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3.5 Year Monitoring of 225 GHz Opacity at the Summit of Greenland

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Abstract

We present the 3.5 years monitoring results of 225 GHz opacity at the summit of the Greenland ice sheet (Greenland Summit Camp) at an altitude of 3200 m using a tipping radiometer. We chose this site as our submillimeter telescope (Greenland Telescope) site, because conditions are expected to have low submillimeter opacity and because its location offers favorable baselines to existing submillimeter telescopes for global-scale Very Long Baseline Interferometry. The site shows a clear seasonal variation with the average opacity lower by a factor of two during winter. The 25%, 50%, and 75% quartiles of the 225 GHz opacity during the winter months of November through April are 0.046, 0.060, and 0.080, respectively. For the winter quartiles of 25% and 50%, the Greenland site is about 10%–30% worse than the Atacama Large Millimeter/submillimeter Array (ALMA) or the South Pole sites. Estimated atmospheric transmission spectra in winter season are similar to the ALMA site at lower frequencies (<450 GHz), which are transparent enough to perform astronomical observations almost all of the winter time with opacities <0.5, but 10%–25% higher opacities at higher frequencies (>450 GHz) than those at the ALMA site. This is due to the lower altitude of the Greenland site and the resulting higher line wing opacity from pressure-broadened saturated water lines in addition to higher dry air continuum absorption at higher frequencies. Nevertheless, half of the winter time at the Greenland Summit Camp can be used for astronomical observations at frequencies between 450 GHz and 1000 GHz with opacities <1.2, and 10% of the time show >10% transmittance in the THz (1035 GHz, 1350 GHz, and 1500 GHz) windows. Summer season is good for observations at frequencies lower than 380 GHz. One major advantage of the Greenland Summit Camp site in winter is that there is no diurnal variation due to the polar night condition, and therefore the durations of low-opacity conditions are significantly longer than at the ALMA site. Opacities lower than 0.05 or 0.04 can continue for more than 100 hr. Such long stable opacity conditions do not occur as often even at the South Pole; it happens only for the opacity lower than 0.05. Since the opacity variation is directly related to the sky temperature (background) variation, the Greenland Summit Camp is suitable for astronomical observations that need unusually stable sky background.

Key words: atmospheric effects – site testing

Online material: color figure

1. Introduction

As various technologies for submillimeter (submm) wave observations have advanced, the prospects for very long baseline interferometry (VLBI) at submm wavelengths have become a reality. Operations at shorter wavelengths improve proportionately the spatial resolution as compared with current centimeter and millimeter VLBI observations; we anticipate that it will be possible to resolve astronomical sources in greater details, by a factor of 10.

The demand for better angular resolution is quite strong, especially for the direct imaging of nearby supermassive black holes (SMBHs); Sagittarius A* (Sgr A*), which is located at the center of our Galaxy and therefore the nearest SMBH, has been imaged at various wavelengths using the VLBI technique. The observed size of Sgr A* is obviously affected by the interstellar scattering at 3 mm or longer wavelengths, following the λ^2 scattering law (e.g., Shen et al. 2005; Bower et al. 2006). This effect, however, lessens at shorter wavelengths, and the size is observed to deviate from the λ^2 scattering law at 1.3 mm (Doeleman et al. 2008). This has strongly motivated submm-VLBI observations toward nearby SMBHs to resolve and image emission from their vicinities.

Upper limits of the intrinsic sizes of SMBHs have been measured so far for Sgr A* (Doeleman et al. 2008) and the nucleus of M87 (Doeleman et al. 2012); upper limits to the sizes of both sources are about 40 μarcsec. These results indicate that much longer baselines and/or higher frequencies are needed to resolve and image the SMBHs. We therefore started to look for a new site to perform submm-VLBI observations with substantially longer baselines than before.

2. Site Selection

For the site selection, we set criteria as follows:

1. Annual precipitable water vapor (PWV) of less than 3 mm for low submm opacity.
2. Longest possible baselines with existing submm telescopes, for obtaining the highest angular resolution (this also means that we do not consider sites that already have submm telescopes).
3. Overlapping sky coverage with the Atacama Large Millimeter/submillimeter Array (ALMA) to achieve the highest possible sensitivity.
4. Accessibility to the site for maintenance and operations.

We checked the satellite-based PWV data measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Aqua and Terra satellites for potential sites with respect to the locations of the available submm telescopes. We found three potential broad regions of interest; western China and Tibet, the highest mountains of southern Alaska, and the high Arctic polar desert, including northern Canada and Greenland. The Western China and Tibet regions do not have common sky with ALMA, so they do not meet the criterion (3). The tallest peaks in Alaska (e.g., Denali, or former official name Mount McKinley) are protected or otherwise inaccessible, so they do not meet the criterion (4). The summit of the Greenland ice sheet, on the other hand, has low PWV conditions throughout the year, has a common sky coverage with ALMA, will create the longest baseline length of about 9000 km for the submm-VLBI, and already has a research facility, Summit Camp, which is operated by CH2M Hill Polar Services (CPS)[4] for the U.S. National Science Foundation (NSF). The Summit Camp, therefore, meets all four criteria.

The Greenland Summit Camp is located at 72°57 N latitude and 38°46 W longitude, at an altitude of 3200 m. The temperature is very low, with winter temperatures between −30 °C and −60 °C, and summer temperatures between 0 °C and −30 °C (Laursen 2010; Martin-Cocher et al. 2014). Due to the combination of the high altitude and the low temperature, very low opacity is expected. Furthermore, the NSF is currently funding the Integrated Characterization of Energy, Clouds, Atmospheric state, and Precipitation (ICECAPS) project at the Summit Camp, which is using active and passive ground-based remote sensors, including two radiometers that observe 16 frequencies from 22.2 GHz to 150.0 GHz, to provide the first complete description of cloud properties above this site (Shupe et al. 2013). They determine the annual cycle of PWV using the radiometer observations at the central frequencies of 23.8, 31.4, 90, and 150 GHz as well as from radiosondes that are launched twice daily by ICECAPS technicians. We, therefore, decided to put a 225 GHz tipping radiometer at this site to measure the atmospheric opacity conditions for possible submm VLBI operations (see the next section for the reason to choose the measurement frequency).

