

Cold Chopper System for Mid-infrared Instruments

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ABSTRACT

We have developed a cold chopper system for mid-infrared observations. This system is installed into the newly developing mid-infrared instrument, MAX38, for the University of Tokyo Atacama 1.0-m telescope. It is cooled to about 9K. The cold chopper mirror is controlled by a piezoelectric actuator with a flexure hinge lever, and enables square-wave chopping at a frequency up to 7.8 Hz. At the moment, the maximum throw of the chopper is 30 arcseconds on the sky. This cooled chopping mirror system can also be applied to the tip-tilt mirror for SPICA infrared space telescope. We carried out the first light with Kanata 1.5-m telescope at Higashi-Hiroshima Observatory (Hiroshima, Japan) in June 2007 and March 2008. In this observation, we demonstrated that the cold chopper could cancel out the atmospheric turbulence noise of a frequency of 5 Hz at 8.9 micron.

Keywords: mid-infrared, chopping, tip-tilt, piezoelectric actuator, SPICA

1. INTRODUCTION

In ground-based mid-infrared observations, atmospheric radiation and telescope emission cause high-level noises. Chopping technique is vital to reduce their noises and detect signals from targets for mid-infrared observations. Conventionally, we employed a chopping secondary, which is a system of oscillating the telescope secondary mirror at a frequency of a few Hz, e.g. Subaru Telescope¹.

Chopping secondary systems, however, are not installed in all of telescopes and many medium size telescopes without them cannot conduct mid-infrared observations. In addition, it is expected that next-generation telescopes will have larger secondary mirrors, which cannot be oscillated for chopping observations. Instead of the chopping secondary systems, we need to develop the other oscillating mirror system to carry out mid-infrared observations. This system must be cooled to cryogenic temperature (below 10K), because mirrors at room temperature cause thermal radiation noises. However, such a cooled chopping mirror system has not been established enough to be applied to astronomical observations. It will be able to use not only chopping mirrors but also widespread applications such as a tip-tilt mirror for SPICA infrared space telescope, which needs a directionality control against vibrations of the satellite.

We have developed the cold chopper system to be installed into the newly developing mid-infrared instrument, MAX38 (Mid-infrared Astronomical eXplorer; Details are described in Miyata et al.²), for the University of Tokyo Atacama 1.0-m telescope. (Details are described in Sako et al.³) This telescope and MAX38 will have a capability for 8-38 micron mid-infrared observations, and the telescope has no chopping secondary system. Therefore, the cold chopper enables MAX38 to carry out mid-infrared observations.

In section 2, we will present an overview of the cold chopper system. In section 3, the performance of this system will be evaluated, and in section 4, we will discuss the result of the evaluations.

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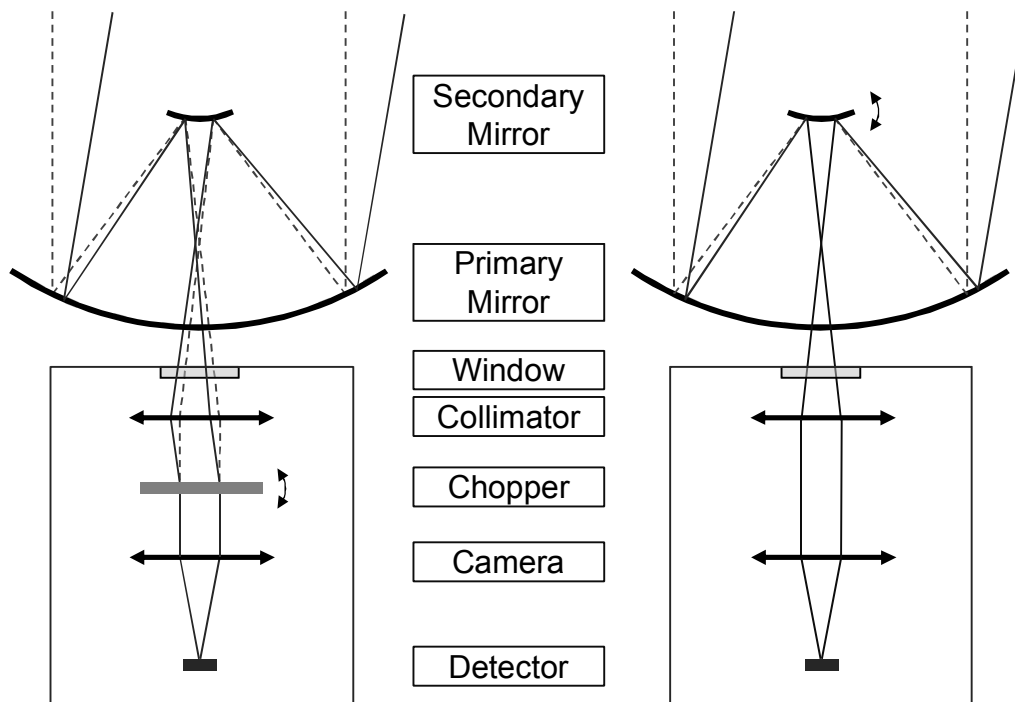


