ALMA memo 458
Preliminary Tests of Cartridge-Type Receiver System at Atacama Site

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Abstract

We have developed a cartridge-type receiver system composed of three cartridge-type receivers and a cryostat, which is designed to test on the Atacama Submillimeter Telescope Experiment (ASTE). It was preliminary evaluated at Pampa la Bola (alt. 4800 m) in the northern Chile since November 2002. The cryostat, which can house 3 cartridge-type receivers, has been developed with following technologies; a central pipe and bellows structure to reduce mechanical vibration; simple and efficient thermal links for plug-in cartridges; 3-stage Gifford McMahon cryocooler and an outdoor compressor. Engineering models of band 3 (100 GHz), band 8 (500 GHz), and band 10 (800 GHz) cartridge-type receivers were independently developed with cartridge-test cryostats. They were integrated into the cryostat at NAOJ, then the system was shipped to the site. We confirmed that the system including three receivers operates as designed and the concept of cartridge-type receiver system is very promising for the ALMA.

Key words: Cryostat, Cartridge, Cryocooler, ASTE

1. Introduction

We have developed a cartridge-type receiver system including three frequency cartridges to test on ASTE 10 m telescope. The main purpose is to test and evaluate cartridge concept of ALMA frontend (FE). The ALMA requires easy assembly and easy maintenance of a large number of heterodyne receivers. To produce and operate several hundred receivers, the cartridge concept was introduced (e.g., Wild et al. 2002). Cartridge-type receivers are equipped with optics, SIS mixers and IF amplifiers, which work under cooled condition. The modular concept with automatic thermal link (Orlowska et al. 2002) is suitable for mass production of ALMA FE. To realize ALMA FE system, it is necessary to test cartridge-type receivers at the site.

Engineering models of band 3 (100 GHz), band 8 (500 GHz), and band 10 (800 GHz) cartridge-type receivers have been developed with cartridge-test cryostats. With these cartridges, alignment of the cartridge to the antenna and stability of receivers were evaluated. In addition, cryogenic system with 3 stage GM cryocooler and compressors were tested at the site.

The ASTE 10 m telescope (Ukita et al. 2000) has been developed as a prototype antenna of the Large Millimeter Submillimeter Array (LMSA, Ishiguro et al. 1998). It was installed on Pampa la Bola following evaluation at Nobeyama.

2. Instruments

2.1. Cryogenic system for the ASTE

A cartridge-type cryostat, which can house 3 cartridge-type receivers, has been developed for the ASTE. The detail of this cryostat was described by Yokogawa et al. (2003). The cryostat is shown in Figure 1. The cylindrical cryostat, whose dimensions are 550 mm in diameter and 650 mm in height, can accommodate 2 cartridges of 170 mm diameter and 1 cartridge of 140 mm diameter. The cryostat is composed of 3 stages, which are connected with corresponding stages of a cryocooler.

The concept of the thermal link for the ALMA receiver was proposed by the Rutherford Appleton Laboratory (RAL) to simplify exchanges of the cartridges and to maintain high thermal conductance between the cartridges and the cryocooler (Orlowska et al. 2002). We have designed and developed a simple and efficient thermal link with high heat conductivity (Sugimoto et al. 2003). This link is composed of 2 components: (1) a crown-like ring made