Our group is in the process of deploying a 12 m diameter submm telescope to Greenland. Overall explanations of this project, the Greenland Telescope (GLT) project, are described in Inoue et al. (2014) for submm-VLBI science and technical details, and in Hirashita et al. (2016) for single-dish science cases. In addition, more detailed information about antennas, receivers, and software for the GLT project are in Raffin et al. (2016), Grimes et al. (2014), and Patel et al. (2016), respectively.

3. Measurement and Data Reduction

For the opacity measurement at the summit of the Greenland ice sheet, we procured a 225 GHz tipping radiometer, RPG-225 Radiometer, from Radiometer Physics GmbH (RPG). This instrument has the ability to operate in very cold environments, and indeed some units are operating at Arctic and Antarctic areas (two radiometers operating as part of ICECAPS mentioned above are also from RPG). The reason for the choice of this operating frequency is that there are many site survey results from all over the world, including the current submm telescope sites, such as the summit of Maunakea, the ALMA (Chajnantor and Pampa la Bola) site, and South Pole. The radiometer has an uncooled double side band heterodyne receiver with a bandwidth of 1 GHz. A tipping paraboloid mirror, which can rotate 360° with its half power beam width of 0°5, is installed in front of the feed horn. A Gortex window covers ±90° from zenith to allow sampling of the sky signal, and a blackbody target, whose temperature is monitored by a thermometer, is located at the bottom (i.e., 180° from zenith). A 140 W blower is located below the window and provides heating to prevent ice formation and accumulation on the window.

We obtained the radiometer in the autumn of 2010, deployed it on the roof of our institute in Taipei, and conducted functional and gain stability tests. We then moved the radiometer to the summit of Maunakea, Hawaii, in the end of 2010, to check the consistency with the 225 GHz tipping radiometer at the Caltech Submillimeter Observatory (CSO). We put our radiometer near the CSO with the same tipping direction, measured the opacity for about two weeks, and confirmed that the results were consistent with each other (linear regression coefficient = 1.04). After this, we moved the radiometer to the Polar Environment Atmospheric Research Laboratory (PEARL), located on a ridge at an altitude of 610 m at 80°05 N and 86°42 W, 15 km away from the Eureka weather station on Ellesmere Island, Canada. We measured the

[4] https://www.ch2m.com/

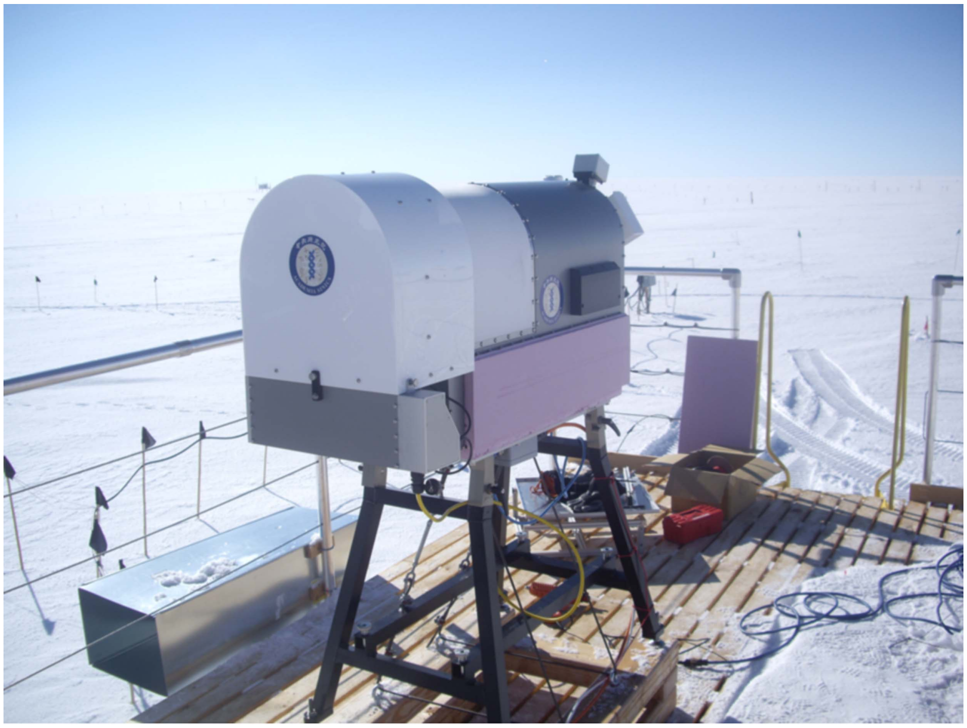

Figure 1. 225 GHz tipping radiometer located on the roof of the Mobile Science Facitily (MSF) at the Greenland Summit Camp.
(A color version of this figure is available in the online journal.)

atmospheric opacity for three months between late winter to early spring, and the results are reported in Asada et al. (2012) and Matsushita et al. (2013). After this measurement, we moved the radiometer to the Greenland Summit Camp. The radiometer was installed on the roof of the Mobile Science Facility (MSF; Shupe et al. 2013), which was built by CPS in support of the ICECAPS project. The roof deck is at about 3 m above the snow surface (Figure 1). The measurement was started from 2011 August 17, and data were collected until 2015 February 12. We present here the data for these ~3.5 years.

To measure the atmospheric opacity, we adopt the tipping method; we observe five angles from horizon (90° = zenith, 42°, 30°, 24°, and $19^\circ\!.2$, which corresponds to $\sec(z)$ of 1.0, 1.5, 2.0, 2.5, and 3.0) with 4 s integration at each angle. We scan the mirror from south to north, namely observe the five angles in both the southern and the northern sky (for the measurements at Greenland). The blackbody target in the bottom of the radiometer is observed before and after the scan for the gain calibration. The total duration of a tipping measurement is 75 s, and each tipping is performed every 10 minutes. Between the tipping measurements, the mirror is pointed toward the zenith and the sky data are recorded every 1 s. The output voltages, together with the mirror position, the blackbody target temperature, and other monitoring data, are recorded every 1 s into the hard disk of the host computer in binary format. The raw binary data are downloaded from Greenland to Taiwan regularly via internet.

