ASTRONOMICAL SEEING AT MAUNA KEA AND IN PARTICULAR AT THE CFHT

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ABSTRACT

The astronomical seeing at the CFHT is excellent. It now averages <FWHM> = 0.9" and is continuously improving as a result of seeing conservation measures in the telescope building. Our studies suggest that the average natural seeing on Mauna Kea should be ~ 0.6". Very high (<0.2") resolution imaging at the CFHT, through adaptive optics, appears feasible.

1. Introduction

The Canada-France-Hawaii Telescope (CFHT) on Mauna Kea is at an altitude of 4,200-m, well above the inversion layer. The CFHT and other observatories (UKIRT, IRTF and UH) share the rims of steep-sloped cinder cones at the summit of an isolate, tall shield volcanic island in the tropical mid-Pacific. They stand above 42 percent of the Earth's atmosphere, higher than any other major observatories, above all of the low altitude convection layers, aerosols and humidity. From these characteristics, the site should be expected to offer unsurpassed image quality. This is indeed the case.

Results of systematic seeing studies on Mauna Kea have been published by Dainty and Scaddan (1973), McInnes (1981), Dyck and Howell (1983) and Walker (1983). As pointed out by Dyck and Howell, the results of these investigations, carried out with different instruments and techniques, are difficult to compare and show significant disagreements. Further site surveys, including seeing-related measurements, are still in progress on Mauna Kea, under the auspices of the National Optical Astronomy Observatories (NOAO) and of the University of California (UC).

To those of us who observe regularly on Mauna Kea, and who have had considerable experience at other good sites, it is somewhat surprising to see,at times, the relative merits of the Mauna Kea seeing still being studied

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and debated. The University of Hawaii (UH) has operated a 2.2-m telescope at the summit for 14 years; the 3.6-m CFH telescope celebrates this month the fourth anniversary of its first run. The reason why the Mauna Kea seeing is still being investigated by the outside community is probably that once a suitable seeing measuring instrument is installed at the summit it is used for astronomy rather than for research in atmospheric turbulence. And we, the users of these instruments, have perhaps failed to publicize and discuss our experience extensively enough. It is hoped that this brief paper may help to rectify the situation. Another reason may be that the natural Mauna Kea seeing is so good that its precise evaluation by time-honored methods is particularily difficult. To be sure, extensive, independent seeing surveys will go on and novel techniques will be used. One may hope that, in time, these studies will confirm the folkloric tales told by astronomers who use the site.

2. Seeing Statistics

Figure 1 summarizes seeing statistics obtained at the CFHT and at the UH 2.2-m telescope. The UH mean line is adopted from Dyck and Howell's (1983) infrared speckle measurements reduced to λ = 500nm at the zenith. All CFHT data have been obtained at visible wavelengths. The early CFHT statistics (1981-83) represent an heterogeneous mixture of visual estimates by various observers, image profiles measured sporadically on direct, image tube or electronographic plates and star trails data. These data are, of course, of varying quality but appeared self-consistent enough when compiled in early 1983 to provide a credible first look at the statistics. Since the third quarter 1983, the CFHT compilation has been restricted to the more quantitative and impersonal data provided by the CCD images obtained after the commissioning of our CCD camera in July, 1983. Three estimates per night are usually recorded. The individual data points for the period covered by the second half of 1983 (31 nights) and by the first quarter of 1984 (14 nights) are plotted in Figure 1 to illustrate the degree of reliabilty of the statistics. These are raw data; no deconvolutions of any kind (guiding errors, image motion, optical aberrations, estimated dome seeing...) were applied to the observed FWHM's before compiling the statistics. The overall mean of these CCD data is <FWHM> = 0.90".

The four sets of data in Figure 1 give a fairly coherent picture of the seeing distribution currently obtained at two different astronomical telescopes on Mauna Kea. Without further analysis it could be stated quite generally that the seeing is of sub-arc second quality two third of the time. We believe,

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however, that the differences between these data sets are significant and largely reflect different degrees of dome seeing contributions, as discussed below.