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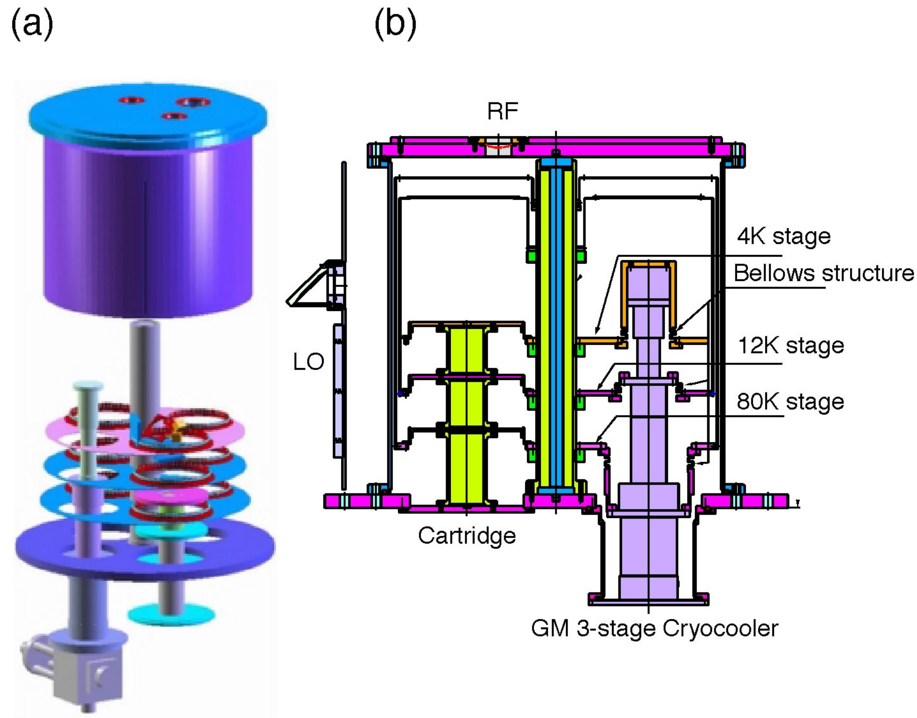

Fig. 1. (a)A schematic drawing of a cryogenic system for the ASTE, which houses 3 cartridge-type receivers. (b)A cross-sectional view of the cryostat. The cryostat is composed of 3 stages (from up to down 4 K, 12 K, and 80 K stage).

of OFCu, and (2) a clamping belt which is a metal spring or a nylon ring. Measured thermal conductance of ϕ170 mm links is 1.7, 5.6, 3.3 W K^{-1} for 4, 12, and 80 K stages. Thermal conductance of ϕ140 mm links is 1.4, 4.4, 3.1 W K^{-1} for 4, 12, and 80 K stages, respectively. This simple and compact links have good performance and can be easily fabricated.

A 3-stage GM cryocooler (Sumitomo RDK 3ST) has a cooling power of 0.8 W at 4.2 K, 8 W at 12 K, and 33 W at 80 K with a 7 kW outdoor compressor (Sumitomo CNA-61), whose dimensions are 1028 mm in width, 321 mm in depth, and 901 mm in hight.

2.2. Cartridge Structure

The concept of the cartridge for the ALMA was proposed by the RAL (Orlowska et al. 2002). NAOJ have developed cartridges which have compatible interface to the ALMA receiver cartridges. The cartridge structure is supported by the central pipe as shown in Figure 2a, b.

There are two kinds of central pipes made of GFRP for cartridge structure. One is 60 mm in diameter and 5 mm in thickness. The other is 90 mm in diameter and 3 mm in thickness. The heat flow of both types is 28 mW, 263 mW and 1.06 W to 4 K from 12 K, to 12 K from 80 K, and to 80 K from 300 K, respectively. The gravitational deformation with 2 kg mass at the 4 K stage is 20 μm and 45 μm for 90 mm diameter and 60 mm diameter, respectively.

