An Analysis of the Millimetre-Wavelength Seeing above Mauna Kea

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1 Introduction

The term 'seeing' as employed in optical astronomy is used to characterise small changes in atmospheric density and, hence, refractive index that arise due to small changes in temperature. Such variations cause the astronomical image to quiver because the average angle of arrival of radiation is affected by the changing refractive index along its path through the atmosphere. In the millimetre and radio regime the dominant fluctuations are not those associated with changes in atmospheric density but with changes in water vapour content. At the JCMT the resulting variation in source position can be significant with respect to the size of the telescope beam and can thus affect the choice of observing mode.

The Smithsonian Astrophysical Observatory (SAO) has installed a radio phase monitor close to the summit of Mauna Kea in order to monitor the atmospheric stability or radio seeing. This instrument comprises two 1.8 m antennae which are separated by approximately 100 m and receive a beacon signal from a geosynchronous satellite at 11.712 GHz. The phases of the two signals give a measurement of the fluctuations in the path length of the two antennae. An estimate of the seeing at JCMT wavelengths is made by assuming that the phase is proportional to frequency. This is expected to be true since the atmosphere is nearly non-dispersive at frequencies where it is optically thin. A detailed technical overview of the instrument is given by Masson et al. (1990)[1].

The purpose of the study described in this document is to investigate the effects of seeing on observing practices at the JCMT. For example, what are the possibilities for day-time observing? Are the shifts timed correctly? Are there any obvious differences between Summer and Winter months or trends with atmospheric opacity? With these aims in mind the millimetre seeing data which are archived at the summit are analysed below.

2 Variations of seeing with time

When fault free the SAO phase monitor provides an estimate of the millimetre seeing once every 5 minutes and operates continuously. The two points to consider are the variation of seeing with time of day and with time of year. In order to limit the number of figures and tables representative cases only are shown. Any conclusions apply to the whole data set but it is stressed that only two years' of data exist in the archive.

[1] Masson J. D., Williams J. D., Oberlander D., Herrnstein J., 1990, Submillimeter Array Technical Memorandum, No. 30

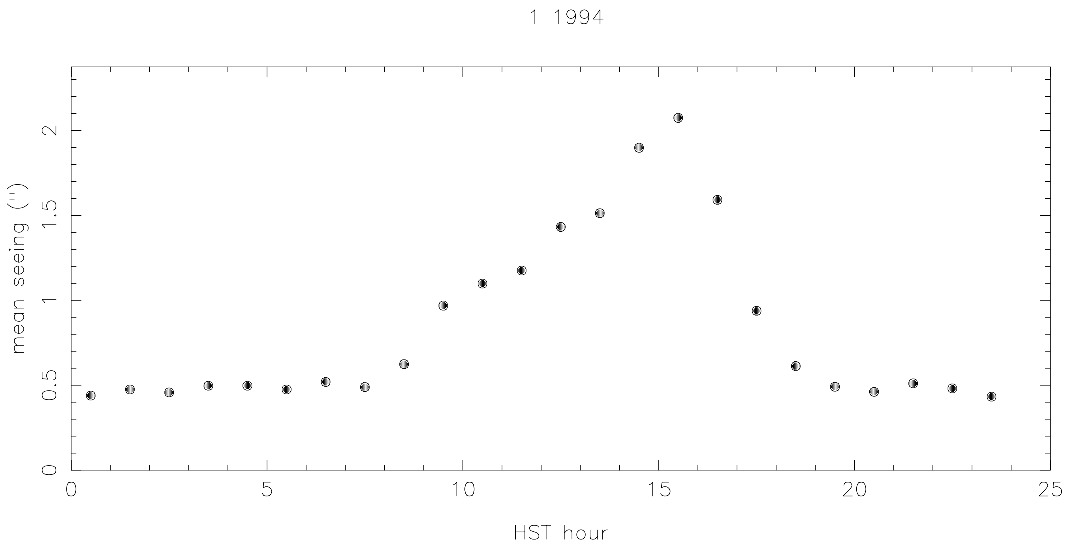

Figure 1: Variation of mean hourly seeing during January 1994

Figures 1–4 show examples of such variations during 1994 where each point represents the mean seeing for that month in each hourly bin. Summer and Winter months are shown for comparison.

