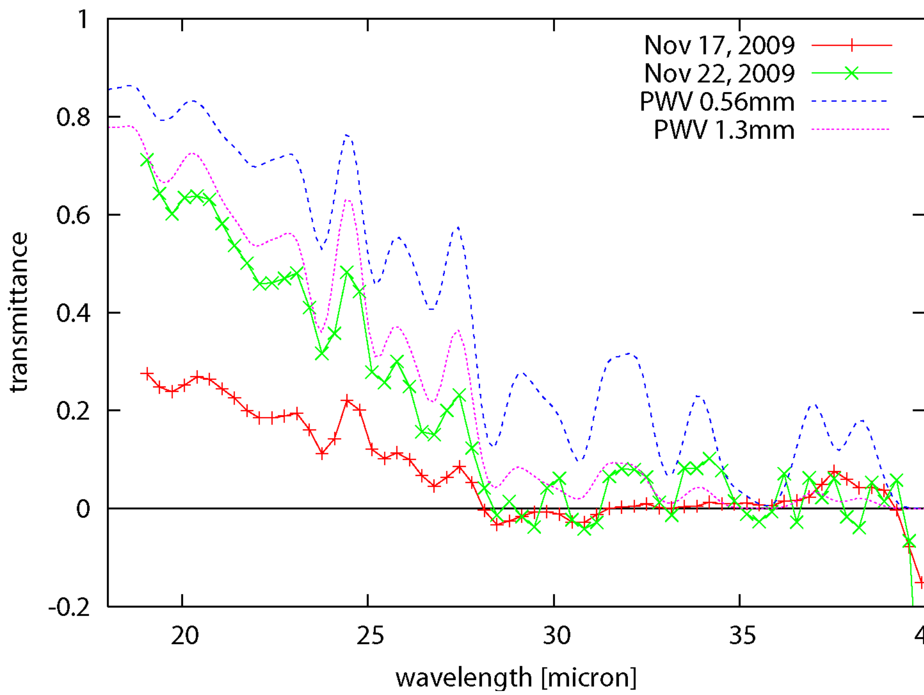

Figure 8. The measured atmospheric transmittance of shown day with the model calculations by ATRAN with PWV equal to 0.56 (25%-tile) and 1.3mm (corresponded to the value of Nov 22). It clearly shows that the atmospheric windows of 30-micron band are available under low PWV conditions. Additionally, the measured transmittance of Nov 22 is well accorded with the calculated one.

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REFERENCES

[1] Sako, S., et al., "The University of Tokyo Atacama 1.0-m Telescope," Proc. SPIE 7012, 70122T (2008).
[2] Minezaki, T., "The University of Tokyo Atacama 1.0-m Telescope," Proc. SPIE, in this conference (2010).
[3] Yoshii, Y., et al., "Tokyo Atacama Observatory Project" Proc. of the IAU 8th Asian-Pacific Regional Meeting, p.35 (2002)
[4] Yoshii, Y., et al., "The University of Tokyo Atacama Observatory 6.5m Telescope Project," Proc. SPIE, in this conference (2010).
[5] 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).
[6] Miyata, T., et al., "Site Evaluations of the Summit of Co. Chajnantor for Infrared Observations," Proc. SPIE 7012, 701243 (2008).
[7] Miyata, T., et al., "A new mid-infrared camera for ground-based 30 micron observations: MAX38," Proc. SPIE 7014, 701428 (2008).
[8] Lord, S. D., "A new software tool for computing Earth's atmospheric transmission of near- and far-infrared radiation," NASA Technical Memorandum, 103957 (1992).
[9] Sako, S., et al., "Developing metal mesh filters for mid-infrared astronomy of 25 to 40 micron," Proc. SPIE 7018, 701853 (2008).
[10] Nakamura, T., et al., "Cold Chopper System for Mid-Infrared Instruments," Proc. SPIE 7018, 70184H (2008).