Development of a Transportable Telescope for Galactic Survey at 500 GHz in Antarctica

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***Abstract*—We have developed a transportable 30-cm submillimeter-wave telescope to operate at the Dome Fuji station in Antarctic plateau. Transportability is an important requirement in the design; the telescope can be divided into several components by hands. The maximum weight of the components is restricted to be below 60 kg, so that the telescope can be assembled without a lifting machine. A small 4K mechanical cooler is used for cooling down a SIS mixer. Total power consumption was designed to be less than 2.5 kW. The 30-cm offset Cassegrain antenna produces a $9'$ beam that is same angular resolution of those of the Columbia-CfA and U. Chile CO (J=1-0) survey. The optical system is designed to satisfy the frequency independent matching condition at the subreflector and the feed horn of the SIS mixer, so we could accommodate a higher frequency receiver without changing mirrors. A quasi-optical filter was employed for single the sideband operation in observation of the CO (J=4–3) line at 461 GHz and the [CI] ($^3P_1$-$^3P_0$) line at 492 GHz. It is equipped with a 1 GHz width spectrometer that covers a velocity width of 600 km·s^{-1} with a velocity resolution of 0.04 km·s^{-1} at 461 GHz. We carried out test observations at a 4400-m altitude site in northern Chile during winters of 2010 and 2011. The typical system noise temperature including atmospheric loss was 3000 K (SSB) at 461 GHz that is mainly limited by atmospheric opacity. The beam size was measured to be $9'.4 \pm 0'.4$ by cross scanning of the sun. We estimated the main beam efficiency to be $87 \pm 5\%$ by observing the new moon. We succeeded in mapping Orion Molecular Cloud A and M17 SW in CO (J=4-3) followed by test observations toward Orion KL in both CO (J=4-3) and [CI] ($^3P_1$-$^3P_0$).**

***Index Terms*—Antarctic plateau, transportable telescope, submillimeter astronomy.**

I. INTRODUCTION

GALactic survey is a fundamental approach to understand characteristics of interstellar medium in the Milky Way. In millimeter-wave region, several surveys have revealed its mass, distribution, kinematic information and physical property. Colombia-CfA and U. Chile 1.2 m telescopes identified giant molecular clouds (GMCs) throughout the Milky Way in the CO (J=1-0) line at 115 GHz [1], [2], [3]. The Massachusetts-Stony Brook Galactic CO surveys essentially detected all clouds of size larger than 20 pc in $8° < l < 90°$ [4]. A 60 cm telescope named AMANOGAWA telescope that surveyed with the CO (J=2-1) line at 230 GHz [5], [6]. Physical parameters of GMCs such as temperature and density are derived by intensity ratio of molecular line in different transitions. They found that global decrease of gas density with the distance from the Galactic center in increasing.

Submillimeter CO lines are preferable to restrict physical condition of GMCs. Atomic carbon and nitrogen may be good probe for atomic phase of interstellar medium. Although some telescopes observed the Milky Way, the observed area is limited only around the Galactic center [7], on the Galactic equator [8] and on some major GMCs because of atmosphere is very opaque for submillimeter-wave.

A dryer and higher altitude site is needed for submillimeter-wave observations. The atmospheric transparency is mainly determined by the amount of water vapor and oxygen. Several sites with better atmospheric transparency have been developed such as Mauna Kea in Hawaii and the Atacama Desert in Chile. The atmospheric transparency at these sites is not high and stable enough for submillimeter-wave observation above 450 GHz. Antarctic plateau is good site for a galactic plane survey in submillimeter-wave. We have developed a transportable telescope for this new survey in the CO (J=4–3) line at 461.04 GHz and [CI] ($^3P_1$-$^3P_0$) at 492.16 GHz in 500 GHz band. In this paper we describe design of the telescope for operation in Antarctica and show results of the performance in the test observations.

