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KI Vis2 Ratio Correction

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Abstract

We have explored schemes for applying a correction for un-balanced arm fluxes to Keck Interferometer (KI) V^2 data. Through simulations of atmospheric and instrumental flux fluctuations statistics, we find that measurements of the single arm fluxes interleaved with the fringe measurements (5 times 5 sec), averaging of the single arm fluxes for the entire fringe acquistion time (120 sec) and computation of a single correction factor derived from the average fluxes works best for KI data. This measurement scheme has been implemented in the KI acquisition sequencer. We also show that applying this correction factor improves the calibration of real KI V^2 sky data, and does not harm it when the fluxes are balanced and the correction is unnecessary.

1 Introduction

In an optical interferometer, one of the sources of system visibility degradation comes from a simple unbalance in the fluxes contributed by each arm. If we denote by V_0 the object visibility, and if each of two interferometer arms contribute fluxes F_1 and F_2, in the abscence of any other instrumental effects, the measured visibility will be (in terms of visibility squared, the quantity actually measured by KI):

$$V^2 = \frac{4 \cdot F_1 \cdot F_2}{(F_1 + F_2)^2} \cdot V_0^2 \leq V_0^2 \tag{1}$$

If the intensity mismatch were static, the visibility loss term would be constant and the effect would calibrate out between target and calibrator observations. In practive however, the individual fluxes vary as a result of atmospheric seeing and possibly instrumental fluctuations of the light coupling onto the fringe detector, on time scales shorter than the target-calibrator switching time.

However, from the relation above, it is clear that if the individual fluxes can be estimated for each observation, a correction factor can be applied to recover V_0^2. Note that the visibility loss factor in the above equation is a relatively weak function of the flux mismatch: in order to reduce V_0^2 by a factor of 0.5, a flux ratio between the two interferometer arms of 6 is required. A large but plausible flux ratio of 2, only reduces V_0^2 by a factor of 0.9.

In some interferometer designs, part of the light from each telescope is split prior to beam combination so that the fluxes can be individually measured simultaneously with the fringe signal. In that case, an essentially perfect correction can be applied [Coude du Foresto et al. 1997]. The KI beam combiner does not have such photometric taps. However, by measuring only average fluxes representative of the conditions during the fringe measurement, an adequate correction may be also be obtained [Shaklan 1992].

2 Simulations of V^2 estimation in the presence of flux fluctuations

Suppose the object visibility is $V_0^2 = 1.0$ (point source). Averaging over some time ([...]), we would measure:

$$V^2 = \frac{4 \cdot [F_1 F_2]}{[F_1 + F_2]^2} \tag{2}$$

If we also independently measure the individual fluxes by averaging over some time, $[F_1]$ and $[F_2]$, the correction factor would be ("ratio correction"):

$$RC = \frac{([F_1] + [F_2])^2}{4[F_1][F_2]} \tag{3}$$

From which one would compute a corrected visibility:

$$V_{RC}^2 = V^2 \cdot RC = \frac{[F_1 F_2]}{([F_1][F_2])} \tag{4}$$

For long averaging times, or for relatively short averaging times if the fluctuations have a white spectrum, $[F_1 F_2] \equiv [F_1][F_2]$, and $V_{RC}^2 \longrightarrow 1.0 = V_0^2$.

For KI however, the photometric fluctuations have a significant low frequency 1/f component, and the question arises as to the optimum scheme for sampling and averaging the individual fluxes that will go into the correction factor (RC) applied to the measured visibilities.

The effects of aperture flux fluctuations with 1/f statistics have been simulated, by generating data sequences with white noise and 1/f noise with knee frequencies at 0.1, 0.01 and 0.001 Hz (normalized to give the same rms). For each spectral shape, 9 cases were run for flux ratios of 1:1, 1:1.25 and 1:1.5; and rms fractional rms fluctuations of 0.1, 0.2 and 0.3. For each run, V^2 was estimated in various ways: **(a)** from a 125 sec average; **(b)** from a 125 sec average using an ideal ratio correction i.e. using simultaneous single-aperture fluxes; **(c)** from a 125 sec average using a "deferred" ratio correction, the deferred ratio is computed from two 25 sec single-aperture flux averages at the end of the 125 sec fringe integration; **(d)** from an interleaved sequence of 5 triplets {25 sec V2, 5 sec delay, 5 sec aperture 1, 5 sec delay, 5 sec aperture 2, 5 sec delay}, no ratio correction; **(e)** using the interleaved sequence and applying the ratio correction calculated as a single factor RC formed from the 5 5 sec single-aperture averages; and **(f)** using the interleaved sequence but applying the ratio correction to each of the 5 triplets, and averaging the 5 V^2 estimates.

