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MEMORANDUM

TO: HST Project, STScI Hubble Mgmt.
FROM: Matt Lallo, Ron Gilliland, John Hershey
DATE: 4 January 2000
SUBJECT: Version 3. OTA Focus Review & Status Entering SMOV3A

This memo consists of five sections:

- Overview of desorption history, commanded mirror moves, focus accuracy
- A discussion of recent focus behavior and an assessment of focus status entering SMOV
- A review of our past focus monitoring & maintenance
- The addressing of concerns & our plan to determine a mirror move in early SMOV
- Supporting plots and figures

Focus history, mirror moves, typical accuracy

The graphite epoxy metering truss assembly controls the OTA primary and secondary mirror relative positions. The graphite epoxy experiences a slow desorption resulting in expected shrinkage with time and progressive focus errors which are corrected by moving the secondary mirror away from the primary using commandable actuators associated with the secondary mirror.

Figure 1A shows the HST desorption range as measured by the FOC and WF/PC prior to 1994 (Hasan 1993), and by WFPC2 from 1994 to present. The break in these two distinct sets of data is indicated by day zero. Over the period 1990 August to 1993 November during the time that all HST instruments were adversely affected by the spherically aberrated optics the full range of desorption was about 90 μm (secondary - primary mirror separation) which was rather coarsely corrected with a total of six secondary mirror moves over 1990-1993. With the late 1993 installation of WFPC2 and COSTAR the imaging performance of HST was dramatically improved via corrections for spherical aberration of the primary mirror. The improved image quality implied tighter constraints needed to be maintained in terms of the HST focus in order to effectively realize the highest possible image quality. Figure 1A (day 0 onward), and figure 1B show the full range of OTA desorption based on WFPC2 monitoring observations since the beginning of 1994. The full desorption from January 1994 to November 1999 is about 35μm and this has been corrected for with 9 separate secondary mirror moves over 1994-1999 (two additional moves were used in NIC3 campaigns and additional moves of large amplitude in early 1994 were used for calibration purposes). The total desorption shrinkage over the 9+ year period is close to 150 μm.

It is worth noting that for the final alignment and characterization of WFPC2 image quality the secondary was repositioned (Krist and Burrows 1995) on 28 February 1994 to both -360 μm and +360 μm settings (and returned successfully to nominal zero). All recent and expected secondary mirror moves through the remaining HST mission to account for desorption remain well within the actuator ranges experienced during this test.

Since the installation of WFPC2, focus monitoring has been conducted using calibration data from WFPC2 and the phase-retrieval analysis of Krist and Burrows (1995). From 1994 to 1997 the OTA focus was nominally maintained to a tolerance of +/- 2.5 μm for WFPC2 and the COSTAR Deployable Optical Bench was adjusted independently to maintain +/- 1.5 μm for the more sensitive Faint Object Camera. Following the installation of STIS and with the expectation of lower desorption rates a nominal tolerance of +/- 1.5 μm for the OTA focus has been adopted. As in any calibration and monitoring program observations related to focus are kept to the minimum deemed reasonable. In the case of focus monitoring any individual measurement has associated uncertainties of 1 to 2 μm, i.e., a value comparable to the desired tolerance. The ongoing focus monitoring program by design only returns information sufficient to correct for slowly varying trends for which averages of many data points can be used. Evaluation of the nominal focus for any single observation also involves correction for OTA "breathing" which has a typical range of +/- 2 μm each orbit, but can range much higher than this following anomalous pointing and thermal conditions.

Over the about 70 months from 1994 - 1999 a review of focus monitoring data shows that we have apparently been outside nominal tolerance levels for multiple months only twice: once for about 4 months at +5 μm compared to nominal 2.5 μm tolerance over November 1996 - March 1997 (the last months of FOS and GHRS during which much less WFPC2 data was acquired than usual) and about 6 months at about -2.4 μm compared to a nominal 1.5 micron tolerance over March 1999 - September 1999. Figure 5 best illustrates these two periods. Taking into account the immanently reasonable desires that (1) a minimum possible number of calibration orbits should be used for monitoring, (2) the OTA secondary mirror actuators be used only when absolutely necessary for the quality of HST's science program, and (3) the overall level of desorption during the WFPC2 era is about 35 μm, perhaps with a non-uniform temporal behavior to be discussed further below -- these results are viewed as good.

Focus offsets lead to a broadening of images in the detector focal plane. Since the HST point spread function is so exquisitely sharp to begin with, even small focus errors can significantly impact the quality of science data. For the PC1 of WFPC2 for which nominal best focus is maintained, offsets of +/- 2 μm (normal orbital breathing range from best focus) lead to relative photometric errors with a 1 pixel radius aperture of about 3.7% for F555W filter and PC1 observations. The small aperture errors exhibit a quadratic dependence on focus offset; with a zero point error of -3 μm the +/- 2 μm typical breathing range over an orbit induces a photometric range error of 13.1%, or a factor of 3.5 larger than for nominal best focus. While this sensitivity to orbital breathing drops for larger radius apertures (e.g., to 1.0 and 4.2% respectively at a 3 pixel radius aperture), demanding applications of HST imaging directly encounter limitations from focus errors at or beyond our adopted 2.5 micron tolerance.

Outside of the issues of preparing this justification for a contingency mirror adjustment during SMOV we are reviewing whether a revision to existing monitoring programs to obtain more frequent data are warranted.

Recent behavior and pre-SMOV focus status

Assuming WFPC2 focus monitoring accurately reflects OTA behavior (*i.e.* that WPFC2's instrumental signature is constant with regards to focus effects), then overall shrinkage of HST's OTA does not follow a simple and predictable curve, as evidenced in Figure 1B which shows WFPC2 PC phase retrieval determinations of focus, with breathing corrections made to the data from 1996 onward, and with the shrinkage-compensating Secondary Mirror (SM) moves backed out to present the accumulated trend. This behavior complicates mirror position determinations and predictions which are important for keeping within desired focus tolerances.

Figure 2 plots all the focus data to date since the last NIC3 campaign in June 1998. It illustrates that during the ~9 months which followed, HST enjoyed virtually no focus trend, and WFPC2 image measurements exhibited only the normal breathing scatter around best focus (dashed straight line fit). However in late March 1999, WFPC2 focus measurements abruptly began indicating a negative SM position of ~ -2.5 µm. This focus behavior once again showed a flat trend over a number of months and persisted until early August (solid straight line fit), when a decision was made to move the SM +3.0µm on 15 September 1999. The magnitude of this move is marked and labeled, and as can be seen, +0.5µm was the expected position after this move, based on a flat trend, and 0.0µm could be expected based on a -0.25µm/month rate. (This -0.25µm/month value is the result of fitting all the data, rather than treating the two flat segments independently.) Monitoring images taken immediately after the SM move had a somewhat low mean of -0.5µm, but given the scatter in our measurements did not indicate anything significantly more negative than expected. Three subsequent visits of the monitoring proposal in October and November however gave breathing-corrected measurements of -2.5, -4.5, and -3µm. These can be seen as the last three points on figure 2 and represent independent measurements, separated by many days, indicating a lower than expected SM position. The error bars only indicate a mean of errors in the image measurement (phase retrieval) and do no not include unmodeled focus variations. Error budgets are discussed in the next section. The last point on this plot (-2.9µm) was taken 4 Nov 99, and represents the last standard focus measurement prior to SMOV, since the zero-gyro safing event precluded the execution of two more visits of the WFPC2 focus monitoring proposal.

Figure 3 represents the data in fig. 2, but with the +3µm 15 September SM move added back into previous data. As in fig. 1, this representation illustrates the focus behavior without the SM move discontinuities. An indication of some resumed negative trend or perhaps another discontinuity becomes more noticeable.

The mean of the points since the 15 September SM move is -2.6µm of SM defocus, while a straight line fit of the corrected continuous data (fig. 3) since June 1999 gives a rate of nearly -1µm /month, and a prediction of -4.5µm at the time of SMOV. Clearly care must be taken in using this subset of data to predict SM position though any method chosen gives a result which is outside of our desired focus tolerance. A routine monitoring frequency that was quite sufficient while the focus trends were more predictable and smooth, may now be inadequate given shorter timescale behavior. Fortunately, monitoring during SMOV will provide very good sampling and is discussed in the third section.

Review of focus monitoring

From shortly after the installation of WFPC2 in the first Servicing Mission, December 1993, the instrument's PC camera with its 0.46"/pixel plate scale has been used to routinely monitor standard stars as a check of HST focus among other things. Earlier monitoring of the better sampled FOC PSF was more expensive in terms of telescope resources, and the results were not easily separable from any COSTAR DOB effect, though FOC data was used as a supplement. NICMOS PSFs suffered from gross time varying instrumental signatures, and STIS observations have thus far been relatively coarse diagnostics of focus for various reasons. Despite a somewhat undersampled Point Spread Function (PSF), focus monitoring is well suited to WFPC2 whose astigmatism breaks the symmetry that makes inside and outside-focus PSFs indistinguishable. Furthermore, it is the only SI without internal focus compensation capability. Therefore the HST focus is tied directly to it.

Since the WFPC2 has proven to be dimensionally stable, the assumption is made that focus variations observed with the camera reflect the behavior of the Hubble Optical Telescope Assembly (OTA). There has been no evidence from the other Science Instrument's (SI's) observations to challenge this assumption, although this is an area of further examination by STScI.

Though various methods were originally used to assess focus from PC PSFs (Casertano, 1995), the most reliable has been the *phase retrieval* software developed by Krist and Burrows (1995). Using details of the HST and WFPC2 optics this algorithm attempts to fit the observed PSF by iteratively generating theoretical PSFs at various focus, tilt and coma values, and has been used consistently since January 1994 to monitor PC focus, expressing the result in terms of the equivalent SM position in microns. Zero corresponds to best PC focus; with negative values indicating an SM too close to the primary. This convention will be used here throughout.

Since January 1994, the WFPC2 photometric monitoring program, of which the focus monitor is a part, has taken place nominally twice a month before and after decontaminations. Since Cycle 8, the sampling has decreased somewhat due to scheduling constraints on the calibration program. This results in obtaining only one relevant visit every other month, and the usual two visits on the alternate months. Each visit consists of between one and three images of a single well-exposed PSF, a GRW standard star, in filters between 439 and 814 nm. The images are short exposures (<15sec.).

The process of modeling HST focus variations (Hershey,1997;Bely et al,1993) and the realistic assessment of measurement error in the phase retrieval are interdependent and difficult to accurately assess, but the following error estimates give a picture of the scatters and timescales involved:

• *Phase retrieval measurement error appears to be between 0.5μm and 1.5μm rms,* depending on the filter used and the amount that the PSF is defocused.

Real focus variation as seen in WFPC2 images on an orbital timescale are usually between +/-1 μm and +/-4μm peak to peak. This behavior is gleaned from particularly suitable GO science observations or special calibrations since the routine WFPC2 monitoring only samples one to three points during an orbit. Of this orbital variation, roughly two thirds is modeled by the Hershey Full Temperature Focus Model (1997). Figure 4 illustrates a particularly good case of model agreement with observations on orbital timescales. In this example measurement error was near a minimum and HST attitude was steady resulting in little trend of the orbital mean. The secondary mirror lightshield temperatures seem to be the most important agent correlating with focus found thus far, though a number of other temperature data comprise the full temperature model. A rough, first-order estimate of the light shield temperatures' affect on focus made via the model and by observations at unusual pointings is approximately: ~ +1°c ΔT at the lightshield = +0.5μm despace of the secondary. This relationship should only be used for a general idea of magnitudes in question.

