MIRROR, DOME, AND NATURAL SEEING AT CFHT

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ABSTRACT

A large and homogeneous set of image quality data, obtained with HRCam at the prime focus
of the CFHT, was correlated with thermal sensor data to identify and quantify "local seeing" effects.
The main findings are as follows.
1. Mirror seeing is an important source of image spread and amounts to FWHM = 0.40"C³/⁶⁵
when the primary mirror is warmer than the air inside the dome.
2. Dome seeing is marginally significant, at the rate of ~ 0.1°C³/⁶⁵ of temperature difference
between the air inside and outside the dome.
3. Optical aberrations from the CFHT primary mirror and from HRCam currently impose a
limit of FWHM = 0.38 to the image quality.
4. The median natural atmospheric seeing at the CFHT site on Mauna Kea is FWHM = 0.43 ±
0.05, the 10th and 90th percentiles being ~ 0.25 and ~ 0.7, respectively.

Key words: image quality—local seeing—mirror seeing

1. Introduction

Astronomical facilities can often deteriorate natural "seeing". While image quality (IQ), the sharpness of
the point-spread function (PSF) delivered by the telescope, is a prime standard of its power as a research instrument,
shortcomings of the telescope and of its environment can deprive the astronomer of the otherwise excellent IQ
offered by the natural seeing at a good site. It has been widely believed that natural atmospheric turbulence is
easily the limiting factor for telescopic IQ and that astronomical imaging with sub-half-arc-sec PSFs remains the
exclusive domain of space facilities or ground-based telescopes equipped with optical systems capable of real-time
wavefront corrections. It is now becoming clear that this traditional belief arose from the universal existence of
IQ deteriorations induced by telescopes and their enclosures. Were these to be eliminated, it is quite probable
that, at least at good sites above the inversion layer, sub-half-arc-sec imaging would be a norm rather than a
rarity.

Optomechanical aberrations of the telescope can readily enough be measured and their contribution to image
spread estimated and, partly, corrected. But, except for defocus, this is not usually done in an active fashion, with
the instrument in normal operation. In "new technology" telescopes, such as the ESO NTT, the benefits of doing so
are beginning to be realized.

Guiding errors are a more stochastic cause of instrumental image spread. Their importance is more difficult
to evaluate as they can depend on the instrument, the available guide star, the observing conditions, or the
observer himself. Wind buffeting and telescope-enclosure coupling can produce image motion at frequencies
exceeding the bandwidth of the control system. The deterioration of IQ by image motion, whether arising in the
telescope or from atmospheric wavefront tilt, can be prevented by still uncommon fast (> 20 Hz) guiders.

It is most difficult, in practice, to directly measure image spread caused by thermal inhomogeneities and
turbulence in and around the telescope (the "local seeing"). This is so because local seeing, like natural seeing,
is a statistical quantity. A large collection of homogeneous and precise IQ and thermal data must be collected before
the local seeing trends can be perceived through the

The Canada-France-Hawaii Telescope is operated jointly by
the National Research Council, Canada, the Centre National de la
Recherche Scientifique, France, and the University of Hawaii.
fluctuations of the natural seeing. Local seeing is, of course, more easily detectable at facilities where the median natural seeing is weak.

This paper reports the results of a study of local seeing at the Canada-France-Hawai`i 3.6-m telescope (CFHT). The specific questions addressed are: How do the temperature differences between the primary mirror and the ambient air, and between the air inside and outside the dome, affect the image spread? The results could suggest further seeing management improvements at the CFHT itself and should serve as more general indications for other existing or planned facilities.

2. The CFHT As a Seeing Study Facility

The fast guiding imager high-resolution camera (HRCam) (McClure et al. 1989) has now been in regular use for more than two years at the prime focus of the CFHT. Well over 2000 science frames obtained so far with this precise and impersonal guider now constitute a good database for synoptic studies of IQ. The median IQ achieved with HRCam is 0.57 (FWHM sec^{-0.6}). The primary mirror and HRCam optics are known to jointly produce ≈ 0.35 of image spread. Anecdotal evidence further suggests that thermal disequilibrium in the telescope and dome still contribute significantly at times to image spread despite considerable efforts throughout the years to reduce local seeing (Racine 1984; Bely 1983, 1987; Cowley & Sovka 1990).

