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MEMORANDUM

To : **MegaPrime: file 42-87**

From : Derrick Salmon

Date : May 28, 2005
Updated May 31, 2005
Updated July 25, 2005

Subject : **A better focus model for MegaPrime – updated again**

Cc: Astros, Thomas, Ho, Barrick, Benedict, Cruise, Puget, OAs

This is a follow up to earlier memos (May 28 and 31, 2005; April 18, 2005 and March15, 2004). The main difference between the data used here and past reports arises from the recent 'discovery' of an Elixir product – file h/data/elixir2/datadir/getfocus.log – in which Elixir-derived focus curve fitting coefficients are recorded. In particular, for each of the four CCD amplifiers processed from a focus image, the parameters a, b, and c of the focus fitting equation: fwhm = a*focus^2 + b*focus + c, are saved. The availability of these coefficients has removed the need to infer best telescope focus from a science frame immediately following a focus frame, and has made a larger set of focus data available.

The model provides focus zero points for each of the u, g, r, i, z and Ha-on filters, and common rates of focus change with temperature(s), zenith angle, and sin(azimuth)*sin(zenith angle). The model was derived from data for the April, May, June and July, 2005 MegaPrime observing runs.

The least-square focus model is given below:

*Focus = -206.2 *T1 - 127.6 * (T2-T1) – 25.6 * (T3-T1) - 59.5 * (T4-T1) + 466.4 * (1-cos(Zenith Distance)) + 19.3 * sin(Azimuth)*sin(Zenith Angle) + Fx0 microns.*

where:

Fu0	*= - 972 microns*
Fg0	*= -2665 microns*
Fr0	*= -2600 microns*
Fi0	*= -2615 microns*
Fz0	*= -2816 microns*
Fhaon0	*= -2007 microns*

and

T1 is telescope truss temperature at probe 97 (fits card TESTTRSH)
T2 is telescope truss temperature at probe 94 (fits card TESTTRNM)
T3 is telescope truss temperature at probe 98 (fits card TESTTRSL)
T4 is telescope truss temperature at probe 69 (fits card TESTTRSE)

Probe 97 is located high on a south upper truss
Probe 94 is located mid-height on a north upper truss
Probe 98 is located low on a south upper truss
Probe 69 is located mid-point on a south-east lower truss

The sin(Azimuth) term was added empirically after examination of model residuals. The sin(Zenith Angle) multiplier was included to avoid nonsense influences near the zenith, but improved the fitting error only very slightly.

After removal of a mean zero point offsets of +15.8, -3.4, +4.4 and –33.7 microns for the April, May, June and July, 2005 observing run respectively, and removal of mean per-amplifier offsets of –8.0 microns, +29.1 microns, -35.4 microns and +14.3 microns for each of the 4 CCD amplifiers numbered 22, 30, 40 and 48 used in focus curve determination, the rms difference between focus exposure and model-derived focus values is 49.9 microns.

The rms deviation of focus values from the T1-only model developed in May, 2005 was 62.3 microns. The rms deviation from the April, 2005 model was 95 um, and from the March, 2004 model, 163 um The April, 2005 model did not include an airmass term, while the March, 2004 model used air temperatures rather than telescope truss temperatures.

It is now clear that deviations of the model from focus-image-derived telescope focus are due mostly to deficiencies in the model, and not, as previously suggested, due to imprecision in determining focus from a single focus image. The sources of the model's errors are not currently understood but are being actively pursued. It is clear that the internal error in determining focus from a single focus image (16.8 microns rms) is much too small to explain model focus residuals which range as high as 100 microns.

Focus Data

Focus-related data is stored in several locations. Focus images themselves can be found in /h/archive/current/instrument/megaprime/. The log file which records the 3 focus-fitting coefficients for each of four CCD amplifiers is located at /h/megacam/elixir/getfocus.log. GIF images of the four amplifier focus plots and the fitted parabolic focus curves derived from each focus frame are stored at /data/elixir2/datdir/plots/file number.focus.gif. Most of the remaining focus-specific data is held in the headers of individual focus exposures available at /h/archive/current/instrument/megaprime. Telescope truss temperatures were made available in the fits headers starting March 31, 2005.

Telescope focus is determined by taking a focus image (stored with extension x.fits). Focus images consist of 5 to 7 individual exposures recoded on a single fits image, with telescope and focus offsets inserted between exposures. Each focus image takes 3 to 5 minutes to complete. Elixir selects many individual star image focus series on each of four CCDs, and plots star image diameter against focus encoder reading for each, and attempts to fit the points with a least-squares parabolic fit, from which are derived estimates of best focus and best image full-width at half maximum. Rather than apply the fit over all stars in the MegaCam field, four separate plots and parabolic fits are developed, one each for the CCD amplifiers 22, 30, 40 and 48. Their locations in the MegaCam CCD array are shown in Figure 1.

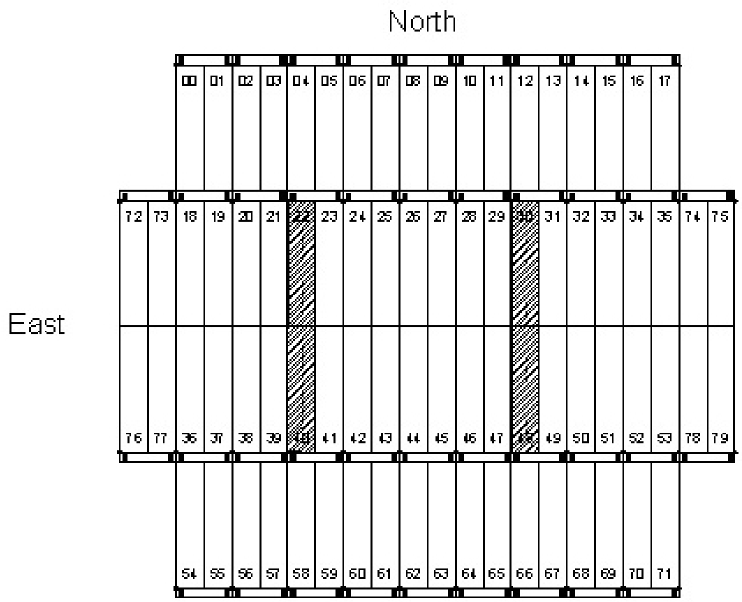


Figure 1 – The locations and amplifier numbers of MegaCam CCDs. The 4 regions used to develop MegaCam focus curves are shaded. Note that these regions are not located symmetrically about the array center.

A small portion of a focus image is shown in Figure 2. Several stars can be seen passing through focus as the telescope is moved and the focus changed between exposures. The telescope is offset in Declination by 5 arsec at each step, while focus is incremented by 100 microns.

An example of Elixir-generated focus plots, together with a least-squares parabolic fit, are shown in Figure 3. The coefficients for the fits are used to develop the focus model.

Figure 2 – A portion of a single focus image showing series of star images with telescope and focus offsets applied between exposures. Elixir processes these focus images to produce the plots of fwhm versus focus and least-squares parabolic fits to the data, examples of which are shown in Figure 3.

The quality of focus plots varies widely. Even for a single focus image, the quality of focus data can vary between amplifiers. In order to ensure that the focus model is based on data of reasonable quality, each of the per-amplifier focus plots (four per focus image) were graded from 0 to 3 - 0, 1, 2 and 3 assigned for no, low, moderate and high confidence levels. Of the 1706 plots graded starting with data taken on March 31, 2005, 638 were assigned a confidence level of 3 (high quality - low data scatter; a well defined minimum; data on both sides of focus), 285 were assigned confidence level 2 (moderate confidence - low scatter but just reaching focus from one side, or moderate data point scatter), 171 were assigned confidence level 1 (low confidence - large scatter, or the image only passes near focus) and 612 were assigned a confidence of 0 (no confidence - very large scatter, or data well away from focus with no unique minimum evident). The focus model was based on data with confidence levels 2 and 3.

