ABSTRACT: MegaCam image quality (IQ) data obtained with both the un-vented and vented dome of the Canada-France-Hawai‘i Telescope are used to assess the impacts of venting the dome on the full width at half maximum intensity – FWHM (asec or ″) – of optics-corrected 500 nm zenith telescopic point spread function. Increasing the dome porosity from 5% with the slit alone to 11% with the vents open
• reduces the median IQ from 0.66″ to 0.50″, thereby removing a 0.37″ contribution to image spread,
• reduces IQ noise and the IQ deterioration downwind with the unvented dome but
• still leaves a residual IQ contribution of 0.20″.

Much of the IQ improvement is already had in near-zero wind speeds. The vents increase the diversity of free air currents and their efficiency at preventing local accumulations of thermal imbalances in the dome air. They lead to fewer significant thermal eddies in the telescope line of sight and better IQ.

1- Introduction

Optically turbulent air in telescope enclosures, i.e. air whose temperature hence refractive index is locally and randomly variable, arises by conduction and radiation at surfaces whose temperature differs from that of the air. Eddies rise above warmer or sink below colder than air surfaces and diffuse through the air volume. They introduce wavefront errors in the telescope line of sight that spread stellar images.

Studies of the image quality (IQ) at the Canada-France-Hawai‘i Telescope (CFHT) have revealed that it can be significantly improved by reducing optical turbulence generated by thermal imbalances. The median of this “dome seeing” to IQ has been estimated to generate a point spread function (PSF) of 0.43″ full width at half maximum intensity (Salmon et al. 2009). In 2010, the CFHT Board approved a recommendation of the Scientific Advisory Committee to provide the CFHT dome with vents in order to better flush the telescope enclosure with free-stream air. Modelling, design, management and commissioning work by the CFHT team led to the vents becoming operational in late January 2014 (Bauman et al. 2014). Figure 1 shows pictures of the CFHT dome taken before and after the vents were installed.
The 16.2 m outer radius of the CFHT dome vertically spans 230°. The slit is 6 m wide and each of 12 vent openings is 1.8 m wide and 5.5 m high above the spring line. Thus, the average porosity of the dome to horizontal winds is 5% with no vents or with the vents closed and 11% with the vents open.

The image quality data from the CFHT wide field prime focus camera MegaCam with the dome vents closed and open are the basis of this assessment of the impact of venting the dome. Supplementary data come from the differential image motion monitor (DIMM) of the MKAM station. It is hoped that this empirical study, based on observed values of telescopic image qualities and environmental parameters, can be a useful complement and, perhaps, a guide to design efforts such as thermal accurate computer fluid dynamics simulations aimed at minimizing “dome seeing”. Figure 2 illustrates such simulations and the complex interactions between air flows, thermal sources and sinks and structures.

![Fig. 2 – A 6 m/s wind comes from the right in these computer fluid dynamics simulations of air flow and isotherms for the unvented (left) and vented (right) CFHT dome (Courtesy of Konstantinos Vogiatzis). Note the differences in the upwind ground layer structure and in the thermal contrast between the two conditions. From Baril et al. 2012.](image)

2- Data Processing and Global Statistics

The median full width at half maximum intensity (FWHM), expressed in arc second (") of uncrowded and unsaturated stellar images on the central CCDs of a MegaCam frame measures image quality. Exposures of at least 10 seconds are selected to suitably sample atmospheric tilts. The fixed but wavelength dependent contributions of the telescope optics to image spread (Salmon et al. 2009) are removed. They range from 0.31" in the i-band to 0.39" in the V-band and 0.53" in the U-band. These optics-corrected FWHM values are then reduced to zenith and to a wavelength of 500 nm, yielding a quantity denoted IQ in what follows. Note that optics contributions removals, wavelength normalizations and zenith corrections are simply made to reduce the scatter of the IQ data. They have no effect on the differences in median IQ between vents closed and vents open situations, which matter here, if the median values of the observing parameters are the same in both cases. This is very nearly so for all subsets of the 93 000 IQ values used here. In what follows subtractions of seeing or IQ values, resulting in ΔIQ estimates, are made in 5/3-power, as befits PSF spreads resulting from Kolmogorov optical turbulence. Much of the IQ values used below are medians of large subsets and are henceforth simply denoted “IQ”. Individual IQ values are denoted as such.

