Site testing at Dome Fuji for submillimeter and terahertz astronomy: 220 GHz atmospheric-transparency

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Abstract

We measured the 220 GHz atmospheric-transparency at the Dome Fuji station in Antarctica from 18 December 2006 to 14 January 2007 using a tipping radiometer. The mean optical depth at zenith was 0.045 ± 0.007, and during 98% of this period we measured an optical depth of less than 0.06. These data indicate that the atmospheric-transparency in summer at Dome Fuji is comparable to that of well-known submillimeter astronomical sites such as the Atacama desert in Chile in their best seasons.

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1. Introduction

There are many astronomically important spectral lines of atoms, molecules, and ions in the submillimeter and terahertz frequency ranges, some of which are listed in Table 1. Recently, radio-receiver technology has been developed to take advantage of higher-frequency bands and it is now possible to construct submillimeter and terahertz radio telescopes. However, submillimeter observations can be obtained only at dry and high-altitude sites such as Mauna Kea in Hawaii, the Atacama desert in northern Chile, Gornergrat in Switzerland, Mt. Graham in Arizona, and the South Pole, because of improved atmospheric-transparency in the presence of reduced quantities of water vapor and oxygen. The atmospheric attenuation is mainly determined by the amount of water vapor and oxygen, and is expressed by the atmospheric optical depth. The atmospheric-transparency at these sites is not sufficiently low for terahertz astronomy; drier and higher-altitude sites are preferable. The Antarctic Plateau may be the best location on earth for astronomical observations in the terahertz band. Site testing has been performed or is currently taking place on the Antarctic Plateau at the South Pole, Dome C, and Dome A (e.g., Lane, 1998; Lawrence, 2004).

The Japanese Antarctic station, Dome Fuji (77°19′S, 39°42′E) is located at an altitude of 3810 m
on a plateau halfway between the South Pole and the ocean (Fig. 1; Watanabe et al., 1999). The annual average temperature at the station is \(-54.4^\circ C\) and the lowest ever temperature was \(-79.7^\circ C\) (Yamanouchi et al., 2003). Because of the combination of low temperature and high altitude, a very small optical depth is expected at Dome Fuji. In addition, the average fraction of the sky obscured by clouds over the period 1995–1997 was just 30\% (Yamanouchi et al., 2003). The mean wind speed is 5.8 m s\(^{-1}\) (Yamanouchi et al., 2003), rarely exceeding 10 m s\(^{-1}\). These stable weather conditions are advantageous for the accurate pointing of telescopes and practical observing time.

We plan to construct astronomical telescopes at Dome Fuji. Measurement of the atmospheric-transparency is a first step toward developing submillimeter and terahertz astronomy at the station. Optical-depth measurements at 220 GHz are useful for comparison with other observatory sites, because many optical-depth records are available (e.g., Chamberlin and Bally, 1994; Otárola et al., 2005; Radford, 2002). In this paper, we report on atmospheric-transparency measurements at 220 GHz obtained at Dome Fuji.

### 2. Instruments

The atmospheric-transparency at zenith was measured with a 220 GHz tipping radiometer. The radiometer is an instrument capable of observing the brightness temperature of the sky using a narrow beam pointing toward a certain elevation angle. Figs. 2 and 3 show a block diagram of the radiometer system and its appearance, respectively. The radiometer was designed to operate at the low temperatures prevalent at Dome Fuji. It was developed by modifying the 220 GHz radiometer used for site testing at the Atacama Large Millimeter/submillimeter Array (ALMA) site (Kohno et al., 1995). An offset 83 mm (diameter) parabolic mirror with a corrugated feed horn at its focus produced a narrow beam of 63 arc minutes diameter. A stepping motor controlled the mirror’s rotation around the elevation axis.

