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MODELLING HST FOCAL-LENGTH VARIATIONS

John L. Hershey, Eng. Team, SESD

Abstract

Two types of models are in development for generating HST focal-length changes, one based on only telescope attitude-related parameters and one based on telescope temperature telemetry. In the attitude-based model, four telescope attitude parameters are used to generate focal-length changes on a 5-minute time grid: day-night, target occultation, sun-angle and off-normal roll. The model is able to generate the general characteristics of the focal-length variations, but cannot represent all observations closely. The temperature-based model uses the four light-shield temperatures near the secondary mirror in a formula similar to that developed by P. Bély in 1993 and in addition includes functions of many other telescope temperature sensors. The full temperature-based model thus far, generally represents the observations somewhat better than the attitude-based model and in recent time intervals reaches near the estimated observational error of the focus positions.

Focus-change models have been generated on a 5-minute time grid from 1994.0 with the attitude model and since 1995.0 for two types of temperature models for use in analysis of images from HST instruments. The files of focus-change models are accessible by way of a Web site, along with guidance for their use and general information related to focus change.

1 Introduction

The HST telescope framework was designed to minimize thermal effects on the focal length of the telescope. The Optical Telescope Assembly (OTA) framework is constructed of a graphite-fiber and epoxy composite chosen for its very low thermal coefficient. Nevertheless small orbit-length periodic changes in focal-length have been found. The focus changes are apparently driven by thermal changes but not necessarily or primarily due to a response of the graphite-epoxy (GE) framework to temperature change, but perhaps to other more thermally susceptible components of the OTA. The long-term contraction of the GE in the OTA was expected due to desorption and is a separate phenomenon from the orbital-period focus-change cycle or "breathing". The GE shrinkage does become involved in the analysis of breathing because the cyclical component must be separated from the cumulative contraction effect in the focus data. Now that most of the expected shrinkage has already occurred, the remaining small amount of shrinkage over several months is comparable in size to the periodic focus excursions due to telescope attitude and orbital phase. Since it is not possible to get intensive coverage of focus positions, there is some difficulty in separation of the periodic and montonic effects without a model of the periodic behavior.

In early 1993 a test of focal position behavior was conducted by Pierre Bély of the STScI Science and Engineering Systems Division (SESD). Observations of a star were taken over several sequential orbits in two extreme orientations, one at sun-angle near 90° in the CVZ and the other at the anti-Sun direction. An analysis was reported by Bély in SESD Document SESD–93–16, (June, 1993). Plots showed the focus oscillating with a period of one HST orbital period along with the temperatures of the light shield just ahead of the secondary mirror supports or "spider". This location of temperature sensors is also termed the "aft light shield", since it is at the back end of the long tube with light baffles, which extends ahead of the telescope secondary mirror. The amplitude of the focus oscillation was found to change in proportion to aft light-shield temperature amplitude.

The long-term drift of the temperature was partially removed by subtracting the mean of the temperatures in the previous orbit. Specifically, if the reference temperature at any time was defined as the mean of the 4 aft light-shield temperatures over the previous orbit, then the difference of the current aft light-shield temperature-mean from that reference value was proportional to the deviation in focus position. Or algebraically:

Focus_deviation = Scale_factor $\times$ [Mean4T $-$ 95min_mean(Mean4T)] + constant,

where Mean4T indicates the mean of the four aft light-shield temperature sensors from a data readout.

This model performed very well on the limited data from which it was developed in 1993 and has been in use ever since. The two intervals of constant sun-angle and roll were equilibrium states for sun-angle, roll, and phase difference of day-night and occultation cycles. In normal use the telescope is continually changing sun-angle, off-normal roll, and phase of day-night *vs.* occultation. Focus measurements covering a range of normal scheduling were not then available. A study of the long-term behavior of the aft light-shield temperatures and the focus measurements accumulated over several years, indicates that there are focus excursions on the time scale of many orbits due to accumulated effects of extreme attitude combinations. Development of a general-purpose model requires focus observations from a variety of attitude histories.

During the second servicing mission (SM2) in February, 1997, damage was found in the external Multi-Layer Insulation (MLI) on the telescope which gave rise to the question of whether any evidence in the engineering or science data indicated that the telescope focus was more vulnerable to orbital cycling and changes due to telescope attitude variations, in the latter part of the time between SM1 and SM2. The focus measurements covering the three years between servicing missions did not show a clear increase in scatter when the desorption curve and the Bély model was removed. However no modelling of the focus variations had been done since 1993 and thus Dana Mitchell, Engineering Team Lead, suggested further modelling to provide a stronger baseline to test for any future changes in focus behavior and to re-examine the past data for evidence of change.

2 Features of the Aft Light-Shield Temperatures

For a broader understanding of the light-shield temperature behavior, plots covering a few months were generated to show the temperature behavior over many combinations and sequences of telescope attitude. It was visually evident that sun-angle, roll, length of occultation and phase of occultation relative to the day-night cycle all contribute to the light-shield temperatures. There is not yet sufficiently intensive focus data to make the attitude dependence of the focus changes visually obvious from plots. Focus data would need to have several observations within an orbit and continue for a contiguous set of orbits to reveal the dependence on attitude and orbital events. The analysis of temperature and focus variation is not a matter of determining a single amplitude and period. The amplitude and phase vary and there are in addition irregular excursions in focal length on time scales of several or many orbital periods which are functions of the recent history of telescope sun-angles and rolls. Without the intensive, continuous focal position data, the temperatures which are available continuously must stand in for a qualitative exploration of the manner in which telescope attitude and orbital events affect the telescope.

