IR image quality at the VLT

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Summary

Analysis of archived ISAAC data was used to produce seeing histograms at J, H and K, which include a small correction for ISAAC image degradation. These therefore are the current best estimates of the VLT delivered image quality in the IR at Nasmyth focus.

Comparison of the ISAAC data with DIMM 500 nm measurements and turbulent seeing models with finite outer scale, shows that this class of models does not fit the data very well.

1 Introduction

KMOS is an IR multi-object spectrograph currently under design for the VLT, with an estimated delivery date of 2010. KMOS will have 24 independent arms, each with an IFU. The IFU pixel scale will need to be optimised to both adequately sample images, yet give a sufficiently large field to allow sky subtraction for compact objects. This optimisation requires knowledge of the delivered IR image quality at the VLT; that is, IR image quality at a Nasmyth focal plane.

There are two approaches to obtaining IR image quality on Paranal. The most obvious is to use archived image quality parameters produced from pipeline reduction of IR instrument data in Garching. This has the advantage of being a direct measurement, but suffers from any effects due to the particular instrument used eg. pixel scale, instrument optical image quality, flexure etc. These data are shown in section 2. The other is a semi-empirical method in which 500 nm DIMM measurements are used and extrapolated into the infrared using reasonably standard formulae. Results from this approach are presented in section 3.

2 Analysis of QC1 parameters

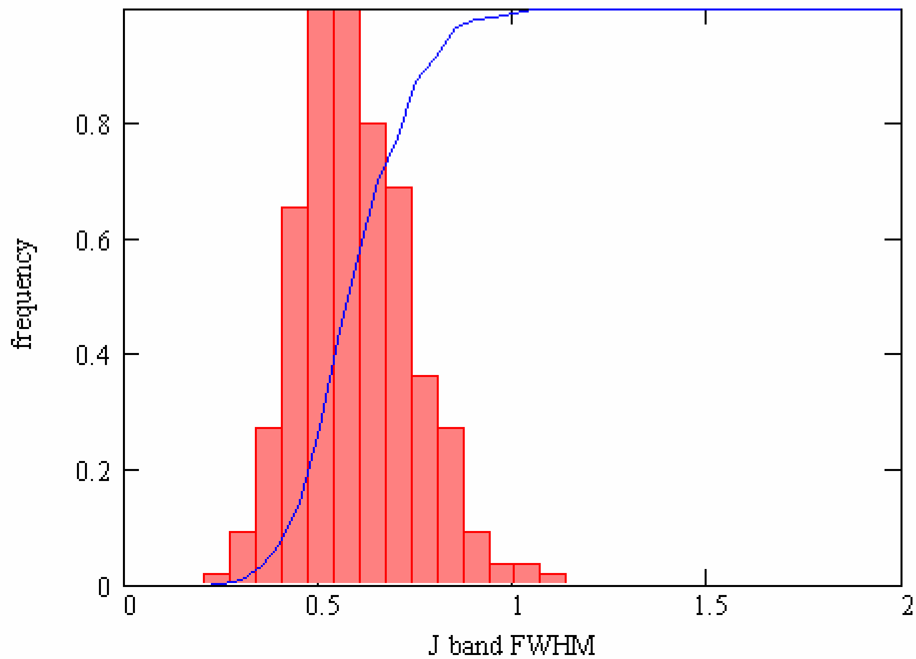
Pipeline processed QC1 parameters from VLT data are routinely archived and can be searched via a simple interface at http://archive/bin/qc1_cgi . ISAAC image quality data as defined by the qc_iq keyword were retrieved from 1999, along with the airmass of each observation and the corresponding DIMM 500 nm seeing. The ISAAC fwhm results from an automatic fitting procedure which also attempts to exclude extended objects such as galaxies. For comparison, data was also retrieved for FORS1 imaging in B and V bands.

Before this data can be binned and histograms produced, a few corrections need to be applied. Firstly, all data was corrected to seeing at 30 degrees zenith angle via a $\sec(z)^{3/5}$ scaling law. Secondly, since we are interested in the delivered image quality at a VLT focal plane, we attempt a small correction in the IR data for ISAAC image degradation, amounting to 0.22 arcsec fwhm. This is based on observations of internal pinholes in a focal plane mask and is approximately consistent with smoothing by the pixel scale (0.15”) and similarly sized optical aberrations. This amount was subtracted quadratically off the observed $(\text{ISAAC fwhm})^2$. No instrument image quality correction was applied to the FORS1 data.