Japanese Antarctic station, the Dome Fuji station is expected as one of the best sites for submillimeter-wave astronomy because of its high altitude of 3800 m and low average temperature of $-54°$C [9]. Dome Fuji is located in latitude $77° \ 19'$ S and longitude $39° \ 42'$ E [10]. Dome Fuji is about 1000 km away from a Japanese station at the coast, Syowa. Basic transportation means are snow vehicles and sledges, although Dome Fuji is accessible by a small plane. Currently, a telescope must be assembled without a lifting machine at Dome Fuji. The capacity of electric power is limited. Fig. 1 shows the location of Dome Fuji and other stations on a map of Antarctica where astronomical observations could be conducted.

It has been known that the average fraction of the sky obscured by clouds has been 30% in 1995-1997 [9]. The mean wind speed is 5.8 m·s^{-1} [9] and the speed hardly exceeds 10 m·s^{-1}. The zenith opacity at 220 GHz in summer was very low and stable (τ_{220} = 0.045 $\pm$ 0.007), that is much better than that of Atacama Desert in Chile in their same seasons and is comparable in their best seasons [11]. We showed in

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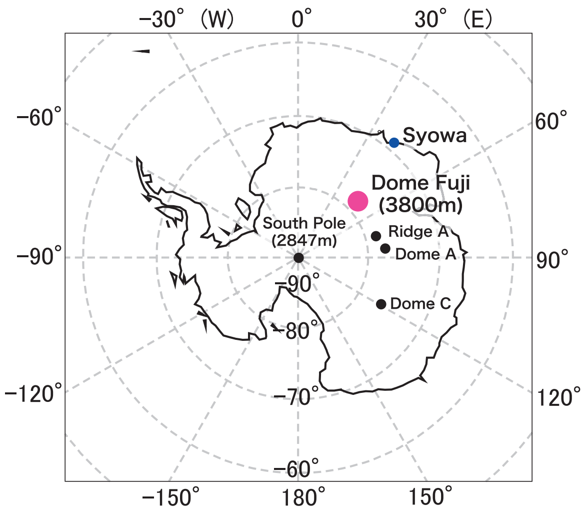

Fig. 1. Location of Dome Fuji and other sites on Antarctica

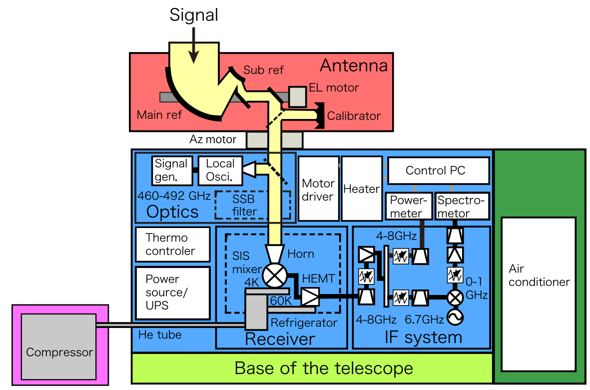

Fig. 2. Block diagram of the system of the 30-cm telescope. The individual components are shown with different colors.

simulation that several submillimeter atmospheric windows open through the year between 340 and 1000 GHz. Several THz windows open in winter at 1.0-2.0 THz. Furthermore, low fluctuation of the opacity is an advantage of Dome Fuji. This enables us to continue a submillimeter-wave observation for a long time under good atmospheric condition. For these advantages of topographic and climatic condition, we are developing Dome Fuji as a site for astronomical observation from submillimeter to near-infrared region [12], [13].

II. The 30-cm Telescope

The size for a main reflector of 30 cm is chosen to produce $9'$ beam at 461 GHz so that we can compare the data with the data of CO (1–0) and CO (2–1) directly. Transportability is important requirement to the 30-cm telescope for the operation at Dome Fuji. We designed the 30-cm telescope to be divided into several components by hands. The maximum weight of each component is restricted to be below 60 kg for fulfilling this requirement. We also set the upper limit on the total power consumption of 2.5 kW to satisfy the condition of the electric capacity at Dome Fuji. Fig. 2 shows a system diagram of the 30-cm telescope. We adopted a standard-type heterodyne radio telescope that consists of an antenna system, a local oscillator (LO), a mixer on a cryo-receiver, an intermediate frequency (IF) system, a back end system, and a control system.