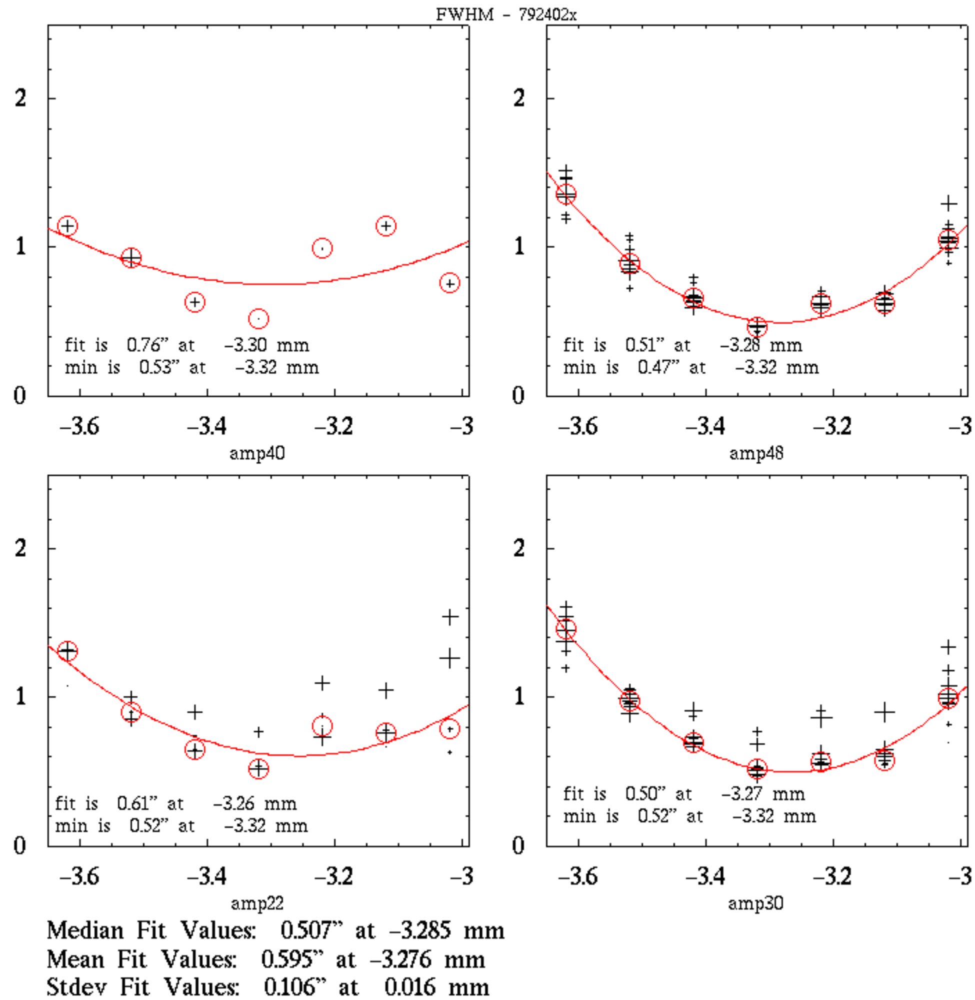


Figure 3 – An Elixir-generated focus plot showing focus data for the four CCDs with amplifiers numbered 22, 30, 40 and 48 The plots on the right are graded 3 (excellent), while the upper left plot is grade 1 at best, and the lower left plot is a grade 2 data set. The coefficients for the four least-square parabolic fits shown in red are saved in file h/data/elixir2/datadir/getfocus.log and provide the basis of the focus model.

Average focus residuals calculated separately for the April, May, June and July runs are + 15.8, -3.4, + 4.4 and – 33.7 microns respectively. Although no appreciable change in focus occurred between April, May and June, the 33.7 micron shift for the July run implies that focus zero points will need to be determined for each observing run, either by direct measurement from focus exposures taken near the start of the run or by other means if we can determine the source of the change. The zero-point offset for the July observing is clearly visible in Figure 4.

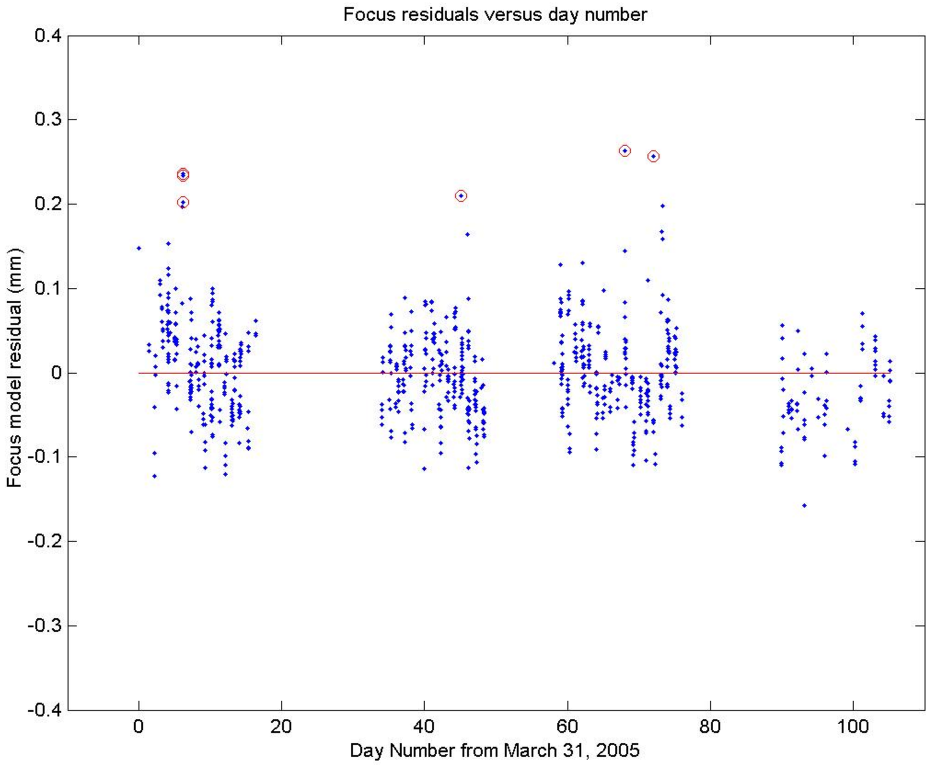


Figure 4 – Focus model residuals for the April, May, June and July, 2005 observing runs. The zero point offset in July – the last of the four data groups - is clearly evident, as are other data trends.

The distribution of focus model residuals, after removal of per-observing-run mean offsets and per-amplifier offsets, is shown in Figure 5. Although the rms of this distribution is 49.9 microns, model errors of up to 100 microns exist sufficiently often that, especially in good seeing condition, telescope focus cannot always be reliably set using the model.

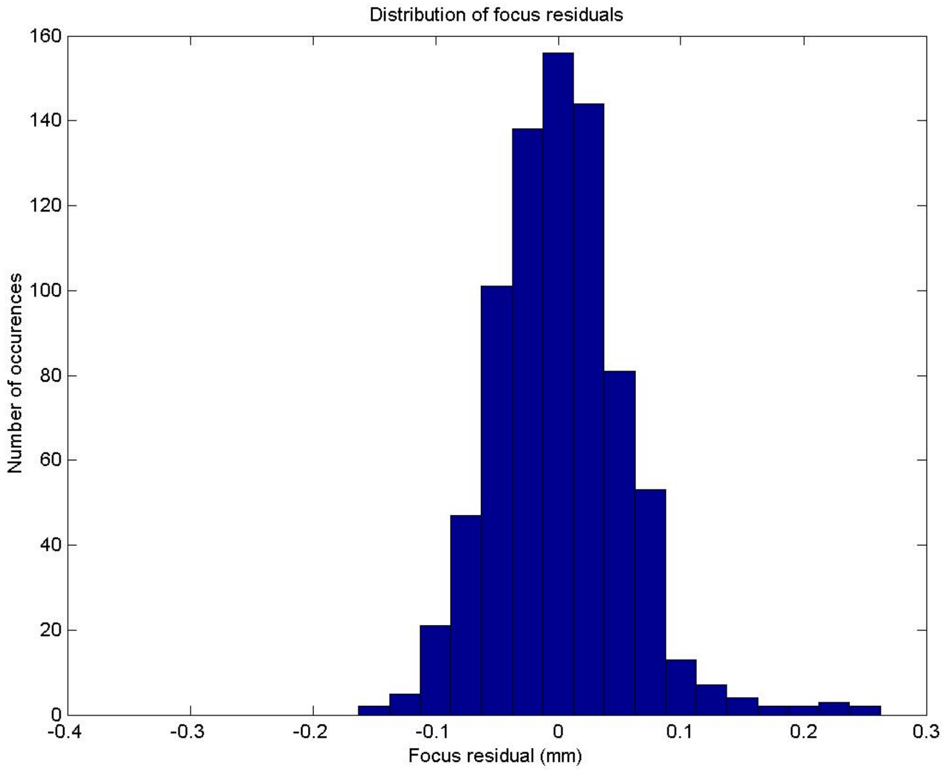


Figure 5 – The distribution of the differences between focus established with a focus exposure and with the focus model.