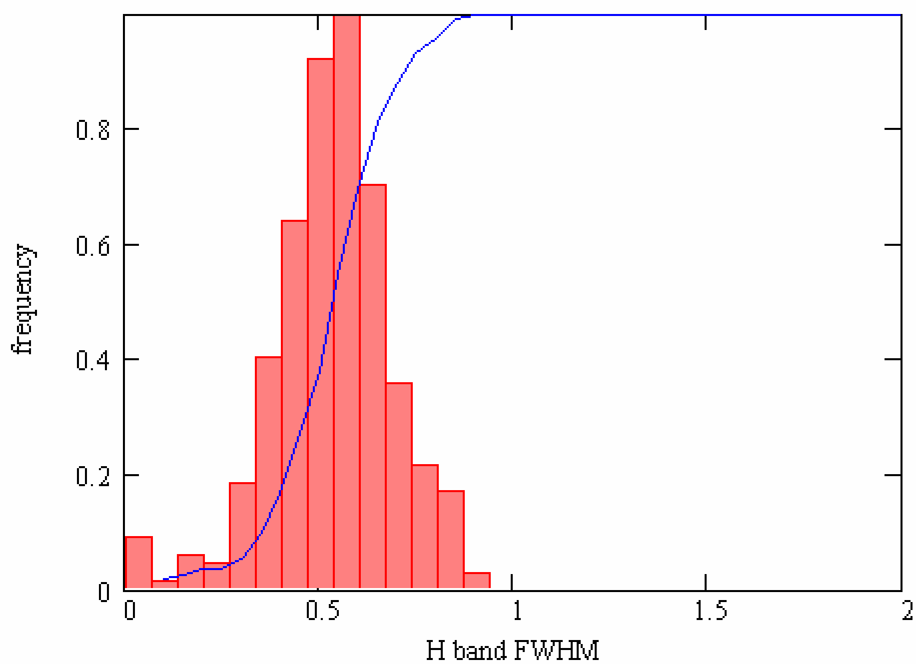
Then the following seeing histograms and cumulative frequency curves result from analysing ISAAC data taken since 1999. All values have been corrected to a zenith angle of 30 degrees.

Conclusion : we note the following

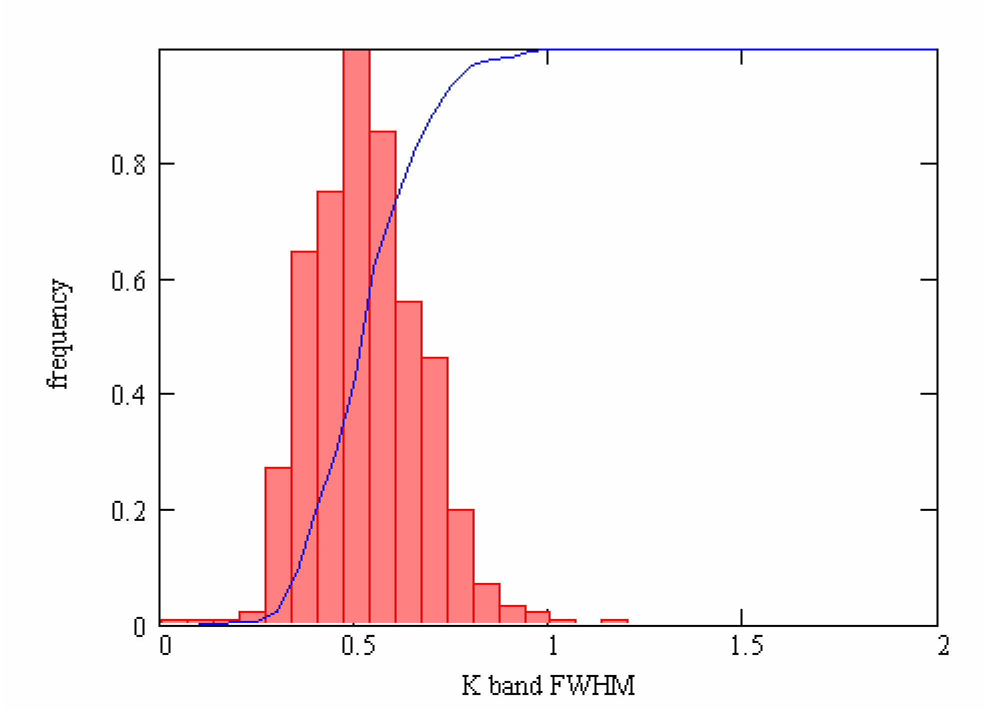
- although wavelength dependence of seeing from J to V is reasonably consistent with $\lambda^{-1/5}$, it does not agree with what would be expected from a turbulent outer scale of ~22m which would result in a much stronger wavelength dependence, as discussed in section 2.
- there are some points with very small unphysical seeing. These are probably image artifacts, but have not been removed from the histograms.
- These data agree well with observed IR FWHM from FIRES data (A.Moorwood) which show 0.25-0.35” for best images at K and J at small airmasses. They also agree with the best-ever IR ISAAC images reportedly seen at Paranal at K (0.3”, C.Lidman).