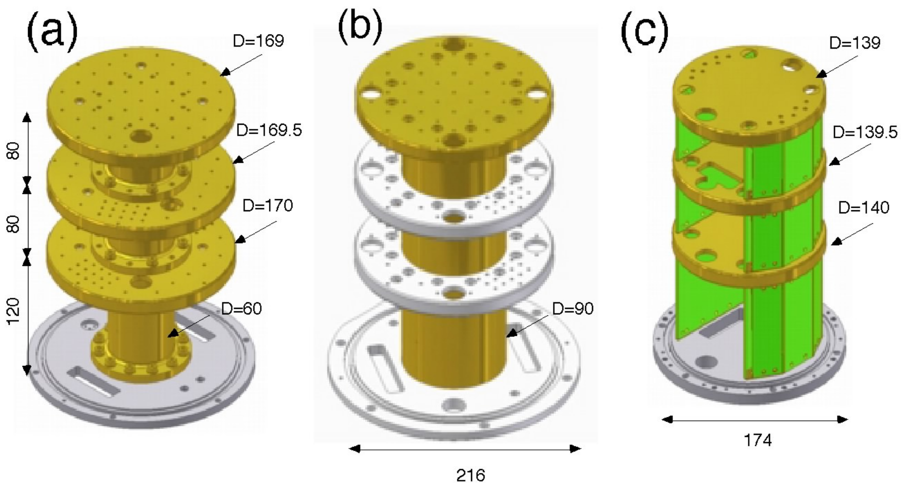

Fig. 2. (a) A schematic drawing of the ϕ170 mm cartridge made by NAOJ. The central pipe is made of glass fiber reinforced plastic (GFRP). With this type cartridge, one can assemble receivers without decomposition of the cartridge. (b) The same in (a), but for ϕ90 mm central pipe. (c) A schematic drawing of the ϕ140 mm cartridge made by Osaka Prefecture University/Nagoya University. Their cartridge is supported by divided plates placed on the circumference. This cartridge provides accessibility and spaciousness.

In comparison with NAOJ cartridge structure, a structure which proposed by the RAL is supported by the outer shell. Although the RAL cartridge is strong against gravitational deformation, decomposition of the cartridge is indispensable to assemble receivers. On the other hand, one can assemble and maintain receivers without decomposition of the NAOJ cartridge. However, a demerit is that there are limited spaces, especially for cold multipliers.

The ϕ140 mm cartridge has been designed and developed by Osaka Prefecture University/Nagoya University is shown in Figure 2c. Support structure of their cartridge is composed of divided plates placed on the circumference. This cartridge provides accessibility and spaciousness.

2.3. Band 10 cartridge-type receiver

An engineering model of band 10 cartridge-type receiver has been developed and is shown in Figure 3. Lamb et al. (2001) proposed a detailed design for the optical configuration for all band receivers. We designed and developed a single mirror optics which couples between a feed horn and the subreflector of the antenna. The optics made of pure Al with total weight of 1.7 kg is cooled on the 4 K stage. The optical axis is inclined to the subreflector with a slope of $\sim$0.92 degree (see Figure 4). However, since no cold multiplier is available at present, a conventional local oscillator (LO) is attached on outside of the vacuum vessel at room temperature. A solution for which RF beam-width is independent on frequency is adopted. The dielectric (Kapton, thickness is 12.5 μm) is used for coupling the RF signal with the LO signal. The coupling factor is -10 dB. The optics was designed for dual polarization, however the parts

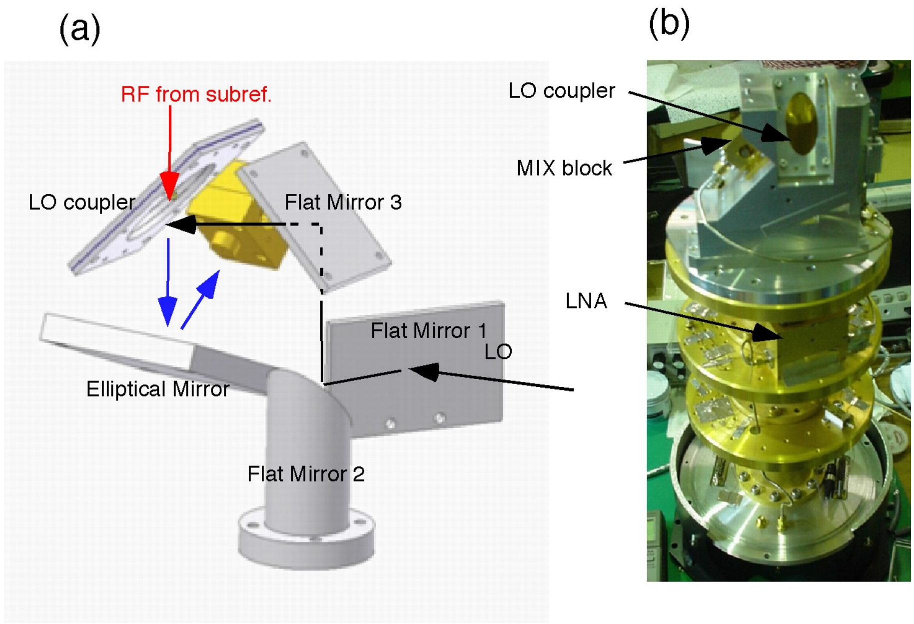

Fig. 3. (a) A schematic drawing of optics of band 10 receiver. (b) A photograph of the band 10 receiver. The RF optics consists of one elliptical mirror. The LO signal, which is introduced from the outside of vacuum vessel, is coupled quasi-optically to the RF signal by the dielectric, Kapton. The coupling factor of LO is -10 dB. The LNA with a gain of 35 dB is attached on the 12 K stage.

of one polarization was only assembled in Figure 3b. A mixer in the receiver is Nb-based parallel-connected twin junction (Shi et al. 1997).