Since 1986 thermal sensors (thermistors) have been installed at numerous locations in and around the CFH telescope and dome. Wind speed is also recorded. Digital readings taken every 10 minutes are fed to a data logger and stored in a disk file. This, and the HRCam IQ data, allow the investigation of correlations between IQ and local temperature differences.

In August 1989 a major readjustment of the primary-mirror support system was made and significantly reduced off-zenith astigmatism and other aberrations due to incorrect support forces. Optical tests have shown that residual astigmatism, zones, and slight irregularities in the mirror surface combine to produce a PSF of FWHM ≈ 0.25, which meets the original specification for the mirror. The HRCam optics themselves and coma arising from decentering with respect to the primary optic axis increase this spread to FWHM ≈ 0.35. This instrumental IQ is sufficiently good for the additional joint contribution from the natural Mauna Kea seeing and local CFHT seeing to be measurable most of the time.

3. The Data

3.1 Thermal Data

The following temperatures were used.

\( T_m \), the surface temperature of the primary mirror measured by a sensor attached to the side of the mirror 5 cm below the rim.

\( T_e \), the air temperature at the top of the Serrurier trusses which is at a point 13 m above the floor and 8.5 m above the primary mirror with the telescope at the zenith. This is taken to be representative of the dome air temperature.

\( T_a \), the outside air temperature.

The relative calibration of the thermal sensors is periodically checked and believed to be uniform and stable to ±0.3°C. Zero-point differences, if they exist, have no effect on the slope of the IQ, \( \Delta T \) relations to be investigated in priority here.

Two thermal indices are defined as follows.

\( \Delta T_m = T_m - T_e \): This measures the temperature excess of the primary mirror above air in the dome and should be correlated with “mirror seeing”. \( T_e \) is preferred to the (also available) mirror cell air temperature as an ambient temperature indicator since cell air data show evidence of being affected by radiative or convective coupling to the mirror.

\( \Delta T_a = T_a - T_e \): This is an indication of the temperature difference between dome air and outside air and should be correlated with “dome seeing”. Positive \( \Delta T_m \)'s or \( \Delta T_a \)'s correspond to convectively unstable conditions and should be expected to produce air turbulence and IQ degradation.

Figure 1 shows the correlation between the outside air and the dome air temperatures. The dome air is generally warmer than the outside air, by \( \sim 1.5^\circ \)C on the average, except when the outside air is above \( +4^\circ \)C. This is due to daytime heating of the dome air by leaks and conduction across the dome skin and to sources of heat inside the dome. The scatter in Figure 1 is large because the relatively narrow slit of the CFHT dome prevents rapid flushing of the dome by the outside air.

Figure 2 shows the correlation between the dome air and the primary mirror temperature. The slope of the correlation is less than unity because the large thermal inertia of the mirror/cell assembly makes its temperature lag the driving temperature of the dome air. Note that in both Figure 1 and Figure 2 the full ranges of temperatures are quite modest (\( \sim 8^\circ \)C), a Mauna Kea feature which is undoubtedly favorable to weak local seeing.

The scatter plot of \( \Delta T_m \) versus \( \Delta T_a \) is shown in Figure 3. The lack of correlation leads us to expect that mirror seeing (due to \( \Delta T_m \)) and dome seeing (due to \( \Delta T_a \)) would be statistically independent at the CFHT.

3.2 Image Quality (IQ)

IQ, expressed as the full width at half-maximum intensity (FWHM) in arc sec of stellar images on CCD frames, is determined by an image-quality evaluation routine (IQER), available to observers who record the results on the CCD observing log sheets. Approximately half of the frames taken are actually documented on archived copies of the log sheets. All CCD frames taken at CFHT and
their headers are also archived on optical disk for future reference. To strengthen the database, it was originally planned to supplement the observer-recorded IQ results by running an IQE on all the still-undocumented frames. Fortunately, this rather ambitious and tedious task became unnecessary after the available data proved amply sufficient to address the questions raised above.

Simulations (McGonegal 1991) confirmed that IQE actually measures the image FWHM and that, for HRCam frames ($\sim 0.11$/px), pixel sampling increases FWHM by a negligible amount ($< 0.02$) and only for the best ($\sim 0.40$) images. The precision of the IQ data is $\sim 0.02$ as determined by measuring different stars on a same frame.