J median FWHM = 0.57 arcsec

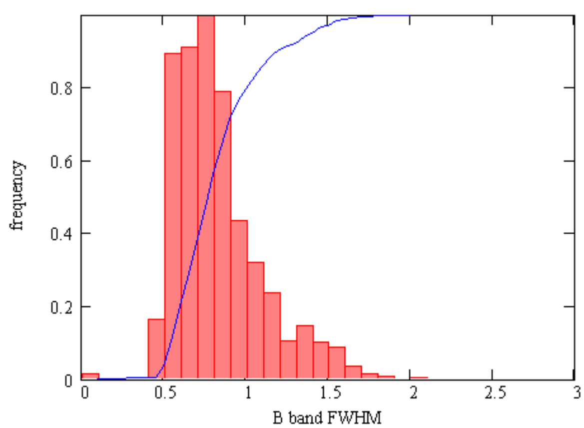


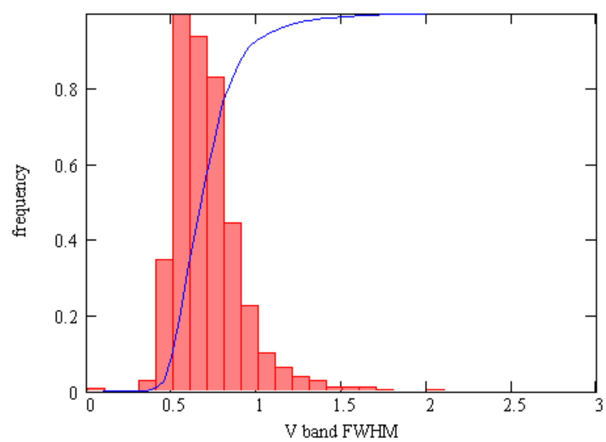
H median FWHM = 0.53 arcsec



K median FWHM = 0.52 arcsec

The following histograms are for FORS1 data over the same period.





