Astrophysics from Antarctica
Proceedings IAU Symposium No. 288, 2012
M. G. Burton, X. Cui & N. F. H. Tothill, eds.

doi:10.1017/S1743921312016638

A worldwide comparison of the best sites for submillimetre astronomy

P. Tremblin[1], N. Schneider[1,2], V. Minier[1], G. Al. Durand[1] and J. Urban[3]

[1]Laboratoire AIM Paris-Saclay (CEA/Irfu - Uni. Paris Diderot - CNRS/INSU), Centre d'études de Saclay, 91191 Gif-Sur-Yvette, France
email: `pascal.tremblin@cea.fr`

[2]Université de Bordeaux, LAB, UMR 5804, CNRS, 33270, Floirac, France

[3]Chalmers University of Technology, Department of Earth and Space Sciences, 41296 Göteborg, Sweden

Abstract. Over the past few years a major effort has been put into the exploration of potential sites for the deployment of submillimetre (submm) astronomical facilities. Amongst the most important sites are Dome C and Dome A on the Antarctic Plateau, and the Chajnantor area in Chile. In this context, we report on measurements of the sky opacity at 200 μm over a period of three years at the French-Italian station, Concordia, at Dome C, Antarctica. Based on satellite data, we present a comparison of the atmospheric transmission at 200, 350 μm between the best potential/known sites for submillimetre astronomy all around the world.

The precipitable water vapour (PWV) was extracted from satellite measurements of the Infrared Atmospheric Sounding Interferometer (IASI) on the METOP-A satellite, between 2008 and 2010. We computed the atmospheric transmission at 200 μm and 350 μm using the forward atmospheric model MOLIERE (Microwave Observation LIne Estimation and REtrieval). This method allows us to compare known sites all around the world without the calibration biases of multiple in-situ instruments, and to explore the potential of new sites.

1. Introduction

A major obstacle to ground-based observations in the submm range (and specifically at wavelengths shorter than 500 μm) is the atmosphere. This part of the electromagnetic spectrum is normally the preserve of space telescopes such as the Herschel space observatory (Pilbratt *et al.* 2010) although large submm facilities such as ALMA will be able to operate down to 420 μm and possibly below in the future (Hills *et al.* 2010). However, submm observations in the 200-μm window with ground-based instruments will always require exceptional conditions (see Marrone *et al.* 2005; Oberst *et al.* 2006).

For ground-based sites, previous studies (e.g. Schneider *et al.* 2009; Tremblin *et al.* 2011; Matsushita *et al.* 1999; Peterson *et al.* 2003) already showed that a few sites are well-suited for submm, mid-IR, and FIR astronomy and their transmission properties are rather well determined (for example by Fourier Transform Spectrometer obervations in the 0.5-1.6 THz range at Mauna Kea/Hawaii (Pardo *et al.* 2001)). The high-altitude ($\geqslant$ 5000 m) Chilean sites are known for dry conditions (see Matsushita *et al.* 1999; Peterson *et al.* 2003), and site testing is now carried out at the driest place on Earth, Antarctica (see Chamberlin *et al.* 1997; Yang *et al.* 2010; Tremblin *et al.* 2011). Comparisons between Antarctic and Chilean sites are difficult and uncertain since they rely on ground-based instruments that use different methods and calibration techniques (see Peterson *et al.* 2003, for example). The working conditions are also an important issue, a single instrument moved from Chile to Antarctica will have a different behavior in the harsh polar environment (−70°C in winter at Dome C). A meaningful comparison is possible if several independent instruments are used at each place. An example of such a study is the one of Tremblin *et al.* (2011) that obtained transmission data at Dome C thanks to radio-soundings and the radiometers HAMSTRAD (Ricaud *et al.* 2010) and SUMMIT08. However, it is rare to have many instruments at one site. The best solution is to use satellite data, which also enables to investigate any location on Earth. Thanks to the IASI (Infrared Atmospheric Sounding Interferometer) on the Metop-A satellite, it is now possible to conduct such a comparison over several years with no instrument bias and with the same working conditions for the detectors. We present here a 3-year study of the PWV of a selection of existing and upcoming submm-sites in Antarctica, Chile, Tibet, and Argentina, as well as for two SOFIA stations, Palmdale/California and Christchurch/New Zealand. A direct comparison is enabled by comparing the individual and cumulated quartiles of PWV and the transmission is given, using these PWV values and the atmospheric model MOLIERE-5 (Urban *et al.* 2004).