The visual study of plots of aft light-shield temperatures relative to telescope attitude parameters shows that the temperature amplitudes are large when the target occultation cycle is nearly in phase with the day-night cycle, as occurs when the telescope is pointed away from the Sun (high sun-angle). The earth is a $300°K$ IR source and radiates energy into the end of the telescope during target occultation by earth. For example, when pointed at the anti-Sun direction, the telescope is in daylight in the same interval in which it is in target occultation (front end receiving the IR radiation of the earth). However another effect also becomes involved since at anti-Sun the solar radiation has zero-projection onto the light shield of the telescope; only the back end is illuminated. Day and occultation are

90° out of phase at sun-angle 90°. The temperature amplitude can vary from near zero (day and occultation nearly out of phase) up to two or three times their average amplitude when in phase. Figs. 1a, b and c illustrate the relative phase of day and occultation for three sun-angles for a target near the plane of the HST orbit. Not shown in the figures is the cause for change in the fraction of the orbital period spent in occultation. As the angle of the target from the plane of the orbit increases, the fraction of the time in occultation decreases, reaching zero in the CVZ.

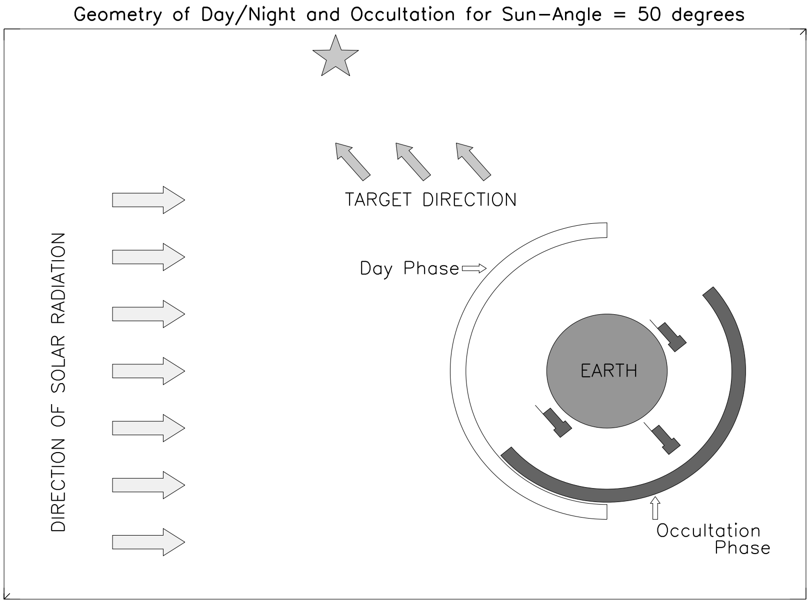

Fig. 1a. The geometry of solar radiation, day-night, and target visibility, for sun-angle 50°. Sun-angle is the angle from Sun to target. 50° is the minimum sun-angle allowed. At this sun-angle the solar radiation input in orbital day is nearly out of phase with the earth radiation input in target occultation.

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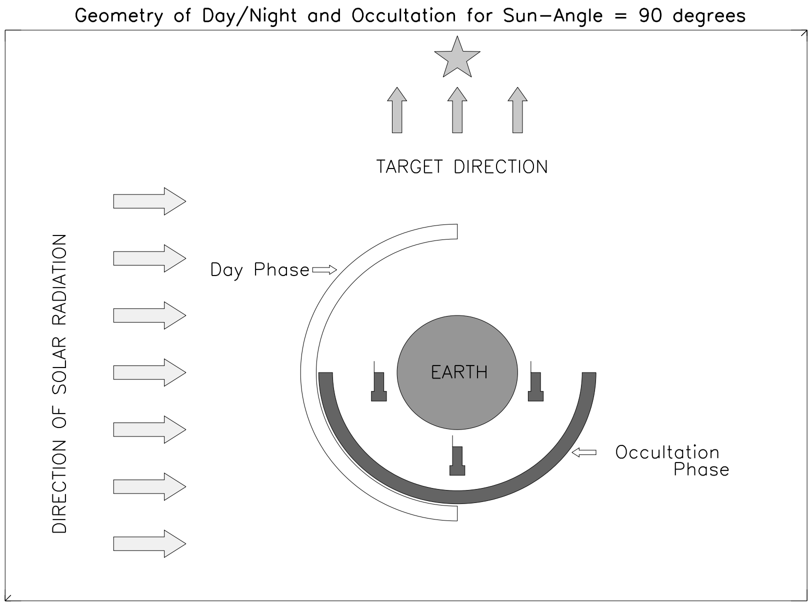

Fig. 1b. The geometry of solar radiation, day-night and target visibility, for sun-angle 90°. Sun-angle is the angle from Sun to target. The solar radiation in orbital day is displaced 90° in phase from earth radiation input in occultation

