Influence of defocus on DIMM

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1 The problem and the method

The theory of DIMM has been thoroughly studied by now. Many subtle effects that can bias the measurements have been taken into consideration: finite exposure time, CCD noise, etc. (2002 PASP, V. 114, p. 1156-1166). The influence of optical aberrations has been overlooked so far. The optical quality of real images formed by the sub-apertures of a DIMM instrument is often far from ideal. Strehl ratios computed on the CTIO DIMMs may go well below 0.3.

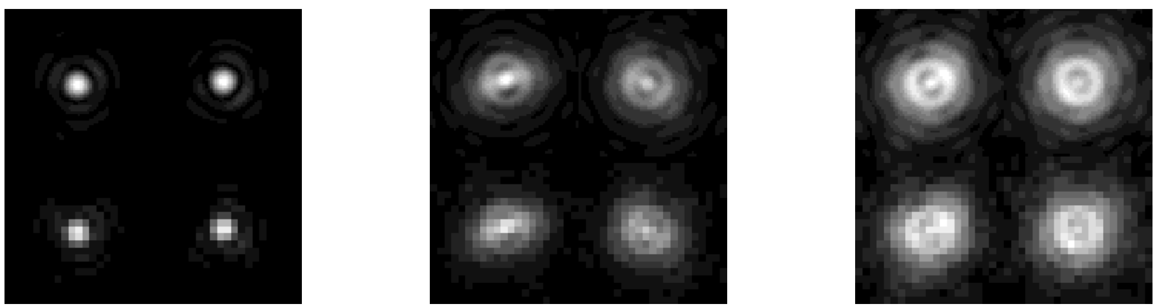

Figure 1: Spots in DIMM for various defocusing: perfect (left), 1 radian (center) and 1.5 radian (right). The upper pairs show the images with square-root intensity stretch, the lower pairs show the simulated CCD images with photon noise.

At first sight, the only adverse effect of the increased size of spots in DIMM is an increased influence of photon noise (through its relation to the image size). Given that photon noise is typically negligible in modern DIMMs (compared to readout noise, for example), it might appear that aberrations are, to the first order, irrelevant.

This statement, however, is wrong. The distribution of light in an aberrated spot depends on the aberrations, hence the center of gravity of the aberrated spot is no longer a measure of the true image centroid. A defocused DIMM may be viewed as a “curvature sensor”: even if the spots were perfectly stationary, changing higher-order aberrations inside the DIMM pupils would produce some image motion. The seeing measurement with aberrated spots will be biased even for a very bright star (no CCD noise).

The influence of defocusing becomes more severe when we consider the intensity fluctuations in the pupil (scintillation). Suppose that 1/2 of the pupil becomes dark and the other half is bright because of the scintillation. This “apodisation” does not shift the center of a perfectly focused image, only makes it a bit larger by diffraction. However, a defocused image will be shifted! Thus, we expect that the error in the seeing measurement by a defocused DIMM will be larger under strong scintillations (high turbulence).

We simulated the DIMM operation with a suitably modified IDL Monte-Carlo code used previously for DIMM studies (dimsimfoc.pro). The DIMM parameters were taken to be those of CTIO DIMMs: aperture diameter 95 mm, baseline 150 mm. The pixel size of the CCD is $0.71''$. Compared to the previous versions of the code, we added variable optical aberrations (defocus and coma, Zernike polynomials number 4 and 8 respectively) and optical propagation between the phase screen and DIMM apertures. The propagation gives rise to scintillation. We simulated a case of bright 0^m star with 10 ms exposure time and no readout noise, to concentrate only on the effect of aberrations.

Images of the spots are computed from the distorted wave-fronts by Fourier transform, for a monochromatic light of 700 nm wavelength. Thus, our code simulates both static aberrations of the DIMM telescope and random aberrations of the atmosphere.