The detailed results of these simulations are included in the Appendix, the main conclusions are as follows:

1. Even with an ideal ratio correction, the estimated V^2 has finite standard deviation.
2. The interleaved V^2 has similar statistics to the continuous V^2.
3. Using a single "deferred" ratio gives worse results than the "interleaved" ratio for 1/f knees of 0.01 Hz or lower, and identical results otherwise.
4. Block averaging V^2 (25 sec blocks) introduces a bias compared to a single 125 sec computation, which is also biased compared to a very long average. The bias can exceed 1% for large fluctuations and 1/f knees of 0.01 Hz and lower.
5. The ratio correction from the interleaved ratios introduce only a small (<0.2%) bias in all cases.
6. With balanced fluxes, the ratio-corrected V^2 is no noisier than the uncorrected V^2, and also corrects most of the bias even in high noise cases.
7. With balanced fluxes, the ratio corrected V^2 is noisier, except for the very high noise cases, where it is slightly quieter. Table 1 contains some examples for the case of ratio 1:1.5 and 0.3 rms fractional fluctuations.
8. V^2 accuracy of 5% is possible in all the cases surveyed here. Accuracy of $\sim 2\%$ is possible with 20% rms flux fluctuations even with a 1:1.5 mismatch. Table 2 summarises the rms for the case where the interleaved ratio correction is applied, for all those cases the bias is $< 0.3\%$ (with respect to unity).

Table 1: Example simulation results for the case of 1:1.5 ratio and 0.3 rms fractional amplitude fluctuations.

Noise 1/f knee	Systematic bias (1:1.5 ratio)	No ratio correction: bias w.r.t. theory	rms	Interleaved ratio correction (**case e**): bias w.r.t 1.0	rms
White	-4%	-0.05%	1.1%	0.12%	2.0%
0.1 Hz	-4%	-0.07%	1.3%	0.25%	2.7%
0.01 Hz	-4%	-0.23%	2.5%	0.32%	3.6%
0.001 Hz	-4%	-0.88%	4.3%	0.23%	3.6%

Table 2: Example simulation results for the case of interleaved ratio correction (**case e**), showing the V^2 rms errors, all the biases are less than 0.3%.

Amplitude fractional rms	ratio	white	1/f 0.1Hz	1/f 0.01Hz	1/f 0.001Hz
0.1	1	0.1%	0.1%	0.2%	0.2%
0.1	1.25	0.4%	0.5%	0.6%	0.6%
0.1	1.5	0.6%	0.8%	1.1%	0.9%
0.2	1	0.4%	0.5%	0.7%	1.0%
0.2	1.25	0.8%	1.0%	1.4%	1.4%
0.2	1.5	1.7%	1.7%	2.3%	2.0%
0.3	1	0.9%	1.0%	1.7%	2.3%
0.3	1.25	1.3%	1.7%	2.5%	2.7%
0.3	1.5	2.0%	2.7%	3.6%	3.6%

3 Implementation at KI

In conclusion, the simulations above show that a good correction (yielding calibration accuracies of 5% or better) may be expected by: (i) interleaving the single arm flux measurements with the fringe measurements, and (ii) averaging the individual fluxes over at least 25 sec. This measurement scheme has been implemented in the KI real time control system, which performs V^2 measurements by **repeating 5 times** the following sequence:

1. measure fringes for 20 sec
2. measure Keck-1 flux for 5 sec
3. measure Keck-2 flux for 5 sec

Resulting in a total of 120 secs of fringe data and 25 secs of single arm flux data (the sequence ends with DARK and FOREGROUND measurements, of no consequence to this discussion, see [R. L. Akeson 2001]). In practice then, the 5 segments of 5 sec single arm flux data are averaged to form a 25 sec average for each arm, a single ratio is formed as $r = [F_1]/[F_2]$, and a single correction factor $RC = (1+r)^2/(4r)$ is applied to all the fringe data acquired in the above sequence [1].