The tipping data have been reduced with the typical data reduction method for tipping measurements (e.g., Matsuo et al. 1998). Since the MSF is a mobile facility on the snow, it can shake due to wind or human activities inside the facility, so that the radiometer tipping angle may be affected. In addition, the leveling accuracy for the radiometer is limited, so that the radiometer may also have a small constant tilt. We assume that the opacity is the same between the southern and northern skies, and the small difference in opacities derived from the southern and northern sky tippings is considered as the result of the tilt of MSF and/or the radiometer. Based on this assumption, we calculate the tilt angle and correct for it when deriving the opacity. In case the difference of the opacities between the southern and northern skies is large (i.e., when the tilt angle is calculated to be larger than two degrees; this value is also to allow some tolerance for the different opacities between the northern and southern sky), we judge this is due to real opacity differences, and we flag the data.

4. Results and Discussions

4.1. Time and Seasonal Variations

Figure 2 displays the measured time variation of the 225 GHz opacity for the 3.5 year period at the Greenland

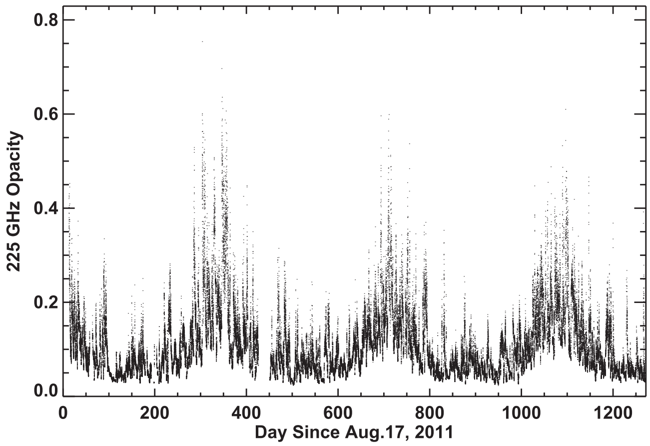

Figure 2. Time variation plot of 225 GHz opacity at the summit of Greenland ice sheet. The measurement has been started from 2011 August 17, which is defined as the day 1 in this diagram.

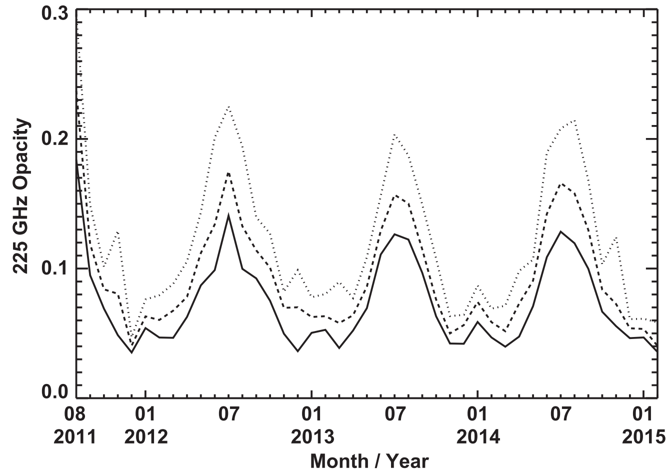

Figure 3. Monthly quartile variation of 225 GHz opacity. Solid, dashed, and dotted lines are 25%, 50%, and 75% quartiles, respectively. The first and the last months of this measurement, namely 2011 August and 2015 February, have fewer data than the other months, so that the statistical significance is low.

Summit Camp. It is clear that there is a seasonal variation; opacity in winter is low, but high in summer. Figure 3 shows the monthly quartile variations (solid, dashed, and dotted lines are 25%, 50%, and 75% quartiles, respectively). December and March tend to have the best opacity conditions, and July tends to have the worst. Note that the first and the last months of this measurement (i.e., 2011 August and 2015 February) have fewer data than the other months, so the statistical significance is lower. In both diagrams, there is no significant annual difference.

4.2. *Cumulative Distribution and Histogram*

We also made cumulative distribution plots and histograms of the measured 225 GHz opacity while separating the seasons into winter and summer (Figure 4). Here we define winter as between the beginning of November and the end of April (solid line plots), and summer as May through October (dashed line plots). The quartiles for each season are 0.046, 0.060, and 0.080 for 25%, 50%, and 75%, respectively, in winter, and 0.089, 0.118, and 0.159 for summer (see also the crosses and the values in the figure). It is obvious that the opacity in winter is about half of that in summer at all the quartiles. The histograms show that the opacities of 0.04 and 0.10 are the opacities that occur most often in winter and summer, respectively.

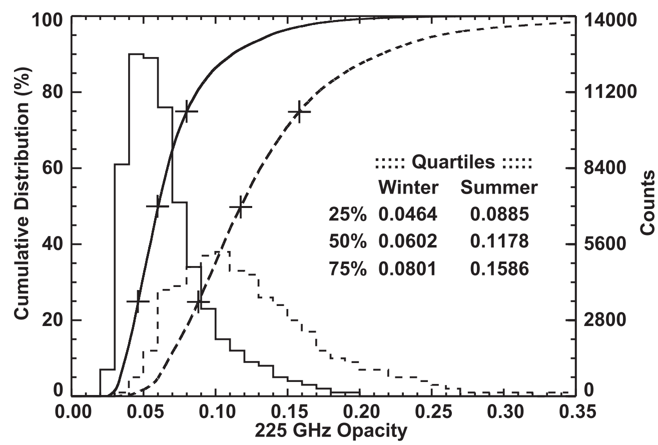

Figure 4. Cumulative distribution plots and histograms of 225 GHz opacity in winter (solid lines) and summer (dashed lines). The vertical axis on the left-hand side is for the cumulative distribution plots, and that on the right-hand side is for the histograms. Crosses on the cumulative distribution plots are the opacity quartiles of each season. The quartile for winter and summer are also listed in the figure.

We then compared the opacity quartiles using our 3.5 year period statistics with those at the ALMA and the South Pole sites, which are well-established sites for submm observations. The 225 GHz opacity data for the ALMA site have been obtained from Radford & Chamberlin (2000) and Radford (2011), whose measurements have been made between 1995 April and 2006 April (∼11 years), and that for the South Pole site from Chamberlin & Bally (1994, 1995) measured between 1992 January and December (one year). Since both the ALMA and the South Pole sites are located in the southern hemisphere, we define winter as between the beginning of May through the end of October, and summer as November through April. The calculated quartiles for these three sites are listed in Table 1.