The main reflector and a subreflector construct an offset Cassegrain antenna system. There is no blockage by the subreflector and its stay. The focal length of the main reflector is 258.40 mm. The subreflector is an offset hyperboloid with the diameter of the subreflector is 60.40 mm. We stipulated for an edge taper level on the subreflector to be -17.0 dB to suppress the side lobe level. We designed the antenna to implement the Mizuguchi condition for minimizing the cross-polarization loss and the Rusch condition for minimizing the spillover loss [14]. This provides us with high main beam efficiency, which is important for observing broad and weak emission lines seen in the galactic plane. The surface accuracy of the main reflector and subreflector is less than 5 μm. This accuracy enables us to observe the radio wave with wavelength of $\sim$ 100 μm in the future.

The beam from the antenna is led to a feed horn at Coudé focus via a transmission optical system, which consists of 4 plane mirrors, 2 ellipsoidal mirrors, wire grids, and a quasioptical single sideband (SSB) filter. We designed the transmission optical system based on Gaussian beam propagation. We also adopted a condition of frequency-independent matching between the subreflector and the feed horn [15]. This enables us to replace the receiver for an observation of higher frequency wave without a replacement of the optical system. We set the edge taper of mirrors after subreflector to -40.0 dB. The edge clearance of the beam for space is set to -50.0 dB. We adopted a diagonal horn as the feed horn because of it produces good beam despite of easy manufacturing. We designed the horn to fit the beam parameter of the optical system based on [16]. A aperture radius and a slant length of the horn are 3.475 mm and 20.00 mm, respectively.

The observation is done with the SSB mode to measure the intensity of lines with high accuracy. We adopt a pair of Frequency Selective Polarizers (FSP) as a quasioptical-type SSB filter. A FSP consists of a wire-grid backed by a flat mirror with a small gap. This filter is a modified Martin-Puplett interferometer and used for Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) [17], [18]. We designed a frequency characteristic of the filter to achieve the SSB observation for CO (4–3) in a lower sideband and [CI] (1–0) in an upper sideband for IF of 7.2 GHz. We found the optimum value of the gap width to be 2.644 mm to transmit two emission lines with high image rejection ratio.

We adopted a Superconducor-Insulator-Superconducor (SIS) mixer associated with Parallel-Connected Twin Junctions (PCTJ) which was made at Nobeyama Radio Observatory. The junction consists of niobium and aluminum oxide as the superconductor and the insulator, respectively. It need no mechanical tuner for impedance matching of the SIS device and low noise (less than 200 K in DSB mode) is expected. The device is mounted on a mixer block, which is made of copper and plated by gold. The RF signal and the LO signal are led to the SIS mixer via the feed horn combined with the mixer block. We selected a small 4K Gifford-McMahon cryocooler for cooling down the SIS mixer with weight and

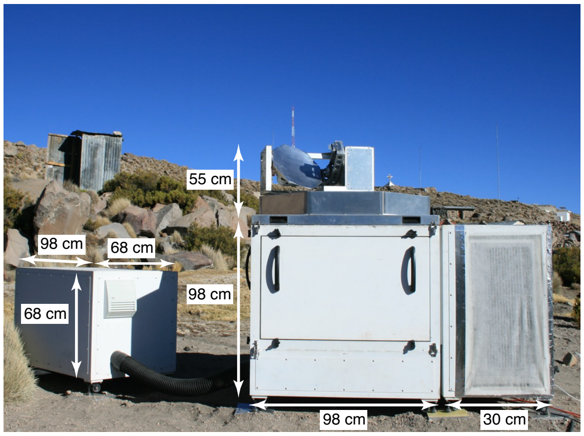

Fig. 3. Photograph of the 30-cm telescope in Chile with its size. The length of the telescope is 98 cm in depth.

power saving. The cryostat has a cylindrical form and its size is 32 cm of diameter and 50 cm of height. The weight of the cryocooler including the cryostat is about 15 kg and its consumption power is 1.3 kW. These are suitable for the operation at Dome Fuji. The cooling capacities of the 60K stage and the 4K stage are 2.5 W and 0.1 W, respectively. A small pot filled with liquid helium is attached to the top of the cryocooler to reduce the fluctuation of temperature of the 4K stage using its large thermal capacity. A HEMT amplifier was employed as a first amplifier on the 60K stage. The gain and the noise temperature of the HEMT amplifier are about 30 dB and 6.5 K within the fist IF band, respectively. The SIS mixer is biased by a port of the isolator using a source meter with the four-wire method. The output signal of the cryostat is transmitted to a spectrometer after amplified again and down-converted to 0–1 GHz in the IF system.