4 Sky tests

We present two sky tests in support of the above scheme. First, we used a test star to demonstrate the basic behaviour of the ratio correction. The experiment summarized in Figure 1. Starting with well balanced arms, we obtained fringe data and ratio calibrations according to the adopted sequence described above, and

[1]The value of this ratio correction factor is one of the L1 data products available to the user, both for the white light channel (SUM data) and the spectral channels (SPEC data).

then intentionally mis-matched the single arm fluxes, repeating a standard measurement sequence for each "mis-matched flux setting". As can be seen in the figure, although the uncorrected visibilities vary as the fluxes are mismatched (blue diamond symbols), the corrected visibilities all yield approximately the same value (red circle symbols).

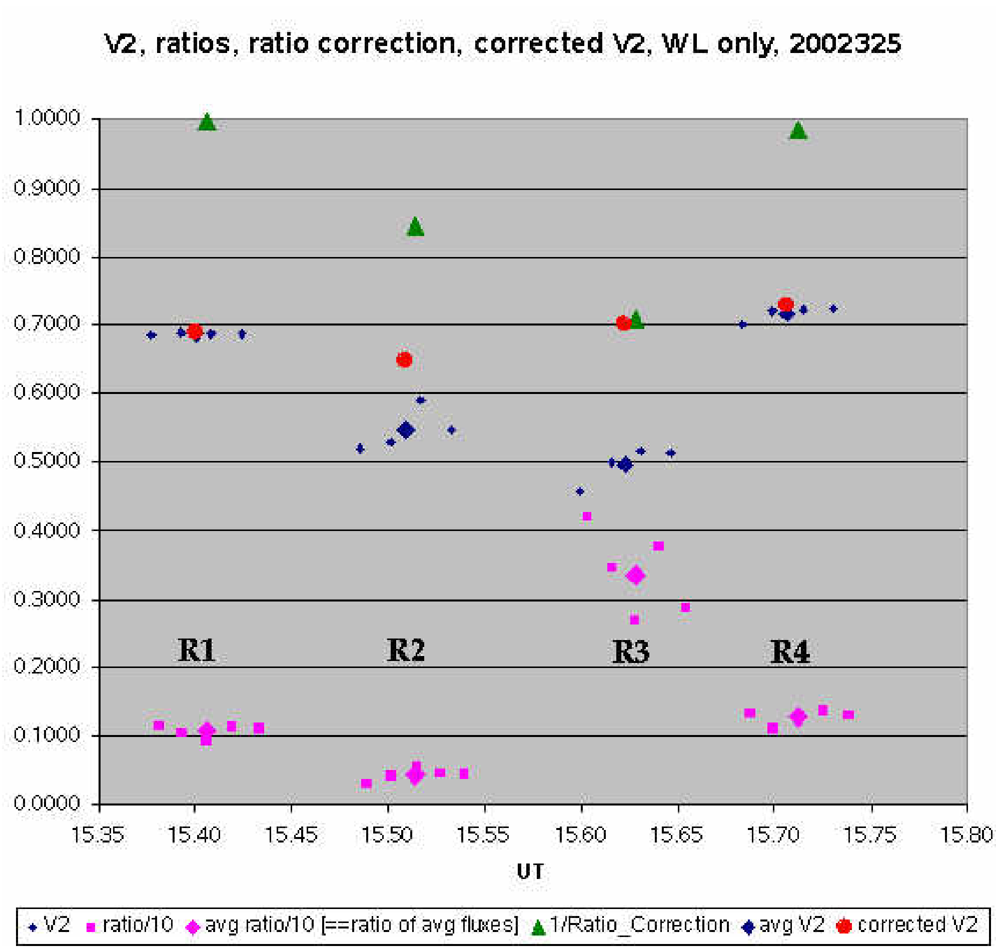

Figure 1: Test of our scheme for measuring and applying a ratio correction. During observations of a test star the single arm fluxes we deliberately adjusted to provide the ratio values indicated by the green triangles. For each setting a full sequence of fringe and single arm fluxes were recorded, according to the scheme described in the text. The resulting V^2 are the blue diamonds (the larger symbols represent averages), and it can be seen that for the 2 mismatched cases they are significantly lower ($V^2 \sim 0.55$ and 0.5) than for the cases where the flux ratios are close to unity ($V^2 \sim 0.7$). For each setting, the pink squares represent the derived ratio correction, divided by 10. so that it can be plotted on the same scale. Finally, the corrected V^2 are the red circles, and they approximately recover the matched-flux system visibility value ($V^2 \sim 0.7$).