• Offsets from orbit to orbit over longer timescales, many orbits to days, are also part of the HST OTA's behavior. These mid-frequency variations are irregular and depend on attitude combinations and history. Though the full temp model (unlike earlier relative breathing models) addresses this behavior to some degree, it is not as effective as when describing orbital effects, since inadequate calibration data was available to properly constrain the solution. This mid-timescale effect is something of a wildcard when attempting to assess SM position from limited data and it is inferred from interpreting the focus data that it can account for up to 3μm of unmodeled scatter, and possibly more given unusual attitude histories. Figures 5 & 6 show the overall focus maintenance for the past six years with and without breathing correction. *The effect of the full temp model correction is impressive, with rms scatters reduced around 50%.* However it is also clear that there is a good deal of remaining scatter which is both beyond that of the measurement error, and clearly not part of any smooth overall OTA trend. The characteristic sawtooth pattern of desorption followed by compensatory mirror moves is also seen in the plots. The 18 March 1997 move *toward* the primary was made to partially offset the previous move which overshot, due to the fact that it was calculated based on a linear fit to the data, which had in fact begun to level off and better follow an exponential. Also note in figure 5 the tight focus control that has been achieved since that last 18 March mirror move, until the recent discontinuous behavior. *During this two year period, HST focus was kept within +/-1.5μm, significantly better than in the pre-SM2 epoch, and with a minimum of mirror moves (two; both built into the NIC3 campaigns).*

• Long term, the OTA shrinks, presumably due to desorption of moisture from the truss. This has resulted in ~150μm of accumulated SM motion towards the primary, and ~35μm since the beginning of 1994, requiring period corrective SM moves to stay within an overall focus tolerance. Figures 7A and 7B show the OTA shrinkage rate deviating from an exponential which was fit to the data after SMOV2.

Concerns & SMOV plan

WFPC2 will begin a PSF monitoring program at HST release +4 days. Three visits on SMOV days 4, 5, and 6 will provide eight focus points spread over one orbit per visit. This total of 24 focus points, which have been *quick-looked* for rapid data receipt, would be measured in a short turnaround mode. These additional data would be a valuable supplement to our existing points, and will refine our understanding of the focus state since the 15 September mirror move. From this, a decision can be made for a mirror move to take place if needed, at its allocated point in the current SMOV timeline (during the gyro calibration), relatively early in SMOV and before all other impacted calibrations.

The SMOV3A WFPC2 monitoring is very similar to those made routinely and during SMOV2, which showed no systematics compared with pre and post-SMOV2 monitoring data. Other concerns associated with an accurate refocusing are addressed below, but note that any elevated relevant temperatures encountered during the SMOV3A focus monitoring would have an effect of moving the secondary away from the primary, producing a positive focus bias. *Therefore if data is measured at low focus, consistent with or below our pre-SMOV points, the concern of elevated temperatures only enhances the justification for a move*. Assuming that SMOV focus measurements return internally consistent results indicative of a negative focus error below the -1.5µm tolerance, then a request will be made for a corrective move to +1µm

SMOV Focus Analysis Timeline:

Day	Activity	Responsible
28/29/30 Dec	WFPC2 visits to be used for focus monitoring analysis. Last visit completed 4 p.m. Thurs. 30 Dec	STScI
30 Dec	all sci. & eng. data (temps.) required that night. Eng. data must be at STScI OPUS by morning 31 Dec.	STScI; science GSFC; eng. data
3 Jan	Focus analysis with model-corrected data completed	STScI
4 Jan	Internal STScI Review	STScI
6 Jan	Focus Telecon/FRR	STScI/GSFC
6 Jan	Data from 2nd set of WFPC2 focus checks available	STScI
7 Jan	Analyze 2nd set of WFPC2 focus data as confirmation	STScI
8 Jan	Send move request to GSFC if 7 Jan check is consistent	STScI/GSFC
9 Jan	Mirror move uplink	GSFC/STScI
> 9 Jan	Assess subsequent WFPC2 visits for focus confirmation	STScI

How well do our observations agree with commanded mirror moves? Due to quantization, commanded mirror moves sometimes vary slightly from those requested by STScI. We can compare our observed determination of the mirror move to the commanded by taking a mean of some number of focus monitoring points before and after a mirror move, and accounting for desorption between the pre- and post-move sets. The observed value is calculated by averaging three visits of the monitoring program before and after a given move. Three visits would contain three to nine actual measurements, span 1.5 to 3 months, and the mean would be affected by any unmodeled focus variations or long-term shrinkage trends. Figure 8a & 8b show observed vs. commanded moves. It is obvious that we are in agreement to first order. Figure 9a gives the o-c in microns vs. commanded move, and figure 9b gives o-c in% vs. commanded move. These plots have 1σ rms scatter of 1 μm, and an average of all the desorption compensating moves' o-c (excluding the NIC3 campaign) is -0.46μm. These data imply that we are achieving to within a few tenths of a micron, the commanded mirror move. The majority of mirror moves lie in the 2-6μm range, and the relative error associated with measuring those deltas is comparatively large. While interpretation of the meaning of these plots is somewhat open, *it is clear that given the scatter in the sparse number of data points averaged, any remaining systematic o-c is trivial compared to the behavior of interest in recent focus monitoring (fig. 2)*. Understanding any systematic offset that exists is important and is an effect that should be accounted for, but the evidence in-hand seems to exonerate the secondary mirror moves as a cause of recent unusual focus behavior, especially when one considers that the first discontinuity in question. (fig.2, March 99) took place in the absence of any commanded mirror move, and the second event of interest, the last three focus monitoring visits, occurred well after the last move in Sept. 99 which had one of the best o-c values seen from initial measurements.

The table below lists requested, commanded, and observed mirror move deltas.

Date	req. move	cmd. move	obs. move	o-c delta
29Jun94	5	4.75	4.72	-0.03
15Jan95	5	4.75	3.92	-0.83
28Aug95	6.5	6.54	4.99	-1.55
14Mar96	6	5.94	5.76	-0.18
30Oct96	5	4.75	4.52	-0.23
18Mar97	-2.4	-2.38	-2.44	-0.06
01Feb98*	2.4	2.57	2.21	-0.36
04Jun98	16.6	16.64	14.99	-1.65
28Jun98	-15.2	-15.35	-13.17	2.18
15Sep99	3.0	2.97	2.57	-0.40

* The 1 Feb 98 move is the net result of two large NIC3 campaign displacements between which no monitoring data was taken. The two moves were thus treated as one.

WFPC2 correlation with STIS. A review of STIS monitoring data, none of which has been taken to support high-fidelity measurements of focus (e.g. narrow band imaging observations or extremely small slits are used for this) do not suggest any anomalies. The most sensitive STIS record examined involves the cross-dispersion width of near-UV spectra, and trending is consistent with a small offset (broader spectral order) during the times WFPC2 monitoring from March to Sept. 99 suggested a despace of -2.5μm.

Can the phase retrieval algorithm discriminate between focus, and tilts or decenters? And is it scaling to mirror position properly? The phase retrieval software generates a model PSF based on an estimate of the optical aberrations and compares that model to the data. The estimates are then tweaked and a new model generated. This procedure iterates until the observed and model PSFs agree to within some predefined error limit. For analysis of monitoring data for which the goal is to determine despace errors, the well established astigmatism and spherical aberration values are fixed, and coma is the only higher order term that is fit. Because coma varies with filter in WFPC2), it is typically given a starting value of 0.0.

The primary factor limiting the fit accuracy is that the observed PSFs are in focus (or nearly so). In this case, the available number of pixels to fit is small and the dynamic range is large over that limited sample. A small change in the centering of the PSF, for instance, could make large changes to the pixellated image. This could lead to non-unique fits. Only when the PSF becomes more defocused is there enough resolution to properly differentiate the wavefront aberrations.

At exactly best focus, it is essentially impossible to derive coma (our only fit parameter other than focus) with any accuracy, given the fairly low levels that exist in the telescope. And since there is some uncertainty due to wavelength-dependent blurring, CCD pixel charge diffusion, and centering, it is also difficult to accurately determine focus +/- 1μm of secondary mirror despace.

The fact that we can measure focus with any reasonable accuracy at all in the monitoring data is due to the presence of a small amount of astigmatism in the HST+WFPC2 system. At larger despaces (>2μm) of the secondary, the ellipticity in the PSF caused by astigmatism becomes significant, and the axis of this ellipticity changes by 90° through focus. Given a good fixed value for the astigmatism, or even a good starting guess, it is fairly easy in this case for the phase retrieval software to change focus and obtain a good fit to the data. Close to focus (< 4μm) there still exists some give-and-take between coma and centering. Without this additional “hint” given by the astigmatism, there would be a larger uncertainty in focus.

In short, we cannot accurately measure changes in coma and astigmatism caused by tilts and decenters of the HST secondary mirror with near-focus WFPC2 data. FGS may be useful for such constraints through s-curve sensitivity; no problem have been noted.

The phase retrieval process produces an estimated wavefront described by a series.

$$W(r, \theta) = \sum_n c_n \alpha_n Z_n$$

where the Z_n's are the modified Zernike polynomials as defined in the OTA handbook (1989), and the c_n's are the rms wavefront error in microns. The focus polynomial used is $Z_4 = r^2 - 0.554450$, r=normalized radius in the pupil plane, and α_4=3.89, (OTA handbook, 1989).

The relation between despace (secondary to primary mirror distance) and c_4 is:

$$c_4 = \frac{1 + m^2}{\alpha_4 8 F^2} SMdespace$$

where:

- F = 24 is the HST focal ratio
- m = magnification = F / $f_{primary}$ = 24 / 2.3 = 10.43

thus:

$$c_4 = 0.0061 \cdot SMdespace$$

The linkage between phase retrieval measured PSF changes and commanded HST secondary mirror motions was verified in the large (360μm) despace tests of 1994 (Krist & Burrows 1995)

Relating to the question of phase retrieval sensitivity to various aberrations, is the question of FGS sensitivity to such parameters as tip/tilt. STScI's FGS group has reviewed data from throughout 1999 and sees no evidence of change in the FGS1R S-curve. Analysis is continuing to produce constraints on any new non-focus errors of the secondary placement.

Are there systematic focus offsets during the SMOV period? Figure 10 is a tri-partitioned plot of the time period around SMOV2. Sharing the same time axis is the secondary mirror spider temperatures (courtesy GSFC), observed focus monitor measurements, and the STScI full temp model predictions. It should be clear from examining this plot that all three parameters indicate the BEA period of observing after the SM2 HST release was thermally stable. *The spider temperatures show a very short timescale after release, passing through the baseline temperatures and steadying at a somewhat low average during the ensuing BEA period*. The full temperature focus model describes quiescent, low amplitude (1-1.5μm peak to peak) orbital swings and very little trending during the period, *a fact which was well supported by our focus monitoring observations during that time period, which as can be seen in the plot were continuous with the pre and post-SMOV monitoring points*. It is this last item, the actual data, that goes the farthest in addressing the question of offsets, with observations a few days following a servicing mission. We did not see any. As per Keith Kalinowski's email request, GSFC is understood to be reviewing thermal and mechanical considerations concerning this question as well.