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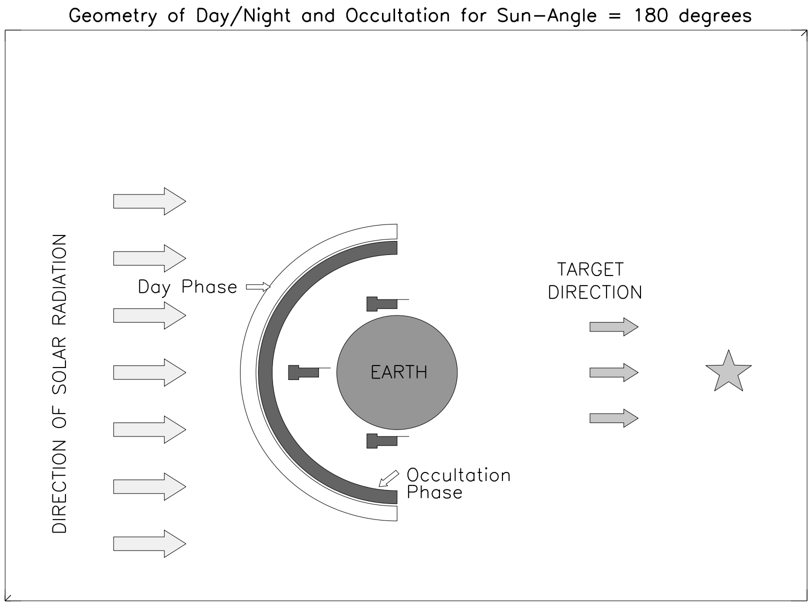

Fig. 1c. The geometry of solar radiation, day-night and target visibility for sun-angle 180°. Sun-angle is the angle from Sun to target. Orbital day and occultation are in phase.

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The interaction of day-night and occultation phase may be seen in plots of attitude states and the focus model from the aft light-shield temperatures which are known to represent the the orbital frequency behavior of the focus closely. Fig. 2 spans about 25 orbits in early 1997 and illustrates the change in amplitude of the orbital-frequency temperature and focus-model changes due to the relation of day-night and occultation phase. As labelled in the figure, the binary day-night and occultation functions are plotted as a pair in the lower part of the figure. The change in phase between the two is apparent as the target direction changed at day 29.9 and day 30.5. The functions of day-night and occultation in the mid-part of the plot, arise from the binary functions, by smoothing, shifting and scaling.

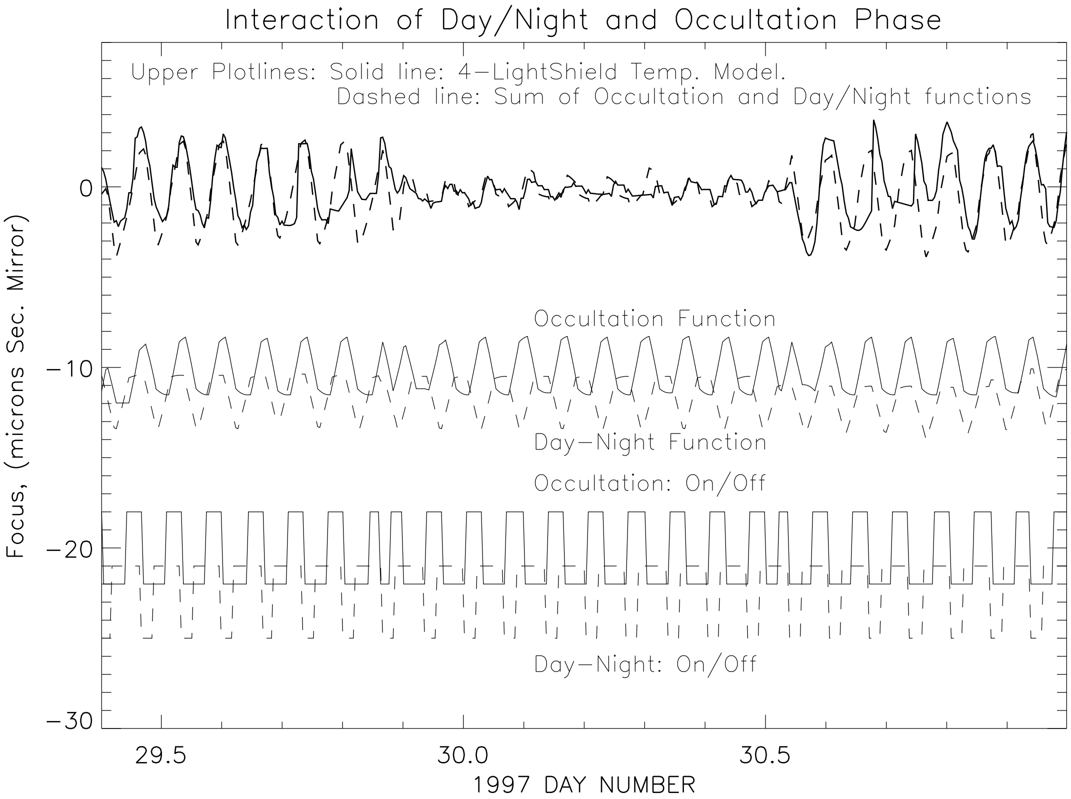

Fig. 2. The effect of day-night and occultation phase on the orbital period temperatures and focus-model amplitudes.

