KI V^2 Recommended Analysis Parameters (Kvis, wb/nbCalib)

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Abstract

We have run the whole suite of MSC analysis software for Keck Interferometer (KI) V^2 data on a series of known-orbit binaries, in order to assess the data quality and establish a recommended analysis method. The Kvis reduction parameters selected (block time = 5 secs, calibration type 3) are used in the pipeline processing of the L1 data. Final accuracies are typically of order 0.03 for both the wide-band and narrow-band channels when the recommended reduction and calibration parameters are used (including the flux bias correction).

1 Introduction

During the shared-risk period of KI operations April 2002 - April 2004), a large amount of science data has been collected while the instrument continued to be developed and improved. The aims of this memo are to (a) describe the analysis method that the MSC has adopted to produce internally calibrated, level-1, data delivered to KI users, (b) describe the recommended method that KI users should use for external calibration of the data using the MSC tools wbCalib and nbCalib, and (c) asses the resulting data quality and accuracy.

To this end, the project has observed a number of binaries with well known orbits previously established by the Palomar Testbed Interferometer (PTI). These observations have been reduced experimenting with various options of the Kvis and Calib programs, and the results compared with the model prediction, as described below, in order to settle on a best method.

2 Calibration Binaries Observed by KI

In Table 1 we summarize the complete list of known binaries observed by KI. During this KI shared-risk period, the data are often affected by one or more instrumental problem, and the table contains comments to this effect in the last column. A brief description of each instrumental problem referred to in the table is as follows:

0: Internal calibrations done manually, not reliable data

1: Spectrometer side of fringe detector not aligned

2: Questionable spectrometer alignment

3: Bin-stroke (clock) problem, see [R. L. Akeson 2003]

4: Partially corrected bin-stroke (clock) problem, see [R. L. Akeson 2003]

5: Bad FOREGROUND measurement (accidentally on-fringe)

6: FATCAT saturation or non-linearity

In an effort to base our conclusions on more than just one observation, we have selected the three observations indicated in boldface in Table 1 for detailed analysis; for being representative, yet with sufficient data quality (number of observations, instrument status and seeing conditions) to enable a realistic comparison with the model predictions. Details about the photometry in each sub-system for the three observations selected are given in Table 2.

Table 1: Calibration binaries observed by KI. The observations selected for detailed analysis presented in this memo are indicated in **boldface**. See the text for a description of the data comment keys. All these stars are PTI targets, and too bright for KI. For most observations, a non-quantified amount of attenuation was introduced to bring the effective K-magnitude below the FATCAT saturation limit (K < 5.5 for the 200 Hz rate), using an ND filter, or de-tuning the flux coupling, or using an aperture stop, depending on the case. For the HD9939 observation in Oct 03, known attenuations were introduced in all sub-systems (4.1 Kmags for FATCAT, 2.5 Jmags for KAT and 4.5 Vmags for AO) in order to test data accuracy in the faint regime. See Table 2 for more details on the observations selected for detailed analysis.

Run	Date (yyyyddd)	System	FATCAT rate (Hz)	Band	K or H mag (un-attenuated)	Data Comments
Apr02	2002117	HD78418	500	K	4.4	0,1,3
Oct02	2002295	HD27901	500	K	5.0	1,3
Jan03	2003018	HD78418	500	K	4.4	2,3
Feb03	2003044	HD102713	500	K	4.5	2,3 (1 cloudy point)
Apr03	2003106	HD144208	500	K	3.9	2,3 (noisy data)
May03	2003140	HD144208	200	K	3.9	2,3,5 (1 scan only)
May03	2003141	HD144208	200	K	3.9	2,3,5
Oct03	2003288	HD9939	200	K	4.9	4,5 (using NDs for faint test)
Oct03	2003289	HD9939	200	K	4.9	4,5 (using NDs for faint test)
Jan04	2003007	HD120064	200	H	4.7	4,6

3 Kvis Parameters

Kvis is the software used by the MSC to reduce and internally calibrate the raw (level-0) interferometer telemetry into level-1 data products provided to KI users. See the Kvis manual [R. L. Akeson 2001] for a detailed description of its principles and options. A description of the method used for V^2 estimation at PTI is also useful in this context, as it bears great resemblance to the KI methods, and can be found in [M. Colavita 1999]. For further background, we also refer the reader to the MSC web documentation on data overview and access (`http://msc.caltech.edu/KISupport/dataOverview.html`) and on data product descriptions (`http://msc.caltech.edu/KISupport/v2/KIV2dataProducts.html`). In this memo, we address the two Kvis input parameters which potentially affect the final data quality:

- Block Time: is the time in seconds by which fringe detector frames are averaged into blocks (recall that one block average corresponds to one line in the L1 SUM and SPEC files). We experiment with values of 25 and 5 secs (the former value is that employed at the PTI, which uses a very similar fringe detection engine; the later value was chosen to produce a relatively large – 20 – number of blocks in a scan).
- Calibration Type: is the method used to estimate the V^2 biases, please refer to [R. L. Akeson 2001] for details:
  - CalType = 3: uses BACKGROUND measurements (a laboratory shutter, not dark sky) to estimate the bias terms Bx, By, BN, as well as the read-noise bias; and a fixed laboratory measured value of the camera gain (k counts/electron) to estimate the photon noise bias term.