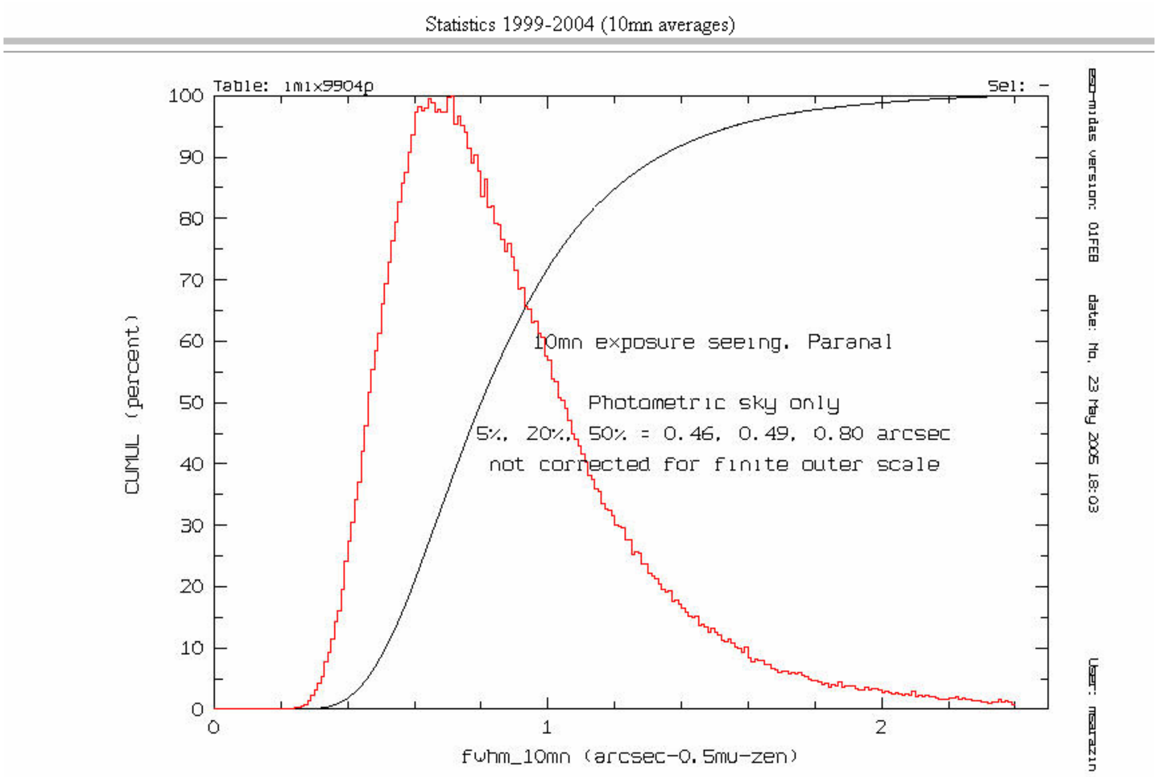
B median FWHM = 0.77”

V median FWHM = 0.67”

3 IR image quality from 500 nm DIMM measurements

3.1 DIMM 500 nm seeing histogram and predicted IR FWHM

The histogram below is for DIMM data from 1999-2004. Seeing is for 10 minute exposures, at Zenith, and assuming an infinite outer turbulent scale to derive the FWHM at 500nm.



(Provided by Marc Sarazin)

The following are predicted J,H,K seeing values in arcsec based on the DIMM histogram above and a finite outer scale model described in the appendix.

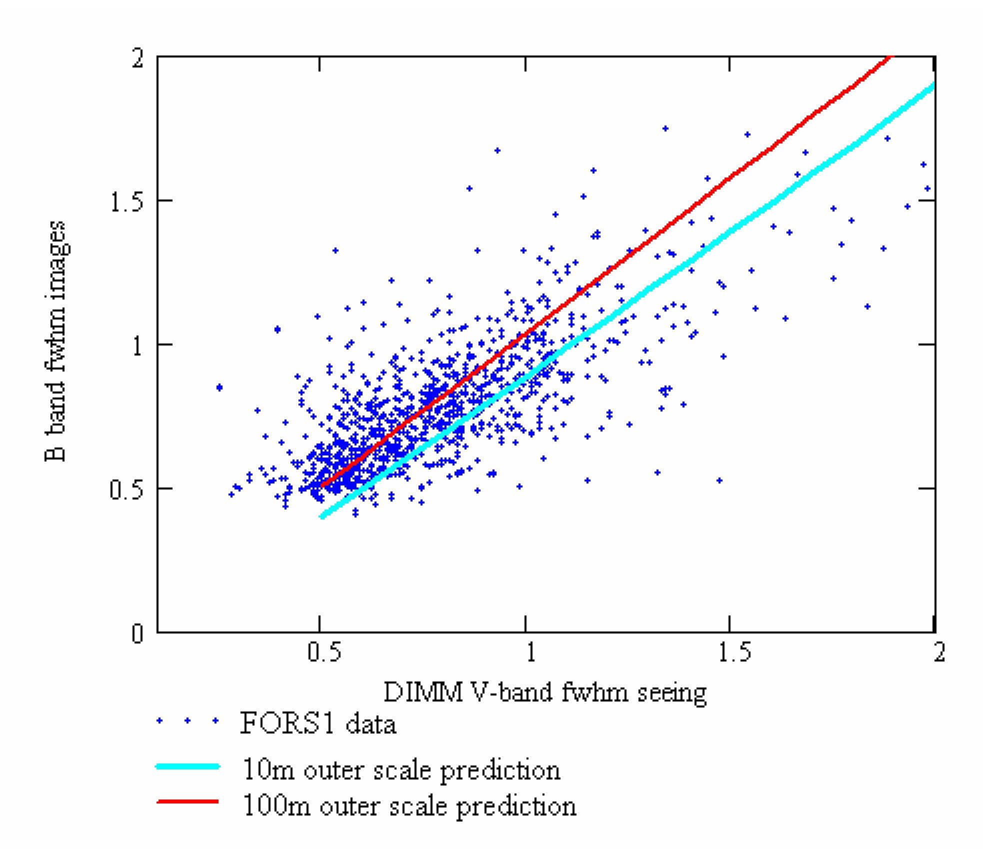
	DIMM 500 nm fwhm seeing at infinite outer scale, at zenith	predicted J band fwhm seeing (30 deg zenith angle, 22m outer scale)	predicted H band fwhm seeing (30 deg zenith angle, 22m outer scale)	predicted K band fwhm seeing (30 deg zenith angle, 22m outer scale)
5% percentile	0.46	0.27	0.24	0.20
20% percentile	0.49	0.29	0.26	0.22
median	0.80	0.52	0.47	0.42