The data for June and December 1994 are presented in a different manner in Tables 1 and 2 which give the percentage time for which the seeing was below 0.5, 1.0 and 2.0 arcsec for each hour in the night averaged over the month.

Table 3 shows the mean seeing for each month and the percentage of the time that the seeing is below 0.5, 1.0 and 2.0 arcsec. This table only includes data taken between HST 18–09 which roughly corresponds to the stable night time conditions (see below).

The following points arise from inspection of these data:

- The seeing clearly deteriorates during the day-time hours, typically reaching a maximum during mid-afternoon. This is probably due to an increase in temperature and precipitable water vapour (pwv) which will result in increased atmospheric turbulence.
- An important effect is that the seeing sometimes remains below 2.0 or 1.5 arcsec for large periods during Winter day-time. Under these conditions observing could continue providing that the pwv is at a tolerable level and the observing programme is suited to the less than perfect conditions. During the Summer months the seeing increases rapidly after sunrise and doesn't stabilize until after sunset.
- During the night-time hours there is essentially no difference in the stable minimum value of seeing that is reached during Winter and Summer.
- At the JCMT the night is divided into two equal shifts of 8 hours. The first shift runs from 5:30pm until 1:30am and the second shift continues until 9:30am. The timing of these shifts can be examined in light of the seeing information presented here. There is again a possible difference between Summer and Winter. During the Summer months the seeing typically stabilizes between 7 and 8pm and then begins to increase between 7 and 8am. During Winter the seeing typically stabilizes between 6 and 7pm and rises again between 8 and 9am. Thus, averaged over a month, first and second shift receive an equal allocation of the best possible conditions. During Winter the