The least-squares parabolic fit to each of the focus image focus curves can be used to calculate both the depth of focus as a function of image quality, and the degree of image degradation associated with a given defocus; specifically, the increase in image fwhm associated with setting telescope focus based on the focus model, and not on a focus image.

Assuming that a 5% increase in image fwhm is an acceptable upper limit to image degradation due to defocus, the depths of focus derived from fitted focus curves have been plotted in Figure 6 as a function of seeing. This graph provides a slightly optimistic estimate of the permissible depth of focus, since the per-amplifier focus offsets have not been accounted for. Still, based on this plot, a useful rule of thumb if image diameter is not to be degraded by more than 5% due to defocus, is that focus must be within 50 microns of true focus for seeing of 0.5 arcsec fwhm, while for 1 arcsec images focus must be set within 100 microns of the optimal focus.

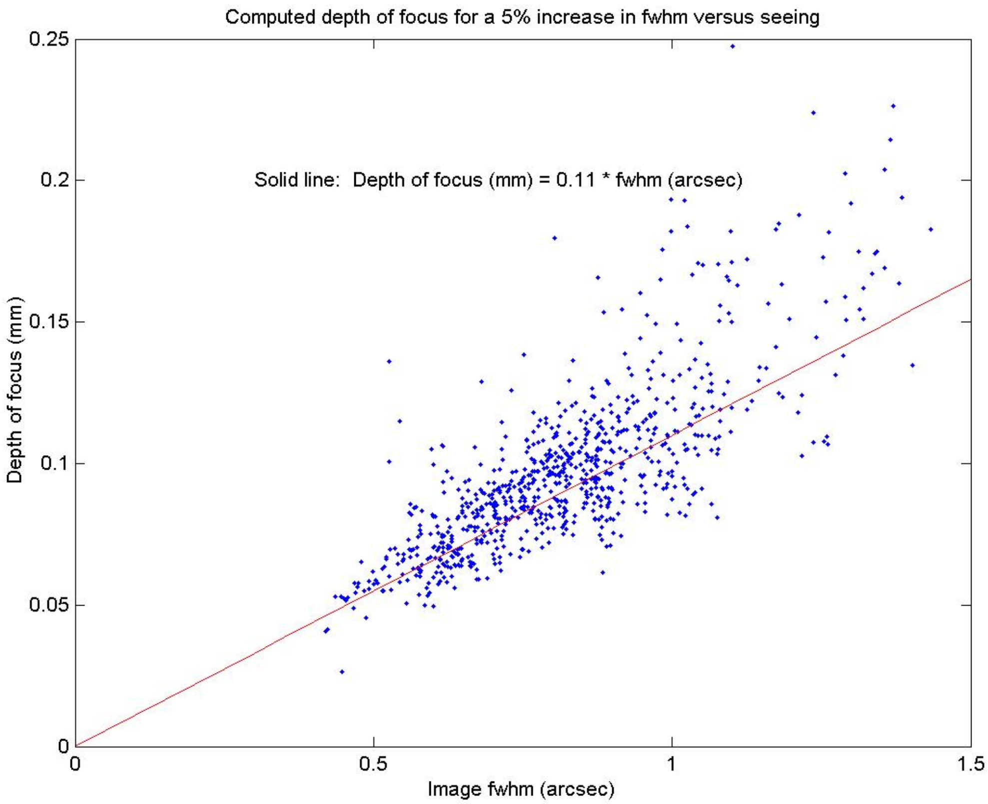


Figure 6 – Calculated depth of focus for a 5% increase in image diameter plotted as a function of seeing.

The depth of focus calculation can be 'reversed' to determine the relative frequencies of specific percentage image degradations, assuming both that the telescope is focused using the focus model, and that all model errors are true focus errors. The results are plotted in Figure 7 below for image fwhm better than 0.7 arcsec and better than 1.5 arcsec. The effects of per-amplifier focus offsets have been included in this plot. Can the focus model be used to focus the telescope without excessive loss of image quality ? Perhaps, but just barely.

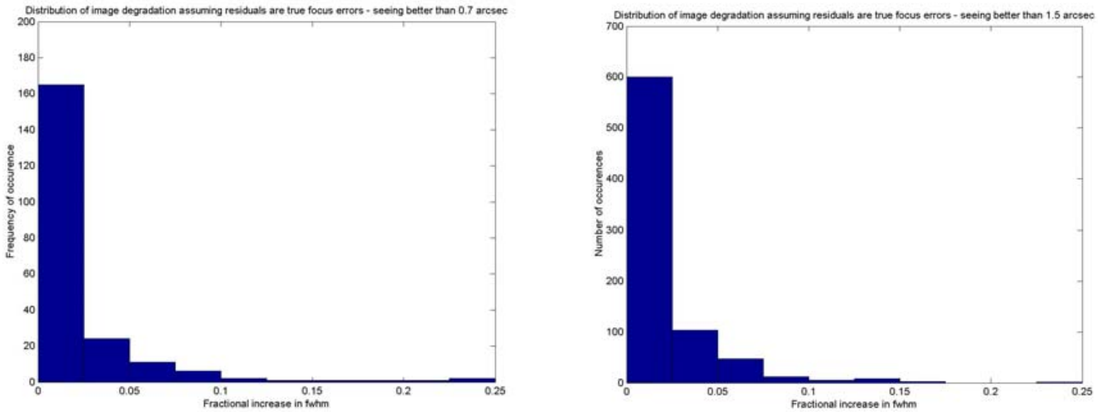


Figure 7 – The distribution of the factional increase of image diameter resulting from setting telescope focus using the focus model assuming that model to focus curve focus differences are entirely due to model (as opposed to focus curve) inaccuracies.

In an earlier report we suggested that the differences between focus-image-derived focus and the model-derived focus might be inherent in the process of determining optimal telescope focus from a single focus image, and that the focus model might therefore provide a more accurate focus value. This report does NOT support this idea. The internal scatter of focus values derived from the separate amplifiers used to develop the focus curves (after removal of consistent inter-amplifier offsets) is 16.8 microns rms which cannot account for difference of up to 100 microns seen between focus exposure and focus model-derived focus values.

A further indication that the focus differences are not a result of imprecision in focus image focus determination comes from the plot of focus residuals as a function of image size in Figure 8. If focus errors were mostly a result of imprecision in fitting to the focus image data, then the errors should decrease markedly as image quality improves. No strong evolution of the residuals with image size is evident.