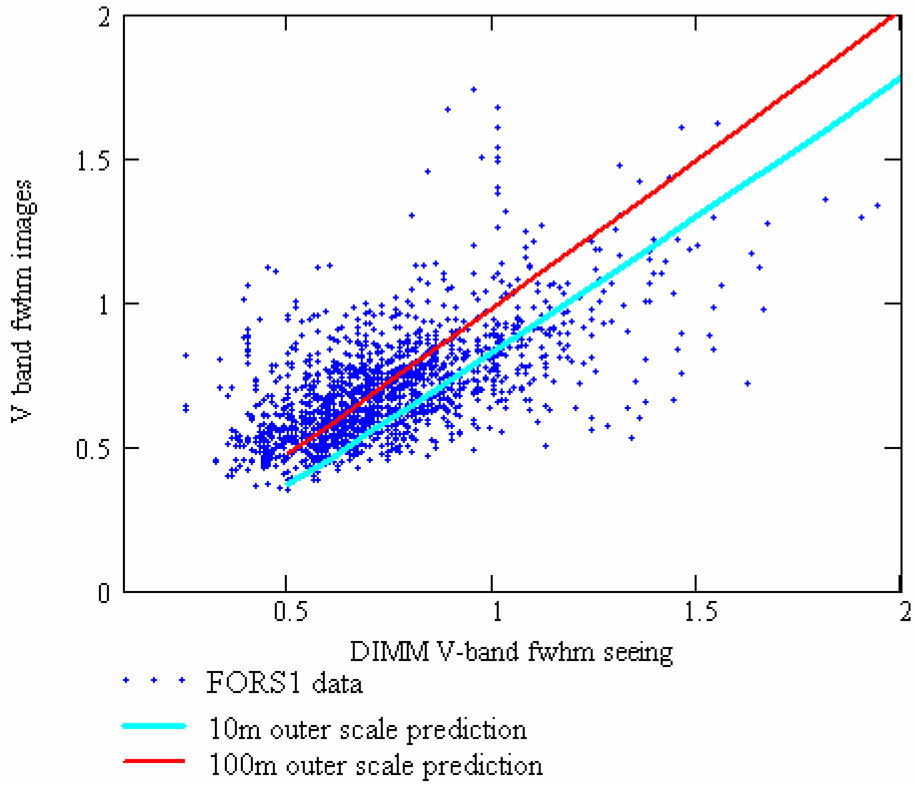
Conclusion: we can see immediately that the DIMM-predicted IR values shown in this table do not agree very well with the observed ISAAC IR image quality histograms shown in section 1. For example, the K-band 20 and 50 % percentiles actually observed are 0.40 and 0.52 arcsec, compared with 0.22 and 0.42 predicted.