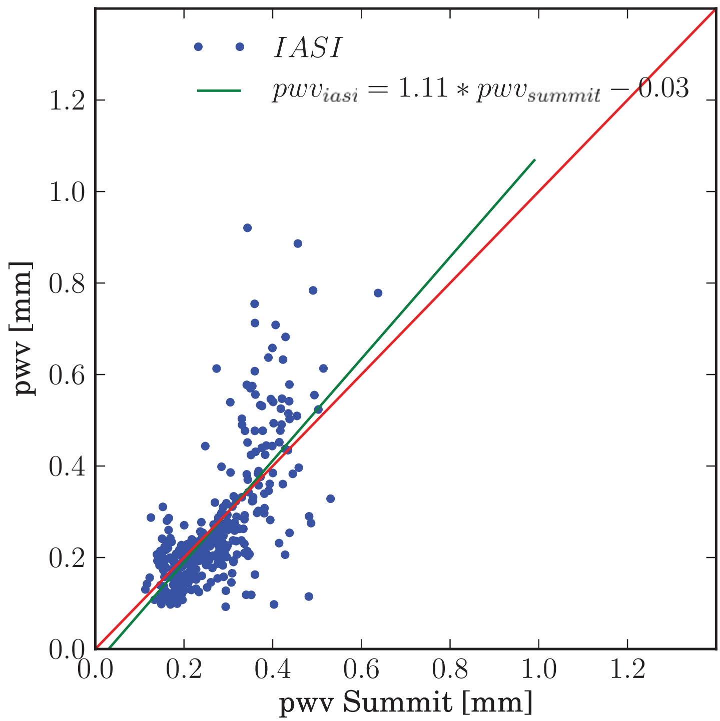

Figure 1. Correlation between in-situ measurements (SUMMIT08) and satellite measurments (IASI) between 2008 and 2010 at the Concordia station in Antarctica.

2. In-situ and satellite PWV measurements

IASI (Infrared Atmospheric Sounding Interferometer) is an atmospheric interferometer working in the infrared, launched in 2006 on the METOP-A satellite (Phulpin *et al.* 2007; Pougatchev *et al.* 2008; Herbin *et al.* 2009; Clerbaux *et al.* 2009). Vertical profiles of tropospheric humidity at ninety altitude levels (resolution 1 km) are retrieved with a typically 10% accuracy (Pougatchev *et al.* 2008). The amount of precipitable water vapour (PWV) is given by the integral of these vertical profiles. All the measurements in a zone of 110 km^2 around the site of interest are averaged. In-situ measurements at the Concordia station in Antarctica were performed between 2008 and 2010 thanks to a radiometer SUMMIT08. These data were compared with the satellite data (see Tremblin *et al.* 2011) and the correlation between the two is given in Fig. 1. There is a negative bias for SUMMIT08 (SUMMIT08 values are lower than the ones for IASI) at high PWV (more than 0.4 mm) that was identified as an instrumental effect of SUMMIT08. Nevertheless, the correlation at low PWV is very good and validates the use of the measurements from IASI to compare the PWV statistics between different sites for astronomical purposes.