Table 1 summarizes the global statistics and gives the numbers of individual IQ values in each case. The formal 1-σ statistical uncertainties are all less than ±0.01". The 2005-2008 data used by Salmon et al. 2009 for their study of the relation between MegaCam IQ and environmental parameters were re-reduced with the same code used here for later data to ensure uniformity. Table 1 shows that, in recent years and in both vents closed and vent OPEN cases, the yearly medians are relatively stable and, most importantly, so are the contributions removed. Opening the vents removes a 0.37" median component of image spread. This is a key result of this study.

Table 1 also shows that, with the vents closed, the IQ value has been slightly larger in recent years (0.66 ±0.01) than during 2005-2008 (0.61 ±0.01). Installation of the vents in 2013 entailed dome skin insulation removal which may have been responsible for the larger IQ for that year.
The counts in Table 1 reveal that the vents remain closed nearly 50% of the time. Some observers have remained uncertain of the benefit of opening them. But the main reason has freezing in joints between the vent door slats. However, as will be seen below, this does not bias the vents-closed statistics to worse site seeing conditions.

Table 1: MegaCam IQ Values and Contributions Removed ΔIQ with Vents Closed and Open

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Vents CLOSED N</th>
<th>Vents OPEN N</th>
<th>ΔIQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-2008</td>
<td>0.61&quot; 36,520</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>2013</td>
<td>0.74&quot; 10,867</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>2014</td>
<td>0.64&quot; 3,756</td>
<td>0.47&quot; 6,329</td>
<td>0.38&quot;</td>
</tr>
<tr>
<td>2014-2017</td>
<td>0.66&quot; 25,689</td>
<td>0.50&quot; 20,348</td>
<td>0.37±0.02&quot;</td>
</tr>
</tbody>
</table>

Table 2 shows how the IQ contributions removed by venting the dome depend on the telescope altitude and on the slit orientations to the wind. This Table is produced mainly to provide comparisons with CFD results which are always for specific orientations and altitudes. Note that, as might be expected, the removals are the least when the slit faces the wind.

The MKAM DIMM median seeing for 2014-2017 was 0.609±0.006" with the vents closed and 0.599±0.004” with the vents OPEN. Thus the differences ΔIQ in MegaCam IQ values are not caused by differences in atmospheric seeing. Likewise, the median wind speeds were similar with the vents closed (6.2 m/s) and open (5.6 m/s).

Table 2: IQ Values (") and Contribution Removals for Two Altitudes and Three Slit-to-wind Orientations.

<table>
<thead>
<tr>
<th>Slit orientation</th>
<th>Vents CLOSED</th>
<th>Vents OPEN</th>
<th>ΔIQ</th>
<th>Vents CLOSED</th>
<th>Vents OPEN</th>
<th>ΔIQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>upwind ±15°</td>
<td>0.66 ±0.02</td>
<td>0.56 ±0.02</td>
<td>0.28 ±0.03</td>
<td>0.53 ±0.03</td>
<td>0.53 ±0.01</td>
<td>0.00 ±0.10</td>
</tr>
<tr>
<td>crosswind ±15°</td>
<td>0.75 ±0.01</td>
<td>0.48 ±0.01</td>
<td>0.51 ±0.02</td>
<td>0.64 ±0.02</td>
<td>0.52 ±0.01</td>
<td>0.31 ±0.03</td>
</tr>
<tr>
<td>downwind ±15°</td>
<td>0.65 ±0.02</td>
<td>0.43 ±0.02</td>
<td>0.43 ±0.02</td>
<td>0.75 ±0.01</td>
<td>0.52 ±0.01</td>
<td>0.47 ±0.03</td>
</tr>
</tbody>
</table>

We will now present some more detailed statistics, to demonstrate that our results are not affected by unrecognized selection effects and to better understand the physics at play in improving IQ through dome venting.