The conventional LO is composed of two frequency triplers and a Gunn oscillator around 90 GHz made by Radiometer Physics. The LO power is around 150 μW from 799 GHz to 831 GHz. The LNA (Nitsuki 0847AD) with a gain of 35 dB in a bandwidth of 4-8 GHz is attached on the 12 K stage. Receiver noise temperature ($T_{\rm rx}$) was about 1000 K in DSB at a LO frequency of 812 GHz.

2.4. Band 8 cartridge-type receiver

An engineering model of band 8 cartridge-type receiver has been developed. The optics and configuration such as LNA etc. are similar to that of the band 10 receiver. Receiver noise temperature ($T_{\rm RX}$) of a mixer T68-A15 was about 240 K (DSB) at 498 GHz.

The SIS mixer is a parallel connected twin junction (Shi et al. 1997). The current density of the junction is ~ 7 kW cm^{-2} and the normal resistance of R_N is 13 Ω. The thickness of the SiO_2 substrate is around 90 μm. Two permanent magnets are used for cancel the Josephson current of the mixer. A conventional LO composed of multipliers and a Gunn oscillator is used. The multiplier is composed of a tripler and a doubler, which were made by Radiometer Physics GmbH. The LO covers $430 - 500$ GHz with power of > 200 μW. A dual mode horn is attached at the output of the multiplier. This receiver was used for noise measurements of hybrid photonic LO (for details, see Sekimoto et al. 2003a).

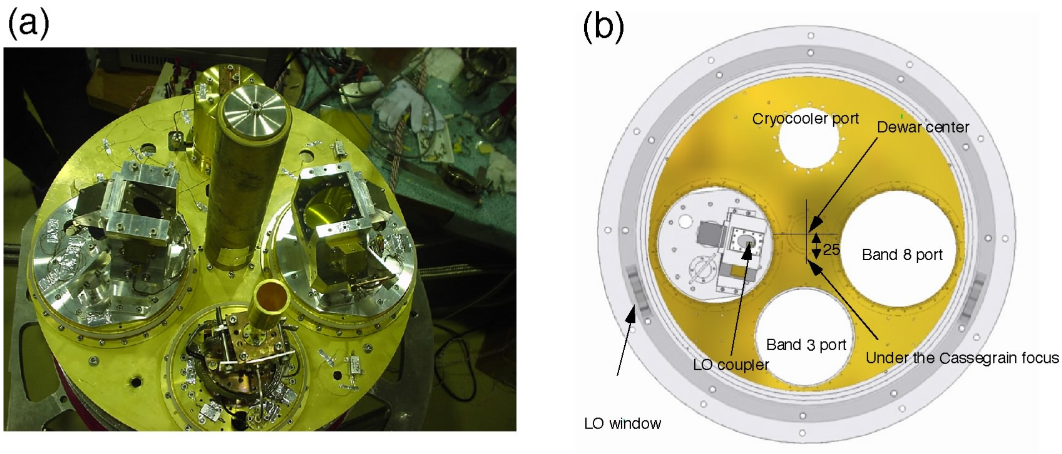

Fig. 4. (a) A photograph of the cryostat. 3 cartridge-type receivers (from right to left, 800 GHz, 100 GHz, 500 GHz) are installed. (b) A schematic drawing seen from the top of receiver system. The optical axis is inclined to the subreflector.

Fig. 5. A photograph of an engineering model of band 3 receiver.

2.5. Band 3 cartridge-type receiver

A engineering model of band 3 cartridge-type receiver (in Figure 5) has been developed as a scaled model of band 4 by Osaka Prefecture University and Nagoya University (Ogawa et al. 2002). We designed flat and ellipsoidal mirror of room temperature and adopted frequency independent solution for receiver optics. The SIS mixer device of band 3 receiver is also a parallel-connected twin-junction (Asayama et al. 2003a; Asayama et al. 2003b). The measured receiver noise temperature is less than 25 K (DBS) in the frequency range of 95 – 120 GHz.