Table 2: Test binaries (boldface) and calibrators. Original and attenuated magnitudes for each KI sub-system (R: AO, J: angle tracker KAT, K: fringe tracker FATCAT), for the three observations selected for detailed analysis. Attenuated magnitudes are given in [brackets]. The key to the three attenuation methods is as follows: (1) FATCAT attenuation only by de-tuning the flux coupling, by a factor of ~ 0.25; (2) FATCAT attenuation only by introducing a ND1.65 filter; and (3) attenuation in all sub-systems: AO by 4.5 mags, KAT by 2.5 mags (ND1) and FATCAT by 4.1 mags (ND1.65).

Name	V	Spectral Type	R	J	K	Attenuation method
HD78418	6.0	G5V	5.5	4.7	4.4 [5.9]	(1)
HD73192	6.0	K2III	5.1	4.4	3.6 [5.1]	(1)
HD79452	6.0	G5III	5.3	4.4	3.9 [5.4]	(1)
HD144208	5.8	A2V	5.7	4.5	3.9 [8.0]	(2)
HD145457	6.6	K0III	7.3	5.0	4.1 [8.2]	(2)
HD144579	6.7	G8V	7.2	5.2	4.7 [8.8]	(2)
HD145675	6.7	K0V	7.3	5.2	4.7 [8.8]	(2)
HD9939	7.0	K0IV	6.4 [10.9]	5.4 [7.9]	4.9 [9.0]	(3)
HD7964	4.7	A3V	4.6 [9.1]	4.8 [7.3]	4.5 [8.6]	(3)
HD7034	5.2	F0V	4.9 [9.4]	4.8 [7.3]	4.4 [8.5]	(3)
HD3765	7.4	K2V	6.7 [11.2]	5.7 [8.2]	5.2 [9.3]	(3)
HD6920	5.7	F8V	5.2 [9.7]	4.9 [7.4]	4.5 [8.6]	(3)

– CalType = 5: uses FOREGROUND measurements (on-star, but off-fringe) to estimate Bx, By and the sum of the read and photon noise biases. BN is estimated from the closest BACKGROUND measurement.

3.1 Special Case: CalType = 5 for bad FOREGROUND data

It can be seen in Table 1 that of the 3 datasets selected, 2 are affected by the problem that the FOREGROUND data was erroneously taken on-fringe. To circumvent this problem, a modification was made to the Kvis program so that it uses the single-arm fluxes (RATIO data) to estimate the photon and read noise biases. This approach however fails in the faint-star regime (e.g. the observation of HD9939 in Oct. 03) by producing an erroneous flux-dependent correction, resulting from the fact that when using two single-arm measurements to reconstruct the two-arm flux term the read-noise term is over-estimated.

4 wb/nbCalib Parameters

wbCalib and nbCalib [A. Boden 2002] are the data reduction packages for KI which externally calibrate level-1 data into level-2 data products ready for astrophysical interpretation. The Calib programs have many options, in this memo we address the two that potentially have the highest impact on the final data quality:

- Ratio Correction: when the two arms of the interferometer do not contribute the same amount of flux, the system visibility is degraded. Unbalanced interferometer arms can be expected from static instrumental mis-alignments, as well as from fluctuations in the atmospheric seeing. If the ratio of fluxes contributed by each telescope is R_{12}, then the measured V^2 at the same instant can be corrected from this effect using the correction factor $S_{12} = (1 + R_{12})^2/4R_{12}$. KI does not measure the ratios and V^2 simultaneously, nevertheless a good correction can be applied by forming an average measurement which represents well the arm unbalance during the fringe integration. KI achieves this by interleaving single-arm flux measurements (lasting 5 seconds) 5 times during a 100 second integration on-fringe. An independent experiment was conducted to demonstrate the validity of this approach: by observing an unresolved test star and deliberately un-balancing the interferometer arms, it has been shown that the balanced-arms system visibilities are correctly recovered. Therefore, we recommend to always enable this option in the Calib programs, and we have done so in all the data presented in this memo.

- Jitter Correction: optical path fluctuations during the fringe acquisition cause “blurring”, reducing the measured visibilities. As for the ratio correction, it is possible to calibrate this effect, provided one understands the statistics of the OPD fluctuations. We have investigated this calibration and our conclusions are documented in a separate memo [R. Millan-Gabet 2004]. We find that we can not propose a correction algorithm with confidence and recommend that this option not be used in the Calib programs. The data presented in this memo does not make use of a jitter correction factor.

  In addition, the ScanThreshold parameter (the time window used to define the maximum scan duration) has been adjusted appropriately for each data set to result in one scan per target visit.

- Flux Bias Correction: In 2007, the KI team quantified a dependence of the measured visibility amplitude on the flux level. This dependence is well characterized as proportional to the log of the flux but no definitive cause has been identified. The investigation of the flux bias and the correction formula are detailed in the Kvis Data memo ”Analysis of the flux bias in KI visibility data” [R.L. Akeson 2007] available from the KI Support web site. A correction factor can be applied with the -fluxBias option in wbCalib/nbCalib (versions 1.4.4 or higher) and given the results of the tests detailed in the memo and summarized in Table 5.1, we recommend that all KI data be calibrated with this option.

5 Analysis

Given the description above, we are left with 2 parameters to try for Kvis; and no free parameters for Calib (ratio correction always used, jitter correction never used).

For each binary observation then, we provide the following metrics for each of the science camera channels (WL = white light pixel, SWL = synthetic white light, SPEC0–3 = each of the 3 spectrometer pixels, identified by wavelength):

- fit RMS: is the weighted RMS of the fully calibrated data with respect to the model prediction, with error bars given by the 1-sigma errors in the model prediction. This quantity indicates which method provides best final accuracy.

- reduced χ^2: useful in order to assess the validity of the V^2 error bars produced by the Calib programs, which contain no systematic terms other than that given by the uncertainty in the calibrator stars diameters.