We employ an FX-type 1 GHz spectrometer and the power meter for the back system. It covers ± 300 km$\cdot$s^{-1} in velocity at 500 GHz band, that is wide enough to cover observed CO (4-3) line width at the Galactic center [7]. The velocity resolution is 0.04 km$\cdot$s^{-1}, which is much narrower than the typical line width of CO line width of a few s^{-1} for molecular clouds. The linearity of the spectrometer is kept within 5% over 10 dB.

III. Performances

We measured the beam pattern of the feed horn by a planer scanning of a submillimeter. The pattern has symmetry shape and its size (HPBW) is 26.3 ± 1.3 mm. The designed value of the HPBW at the position is 26.0 mm with taking into account the effect of the beam width of a probe horn. Therefore there is no discrepancy between this results and the design.

The receiver noise temperature is 900 K in SSB mode at the output port of the IF system. The little bit high noise temperature results from high physical temperature of 4.9 K of the SIS mixer, 60 K of the HEMT, and loss in the IF cable between the SIS mixer and the HEMT.

The 30-cm telescope was evaluated by the test observation in Chile during winters 2010 and 2011 after the laboratory testing. It aims to operate and measure performance of the telescope before observations at Dome Fuji. We selected Parinacota in northern Chile as a site for the test observation as shown in Fig. 3. It is located about 2000 km north from Santiago and its latitude is 4400 m. Its latitude and longitude are $18°12'$ S and $69°16'$ W, respectively. We succeed in assembling the telescope only by four peoples within three days. The weight of equipment in the telescope is about 300 kg. The total weight of the whole system of the telescope that includes 2 generators and 5 wooden boxes for the transportation is 700 kg. The heaviest one in these components is the antenna system whose weight is about 55 kg.

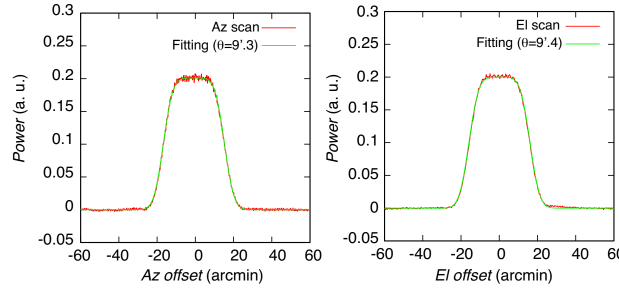

Fig. 4. Results of scanning of the sun (a red line) and fitting (a green line) by model of beam pattern. The left figure is IF output in azimuth direction and the right figure is ones in elevation direction.

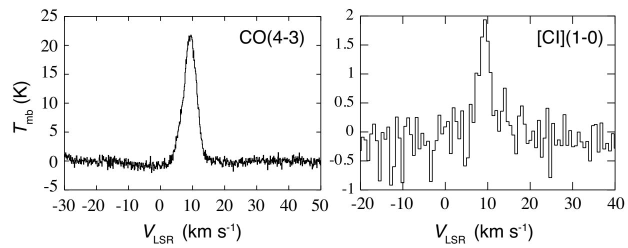

Fig. 5. Spectra of CO (4–3) and [CI] (1–0) toward Orion KL

The beam pattern of the antenna was evaluated by the scanning of the sun. The IF output is a convolution of the beam pattern and the brightness distribution of the sun. The Gaussian beam pattern is evaluated assuming that sun is modeled as a flat uniform circle. We fitted the scanning data using this model to estimate the angular resolution (HPBW) of the telescope. Fig.4 illustrates the scanning data and the beam pattern in the azimuth (left) and elevation (right) direction. The red and green lines represent the IF output by scanning and the fitting curve described further below, respectively. The HPBW of the beam in the azimuth and elevation directions is estimated to be $9'.4 \pm 0'.4$ and $9'.3 \pm 0'.4$ at 461 GHz, respectively.