The IQ data selected were those measured on HRCam frames taken at full 3.6-m aperture and without image selection (a subpupil mode and a fast-shutter selection mode are also available) on 1990 and 1991 nights which were completely clear and when the wind speed was less than 40 knots (20 m s$^{-1}$). This selection was made to (1) avoid noise from guiding errors, (2) limit data to a uniform (and improved) optical quality of the telescope, (3) avoid gradients in local or high-altitude perturbations which could accidentally be correlated with temperature evolution, and (4) limit wind-driven turbulence in the lower part of the dome and around the primary mirror. IQ data from 562 CCD frames taken on 25 nights between 1990 June 19 and 1990 February 12 (UT) were thereby available for analysis. The vast majority of the CCD frames were taken at $0.55 < \lambda$ ($\mu$m) $< 0.85$ and the $\lambda$-dependence of IQ was not investigated. The mean effective wavelength is thus $0.7$ $\mu$m. Exposure times range from a few hundred to a few thousand seconds.

Because HRCam effectively removes overall wavefront tilts due to tracking errors and atmospheric turbulence, the FWHM values obtained are smaller than those which are obtained in the usual slow-guiding mode. Experience shows that HRCam reduces $<\text{FWHM}>$ by a factor of $\sim 1.3$, from 0780 to 0760. The reader is referred to Roddier, Northcott & Graves 1991 for an illuminating discussion of the resolution gain provided by low-order adaptive systems.

The correlation between IQs and $\Delta T$s is established using the UT times recorded on the CCD log sheets and by the data logger as reference. The time resolution of the data logger is 10 minutes and, on occasion, two or three adjacent readings must be averaged to estimate the $\Delta T$s.

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to ± 0.1°C. Yet, a number of instances were noticed where rapid ΔT changes (> 1°C/20 min) were accompanied by rapid IQ variations in the expected direction (worse IQ at larger ΔT).

Figure 4 shows the frequency distribution of the raw IQ data. A log-normal curve is fitted to the total population in the histogram and to the shape of the distribution at FWHM > 0'60. There appears to be a significant lack of images with FWHM < 0'40. The sharpest images on record are at FWHM = 0'39. This is a manifestation of the "wall" imposed by the optics and below which images cannot be obtained. From this, from what is known about the optics of the CFHT and of the HRCam, and from what is derived later about the natural seeing (Sec. 4.4), the performance limit imposed by the optics is estimated as 0'38 ± 0'02.

The frequency distribution of the IQ data when ΔTm does not exceed +0.5°C is also shown in Figure 4. The median and 90th percentile points of this distribution are at slightly smaller FWHMs (by 0'06 and 0'09) than when data at all temperatures are included. This alone suggests that smaller ΔTs tend to favor sharper images.

Figure 5 displays the IQ data against the air mass (sec z) at the time of observation. It is seen that poor (> 0'8) IQ values are gradually eliminated as more stringent restrictions are imposed on the ΔTs, and that mirror seeing is more detrimental to IQ than dome seeing. The lower envelopes in Figure 5, which must correspond to occasions of best global seeing (~ 2 percentile or ~ 15 data points out of 562 for all data), are rather well-defined by the full data set. Its level is mostly set by the 0'38 of optics spread to which ~ 0'2 of natural seeing is added. We will revisit the question of the natural atmospheric seeing more quantitatively in Section 4.4, after we have learned how to take into account local seeing effects. This will be facilitated by the use of a simple theoretical model.

4. Analysis and Discussion

4.1 A Simple Model

The spread angle ω produced by Kolmogorov turbulence in an atmospheric layer characterized by a temperature structure index C_T is quite generally given (Fried 1966) by

$$\omega \propto \left[ \int_{\text{path}} C_T^2 \, dl \right]^{\nu_5}. \quad (1)$$

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Image degradation from different turbulent layers thus add by a 5/3-power law:
\[ \omega^{5/3} = \omega_1^{5/3} + \omega_2^{5/3} + \ldots + \omega_N^{5/3}. \]  
(2)

\( C_T \) is proportional to the temperature gradient across a layer. The air layer between two points separated by a distance \( l \) and differing in temperature by \( \Delta T \) will thus produce an image spread \( \omega \propto \Delta T^{5/3}/l^{5/3} \) as can be seen from equation (1). In a horizontally stratified layer, which is the case for natural atmospheric seeing \( \omega_0 \), \( dl = dl_0 \sec z \) and by equation (1)
\[ \omega_0(z) = \omega_0(0) \sec z^{0.6}. \]  
(3)