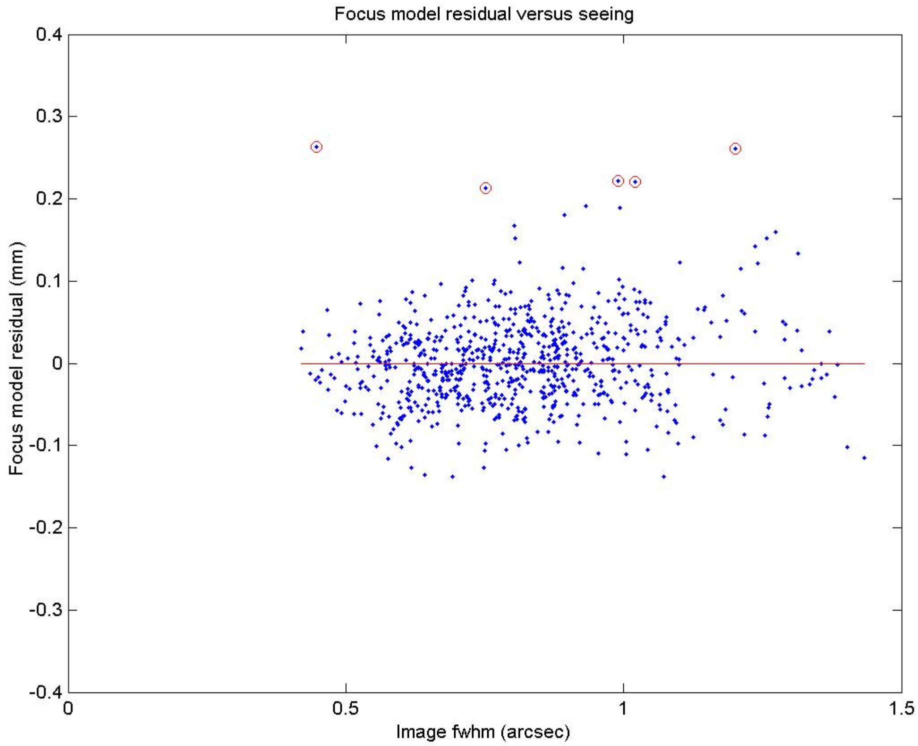


Figure 8 – Differences between focus derived using a single focus image and focus derived from the focus model, as a function of image quality. The fact that the residuals do not decrease with improved seeing suggests that the focus model residuals cannot be explained by imprecision in determining focus from focus images.

Unexplained trends are evident in plots of focus residuals versus time. These can be seen on filter-by-filter plots of model focus residual (where each filter set covers all four observing runs) shown in Figure 9, and on nightly trends, for which a sample is provided in Figure 10.

We are in the process of instrumenting the telescope to measure the axial position of the primary mirror with respect to its cell, and have added more temperature probes to the upper end structure, in the hope of improving the focus model to the point that errors can be kept below 50 microns. If this level of accuracy can be achieved, then a fully model-driven telescope focus could be realized, with the need only for an occasional focus image to verify model performance.

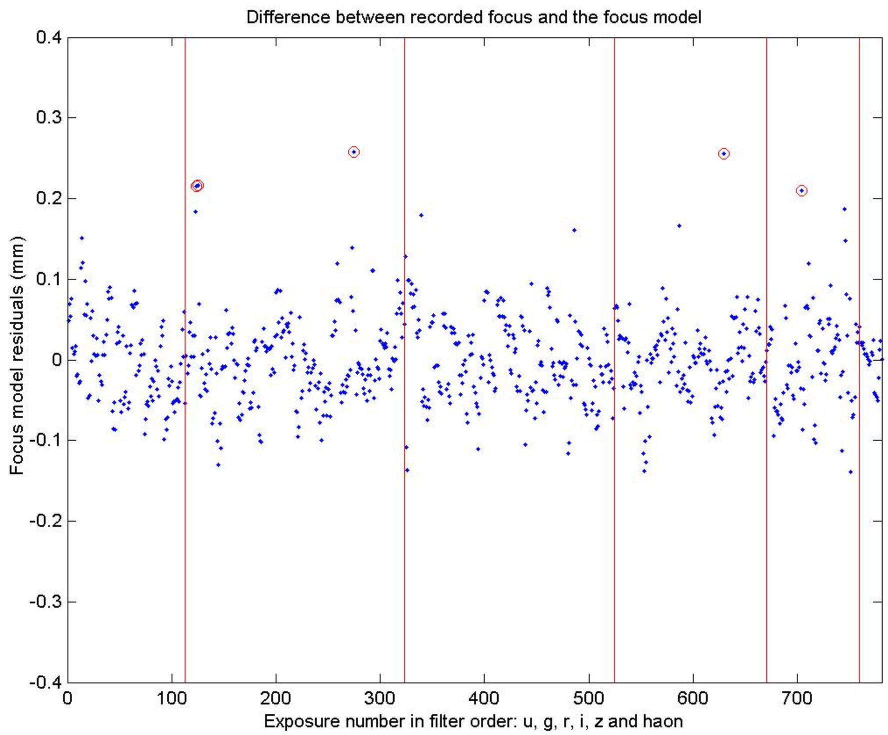


Figure 9 – Focus model residuals plotted for each of the MegaCam filters. Data for all four observing runs (April, May, June and July, 2005) are concatenated for each filter. Trends are evident, particularly in the g,r, and i focus residuals.