Fig. 1. Schematic diagrams of internal chopping (left) and secondary chopping (right). Conventionally, we used secondary chopping to switch between two positions of the field of view. Instead of this system, we use the cold chopper, which is installed in the optics of the instrument.

2. OVERVIEW OF COLD CHOPPER

Figure 2 shows an external view of the cold chopper, and figure 3 shows an internal structure of this system. It is built into the optics system of MAX38 dewar. The optics including the chopper is cooled to about 9K. 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. The following is explanations of each element of the chopper.

2.1 Mirrors

The cold chopper has two mirrors, the chopping mirror and the fixed mirror. The incoming beam to the chopper is reflected by the chopping mirror placed at a tilt angle of 45 degree, and then travels to the fixed mirror. The surface of the fixed mirror is a pupil plane of the optics of MAX38. The beam reflected by the fixed mirror is reflected by the chopping mirror once again, and go out of the chopper. As a result, the light path of the outgoing beam is tilted at quadruple as much degree as the chopping mirror is.

The chopping mirror should be placed on a pupil plane of the optics, because the pupil plane is the only place where the lights from point sources diffuse uniformly in whole of the beam. This system, however, employs two mirrors to amplify the tilt degree of the outgoing beam path, and increase the chopping throw on the images. This two-mirror optics redeems short strokes of the piezoelectric actuators at cryogenic temperature. This optics has a very small effect on the quality of the images.

The chopping mirror must fulfill the following specifications; light enough to be driven at a high frequency, and no deformations even when the system is cooled to cryogenic temperature. We use a diamond-turned aluminum mirror deposited by gold evaporation developed by the advanced technology center of the national astronomical observatory of Japan. Since parts of the chopper are made of aluminum alloy, the deformations of whole system are minimized. The mirror size is 60mm x 60mm x 6mm, and it has a diagonal pivot axis.

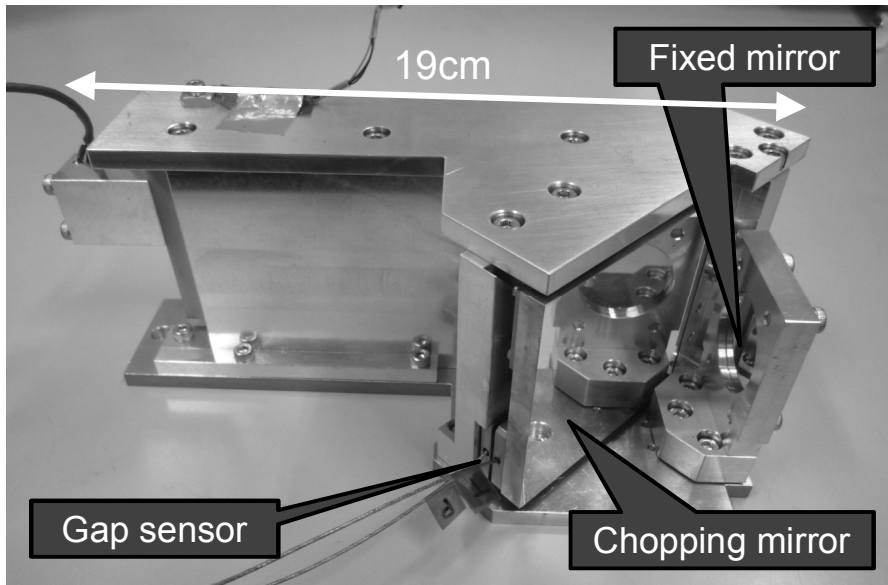


Fig. 2. External view of the cold chopper system. The right-hand circular mirror is fixed and placed on a pupil plane of the optics of MAX38. The chopping mirror is a 6-cm square plane mirror driven by the piezoelectric actuator. The gap sensors monitor the position of the chopping mirror for feedback control.