Figure 11a shows the spider temperatures during SMOV1. We note a distinctly different signature in the SMOV1 temperatures after release, with a cooling trend continuing up to 10 days after release. This may have been interpreted by some to mean there are thermal inertias at work here on those timescales, however SMOV1 had no BEA period, and various attitudes of observing ensued during that time. Some of these attitudes involved sun angles towards the back end of HST, which is known to produce cool temperatures and low focus. Unfortunately we have no focus data taken during that time as an observational check, but figure 11b gives the various attitude histories extracted for that period, and overplots our resulting attitude-based focus model which describes to some degree the negative excursions, mainly as a result of the large sun angle. How well the attitude model correlates with the spider temperature behavior is of secondary importance, and the attitude information is presented here to illustrate that *the post-release phenomenon noted in figure 11a is likely not the result of a thermal relaxation time, but rather an artifact of our dynamic observing program at the time*, which unlike SMOV3A and SMOV2, involved no constrained BEA period.

We will monitor temperature data during SMOV3A, in order to observe any offsets that may be preset. We are expecting the focus model to reflect any jump or depression in temperatures with a correlated change in predicted focus, though as noted earlier, the model is somewhat less effective over time periods greater than a few orbits.

Thermal relaxation periods. Figures 10 & 11 give an indication of thermal relaxation timescales, at least for the spider/light shield temperatures after shuttle release. Valuable practical evidence of expected timescales comes from a 1995 observation when on day 54 HST, as part of a campaign to observe Mars at opposition, sustained large sun angles between 130° and 170° for 4.5 days (Miebach 1995). This was followed by a constant 170° sun angle for 12 consecutive orbits. This prolonged near-antisun attitude (180°=sun at -V1, normal to aft shroud base) produced unprecedented cold metering truss temperatures of -16°C and very cold lightshield temperatures of ~-45° Though FOC observations taken immediately following this attitude were affected by poor focus, *the lightshield temperatures relaxed back to nominal in ~10 orbits*, and subsequent FOC observations taken at the end of that period showed nominal focus. This timescale may be slightly optimistic however since HST assumed a rather warm +60° sun angle following the antisun pointing, maximizing the ΔT and thus the rate of equilibration.

Long-term change in OTA temperature variations. Figure 12 illustrates the rms scatter in OTA temperatures since 1996. The RMS's have been been generated in a moving window of about one orbit in time. The plot is only to show changes or constancy in the scatter values, so is in arbitrary undisplayed units. The light shield RMS values are much larger than the others because the light shield is most sensitive to the orbital cycle, and its scale has been greatly reduced to be compatible with the other paramters.

Figure 13 shows monthly averages of the Full Temperature Focus Model generated on a time grid of 5 minute steps. Since the model is a function of observed temperatures only, it should reflect those systematic changes in the temperatures which affect focus. There do not appear to be any clear, overall monotonic trends in the focus model across the nearly 4 years. The high point near

1998.8 has been influenced by the long-term pointing for the Hubble Deep Field South. With that point omitted there is slight evidence of an increasing variation in the last two years, and this could be due to different attitude distributions and observing strategies (e.g. increase in long programs).But it should be noted in any case the peak to peak scatter is scarcely a micron of equivalent Secondary Mirror Position, a level near the error of focus measurement.

STScI is prepared to support a telecon and/or FRR on or around 5 January 2000 to further discuss SMOV focus and a mirror move.

Figure 1A

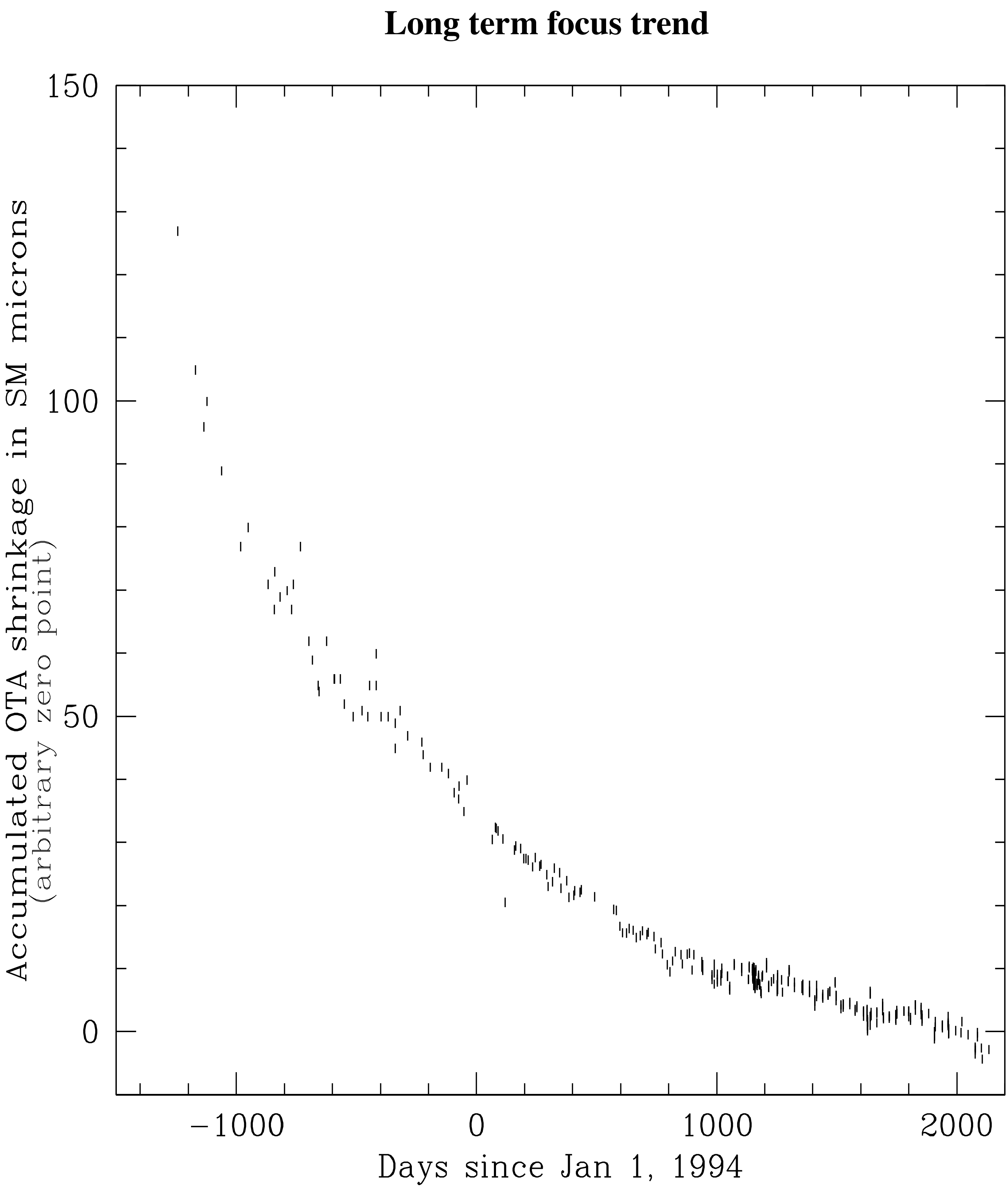

Long term focus trend
150
100
50
0
−1000
0
1000
2000
Days since Jan 1, 1994
Accumulated OTA shrinkage in SM microns
(arbitrary zero point)