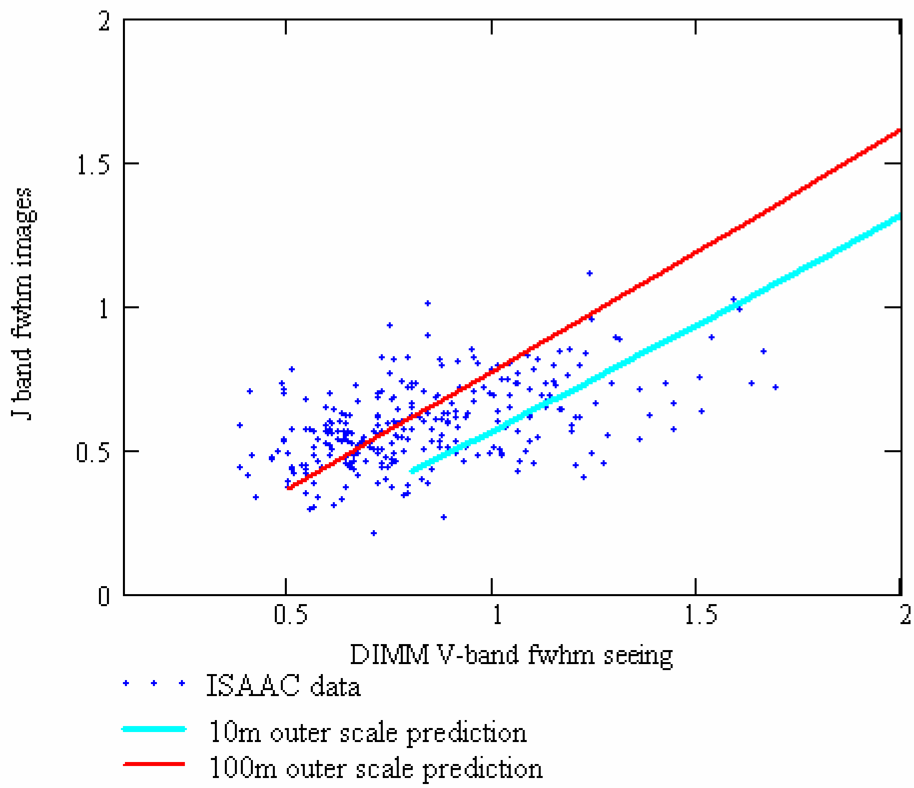
3.2 Detailed IR-DIMM comparison

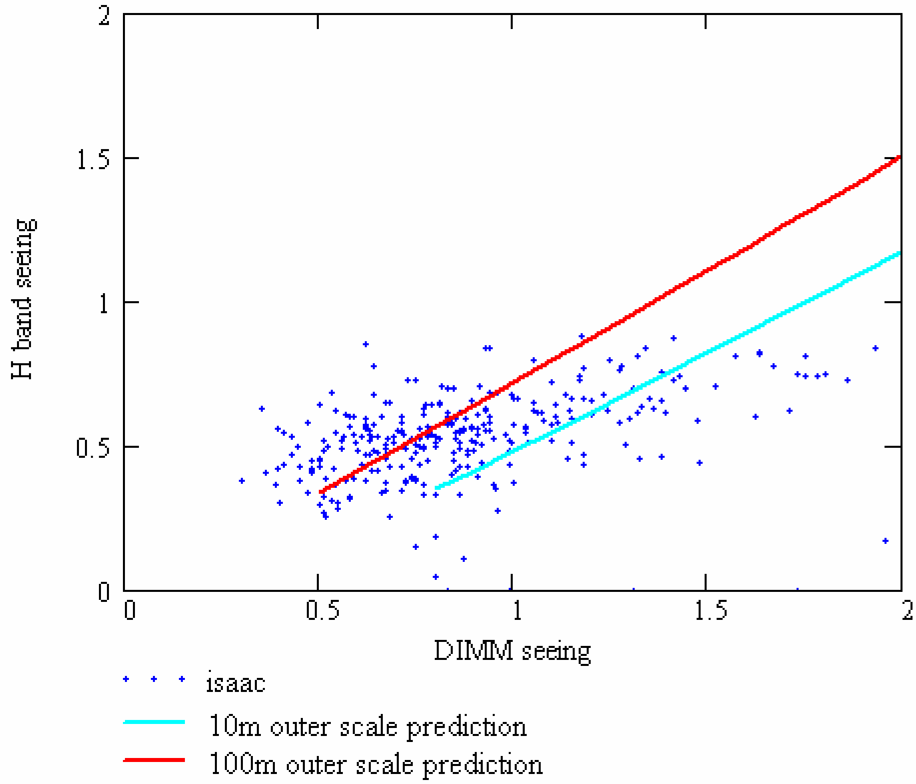
Plots of observed vs. DIMM-predicted image quality are shown here from B to K for the period 1999-2005. The following should be noted