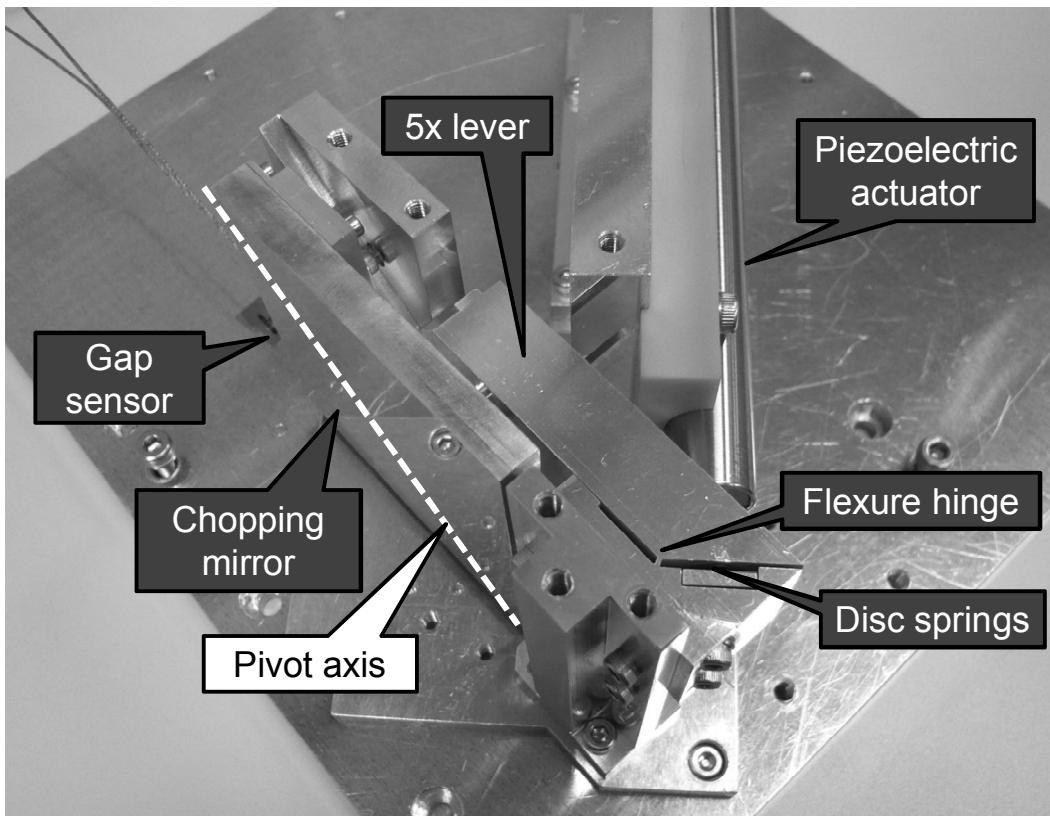


Fig. 3. Internal structure of the cold chopper system. The piezoelectric actuator drives the chopping mirror through the 5x flexure hinge lever. The mirror tilts around the diagonal pivot axis. The disc springs press the lever and help to improve the resonance frequency of the chopper.

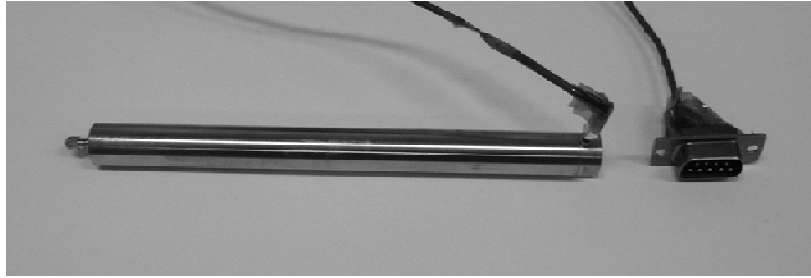


Fig. 4. Piezoelectric actuator (PZT). the original connector are replaced with D-sub 9-pin connector to use under a cryogenic temperature.