To obtain a functional relation for the zenith distance dependence of image spread produced by an inclined mirror of diameter \( D \) at a temperature \( \Delta T_m \) above ambient, let us assume that isotherms remain parallel to the mirror surface as they rise into a vertical cylinder and their temperature decreases (by mixing with ambient air) with a scale height \( h_0 \). Integrating equation (1) along light rays within the cylinder of rising turbulence and averaging over the (cylindrical) beam yields
\[ \omega_m^{5/3} \propto \Delta T_m^2 \left( 1 - e^{-D \cot z/h_0} \right). \]  
(4)

Mirror seeing \( \omega_m \) depends very weakly on \( z \) when \( D/h_0 \gg 1 \), as is intuitively expected since the turbulent cells decay while still in the light path; \( \omega_0 \) is then the same at all \( z \) as it is at \( z = 0 \) for any value of \( D/h_0 \). For \( D/h_0 \ll 1 \), \( \omega_m \) decreases precipitously off-zenith, as \( (D \cot z/h_0)^{5/3} \), because the light beam is free of the column of turbulence except when very near the mirror surface.

An appropriate value for \( h_0 \) is \( \sim 0.5 \) m (Iye et al. 1991). For the CFHT (\( D = 3.6 \) m), mirror seeing should be nearly independent of zenith distance for \( z < 70^\circ \) which covers the range over which IQ data are available.

Image spread due to the optics, assumed to be best collimated at the zenith, should develop an \( \sim k \sin z \) component away from zenith as flexures and decollimation increase. The analysis of the zenith distance dependence of image quality (Fig. 9 and Sec. 4.4) will show that increase in optical aberrations off-zenith does not contribute significantly to image spread at the CFHT. Quite generally the median global image spread \( \omega \) recorded at the telescope focus can then be written...
\[ \omega^{53} = \omega_n^{53} \sec z + \omega_p^{53} + \alpha_m^{53} \Delta T_m^2 + \alpha_d^{53} \Delta T_d^2. \] (5)

where \( \omega \) is the median global image spread
\( \omega_n \) is the median natural seeing at the zenith
\( \omega_p \) is the optics spread
and the \( \Delta T^2 \) terms characterize mirror and dome seeing.

For small \( \Delta T \)s (weak local seeing) image spread is dominated by the natural seeing and optical aberrations.

FWHM can be used as a measure of \( \omega \). Once the mirror and dome-seeing coefficients \( \alpha_m \) and \( \alpha_d \) are determined from the data, correlations such as those in Figure 5 can be corrected point by point and the distribution of \( \omega_n \) retrieved from the scatter about the regression lines. Scatter will also be produced by time-dependent differences between the simple model of equation (6) and reality, such as the effect of wind across the primary mirror. This will broaden histograms of \( \Delta T \)-corrected FWHMs, a point to keep in mind in the interpretation of the results.

4.2 Mirror Seeing

Figure 6 demonstrates that FWHM becomes larger as \( \Delta T_m \) becomes increasingly positive and that mirror seeing can be important. Only data at sec \( z < 1.7 \) (\( z < 55^\circ \)) are plotted to reduce the contribution from the natural seeing growth at large \( z \). The ridge line drawn through the data represents a plateau of FWHM = 0.56 to which a mirror seeing of \( \omega_m = \alpha_m \Delta T_m^{0.5} \) is added in a 5/3-power-law fashion for \( \Delta T_m > 0^\circ \). A least-squares fit yields \( \alpha_m = 0.40 \pm 0.05/^{\circ}C^{0.5} \). The plateau is again understood in terms of the 0.38 contribution from the optics combined with an average seeing (natural + local, excluding mirror) of 0.37. This simple model represents the data reasonably well. In particular, mirror seeing appears to set in as soon as \( \Delta T_m > 0 \) and has become quite significant at \( \Delta T_m = +1^\circ \). There is a faint suggestion of weak mirror seeing when \( \Delta T_m < 0 \) (mirror colder than air) but the rate is at most 1/3 of the one for \( \Delta T_m > 0 \).

An independent estimate of the mirror seeing coefficient \( \alpha_m \) at the CFHT can be made as follows. When the
primary mirror is reinstalled in the telescope after aluminizing, its temperature is $15 \pm 2^\circ C$ above dome air temperature. On occasions, for collimation purposes, stellar images have been observed close to zenith in these conditions and found to have FWHM = 7 ± 2 arc sec. This leads to $\alpha_m = 0.27 \pm 0.08^\circ/\text{C}^{65}$. The rough agreement with $\alpha_m = 0.40 \pm 0.05^\circ/\text{C}^{65}$ found above provides some reassurance that the simple model remains appropriate even for a $\Delta T_m$ range 6 times larger than the one covered by the IQ-$\Delta T$ data.

