

# Keeping the Hubble Space Telescope in focus.

Colin Cox and Matthew Lallo,

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland, 21218

## ABSTRACT

The Hubble Space Telescope is a Ritchie-Chrétien optical design with a main primary concave mirror followed by a convex secondary. The focus is determined by the position of each of these two mirrors. The truss containing them is made of graphite epoxy which has very low thermal expansion. Nevertheless, temperature variations do cause the mirror separation to vary by several microns within an orbit. Additionally, outgassing of water vapor causes a long-term shrinkage which soon after launch in 1990 varied by more than 2 microns per month. This necessitated adjusting the position of the secondary mirror every few months. Currently this rate is greatly reduced and adjustments are needed less than once per year.

The focus is monitored monthly to continually assess the need for such adjustments. The measurements have been used to develop models to predict the focus at times between measurements to assist in the analysis of observations. Detailed focus knowledge is of value in photometry, coronagraphy and image deconvolution. The various focus models that have been applied so far are described with an evaluation of their performance. Continuing attempts to refine the model will be discussed.

**Key words:** HST, Focus, Point-spread function, Thermal model.

## THE TELESCOPE

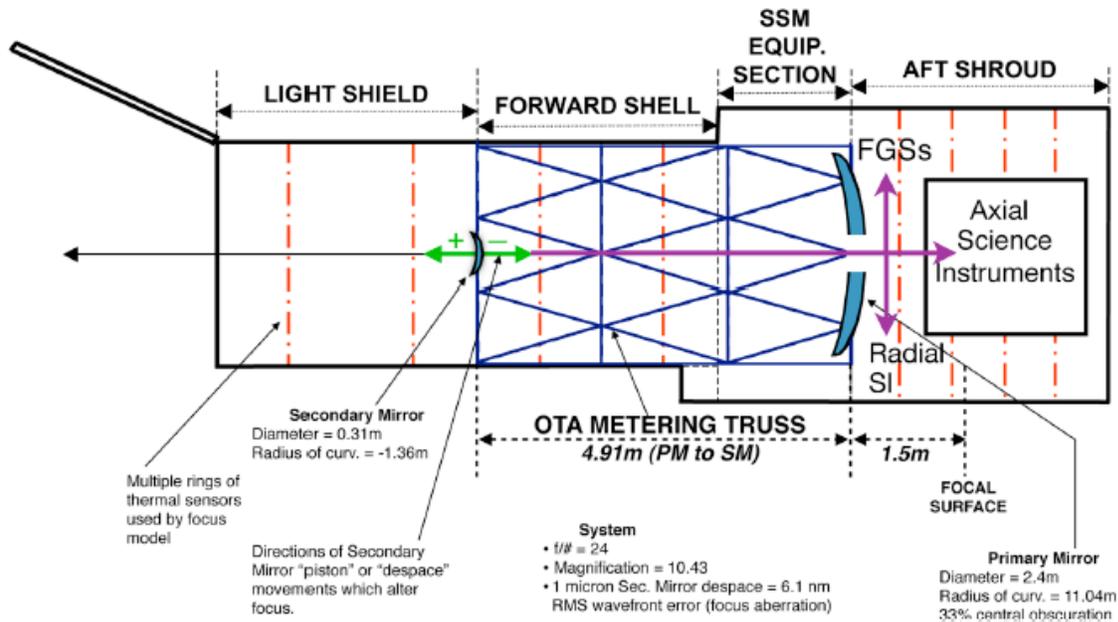


Figure 1. Schematic diagram of the Hubble Space Telescope showing the structures surrounding the optical platform.

The Hubble Space Telescope is a Ritchie-Chrétien optical design with a 2.4 m diameter main primary concave mirror followed by a convex secondary. The separation between the primary and secondary mirrors is 4.91m and the combined focal length is 57.6 m. The mirrors are supported on a graphite-epoxy metering truss consisting of 48 tubular elements

selected according to their thermal coefficients of expansion to minimize fluctuations in bending and overall length. The resulting stability is impressive; as the telescope orbits the Earth the truss is subject to temperature variations of more than 20 degrees centigrade, while the mirror separation varies by less than 10 microns over the 4.9 m length.

However, when considering optical phenomena measured in terms of optical wavelengths these shifts are significant and measurably degrade the image. A one-micron change in the relative mirror separation causes 6.1 nm of wavefront error at the focus. Typically the orbital variation is about 5 microns leading to 30 nm of wavelength shift or about 1/16<sup>th</sup> of a 500 nm wavelength. Such a variation is easily measured in the point spread function as produced by the image of a star. While this may not be readily discerned by looking at an image, a photometric measurement or the flux through a spectrographic slit can be affected by a few percent, sometimes significant in scientific analysis.