The amplitude of the static aberrations is specified as Zernike coefficients in radians. According to the Maréchal approximation, 1 radian of rms aberration should degrade Strehl ratio to $e^{-1} = 0.37$, which is born out by the actual numbers.

A defocused wave-front can be described by a path-length difference $l = r^2/(2r_c)$, where r is the radius in pupil plane and r_c is the curvature radius. The phase of the defocused wave-front ϕ (in radians) is related to the path-length difference l and, on the other hand, to the Zernike coefficient z_4 and aperture radius R:

$$\phi(r) = z_4 2\sqrt{3}(r/R)^2 = 2\pi l/\lambda. \tag{1}$$

This leads to a relation between z_4 and r_c:

$$z_4 = \frac{\pi R^2}{\lambda r_c 2\sqrt{3}} \tag{2}$$

For our adopted DIMM parameters ($R = 0.0475$ m) 1 radian Zernike defocus corresponds to $r_c = 2900$ m. The deviation of DIMM spots from their nominal positions due to the defocus is equal to the derivative of l over r, i.e. to b/r_c for a DIMM baseline b. For $b = 0.15$ m we get $10.6''$ or 15 CCD pixels. Thus, we can relate the defocus in radians to the change of spot separation.

2 Results

We show the results of the simulations in Fig. 2 as a bias in the measured seeing vs. defocus. The bias in the image motion variance was converted to the bias in seeing (power 0.6) and averaged between longitudinal (x) and transverse (y) directions. As expected, defocused images lead to the over-estimation of the measured seeing compared to the true seeing, by a factor as large as 2. This bias does not depend on the seeing itself, as expected: both the image motion (measured signal) and random aberrations (wrong signal) are proportional to the same parameter, r_0. The dotted line depicts the drop of the Strehl ratio with increasing defocus.

The conclusion is clear: in order to keep the bias in seeing within 10%, we should keep the defocus within ± 0.5 radian. It will be sufficient to maintain the separation of the spots in DIMM to ± 7 pixels. However, in reality the defocus is not the only aberration in DIMM: the optical quality of the

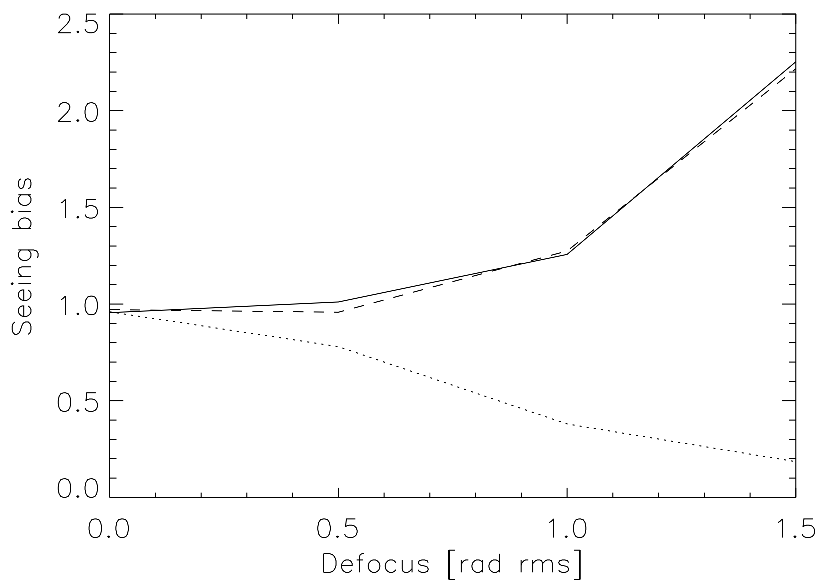

Figure 2: The bias in the measured seeing as a function of defocus. Solid line: 0.5″ seeing, dashed line: 1″ seeing. The dotted line shows the Strehl ratio. Turbulence is at the ground level (no scintillation), the seeing is the average of longitudinal and transverse. The dotted line shows the Strehl ratio.

telescope and wedge prism is not perfect, and even with most careful focusing Strehl ratios of spots reach only 0.5 or so. We simulated the coma aberration and found that it also leads to a bias in seeing, as expected. So, the criterion for valid measurements should be Strehl no less than 0.5. At Strehl ratios of 0.3 and below the bias becomes unacceptably large.