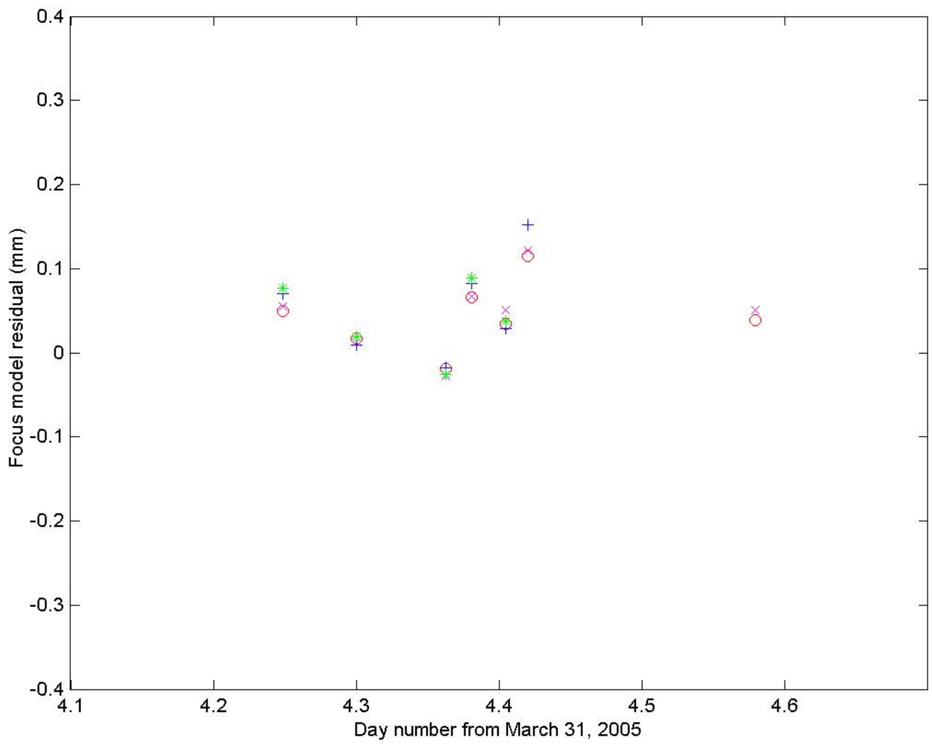


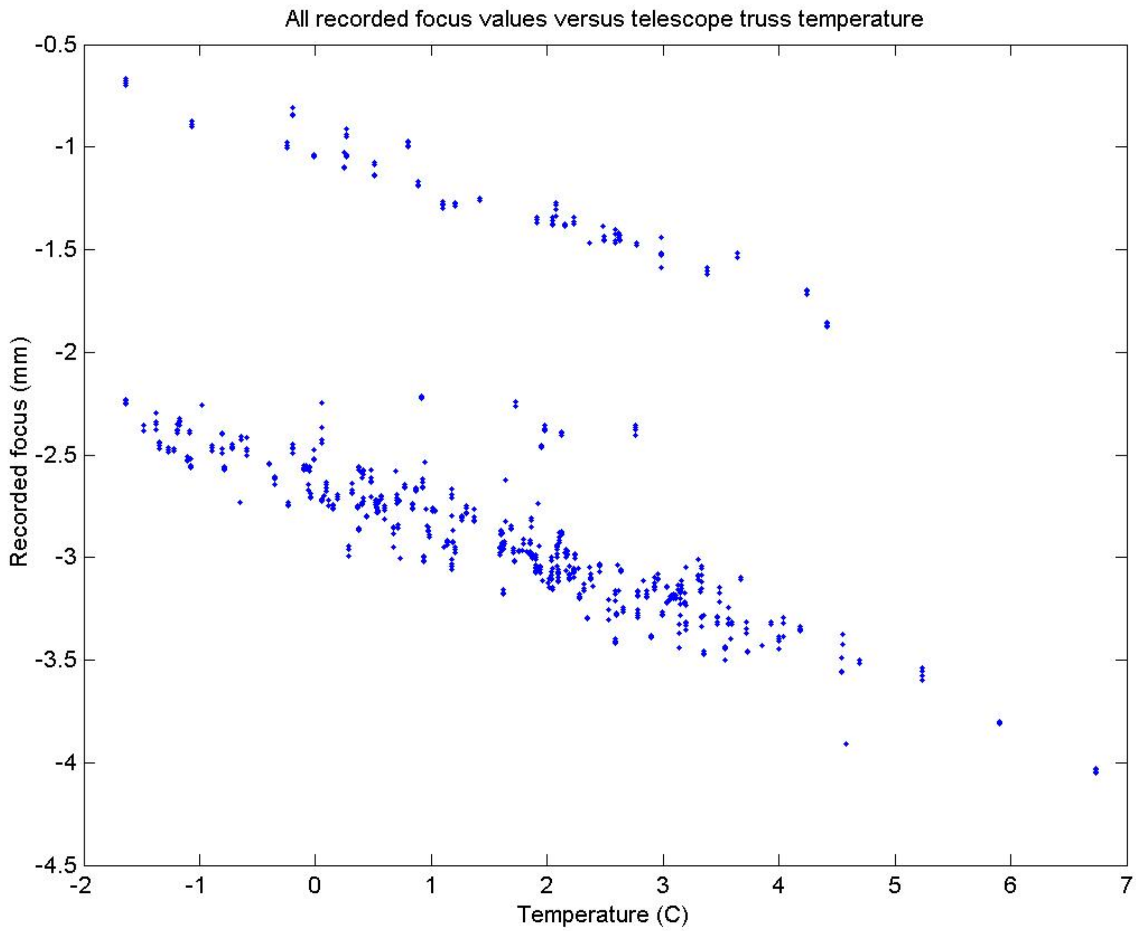
Figure 10 – Focus residuals for the night of April 4, 2005. Focus determined from each of the four CCD amplifiers are recorded separately 7 times throughout the night. Focus variations from focus image to focus image greatly exceed the scatter in the per-amplifier focus estimates, strongly suggesting that the focus model is not accounting for an important variable. In this plot, focus changes of up to 100 microns occur in two cases on a time scale of 30 minutes.

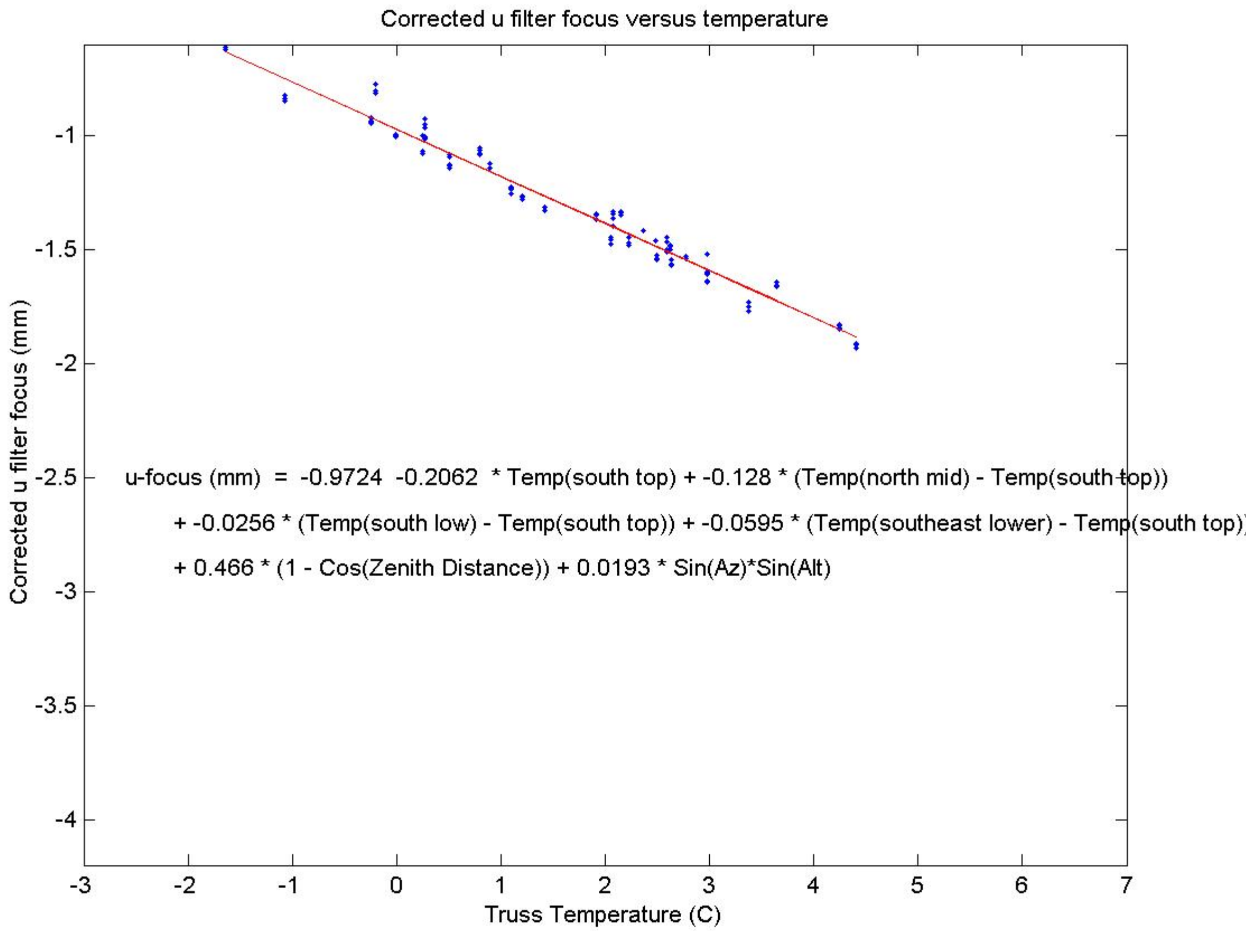
In an earlier report we also noted that focus residuals plotted as a function of the time-of-day at times showed large deviations from the model in the first half hour of the night. These anomalies have since been traced to the practice of taking of purposefully defocused calibration exposures at the start of the night, immediately after taking a focus exposure, and to the manner in which focus values for the earlier reports were determined indirectly from *object (not focus)* images. With the current use of focus exposure data alone, these anomalies no longer exist.