### FOCUS HISTORY

The HST focus as represented by the mirror separation has varied over the last 22 years as shown in Figure 2 which shows the long-term change attributed to the outgassing of the graphite–epoxy truss and consequent shrinkage. The launch date was April 24<sup>th</sup> 2009 and day 8000 was March 19<sup>th</sup> 2012. The last 1000 days are shown in the inset.

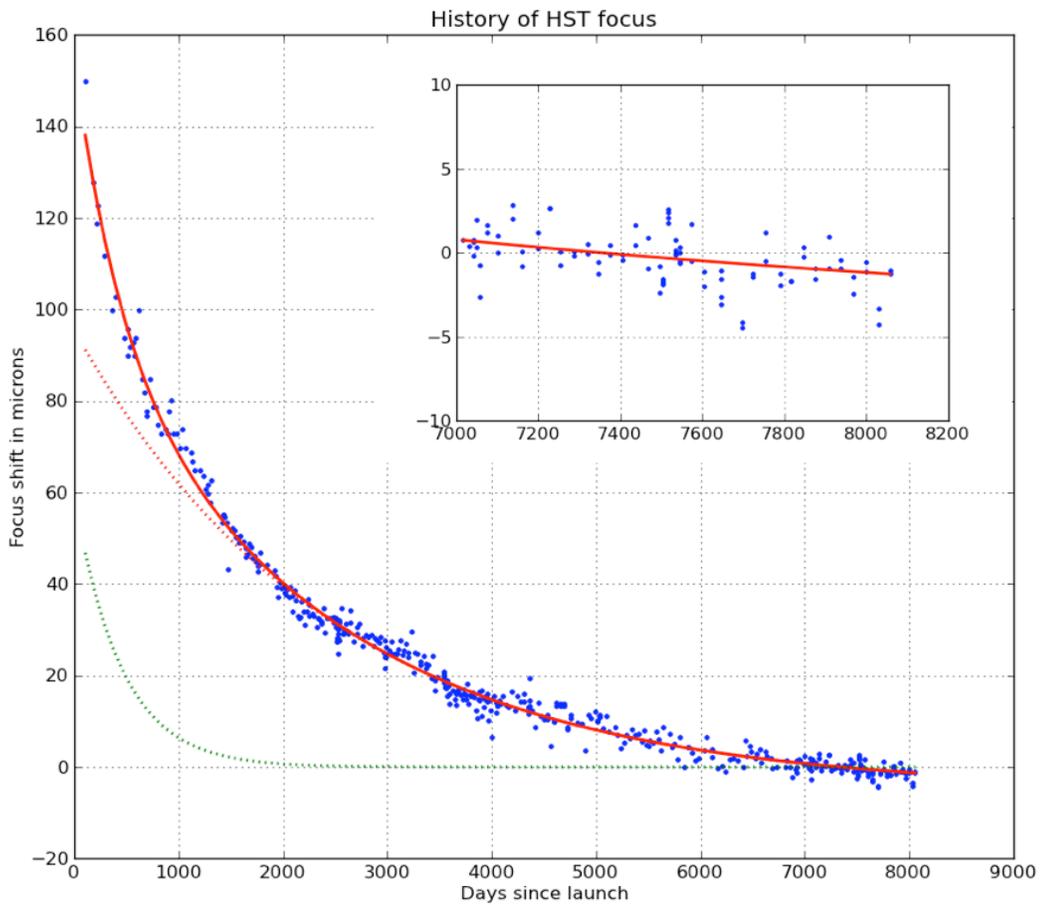


Figure 2. Historical focus shift relative to current position with exponential curves showing the long-term fit. The inset shows just the last 1000 days

In the first year of operation the separation shrank by over 80 microns but currently the rate is about 0.8 microns per year. In the first year of operations, adjustments to the secondary mirror position were made every month or two with the aim of staying within 5 microns of best focus. Initially the telescope also suffered from spherical aberration that was corrected by two methods in the 1993 servicing mission. The Wide Field Camera 2 replaced the original Wide Field Camera and incorporated corrective optics. At the same time a second instrument known as COSTAR (Corrective Optics

Space Telescope Axial Replacement) was installed. This contained small mirrors that intercept the light path of the Faint Object Camera, the Faint Object Spectrograph, and the Goddard High Resolution Spectrograph and provided spherical aberration correction to these instruments. From then on adjustments were made less frequently reducing from about twice a year in 1993 to the present time where adjustments are made less than once every two years. This, despite the fact that we now manage to stay within one or two microns of best focus. From the inset in Figure two it can be seen that short-term fluctuations now have a greater effect than the long-term shrinkage.