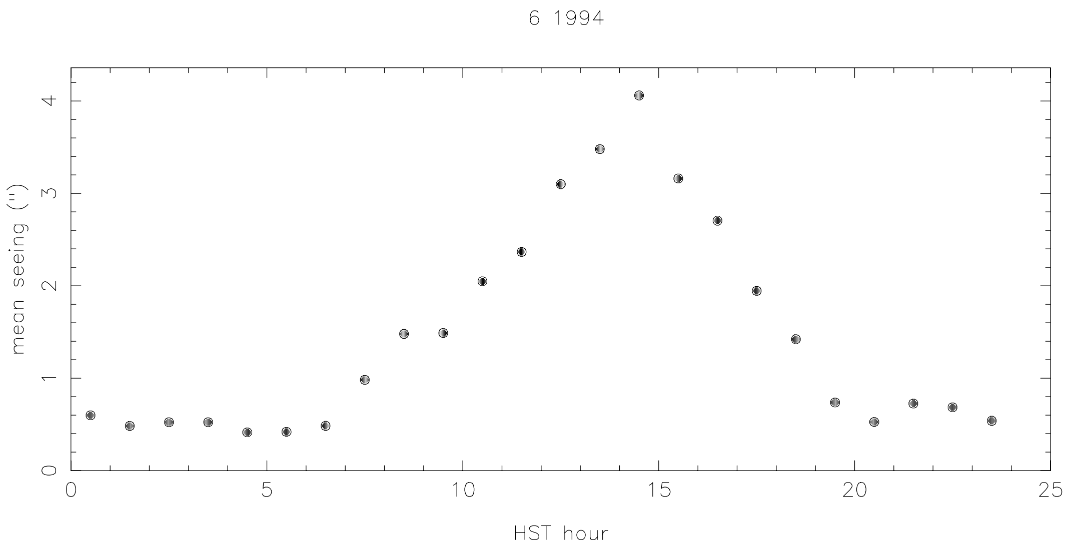

Figure 2: Variation of mean hourly seeing during June 1994

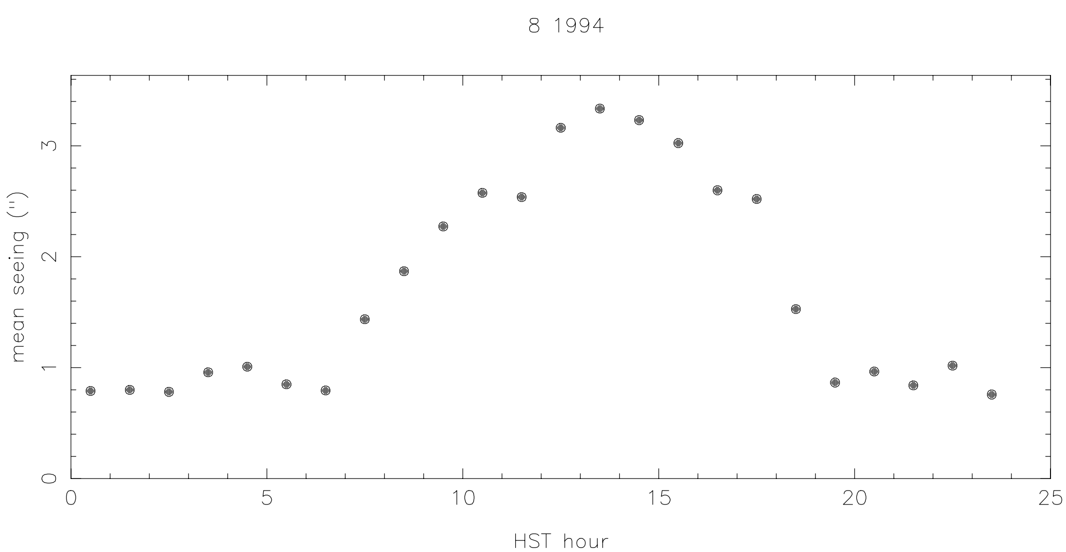

Figure 3: Variation of mean hourly seeing during August 1994

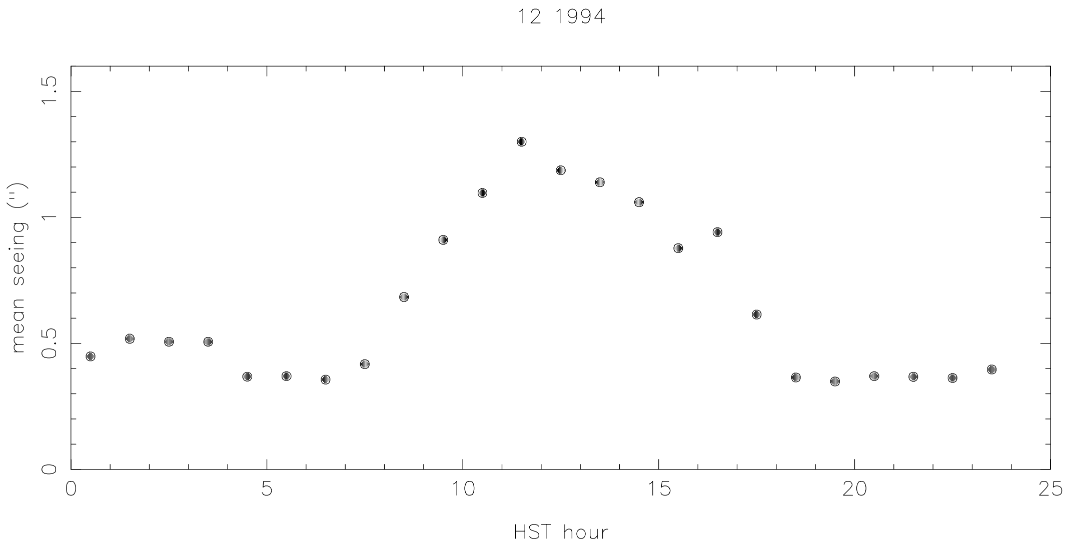

Figure 4: Variation of mean hourly seeing during December 1994

Table 1: Percentage of time that the seeing is below 0.5, 1.0 and 2.0 arcsec during June 1994. Each night is split into hourly bins which are averaged over the month.