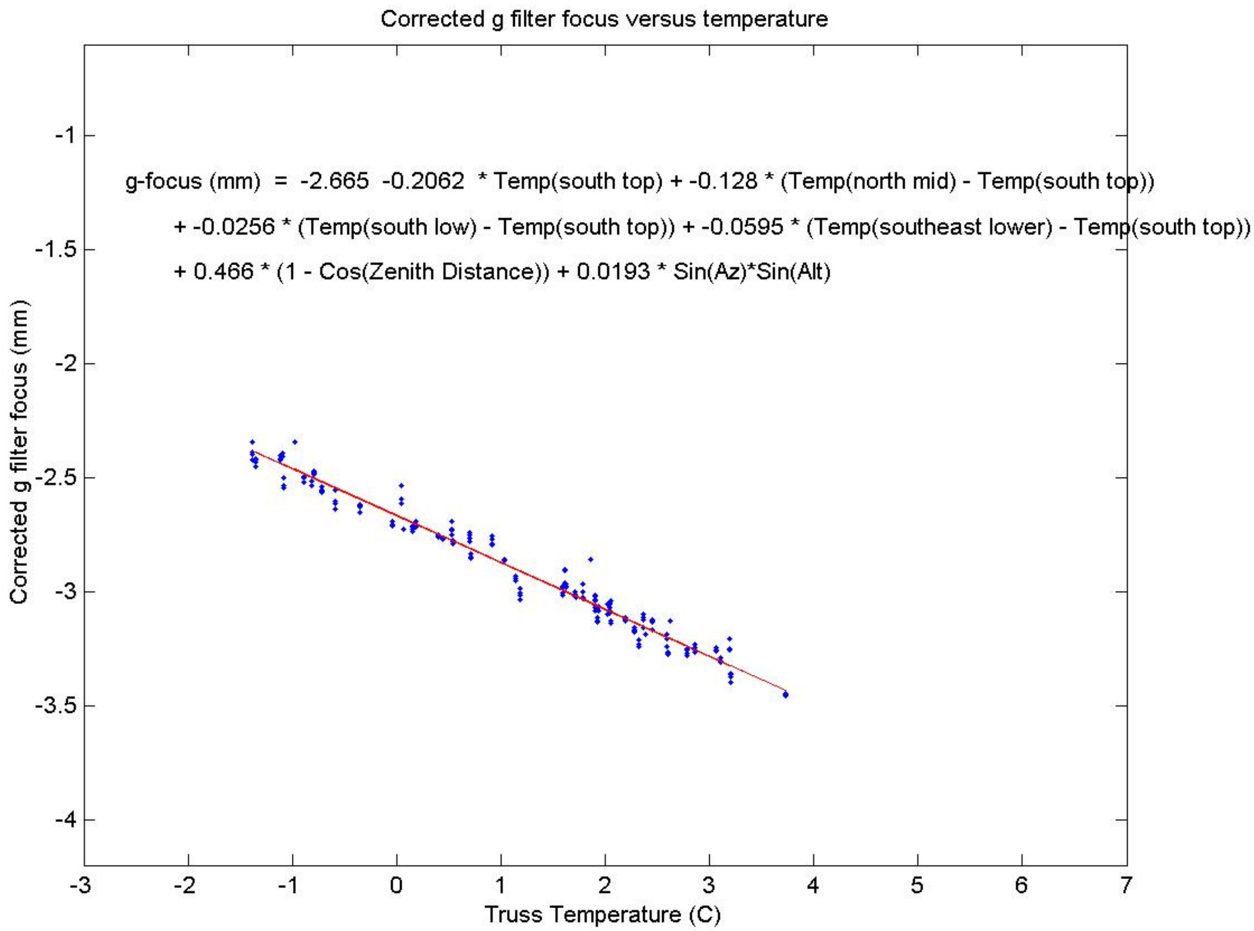
Several graphs of focus data and the differences between modeled and focus plot derived focus are attached at the end of this note.

Megaprime Focus Data
April, May, June and July, 2005

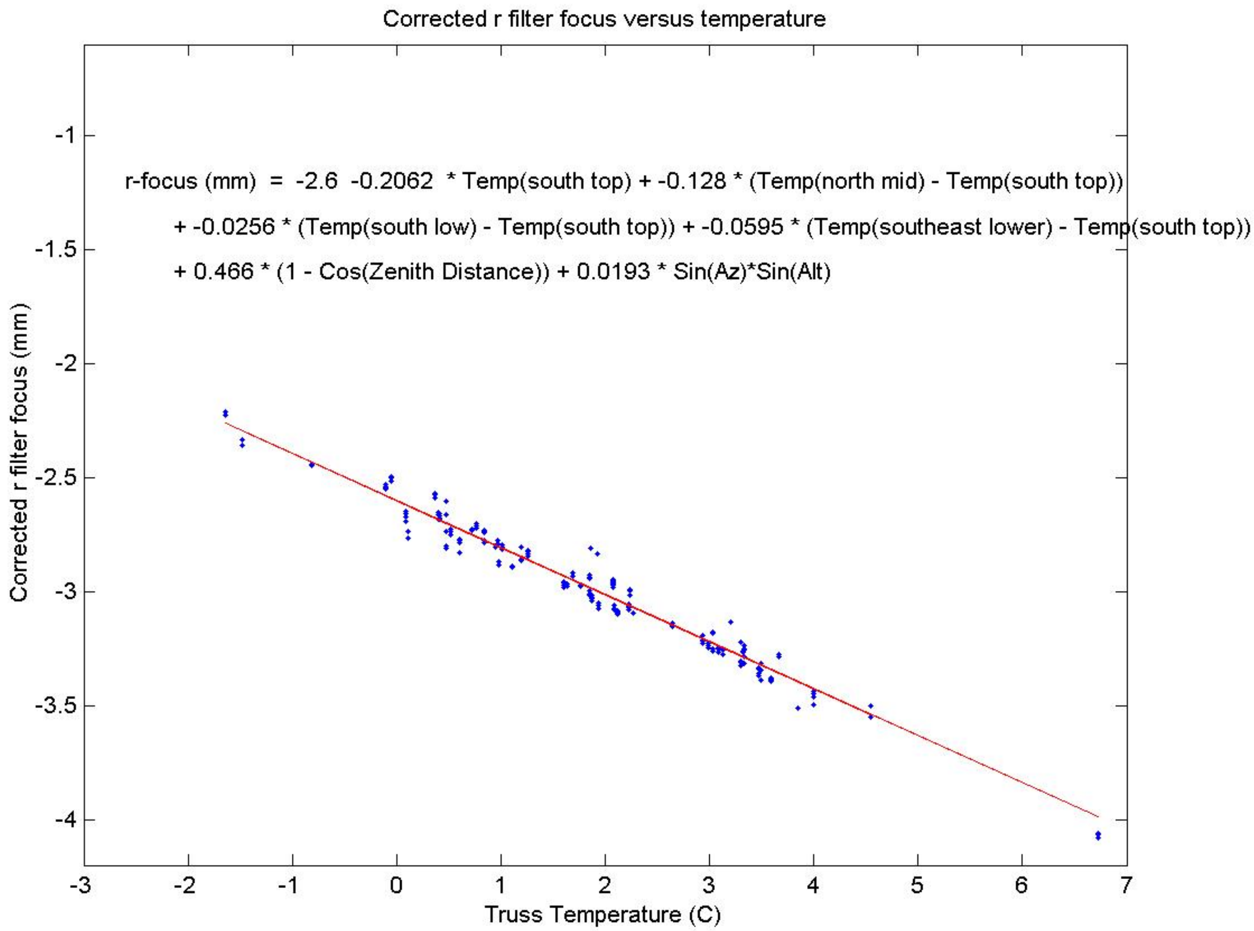
Filters u, g, r, i , z and Ha-on


All recorded focus values versus telescope truss temperature
Recorded focus (mm)
Temperature (C)
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-2
-1
0
1
2
3
4
5
6
7