We have also tested the ratio calibration against a full comparison of KI data with a model prediction, for observations of a binary star of known orbit and hence of known V^2 response. This observation is part of the test suite described in [R. Millan-Gabet 2004] [2]. We have applied the full KI V^2 standard data reduction, and we have performed the data calibration with and without the ratio correction described above [3]. As can be seen in Figure 2, although the values of the ratio correction factor are generally low (near 1.0), the

[2]In particular we note that for these observations the V, J and K magnitudes were strongly attenuated in order to test the data accuracy in a relatively faint regime.

[3]as described in [A. Boden 2002], use of the correction in the wb/nbCalib programs can be controlled with the command line argument –ratioCorrection.

data set contains one observation (near UT 9.0) for which the flux mismatch is high (between 1.6 and 1.8, depending on the pixel), providing a good test of the ratio correction scheme. The results are summarized in Figure 3 and Figure 4: if the ratio correction is not applied, the calibrated data strongly deviates from the correct answer. In all our analyses of KI V^2 data, this result is maintained: to the extent that it is significant, the ratio correction always improves the calibration, and when the flux mismatches are not significant, it has no detrimental effects.

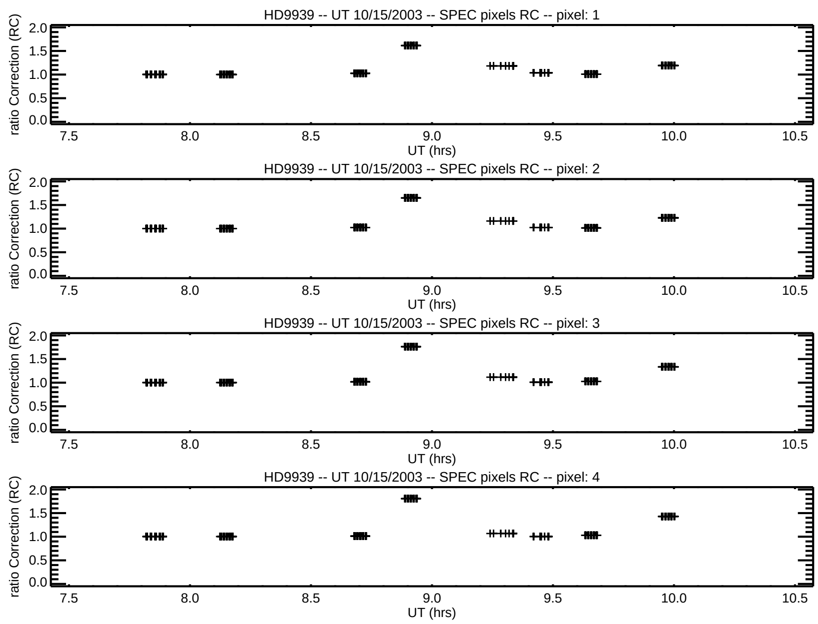

Figure 2: Sky data showing the computed values of the ratio correction (RC), according to the recipe described in the text. The four panels correspond to each of the four spectrometer pixels in the KI fringe detector. As can be seen, the values of RC are generally close to 1.0, indicating a balanced fluxes between the two interferometer arms. However, for the observation near UT = 9.0, the fluctuating fluxes result in highly unbalanced fluxes, and provides a good test of our method for correcting the measured V^2 for this systematic effect, as shown in Figure 3 and Figure 4.