5.1 Updated analysis for flux bias correction

As detailed in the flux bias memo, the three binaries presented in Appendix A, B, and C as well as two addtional binary observation sets not available for the original analysis were analyzed for the effect of the flux bias correction. Those results, which also use all the other recommend settings, are summarized in Table 5.1.

6 Results and Conclusions

The detailed results for the pre-flux bias analysis are given in Appendices A, B and C. In those appendices we also illustrate the final data quality for the best method in a series of plots. For each observation, there are 5 pairs of plots, one for each of the WL (or SWL) and SPEC pixels. For each pixel, the top plot shows the raw V^2 for the calibrators and target star, along with the scan-averaged target and system V^2 produced by wb/nbCalib; while the bottom plot shows the calibrated target V^2, along with lines representing the model prediction and its uncertainty.

From the results for the most recent binary analysis (with the flux correction) our conclusions are as follows:

1. Block Time: no significant difference results in the final accuracies from using 5 or 25 sec block averages. However, we favor the use of a 5 sec block averaging time for the simple reason that these Kvis products do not come with an associated error estimate, and therefore using the shorter averaging time has the

Night	Channel (μm)	Mean Dev.	Abs. Dev.	σ	χ_r^2	Mean Dev.	Abs. Dev.	σ	χ_r^2
		Without correction				With correction			
2003018	WL	0.022	0.022	0.016	2.56	0.018	0.018	0.016	1.71
	2.0	0.042	0.043	0.026	3.65	0.036	0.038	0.027	2.79
	2.1	0.044	0.044	0.021	6.02	0.038	0.038	0.022	4.43
	2.2	0.047	0.047	0.019	8.67	0.042	0.042	0.019	6.73
	2.3	0.049	0.049	0.018	10.17	0.045	0.045	0.019	8.33
2003141	WL	-0.020	0.020	0.025	1.15	-0.006	0.014	0.024	0.49
	2.0	-0.043	0.043	0.032	2.27	-0.015	0.024	0.030	0.76
	2.1	-0.046	0.046	0.027	3.68	-0.017	0.020	0.025	0.90
	2.2	-0.046	0.046	0.024	4.50	-0.016	0.016	0.022	0.97
	2.3	-0.042	0.042	0.023	3.94	-0.014	0.014	0.022	0.72
2003288	WL	0.007	0.075	0.101	0.59	-0.002	0.079	0.103	0.62
	2.0	-0.027	0.027	0.291	0.02	-0.038	0.038	0.295	0.02
	2.1	-0.069	0.069	0.115	0.45	-0.084	0.084	0.117	0.58
	2.2	-0.052	0.055	0.102	0.28	-0.075	0.075	0.104	0.44
	2.3	-0.047	0.056	0.098	0.28	-0.070	0.070	0.101	0.43
2006137	WL	0.009	0.033	0.070	0.37	-0.010	0.033	0.071	0.26
	2.032	0.072	0.072	0.065	2.62	0.020	0.036	0.068	0.48
	2.098	0.051	0.051	0.062	1.51	-0.008	0.021	0.066	0.10
	2.186	0.046	0.046	0.058	1.34	-0.015	0.018	0.062	0.08
	2.282	0.052	0.052	0.055	1.63	-0.008	0.013	0.058	0.05
	2.360	0.060	0.060	0.052	2.13	0.004	0.011	0.054	0.10
2006343	WL	0.003	0.003	0.046	0.04	-0.005	0.008	0.046	0.04
	1.995	0.069	0.069	0.071	1.25	0.059	0.059	0.073	0.95
	2.059	0.051	0.051	0.057	1.12	0.038	0.039	0.059	0.70
	2.106	0.052	0.052	0.054	1.21	0.037	0.037	0.056	0.69
	2.151	0.053	0.053	0.052	1.38	0.040	0.040	0.053	0.82
	2.201	0.047	0.047	0.051	1.05	0.032	0.032	0.053	0.55
	2.260	0.047	0.047	0.052	1.09	0.032	0.032	0.053	0.60
	2.307	0.046	0.046	0.052	1.00	0.031	0.031	0.053	0.56
	2.358	0.049	0.049	0.054	1.05	0.034	0.034	0.055	0.58
	2.400	0.049	0.049	0.056	0.99	0.035	0.035	0.057	0.56
	2.433	0.052	0.052	0.057	1.11	0.037	0.037	0.058	0.67

Table 3: The mean deviation, mean absolute deviation, total uncertainty (σ) and reduced chi-squared (χ_r^2) of the binary observations as compared to the predicted visibility.

advantage that more such averages are available (from a maximum of 4 to a maximum of 20) for empirical error estimation in the calibration step.

2. Calibration Type: For HD9939, CalType 5 fails because it has bad FOREGROUND data and, as discussed above, use of the RATIO data to construct the photon bias fails in the read-noise limited regime. Both HD78418 and HD144208 are in the bright, photon-noise limited regime (and HD78418 does have good FOREGROUND data) and yet in no case does CalType 5 improve the final accuracies. Since CalType 5 potentially provides a better estimate of the photon noise bias, this method is expected to be superior particularly in the bright-regime. This not being the case, we recommend use of the CalType 3, at least until this issue can be further investigated.

3. Both for bright (K $\sim$ 6) and faint (K $\sim$ 9) sources, final accuracies are in the range 3-4% (relative to $V^2 = 1.0$) for the white light channels, and 3-4% for the SPEC channels, particularly for the more recent data. The channel-to-channel relative calibration is 0.02 for the 4 and 5 channel settings and 0.01 for the 10 and 42 channel settings.