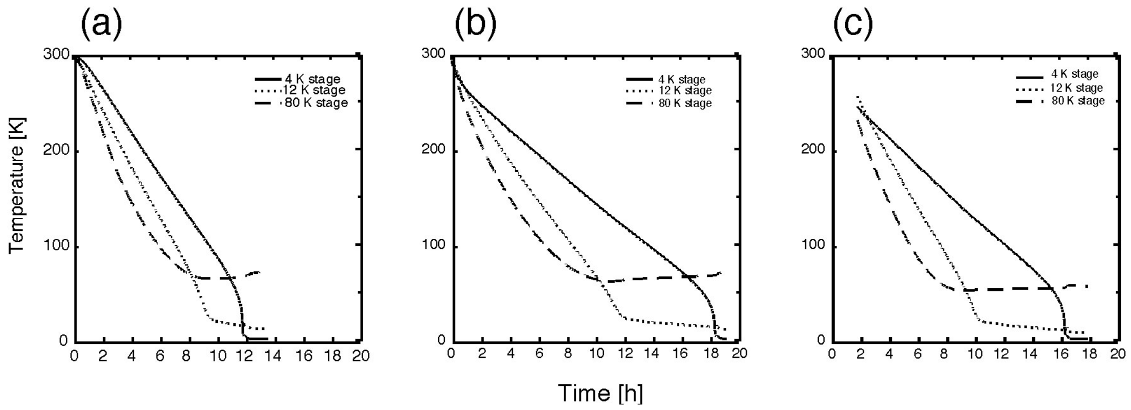

Fig. 6. (a) Cooling time of the cryostat in the case of 2 ϕ170 mm cartridges (without optics) inserted. It takes 12.5 hours for the stabilization of temperature. The temperature on the 4 K stage reached 3.5 K. (b) Cooling time of the cryostat in the case of two ϕ170 mm and one ϕ140 mm cartridges (with optics, LNA etc.)inserted. It takes 19 hours. (c) Cooling time of the cryostat at ASTE site. It takes 16.5 hours. In any case, there is no difference of reached temperature.

Table 1. Cooling time of the cryogenic system

occupation	place (altitude)	time [hour]
2 blank cartridges	Lab. (59 m)	12.5
band 3, 8, and 10	Lab. (59 m)	19.0
band 3, 8, and 10	ASTE (4800 m)	16.5

3. Integration of 3 cartridges

Three cartridge-type receivers have been independently developed with cartridge-test cryostats, which are developed for tests in laboratories (Sekimoto et al. 2003b). Then, three receivers were integrated into the cryostat at the Mitaka campus of NAOJ.

Firstly, we verified condition of evacuation, cooling properties, and mechanical interference of three cartridge-type receivers. Secondary, we checked the electronic properties of three cartridges. Then, we measured RF performance of the three cartridge-type receivers. We confirmed that their performance is almost same as that measured with the cartridge-test cryostat. The picture of the cryostat, in which 3 cartridge-type receivers were installed, is shown in Figure 4a. The total weight including three cartridge was 160 kg. After the integration, the system was shipped to the ASTE site.

Cooling time of the cryostat was measured for several cases (Figure 6, Table 1). The lowest temperatures were 3.5 K on the 4 K stage of the cartridge, 13.4 K on the 12 K stage, and 78.3 K on the 80 K stage.

Table 2. ALMA 12 m optics (Lamb 1999) and ASTE optics.