For winter, the ALMA site is the best at the 25% quartile, South Pole is next, and Greenland Summit Camp is the worst, but only by ∼0.005 (∼12%) difference in opacity between each site. At the 50% quartile, the ALMA and South Pole sites are almost the same, and the opacity is about 0.01 (about 25%)

Table 1
Comparison of 225 GHz Opacity Quartiles Between Three Sites

Site	Season	Quartiles		
		25%	50%	75%
GL Summit Camp	Winter	0.046	0.060	0.080
	Summer	0.089	0.118	0.159
ALMA	Winter	0.035	0.050	0.080
	Summer	0.071	0.131	0.261
South Pole	Winter	0.041	0.048	0.057
	Summer	0.050	0.062	0.076

worse at Greenland Summit Camp. At the 75% quartile, South Pole is the best (40% better) and the opacity is the same between the ALMA and the Greenland sites.

For summer, South Pole is the best for the 25% quartile, ALMA is the next, and Greenland is the worst with ∼0.02 difference in opacity between each site. At the 50% and 75% quartiles, South Pole is again the best, but Greenland is next and the ALMA site is the worst. The South Pole site is about twice better in opacity as compared with the Greenland site, and the ALMA site is significantly worse than these two sites.

We note here that there are many studies that compare the opacity conditions at the summit of Maunakea, which is also a well-established submm site, with those at the ALMA and South Pole sites; opacity quartiles of Maunakea are ∼50% higher than those of the ALMA site (Matsushita et al. 1999; Radford & Chamberlin 2000; Radford 2011; Radford & Peterson 2016).

In summary, the South Pole site has little seasonal differences in opacity over the annual cycle, with a factor of two difference between seasons. On the other hand, the ALMA site has large variations between winter and summer, with significantly worse conditions in summer, known as the Bolivian Winter around February and March. The opacity conditions at the Greenland Summit Camp are roughly intermediate between the South Pole and the ALMA sites.

4.3. Diurnal Variation

The top row of Figure 5 shows the diurnal opacity variations in winter (left column) and summer (right column) at the Greenland Summit Camp. Solid, dashed, and dotted lines are 25%, 50%, and 75% of the hourly quartiles. It is obvious that there is no diurnal variation in both seasons. This can be easily explained by the polar conditions; only nighttime in winter and daytime in summer. It is also clear that the opacity in winter is half of that in summer, as mentioned in the cumulative distribution plot (Figure 4) above.

The middle and bottom rows of Figure 5 show the diurnal variation at the ALMA and the South Pole sites, respectively. It is obvious that there is a clear diurnal variation in the ALMA data, which is naturally explained by the mid-latitude conditions, leading to a strong diurnal cycle compared to polar regions, while the South Pole data are very similar to the Greenland Summit Camp (i.e., no diurnal variation).

For winter, the South Pole site is always the best at all quartiles. Opacities at the 25% and 50% quartiles at the ALMA site are almost always statistically better than those at the Greenland Summit Camp, but for the 75% quartile, the daytime opacity is statistically better at the Greenland Summit Camp than at the ALMA site due to the diurnal variation.

For summer, the South Pole site is again always the best at all quartiles. For opacities at the 25% and 50% quartiles, the Greenland Summit Camp is always better between ∼12 and ∼20 hr than the ALMA site (i.e., daytime at the ALMA site) due to no diurnal variation. For opacities at the 75% quartile, the Greenland Summit Camp is always better than the ALMA site.

4.4. Duration of Opacity Lower than Certain Values

We then calculated time durations of opacity conditions continuously lower than certain values. We focused on opacities lower than 0.05, 0.04, and 0.03, which are excellent opacity conditions that only occur in $\lesssim$30% of the winter season at the Greenland Summit Camp. The resultant histograms for the Greenland Summit Camp are presented in Figure 6(a). Since the tipping measurements are done every 10 minutes as mentioned in Section 3, the lower limit of the measurements are located at 0.17 hr. The counts (vertical axis) are normalized with the number of annual data points, assuming one data point takes 10 minutes (Section 3). We intentionally cut the count limit to 70 in the plot for presentation purpose.

For opacity less than 0.05 or 0.04 at the Greenland Summit Camp, there were several occasions for which more than 100 hr were continuously showing opacities lower than those values, and there are many occasions that continued for more than 10 hr or several hr. The counts for durations between 1 hr and 20 hr are almost the same, and that for durations between 20 hr to several tens of hr are roughly half of the shorter duration. For the opacity less than 0.03, there were several occasions when the opacity was continuously low for more than 10 hr of time, and more occasions exist for durations of more than an hour. This is obviously due to the polar conditions (no diurnal variation) as mentioned above, and it is very difficult to achieve similar values at other submillimeter sites that are not at polar regions, such as in the Hawaii (Mauna kea) or Northern Chile (ALMA) site.

Indeed, we also calculated the time duration of opacity conditions for the ALMA site under the same opacity conditions as the Greenland Summit Camp (Figure 6(b)), and