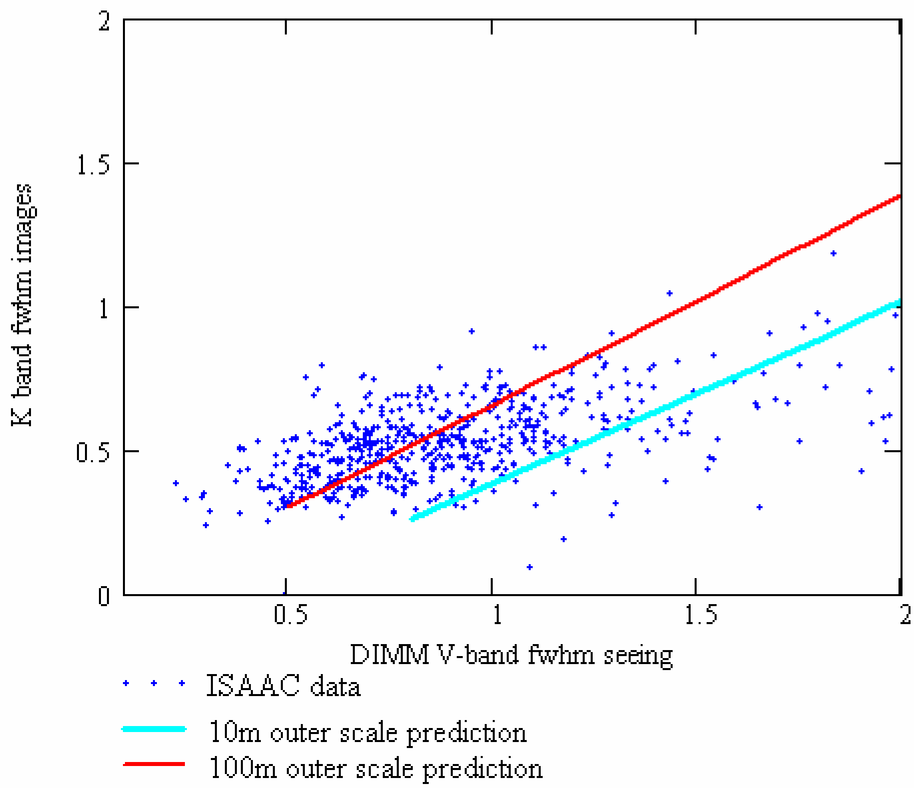
- all DIMM and IR observed data, and modelling have been corrected to a zenith angle of 30 degrees using a $\sec(z)^{3/5}$ scaling
- Paranal data (see appendix) show that the turbulent outer scale at Paranal lies between 10 and 100m most of the time, with a median of 22m. The lines in each plot show predicted IR image quality based on 10 and 100m outer scale.




2
1.5
1
0.5
0
V band fwhm images
0.5
1
1.5
2
DIMM V-band fwhm seeing
FORS1 data
10m outer scale prediction
100m outer scale prediction