The measurement of the focus has been performed by several methods in the past but the most successful method is that of phase retrieval as developed by Krist and Burrows<sup>1</sup> and supplied as a computer program which we have used since 1995. This is based on the Gerchberg-Saxton method. This relies on the fact that in the Fraunhofer approximation, the waveforms in the pupil and image planes are Fourier transforms of each other. The software iteratively hunts for amplitudes and phases in the two planes which match the amplitudes in the image plane and fits the shape of the borders in the pupil plane. The shape of pupil plane is fairly complex including a central zone blocked by the secondary mirror and other areas covered by the spiders and pads supporting the primary mirror. This complexity actually makes it easier for the method to find a solution. The solutions are expressed in terms of Zernike polynomials modified to account for the central obscuration. By this means we separate the effects of defocus, coma, astigmatism and higher order distortions plus other effects such as charge diffusion in the detector.

## FOCUS MODELING

We find two main drivers of the focus behavior, the long-term effect attributed to the truss shrinkage and the short-term linked to temperature changes within an orbit. The long-term behavior illustrated above clearly has the broad form of an exponential decay. In attempting to fit the whole period we find that a double exponential is required. The two separate exponentials are shown with dotted lines while the solid line represents the combined solution. The e-folding times for the two components are 450 days or 1.2 years and 2464 days or 6.7 years.

The modeling of the temperature dependence has been attempted several times with gradually improving results. The first attempt in 1993 by Bély, Hasan and Meibach<sup>2</sup> remains the basis for our current mode<sup>1</sup>. The main component appeared to be a time dependent temperature difference found by comparing the instantaneous average temperature of the Light Shield (see Figure 1) with its average over the previous orbit. The term was given as  $SM=0.7(LS-MLS)$  where LS is the mean of four Light Shield temperatures and MLS is the average of these values in the previous orbit. This has been referred to as the breathing term. This relates quite well to the relative focus shift over an orbit but gives little information about the overall displacement.

There are a total of 42 temperature sensors within the four structural elements, Light Shield, Forward Shell, Aft Shroud and Metering Truss, any of which may be correlated with the focus position although this model only used four within the Light Shield.

In 1998 John Hershey<sup>3</sup> attempted to relate the focus to the telescope attitude and was able to represent the general characteristics of the focus variations. The telescope attitude determines the relative orbital timing of the illumination from the sun and from the earth and these effects were clearly seen. Had this model worked better it would have been possible to predict focus variations of planned observations.

While Hershey's analysis related the temperature changes to the telescope attitude and provided considerable physical insight, we still continued to use the measured temperatures to drive the model. Ultimately Hershey combined the Bély model with five other temperature terms. The temperature of the Aft Shroud has a particularly large effect. For a series of measurements carried out over one month in 1997 this new model matched the observed values to within 0.5 microns which is approximately the same size as the accuracy of the measurements. It still remains a problem to include all the longer-term effects, which do not precisely follow the exponential model.

In 2008, Di Nino et al.<sup>4</sup> utilized more of the temperature sensors to provide a fuller model. It is naturally true that many of the temperatures are correlated; so attempting to use all of them does not give a significantly better solution than using a carefully chosen subset. The newer model includes groups of temperature sensors in each of the structures. The extra factor having the most influence was labeled the Truss Axial Differential Temperature and referred to the difference between the mean values of two groups of sensors at different positions along the optic axis within the Metering Truss. The model also included a linear long-term component implying a contraction of about 1.9 microns per year. The formula given for the secondary mirror shift is

$dSM = C - 0.0052.MJD + 0.48.T_{LS4} + 0.81.T_{MTS-ax} - 0.28.T_{AS} + 0.18.T_{FS} + 0.55.T_{breath}$  in which  $T_{MTS-ax}$  is the Truss Axial Differential Temperature, MJD is the modified Julian date.  $T_{breath}$  is the breathing term discussed earlier. Several other groups of temperatures are included. Note that this implies a linear shrinkage with time, a reasonable approximation over a recent period of a year or two. This model has been successful in modeling the focus value with an RMS error of about 1.5 microns for long-term estimates and to within 0.5 to 0.6 in the short term, meaning that within a single orbit the model follows the shape of the variation to within about 0.5 microns although there may be an overall offset which is usually within one but occasionally reaches two or three microns.