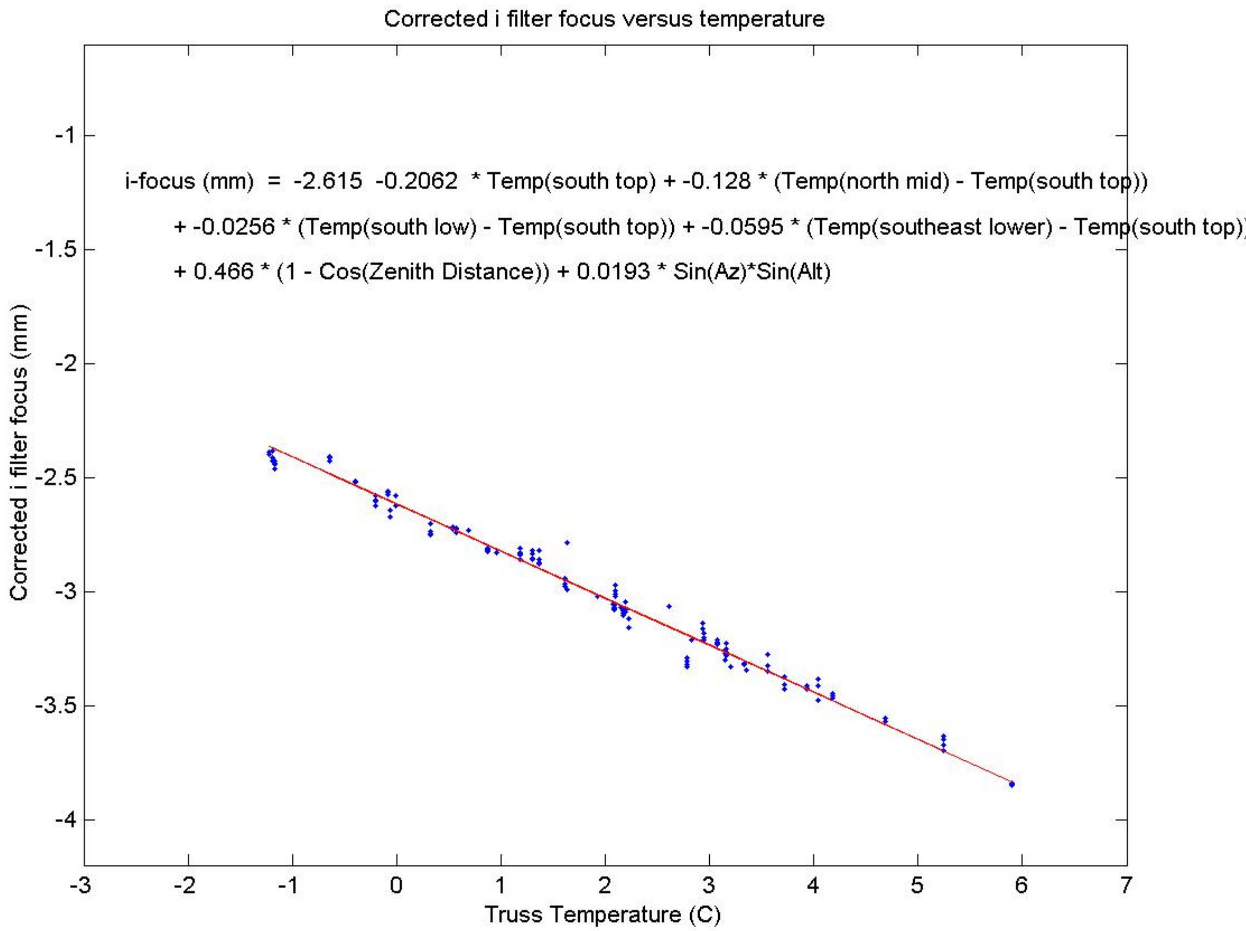

Corrected u filter focus versus temperature
Corrected u filter focus (mm)
Truss Temperature (C)
-1
-1.5
-2
-2.5
-3
-3.5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
u-focus (mm) = -0.9724 -0.2062 * Temp(south top) + -0.128 * (Temp(north mid) - Temp(south top))
+ -0.0256 * (Temp(south low) - Temp(south top)) + -0.0595 * (Temp(southeast lower) - Temp(south top))
+ 0.466 * (1 - Cos(Zenith Distance)) + 0.0193 * Sin(Az)*Sin(Alt)

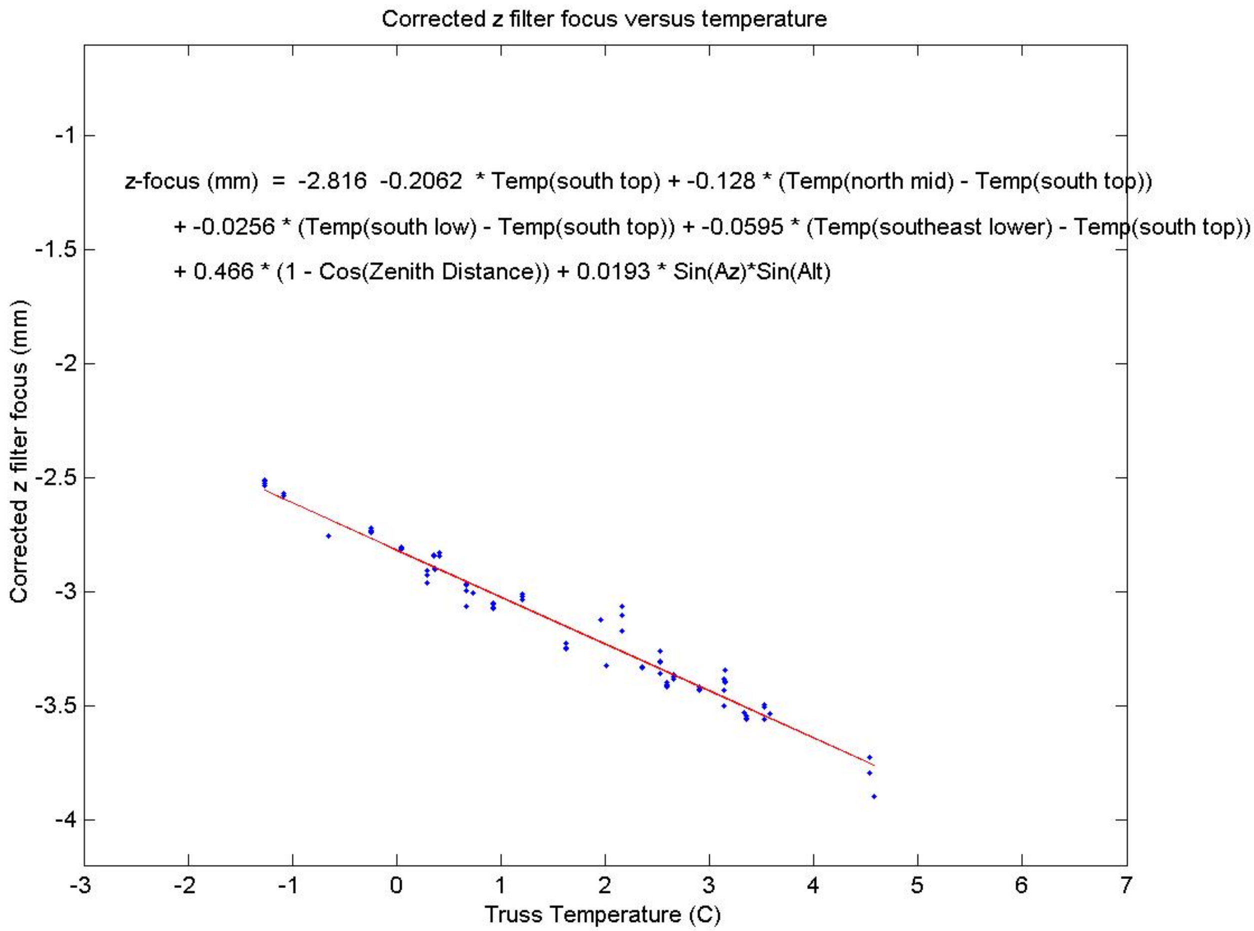


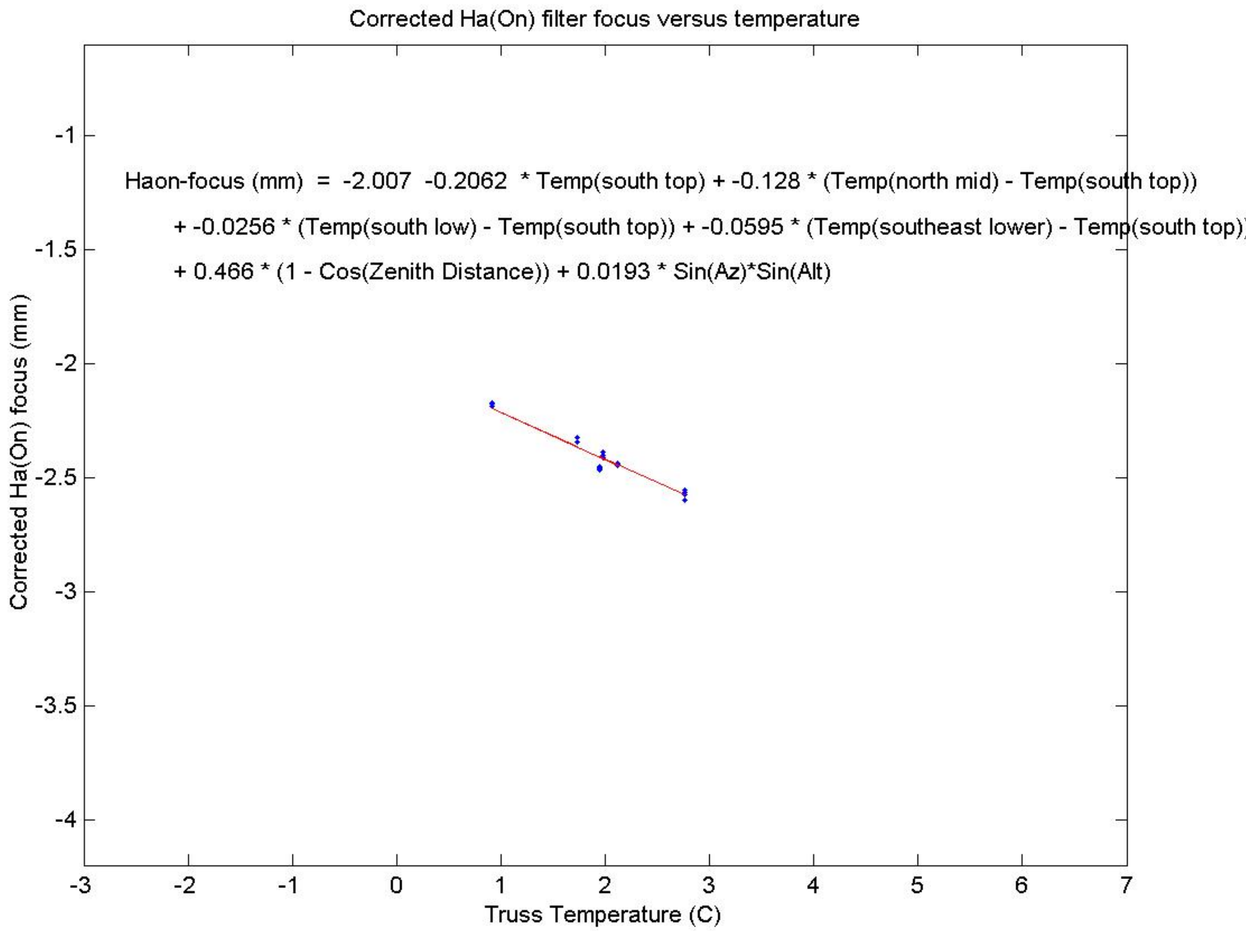
Corrected g filter focus versus temperature
g-focus (mm) = -2.665 -0.2062 * Temp(south top) + -0.128 * (Temp(north mid) - Temp(south top))
+ -0.0256 * (Temp(south low) - Temp(south top)) + -0.0595 * (Temp(southeast lower) - Temp(south top))
+ 0.466 * (1 - Cos(Zenith Distance)) + 0.0193 * Sin(Az)*Sin(Alt)
Corrected g filter focus (mm)
-1
-1.5
-2
-2.5
-3
-3.5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Truss Temperature (C)