Clearly, in Fig. 2, from day 29.4 to 29.9 the two functions are roughly in phase, then at 29.5 they go approximately out of phase and fill in for each other. The dashed line at the top closely following the focus model plot, is the sum of the day-night and occultation functions and changes amplitude in agreement with the model. After day 30.5 the target direction has changed and the two are approximately in phase again restoring the focus amplitude. Thus the change in focus-variation amplitude is a result of the relative phase of day and occultation and the amplitude change of a factor of 5 or more, can be represented by focus models.

The effect of sun-angle and off-normal roll is also apparent from the study of temperature versus attitude plots covering many days. The effects of a large change in sun-angle can continue on for many orbits after the change. The projection of sunlight onto the side of the telescope is a maximum at sun-angle 90°, that is for telescope tube perpendicular to the rays of the Sun. The long-term effects of sun-angle can amount to drift in light-shield temperatures several times larger than the orbital-period amplitudes. Normally the roll of the telescope is set so that the aperture door is toward the Sun for maximum shadowing of the front end of the telescope tube. Off-normal roll is the angle in roll from the angle of maximum shadowing, and results in equal effects on the light-shield temperatures in both directions off the normal roll. Large changes in off-normal roll can be seen to affect several subsequent orbits after a change. Off-normal roll is used to make guide stars available or to place targets in a specific angle in the scientific instruments.

The persistence of effects due to attitude are longest after a sudden change is made from a long time at one extreme of sun-angle projection to a long time at another. For example, a day at anti-Sun (180° sun-angle) followed by a day at 90° sun-angle or vice-versa will leave a long trail in the temperatures. The effect could be accentuated by a large off-normal roll in one sun-angle and no off-normal roll in the other.

Throughout this paper, the term "focus" is generally used as an abbreviated term for focus position, focal length or focus position change with time. Similarly the term attitude is generally used in place of "attitude in combination with orbital events". Orbital "events" used here are beginning and end of day, and beginning and end of occultation. The times of these events are given in the files which command the HST operations.

3 An Attitude-Based Model

Since the light-shield temperatures correlated well in the 1993 model with focus change, and the explorations described above in Section 2 showed clear dependence of the light-shield temperatures with attitude parameters, it was decided to assume that the attitude parameters could provide the basis for a model of the focus variations. Although focus changes on the telescope might be physically more closely related to temperature than attitudes, an attitude-based model can reveal something of the geometry and time-scales of heat flow in and out of the telescope. Focus position data were available from WFPC2 images, and are described in Section 3. First some guesses were made for parameters, then many trial-and-error runs were made, cycling through all parameters one at a time. Later a differential correction program was written to simultaneously solve for improvements to subsets of parameters, cycling several times through all parameters, one group at a time. A more direct version does least-squares fits for coefficients of all four attitude functions, allowing any one parameter within each function to be varied in a series of solutions for best fit. In both methods the optimization algorithms assume certain functional forms and search for optimum parameters for the functions. The functional forms can only be set up from interpretations of the behavior of the data and the models. The functional forms must then be tested with internal parameter variations.

Initially the model was developed on post-SM2 focus position data from early 1997, which has a denser coverage of WFPC2 focus observations than at any time between the two Servicing Missions. Four attitude functions are used, each based on the attitude components day, occultation, sun-angle, and off-normal roll. The sum of the functions is assumed to be able to represent the focus behavior. A time grid of 5-minute steps is used throughout, partly as a result of the OMS light-shield temperature data readouts being provided in 5-minute time steps. The choice of time steps for the model is a trade-off between time resolution of focus change *vs.* file size, computer memory space and runtime. The generation of each of the four functions of attitude in the current model is briefly described in the following subsections.

Day – Night Function:

The day-night binary function (day=1, night=0) is generated for the 5 minute time steps. A time delay of 5 minutes (1 point) is applied and the function is smoothed into a quasi-sinusoid. Smoothing spreads information foward in time which is compensated by a backward shift. A new function, f_2, is formed for each point of f_1 by taking the mean of f_1 backwards over a range of 2 hours (a form of convolution). The window for the mean presumably represents a time scale of heat-flow, in or out. A new function, f_3 is formed by a weighted sum of f_1 and f_2: $f_3 = f_1 + 0.5 \times f_2$. Each point of f_3 is multiplied by sine(sun–angle), the projection factor of sunlight onto the side of the telescope, and finally multiplied by a scale factor.

Parameters: Scale-coefficient, delay, smooth window width, back window width, combination fraction.

Functions: Shift, smooth, convolution or back-integration, weighted mean, sine, scale.

Occultation Function:

The occultation binary function is generated: (occultation = 1, visibility=0). A time delay of 20 minutes is applied. The function is smoothed into a quasi-sinusoid and corrected for the forward time spread. A new function, f_2 is formed for each point of f_1 by taking the mean of f_1 backwards in time for 2 hours. A new function, f_3 is formed by adding f_1 and f_2. A scale factor is applied to f_3.

Parameters: Scale-coefficient, delay, smooth window width, back window width, combination fraction.

Functions: Shift, smooth, convolution, weighted mean,scale.