HST hour	seeing < 0.5 (%)	seeing < 1.0 (%)	seeing < 2.0 (%)
0–1	71.6	86.7	93.7
1–2	72.5	88.4	97.0
2–3	69.9	84.7	96.0
3–4	73.0	86.0	94.7
4–5	77.0	89.8	98.4
5–6	76.6	92.1	98.8
6–7	69.7	88.2	97.0
7–8	33.5	61.6	90.0
8–9	7.2	30.0	80.8
9–10	8.6	34.9	79.6
10–11	4.5	22.8	61.9
11–12	2.8	15.1	48.5
12–13	2.4	10.1	37.8
13–14	0.6	6.8	26.2
14–15	0.0	4.5	23.2
15–16	0.0	1.8	23.0
16–17	0.3	8.0	40.4
17–18	8.0	24.4	62.8
18–19	23.1	51.8	75.4
19–20	44.9	77.7	95.7
20–21	62.4	91.5	97.9
21–22	59.9	83.9	94.8
22–23	64.8	83.9	92.1
23–24	71.8	88.3	95.1

Table 2: Percentage of time that the seeing is below 0.5, 1.0 and 2.0 arcsec during December 1994. Each night is split into hourly bins which are averaged over the month.

HST hour	seeing < 0.5 (%)	seeing < 1.0 (%)	seeing < 2.0 (%)
0–1	76.5	92.3	96.9
1–2	72.7	88.4	96.8
2–3	75.7	90.5	96.2
3–4	80.7	93.3	96.3
4–5	83.7	91.9	100.0
5–6	76.1	94.7	100.0
6–7	83.8	96.1	99.5
7–8	82.8	93.8	97.2
8–9	60.5	78.6	95.5
9–10	33.6	67.3	94.2
10–11	21.1	54.5	91.5
11–12	10.7	41.4	85.7
12–13	19.7	48.4	84.9
13–14	15.4	60.6	88.7
14–15	24.9	61.2	89.6
15–16	21.5	64.6	98.5
16–17	23.7	61.5	96.6
17–18	58.6	82.4	98.4
18–19	81.8	97.7	100.0
19–20	83.2	98.6	100.0
20–21	81.0	97.5	100.0
21–22	78.9	97.6	100.0
22–23	79.0	95.9	100.0
23–24	80.5	92.8	99.0

Table 3: Variation of seeing with time of year; only data from the stable hours HST 18–09 are included. The last column shows the number of data points analysed each month.

Year/Month	Mean seeing (arcsec)	< 0.5 (%)	< 1.0 (%)	<2.0 (%)	n
9401	0.5	69.1	89.4	98.5	5898
9402	1.1	44.5	66.3	86.9	4967
9403	0.6	68.4	85.7	93.9	5862
9404	0.4	82.5	92.7	98.5	5771
9405	0.6	61.0	83.8	96.1	5839
9406	0.8	55.6	76.3	92.3	5278
9407	1.4	32.1	57.9	80.8	5167
9408	1.1	52.3	71.3	86.4	5328
9409	0.7	56.6	83.4	99.6	265
9410	0.6	68.0	84.8	96.4	5318
9411	1.0	49.2	71.2	87.1	3546
9412	0.5	75.7	91.7	98.2	6893
9501	0.6	64.2	83.2	97.1	2403
9502	1.8	30.9	56.2	72.5	3215
9503	1.0	48.5	73.0	87.9	5562
9504	1.1	48.0	68.2	85.6	5686
9505	1.1	57.7	76.2	87.1	5498
9506	0.6	66.4	85.7	94.8	3365
9507	0.9	57.2	75.9	88.8	3899
9508	0.6	74.0	84.9	93.6	5155
9509	0.6	70.4	83.6	93.5	3948
9510	0.8	51.5	80.2	94.0	13142