5 Conclusions

We have devised a method for applying a V^2 correction for single-arm flux mismatches at KI, and implemented a fringe measurement scheme that provides the required observables. The method has been tested on the sky with good results. We therefore recommend that the ratio correction always be used when analysing KI V^2 data.

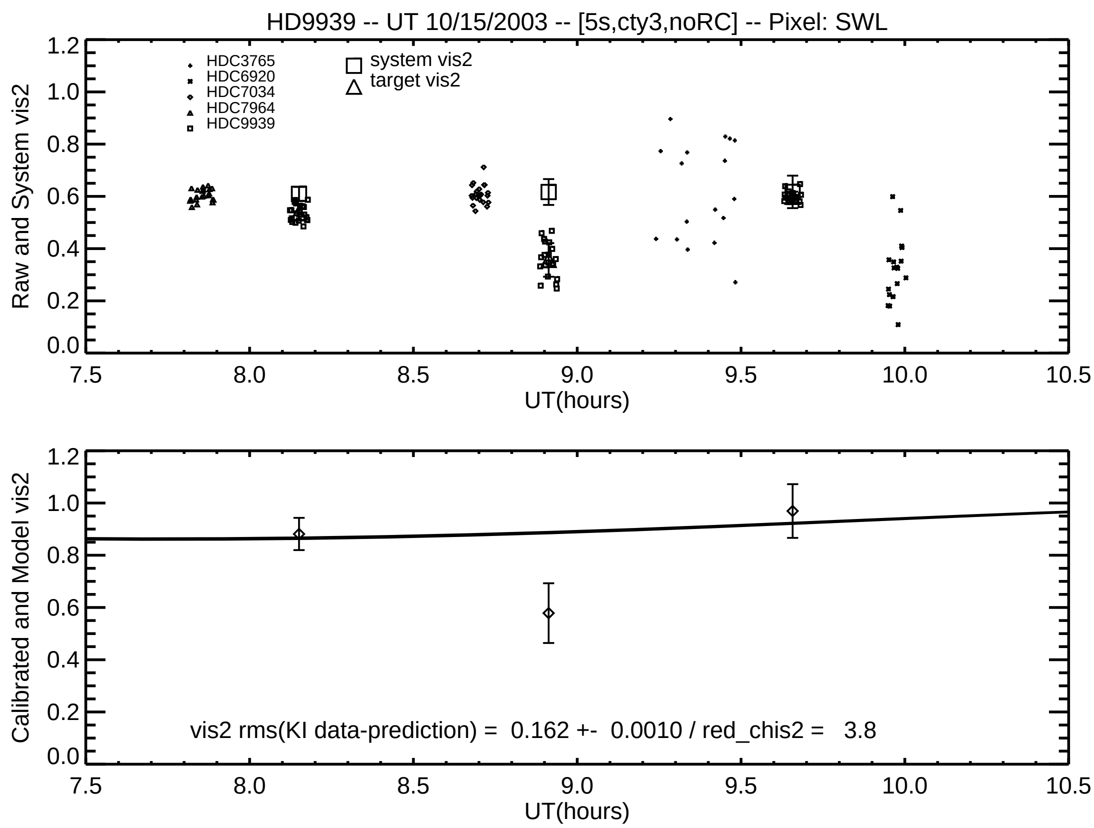

Figure 3: Sky data showing the effect of non-corrected flux mismatches. These data correspond to the synthetic white light (SWL) pixel, formed from the 4 spectrometer pixels across the K-band. The top plot shows raw visibilities (small symbols) (from a SUM file, ratio correction not applied), as well as the target averages (big triangles) and system visibility estimates (big squares) produced by wbCalib. As can be seen, the measurement near UT = 9.0 has low V^2 compared to the other scans in the observation, and this is due to relatively large flux mismatches for the spectral channels (see Figure 2). As shown in the bottom plot, when the ratio correction is not applied at the calibration step (wbCalib) the calibrated V^2 are strongly under-estimated compared to the model prediction (solid lines).