Figure 1B

Long term focus trend WFPC2 phase retrieval data only

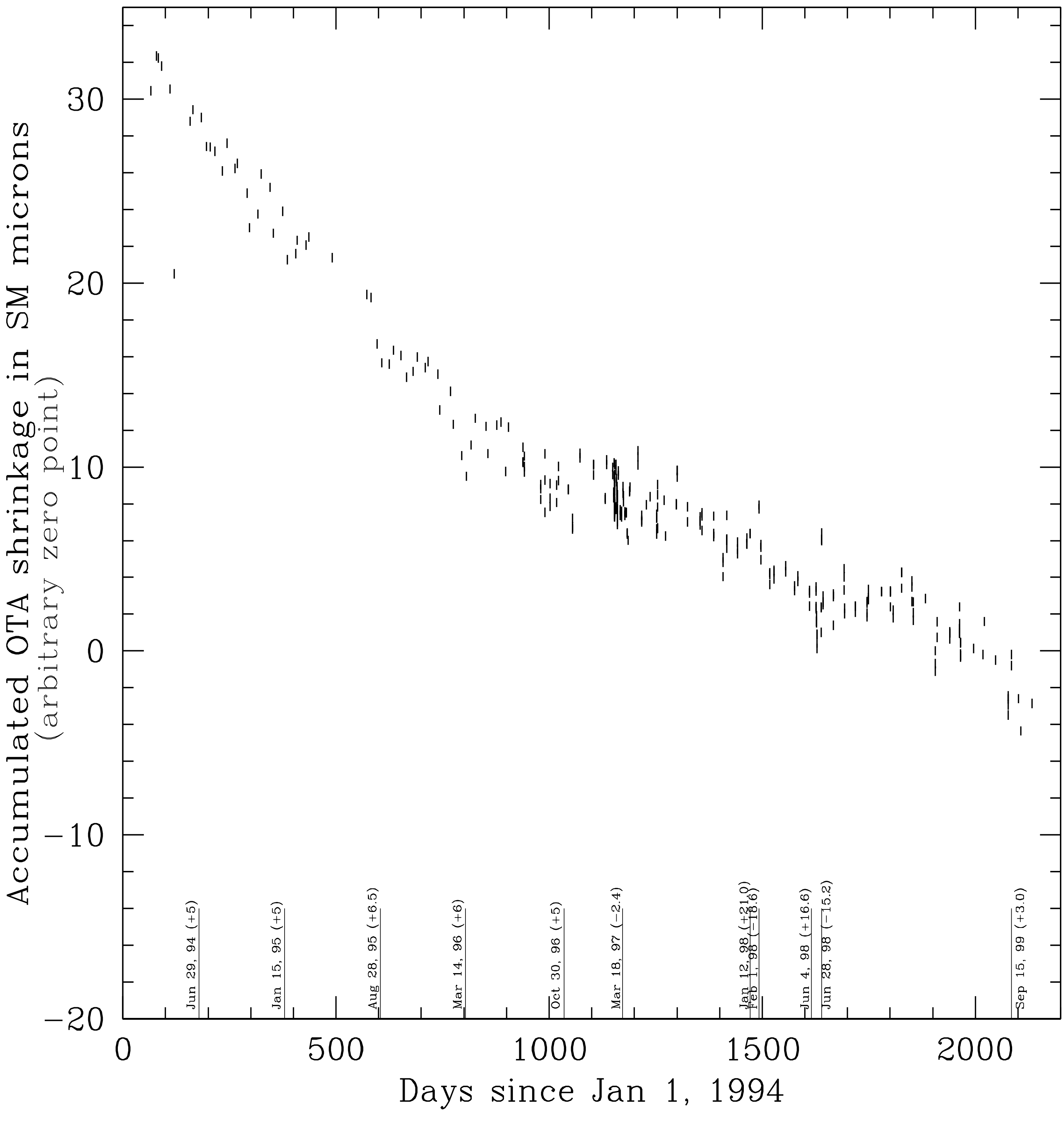


Figure 2

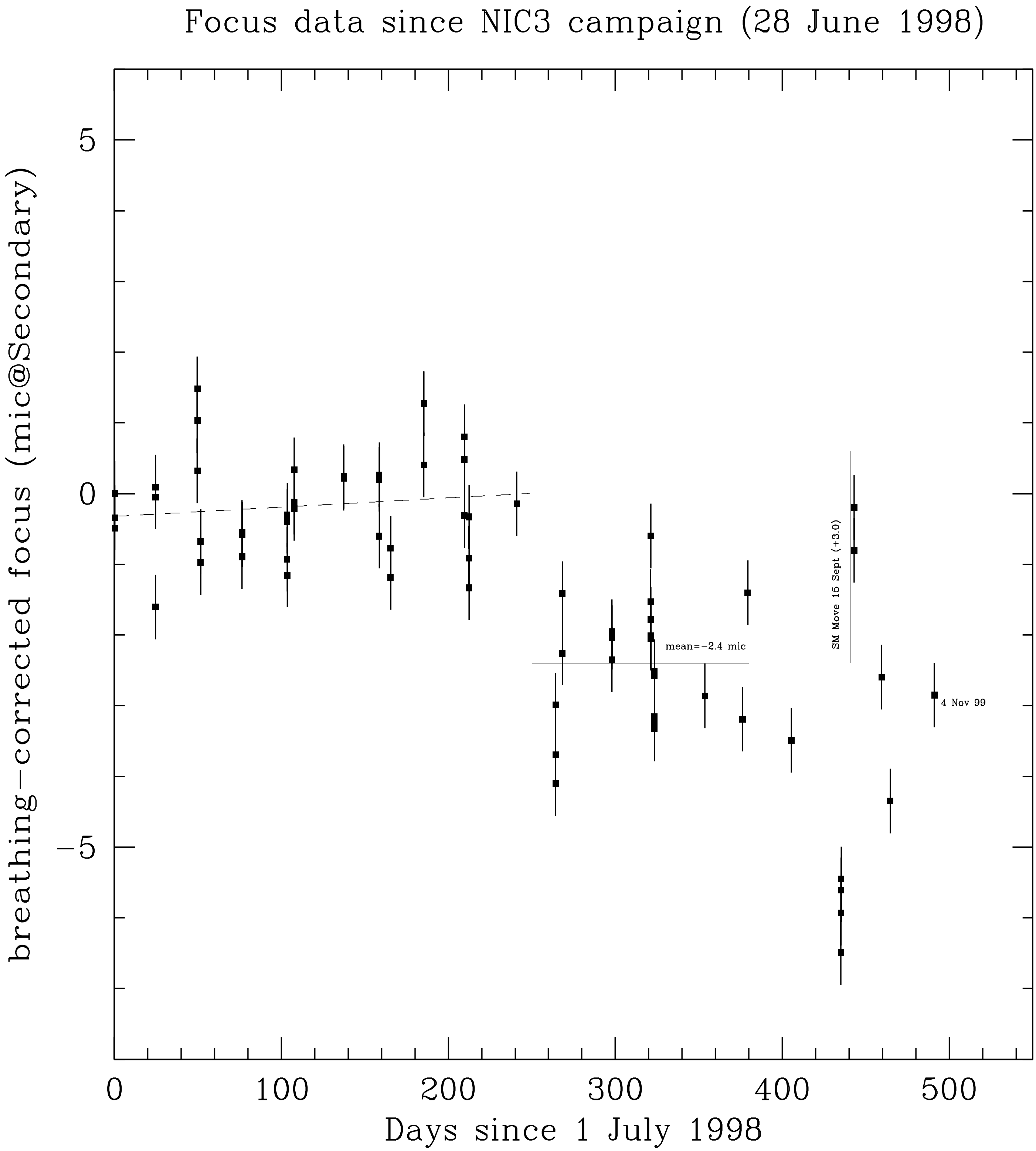
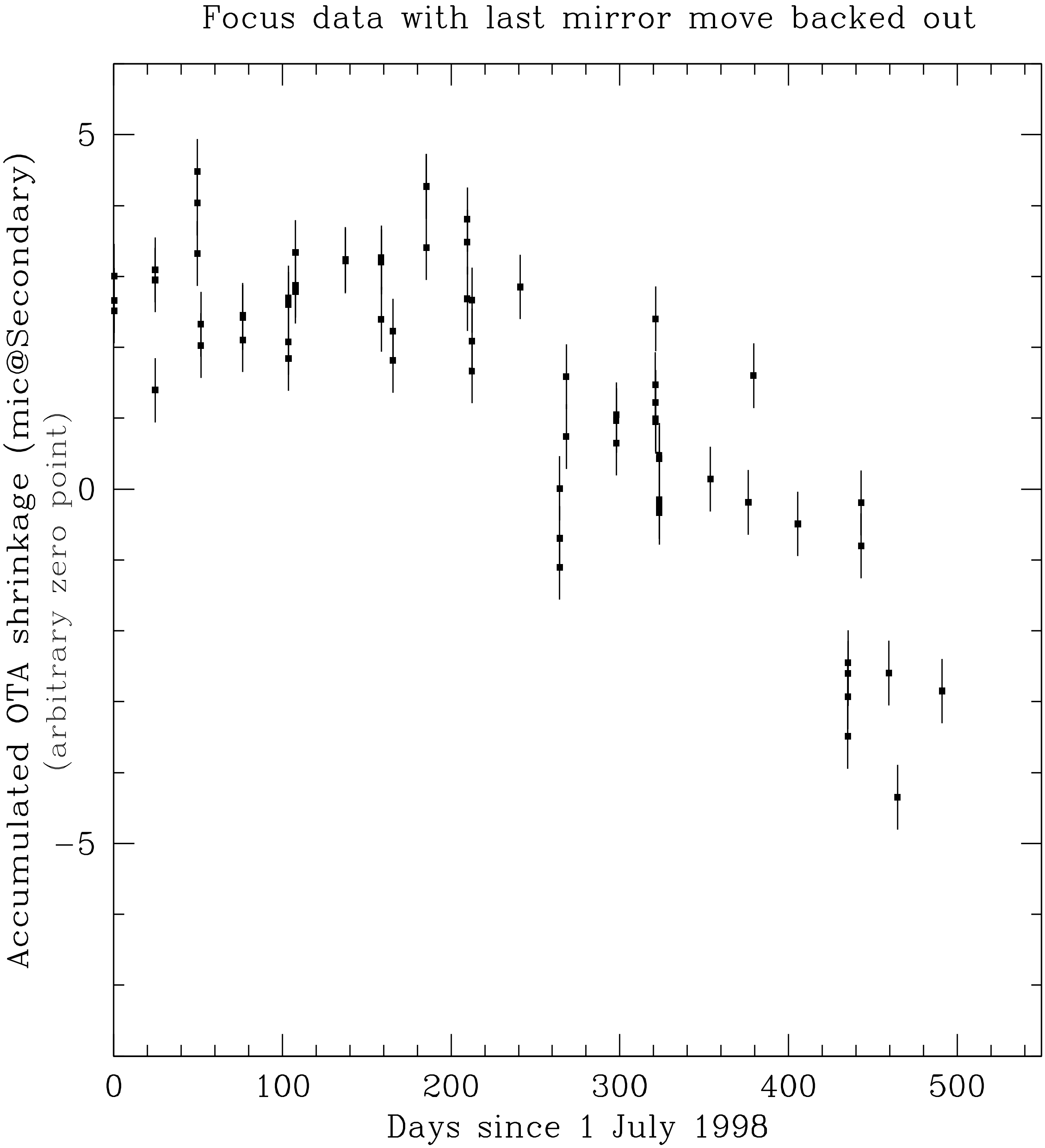

Focus data since NIC3 campaign (28 June 1998)
breathing-corrected focus (mic@Secondary)
Days since 1 July 1998
5
0
−5
0
100
200
300
400
500
mean=−2.4 mic
SM Move 15 Sept (+3.0)
4 Nov 99

Figure 3



Focus data with last mirror move backed out
Accumulated OTA shrinkage (mic@Secondary)
(arbitrary zero point)
5
0
−5
0
100
200
300
400
500
Days since 1 July 1998

Figure 4

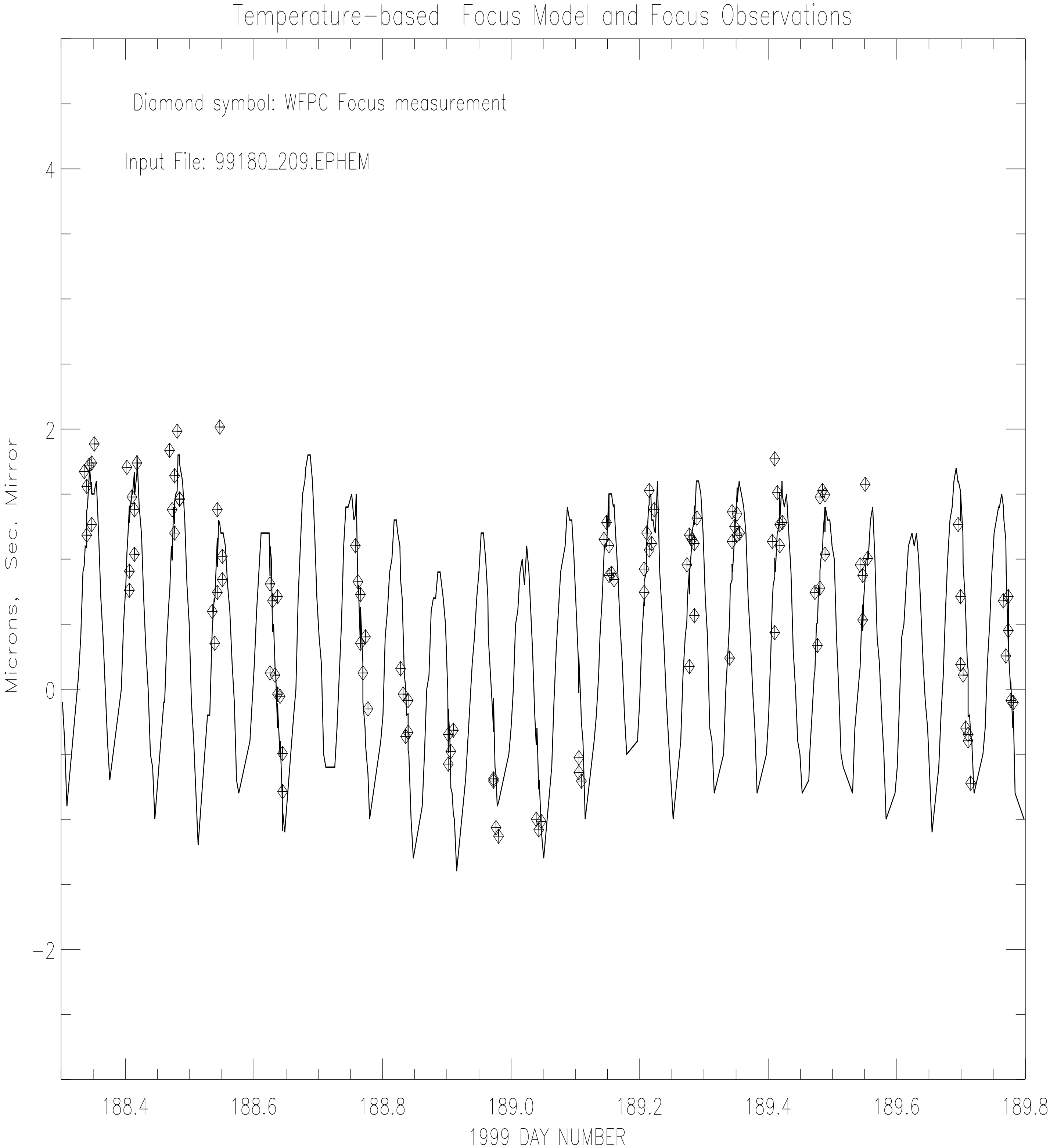

Temperature-based Focus Model and Focus Observations
Diamond symbol: WFPC Focus measurement
Input File: 99180_209.EPHEM
Microns, Sec. Mirror
4
2
0
-2
188.4
188.6
188.8
189.0
189.2
189.4
189.6
189.8
1999 DAY NUMBER