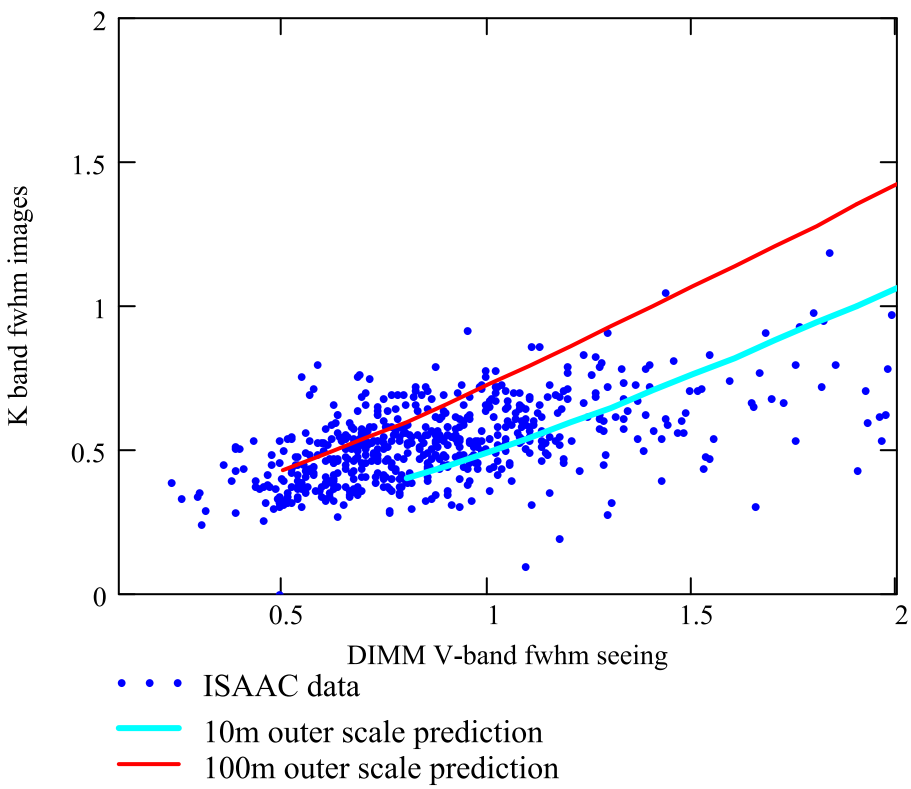

2
1.5
1
0.5
0
J band fwhm images
0.5
1
1.5
2
DIMM V-band fwhm seeing
ISAAC data
10m outer scale prediction
100m outer scale prediction


2
1.5
1
0.5
0
H band seeing
0
0.5
1
1.5
2
DIMM seeing
isaac
10m outer scale prediction
100m outer scale prediction


2
1.5
1
0.5
0
K band fwhm images
0.5
1
1.5
2
DIMM V-band fwhm seeing
ISAAC data
10m outer scale prediction
100m outer scale prediction

Conclusion: The model predictions seem to work reasonably well at B, but as the wavelength gets longer and the image quality better, there is substantial disagreement between the data and the models. When the seeing is bad the DIMM + Model OVERESTIMATE the seeing actually observed on the VLT. This is well known (M.Sarazin), but not currently understood.

On the other hand, when the seeing is good, the DIMM + Model UNDERESTIMATES the observed seeing. This is not understood either, but could be explained by an additional component (~0.3”) of image degradation arising in the instrument, telescope or enclosure. However, this seems unlikely to be a static degradation (eg. due to mis-focus or optical aberrations) since best images of ~0.3” indicate that any static component must be significantly less than this. As an illustration of this, the following plot shows the K band data along with model predictions in which a 0.3” seeing component has been added quadratically.



4 FWHM and 50% encircled energy

Since the empirical data does not fit a finite turbulent outer scale model very well, and shows the existence of a pedestal whose nature is uncertain, it probably makes sense to assume the simplest case for the PSF shape. In the case of a PSF generated from Komogorov turbulence, the 50% encircled energy is related to the FWHM by

EE50 = 1.17 FWHM

5 Appendix - Seeing and wavelength conversion

For observations away from zenith, the seeing fwhm is assumed to increase as

$$\sec^{3/5}(z)$$

For an infinite outer turbulent scale (section 1 above), the fwhm (f) at arbitrary wavelength is given by

$$f(\lambda, z) = \frac{0.98\lambda}{r_0} = f_{0.5} \times \left[\frac{\lambda}{0.5}\right]^{-0.2} \times \sec^{3/5}(z)$$

relative to a fwhm at 0.5 microns, at zenith.

For a finite outer turbulent scale, a correction factor must be applied. Studies at Paranal are consistent with a finite outer scale (Lo) of median value 22 metres, which results in the following predicted correction factors based on the equations in Tokovinin, 2002, PASP, 114,1156,

$$factor = \sqrt{1 - 2.183\left(\frac{r_0}{L_0}\right)^{0.356}}$$

or

$$factor(\lambda) = \sqrt{1 - 2.183\left(\frac{0.98\lambda}{f(\lambda, z).L_0}\right)^{0.356}}$$

which then gives the final delivered FWHM to be

$$FWHM(\lambda) = f_{0.5} \times \left[\frac{\lambda}{0.5}\right]^{-0.2} \times \sec^{3/5}(z) \times factor(\lambda)$$

The Turbulent Outer Scale measured at Paranal.