3 – Dependences on Slit-to-Wind Azimuth Differences

The two panels of Fig. 3 show the dependence of the individual MegaCam IQ values on the slit-to-wind azimuth difference with the vents closed and open. Figure 4 displays the runs of the median values. Opening the vents much reduces the IQ noise, thus facilitating the planning of observing programs, and eliminates the IQ tendency to deteriorate downwind.

The IQ deterioration downwind of the unvented dome is easily understood from Fig. 2: air eddies of thermally inhomogeneous air, hence optically turbulent escape in the mid-altitude telescope’s line of sight through the downwind slit. Also worth noting is the upwelling to the top of the dome of air in contact with super-cooled surfaces in the lee of the building. Nighttime IR photos show a strong temperature depression of >5°C on lee-side terrain, and water tunnel tests show strong upwelling to the top of the dome and into the slit with the slit pointed downwind (Baril et al. 2012). Thus the worst - numerically larger - MegaCam IQ (0.75") occurs at mid-altitude downwind.
When the telescope points at high altitude with the vents closed, at all slit-to-wind orientations it looks through the optically turbulent air being sucked out by the Venturi effect of the accelerated airflow atop the dome. This was first noticed by John Glaspey in the early years of CFHT operation and affectionately termed “the chimney effect”. It is responsible for the removals to be the largest at high altitudes. Opening the vents reduces this effect by sucking out dome air horizontally through the vents.

The $\Delta IQ$'s are the least when the slit is upwind. At intermediate altitude $\Delta IQ$ is essentially zero there. Dome air is then of course the least likely to exhaust through the slit.

![Fig. 3 – The MegaCam IQ values are plotted against the slit-to-wind azimuth differences for the vents closed and OPEN situations.](image)

![Fig. 4 – The MegaCam IQ values are plotted against the slit-to-wind azimuth differences for the vents closed (dots) and open (circles) situations. The squares are the IQ contributions removed by opening the vents, $\Delta IQ$. The 1-$\sigma$ uncertainties are smaller than the symbols.](image)

4 – IQ through the Night and Year

Figure 5 shows how IQ values evolve through the night. When the vents are closed (dots) IQ tends to deteriorate later in the night. The MKAM DIMM seeing (asterisks), transformed to the IQ scale as per Tokovinin 2001, does not show such a trend. The closed-vents IQ trend must result from accumulated heat release from telescope hydraulics, etc. With the vents open (circles), like for the DIMM (asterisks) but in a more prolonged way, the MegaCam IQ improves during the first hours of the night then rises slightly to a plateau at 0.50$''$. 
The $\Delta I/Q$ contributions removed by opening the vents steadily grow until ~4 hours after sunset as the dome air is being purged. Then the trend closely follows that of the closed-vent $I/Q$, with a lull around midnight and a climb toward night end. The benefits of venting thus follow the level of the thermal imbalances.

![Graph](image_url)

**Fig. 5** – The MegaCam $I/Q$ values for vents closed (dots) and open (circles) episodes, the MKAM DIMM seeing transformed to $I/Q$ values (asterisks) and the removed contributions to image spread $\Delta I/Q$ (squares) are plotted against the time of night. The 1-$\sigma$ statistical uncertainties are smaller than the symbols.

Figure 6 shows the $I/Q$ evolution through the year. With closed vents (dots) $I/Q$ is markedly better in the summer. The DIMM data (asterisks) show a similar but less marked trend and the vents open data are more uniform with the seasons.