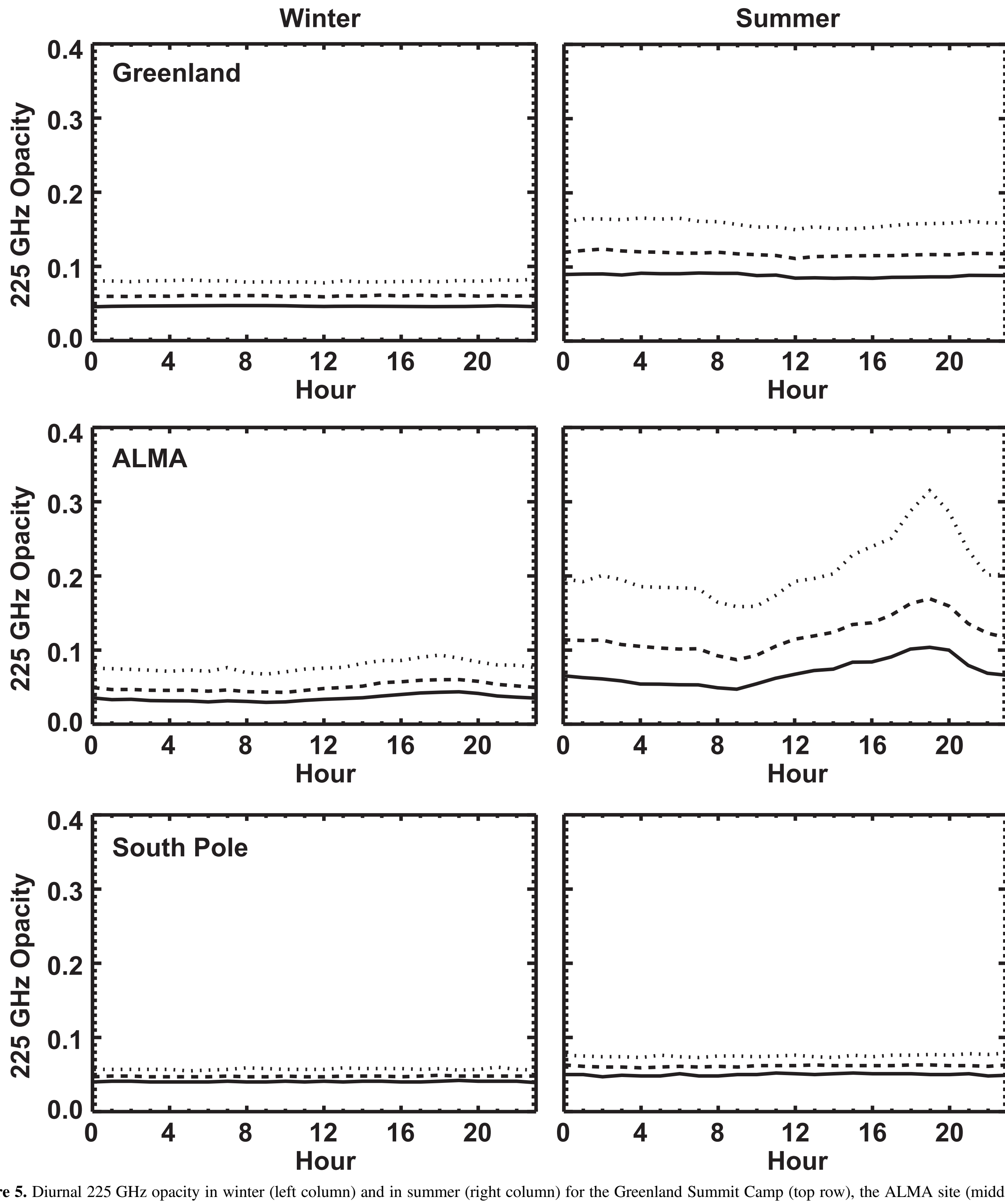

Figure 5. Diurnal 225 GHz opacity in winter (left column) and in summer (right column) for the Greenland Summit Camp (top row), the ALMA site (middle row), and the South Pole site (bottom row). Solid, dashed, and dotted lines are 25%, 50%, and 75% of the hourly quartiles, respectively.

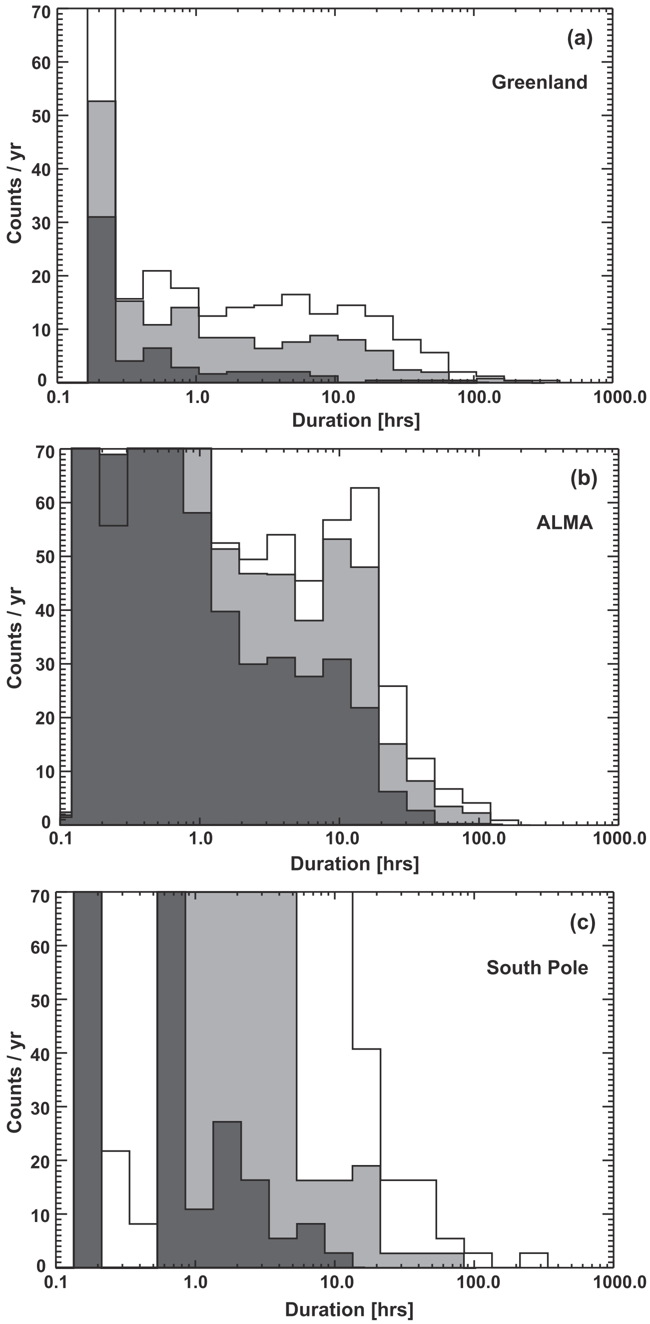

Figure 6. Histogram of time duration for opacity continuously lower than 0.05 (white), 0.04 (light gray), and 0.03 (dark gray) for (a) the Greenland Summit Camp, (b) the ALMA site, and (c) the South Pole site. Vertical axis is counts per year.

the difference is obvious. At the ALMA site, there are many occasions for the opacity less than 0.05, 0.04, and even 0.03 continues for up to 20 hr, but the occasions for the duration longer than 20 hr are significantly smaller, about one-fifth, than the shorter durations. The duration longer than 100 hr has only been recorded for opacity lower than 0.05, and never happened for opacities lower than 0.04 or 0.03 in the 11 years long data.