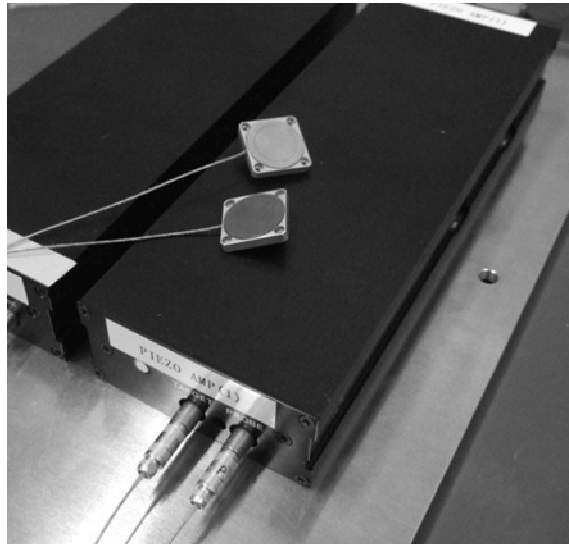


Fig. 5. Gap sensor electrodes and module. They work when the distance of electrodes is between 250- and 750-micron

2.2 Piezoelectric actuator (PZT)

Drive elements for the chopping mirror are required to have high response speed and low power loss. Piezoelectric actuators (PZTs) are one of the best devices for this system. The PZTs utilize piezoelectric effect of ceramic material, and it consists of a large number of contacted ceramic disks. The head of the PZT is a round-head shape to push the lever, and the bottom of the PZT is fixated by a screw.

We employ a low voltage piezoelectric actuator PSt150/7/160 VS12 for cryogenic operation manufactured by Piezomechanik GmbH⁴. It has a length of 15 cm, and load force of 1000 N. The stroke without load is about 130 micron at 300K and 4 micron at 10K, which is not enough for the chopping observations. We have applied a flexure hinge lever to amplify the stroke of the PZT.

2.3 Flexure hinge lever

We use the 5x flexure hinge lever to amplify the stroke and get a enough tilt of the mirror. Flexure hinges are suitable and widely applied for fine motion mechanisms. The sizes of this hinge are determined by considering the balance between the resonance frequency of the chopper mirror and the load forces for the PZT head. The hinge sizes are 0.5mm x 1mm x 20mm at the side of the PZT and 0.6mm x 1mm x 2mm at the side of the chopper mirror. Disc springs are placed between the flexure hinge lever and the stationary part of the chopper. The springs help to improve the resonance frequency of the chopper.

2.4 Gap sensor

The gap sensor is a device to monitor the position of the chopping mirror for closed-loop feedback control. We use a NX NanoSensor® NXC and a sensor controller NS2000 manufactured by Queensgate Instruments Ltd⁵. The NanoSensor consists of two sensor electrodes, Target and Probe, which form plates of a capacitor. They are connected to the NS2000

module, which produces an analogue output proportional to the sensor spacing. The accuracy of the measurement of the spacing is 0.5 micron, which is sufficient for the closed-loop control. The measurement bandwidth is 5 kHz, which is higher than the mechanical resonance frequency of the chopping system. In this system, the Probe sensor is attached to backside of the chopping mirror, and the Target sensor is fixed. They will not be exactly parallel while the mirror is tilting, but it affects no problems for feedback control using output voltages of the gap sensor module.

2.5 Feedback control

We employ a Proportional-Integral-Derivative (PID) feedback control for driving PZT. Figure 6 shows the feedback system. The computer monitors the output of the gap sensor module using the analog-digital converter board at a 5 kHz sampling rate, and drives the PZT through PZT amplifier module at the same rate. The operating system of the computer is Vine Linux patched with RTAI⁶, the RealTime Application Interface, which enables the real-time device control on the computer. The PID parameters are empirically adjusted at present.