![Graph](image_url)

**Fig. 6** – The MegaCam $I/Q$ values for vents closed (dots) and open (circles) episodes and the MKAM DIMM seeing transformed to $I/Q$ values (asterisks) are plotted against fractional year.
5 - Thermal Imbalances and IQ

Figure 7 shows IQ plotted against air temperature differences $\Delta T$ between the spigot, at the declination axis level inside the telescope central section, and the telescope top ring, i.e. along the telescope tube, for vents closed and open episodes. Similar trends for other pairs of temperature were removed, hence the ordinate label. The increase of IQ with $|\Delta T|$ follows expected $k\cdot\Delta T^{6/5}$ laws (curves), $k$ being $\sim 0.05/°C^{6/5}$ for $\Delta T > 0$. The thermal sensors are a few centimetres away from metallic surfaces. Thermal inertia leads to venting the dome having only a marginal effect on the ranges of air temperature differences. For instance, the open/closed ratios of the temperature dispersions are 1.3 (larger than unity!) for the “spigot to top-end” leg, and 0.8 for the “2m above floor to top-end” leg and for the “top-end to outdoor weather tower” leg. But, as seen in Fig. 5, at a given $\Delta T$ the contributions to image spread are weaker with the vents open. This is because the density of optically turbulent eddies is lower in the vented dome air. With the vents open the IQ at zero $\Delta T$ is 0.42″. Since the contributions from the optics have been removed this can be taken as the IQ an optically and thermally perfect telescope would deliver at the CFHT site from the 22 m elevation of the primary mirror. For a 30-m outer scale of turbulence this corresponds to a median DIMM seeing of 0.52″ (Tokovinin 2002).

![IQ vs Delta T](image)

Fig. 7 – The IQ values, corrected for other $\Delta T$s, are plotted against the air temperature differences between the spigot in the telescope central section and the top ring, i.e. along the telescope tube for vents closed and open episodes. At thermal equilibrium ($\Delta T = 0°C$) and with the dome open IQ is 0.42″.

6 - MKAM DIMM Seeing, MegaCam IQ and Wind Speed

The 2005-2017 MKAM DIMM data in Figure 8 show how the seeing at the CFHT site depends on wind speed. At near-zero wind, the DIMM is affected by optical turbulence generated by air-ground thermal exchanges and, possibly, by the DIMM’s own structure (Tokovinin 2010). As wind speed increases that local turbulence is blown away but the turbulence induced by the orography increases. The best seeing occurs in winds of a few meters per second.

The median MKAM DIMM seeing is 0.60″. This is larger than the 0.52″ derived in Sec. 3 from the perturbation-free MegaCam IQ, by a 0.24″ contribution. This is close to the 0.28″ contribution of the ground layer between the 7m DIMM and 22m CFHT primary elevations that can be derived from the Gagné et al. 2011 turbulence profile for the MKAM site.
Figure 8 – The median seeing values from the MKAM DIMM are plotted against wind speed.

Figure 9 shows, for three slit-to-wind orientations and for all combined, the evolutions with wind speed of the MegaCam IQ with the vents closed and open. Also shown are the closed-minus-open differences \( \Delta IQ \), the thermal contributions removed by opening the vents.

Opening the vents merely increases the dome porosity from 5% to 11%. Yet, even in near-zero winds that removes an additional thermal IQ contribution of 0.36" (Fig. 9D) over what the slit alone enables or, as will be seen below, 70% of the wavefront variance caused by thermal imbalances. This is because dome venting generates a greater diversity of air flow paths and not merely let more free-stream air flow through the dome. The diversity of air flows better flushes various air spaces where thermal imbalances would accumulate increasing sources of optical turbulence. Even at speeds as low as 0.1 m/s air currents traverse the 32 m diameter dome in only 5 minutes. By opening vents in the dome the diversity of air currents and their thermal imbalance flushing efficiency are increased thereby leading to a lower density of thermal eddies in the air volume and better IQ.