Laboratory studies of image deterioration by and convection above heated mirrors have been published by Lowne 1979, by Barr et al. 1990, and by Iye et al. 1991. Lowne used a $D = 254$-mm spherical mirror, source and image being at the center of curvature where $f/D = 8$. A broad temperature range ($-2 \leq \Delta T_m$ $(^\circ C) \leq +8$) was explored for $z = 0^\circ$, $20^\circ$, and $50^\circ$. The 75% energy diameter (denoted here $\omega_75$) was used to measure image spread. Table 1 gives the image growth rates observed by Lowne at the three zenith distances. Although the condition $D/h_0 \gg 1$ (eq. (4)) probably does not hold for a 254-mm mirror, Lowne’s results should be roughly comparable to ours at $z = 0^\circ$. There, they yield $\alpha_m = 0.21 \pm 0.03^\circ/\text{C}^{65}$. This is significantly smaller than the value observed at the CFHT ($0.40 \pm 0.05^\circ/\text{C}^{65}$, Fig. 6), possibly because mixing with ambient air at the mirror edge is relatively more effective for a smaller mirror.

The decrease in mirror seeing away from zenith observed by Lowne is well explained by equation (4) if $D/h_0 = 0.06$ (see Table 1). Because the diameter of the short (2-m) converging beam in Lowne’s experiment decreases significantly over a distance of $h_0$, the amount of turbulence within the beam off-zenith is reduced and so is the effective beam diameter $D_\ast$ to be used in equation (4). And, again, edge effects in the column of turbulence should be relatively more important in also reducing $D_\ast$ for a small mirror than for the 3.6-m CFHT mirror. The small value derived for $D/h_0 (~0.06)$ thus indicates $h_0 < 4$ m. Iye et al. 1991 measured a mixing length of $\approx 0.5$ m above a 62-cm zenith pointing mirror. At the CFHT, then, $D/h_0 > 1$ and the zenith dependence of mirror seeing predicted by equation (4) is weak ($\alpha_m (60^\circ)/\omega_m (0^\circ) > 0.8$).

Barr et al. 1990 studied mirror seeing on a 1.8-m mirror over the range $-1.5 \leq \Delta T_m$ $(^\circ C) \leq +1.9$ under quite variable test-tower seeing conditions. Since, furthermore,
mirror seeing effects were ~10 times smaller than the aberrations due to the mirror figure and to changes in tilt and focus during the observations, a Zernicke polynomials analysis was used to reconstruct the wavefront and to also remove low-order (tilt and focus) instrumental and seeing-induced aberrations. Images reconstructed by Fourier transforms of the corrected phase maps and structure functions led the authors to conclude that image FWHM was essentially unaffected by seeing although the Strehl ratio was reduced, but only significantly so when $\Delta T_m = +1^\circ$ C. The characteristics of these data and experiments (diffraction-limited reconstructed FWHMs of ~0\textdegree.08; fans blowing on mirror to establish the "no mirror seeing" reference conditions) are so different from the one for the CFHT observations that direct comparisons are difficult. We will only note that the 5 data points in Barr et al.'s Figure 9 for $\Delta T_m > 0^\circ$ C do admit mirror seeing effects starting as soon as $\Delta T_m > 0^\circ$ C, especially if one takes into account that the ~10% reduction in the Strehl ratio observed at $\Delta T_m < 0^\circ$ C by Barr et al. may be real and due to fan-induced turbulence, for instance.

In their experiment, Iye et al. 1991 observed that microthermal activity develops above the mirror as soon as $\Delta T_m > 0$ but is much weaker or absent at $\Delta T_m < 0$. This

<table>
<thead>
<tr>
<th>$z$ (\textdegree)</th>
<th>$\omega_{75}/\Delta T_m^2$</th>
<th>$\sigma_{75} (&quot;/&quot;^0.05)$</th>
<th>$\sigma_{4} (&quot;/&quot;^0.05)$</th>
<th>Eq. 4 (D/h=0.06)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.40 ±0.05</td>
<td>0.57±0.08</td>
<td>0.21±0.03</td>
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</tr>
<tr>
<td>20</td>
<td>0.067±0.007</td>
<td>0.20±0.03</td>
<td>0.07±0.01</td>
<td>0.07</td>
</tr>
<tr>
<td>50</td>
<td>0.024±0.007</td>
<td>0.11±0.03</td>
<td>0.04±0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>
agrees with our finding that mirror seeing develops at \( \Delta T_m > 0 \) and is very weak at \( \Delta T_m < 0 \) (Fig. 6).