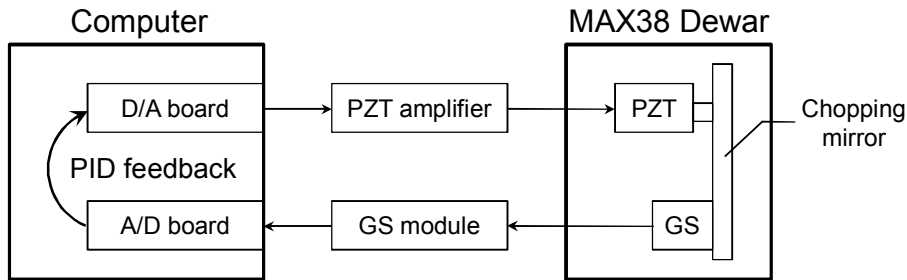


Fig. 6. The diagram of MAX38 chopper feedback system.

3. PERFORMANCE EVALUATION

We evaluated the characteristic frequency, the settling time, the stability, the residual patterns from chopping subtraction and the denoising performance for atmospheric turbulence noise. The evaluation of the characteristic frequency is carried out in a laboratory at Institute of Astronomy, University of Tokyo (Tokyo, Japan), and the other evaluations are carried out with Kanata Telescope at Higashi-Hiroshima Observatory (Hiroshima, Japan).

3.1 Characteristic frequency

We observed the characteristic frequency of Chopping mirror by controlling PZT with open-loop control. When PZT extends, a damped sinusoidal oscillation is seen in the output of the gap sensor. The time of the PZT extension is negligible because it is much smaller than the period of the characteristic oscillation. Figure 7 shows the output from gap sensors in controlling PZT with open-loop control. This curve is fitted closely a damped oscillation curve with a frequency of 130Hz.

3.2 Settling time and stability under closed-loop control

We drove the PZT at a square wave with a closed-loop feedback control. The gap sensor response during the closed-loop control is in the left of figure 8. It takes less than 30 milliseconds until the chopping mirror moves from one position to another. Once the chopping mirror settles in one position, the root-mean-square value of fluctuation of the chopper mirror is 0.7 pixels on the MAX38 detector, which corresponds to 0.8 arcseconds on the sky. When the chopping frequency is 7.8 Hz, the exposure time is the half of the total observing time. It will be the maximum limit of the chopping frequency. In the 2-Hz chopping observation, the exposure time is the 87% of the total observing time.

The chopper is installed in the MAX38 camera on the Cassegrain focus. It is inclined during observations. We examined the behavior of the chopper when the chopper is inclined. The right of figure 8 shows the gap sensor response while the chopper inclines at a 60-degree angle, i.e. the telescope pointing at 30-degree elevation. There is no clear difference in the settling time and the stability of the chopping mirror.

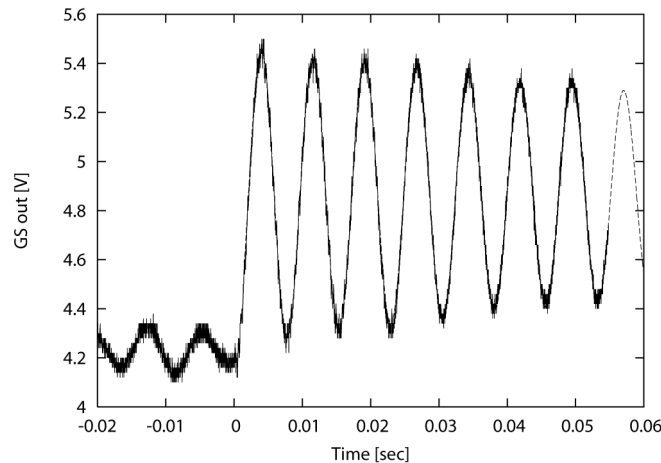


Fig. 7. The response curve of the gap sensor (GS) when the PZT is applied a voltage and expands. The dashed line is a damped oscillation curve fitted in the response curve. Two curves are almost overlapping. The frequency of the fitted curve is 130 Hz.