The bias caused by defocus is more significant in the transverse direction than in the longitudinal direction. This happens because the transverse image motion is smaller, hence the same amount of noise causes a larger bias. The disagreement between image FWHM in x- and y-directions could be used as a check for this bias. However, other effects intervene here. For example, a coma in the x-direction biases only longitudinal FWHM, i.e. acts in opposite sense compared to defocus.

In Fig. 3 the effect of the propagation is investigated. A single layer with typical turbulence (1″ seeing) is simulated. The bias is less when this layer is close to the ground (no scintillation, only curvature-sensing effect). The same layer at 10 km causes scintillation of 12% in the DIMM apertures. A focused DIMM under-estimates this turbulence because of the propagation effects (less tilt, part of turbulent energy is transferred to scintillation; the DIMM theory is strictly valid only for near-field turbulence when aperture size is much larger than the Freshel radius.). But for a defocused DIMM the bias is indeed severe. In Fig. 4 the dependence of the bias on the seeing is studied for a “moderate” defocus of 1 radian (Strehl of 0.37) and a layer at 10 km.

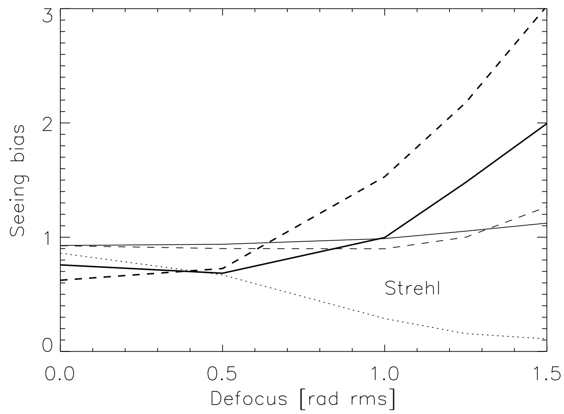

Figure 3: The bias in the seeing measured in the longitudinal (full lines) and transverse (dash) directions as a function of defocus. The seeing is $1''$ ($r_0 = 0.1$m) and the turbulent layer is either at the ground (thin lines) or at the altitude of 10 km (thick lines). The dotted line shows the Strehl ratio.

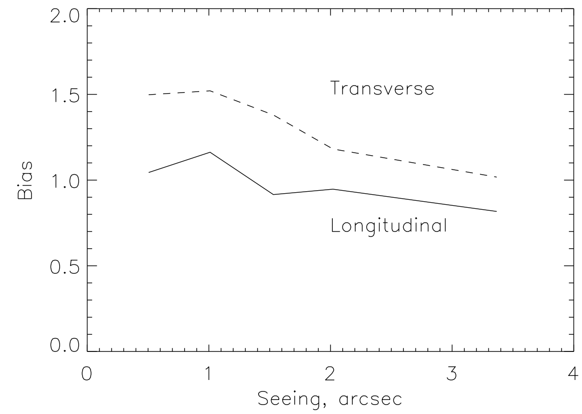

Figure 4: Bias in longitudinal (full line) and transverse (dash) seeing for a turbulent layer at 10 km as a function of the seeing itself. The defocus is 1 radian.

3 Conclusion

It is shown that DIMM measurements can be severely biased by defocus. A simple and efficient method to control this bias is by computing the Strehl ratio. Data with Strehl below 0.5 should be rejected. We verified that without aberrations, Strehl stays above 0.8 even for $2''$ seeing, thus if data with low Strehls are rejected the bias in a seeing statistics for a given observatory should not be a problem.