We employed heterodyne detection, which generates down-conversion of higher-frequency to intermediate-frequency (IF) signals, because direct detection of the 220 GHz signal was difficult. A GaAs Schottky-barrier diode harmonic mixer produced an IF signal at 1.2–1.6 GHz by mixing the signal from the sky with a second harmonics of local signal. The local signal at 109.13 GHz was generated by a Gunn oscillator. The mixer operated in double-sideband (DSB) mode so that the IF signal at 1.2–1.6 GHz contained the sky signal in both sidebands at 219.28–219.68 and 216.84–217.24 GHz. The IF signal was detected by a power meter and subsequently recorded using a personal computer. Receiver sensitivity is expressed by the equivalent noise temperature. The receiver noise temperature was measured based on the Y-factor method, which measures the difference in response of the receiver when its input port is terminated by hot...
and cold loads. The noise temperature was 1200 K, which is low enough to observe typical emission from the atmosphere for an integration time of 2 s.

The radiometer was covered by metal with thermally insulating material, except for the signal window. The window was sealed by a 250 μm-thin Zitex (porous Teflon) sheet. The measured loss of 0.009 dB at 220 GHz is negligible for this observation. Electrical heaters were installed on a motor and inner frame of the radiometer. We kept the temperature of the radiometer above $-15^\circ$C during the operation, at an average ambient temperature of $-30^\circ$C at Dome Fuji. Electrical parts of the radiometer were placed in the inner frame, which is separated from the outer frame by elastic material so as to minimize vibration during transportation.

3. Observations

The radiometer was packed into a paper box of 60 cm (width) × 86 cm (length) × 96 cm (height), with a total mass of 64 kg. The instrument was returned to Japan without damage.

The radiometer was placed on a base frame on snow at Dome Fuji (Fig. 4). Its pointing reference plane was set with an accuracy of better than 0.1°. The tipping
scan direction was chosen from the zenith to the south, to minimize any effects due to solar radiation. We put metal plates on the eastern and western sides of the mirror to avoid stray sunlight; however, it was difficult to protect the atmospheric data from the direct incidence of sunlight from the south—north direction (i.e., the direction perpendicular to the mirror’s rotational axis); thus, data affected by sunlight were discarded. The scanning mirror was programmed to scan the sky every 2 min with a zenith angle between \( Z = 0 \) (sec \( Z = 1.0 \)) and 70.5° (sec \( Z = 3.0 \)) at intervals of 0.1 in sec \( Z \). Fig. 5 shows an example of one data scan. The zenith optical depth, \( \tau_0 \), was derived by reducing the data for one scan (see Appendix A). The radiometer was in operation from 18 December 2006 to 14 January 2007 at Dome Fuji, in the summer season in the Southern Hemisphere.

4. Results and discussion

4.1. Atmospheric-transparency

Fig. 6 shows the 220 GHz optical depth for 27 days from 18 December 2006, and Fig. 7 presents a histogram of the data. In the figures, two sources of spurious emission were removed. One of these sources was spike-like and appeared every 3 h; it was identified as originating from satellite communications. The other was scattered sunlight at midnight. Some data in the observing period were unavailable because the radiometer was out of service due to maintenance and power failure. The average optical depth was 0.045, with a standard deviation of 0.007, during the entire measurement period. This small deviation means that the optical depth was very stable at Dome Fuji. Fig. 8 shows the cumulative distribution of the optical depth, corresponding to the percentage of the optical depth below a specified value.
The 220 GHz optical depth correlates with the submillimeter atmospheric optical depth (Chamberlin et al., 1997; Hirota et al., 1998; Masson, 1994; Matsuo et al., 1998). The submillimeter optical depths observed at 495, 670, and 820 GHz were almost the same as those observed at Mauna Kea and in the Atacama desert (Masson, 1994; Matsushita et al., 1999). The optical depth $\tau_{495}$ at 495 GHz was estimated empirically from $\tau_{220}$ (obtained at 220 GHz) by

$$\tau_{495} = a\tau_{220} + b$$

where $a$ and $b$ are constants optimized for the observations. We use this equation to estimate the optical depth $\tau_{495}$ at Dome Fuji from the 220 GHz measurements, adopting $a = 23.28$ and $b = -0.37$. We adopt the average values at the South Pole for $a$ and $b$ (Chamberlin et al., 1997) because of the similarity in climate between the South Pole and Dome Fuji. Astronomical observations become difficult above zenith optical depth of 1.0 because of strong atmospheric attenuation. According to Equation (1), a zenith optical depth of $\tau_{495} = 1.0$ corresponds to $\tau_{220} = 0.06$. A zenith optical depth, $\tau_{220}$ of less than 0.06 corresponds to 0.98 in the cumulative distribution shown in Fig. 8. This finding indicates that submillimeter observations are always possible at Dome Fuji, even in summer. We note that Equation (1) and the coefficients $a$ and $b$ at Dome Fuji may be different from those at South Pole; thus, it is important to undertake direct measurements of the relation between $\tau_{220}$ and $\tau_{495}$ at Dome Fuji.