In 2011, Cox and Niemi<sup>5</sup> reviewed the focus history and matched it with the model to improve the long-term component, basically by re-introducing and calibrating the exponential form. Unfortunately the High Resolution Camera, which had the best sampling size, ceased to function in January 2007, but we now had more data from the Wide Field and Planetary Camera 3 installed in May 2009. By applying the time dependent correction to the raw measurements and then fitting the double exponential to the corrected values we were able to build up a good contemporary model and calculate offsets to apply to each camera. This is the model currently in use. Access to this model is available on a web site <http://www.stsci.edu/hst/observatory/focus>, which includes a discussion and instructions for using this model. This page also includes further discussion of topics mentioned in this paper and links to all publications referred to in this paper. Examples of the focus model output are given in Figure 3.

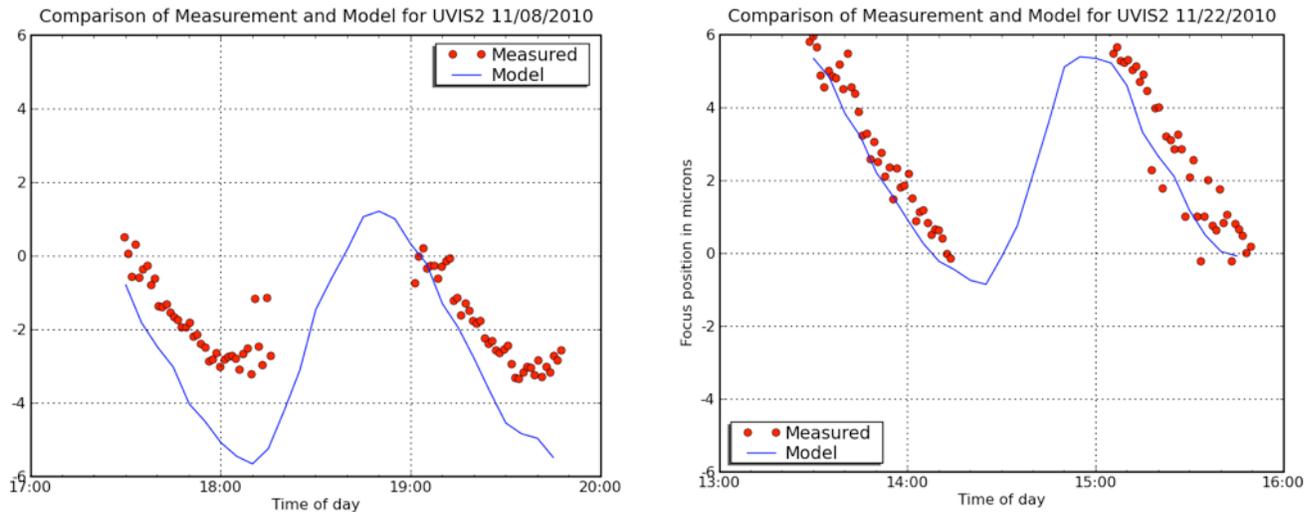


Figure 3 Comparison of focus measurements with model for two periods in 2010

It can be seen that whereas the short-term performance is fairly well represented, there are sometime offsets between model and observation of several microns. We are therefore continuing efforts to improve the model. Recognizing that most of the measured temperatures are highly correlated we have investigated the method of Principal Component Analysis. This method initially takes account of all 42 temperatures but extracts linear combinations that are orthogonal, i.e. non-correlated. Although there are 42 such combinations, some are much more strongly correlated with the focus positions than others. The aim is to determine a small number of such components that explain a large fraction of the focus variation.

Figure 4 shows the absolute magnitude of the correlations of each component with temperature in decreasing order. The decreasing component correlation supports the notion that only the first few need be included, Taking the first 7 components results in a fairly good fit to all the measurements from 2005 giving an RMS deviation of 1.08 microns and explaining 69% of the initial variance.