Parameter	ALMA 12 m [mm]	ASTE [mm]
Primary diameter	12000	10000
Primary focal length	4800	3500
Secondary diameter	750	620
Magnification	20	25.37
Secondary eccentricity	1.105	1.082
Equivalent focal length	96000	88780
Primary focal ratio	0.4	0.35
Secondary focal length	309.6	221.4
Distance between primary and secondary foci	6177	5606
Half angle subtended by secondary	3.576	3.226

4. Evaluation of cartridge-type receivers and test observation

4.1. ASTE

The cryostat with the same interface to the ALMA receivers and is designed to be installed in a telescope, the Atacama Submillimeter Telescope Experiment (ASTE) (Sekimoto et al. 2001a), which is a 10 m submillimeter telescope developed as a prototype antenna of the LMSA. The ASTE was installed at Pampa la Bola (4800 m altitude) in Atacama de Chile in March 2002. It plays a role as one of the research and development activities for the LMSA and now for ALMA. The antenna was designed for high surface and pointing accuracy, and fast position switching capability (Ukita et al. 2000). The ASTE is equipped with SIS receivers for 100, 230, and 345 GHz (Sekimoto et al. 2001b ; Sekimoto et al. 2001c), a continuum detector in the receiver cabin. It has 4 digital autocorrelators with output 1024-channel power spectrum of 512 (or 128) MHz bandwidth (Sorai et al. 2000) in a separate container.

The optical parameters of ALMA 12 m and ASTE 10 m are similar. The optics of cartridge-type receivers is designed for ALMA 12 m. However, the inclination angle for the subreflector is only changed for ASTE 10 m. The difference between ALMA 12 m optics (Lamb 1999) and ASTE 10 m optics is tabulated in Table 2.

4.2. Installation and first lights

In November 2002, 3 cartridge-type receivers were installed to the ASTE and its photograph is shown in Figure 7. At the ASTE site, we checked vacuum condition of the cryostat and electronic condition of three cartridge-type receivers. Then, the cryostat was attached under the Cassegrain focus.

The cooling time of the system mounted on the telescope is shown in Figure 6c and in Table 1. The cooling time was shorter than that measured at the laboratory. The reason

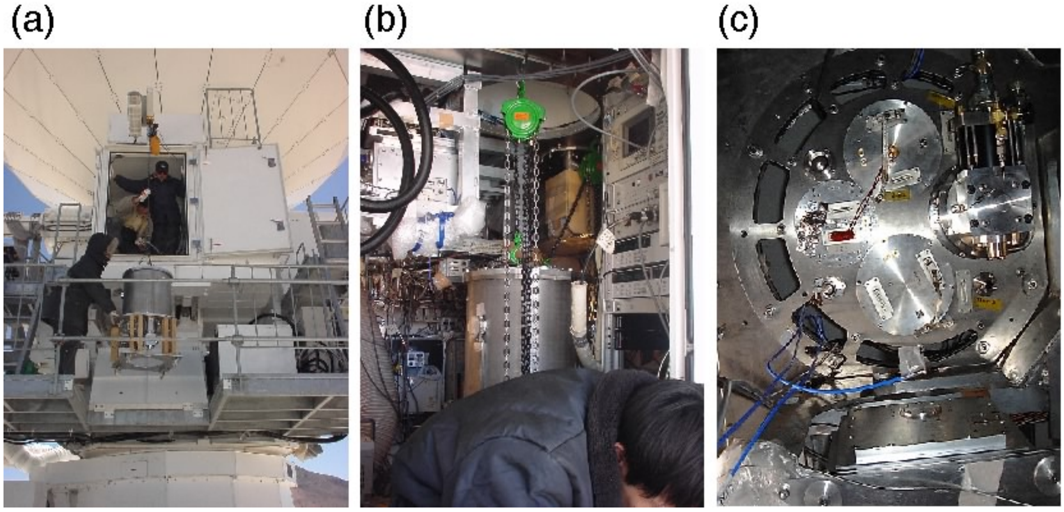

Fig. 7. (a) A photograph of carrying the receiver system into the receiver cabin. (b) A photograph before installation of the receiver system. (c) A photograph after installation. Bottoms of three cartridges and the cryocooler are seen. The warm IF amplifiers and bias electronics are not mounted.

is that the ambient temperature of the compressor and the cryostat at Pampa la Bola was 0 degree in comparison with that of 20 degree at the laboratory. We confirmed that the outdoor compressor (Sumitomo CNA61) operates properly even in a condition of atmospheric pressure of 550 hPa at an altitude of 4800 m.

Elevation dependence of temperature on the 4 K stage is shown in Figure 8. A difference of temperature between at 90 degree and at 30 degree was about 40 mK. The temperature change of 40 mK at the cartridge interface is relatively large. However, it will be reduced to be much smaller at the mixer-block. In the practical observations, the elevation change in the on-off switch mode is less than 10 degree, so that the temperature change is less than 4 mK. To reduce the temperature change, we are trying to add a thermal buffer between the mixer-block and optics.