4.3 Dome Seeing

Figure 7 shows that dome seeing is much weaker than mirror seeing, a conclusion already apparent from Figure 5. A least-squares fit to the FWHM-\( \Delta T_d \) data for \( \Delta T_m > +0.5^\circ \) C in Figure 7 gives \( \alpha_d = 0\'10 \pm 0\'05/\Delta T_d \). This is \( \sim 4 \) times smaller than \( \alpha_m \) and suggests that the mixing length \( l_0 \) between air volumes across the dome slit, which one intuitively expects to be approximately equal to the slit width (6 m), is larger than the scale height of convection above the mirror, \( h_0 \), by a factor of \( \sim 4^{50} \sim 10 \). Then \( h_0 \) would be \( \sim 0.6 \) m, which is consistent with Iye et al.’s findings.

Note that with \( \Delta T_d \) reaching \( +3.5^\circ \) C dome seeing can still amount to \( \sim 0\'4 \). This is less than the worst mirror seeing observed \( \sim 1\'1 \), Fig. 6) but remains significant. The weakness of the dome seeing at the CFHT is the result of many years of efforts to eliminate air leaks and heat sources above the refrigerated observing floor. The design of the building itself (control room and all heated areas located under the refrigerated floor, aspiration of dome air downstairs to prevent leaks . . .) helps control dome seeing. But numerous measures taken over the years, most significantly the cooling of the telescope hydraulic oil, have continuously improved the situation. We believe that the most important heat source to the dome air is now solar heating conducted by the structural members of the dome. On a sunny day, the dome intercepts \( \sim 600 \) kW of solar radiation, some 15\% \( \sim 100 \) kW being absorbed by the outer dome skin. Convection and wind-driven circulation between the outer and inner skins carry \( \sim 2/3 \) of this heat away through the upper venting louvers. This leaves \( \sim 30 \) kW to heat the inside of the dome during the day, enough to raise the dome air temperature by \( \sim 5^\circ \) C and produce \( \sim 0\'5 \) of dome seeing when the slit is first opened. Fortunately, the cooling floor and the air chiller units in the telescope area are available to prevent dome air heating during the day.

“Louver seeing” is a peculiar form of dome seeing identified during this investigation. The air venting from the top louvers at night can be 5\% or more warmer than the outside air. When observing close to zenith in the lee of the vents the light path crosses this layer of warm air and image quality can be significantly poorer than when the dome slit faces the wind. This effect is correlated with the dome seeing discussed above since louver-air and

![Fig. 7](image-url)
dome-air temperatures tend to be correlated. Louver seeing is eliminated simply by closing the motorized louvers during the observations. Other idiosyncratic dome-seeing effects can probably be identified (air shedding from the radiatively overcooled outer skin, slit-edge turbulence . . .) and which may be responsible for some of the scatter in Figures 6 and 7. But the available data are insufficient to fully document these and to quantify their effects.

The time-of-night dependences of IQ, $\Delta T_n$, and $\Delta T_d$ were examined. No clear trends are apparent when all nights are combined. But on those few nights where strong mirror seeing occurred, an obvious relation between dome air cooling and increasing FWHM as the night progresses can be seen.

### 4.4 Natural Seeing

Natural atmospheric turbulence still remains a significant source of image spread at the CFHT! But Figure 5 already suggested that this can be quite small. The data were examined to ascertain that no strong selection effects prevailed, like the tendency to only work at large zenith distances when the near-zenith IQ is excellent. This does not appear to be the case, large-sec $z$ episodes being preceded by near-zenith IQs ranging from 0'4 to 1'0. Figure 8 illustrates two such examples. The median natural seeing at the zenith, $\omega_n(0)$, which prevailed when the HRCam observations were made, can then be obtained by plotting

$$\text{FWHM}_n = [\text{FWHM}^{50} - \omega_n^{50} - (\kappa \tan z)^{50}]^{1/5}$$  \hspace{1cm} (6)

against (sec $z$)$^{0.6}$ since $\omega_n(z) = \omega_n(0)(\sec z)^{0.6}$. The coefficient of vertical atmospheric dispersion $\kappa$ on Mauna Kea ranges from 0'13 across the $I$ band to 0'18 across the $V$ band. A correction of half the average ($\kappa = 0'08$) was applied to remove its effect from the data. Corrections for mirror seeing could also be made to reduce the scatter and eliminate the bias this local effect introduces. But, conservatively, the data will be limited to $\Delta T_n \leq 0.5^\circ$ C. Slit and dome air turbulence, being mostly driven by wind rather than by convection, is highly variable and