Off–Normal Roll Function:

The absolute value of the off-normal roll is formed, since the effects of off-normal roll are expected to be the same in either direction. The function is smoothed and backward shifted to compensate for the forward smooth spread to form function f_1. A mean is formed backward in time over a window of 3 hours to form function f_2. Function f_3 is formed by $f_1 + f_2$. The final function is formed by applying a scale-factor to f_3.

Parameters: Scale-coefficient, smooth window width, back window width, combination fraction. Functions: absolute value, smooth, convolution, scale.

Sun – Angle Function:

The sine of the sun-angle is formed for all points and multiplied by a scale factor to form function f_1. f_1 is back-integrated 17 hours in product with a negative exponential in time (a form of convolution). The convolution is normalized by the number of points in the window to form function f_2. f_2 is multiplied by a scale factor.

Parameters: Scale-coefficient, back window width, exponent.

Functions: Sine, convolution, scale.

The final focus model is the sum of the above four attitude-based functions with the mean removed. The zero-points or net offsets of the four functions are disregarded as they are formed and drop out in the end with the mean of their sum. This is a weak point in the present stage of development which needs study.

Experimentation with model functions.

Many experiments with model functions were performed; for example the projection-effect function was tried in the form of the square, square root and other powers of sine(sun-angle). For initial exploration of other functions, code was set up to test the residuals for correlation with many functions which seemed plausible. If a correlation was found, the function was tested in the full model determination process. The search for better functions is not regarded as exhaustive; as more focus data becomes available other functional forms and parameters may become better constrained.

Experiments were conducted with two levels of occultation, a high level for bright earth and a low level for dark earth. No ratio of bright-to-dark seemed to improve the fitting process. Apparently the amount of IR radiation flowing down the telescope tube from sunlit and dark earth varies in keeping with the small absolute temperature variation of day and night on earth which is at the level of one percent of the mean absolute temperatures.

Throughout the model development a weighting system was in place to allow the setting of apparent outliers to zero weight as a check on whether faulty points were distorting the solution. The zero-weight points could be dropped out of model determination, but plotted along with the others with a different symbol to see their relationship to the other data. The outliers are only marginally so, lying in group at the edge of the residual histograms, A strong case could not be made for outliers in the sense of faulty data lying clearly apart from the spread of a normal distribution. Removing points with large residuals did not change model parameters greatly.

Presumably more data would help develop a better attitude-based focus model. The available focus data usually does not cover much of the full orbital cycle variation and is far too limited in sampling to constrain models to the correct behavior in the vast number of possible combinations in time sequence of the four attitude parameters. More data might suggest new functions to add to the model, though there is no certainty of that; the focus effects may be too complicated to visually suggest mathematical functions.

Other influences on the focal length.

The attitude-based model as described assumes a contant intensity of solar radiation. Because of the eccentricity of the earth's orbit combined with the inverse square law of radiation intensity, the solar intensity varies with a half-amplitude of 3% with the maximum near the beginning of the calendar year. The sun-angle, off-normal roll and day-night functions have been modulated by this effect. If the effect is also in the radiation from the earth during occultation it would be affected by seasonal lag, and vary as the telescope views a variety of earth latitudes and seasons in each orbit. No attempt has been made to model these effects in the occultation function.

Another orientational effect which is not explicitly modeled is the change of the direction of the pole of the HST orbit relative to the earth orbit plane which contains the direction to the Sun. The precessional period of the HST orbital pole is approximately 56 days in length. It is implicitly included in the attitude-based model by variations in the lengths of day and night and occultation. NICMOS focus data has been showing a strong 56-day period which may be due in part to temperature changes in or near the instrument (A. Suchkov, ISR NICMOS-98-000). A periodogram of the WFPC focus data shows a clear 56 day period. The residuals from the attitude model show that most of it is removed by the model. A provision has been added to remove any remaining 56-day effect remaining in the residuals from the model, and usually the residuals can be significantly reduce by removal of a 56-day periodicity. Apparently some aspect of the orbital plane change is fully not covered by the attitude and events information provided the model, or an additional term for one or more of the functions needs to be found.

General comments on the attitude-based model.

A purely attitude-based model can predict focus change from a calendar before the observations are executed on the telescope. A temperature-based model is grounded in the physical conditions experienced by the telescope, but only an attitude-based model can generate a focus displacement for times in the past where temperature data are not available, or predict the focus behavior before commands are executed on the telescope.

The attitude model also suggests something of the physical processes involved in focus change. The model shows that the heat input from solar day and earth occultation contribute separately to the focus change and that the phase and duration of occultation have a direct effect. The short time scales of the day and occultation components suggest direct passage of heat radiation to the temperature-sensitive components and the longer time scales for sun-angle and off-normal roll suggest that the conduction of heat through insulation and structures may be involved. As a general principle, the focus change results from model characteristics which seem to represent the amount of heat entering the telescope, modified by time delays of various forms.

The behavior of the attitude-based focus model for a week is shown in Fig. 3. A similar plot can be generated a week or more in advance of execution from the Mission Scheduler files. The four attitude sequences are shown, each paired with its respective function of attitude. The model is the sum of the four attitude functions (the upper line of the pairs). None of the model components are shown to correct scale or zero-point. The sun-angle plot-line is crossed with three gray dotted lines which represent sun-angle 50°, 90° and 180°. The high-frequency component in the model is the orbital frequency or "breathing". The multi-orbit excursions in the model are due to sun-angle and off-normal roll as can be seen from the component plot-lines below.