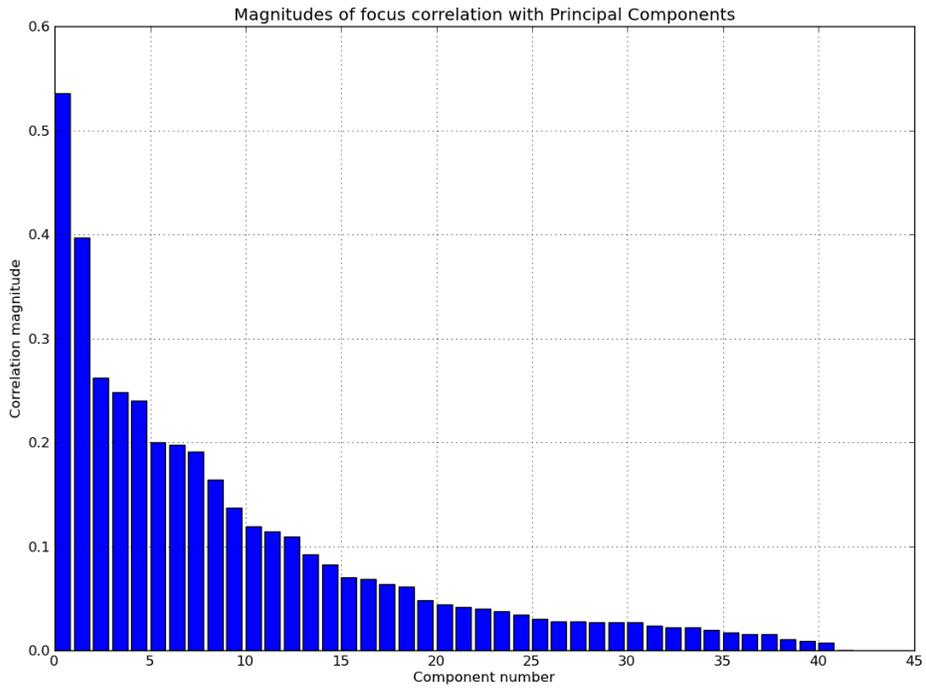


Figure 4. Magnitudes of correlation between focus position and principal components in descending order.

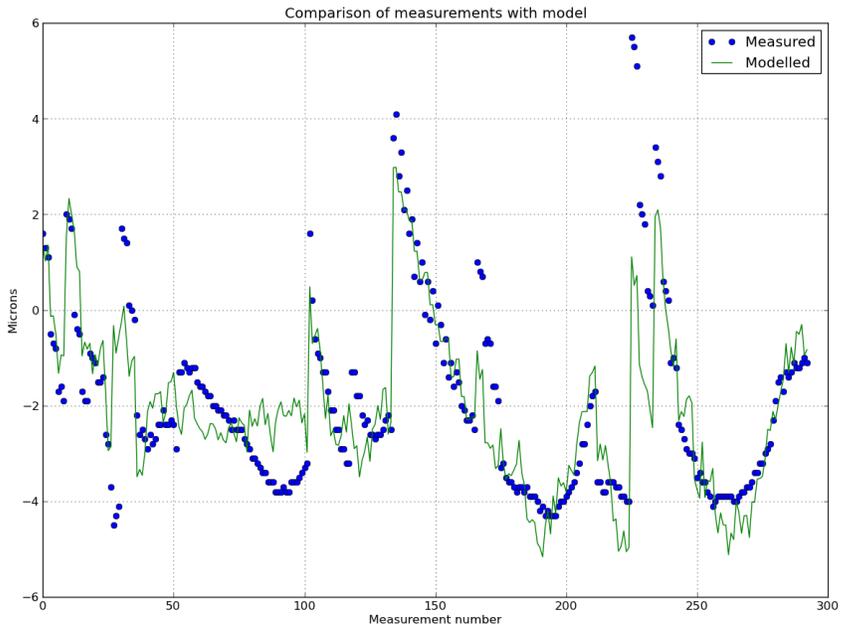


Figure 5. Model generated from all of 2005 data compared with focus data.

Initial results show that while good fits to existing data can be obtained there are still periods when the model seems to stray such as in the range of measurements 50 to 100. Clearly some significant temperature or other effect is not included in the model. Only the most significant five components have been included and some experimentation will be needed to determine the best set while avoiding over-determining the solution, effectively fitting to spurious correlations. Note that this graph includes data from a whole year whereas the earlier plots show time ranges of about one hour. The x axis is simply in terms of measurement number. Plotting against time when the measurements cover about one hour each month does not show a useful distribution.

The predictive capability is still limited. That is to say that while a good fit may be obtained to all the data from one year, using the fitted solution to calculate values for the succeeding year still exhibits deviations of several microns. Figure 6 compares measurements made throughout 2006 with a model based on measurements from 2005.