The use of vertical satellite profiles is slightly trickier for a mountain site. Since we take all measurements in a zone of 110 km^2, we sometimes get profiles that do not contain mountain altitude but include lower ones. This would bias the retrieved PWV to high values. To overcome this difficulty, we generally truncated the profiles at the altitude of the site of interest. This method was already used by Ricaud *et al.* (2010) to compare IASI measurements with the HAMSTRAD radiometer, over the Pyrenees mountains. They showed a very good correlation for the integrated PWV. We also determined in this way the PWV content at high altitudes ($\geqslant$ 11 km) over Palmdale, USA and Christchurch, New Zealand for the on-going and future flights of SOFIA. Table 1 shows the comparison between all the sites with the first decile and the quartiles of the PWV statistics between 2008 and 2010. These results clearly show that Antarctic sites are the driest sites followed by South-American sites and then northern-hemisphere sites. Our long-term satellite statistic of PWV shows that the site of Summit in Greenland offers comparable observing conditions (PWV and altitude) to Mauna Kea, which opens a new perspective for submm astronomy in the northern hemisphere.

Table 1. First decile and quartiles of the PWV for all the studied sites.

Time fract. 2008-2010	SOFIA Palm./Christ.	Dome A	Dome C	South Pole	Cerro Chaj.	Chaj. Plat.	Sum-mit	Cerro Macon	Mauna Kea	Yang-bajing
0.10	0.006/0.004	0.11	0.17	0.15	0.27	0.39	0.36	0.47	0.62	1.21
0.25	0.006/0.005	0.16	0.22	0.21	0.37	0.53	0.51	0.66	0.91	2.47
0.50	0.007/0.006	0.21	0.28	0.30	0.61	0.86	1.94	0.02	1.44	inf
0.75	0.009/0.007	0.26	0.39	0.49	1.11	1.63	1.96	1.66	2.57	inf

3. Transmission at 200 μm and 350 μm

For the determination of the tropospheric transmission corresponding to the PWVs of the various deciles and quartiles for each site, we use MOLIERE-5.7 (Microwave Observation and LIne Estimation and REtrieval), a forward and inversion atmospheric model (Urban *et al.* 2004), developed for atmospheric science applications. It has previously been used to calculate the atmospheric transmission up to 2000 GHz ($\approx$ 150 μm) for a large number of astronomical sites (see Schneider *et al.* (2009) and `http://submm.eu`). The first decile and the quartiles of the transmission at 200 μm and 350 μm are given in Table 2. For the first quartile, only the transmission at Cerro Chajnantor catches up Antarctica thanks to the high altitude of the site. However for the second and third quartiles Antarctic sites have a better transmissions based on the long term statistics, especially at 350 μm. For the three sites, Chajnantor Plateau, Cerro Macon and Mauna Kea, the transmission window at 350 μm opens significantly while it is only rarely possible to observe at 200 μm.

The stability of the transmission can be compared thanks to the site photometric quality ratio (SPQR) introduced by De Gregori *et al.* (2012). It consists in the ratio

https://doi.org/10.1017/S1743921312016638 Published online by Cambridge University Press

of the monthly averaged transmission to its monthly standard deviation, on a daily time-scale. The averaged value of the SPQR ratio for the transmission at 200 μm between 2008 and 2010 are given in Table 2. A first look at the values shows that all temperate sites have a SPQR ratio lower than 1 while Antarctic sites have a ratio greater than 1. The averaged transmission is lower than its fluctuations on temperate sites i.e., the transmission is highly variable. Note that the Arctic site on the Summit mountain is also highly variable, hence Antarctica is really unique even among polar environments. On the Antarctic plateau, Dome A has the best SPQR ratio with a monthly-averaged transmission that is typically 3-4 times higher than the fluctuations. Dome C achieves also very good conditions with a ratio of the order of 2-3 while the South Pole has a monthly-averaged transmission of the same order of the fluctuations comparable to the conditions reached at Cerro Chajnantor.

Table 2. First decile and quartiles of the 350-μm (top) and 200-μm (middle) transmissions for all the studied sites. Bottom: averaged value of the SPQR ratio at 200 μm between 2008 and 2010.