For the South Pole site (Figure 6(c)), the duration is obviously shorter than that of the Greenland Summit Camp. There are many occasions for the opacity less than 0.05, which continues up to 10 hr, but there are significantly fewer occasions for the duration longer than 10 hr. Similar to the ALMA site, the duration longer than 100 hr has only been recorded in opacity lower than 0.05, and never happened for opacity lower than 0.04 or 0.03. For the opacity lower than 0.03, the duration is only up to about 10 hr, and has never been longer. Although the South Pole data are taken only for a year and the opacity statistics are better than for the Greenland Summit Camp (Sections 4.2, 4.3), good opacity duration time is shorter.

Table 2 shows that low opacity conditions continue for more than 24, 50, 100, 150, and 200 hr at the Greenland Summit Camp, ALMA, and the South Pole. The ALMA and South Pole sites have better atmospheric opacities over time durations longer than 24 hr and 50 hr at opacity conditions lower than 0.05 and 0.04, respectively. But for time durations longer than 100 hr at opacity conditions lower than 0.04, the Greenland Summit Camp clearly has lower atmospheric opacities.

These results are also clearly seen in Figure 7, which compares the cumulative distributions of the time durations for the three sites discussed above. Figures 7(a) and (b) show the cumulative distributions of the time durations of opacities less than 0.05 and 0.04, respectively, and it is clear that the Greenland Summit Camp (solid line) has a long tail toward the long duration of more than a hundred hours. The ALMA site always exhibits higher cumulative distributions than that of the Greenland Summit Camp, and reaches 100% around several tens of hours. The South Pole site shows the steepest cumulative distribution, and reaches 100% around a few tens of hours, much shorter than the other two sites. The cumulative distributions of the time durations of opacity less than 0.03 (Figure 7(c)) display very similar distribution between the Greenland and the ALMA site, but the Greenland Summit Camp shows a long tail up to several tens of hours. Again, the South Pole site is much shorter, only up to 10 hr.

In summary, for the low opacity duration, the Greenland Summit Camp is the best site to have continuous low opacity conditions. Since the variation of opacity is directly related to the variation of sky temperature (background), these long stable opacity conditions will be a significant advantage for astronomical observations, which need unusually stable sky background, such as THz observations or wide-field submillimeter continuum observations.

5. Estimation of Opacities and PWVs at Other Frequencies

Using our 225 GHz opacity data and the radiative transfer program "*am*" (Paine 2016), we estimated the atmospheric

Table 2
Atmospheric Opacity Counts Per Year Over Specific Time Intervals

Site	$\tau_{225\ \mathrm{GHz}} < 0.05$					$\tau_{225\ \mathrm{GHz}} < 0.04$				$\tau_{225\ \mathrm{GHz}} < 0.03$	
	>24 h	>50 hr	>100 hr	>150 hr	>200 hr	>24 hr	>50 hr	>100 hr	>150 hr	>24 hr	>50 hr
	Counts yr^{-1}					Counts yr^{-1}				Counts yr^{-1}	
GL Summit Camp	17.7	6.4	2.0	1.2	0.8	6.0	2.4	1.2	0.4	1.2	0.4
ALMA	30.6	10.7	1.5	0.2	0.0	17.6	4.7	0.0	0.0	4.1	0.3
South Pole	32.6	13.6	5.4	2.7	2.7	8.1	2.7	0.0	0.0	0.0	0.0

transmission spectra between 0 GHz and 1600 GHz in both winter and summer at the Greenland Summit Camp. First, from the NASA Modern-Era Retrospective analysis for Research and Applications, Version 2 (Rienecker et al. 2011; Molod et al. 2015 MERRA-2) reanalysis data interpolated to the location of the Greenland Summit Camp, we computed various percentiles of the temperature, H_2O mixing ratio, and O_3 mixing ratio at each MERRA pressure level, for the winter and summer months covering the same period as the radiometer measurements. The *am* model files were then constructed such that each percentile model used the corresponding percentile temperature and H_2O profile, whereas all models used the 50% quartile O_3 profile. Here we assumed that temperature and water vapor should be highly correlated, such that it is physically meaningful to associate a percentile profile with the corresponding percentile statistics on each level. On the other hand, O_3 is relatively uncorrelated with either temperature or water vapor, so that it makes sense to simply use the median profile.

For each set of MERRA-2 percentile profiles, we found a scaling factor on the tropospheric part of the H_2O profile, which reproduced the corresponding 225 GHz opacity percentiles from our measurements. The scale factor on the median MERRA H_2O profile to match the median 225 GHz opacity was 1.09 in winter and 1.10 in summer, indicating a dry bias of approximately 10% for MERRA-2 relative to our measurements. From a radiative transfer model using the percentile profiles scaled to our measurements, we then estimated the corresponding percentile atmospheric transmission spectra.

The estimated atmospheric transmission spectra for the 2%, 10%, 25%, and 50% opacity conditions in winter season are plotted in Figure 8(a). Note that these opacity conditions correspond to the 225 GHz opacity of 0.031, 0.037, 0.046, and 0.060, respectively. These spectra suggest that it is possible to observe astronomical sources with little atmospheric attenuation (opacities <0.5) most of the winter time at the Greenland Summit Camp for frequencies lower than 450 GHz, and half of the time for frequencies between 450 and 1000 GHz with opacities <1.2. For the THz windows (1035, 1350, and 1500 GHz), 10% of the winter time will have an atmospheric transmission of more than 10%.

