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POSSIBILITY OF TERAHERTZ OBSERVATIONS AT THE ALMA SITE

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RESUMEN

El porcentaje de observación con opacidades menores que 3.0 y 2.0 en frecuencias THz en el lugar del Atacama Large Millimeter/submillimeter Array (ALMA), han sido calculadas usando el monitoreo de los datos radiométricos a 225 GHz y la correlación de opacidades entre 225 GHz y el rango de frecuencias THz. Este porcentaje de observación con opacidades menores que 3.0 en frecuencias THz se da el 12.4% del año, y durante el verano austral (noviembre–abril) es cerca de dos veces mayor que en invierno austral (mayo–octubre). Este porcentaje de observación muestra una larga variación sinusoidal a lo largo del año, y parece estar relacionado con los fenómenos del Niño y la Niña; durante los años en los que sucede el fenómeno de la Niña el porcentaje de observación tiende a ser más alto, pero en los años en que el fenómeno del Niño se manifiesta, el porcentaje decrece. Por otro lado, el porcentaje de observación con opacidades menores que 2.0 en frecuencias THz es tan solo del 1.9% y no muestra una variación anual obvia entre las diferentes estaciones. Esto indica que las observaciones en THz bajo condiciones de baja opacidad menor que 2.0 son muy complicadas de realizar en ALMA.

ABSTRACT

Observational rates under terahertz (THz) opacities less than 3.0 and 2.0 at the Atacama Large Millimeter/submillimeter Array (ALMA) site have been calculated using the 225 GHz tipping radiometer monitoring data and the opacity correlation between 225 GHz and THz opacities. The observational rate with THz opacity condition less than 3.0 is 12.4% in a year, and in austral summer (November–April) it is about twice higher than in austral winter (May–October). This observational rate shows a large sinusoidal annual variation, and it seems to have relation with the El Niño and La Niña phenomena; the La Niña years tend to have high observational rates, but the El Niño years show low rates. On the other hand, the observational rate with the THz opacity condition less than 2.0 is only 1.9%, and no obvious annual and seasonal variations are observed. This indicates that THz observations under low opacity condition of less than 2.0 at the ALMA site are very difficult to be performed.

Key Words: atmospheric effects — site testing — submillimeter: general

1. INTRODUCTION

At the terahertz (THz) frequency range, various emission/absorption lines can be seen from astronomical sources; high transition molecular lines (e.g., CO J = 11–10 or higher), atomic lines (e.g., [N II] 205 μm), and redshifted infrared lines (e.g., [C II] 158 μm and [O I] 63 μm), which are useful for the study of warm gas in various sources. In addition, low temperature (a few 10 K) dust continuum emission also peaks around this frequency range. However, this frequency range is very difficult to be observed from ground telescopes since the atmospheric absorption is very strong, and therefore it is observable at very limited sites under very limited weather conditions. Going to space or upper atmosphere is another option, but it is usually very expensive, so it is also not easy. Here, in this paper, I present an estimation of the observable time at the THz range at one of the best observation sites in the world, the Atacama Large Millimeter/submillimeter Array (ALMA) site.

ALMA is composed by up to eighty high-precision antennas, located at the Chajnantor plain of the Chilean Andes, near San Pedro de Atacama, 5000 m above the sea level. It is currently under construction and commissioning with the collaboration between East Asia, Europe, and North America (Hills et al. 2010; Wootten & Thompson 2009). Before starting the construction, various site testing measurements had been done around this site, including the 220 GHz/225 GHz tipping radiometer measurements (Kohno et al. 1995; Radford & Holdaway 1998; Radford & Chamberlin 2000; Radford et al. 2001; Radford 2002; Sakamoto 2002) and

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TABLE 1

ANNUAL AND SEASONAL OBSERVATIONAL RATES AT TERAHERTZ

	$\tau_{\rm THz} < 3.0$	$\tau_{\rm THz} < 2.0$
Summer (Nov. - Apr.)	8.7%	1.7%
Winter (May - Oct.)	16.8%	2.0%
Annual	12.4%	1.9%

the Fourier Transform Spectrometer (FTS) measurements (Matsuo et al. 1998; Matsushita et al. 1999; Paine et al. 2000; Matsushita & Matsuo 2003). The former measured data provided the long-term (up to a decade) 220 GHz/225 GHz opacity variation, and the latter measured data provided the atmospheric opacity spectra from millimeter to submillimeter wavelengths, and even up to THz opacity. In addition, some of the latter data also provided the correlation between 220 GHz/225 GHz opacity and other opacities. In this paper, I use the 225 GHz opacity data taken with the National Radio Astronomy Observatory (NRAO) tipping radiometer and the opacity correlation derived from the National Astronomical Observatory of Japan (NAOJ) FTS opacity spectrum data, to estimate the time variation of the THz opacity.