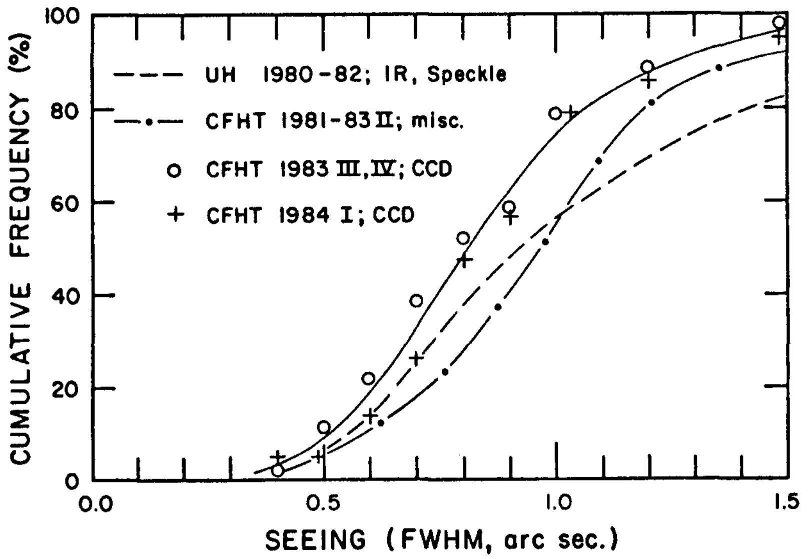

Fig. 1. Seeing statistics from CFHT and UH telescopes on Mauna Kea

The mean line drawn through the CFHT CCD data corresponds to a log-normal differential distributions of x = FWHM of the form

$$P(x)dx = K \exp \left\{-1/2 \left[\frac{\ln (x/\langle x\rangle)}{\ln (\sigma/\langle x\rangle)}\right]^2 \right\} \qquad (1)$$

with $\langle x\rangle = 0.75''$, and $\sigma/\langle x\rangle = 1.4$

Characteristic cumulative frequencies of seeing are given for reference in Table 1.

TABLE 1

Seeing Statistics at the CFHT

FWHM (")	% Occurence
<0.50	10
<0.75	40
<1.00	73
<1.50	96

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3. Where Does the Seeing Come From?

One can arbitrarily define three distinct regions of the atmosphere responsible for global image spread, or seeing: the free atmosphere, the local boundary layer and the air inside the dome.

Bely (1983) has applied Van Zandt's stochastic model (Van Zandt et al., 1978, 1981) to compute the image spread due to the free atmosphere above Hawaii. He used data from radio sondes launched from Hilo on 207 clear nights. His results give a free atmosphere seeing distribution with a mode of 0"35 and a mean of 0"45.

Echo sounders are currently being used by the NOAO and UC teams to study the turbulence structure of the boundary layer above the summit cinder cones of Mauna Kea. Very preliminary results (Cudaback, priv. comm.) give structure constants $C_N^2 \simeq 2 \times 10^{-15}$ near the surface and becoming unmeasurably small ($< 1 \times 10^{-17}$) at heights of 100-150 meters. From this, one would expect $\omega \simeq$ 0"4 for the boundary layer seeing. We have measured the temperature structure constant, C_T, outside the CFHT dome on two nights using probes carried by a tethered balloon. We found C_T = 0.10 and 0.02 $^{o}C.^{-1/3}$ at heights of 10 and 50 meters; this leads to $\omega \simeq$ 0"3.(1) As these studies continue, a more precise knowledge of the boundary layer turbulence will be obtained. These early results suggest that this layer produces an image spread of 0"3 to 0"4.

Evidence that the seeing at the CFHT is not dominated by boundary layer turbulence is provided by the observation that the correlation between the seeing quality and the wind speed is, at best, very weak. Sub-arc second

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(1): The relations between ω, C_N and C_T are:

$$\omega = 2.6 \times 10^{7} \left[\int C_N^2 \, dh \right]^{0.6}$$
$$C_N = 7.9 \times 10^{-5} \left(\frac{P}{T}2\right) C_T \quad \text{(Wyngaard et al., 1971)}$$

Where P is the local pressure in millibars (P ≃ 600 at Mauna Kea) and T the absolute temperature (T ≃ 270 ^{o}K).

seeing often occurs in winds up to 50 knots. Dyck and Howell (1983) also failed to find a correlation with wind speed or direction in their UH 2.2-m seeing data.