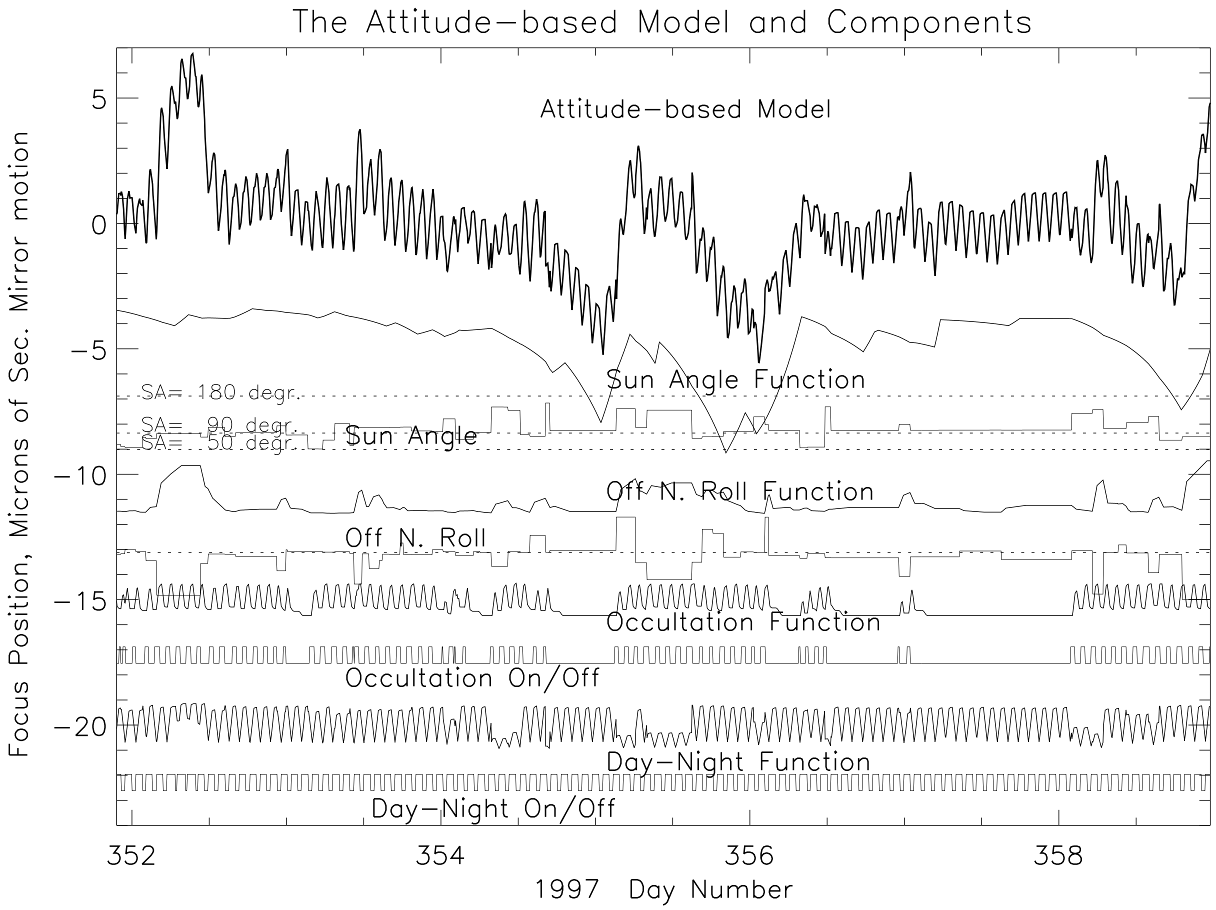

Fig. 3. A week of the attitude-based model and its components.

Long term changes due to sun-angle and off-normal roll are shown in Figs. 4a. and b. Both figures show 1-day intervals of models, components of the attitude-based model, and an observation of focus. Both show large changes in the focus model and a relatively close fit to the observations, compared to the large excursions of the model throughout the interval. At present no temperature data has been extracted for a temperature-based model for Fig. 4a in order to check whether the temperature-based model would fit this large focus deviation.