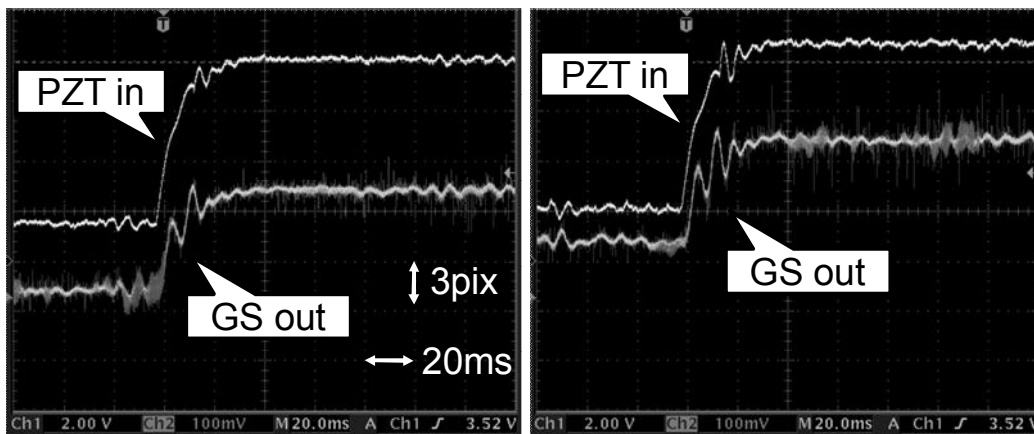


Fig. 8. The input voltage to the piezoelectric actuator (PZT) and the output voltage from gap sensor (GS) during a closed-loop feedback control. The left figure is data when the telescope points at the zenith and the chopper stands, and the right one is those when the telescope points at 30-degree elevation and the chopping mirror is in a downward direction. They show we can control the chopping mirror with a properly closed-loop control irrespective of inclination of the chopper.

3.3 Residual pattern from chopping subtraction

Since the optical paths of two chopped beams are slightly different from each other, a subtracted image obtained from one beam image to another one has residual patterns. In the conventional secondary chopping, the residual is mainly caused by the different illumination of the primary (the right of figure 1). In the internal chopping, the radiation from the window and the optics of the instrument cause additional residual patterns (the left of figure 1).

A sample of the residual patterns obtained with the internal chopping is shown in the left of figure 9. These images were taken by 1.9-Hz chopping and using a 9.8-micron filter. The amount of the residual pattern is less than one percent of that of the raw image. This pattern is thought to be mainly caused by the radiation from the dewar window, because almost the same pattern appears without the dewar mounting on the telescope. The residual patterns can be canceled out by nodding, which is the technique that the telescope takes a several tens of arcseconds move on the sky every several tens of seconds. We can remove the residual patterns by subtracting between the images of two nodding positions. The right of figure 8 is the image of the result of the nodding subtraction. The background of the image becomes flat, and the counts of the background decrease less than a 0.1% of those of the residual pattern. The root-mean-square deviation is

150% of the photon shot noise. It means chop and nod observations with this system are effective for reducing atmospheric turbulence noise. In addition, the images of the star, S Vir, achieve diffraction-limited spatial resolution, indicating that the optics including the chopper with closed-loop control gives good optical performance.