4. In general, Calib error bars under-estimate the true total error in the data, indicating that an additional systematic error term must be added. An empirical estimate of the true total error may be obtained from the listed RMS deviations with respect to the model prediction.

References

[R. L. Akeson 2001] R. L. Akeson, 2001, “Users Guide for Kvis”. [1]

[R. L. Akeson 2003] R. L. Akeson, 2003, MSC Data Memo: “Applying clock correction factors in KI data reduction”. [2]

[R.L. Akeson 2007] R.L. Akeson, M. M. Colavita and R. Millan-Gabet, MSC Data Memo: ”Analysis of the flux bias in KI visibility data” [3]

[A. Boden 2002] A. Boden, 2002, “Users Guide for wbCalib”. [4]

[M. Colavita 1999] M. M. Colavita, 1999, PASP, 111, 111

[R. Millan-Gabet 2004] R. Millan-Gabet and M. M. Colavita, 2004, “Applying Jitter Correction to KI $V2$ Data”. [5]

[1] available at: http://msc.caltech.edu/software/Kvis/usersGuide/usersGuide.html
[2] available at: http://msc.caltech.edu/KISupport/dataMemos/Kvis_clock.pdf
[3] available at: http://msc.caltech.edu/KISupport/dataMemos/fluxbias.pdf
[4] available at: http://msc.caltech.edu/software/wbCalib/index.html
[5] available at: http://http://msc.caltech.edu/KISupport/dataMemos/jitter_memo.pdf

A Binary 75 Cnc – Jan 2003. Detailed Results.

```
75Cnc = HD78418                         |
KI data of UT 18 Jan 2003 -- 2003018    |
Calib: ratio_c: YES, jitter_c: NO       |
----------------------------------------|
numbers are:                            |
vis2 fitRMS WL            / red_chis2   |
vis2 fitRMS SWL           / red_chis2   |
vis2 fitRMS SPEC0 (2.3um) / red_chis2   |
vis2 fitRMS SPEC1 (2.2um) / red_chis2   |
vis2 fitRMS SPEC2 (2.1um) / red_chis2   |------------------------------------------------
vis2 fitRMS SPEC3 (2.0um) / red_chis2   |      Kvis CalType
----------------------------------------------------------------------------------------
Kvis BlockTime (sec)                    |      3                        5
----------------------------------------------------------------------------------------
5                                              0.027+-0.003 / 2.5       0.036+-0.003 / 3.8
                                               0.044+-0.003 / 3.9       0.064+-0.003 / 6.0
                                               0.109+-0.004 / 32.6      0.106+-0.004 / 22.0
                                               0.064+-0.003 / 10.3      0.070+-0.003 / 8.7
                                               0.043+-0.003 / 3.5       0.074+-0.003 / 7.8
                                               0.060+-0.003 / 4.5       0.109+-0.003 / 11.3

25                                             0.026+-0.003 / 7.0       0.036+-0.003 / 10.4
                                               0.045+-0.003 / 14.8      0.069+-0.003 / 24.9
                                               0.124+-0.004 / 162.8     0.093+-0.003 / 48.6
                                               0.069+-0.003 / 43.2      0.063+-0.003 / 21.4
                                               0.041+-0.003 / 11.1      0.084+-0.003 / 35.0
                                               0.062+-0.002 / 13.6      0.127+-0.003 / 52.9
----------------------------------------------------------------------------------------
CONCLUSIONS:
(a) SWL and SPEC worse than WL
(b) BT5 and BT25 roughly equivalent
(c) CTY3 better than CTY5
(d) calib error bars are under-estimated
----------------------------------------------------------------------------------------
```

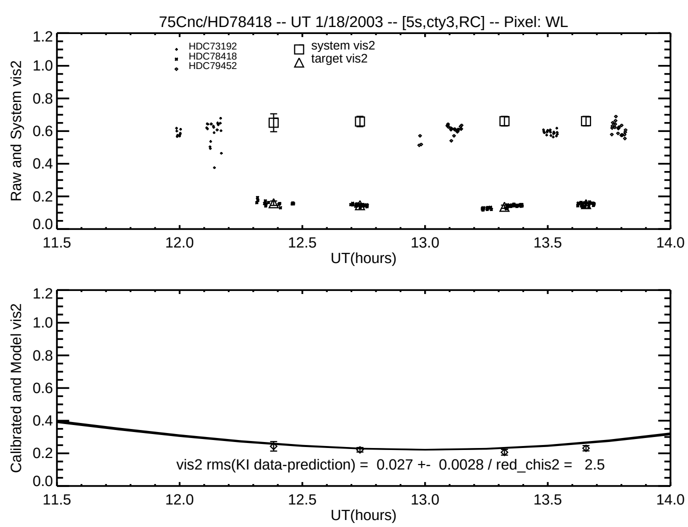


Figure 1: Best-method results for HD78418, for WL pixel.