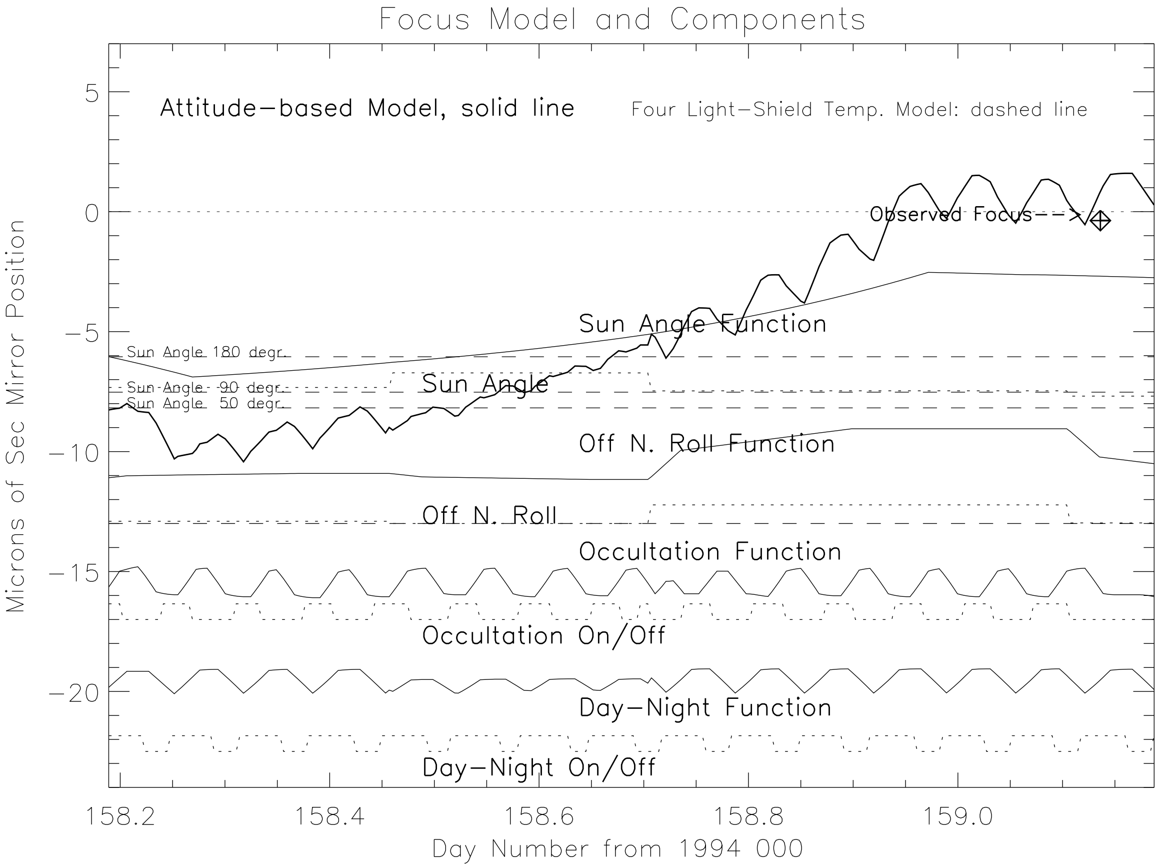

Fig. 4a. A one-day interval showing a case where large sun-angle and off-normal roll changes cause a large excursion in the model, but the model meets the observation at day 159.15. No temperatures were available for the 4-temperature based model.

Fig. 4b. An interval with sun-angle at 180° for a day. The sine of the sun-angle causes the day-night function to go to zero. The observed focus at −9 microns in terms of secondary mirror motion is the largest deviation of focus in over 4 years of focus data. The attitude-based model reaches within about 15% of the focus value. The plot shows that the large negative focus value is due to sun-angle reaching 180° on day 120.6 and staying there for most of a day. The function of sun-angle drops across the whole plot and drives the model downward.