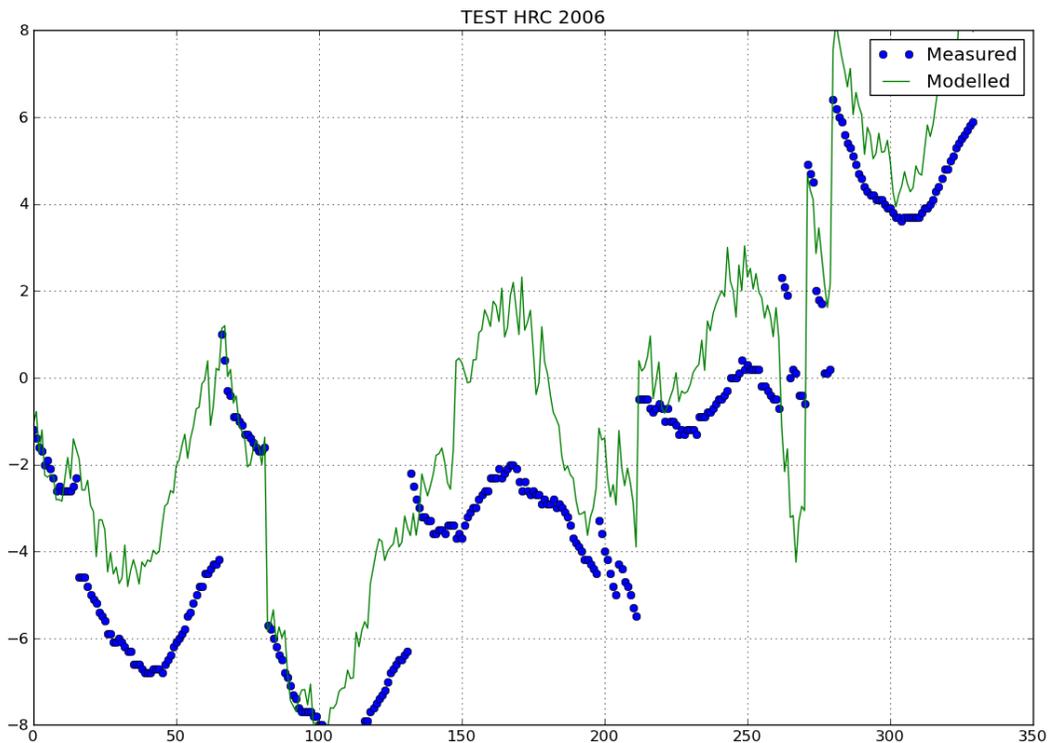


Figure 6. Model generated from 2005 data matched against year 2006 measurements.

The success of the Bély model suggests that some temperatures have a delayed effect on the focus and it is certainly reasonable to expect temperature changes to be transmitted through the telescope with some lag time. Therefore the temporal correlation between each of these components and the focus requires study. This work is still in progress.

There may well be focus changes that we will be unable to model, being neither part of the smooth long-term shrinkage or the direct temperature effect or possibly resulting from untelemetered temperatures.. We suspect occasional step changes occur in the truss, as if a stress builds up and then is suddenly released. With the current overall slow shrinkage of less than one micron per year, these changes are not large enough to cause serious defocus. In fact, even though we closely monitor the focus every month, we have not seen a need to adjust the secondary mirror position since July 2009.

## POINT-SPREAD-FUNCTION MODELING

The Point-Spread Function, (PSF) is only measured for about one orbit per month and then only for a few positions on two cameras. To provide estimates of the PSF at other times and for other cameras we turn to PSF modeling provide by the program Tiny Tim written by John Krist. This is fully described in a users guide<sup>5</sup>. We have recently connected the focus modeling to the software that performs the PSF calculation. The calculated offsets from our focus model may be directly used as input to the PSF model thereby supplying values appropriate to a given observation. Again, a description and instructions for using this software are provided on the above-mentioned web site.

The width of the PSF is commonly between one and four pixels so that the central core is critically sampled or undersampled. Consequently the detailed shape of the PSF depends on how the center of the PSF aligns with the center of a pixel. The method of effective PSFs described by Anderson and King<sup>6</sup> provides a way of modifying the Tiny Tim generated PSF to match a target in a specific observation. Use of this method considerably improves astrometry and has a positive influence on photometry in crowded fields.

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