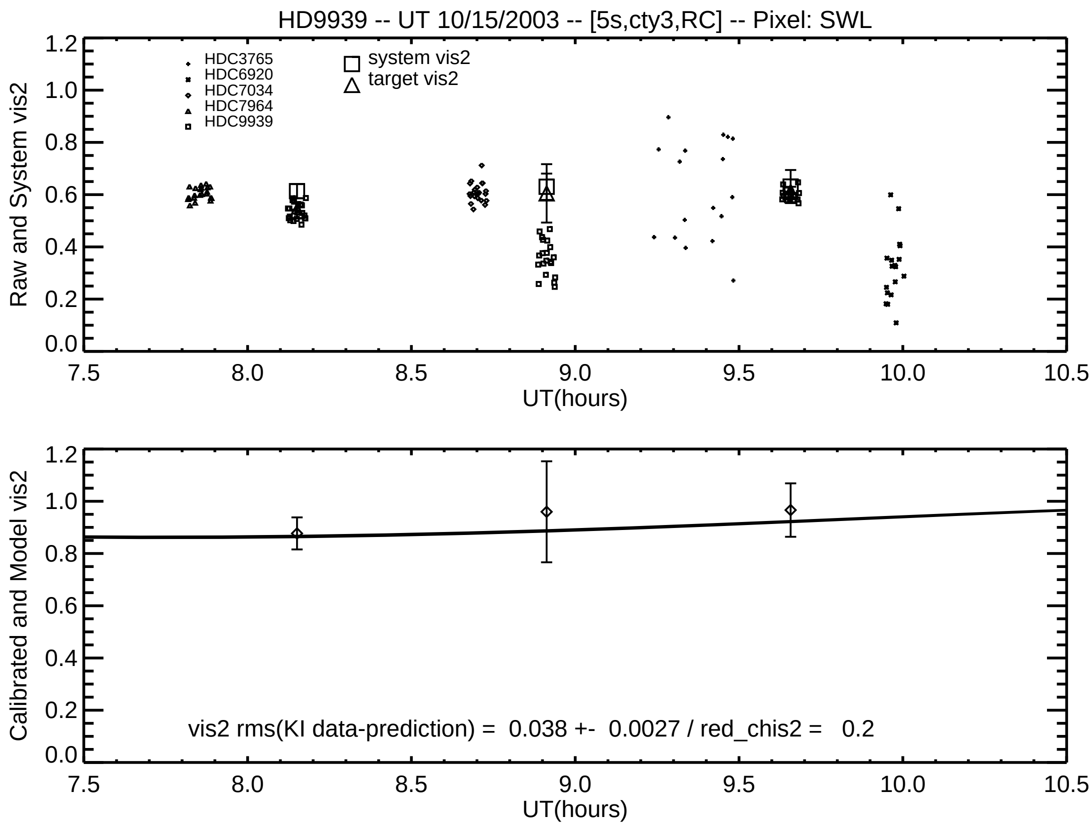

Figure 4: Same as Figure 3, but this time the ratio correction option has been appplied in wbCalib. The SUM data output (small symbols in top plot) are still shown without the ratio correction applied, but the ratio correction option has been used in wbCalib. Consequently, the average produced by wbCalib (big triangles in top plot) for the target scan near UT = 9.0 is higher than in Figure 3, and the calibrated V^2 (bottom plot) agrees better with the model prediction. Note that the other data points are essentially unchanged compared to Figure 3, as expected since they correspond, by chance, to essentially matched fluxes ($r \sim 1.0$).