Figure 5

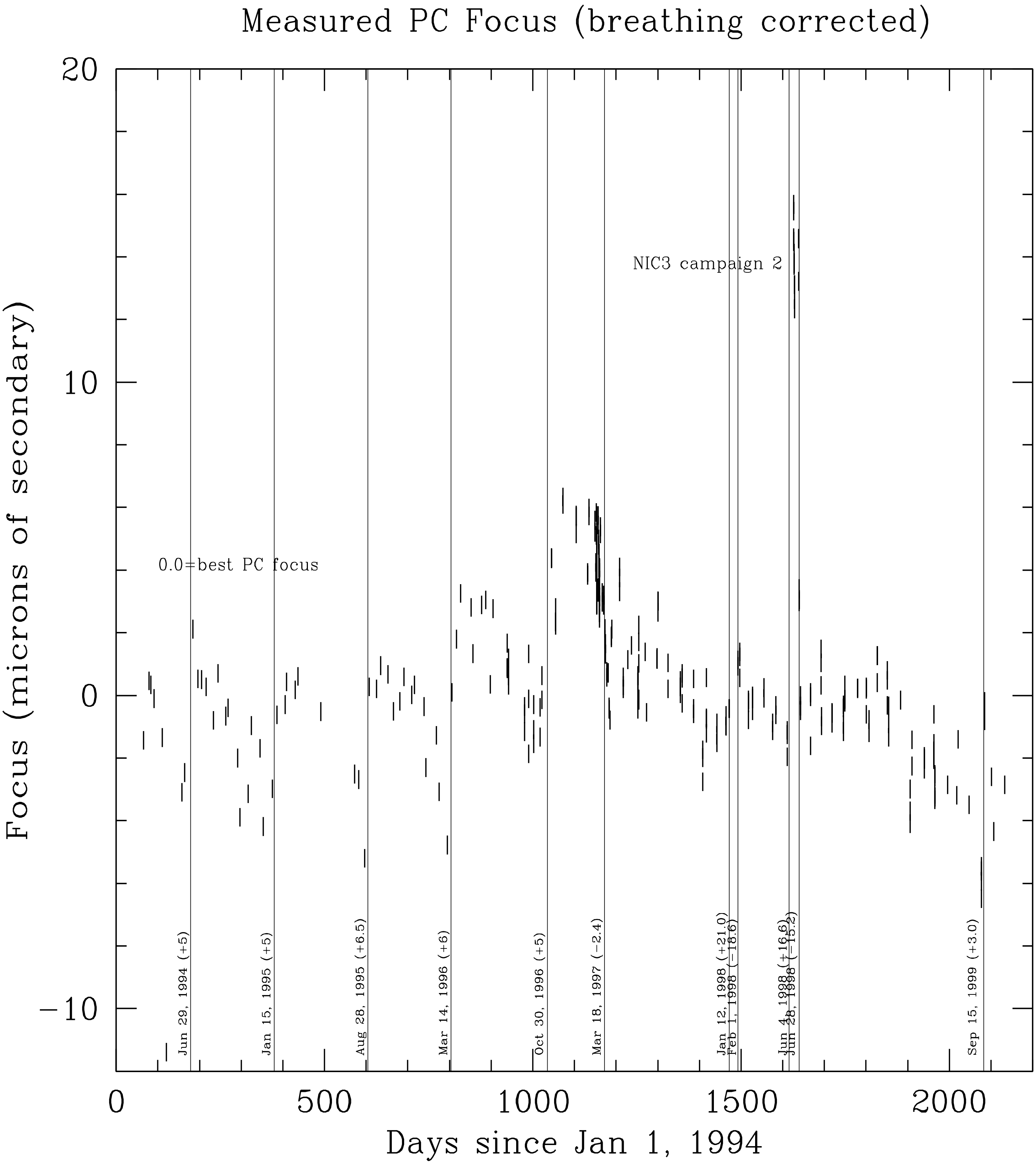

Measured PC Focus (breathing corrected)
Focus (microns of secondary)
Days since Jan 1, 1994
20
10
0
−10
0
500
1000
1500
2000
0.0=best PC focus
NIC3 campaign 2
Jun 29, 1994 (+5)
Jan 15, 1995 (+5)
Aug 28, 1995 (+6.5)
Mar 14, 1996 (+6)
Oct 30, 1996 (+5)
Mar 18, 1997 (−2.4)
Jan 12, 1998 (+21.0)
Feb 1, 1998 (−18.6)
Jun 4, 1998 (+16.6)
Jun 28, 1998 (−15.2)
Sep 15, 1999 (+3.0)

Figure 6

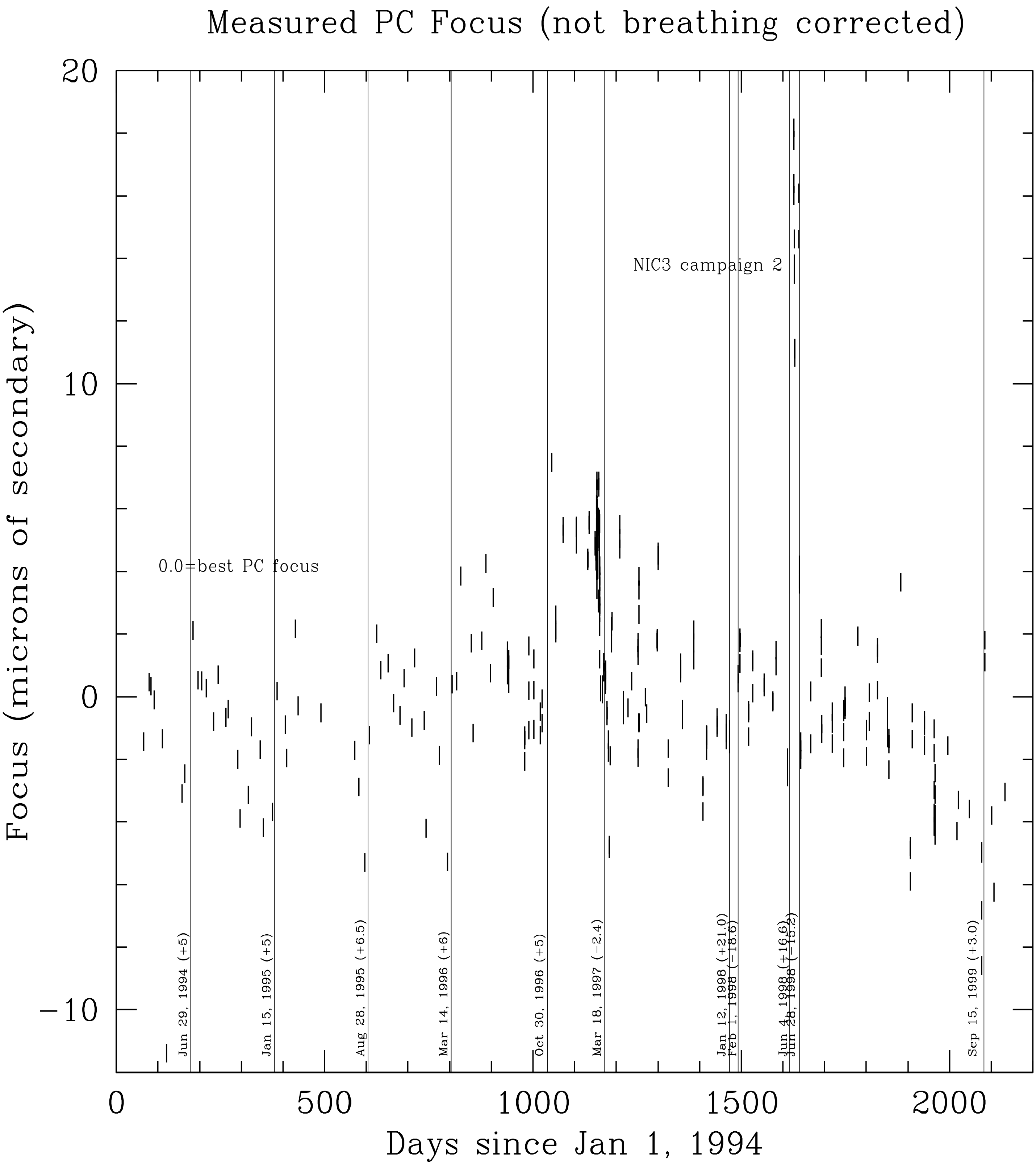
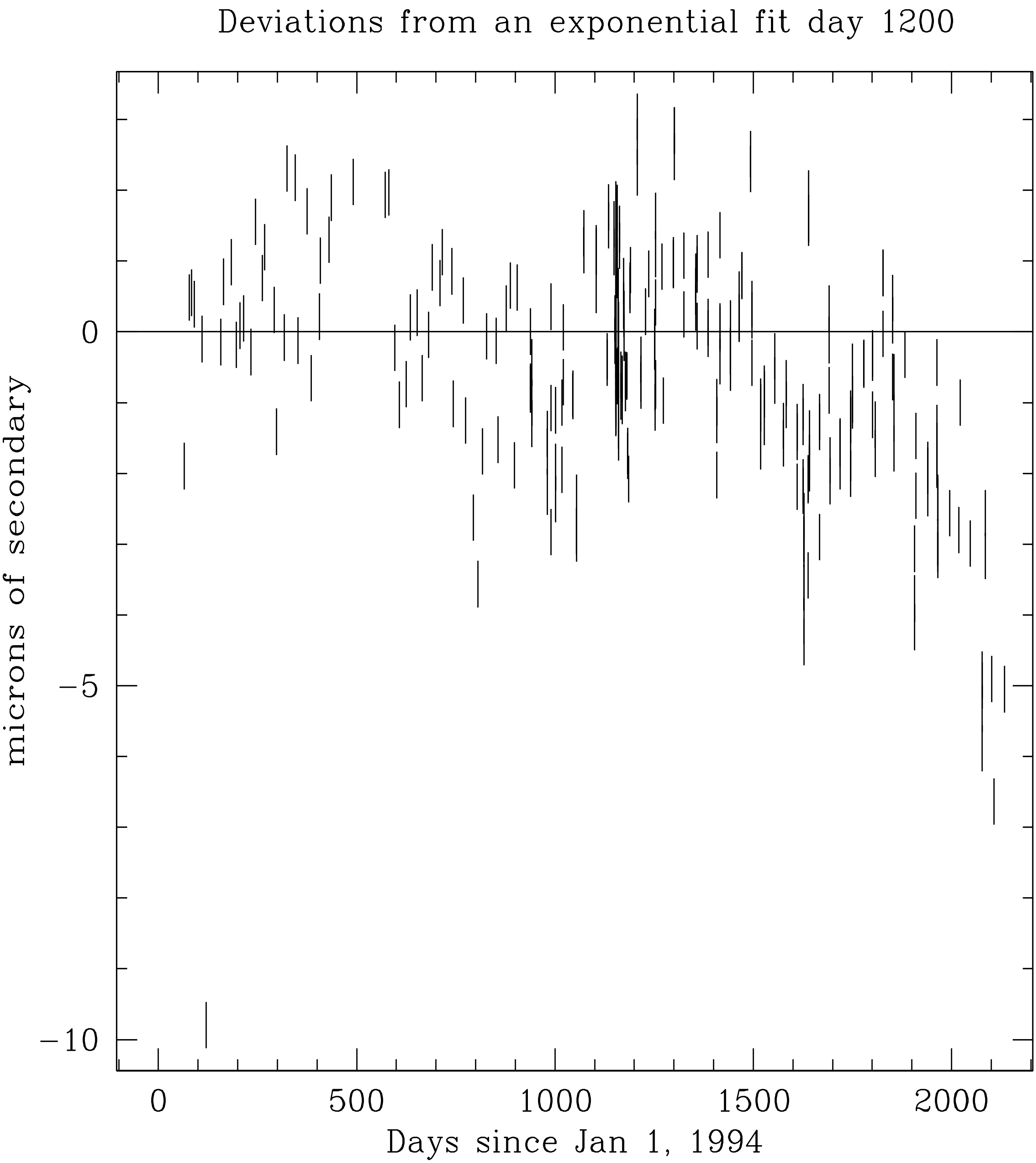
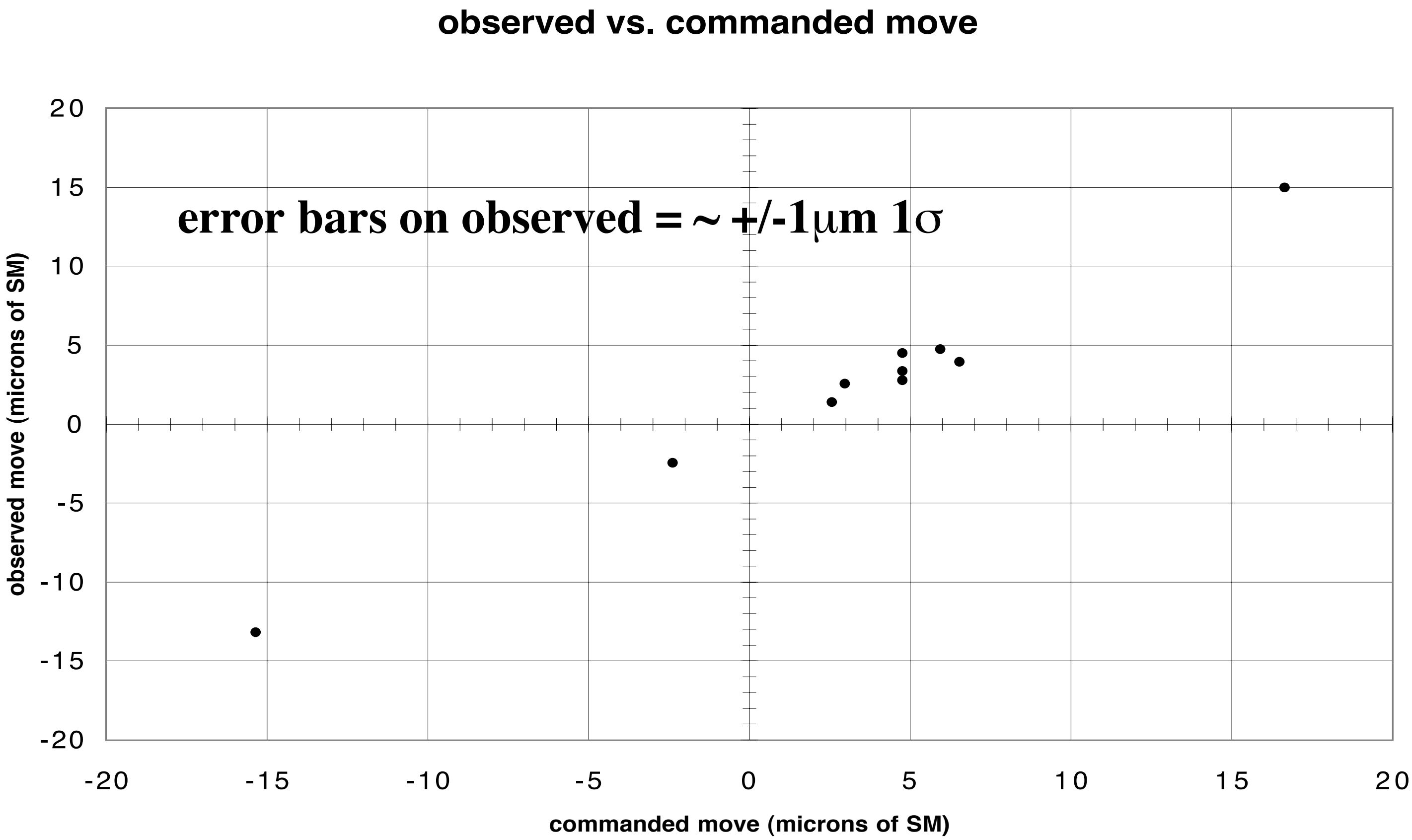