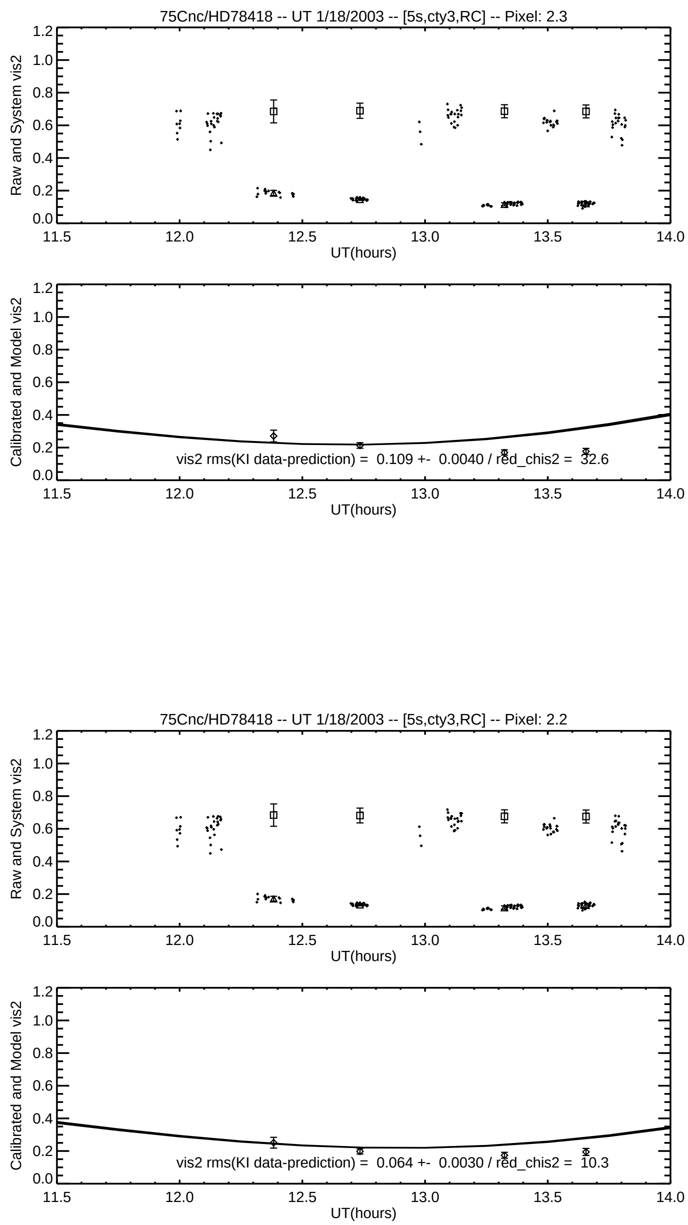


Figure 2: same as previous figure, for SPEC pixels.

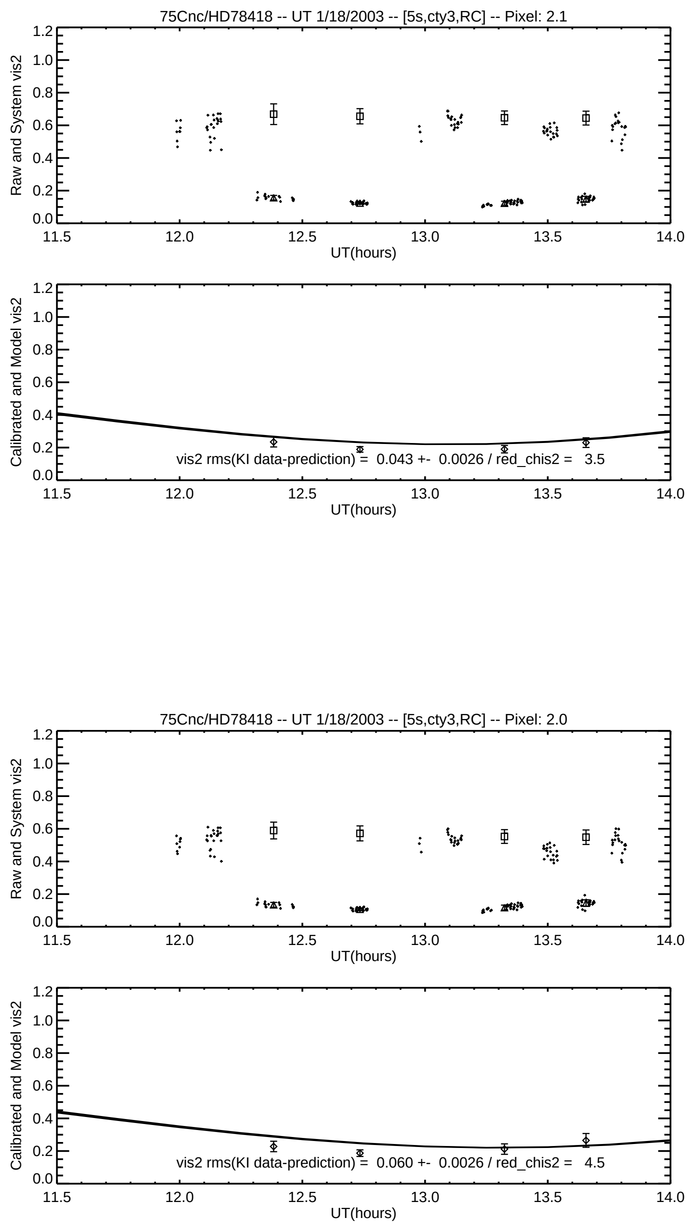


Figure 3: same as previous figure, for SPEC pixels.