The estimated atmospheric transmission spectra for the same opacity percentiles as above, but in summer season are plotted in Figure 8(b). Note that these opacity conditions correspond to the 225 GHz opacity of 0.052, 0.068, 0.088, and 0.118, respectively. These spectra suggest that it is possible to observe astronomical sources with little atmospheric attenuation (opacities <0.5) most of the summer time for frequencies below the 380 GHz water vapor line, and more than half of the time for the 450 GHz atmospheric window with opacities <1. For the windows between 450 and 1000 GHz, 25% of the summer time will have an atmospheric transmission of more than 10%. The THz windows are totally opaque in summer.

We also calculated the relationships between 225 GHz opacity and other submillimeter atmospheric window opacities using the above estimates. This is useful for estimating the opacities at higher frequencies from the observations of the opacity at 225 GHz. Relations between two opacities turned out to be all linear, and therefore the linear coefficients and offsets have been calculated. The calculated values are in Table 3. Opacities at the 492, 675, and 875 GHz windows are about 25–30 times larger than the 225 GHz opacity, and those at the THz windows are about 130–140 times larger.

These values can be compared with the measurement results at the ALMA site (Matsushita et al. 1999, 2000): For the 345 and 410 GHz windows, there are only a few % differences between the Greenland Summit Camp and the ALMA site, but for higher frequencies, the Greenland Summit Camp is about 10%–15% worse than the ALMA site for the 492, 1035, and 1350 GHz windows, and about 25% worse for the 675, 875, 937, and 1500 GHz windows (Table 3). This is due to the altitude difference. The altitude of the Greenland Summit Camp is only 3200 m, much lower than that of the ALMA site at 5000 m, and this difference increases the opacity in the pressure-broadened wings of saturated H_2O lines at high frequencies. In addition, the lower altitude introduces larger dry air continuum absorption at the Greenland Summit Camp; the dry air continuum absorption increases at higher frequencies, up to the middle of the N_2–N_2 collision-induced absorption band near 3 THz (Pardo et al. 2001a, 2001b; Paine 2016).

The "*am*" program also estimates the PWVs together with the transmission spectra, and we present those in Table 4. Using these values, it is possible to derive the relation between the 225 GHz opacity and PWV at the Greenland Summit

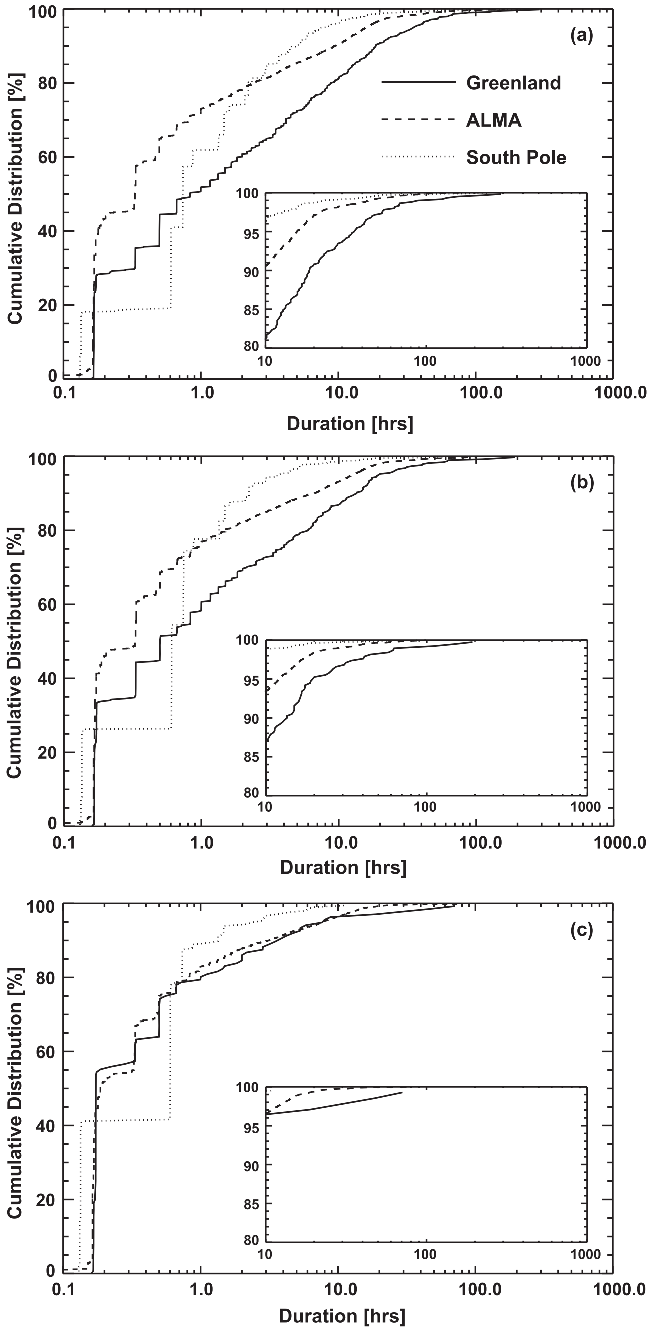

Figure 7. Cumulative distribution plots of time duration for opacity continuously lower than (a) 0.05, (b) 0.04, and (c) 0.03 for the Greenland Summit Camp (solid lines), the ALMA site (dashed lines), and the South Pole site (dotted lines). Each plot also displays an inset that is a zoomed plot of the cumulative distribution between 80% and 100% and the time duration between 10 and 1000 hr.

Camp, which turned out to be

$$\tau_{225\,\mathrm{GHz}} = 0.048 \times \mathrm{PWV}\,[\mathrm{mm}] + 0.022, \quad (1)$$

where $\tau_{225\,\mathrm{GHz}}$ is the 225 GHz opacity. With this equation, together with the relationship between the 225 GHz opacity and that of other frequencies (Table 3), it is also possible to compare various atmospheric window opacities and PWV.