Measured PC Focus (not breathing corrected)
Focus (microns of secondary)
Days since Jan 1, 1994
0.0=best PC focus
NIC3 campaign 2
Jun 29, 1994 (+5)
Jan 15, 1995 (+5)
Aug 28, 1995 (+6.5)
Mar 14, 1996 (+6)
Oct 30, 1996 (+5)
Mar 18, 1997 (−2.4)
Jan 12, 1998 (+21.0)
Feb 1, 1998 (−18.6)
Jun 4, 1998 (+16.6)
Jun 28, 1998 (−15.2)
Sep 15, 1999 (+3.0)
20
10
0
−10
0
500
1000
1500
2000

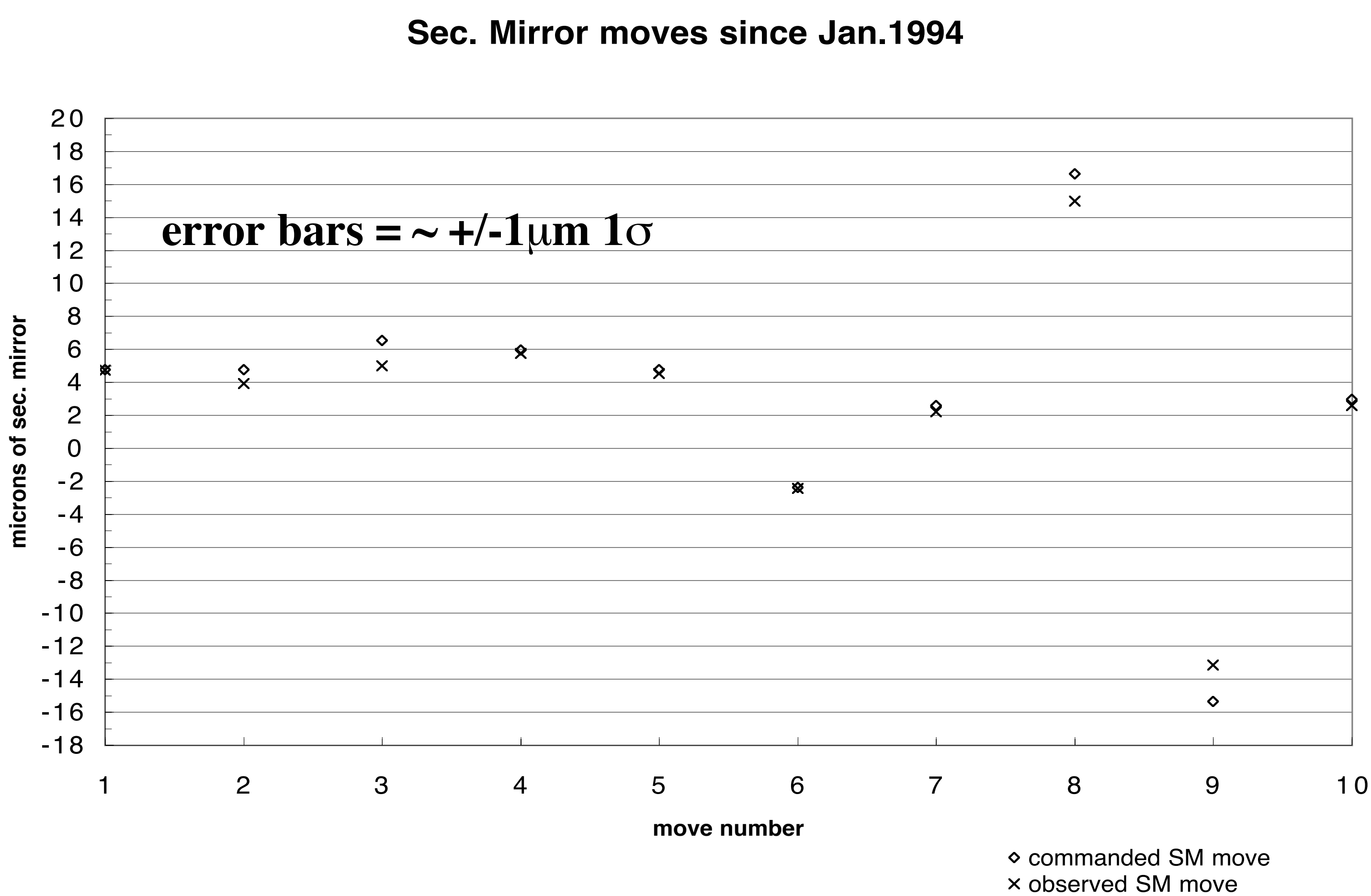
Figure 7



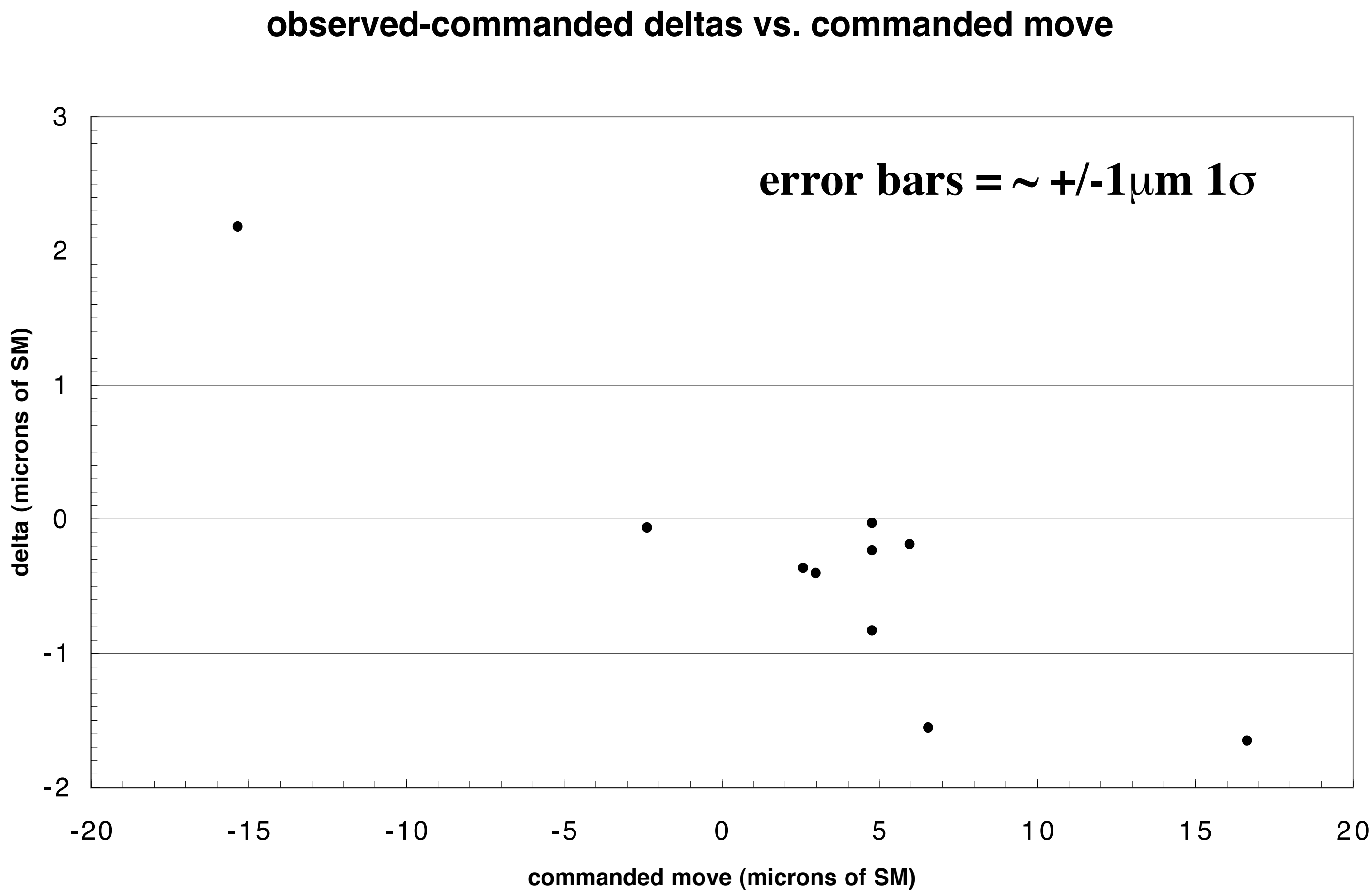
Deviations from an exponential fit day 1200
microns of secondary
0
−5
−10
0
500
1000
1500
2000
Days since Jan 1, 1994