2. DATA REDUCTION

For the opacity time variation data of the NRAO 225 GHz tipping radiometer data, I used data between April 1995 and April 2006 from the NRAO ALMA Site Characterization Homepage[3] and Simon Radford's Chajnantor Site Evaluation Homepage[4]. I convert these 225 GHz opacity data into the THz opacity using the opacity correlation between 225 GHz and THz derived from the NAOJ FTS data: the correlation coefficient between the 220 GHz opacity and the opacities at 1035 GHz, 1350 GHz, and 1500 GHz atmospheric windows are derived as 123±5, 115±29, and 105±32, respectively (Matsushita et al. 1999). In this paper, I assume THz opacity is 105 times larger than 225 GHz opacity, namely [THz opacity] = 105× [225 GHz opacity].

First, I multiply by 105 all the available 225 GHz opacity data to derive the THz opacity, and then I calculate how much data points are below the following two opacity conditions (i.e., observational rates); one is the THz opacity, $\tau_{\rm THz}$, less than 3.0 ($\tau_{\rm 225\ GHz} < 0.029$), and another less than 2.0 ($\tau_{\rm 225\ GHz} < 0.019$). These calculated values have been used to estimate the annual and seasonal (summer and winter) variations of the observational rates. Here, I assume summer as the time between November and April, and winter between May and October.

[3] http://science.nrao.edu/alma/site-characterization.shtml.

[4] http://www.submm.caltech.edu/~sradford/site-eval/.

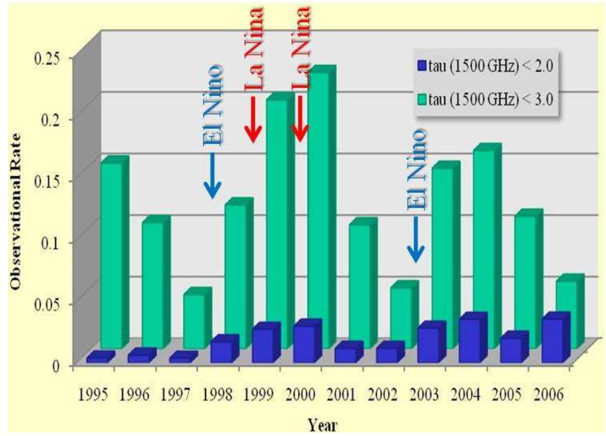

Fig. 1. Annual variation of the observational rates under the conditions of $\tau_{\rm THz} < 3.0$ (light histogram in the back) and $\tau_{\rm THz} < 2.0$ (dark histogram in front) between 1995 and 2006.

3. RESULTS

Table 1 shows the observational rates under two opacity conditions. Under the condition of $\tau_{\rm THz} < 3.0$, it is possible to observe 12.4% of a year (∼45 days). Seasonal difference is obvious, 16.8% of the time is observable at winter, but only about a half (8.7%) in summer. On the other hand, under the condition of $\tau_{\rm THz} < 2.0$, which is the best weather condition at the ALMA site, there is no clear seasonal difference, and the observational rate is only 1.9% of a year, and 2.0% and 1.7% for winter and summer, respectively.

Figure 1 depicts the annual variation of the observational rates under the conditions of $\tau_{\rm THz} < 3.0$ (light histogram) and $\tau_{\rm THz} < 2.0$ (dark histogram) between 1995 and 2006. The observational rate under the condition of $\tau_{\rm THz} < 3.0$ shows large annual variation, with the highest (22.4% or 82 days on 2000) and the lowest (4.4% or 16 days on 1997) rates differs for almost 20%. In addition, it exhibits a sinusoidal variation within an epoch of about 4–5 years, with high observational rate on 1995, 1999/2000, and 2003/2004, but low on 1997, 2002, and 2006. On the other hand, the observational rate under the condition of $\tau_{\rm THz} < 2.0$ shows small annual variation, with the highest (3.5% or 13 days on 2004 and 2006) and the lowest (0.36% or 1 day on 1997) rates differing only a few %.