References

[R. L. Akeson 2001] R. L. Akeson, 2001, "Users Guide for Kvis". [4]

[A. Boden 2002] A. Boden, 2002, "Users Guide for wbCalib". [5]

[Coude du Foresto et al. 1997] V. Coude du Foresto et al. 1997, "Deriving object visibilities from interferograms obtained with a fiber stellar interferometer", A&A, 121, 379

[R. Millan-Gabet 2004] R. Millan-Gabet, R. Akeson and A. F. Boden, 2004, "KI V^2 Recommended Analysis Parameters (Kvis, wb/nbCalib)". [6]

[Shaklan 1992] S. B. Shaklan, M. M. Colavita & M. Shao, 1992, "Visibility calibration using single-mode fibers in a long-baseline interferometer", ESO Conf. and Workshop Proc. 39, High Resolution Imaging by Interferometry II, ed. F. Merkle, 1271

[4] available at: http://msc.caltech.edu/software/Kvis/usersGuide/usersGuide.html
[5] available at: http://msc.caltech.edu/software/wbCalib/index.html
[6] available at: http://http://msc.caltech.edu/KISupport/dataMemos/kvis_params.pdf

Appendix: Detailed simulation results

	rms	ratio	theory	cont		cont w/ ideal ratio		cont w/ deferred ratio		interleaved		interleaved w/ ratio		block average	
	0.1	1	100.0%	-0.01%	0.1%	0.00%	0.1%	0.01%	0.1%	-0.01%	0.1%	0.01%	0.1%	-0.02%	0.1%
white	0.1	1.25	98.8%	-0.01%	0.2%	0.00%	0.1%	0.02%	0.4%	-0.01%	0.2%	0.01%	0.4%	-0.02%	0.2%
	0.1	1.5	96.0%	-0.01%	0.3%	0.00%	0.1%	0.02%	0.6%	-0.01%	0.3%	0.01%	0.6%	-0.02%	0.3%
	0.2	1	100.0%	-0.03%	0.4%	-0.01%	0.4%	0.05%	0.4%	-0.02%	0.4%	0.05%	0.4%	-0.09%	0.4%
	0.2	1.25	98.8%	-0.03%	0.5%	-0.01%	0.4%	0.06%	0.8%	-0.02%	0.5%	0.05%	0.8%	-0.09%	0.5%
	0.2	1.5	96.0%	-0.02%	0.6%	-0.01%	0.4%	0.07%	1.3%	-0.02%	0.6%	0.05%	1.3%	-0.08%	0.6%
	0.3	1	100.0%	-0.06%	0.8%	-0.02%	0.8%	0.12%	0.9%	-0.06%	0.8%	0.12%	0.9%	-0.20%	0.8%
	0.3	1.25	98.8%	-0.06%	0.9%	-0.02%	0.8%	0.13%	1.4%	-0.05%	0.9%	0.12%	1.3%	-0.19%	0.9%
	0.3	1.5	96.0%	-0.05%	1.1%	-0.02%	0.8%	0.15%	2.1%	-0.05%	1.1%	0.12%	2.0%	-0.17%	1.1%
1/f to 0.1 Hz	0.1	1	100.0%	-0.01%	0.1%	0.00%	0.1%	0.03%	0.1%	-0.01%	0.1%	0.03%	0.1%	-0.04%	0.1%
	0.1	1.25	98.8%	-0.01%	0.2%	0.00%	0.1%	0.03%	0.5%	-0.01%	0.2%	0.03%	0.5%	-0.04%	0.2%
	0.1	1.5	96.0%	-0.01%	0.4%	0.00%	0.1%	0.04%	0.9%	-0.01%	0.3%	0.03%	0.8%	-0.03%	0.3%
	0.2	1	100.0%	-0.04%	0.4%	-0.01%	0.4%	0.11%	0.5%	-0.04%	0.4%	0.10%	0.5%	-0.16%	0.4%
	0.2	1.25	98.8%	-0.04%	0.6%	-0.01%	0.4%	0.13%	1.1%	-0.03%	0.6%	0.10%	1.0%	-0.15%	0.5%