Time fraction 2008-2010	Dome C	Dome A	South Pole	Cerro Chaj.	Chaj. Plat.	Cerro Macon	Mauna Kea	Summit	Yangbajing
0.10	0.62	0.72	0.61	0.65	0.56	0.49	0.47	0.42	0.19
0.25	0.57	0.67	0.56	0.58	0.46	0.41	0.36	0.31	0.02
0.50	0.51	0.62	0.47	0.44	0.31	0.29	0.21	0.15	0.00
0.75	0.41	0.57	0.34	0.24	0.12	0.15	0.07	0.02	0.00
Time fraction 2008-2010	Dome C	Dome A	South Pole	Cerro Chaj.	Chaj. Plat.	Cerro Macon	Mauna Kea	Summit	Yangbajing
0.10	0.17	0.32	0.16	0.20	0.09	0.05	0.05	0.03	0.00
0.25	0.11	0.22	0.11	0.12	0.04	0.02	0.02	0.01	0.00
0.50	0.07	0.16	0.05	0.04	0.01	0.00	0.00	0.00	0.00
0.75	0.03	0.11	0.01	0.00	0.00	0.00	0.00	0.00	0.00
SPQR ratio	2.7	3.6	1.3	1.1	0.7	0.7	0.7	0.6	0.3

4. Conclusions

Among all the sites studied, Cerro Chajnantor and the Antarctic Plateau present the best conditions for submm astronomy. However only Dome A and Dome C have a stable transmission that will allow unique science such as time-series and large surveys to be performed there. The method used to compare the different sites is robust and based on only one instrument, IASI, and the atmospheric model MOLIERE. A calculator to show the PWV statistics and to compute the corresponding transmission at any given wavelength is available to the community at `http://irfu.cea.fr/submm` and `http://submm.eu` for all the sites presented here and for the three years 2008, 2009 and 2010.

References

Chamberlin, R. A., Lane, A. P., & Stark, A. A. 1997, *ApJ*, 476, 428
Clerbaux, C., Boynard, A., Clarisse, L., *et al.* 2009, *ACP*, 9, 6041
De Gregori, S., de Petris, M., Decina, B., *et al.* 2012, *MNRAS*, 425, 222
Herbin, H., Hurtmans, D., Clerbaux, C., Clarisse, L., & Coheur, P. F. 2009, *ACP*, 9, 9433
Hills, R. E., Kurz, R. J., & Peck, A. B. 2010, *SPIE*, 7733, 773317
Marrone, D., Blundell, R., Tong, E., *et al.* 2005, *STT*

Matsushita, S., Matsuo, H., Pardo, J. R., & Radford, S. J. E. 1999, *PASJ*, 51, 603
Oberst, T. E., Parshley, S. C., Stacey, G. J., *et al.* 2006, *ApJ*, 652, L125
Pardo, J. R., Cernicharo, J., & Serabyn, E. 2001, *IEEE*, 49, 1683
Peterson, J. B., Radford, S. J. E., Ade, P., *et al.* 2003, *PASP*, 115, 383
Phulpin, T., Blumstein, D., Prel, F., *et al.* 2007, *AERSDPU III*, 6684, 12
Pilbratt, G. L., Riedinger, J. R., Passvogel, T., *et al.* 2010, *A&A*, 518, L1
Pougatchev, N., August, T., Calbet, X., *et al.* 2008, *EOS XIII*, 7081, 18
Ricaud, P., Gabard, B., Derrien, S., *et al.* 2010, *ITGRS*, 48, 2189
Schneider, N., Urban, J., & Baron, P. 2009, *PSS*, 57, 1419
Tremblin, P., Minier, V., Schneider, N., *et al.* 2011, *A&A*, 535, 112
Urban, J., Baron, P., Lautié, N., *et al.* 2004, *JQSRT*, 83, 529
Yang, H., Kulesa, C. A., Walker, C. K., *et al.* 2010, *PASP*, 122, 490