On 17 November 2002, we detected continuum signals from the moon with all three receivers and shown in Figure 9. After adjusting position of subreflector, elevation dependence of subreflector parameters were measured with the band 3 receiver. Measured elevation dependence and elevation dependence of only the subreflector, which are calculated by a simulation, are shown in Figure 10. Difference between the measured value and the simulation is originated from the elevation dependence of the receiver system. This difference can be explained by gravitational deformation of the band 3 cartridge. The moon and Jupiter efficiency of the band 3 receiver were 90 % and 73 % at 100 GHz, respectively. ^{12}CO $J = 1-0$ (115.27 GHz) spectrum with the band 3 receiver is shown in Figure 11.

The optical depth at the zenith was much larger 1 at 490 GHz in two weeks of December 2002. The pointing accuracy at 498 GHz was about $1''$, which derived from measurements of

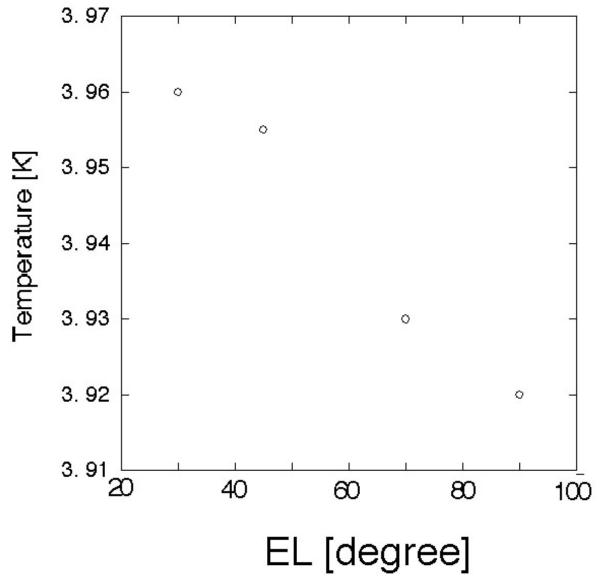

Fig. 8. Elevation dependence of temperature on the 4 K stage of the band 8 cartridge. A difference of temperature between at 90 degree and at 30 degree was about 40 mK.

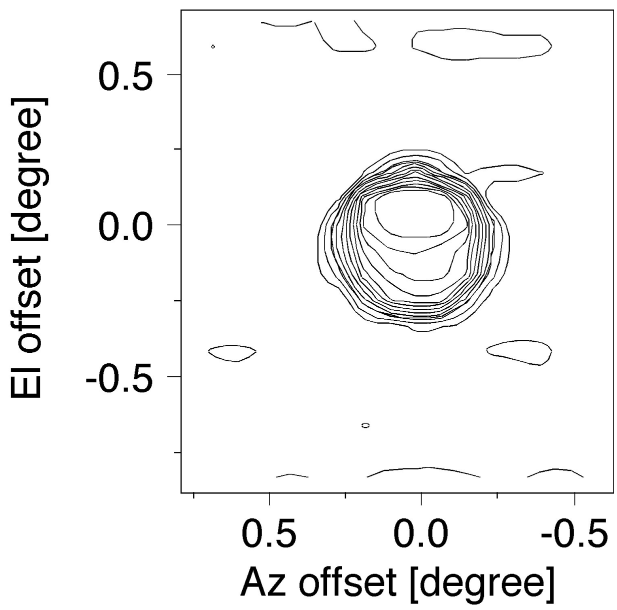

Fig. 9. First light of the moon with the band 10 receiver (LO frequency = 812 GHz). Age of the moon was about 12.4 days on 18 November 2002.