In near-zero wind (Table 3), with the vents open the IQs are similar for all slit-to-wind azimuths. With the vents closed, the \( \Delta IQ \) values range from 0.20" upwind to 0.44" downwind. This again shows that, even in very low winds, the flow of thermal turbulence in the telescope line of sight is different between closed and open vents and more uniform with the vents open. As the wind speed increases the \( \Delta IQ \) values increase slightly: dome air flushing by free stream air further removes thermal contributions and bring surfaces in closer thermal balance with the air.

<table>
<thead>
<tr>
<th>Slit Orientations</th>
<th>0 m/s Wind</th>
<th>20 m/s Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IQ</td>
<td>( \Delta IQ )</td>
</tr>
<tr>
<td>Upwind ±15°</td>
<td>0.54&quot;</td>
<td>0.20&quot;</td>
</tr>
<tr>
<td>Crosswind ±15°</td>
<td>0.53&quot;</td>
<td>0.36&quot;</td>
</tr>
<tr>
<td>Downwind ±15°</td>
<td>0.49&quot;</td>
<td>0.43&quot;</td>
</tr>
<tr>
<td>All</td>
<td>0.51&quot;</td>
<td>0.37&quot;</td>
</tr>
</tbody>
</table>
The MegaCam IQ values are plotted against the wind speed for the vents closed (solid dots) and OPEN (open dots) and for different orientations of the dome slit with respect to the wind Δaz. The squares are the differences between the closed and open vents values, i.e. the IQ contribution removals ΔIQ from venting. The statistical 1-sigma uncertainties are all less than ±0.02". The lines are empirical low order fits to the data. Note that the benefit of opening the vents is quite significant in near-zero wind.

7 - Removed and Residual Thermal Contributions to IQ

The ΔIQ values in Fig. 9 level off at high wind speeds. This indicates that the thermal contributions have then been essentially purged and that, with the vents open, IQ has reached the site-limit. At 20 m/s, the median thermal contribution removed is 0.46". It is reasonable to take this value as an estimate of the median thermal contribution itself. In low winds, i.e. with little ground layer uplift, the MKAM DIMM seeing is 0.54" (Fig. 6) for an IQ of 0.43". With the vents closed IQ is then 0.67" (Fig. 9D). This leads to an estimate of 0.45" for the median thermal contribution. These two independent estimates, 0.46" and 0.45", are only slightly larger than that of 0.43" derived by Salmon et al. 2009 for the no-vents dome. With the vents open, IQ is 0.50" in low winds (Fig. 9D) and 0.48" in high winds. The small difference between the 0.49" average and the 0.43" level expected from the DIMM corresponds to a residual thermal contribution of 0.20".

To summarize: in 2014-2017 the median thermal contributions of the CFHT dome to IQ were 0.45" with the vents closed and 0.20" with the vents open. Venting reduces the optical wavefront variance by a factor of \(\frac{0.45/0.20}{\sqrt[3]{0.45/0.20}}\) or "4. Much (70%) of that factor is obtained in near-zero winds, by merely making the dome more porous and allowing cross flow of the dome air. A porosity increase from 5% to 11% brings significant benefits.

Figure 10 shows histograms of the IQ values (solid lines) and distributions (dashed lines) from Monte Carlo combinations of values from a DIMM IQ distribution with local contributions log-normally distributed with the medians estimated above. The fits of the combinations were optimized by adjusting the logarithmic dispersions of the local contributions as indicated in the Figure and the median of the DIMM distribution at 0.41". The latter is close to the 0.43" estimate from the zero ΔT IQ in Fig. 5 and strengthens our estimate of the median perturbation-free telescopic IQ. The logarithmic dispersions of
the local contributions are much larger than those of the 13 seeing distributions examined by Racine 2015 which average 0.39 neper with a 0.03 $\sigma$. Dome seeing is very noisy!

Fig. 10 – The solid lines are the observed frequency distributions of the MegaCam IQ values with the vents closed and OPEN. The dashed lines are from Monte Carlo simulations. See text for details.