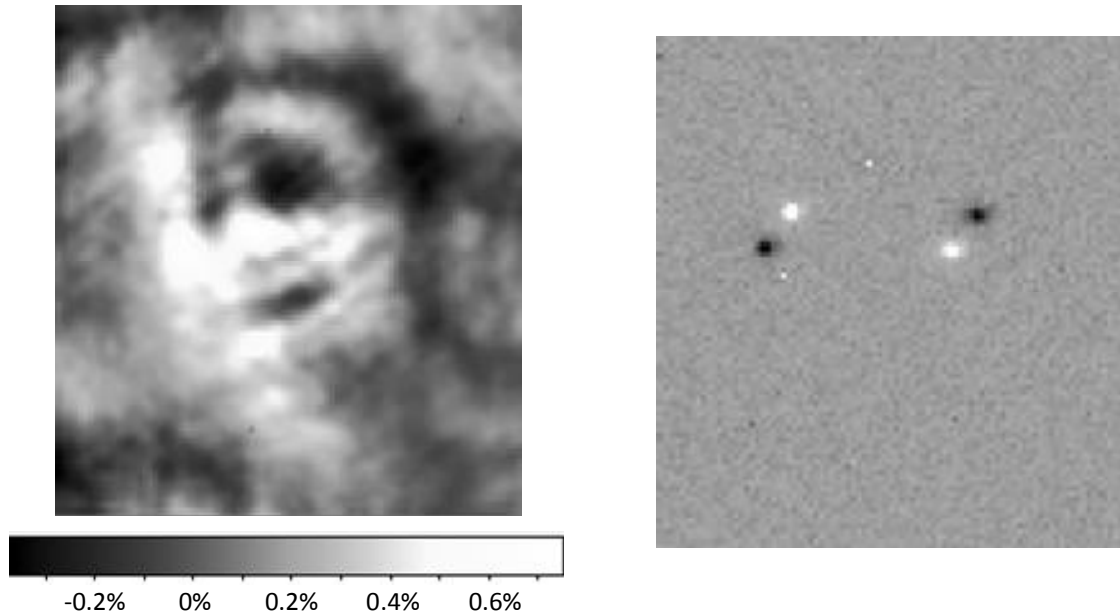


Fig. 9. (Left) a residual image after chopping subtraction. (Right) an image after nodding subtraction. The images were taken by 1.9-Hz chopping and using a 9.8-micron filter. The residual pattern of left image is mainly caused by the radiation from the window of the dewar. This pattern can be reduced by nodding subtraction.

3.4 Denoising performance for atmospheric turbulence noise

We confirmed the denoising performance for atmospheric turbulence noise. Atmospheric turbulence noise is caused by mainly two origins, a “ $1/f$ ” noise due to variations in sky background radiation and a Kolmogorov turbulence, which has an $f^{5/3}$ noise. Because the powers of noises are functions of the frequency, the denoising performance of chopper varies with the chopping frequency. A chopping at a proper frequency can reduce these noises and they will be negligible compared with photon shot noises. This frequency depends on the site of the telescope and the atmospheric condition.

Figure 10 shows the power spectrum of sky noise measured at the KANATA Telescope. The spectrum is derived from imaging sky blank frames every 20 milliseconds. We also derived the power spectrum of photon shot noise from the counts of adjacent pixels on an image. The photon shot noise spectrum is consistent with the theory that it is equal to the variance of the counts. The power spectrum of the atmospheric turbulence noise can be fitted in an $f^{1.44}$ curve. The power of -1.44 is between -1 of a “ $1/f$ ” noise and $-5/3$ of a Kolmogorov noise.

Next, we carried out the chopping observations at various chopping frequencies. Figure 11 shows the relation between chopping frequencies and observed noises. The observed noises are consistent with the line fitted into the spectrum of sky noise, and the noises almost agree with the photon shot noise with a frequency of more than 5 Hz. Therefore, it is confirmed that the atmospheric turbulence noise is almost cancelled out when the chopping frequency is more than 5 Hz.

Table 1 shows the specifications of the cold chopper on MAX38.

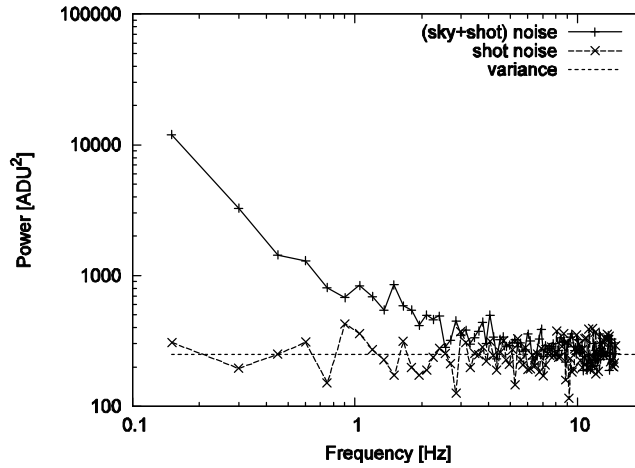


Fig. 10. Power spectrum of the combination of atmospheric turbulence noise and photon shot noise (solid line) and that of only photon shot noise (dashed line). The dotted line shows the variance of counts of each pixel, which corresponds to photon shot noise. The slope of the (sky + shot) noise line is approximately -1.44. This is consistent that the noise is a combination of “1/f” noise and a Kolmogorov noise.