### 4.2. Comparison of optical depth at other sites

Table 2 lists the quartiles of the cumulative distribution of the 220 GHz optical depth measured at Dome Fuji, together with data from other sites at 225 GHz, including the ALMA site in Chile (altitude, 5060 m), the South Pole (2835 m), and Mauna Kea in Hawaii (4100 m), taken from the literature (Chamberlin and Bally, 1994; Hogg, 1992; Ota´ rola et al., 2005). The frequency dependence of the optical depth between 220 and 225 GHz is small, at less than 3% of the tabulated values (Radford et al., 2001). In addition, there is an annual variance of the quartiles at the other sites. Therefore, Table 2 gives the data obtained in the season when the best median value was recorded. It is clear that the optical depth at Dome Fuji is smaller than that at Mauna Kea in all seasons. This can be explained by the difference in the amount of water vapor (i.e., extremely dry conditions at Dome Fuji). The precipitable water vapor (pwv) at Dome Fuji is estimated at 0.6 mm during the observing period (see Section 4.3), while the average pwv for Mauna Kea is 2.3 mm (Lane, 1998). The quartiles of the cumulative optical depth at Dome Fuji are smaller than those at the South Pole in summer, reflecting the difference in altitude. Dome Fuji’s altitude of 3810 m is approximately 1000 m higher than that at the South Pole (2835 m). The quartiles at Dome Fuji in summer are

<table>
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<tr>
<th>Quartile</th>
<th>Dome Fuji</th>
<th>South Pole$^a$</th>
<th>Atacama$^b$</th>
<th>Mauna Kea$^c$</th>
</tr>
</thead>
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<tr>
<td>Summer†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec 06–Jan 07</td>
<td>0.041</td>
<td>0.040</td>
<td>0.052</td>
<td>0.029</td>
</tr>
<tr>
<td>Apr–Sep 93</td>
<td>0.045</td>
<td>0.046</td>
<td>0.062</td>
<td>0.040</td>
</tr>
<tr>
<td>Oct 93–Mar 94</td>
<td>0.050</td>
<td>0.055</td>
<td>0.076</td>
<td>0.065</td>
</tr>
<tr>
<td>1st (25%)</td>
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<td>2nd (50%)</td>
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<tr>
<td>3rd (75%)</td>
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$^b$ http://www.alma.nrao.edu/development/site/Chajnantor/data.c.html.

comparable to those at the South Pole, even in winter. This leads to the conclusion that the atmospheric optical depth at Dome Fuji is superior to those at both Mauna Kea and the South Pole.

Recently, many submillimeter telescopes have been constructed in the Atacama desert in Chile. We now compare the detailed atmospheric properties at Dome Fuji with those in the Atacama desert. Fig. 9 shows temporal variations in optical depth at Dome Fuji and in the Atacama desert. The data for the Atacama consist of the best records obtained from 1995 to 2004 (data are from http://www.alma.nrao.edu/development/site/Chajnantor/data.c. html). One remarkable advantage of Dome Fuji is the stability of the optical depth in the summer season, as shown in Fig. 9(a) and (b). The standard deviation of the optical depth was 0.007 at Dome Fuji, while it was 0.07 in the Atacama desert. Water vapor has a strong influence on optical depth. Bad weather in Chile causes large optical depths and high standard deviations in summer, whereas the weather is always fine at Dome Fuji. The difference in stability is confirmed by the large difference in the second quartile of the cumulative optical depth (see Table 2). Furthermore, the winter optical depth in the Atacama desert is comparable to the summer optical depth at Dome Fuji, as shown in Fig. 9(a) and (c), although the best optical depth in the Atacama is better than that at Dome Fuji (see Fig. 8 and the first quartile of Table 2).