Figures 8A & 8B





Figures 9A & 9B



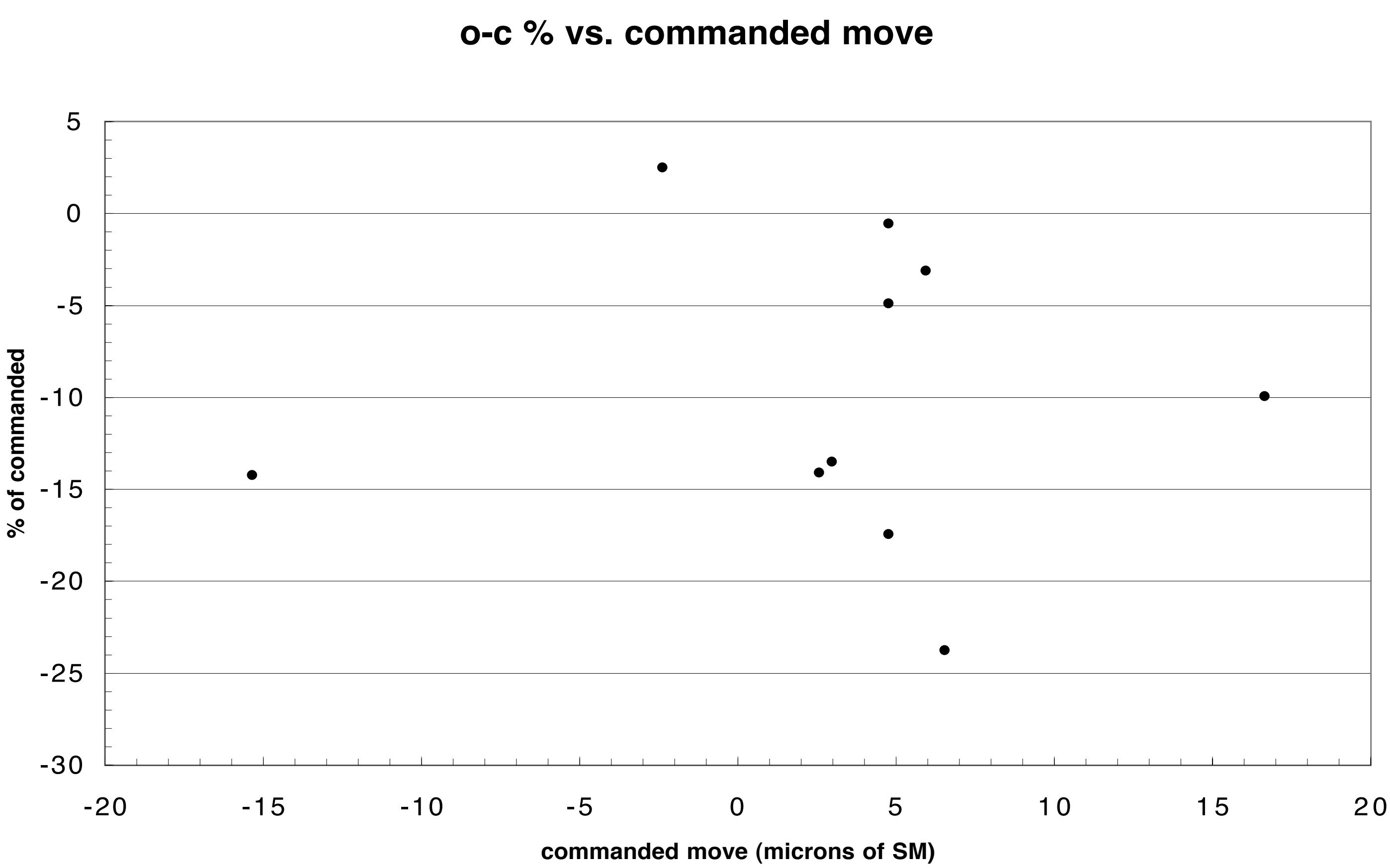


Figure 10

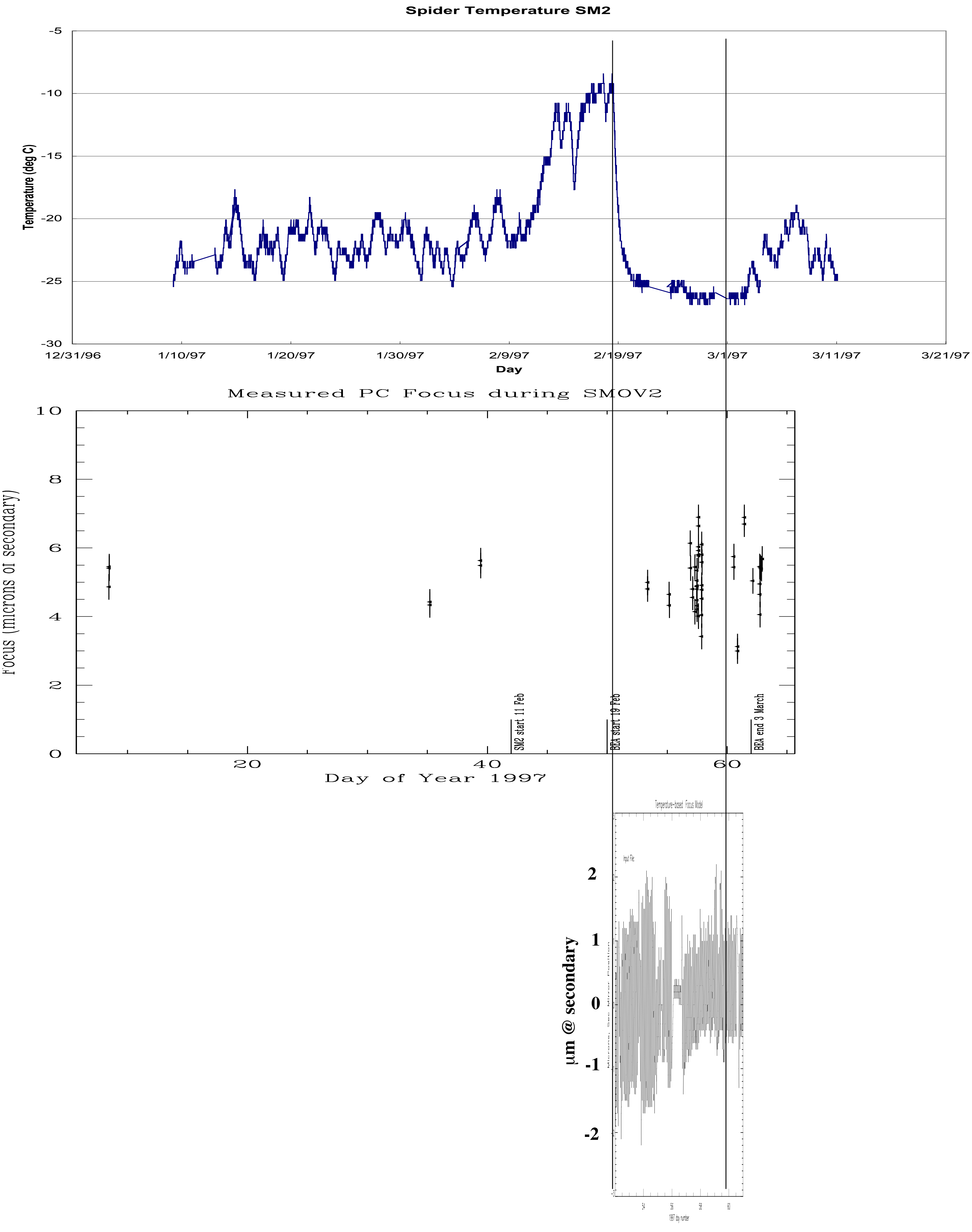
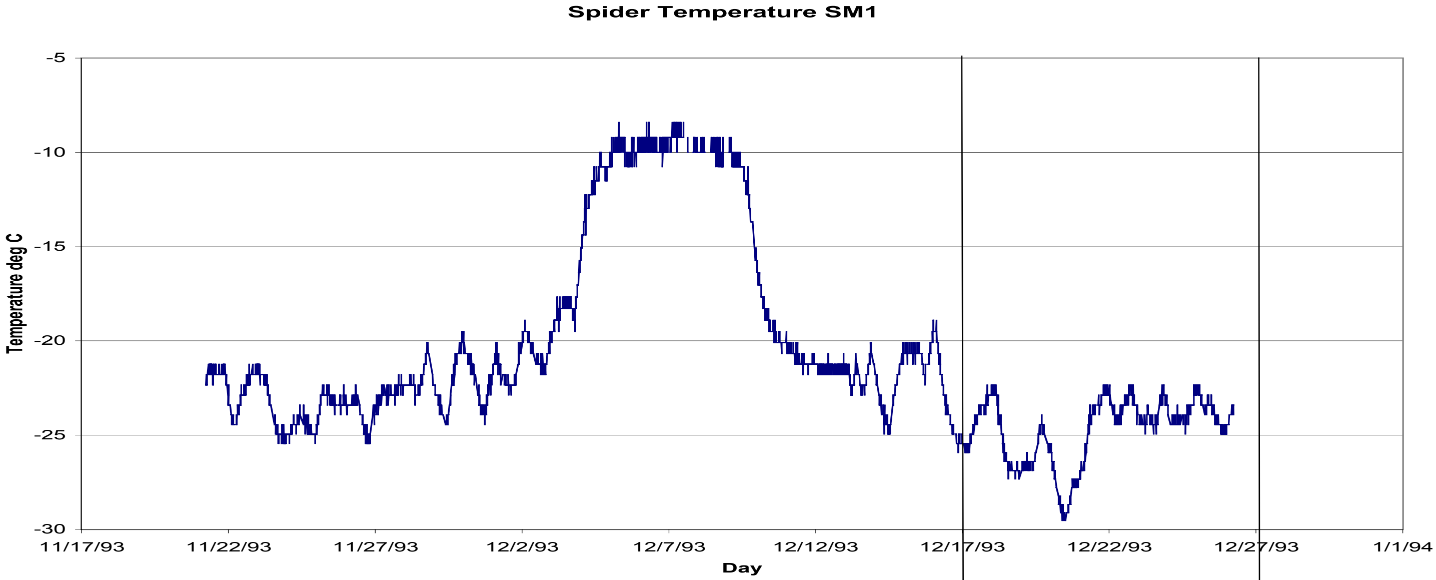