8 – A Simplistic Scaling Law

The air temperature differences $\Delta T$‘s in a telescope enclosure are inversely proportional to the free stream air flushing efficiency hence to the skin porosity $p$. The variance of the optical phase from temperature differences is proportional to $\Delta T^2$. For a Kolmogorov phase structure function IQ goes as $\Delta T^{6/5}$. The air temperature differences must also be proportional to a fraction $f$ of the total electrical power $W$ dissipated in the building and inversely proportional to the air volume $R^3$. The PSF spread increases as the optical path length inside the enclosure $R^{3/5}$. Putting all these factors together one expects the thermal IQ contribution to scale as

$$IQ_{\text{thermal}} = \frac{1}{R^3} \left( f \cdot \frac{W}{p} \right)^{6/5} \tag{1}$$

The parameter values for the CFHT enclosure and the resulting values of $IQ_{\text{thermal}}$ for $f$ adjusted at 0.24 are given under “model” in Table 5. Their agreement with the data obtained above is sufficient to give some credence to this simplistic model.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>$IQ_{\text{thermal}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$ (kW-Hr)</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>$R$ (m)</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>$f$</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>$p$(w/o vents)</td>
<td>0.05</td>
<td>0.48”</td>
</tr>
<tr>
<td>$p$(w/vents)</td>
<td>0.11</td>
<td>0.18”</td>
</tr>
</tbody>
</table>

This analysis neglects dome skin effects such as daytime heating by the Sun and super-cooling to the night sky. It thus assumes a perfectly insulated dome skin. On the other hand, solar heating effects must
disappear early in the night and super-cooled outer skin air is a thin layer with, presumably, limited IQ spread effect.

The validity of Eq. 1 for different facilities remains to be tested. Their factor $f$ may be lower than for CFHT if more efficient measures are in place to avoid leaking air from warm rooms or equipment to the telescope area. The CFHT power consumption rate in Table 4 is the total for the whole building, not just for equipment above the observing floor. And the floor itself is refrigerated to the expected night-time air temperature. So, reasonable care is taken to minimize thermal imbalances. Yet they are not negligible, as shown above.

Larger telescopes might benefit from larger enclosures since thermal IQ decrease as $R^3$. But the power dissipation might increase if only because more powerful hydraulic bearings and machinery are used. Empirical studies of thermal IQ like the present one at other facilities would be very informative.

The effectiveness of venting telescope enclosures has been documented at other facilities. The median EE50 of stellar images at the Hobby-Eberly Telescope has been improved from 2.7” to 2.1”, a 1.7” EE50 (1.1” FWHM) contribution removal, by opening louvers that increase the porosity of the enclosure from 11% to 24% (Hill et al. 2004). At the KPNO 4-m Mayall telescope increasing the dome porosity from ~4% to ~7% improved the median IQ from ~1.10” to ~0.95” (Frogel 2002).

9 - Conclusion

The median 500 nm optics-removed zenith MegaCam IQ in the unvented CFHT dome was 0.66” between 2014 and 2018. The removal, by dome venting, of a local contribution 0.37” reduces that median to 0.50” and leaves a residual contribution of 0.20”. Such a venting benefit is already largely achieved in very low winds condition since the 32 m diameter enclosure crossing time for even 0.1 m/s air currents is only a few minutes. The dome vents allow free stream air currents to more completely flush the various sources of thermal imbalance in the enclosure than the slit alone does. The diversity of air currents enable by multiple openings is more beneficial than the increase in total air flow higher winds produce.

This study was made possible thanks to contributions from CFHT engineers and technicians over many years who, with the present authors, produced the papers referenced below. We are also grateful to the numerous CFHT visiting astronomers and to the service observers who generated the 93 424 MegaCam frames used. Finally, University of Washington Dr. Robert Blumenthal was most generous in providing advice and access to the water tunnel facility. The flow modeling was very instructive in understanding the unvented and vented flow patterns in and around the dome.

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