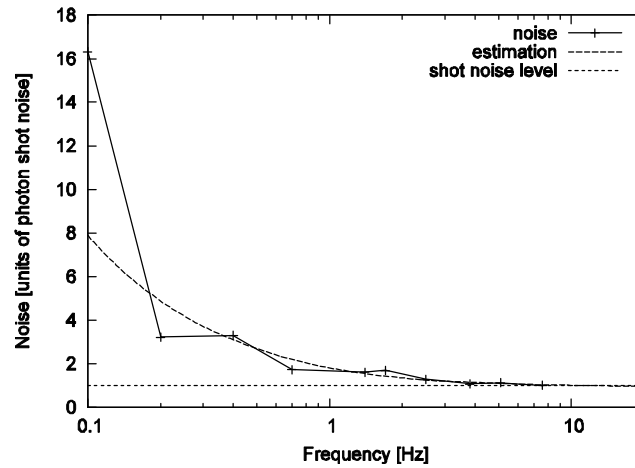


Fig. 11. Relation between chopping frequencies and observed noises. The noises are normalized by the photon shot noise level. The gray dashed line is a line of a -1.44 slope in Figure 9, which is the approximation of the (sky + shot) noise. The points of noises at each chopping frequency are consistent with this estimation line.

Table 1. The specifications of the cold chopper system on MAX38.

Drive axis	1 axis	
Max. mirror tilting angle	4.1 arcmin	
Max. chopping throw angle	30 arcsec	On the mini-TAO telescope
Control precision	0.8 arcsec	0.7 pixel on the detector
Resonant frequency	130 Hz	
Max. chopping frequency	7.8 Hz	At two-point chopping
Power loss	< 100mW	
Reachable temperature	9 K	

4. DISCUSSION

The results of the observation show the cold chopper is practical for mid-infrared chopping observations. The chopper has an adequate ability to carry out photometric observations of point-like sources and many diffuse sources. However, we need some improvements on the chopper for observing some extended targets or applying to SPICA tip-tilt mirror.

First, the chopper needs to have biaxial mechanics. It enables to move the targets freely on the detector. This mechanics is essential for the SPICA tip-tilt mirror. We expect to make biaxial mechanics by changing the pivot structure of holding the chopper mirror. Second, the maximum chopping angle is to be increased. We need 60-arcseconds chopping to observe extended sources, such as the center of the Galaxy. We will improve the flexure hinges. Finally, the power loss is needed to decrease. The power loss of the PZT is about 100 mW at a maximum chopping throw and frequency. The decrease of one or two order of magnitude is desired for satellite telescopes such as the SPICA. We are developing a lower power loss and larger stroke PZT by choosing the type of ceramics, which is suitable for a cryogenic temperature. When the development of PZT is completed, the chopper will have a sufficient capacity for applying a variety of use.

5. CONCLUSION

We have developed the cold chopping system for mid-infrared instruments. This system was installed in the new mid-infrared camera MAX38 for the Atacama 1.0-m telescope, and it is cooled to about 9K. The cold chopper mirror is controlled by a piezoelectric actuator with a flexure hinge lever. The chopper has the capability to conduct a 7.8 Hz chopping observation. The maximum throw of the chopper is 30 arcseconds on the sky. This system can be applied to the tip-tilt mirror for SPICA infrared space telescope when we carry out some improvements to it. The first light observations with Kanata 1.5-m telescope at Higashi-Hiroshima Observatory (Hiroshima, Japan) were carried out in June 2007 and March 2008. We demonstrated that the cold chopper has the capability to cancel out the atmospheric turbulence noise in chop and nod observations.

We are grateful to all of TAO project members and SPICA working group members for their support to this project, and to Mr. Okada, Mr. Fukushima, Mr. Mitsui, and Mr. Obuchi of the Advanced Technology Center, National Astronomical Observatory of Japan for their helpful support for the development of the aluminum mirrors and the flexure hinge levers. We also thank the staff of the Higashi-Hiroshima Observatory for their kindly help for the test observations. This research was supported by Ministry of Education, Culture, Sports, Science and Technology of Japan, Grant-in-Aid for Scientific Research on Priority Areas, "Development of Extra-solar Planetary Science," National Astronomical Observatory of Japan, Research Grant for Joint-development, and Japan Aerospace Exploration Agency.

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