B Binary HD144208 – May 2003. Detailed Results.

```
HD144208                                |
KI data of UT 21 May 2003 -- 2003141    |
Calib: ratio_c: YES, jitter_c: NO       |
----------------------------------------|
numbers are:                            |
vis2 fitRMS WL            / red_chis2   |
vis2 fitRMS SWL           / red_chis2   |
vis2 fitRMS SPEC0 (2.3um) / red_chis2   |
vis2 fitRMS SPEC1 (2.2um) / red_chis2   |
vis2 fitRMS SPEC2 (2.1um) / red_chis2   |------------------------------------------------
vis2 fitRMS SPEC3 (2.0um) / red_chis2   |       Kvis CalType
-----------------------------------------------------------------------------------------
Kvis BlockTime (sec)                    |       3                       5
-----------------------------------------------------------------------------------------
5                                               0.026+-0.003 / 1.2      0.025+-0.003 / 1.0
                                                0.051+-0.004 / 4.4      0.053+-0.004 / 4.4
                                                0.020+-0.004 / 0.8      0.020+-0.004 / 0.7
                                                0.043+-0.004 / 3.4      0.043+-0.004 / 3.2
                                                0.059+-0.003 / 5.1      0.057+-0.004 / 4.7
                                                0.075+-0.003 / 5.8      0.084+-0.003 / 6.7

25                                              0.027+-0.003 / 4.3      0.026+-0.003 / 3.9
                                                0.048+-0.004 / 16.4     0.048+-0.004 / 12.8
                                                0.015+-0.004 / 1.5      0.015+-0.004 / 1.1
                                                0.038+-0.004 / 9.4      0.037+-0.004 / 7.0
                                                0.054+-0.004 / 21.1     0.051+-0.004 / 14.9
                                                0.072+-0.003 / 33.4     0.080+-0.003 / 28.2
------------------------------------------------------------------------------------------
CONCLUSIONS:
-----------
(a) SWL and SPEC worse than WL (except SPEC0)
(b) BT5 and BT25 equivalent
(c) CTY3 and CTY5 equivalent, except for last spec pixel
(d) calib error bars are generally under-estimated
------------------------------------------------------------------------------------------
```

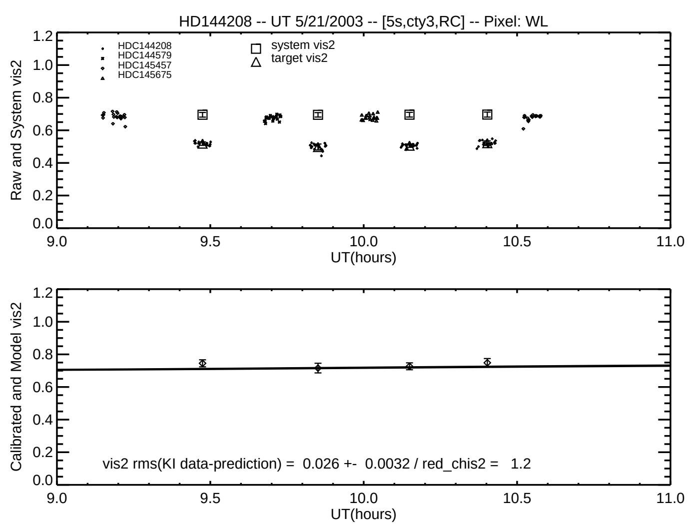


Figure 4: Best-method results for HD144208, for WL pixel.

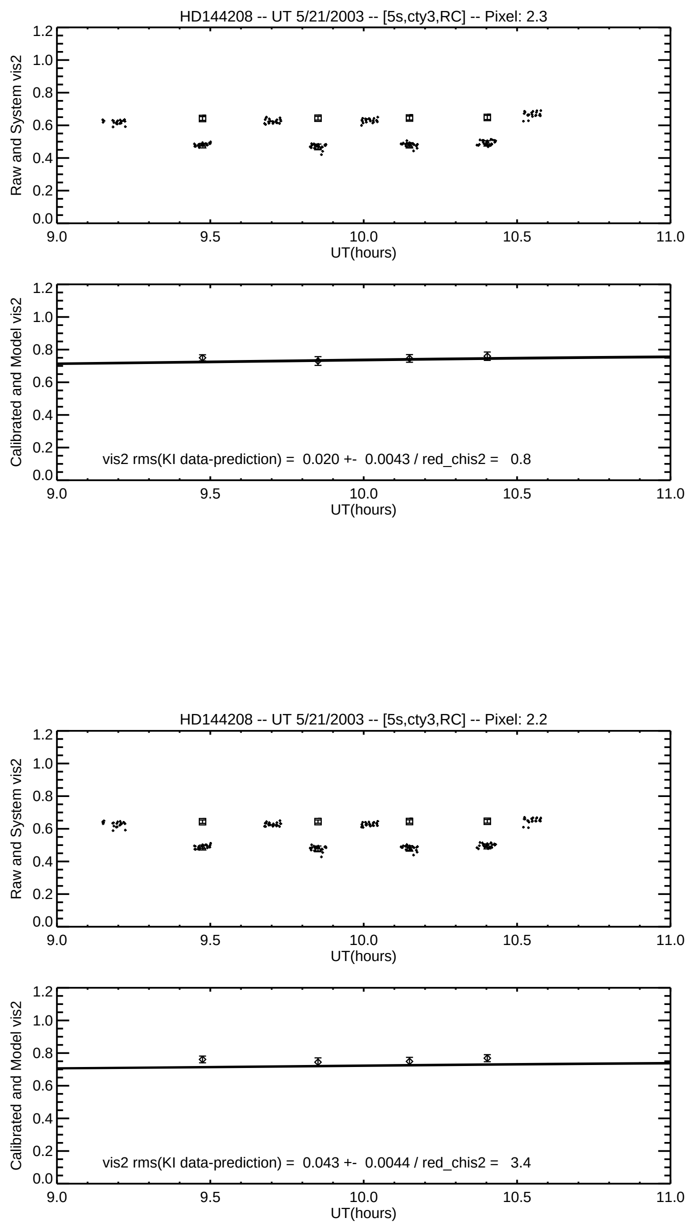
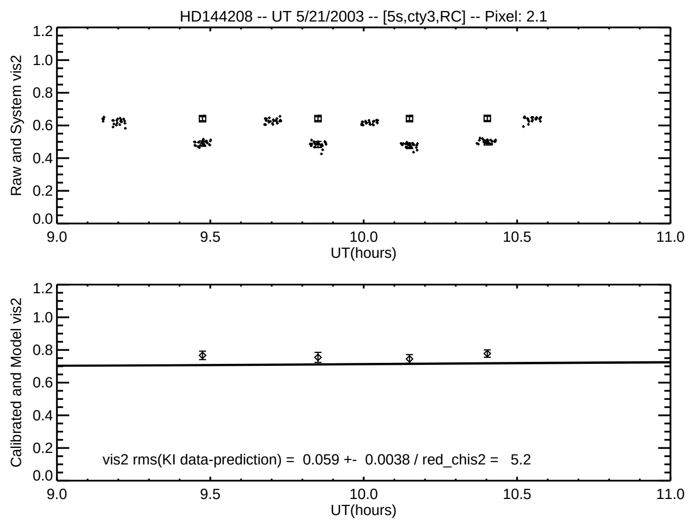