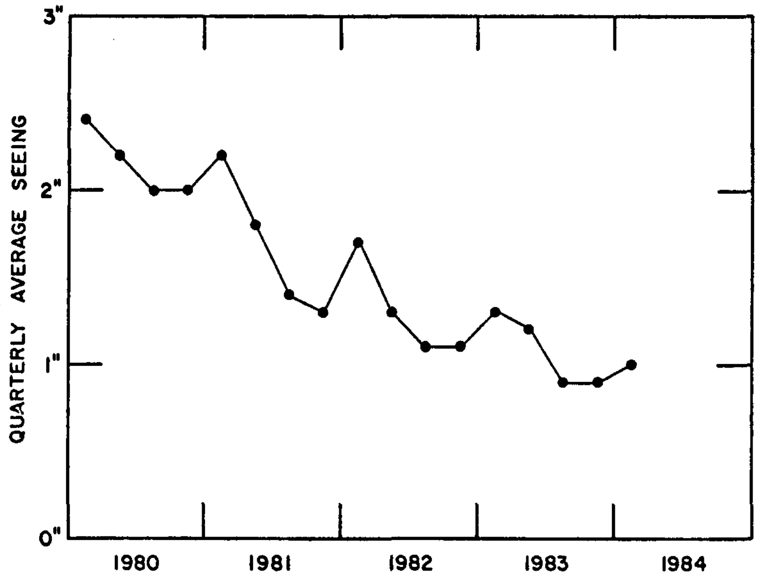

Fig. 2. The historical evolution of the seeing quality recorded at the CFHT. This shows that "dome seeing" has been steadily reduced over the years.

Figure 2 dramatically demonstrates that dome seeing has historically been a very significant cause of image deterioration at the CFHT. As a result of a large number of precautions taken to identify and eliminate heat transport to the telescope area (Bely, 1983) the average global seeing has been improved from 2"5 in early 1980 to 0"9 in late 1983. The beneficial effect of the chilled observing floor is particularily well known to our observers. When the chillers are off, the seeing is always had (>1"5)!

The repeated peaks in the data of Fig. 2 for the first quarters of each year show that the average seeing is considerably poorer during the winter months. Bely (1983) has suggested that this may be explained by the higher winds prevailing in the upper atmosphere at that season. A detailed comparison of the radio sondes predictions with actual seeing values shows, however, that this cannot explain the full effect. Since the winter months are windier and colder, more energy is expended inside the building to heat working paces; air leaks and heat losses to the telescope area are certainly more detrimental during that season.

If much of the seeing at the CFHT and at the UH telescope originates within the immediate environment of the domes, one would expect little correlation between pairs of individual seeing measurements made simultaneously at both telescopes. The data base on which this comparison can be made is unfortunately limited to sporadic log-book entries of rather inaccurate visual estimates. These data, for 60 nights in common during the period July 1982 to February 1984 are compared in Figure 3; the two sloping lines bound the area where data points would fall if the correlation was perfect and individual estimates had a maximum error arbitrarily chosen as 30%. From Fig. 3 one sees that the two observers generally agree to call the seeing very poor when it exceeds 2". In better seeing, the pair of estimates shows no correlation. Although the quality of the data is admittedly poor, the fact that either of the observer can quote a 0"5 seeing while the other quotes 1"5 to 2"0 strongly suggests that local seeing is, at times, important in either dome.

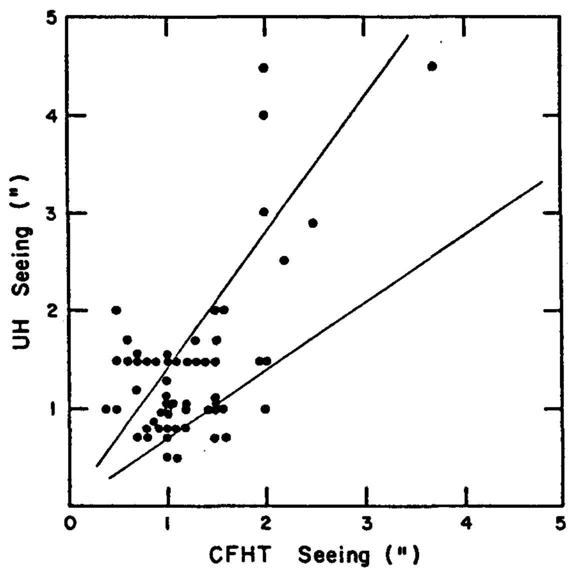

Fig. 3. Comparison of simultaneous seeing estimates made at the CFHT and at the UH telescopes. The poor correlation is, in part, due to dome seeing.