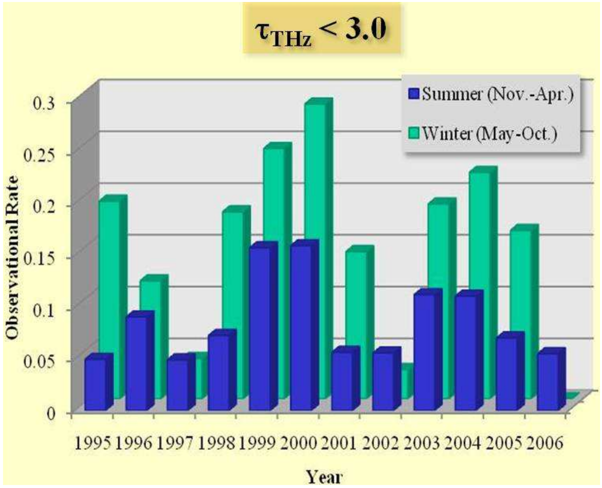

Fig. 2. Annual variation of the observational rates in winter (light histogram in the back) and summer (dark histogram in front) under the conditions of $\tau_{\mathrm{THz}} < 3.0$ between 1995 and 2006.

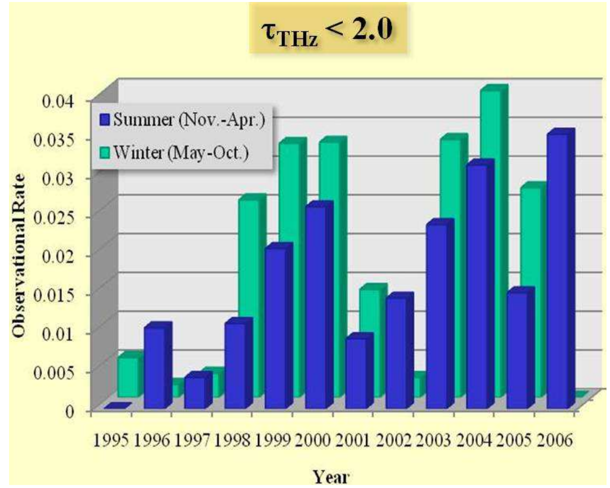

Fig. 3. Annual variation of the observational rates in winter (light histogram in the back) and summer (dark histogram in front) under the conditions of $\tau_{\mathrm{THz}} < 2.0$ between 1995 and 2006.

Figure 2 depicts the annual variations of winter (light histogram) and summer (dark histogram) under the opacity condition of $\tau_{\mathrm{THz}} < 3.0$. The annual variation of the winter season follows well the sinusoidal trend of the annual variation mentioned above, which is high observation rate on 1995, 2000, and 2004, but low on 1997, 2002, and 2006. In addition, the difference between the high and low observation rate is more pronounced than that of the annual variation mentioned above; the highest rate is 28.5% (or 52 days) on 2000, but the lowest rate is only 2.8% (or 5 days) on 2002, with a difference of more than 25% (note that there is no data in the winter season of 2006). On the other hand, the summer season shows less variation than that of the winter season, with less pronounced sinusoidal variation. It is interesting to note that in the year of the low observational rate (1997 and 2002), there is almost no difference in the observational rates between winter and summer (actually, the rate in summer is higher than that in winter, although it is very small difference).

Figure 3 exhibits the annual variations of winter (light histogram) and summer (dark histogram) under the opacity condition of $\tau_{\mathrm{THz}} < 2.0$. Compared to the annual variation of the condition of $\tau_{\mathrm{THz}} < 3.0$, that of the condition of $\tau_{\mathrm{THz}} < 2.0$ shows less seasonal variation, and sometimes it shows good observational rate in summer than in winter. The sinusoidal annual variation is also less pronounced.

4. DISCUSSION

The observational rate under the opacity condition of $\tau_{\mathrm{THz}} < 3.0$ ($\tau_{225\ \mathrm{GHz}} < 0.029$) clearly shows that there are large seasonal variations, suggesting that observations under this opacity condition should be done in winter. The observational rate under this opacity condition also exhibits large annual variation. I compared the occurrence of El Niño and La Niña with this annual variation. The El Niño and La Niña phenomena are derived from the Oceanic Niño Index (ONI) table in the homepage of the National Oceanic and Atmosphere Administration (NOAA)[5]. From this comparison, it is found that the observational rate under $\tau_{\mathrm{THz}} < 3.0$ is clearly bad at El Niño years (1997 and 2002), but obviously very good at La Niña years (1999 and 2000; see Figure 1). This clearly suggests that El Niño and La Niña phenomena affect the THz (and also millimeter and submillimeter) observational rates at the ALMA site.

On the other hand, the observational rate under the best opacity condition at the ALMA site, namely $\tau_{\mathrm{THz}} < 2.0$ ($\tau_{225\ \mathrm{GHz}} < 0.019$), exhibits less annual and seasonal variations with very rare observational occasion of only about 2% per year. This indicates that very good opacity conditions are very rare during all the year, and it is not very recommended to target these weather conditions at the ALMA site.

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