The similarity between the winter optical depth in the Atacama and the summer optical depth at Dome Fuji suggests that the combined conditions of high altitude and low temperature are comparable in terms of optical depth. The winter temperature at the Atacama’s altitude of 5060 m is about \(-10{\degree}C\), while the summer temperature at Dome Fuji’s altitude of 3810 m is \(-30{\degree}C\), but the low average pressure (598.6 hPa) at Dome Fuji (Yamanouchi et al., 2003) corresponds to an altitude of 4300 m at mid-latitudes. The Atacama’s higher altitude is advantageous in terms of reduced levels of atmospheric constituents such as water vapor and oxygen, which absorb radio waves. Low temperatures at Dome Fuji have both positive and negative effects on the optical depth: they reduce the amount of water vapor in the atmosphere but also cause absorption of atmospheric constituents at low energy levels because of changes in the partition function (Pardo et al., 2001). Our results suggest that low temperatures are beneficial overall in terms of obtaining small optical depths at Dome Fuji.

Dome Fuji may be of use for rapid astronomical mapping of large areas, even for similar optical depths, because the noise generated by fluctuations in the optical depth is small at Dome Fuji (Fig. 9). It should be noted that extremely low optical depths have been recorded in the Atacama desert in winter, as shown by the small value of the first quartile in Table 2. Indeed, very low optical depth (<0.03) is only available in the Atacama, as shown in the cumulative diagram of Fig. 8. In winter, the 220 GHz optical depth at Dome Fuji is expected to be very low, due to dry conditions and low pressure; thus, we can regard the present data as an upper limit of the annual variation of the optical depth. We conclude that the atmospheric-transparency at Dome Fuji is better than that at any other sites presently available for submillimeter astronomy.

4.3. Simulated spectrum of transparency

We simulated spectra of the atmospheric-transparency with the “am” program (Paine, 2004). The program simulates the transparency as a function of frequency.

Fig. 9. Comparison of variations in the 220/225 GHz optical depth between Dome. Fuji and the Atacama ALMA site. (a) Dome Fuji in summer (17 December 2006–14 January 2007), (b) Atacama in best summer (17 December 2002–14 January 2003), and (c) Atacama in best winter (17 August 1999–14 September 1999).
by calculating the radiative transfer equation for an atmosphere model consisting of several plane—parallel layers. Each layer is characterized by uniform pressure, temperature, and column density of oxygen, ozone, nitrogen, and water vapor. We used the data of high-altitude pressure and temperature measured with radiosondes at Dome Fuji (Hirasawa et al., 1999; Sato, 1999). In addition, we used the U.S. standard atmosphere (1976) to obtain the column density of oxygen, ozone, and nitrogen at each pressure. The column density of water vapor in a given layer was calculated from pwv, assuming hydrostatic equilibrium. pwv linearly correlates with optical depth at 220 GHz (Chamberlin and Bally, 1994; Masson, 1994); consequently, we used pwv as a parameter in the simulation. Fig. 10 shows a simulated spectrum of the atmospheric-transparency for 0.6 mm of pwv, which reproduces the observed average 220 GHz optical depth of 0.045 at Dome Fuji in summer (transparency of 0.96). Despite the summer conditions, the spectrum maintains a high transparency up to a frequency of 0.5 THz and has “windows” at 0.68 and 0.85 THz.

Lawrence (2004) simulated the atmospheric-transparency at infrared and submillimeter wavelengths at Dome Fuji, assuming 105 μm of pwv. Our model reproduces his results with higher resolution in terms of the frequency range of the atmospheric windows and the peak transparency of each window.

We also show the simulated spectrum for the case of 50 μm pwv, which is expected at Dome Fuji in winter, because such a low pwv has been recorded previously at the South Pole in winter (Chamberlin et al., 1997). Fig. 11 shows the resulting transparency spectrum, in which there are several windows (where a “window” is defined as a frequency range with a transparency of better than 0.3, at 1.0—2.0 THz). On earth, these windows are only available upon the Antarctic Plateau in winter. It should be noted that some important astronomical spectral lines (Table 1) occur in these windows.