Spider Temperature SM2
Temperature (deg C)
-5
-10
-15
-20
-25
-30
12/31/96
1/10/97
1/20/97
1/30/97
2/9/97
2/19/97
3/1/97
3/11/97
3/21/97
Day
Measured PC Focus during SMOV2
Focus (microns of secondary)
10
8
6
4
2
0
20
40
60
Day of Year 1997
SM2 start 11 Feb
BEA start 19 Feb
BEA end 3 March
Temperature-based Focus Model
µm @ secondary
2
1
0
-1
-2

Figure 11


Spider Temperature SM1
-5
-10
-15
-20
-25
-30
Temperature deg C
11/17/93
11/22/93
11/27/93
12/2/93
12/7/93
12/12/93
12/17/93
12/22/93
12/27/93
1/1/94
Day

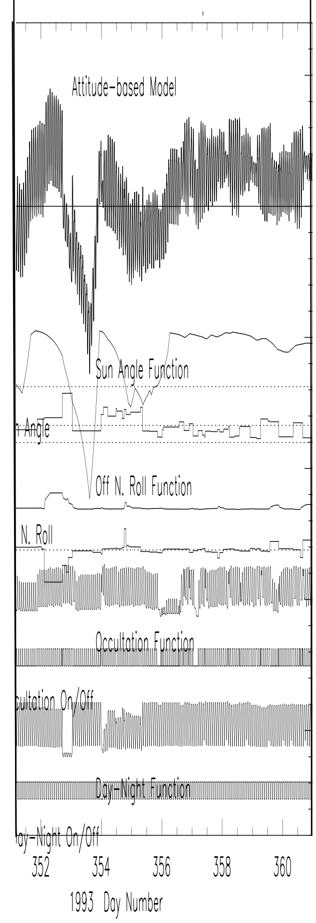

Attitude-based Model
Sun Angle Function
Off N. Roll Function
N. Roll
Occultation Function
Day-Night Function
352
354
356
358
360
1993 Day Number

Figure 12

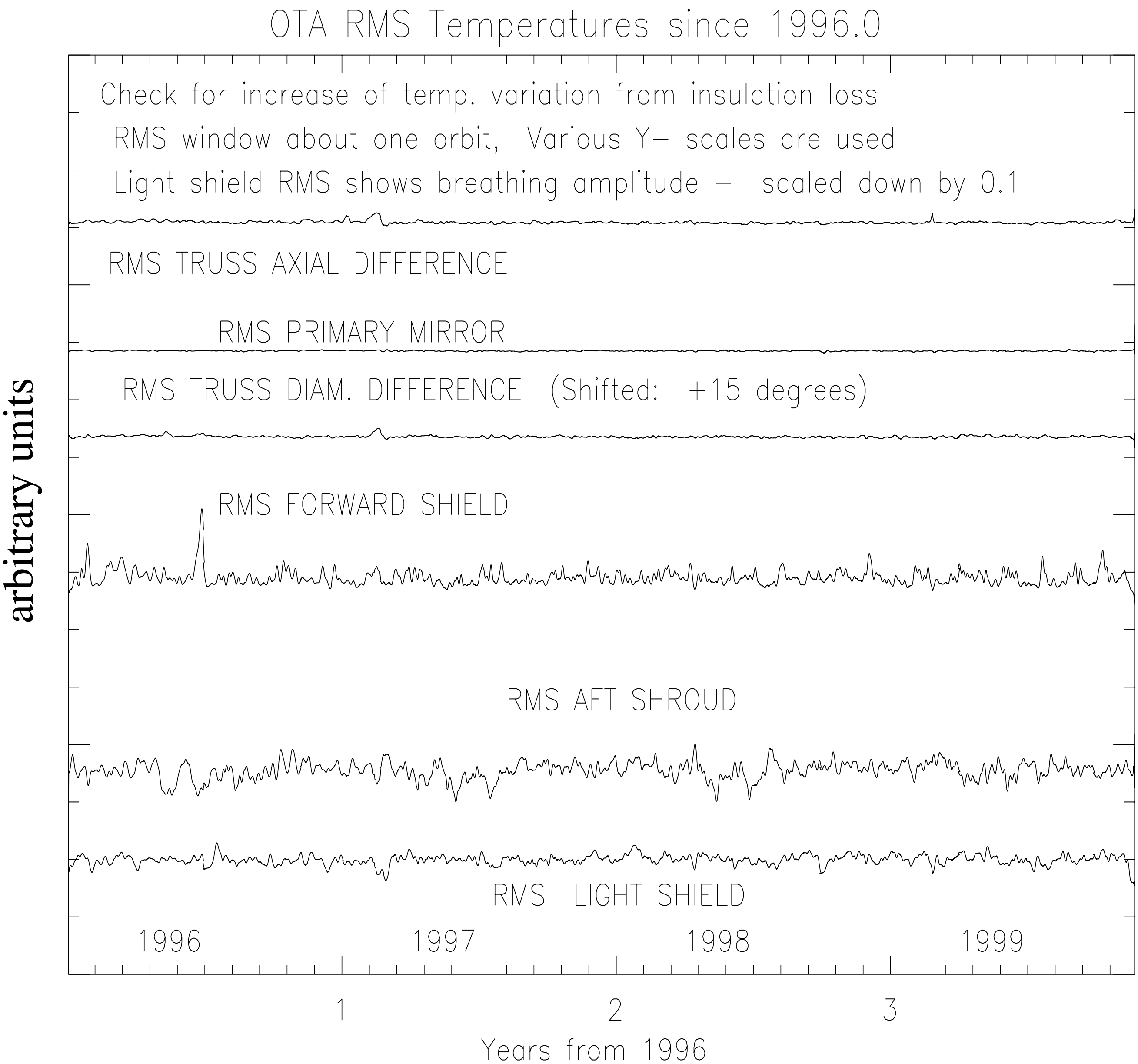
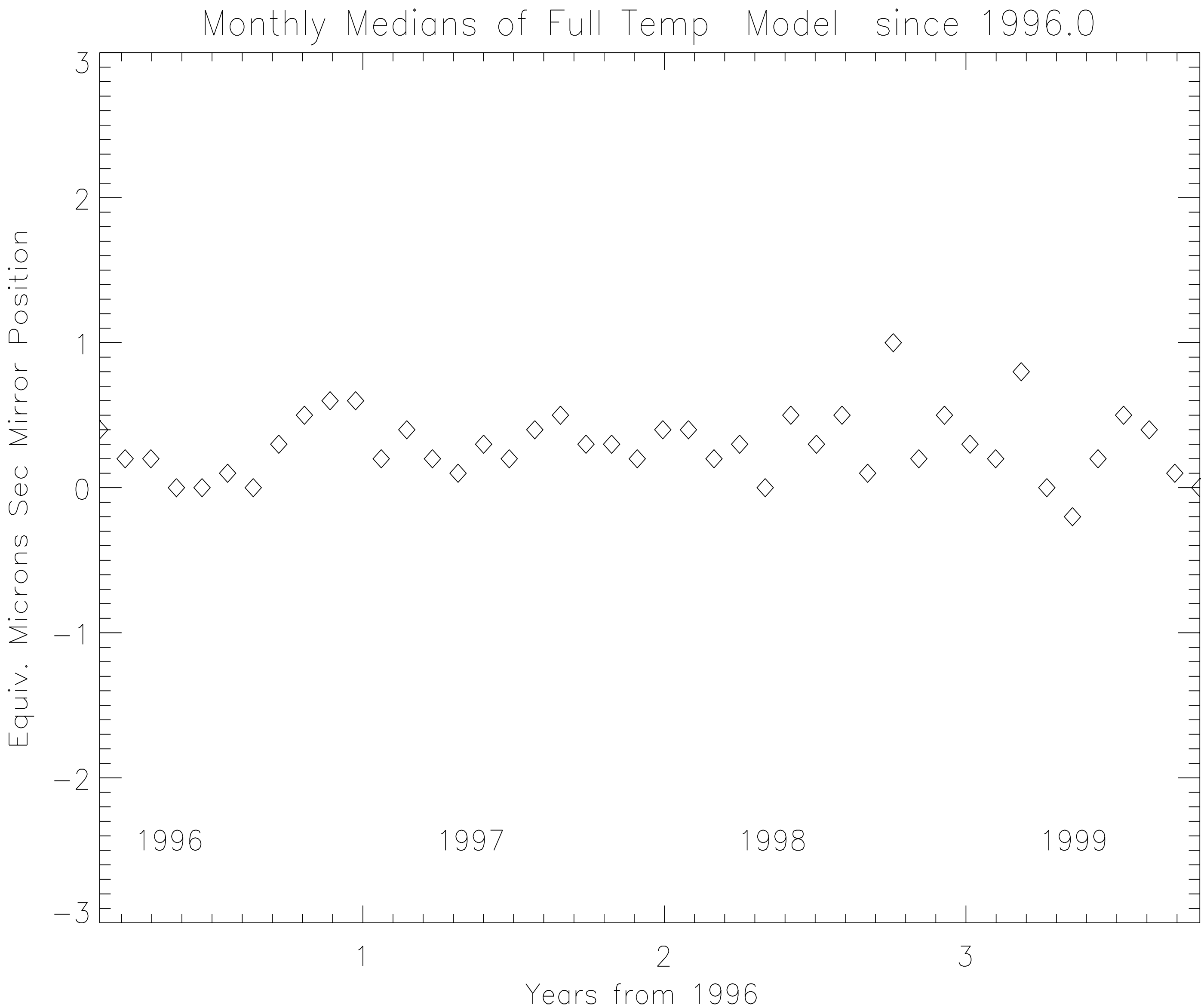

OTA RMS Temperatures since 1996.0
Check for increase of temp. variation from insulation loss
RMS window about one orbit, Various Y- scales are used
Light shield RMS shows breathing amplitude - scaled down by 0.1
RMS TRUSS AXIAL DIFFERENCE
RMS PRIMARY MIRROR
RMS TRUSS DIAM. DIFFERENCE (Shifted: +15 degrees)
RMS FORWARD SHIELD
RMS AFT SHROUD
RMS LIGHT SHIELD
1996
1997
1998
1999
1
2
3
Years from 1996
arbitrary units

Figure 13


Monthly Medians of Full Temp Model since 1996.0
Equiv. Microns Sec Mirror Position
3
2
1
0
−1
−2
−3
1996
1997
1998
1999
1
2
3
Years from 1996

References

Bely, P., Hasan, H., Miebach, M., *Orbital Focus Variations in the Hubble Space Telescope,* internal STScI report, 12/93

Burrows, C., HST OTA handbook V.1, 5/89

Casertano, S., *Focus Monitoring and recommendations for secondary mirror move,* Instrument Science Report OTA-18, 1/95

Hasan, H. *Pre-COSTAR Status of OTA Focus,* Instrument Science Report OTA-14, 12/93

Hershey, J., *Modeling HST Focal-Length Variations V.1.1,* SESD-97-01, 11/97

Krist, J., Burrows, C., *Phase Retrieval Analysis of pre- and post-repair Hubble Space Telescope Images,* Applied Optics, 34, 22, 8/95

Miebach, M., "*Out-of-focus" Observations in FOC Proposal 5144: Engineering Analysis*. Telescope and Instruments Performance Summary Report, 3/95