Figure 5: same as previous figure, for SPEC pixels.



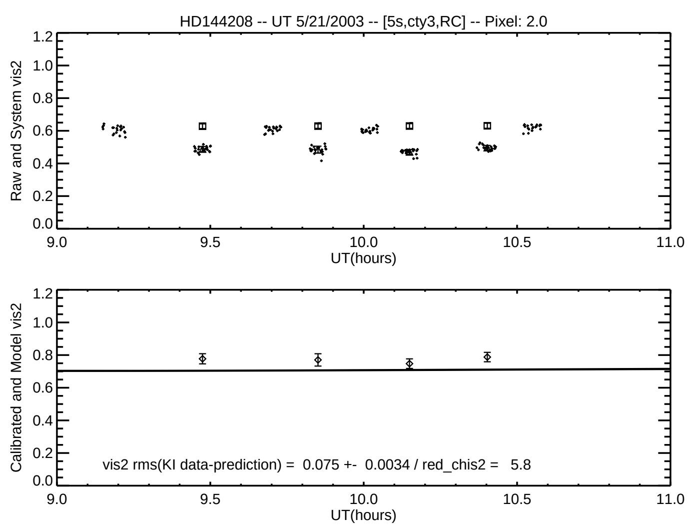


Figure 6: same as previous figure, for SPEC pixels.

C Binary HD9939 – Oct 2003. Detailed Results.

```
HD9939                                  |
KI data of UT 15 Oct 2003 -- 2003288    |
Calib: ratio_c: YES, jitter_c: NO       |
----------------------------------------|
numbers are:                            |
vis2 fitRMS WL            / red_chis2   |
vis2 fitRMS SWL           / red_chis2   |
vis2 fitRMS SPEC0 (2.3um) / red_chis2   |
vis2 fitRMS SPEC1 (2.2um) / red_chis2   |
vis2 fitRMS SPEC2 (2.1um) / red_chis2   |--------------------------------------------------
vis2 fitRMS SPEC3 (2.0um) / red_chis2   |       Kvis CalType
-------------------------------------------------------------------------------------------
Kvis BlockTime (sec)                    |       3                        5
-------------------------------------------------------------------------------------------
5                                               0.097+-0.001 / 1.1       NA
                                                0.038+-0.003 / 0.2       NA
                                                0.071+-0.003 / 1.0       NA
                                                0.052+-0.003 / 0.5       NA
                                                0.063+-0.002 / 0.6       NA
                                                0.013+-0.002 / 0.003     NA

25                                              0.100+-0.001 / 4.4       NA
                                                0.033+-0.003 / 2.6       NA
                                                0.062+-0.004 / 2.6       NA
                                                0.045+-0.003 / 1.5       NA
                                                0.059+-0.003 / 1.9       NA
                                                0.014+-0.001 / 0.02      NA
-------------------------------------------------------------------------------------------
CONCLUSIONS: [note: these were attenuated stars, K = 8-9]
(a) SWL and SPEC better than WL
(b) BT5 and BT25 similar, maybe BT25 a bit better
(c) CTY5 fails -- problem is that gives lower raw vis2 for fainter sources
(d) calib error bars generally over-estimated
-------------------------------------------------------------------------------------------
```

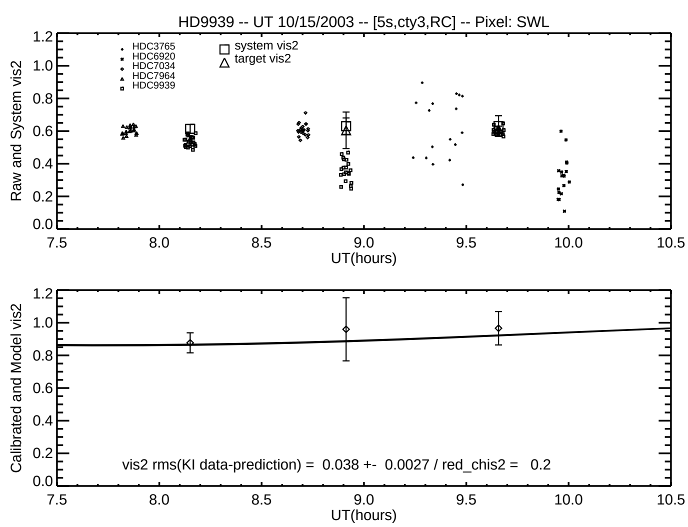


Figure 7: Best-method results for HD9939, for SWL channel.