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**Fig. 8**—Examples of periods of good IQ (open squares) and bad IQ (filled squares) when observations at large zenith distances were made. Both lines correspond to a natural seeing of 0'40 in the zenith. For the "good period" (1991 February 10), $\Delta T_n = \Delta T_d = 0^\circ$ C. For the "bad period" (1990 August 13) $\Delta T_n = +1.5^\circ$ C and $\Delta T_d = +3.0^\circ$ C. The offset between the lines at sec $z = 1$ is the additional local seeing expected from the large $\Delta T$s on 1990 August 13.
could hardly be corrected for, but the scatter and bias it introduces can likewise be reduced by selecting only the data at $\Delta T_d < +2^\circ$ C. Optical aberrations, if incorrectly taken into account in the definition of FWHM$_z$, will bias the intercept at sec $z = 0$ but should hardly affect the slope of the FWHM $- \langle \text{sec } z \rangle^{0.6}$ ridge line if they do not vary with zenith distance. The result of this exercise is displayed in Figure 9 which includes 266 data points at $\langle \text{sec } z \rangle^{0.6} \leq 1.6$ (sec $z < 2.2$). A linear least-squares fit yields

$$\text{FWHM} = 0^\prime.32 \left[ (\text{sec } z)^{0.6} - 1 \right] + 0^\prime.32 \pm 0^\prime.04 \pm 0^\prime.02 \quad (7)$$

The slope of this line gives a zenith seeing of $0.32 \pm 0.04$ FWHM. The intercept at sec $z = 1$ is made to give the same zenith seeing after a 5/3-power-law removal of optics spread. This requires $\omega_z = 0^\prime.38 \pm 0^\prime.02$. The agreement between this value and the estimate $\omega_z = 0^\prime.35$ from optical tests value supports the conclusion that optical aberrations do not significantly increase off-zenith. Table 2 shows how the least-squares slope and intercept at sec $z = 0$ co-vary with the adopted values of $\omega_z$ and $\kappa$. It can be seen that all self-consistent (intercept $< 0^\prime.1$) and realistic ($\kappa \leq 0^\prime.05$) solutions lead to a slope $\omega_z = 0^\prime.30$. A median zenith seeing of $0^\prime.32$ corresponds to a tip-tilt corrected Fried parameter $r_0(\lambda = 0.7 \mu\text{m}) = 45 \text{ cm } [(D/r_0)_{\text{stab}} = 8.0]$ and to a median unstabilized Mauna Kea seeing of $0^\prime.43 \pm 0^\prime.05$ FWHM (see Roddier et al. 1991 for conversion to unstabilized seeing). In Table 3 this result from direct measurements of image sizes at the focus of a large telescope is compared to those derived by other methods. A “best” value for the Mauna Kea zenith seeing appears to be close to $0^\prime.45$ FWHM. The 10th and 90th percentiles should be $\sim 0^\prime.25$ and $\sim 0^\prime.7$. These figures provide challenging goals for telescope designers, builders, and managers.

Figure 10 shows histograms of the HRCam IQ data corrected for $0^\prime.38$ of optics spread and reduced to the zenith, FWHM$_{z,1} = \text{FWHM}_z / (\text{sec } z)^{0.6}$. The unshaded histogram is for all data and the shaded one for $\Delta T_n < +0.5^\circ$ C and $\Delta T_d < +2^\circ$ C. Whereas the $\Delta T$ restrictions virtually eliminate all FWHM$_{z,1} > 0^\prime.6$, they only reduce the median slightly, from $0^\prime.36$ to $0^\prime.32$ while the sample is reduced by more than a factor of 2. This must be because large $\Delta T$s are necessary but insufficient to induce strong local seeing. Wind blowing on the primary mirror can

![Graph](image-url)
sweep away $\Delta T_m$-induced convection; large $\Delta T_m$s only produce strong dome seeing when strong air mixing occurs at the dome slit. The fact also remains that extreme local seeing conditions are rare at the CFHT (e.g., $\Delta T_m > +1.5^\circ$ C less than 2% of the time) and only slightly increase the average image spread.