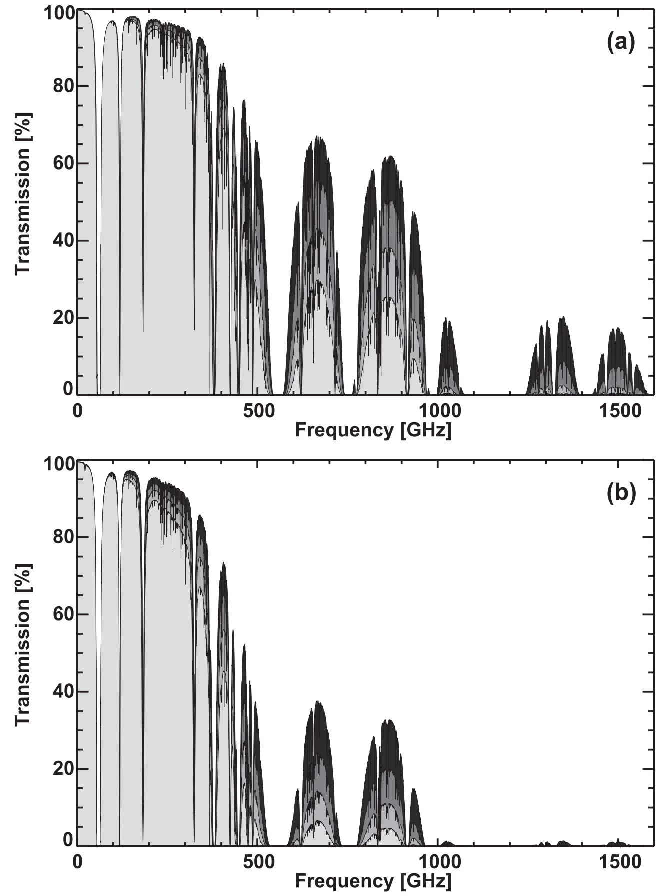

Figure 8. Estimated atmospheric transmission spectra at the Greenland Summit Camp in (a) winter and (b) summer seasons. Spectra at 2%, 10%, 25%, and 50% opacity conditions are plotted in grayscale with darker to lighter gray.

Table 3
Calculated Linear Correlation Between 225 GHz and Submm Atmospheric Window Opacities at the Greenland Summit Camp

Frequency	Coefficient	Offset	Difference from the ALMA site
345 GHz	3.80	−0.032	4%
410 GHz	7.34	−0.064	−3%
492 GHz	26.4	−0.31	12%
675 GHz	27.7	−0.45	24%
875 GHz	31.0	−0.48	28%
937 GHz	55.5	−0.96	26%
1035 GHz	140	−2.7	14%
1350 GHz	129	−2.4	12%
1500 GHz	130	−2.3	29%

The 3 year (2008–2010) PWV statistics and the atmospheric transmission spectra of the summit of Greenland have also been derived by Tremblin et al. (2012) using the water vapor product

Table 4
Estimated PWV for Winter and Summer Seasons

Percentile	Winter		Summer	
	225 GHz Opacity	PWV (mm)	225 GHz Opacity	PWV (mm)
2%	0.0311	0.186	0.0516	0.623
10%	0.0375	0.321	0.0679	0.965
25%	0.0464	0.506	0.0885	1.396
50%	0.0602	0.790	0.1178	2.054
75%	0.0801	1.205	0.1586	2.942

from the Infrared Atmospheric Sounding Interferometer (IASI) instrument on the Meteorological Operation (MetOp)-A satellite. They found a median annual PWV of 0.94 mm over the summit of Greenland. Our radiometer-derived median PWV for the three-year subset of our data from 2011 October to 2014 September is 1.28 mm. To connect these two periods, we note that the MERRA-2 median PWV for 2008 January—2010 December is 1.27 mm, whereas for 2011 October—2014 September it is 1.16 mm. If we assume the MERRA-2 dry bias of approximately 10% is consistent between these periods, then the implied median PWV for 2008—2010 is 1.40 mm. This would suggest that the PWV for Summit in Tremblin et al. (2012) is systematically lower than the actual PWV by approximately 33%.

There are two reasons why a single satellite data set could produce significantly biased PWV statistics. First, although IASI is able to retrieve surface temperature, the water vapor retrieval accuracy in the lower troposphere necessarily suffers from a lack of thermal contrast with the surface (Wulfmeyer et al. 2015). The second reason is temporal sampling bias. Typically satellite sounders are in Sun-synchronous orbits that pass over a given point on the Earth's surface at the same pair of local times each day; these are 9:30 and 21:30 in the case of IASI (Hilton et al. 2012). In comparison, a reanalysis such as MERRA-2 can be expected to produce more realistic PWV statistics because it assimilates multiple satellite, surface, and upper air measurements using a model with realistic dynamics.

6. Summary

We present the 3.5 years monitoring of the 225 GHz opacity at the Summit of the Greenland ice sheet using a tipping radiometer.

Opacity variations clearly show a seasonal variation between winter (≈nighttime) and summer (≈daytime), but no diurnal variation, with the opacity in winter being about half of that in summer. This is similar to the opacity variations at the South Pole site due to the polar conditions, but the absolute opacity value is about 10%–30% higher than that of the South Pole site in winter, and about double in summer. In contrast, the ALMA site shows clear seasonal and diurnal variations due to mid-latitude conditions; the opacity at the ALMA site is up to 20% better than at the Greenland site in winter, but up to 40% worse in summer.

The estimated atmospheric transmission spectra suggest that most of the winter time is useable for astronomical observations at frequencies lower than 450 GHz, half of the time is useable for frequencies between 450 GHz and 1000 GHz, and 10% of the time is useable for the THz atmospheric windows. Most of summer time is useable at frequencies lower than 380 GHz, and half of the summer time is useful at the 450 GHz atmospheric window. The linear correlations between 225 GHz and submillimeter atmospheric window opacities are derived, and opacities at the 492, 675, and 875 GHz windows are about 25–30 times larger, while those at THz windows are about 130–140 times larger than the opacity at 225 GHz. These opacities are up to 25% higher than those at the ALMA site, which is due to the altitude difference between the Greenland Summit Camp (3200 m) and the ALMA site (5000 m).

The biggest advantage of the opacity conditions at the Greenland Summit Camp is the long time durations of low opacity. At the Greenland Summit Camp, opacities lower than 0.04 or 0.05 can continue for more than a hundred hours occasionally, and opacities lower than 0.03 can continue for more than several tens of hours in some cases. In case of opacity lower than 0.04, the Greenland Summit Camp is the only site that can continue this condition for more than one hundred hours, indicating that the Greenland site is suitable for observations that need stable opacity conditions for a long time.

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