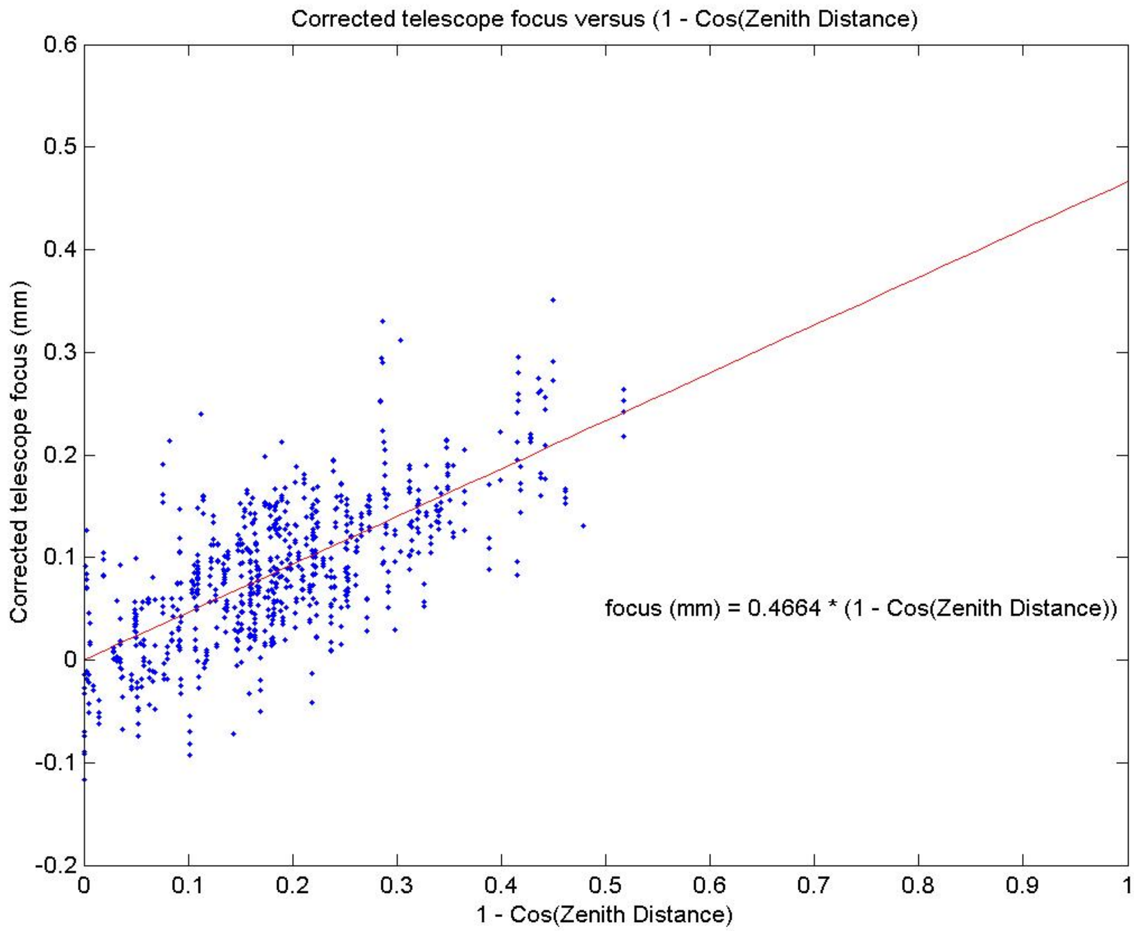


Corrected r filter focus versus temperature
r-focus (mm) = -2.6 -0.2062 * Temp(south top) + -0.128 * (Temp(north mid) - Temp(south top))
+ -0.0256 * (Temp(south low) - Temp(south top)) + -0.0595 * (Temp(southeast lower) - Temp(south top))
+ 0.466 * (1 - Cos(Zenith Distance)) + 0.0193 * Sin(Az)*Sin(Alt)
Corrected r filter focus (mm)
Truss Temperature (C)
-1
-1.5
-2
-2.5
-3
-3.5
-4
-3
-2
-1
0
1
2
3
4
5
6
7


Corrected i filter focus versus temperature
i-focus (mm) = -2.615 -0.2062 * Temp(south top) + -0.128 * (Temp(north mid) - Temp(south top))
+ -0.0256 * (Temp(south low) - Temp(south top)) + -0.0595 * (Temp(southeast lower) - Temp(south top))
+ 0.466 * (1 - Cos(Zenith Distance)) + 0.0193 * Sin(Az)*Sin(Alt)
Corrected i filter focus (mm)
-1
-1.5
-2
-2.5
-3
-3.5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Truss Temperature (C)


Corrected z filter focus versus temperature
z-focus (mm) = -2.816 -0.2062 * Temp(south top) + -0.128 * (Temp(north mid) - Temp(south top))
+ -0.0256 * (Temp(south low) - Temp(south top)) + -0.0595 * (Temp(southeast lower) - Temp(south top))
+ 0.466 * (1 - Cos(Zenith Distance)) + 0.0193 * Sin(Az)*Sin(Alt)
Corrected z filter focus (mm)
-1
-1.5
-2
-2.5
-3
-3.5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Truss Temperature (C)


Corrected Ha(On) filter focus versus temperature
Haon-focus (mm) = -2.007 -0.2062 * Temp(south top) + -0.128 * (Temp(north mid) - Temp(south top))
+ -0.0256 * (Temp(south low) - Temp(south top)) + -0.0595 * (Temp(southeast lower) - Temp(south top))
+ 0.466 * (1 - Cos(Zenith Distance)) + 0.0193 * Sin(Az)*Sin(Alt)
Corrected Ha(On) focus (mm)
Truss Temperature (C)
-1
-1.5
-2
-2.5
-3
-3.5
-4
-3
-2
-1
0
1
2
3
4
5
6
7



Corrected telescope focus versus (1 - Cos(Zenith Distance)
Corrected telescope focus (mm)
1 - Cos(Zenith Distance)
focus (mm) = 0.4664 * (1 - Cos(Zenith Distance))
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1