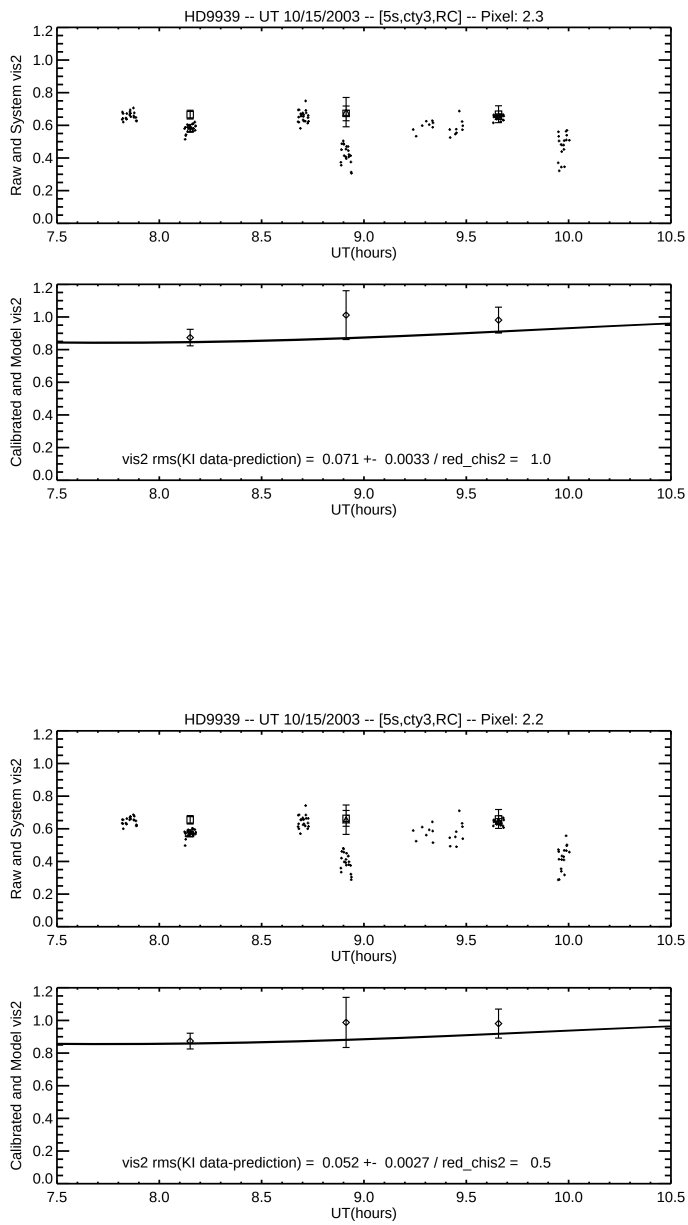


Figure 8: same as previous figure, for SPEC pixels.

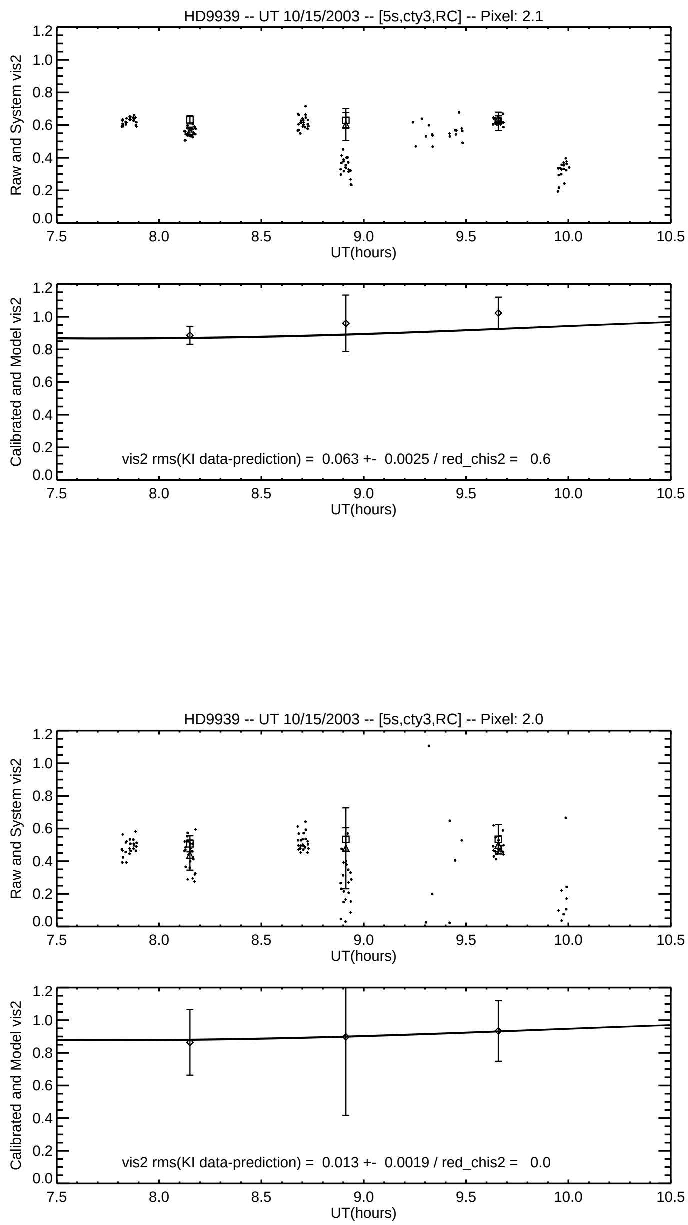


Figure 9: same as previous figure, for SPEC pixels.