### 5. Conclusion

The median image quality currently experienced by CFHT observers (all instruments) is $\sim 0.8$ FWHM and is $\sim 0.6$ with HRCam (Fig. 4). These are respectable figures. Indeed, an oft-cited justification in CFHT observing time requests is the need for and expectation of “good seeing”. Yet, it is now clear that local perturbations, which can be reduced, can limit the imaging performance, a fact already apparent from P. Y. Bely’s pioneering studies done in 1982–83 (Bely 1987).

Now that the main causes of local seeing at the CFHT have been identified and their effects quantified, measures are being taken to further improve image quality at the telescope. Mirror and dome seeing, due to temperature differences, can be avoided by implementing ventilation and cooling procedures for which the facility is already equipped. A procedure to prevent the primary mirror from warming up during the day, by ducting air from the dome air chillers to the sealed mirror cell, has been experimented with and has given encouraging results (Salmon 1990). But to take full advantage of the best natural seeing sites such as Mauna Kea can offer ($\sim 0.2$), the $\Delta T$s must be below $0.5^\circ$ C, a difficult goal to reach.

Image spread due to optical aberrations frequently imposes the limits to image quality. This can be substantially ameliorated by corrective or active optics incorporated into the instruments themselves. Such a device (variable astigmatism corrector) has now been built into HRCam. Adaptive optics, when in use, will of course also largely correct these aberrations. It is then that the greatest benefits will be reaped from the elimination of local seeing.

It is now clear that the most significant gains in image quality at the CFHT will come from further improvements of the telescope optics. Reduction of local seeing

### TABLE 2

Co-variance of the least-squares slope/intercept in Fig. 10 with the parameters $\omega_o$ and $k$ in Eq. (7)

<table>
<thead>
<tr>
<th>$\omega_o$</th>
<th>$k$</th>
<th>0.00</th>
<th>0.05</th>
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<td>0.00</td>
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<td>0.27</td>
<td>0.26/</td>
<td>0.28</td>
</tr>
<tr>
<td>0.20</td>
<td></td>
<td>0.30/</td>
<td>0.19</td>
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<tr>
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<td></td>
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</tr>
<tr>
<td>0.40</td>
<td></td>
<td>0.37/</td>
<td>0.05</td>
<td>0.35/</td>
<td>0.03</td>
</tr>
<tr>
<td>0.50</td>
<td></td>
<td>0.52/</td>
<td>0.39</td>
<td>0.49/</td>
<td>0.37</td>
</tr>
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</table>

### TABLE 3

Estimates of Zenith Seeing ($\lambda=0.7$ $\mu$m) for Mauna Kea

<table>
<thead>
<tr>
<th>Method</th>
<th>FWHM$_{\text{median}}$ (arcsec)</th>
<th>References</th>
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</thead>
<tbody>
<tr>
<td>radiosonde profiles</td>
<td>$0.35 \pm 0.05$</td>
<td>Bely 1987</td>
</tr>
<tr>
<td>image motion ($h=20$m)</td>
<td>$0.45 \pm 0.10$</td>
<td>Merrill and Forbes 1987,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forbes 1989</td>
</tr>
<tr>
<td>SCIDAR(*)</td>
<td>$0.42 \pm 0.04$</td>
<td>Roddier et al. 1990</td>
</tr>
<tr>
<td>inter-telescope correlation</td>
<td>$0.50 \pm 0.10$</td>
<td>Racine 1990</td>
</tr>
<tr>
<td>image sizes</td>
<td>$0.43 \pm 0.05$</td>
<td>this paper</td>
</tr>
</tbody>
</table>

(*) Scintillation Detection and Ranging, from which a C$_2$ profile is derived.
will eliminate the occurrence of really poor images (FWHM > 0.8) but will have a marginal effect on the median value, reducing it by $\sim 0.05$ to $\sim 0.55$ for HRCam observations. Improved optics, combined with these measures, can, however, make the median IQ $\sim 0.4$ and open up the 0.25 domain, a truly exciting perspective. These improvements will, in time, make the CFHT a far more powerful astronomical facility than it already is.

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