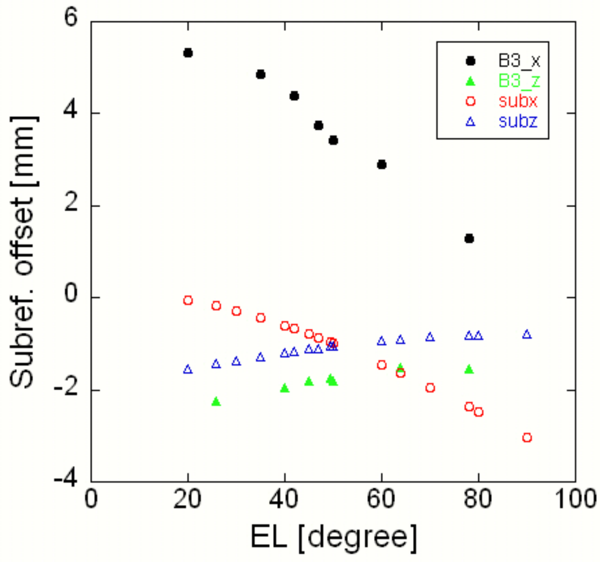

Fig. 10. Elevation dependence of optimum subreflector positions. The X and Z axis are vertical and focal offsets of the subreflector. Filled circles show best-fitted X-position of the subreflector measured by the band 3 receiver. Open circles show X position of the subreflector by a simulation. Triangles are the same as that of circles but for the Z axis. The relative difference between the measurements and the simulation can be explained by gravitational deformation of the band 3 receiver.

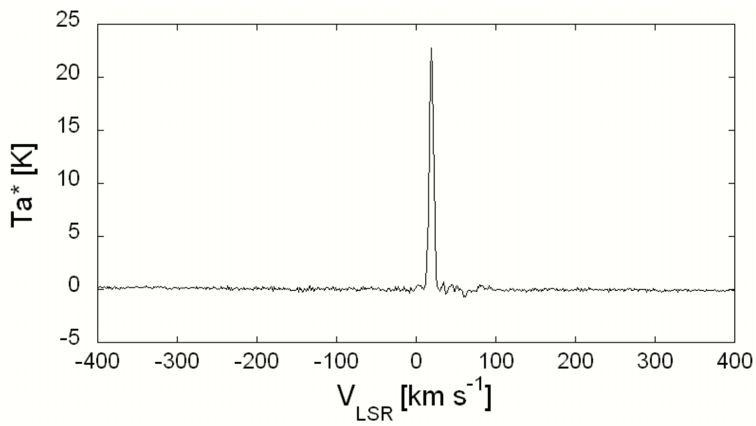

Fig. 11. A spectrum of ^{12}CO $J = 1 - 0$ from M17SW. Integration time was 2 minutes.

the Jupiter and the Saturn. In spite of not adjusting tilt parameters of the subreflector, the moon and Jupiter efficiency were 82 % and 42 %, respectively. After waiting good atmospheric condition ($\tau < 1.3$) in several days, on 9 December 2002, we observed a spectrum of CI (rest frequency = 492.16 GHz) from Orion (Figure 12). At that night, the optical depth at zenith was ~ 1.0 and the system noise temperature was around 1000 K.

We have confirmed that the engineering models of three cartridge-type receivers work as designed and the cartridge-type receivers are very promising for ALMA.

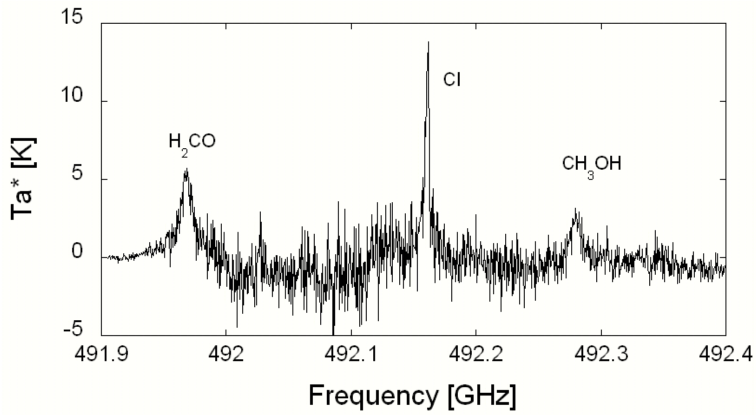

Fig. 12. A spectrum of CI ($^3P_1 - ^3P_0$) from Orion KL. The beam is averaged over 2 arcminutes. H_2CO (491.97 GHz)and CH_3OH (492.28 GHz) lines also were detected. Integration time was 1 minute.

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