	0.2	1.5	96.0%	-0.03%	0.8%	-0.01%	0.4%	0.14%	1.8%	-0.03%	0.8%	0.11%	1.7%	-0.13%	0.8%
	0.3	1	100.0%	-0.09%	1.0%	-0.02%	0.9%	0.26%	1.1%	-0.08%	0.9%	0.24%	1.0%	-0.36%	0.9%
	0.3	1.25	98.8%	-0.08%	1.1%	-0.02%	0.9%	0.28%	1.8%	-0.08%	1.1%	0.24%	1.7%	-0.34%	1.1%
	0.3	1.5	96.0%	-0.08%	1.4%	-0.02%	0.9%	0.31%	2.8%	-0.07%	1.3%	0.25%	2.7%	-0.30%	1.3%
1/f to 0.01 Hz	0.1	1	100.0%	-0.04%	0.2%	0.00%	0.2%	0.12%	0.3%	-0.03%	0.2%	0.03%	0.2%	-0.16%	0.1%
	0.1	1.25	98.8%	-0.04%	0.5%	0.00%	0.2%	0.13%	1.0%	-0.03%	0.4%	0.03%	0.6%	-0.15%	0.4%
	0.1	1.5	96.0%	-0.03%	0.8%	0.00%	0.2%	0.15%	1.8%	-0.03%	0.7%	0.04%	1.1%	-0.13%	0.7%
	0.2	1	100.0%	-0.16%	0.7%	0.00%	0.7%	0.49%	1.2%	-0.12%	0.7%	0.12%	0.7%	-0.64%	0.6%
	0.2	1.25	98.8%	-0.15%	1.1%	0.00%	0.7%	0.53%	2.3%	-0.12%	1.0%	0.13%	1.4%	-0.61%	0.9%
	0.2	1.5	96.0%	-0.13%	1.7%	0.00%	0.7%	0.58%	3.8%	-0.10%	1.5%	0.14%	2.3%	-0.54%	1.4%
	0.3	1	100.0%	-0.35%	1.6%	0.01%	1.5%	1.17%	2.9%	-0.27%	1.5%	0.28%	1.7%	-1.46%	1.3%
	0.3	1.25	98.8%	-0.33%	2.1%	0.01%	1.5%	1.25%	4.3%	-0.26%	1.9%	0.29%	2.5%	-1.40%	1.7%
	0.3	1.5	96.0%	-0.29%	2.7%	0.01%	1.5%	1.35%	6.4%	-0.23%	2.5%	0.32%	3.6%	-1.25%	2.3%
1/f to 0.001 Hz	0.1	1	100.0%	-0.15%	0.3%	0.00%	0.2%	0.12%	0.4%	-0.11%	0.2%	0.02%	0.2%	-0.27%	0.2%
	0.1	1.25	98.8%	-0.14%	0.9%	0.00%	0.2%	0.14%	1.2%	-0.11%	0.8%	0.02%	0.6%	-0.25%	0.8%
	0.1	1.5	96.0%	-0.13%	1.5%	0.00%	0.2%	0.16%	2.1%	-0.10%	1.3%	0.02%	0.9%	-0.22%	1.3%
	0.2	1	100.0%	-0.61%	1.1%	0.01%	0.6%	0.51%	1.9%	-0.45%	1.0%	0.08%	1.0%	-1.08%	0.9%
	0.2	1.25	98.8%	-0.58%	2.0%	0.01%	0.6%	0.56%	3.1%	-0.43%	1.7%	0.08%	1.4%	-1.03%	1.7%
	0.2	1.5	96.0%	-0.51%	3.1%	0.01%	0.6%	0.63%	4.7%	-0.38%	2.7%	0.09%	2.0%	-0.92%	2.6%
	0.3	1	100.0%	-1.39%	2.5%	0.02%	1.5%	1.37%	5.3%	-1.04%	2.3%	0.19%	2.3%	-2.54%	2.2%
	0.3	1.25	98.8%	-1.33%	3.5%	0.02%	1.5%	1.47%	6.5%	-0.99%	3.1%	0.21%	2.7%	-2.42%	2.9%
	0.3	1.5	96.0%	-1.18%	4.9%	0.02%	1.5%	1.61%	8.6%	-0.88%	4.3%	0.23%	3.6%	-2.17%	4.1%

Table 3. Detailed simulation results. Columns are: (1) input fractional rms of amplitude fluctuations, (2) intensity ratio, (3) theoretical visibility, (4) → (15) V^2 bias (mean difference w.r.t. theroretical or unity value) and rms; for the 6 cases (a) → (f) described in the text. For cases (a,d,f) the bias is expressed w.r.t. the theoretical value; for cases (b,c,e) the bias is expressed w.r.t. unity.