5. Conclusion

We measured the 220 GHz atmospheric-transparency at Dome Fuji in Antarctica, using a tipping radiometer. The average optical depth was $\tau = 0.045 \pm 0.007$ for 27 days from 18 December 2006. The optical depth was less than 0.06 for 98% of the observing period. The results strongly suggest that Dome Fuji is potentially of significant advantage for submillimeter astronomy, compared with other sites currently available. The spectrum of the atmospheric-transparency at Dome Fuji was simulated up to 2 THz based on observational data. We found several “windows” for astronomical observations. Some “windows” in the 1.0—2.0 THz range are available only on the Antarctic Plateau.

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Appendix A. Measurement of atmospheric-transparency

The atmospheric-transparency is described in the framework of radiative transfer. The brightness temperature of the sky, $T_{\text{sky}}$, is given by

$$T_{\text{sky}} = T_b \exp(-\tau) + \tau_{\text{atm}} \{1 - \exp(-\tau)\},$$

where $\tau$ is the optical depth of the atmosphere, $T_b$ the brightness temperature of a celestial object, and $\tau_{\text{atm}}$ the physical temperature of the atmosphere. This equation implies that the atmosphere attenuates radiation from celestial objects and adds thermal radiation. The latter depends on optical depth and temperature. The atmospheric-transparency, $\eta$, is described by

$$\eta = \exp(-\tau).$$

When a radiometer points to a blank area of sky, $T_b$ corresponds to the brightness temperature of the cosmic background radiation, $T_b = 2.7 \text{ K}$. In this case, the first term of $T_{\text{sky}}$ is negligible ($T_b \ll T_{\text{atm}} \sim 250 – 300 \text{ K}$) and

$$T_{\text{sky}} \approx \tau_{\text{atm}} \{1 - \exp(-\tau)\}.$$  \hspace{1cm} (4)

The optical depth is proportional to the path length of the atmosphere along the line of sight. The path length is a function of zenith angle, $Z$, in the plane-parallel atmosphere model, as shown in Fig. 12. Using the optical depth at zenith, $\tau_0$, we can express the optical depth at $Z$ as follows:

$$\tau(Z) = \tau_0 \sec Z.$$  \hspace{1cm} (5)

The input of the radiometer at each $Z$ is given, in terms of temperature, as

$$T(Z) \approx \tau_{\text{atm}} \{1 - \exp(-\tau_0 \sec Z)\} + T_{\text{rx}},$$

where $T_{\text{rx}}$ is the noise temperature of the radiometer. The output power of the radiometer at $Z$ is

$$P(Z) = k_B BG \{T_{\text{atm}} \{1 - \exp(-\tau_0 \sec Z)\} + T_{\text{rx}}\},$$

where $k_B$ is Boltzmann’s constant, $B$ the frequency bandwidth, and $G$ the radiometer’s gain. When the radiometer is terminated by a reference source (load) at the ambient temperature, $T_{\text{amb}}$, the output power is

$$P_{\text{ref}} = k_B BG (T_{\text{amb}} + T_{\text{rx}}).$$

If we assume $T_{\text{atm}} \approx T_{\text{amb}}$, the zenith optical depth is derived as the proportionality constant of $\sec Z$ as

$$P_{\text{ref}} - P(Z) = k_B BG T_{\text{amb}} \exp(-\tau_0 \sec Z),$$

$$\ln \{P_{\text{ref}} - P(Z)\} = \ln k_B BG T_{\text{amb}} - \tau_0 \sec Z.$$  \hspace{1cm} (10)

Thus, we can obtain the optical depth of the atmosphere by least-squares fitting of Equation (10), as shown in Fig. 5.

The assumption of $T_{\text{atm}} \approx T_{\text{amb}}$ does not significantly affect the derivation of the optical depth. The error in the derived transparency caused by this assumption is less than 5%, even for $T_{\text{atm}} - T_{\text{amb}} = \pm 30 \text{ K}$.

References