At the CFHT, we have recently (April, 1984) initiated routine recording of the temperature structure constant, C_T, as read by a pair of probes attached to the telescope tube, near the center of the dome. This is done to monitor the results of our continuing experiments aimed at reducing the turbulence within the dome. Early results yield $0.02 < C_T$ ($^oC/m^{1/3}$) <0.08 at night with the shutter open. From this one would expect a spread angle of 0"1 < ω <0"4 for the 30 meter long light path inside the dome.

We can then summarize our still fragmentary investigations of the sources of seeing at Mauna Kea and at the CFHT by attributing the contributions given in Table 2 to the three segments of the light path.

TABLE 2

Contributions to Global Seeing

Zone	Contribution
free atmosphere	0"45
boundary layer	0"35
dome air	0"25
total path	0"70

This accounting falls somewhat short of the currently observed mean value ω = 0"90 for the global seeing; an additional contribution of some 0"45 is still to be found. Part of this is undoubtedly due to the telescope optics themselves. We know, from Hartmann tests, that the mirrors' figures, the residual aberrations of the correctors and small collimation errors contribute a typical image spread of 0"2 to 0"3. Slight focussing and guiding errors will further broaden the recorded images. At such a site as Mauna Kea, the total instrumental error budget must be maintained below 0"3 to take good advantage of the observing conditions. This is proving to be a very difficult challenge to meet! Finally, more extensive statistics on the turbulence within the boundary layer and inside the dome should help to clarify the situation.

4. Conclusion

The excellent image quality currently observed at the CFHT can certainly still be improved through scrupulous efforts to further minimize the turbulence inside and around the dome and the opto-mechanical imperfections of the instrument. Table 2 and Figure 2 indicate that a mean image spread of $\omega \simeq$ 0"6, due to the uncontrollable free atmosphere, and to some of the boundary layer, appears within reach. The natural Mauna Kea seeing can then offer images with ω <0"4 on some 25 percent of the nights. Such small images correspond to a Fried (1966) parameter r_o> 30 cm at λ = 500nm. Mathematical models of astronomical seeing Roddier 1981, Coupinot and Hecquet 1984) predict that by removing the rapid (10-30 Hz) image wander, due to the varying mean tilt of the wavefront, a maximum resolution gain of 2.0 can be achieved for long (>1sec.) exposures when the pupil diameter is $d=3.5r_o$. Thus, a telescope on Mauna Kea with a segmented pupil made of suitably driven elements of $d \approx 1$ meter would produce images with a resolution of 0"2. Such a pupil element collects enough flux in 50m sec. to use an 18th magnitude source as a "guide star". Experiments with this type of Very High Resolution Imager are being pursued with some success at the CFHT (Christian et al. 1983).

Acknowledgements

It is a pleasure to thank the scientific and engineering staff of the CFHT Corporation for continuous discussions on the evaluation and conservation of the seeing at the CFHT. I am especially grateful to our Chief Engineer, P.-Y. Bely for illuminating arguments about his extensive studies of air turbulence, and to the summit crew for putting up with such good grace with the work and discomfort required over the years to bring the CFHT seeing down to a size we can live with!

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DISCUSSION

F. Forbes: Have you calculated C_T^2 for the dome interior and thereby accounted for your observed seeing degradation?

R. Racine: This is a crucial question to which, I am ashamed to say, we don't have a complete answer yet because no thorough enough microthermal data have yet been obtained under observing, nighttime conditions, inside the dome, along the light path. When the dome shutter is closed, the microthermal activity inside the dome is exceedingly small and certainly insufficient to explain a $0\overset{''}{.}5$ to $1\overset{''}{.}0$ seeing spread. When the shutter is open the activity at the base of the slit increases dramatically. But whether this extends all along the light path is still unknown.

R. Bingham: Does the improvement in seeing on the CFHT correlate in detail with the improvements made in the building, so that one could find the value of individual modifications?

R. Racine: The various corrective measures (see Bely, 1983) were not taken and evaluated independently enough to give a point by point answer to this question. The two most beneficial measures are: 1) driving the cooling floor quite hard, to 5 or 7°C below outside air temperature, and 2) sealing gaps around the telescope pier which let warm air from below escape to the observing area. The rest are a series of small individual precautions which together produce significant improvements in seeing quality.