We derived the moon efficiency $\eta_{\rm moon}$ using the scanning data of the new moon. We used a following equation, $\eta_{\rm moon} = T_{\rm A}^{*}/T_s$, where T_A^* is the measured antenna temperature of the new moon, T_s is the brightness temperature of the new moon, which is assumed to be 110 K (brightness temperature at $\lambda = 1$ mm, [19]). The moon efficiency was estimated to be 87 ± 5% at 461 GHz by this equation. The aperture efficiency $\eta_{\rm A}$ is also calculated to be 70 ± 4% at 461 GHz assuming that the moon efficiency is regarded as the main beam efficiency. We also regard the moon efficiency as the main beam efficiency when we derive the main beam temperature from the intensity of the line.

The atmospheric opacity at 461 GHz is measured with the tipping-scan method using the telescope at Parinacota. The zenith opacity of the atmosphere ranged 0.6–1.5. The system noise temperature including atmospheric loss was 2000–5000 K during the observation. These values indicate the receiver noise temperature is about 900 K in SSB mode. Therefore there is no discrepancy between the results at laboratory and the observing site. An average of the system noise temperature was 3000 K during observation. We abandoned the observed data with the system noise temperature higher than 5000 K.

We show our first CO (4–3) and [CI] (1–0) spectra toward Orion KL in Fig. 5. In CO (4–3) spectrum, the peak temperature is 21.7 ± 0.5 K and integrated intensity from 6 and 12 km·s^{-1} is 92 ± 2 K km·s^{-1}. The peak velocity is 9.4 ± 0.1 km·s^{-1} and the velocity width (FWHM) of the spectrum is 4.4 ± 0.1 km·s^{-1}. In order to assess the adequacy of the data, we compared our CO (4–3) spectrum with an existing data taken by the 2.2-m ESO telescope at La Silla in Chile [20]. The velocity and integrated intensity was compared after applying convolution to correct for the difference of the angular resolution of the telescope. The corrected values were coincident each other within the error. We also detected the [CI] (1–0) as is shown in right of Fig.5.

We performed large-scale mapping of CO(4–3) in Orion A GMC during September and October, 2011. Fig.6 shows an integrated intensity map of CO(4–3) toward Orion A. The velocity range for integration is between 0 and 20 km·s^{-1} in v_{LSR}. We also mapped M17 GMC with CO(4–3).

We are upgrading the receiver to install a sideband-separating SIS mixer based on the ALMA band 8 receiver [21]. We expect to achieve lower noise temperature of the receiver with this upgrading. The telescope will be tested its performance in cold environment in a laboratory. After the test, we plan to start the operation at Dome Fuji in 2014.

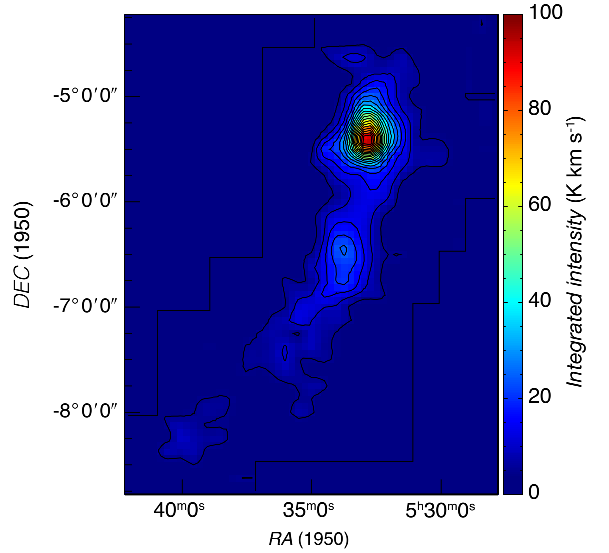

Fig. 6. Integrated intensity map of the CO(4–3) toward Orion A GMC

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