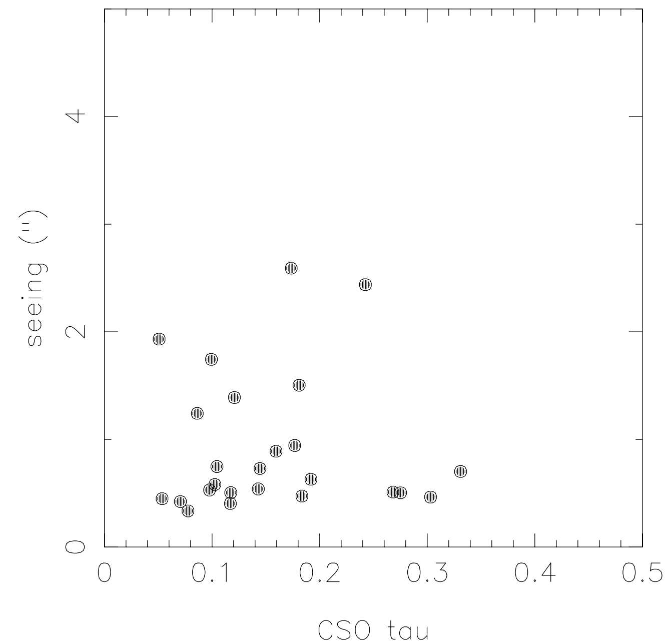

Figure 5: Variation of seeing with CSO tau during August 1994. Each point represents the mean value of each quantity over the period HST 18–09 h.

best conditions persist for about two hours longer than for the Summer months which is probably due to the longer night. Observing programmes that require the best possible conditions, such as continuum polarimetry (seeing < 0.5 arcsec) or diffraction limited mapping at submillimetre wavelengths, will be able to continue for an extra two hours per night during the Winter.

3 Variations of seeing with atmospheric opacity

The main contribution to atmospheric opacity in the millimetre/submillimetre regime is water vapour. A simple linear relationship exists between the pwv and the atmospheric extinction coefficent at 225 GHz which is monitored by the Caltech Submillimeter Observatory (CSO). This latter quantity is traditionally referred to as the 'CSO tau'. In this section the relationship between the CSO tau and the millimetre seeing is investigated.

Figures 5 and 6 show examples of the dependence of seeing on CSO tau. Each point represents the mean value of each quantity for each night in the month; the times are again restricted to HST 18–09 h to match the analysis with the stable night-time conditions. The data set is limited further by eliminating points for which either data set contained less than 50 points on any given night. Only values of CSO tau < 0.5 are included.

The following general conclusions are made:

- On inspection of the complete data set there are no obvious trends with time of year.
- In general the seeing and CSO tau are correlated. Bad seeing corresponding to high levels of

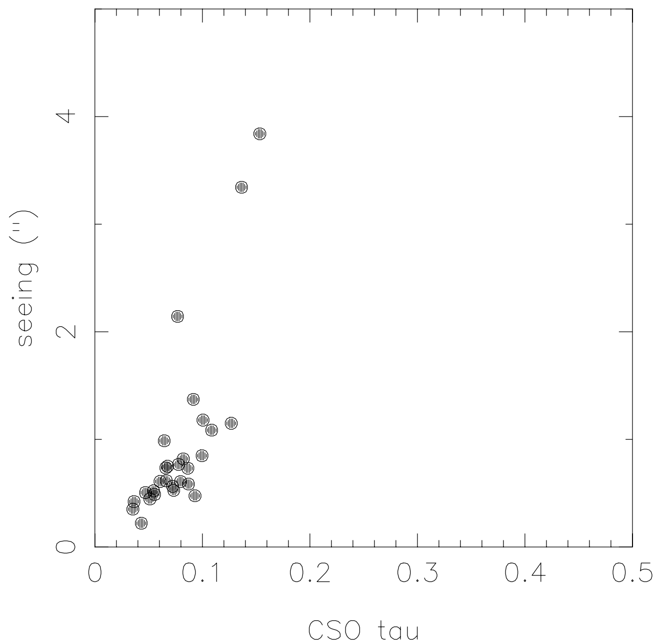

Figure 6: Variation of seeing with CSO tau during March 1995. Each point represents the mean value of each quantity over the period HST 18–09 h.

PWV (cf. Figure 6) and vice-versa.

- On occasion bad seeing can correspond to low levels of pwv ($<$ 1 mm or CSO tau $<$ 0.05) and coversely good seeing conditions are not uncommon on nights with poor atmospheric transmission (pwv $>$ 5mm; CSO tau $>$ 0.3).