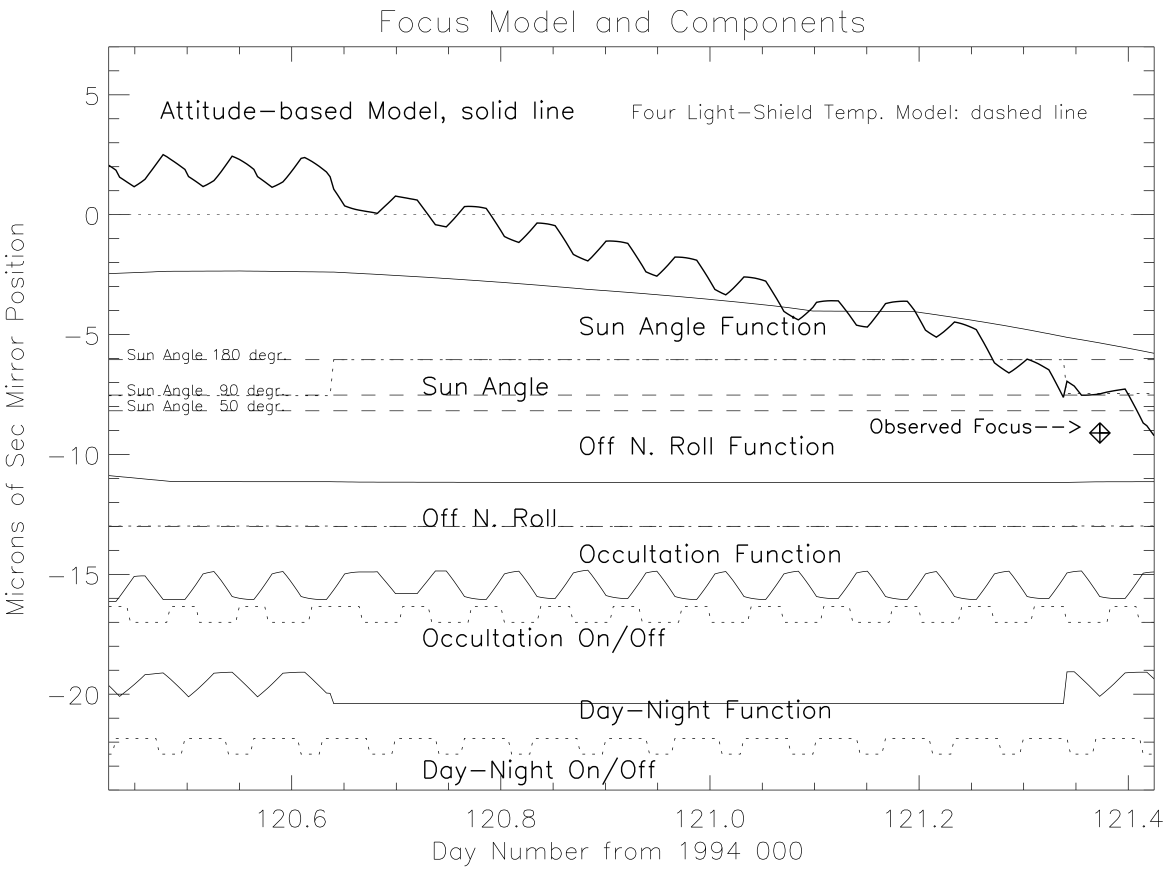

Fig. 4b. A one-day interval showing the case of the largest observed focus deviation, equivalent to −9 microns of secondary mirror motion. No temperatures were available for the 4-temperature based model.

Fig. 5 shows the focus data for a month in 1997 along with the model and the functions composing it. Observations in an orbit are surround by intervals of about 2 hours showing the model behavior in the neighborhood of the observations. Large gaps of time elapse between many of the observation points or groups of points. The four attitude functions appear in the lower half of the plot for each time interval.

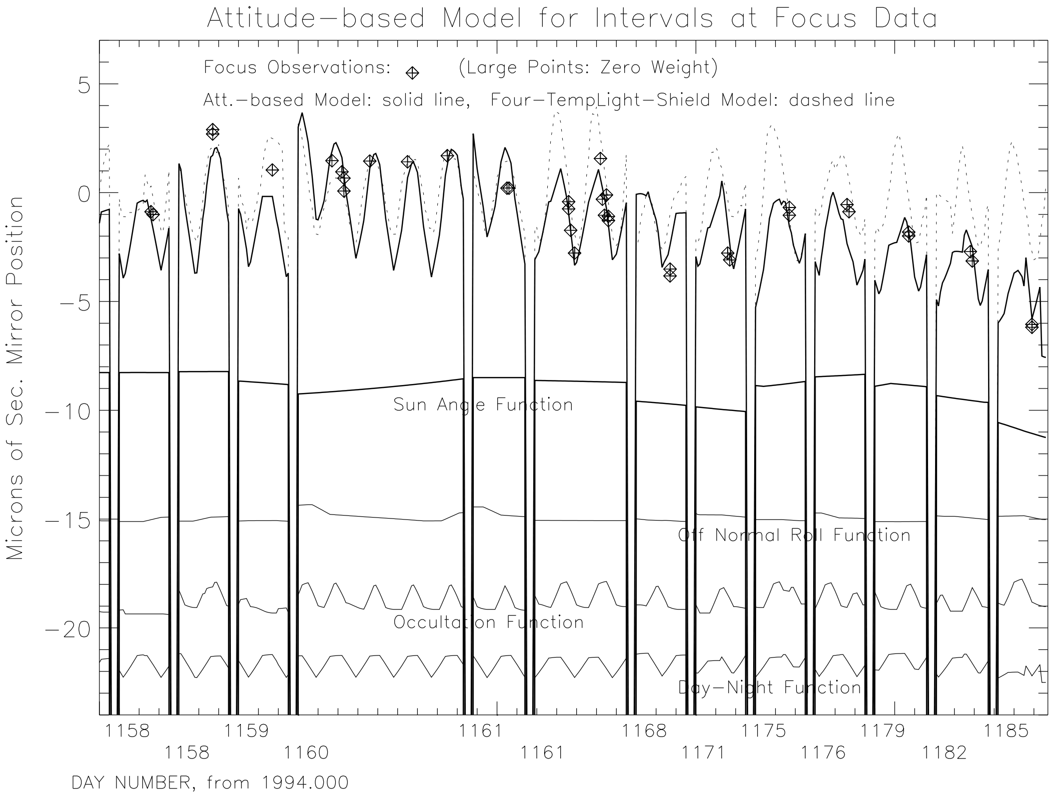

Fig. 5. Focus data and model for a month of relatively intensive focus measurements in 1997. The attitude-based model reaches the rather large downward focus excursion at −6.0 microns on day 1185.

An independent check on the attitude-based model from another instrument has been carried out with data from the Faint Object Camera. About 20 points across 3 years show a correlation with the model as reported by R. Jedrzejewski in Instrument Science Report OSG-FOC-98-01, page 6 and Fig. 2.

4 A New Temperature-based Model

A temperature-based model has the advantage of being based on physical conditions experienced by the telescope structure which should be closely related to focal length, in contrast to an attitude-based model which must represent the much longer causal sequence from attitude to heat flows to focus change. As described in the Introduction, a temperature-based model was developed by Bély in 1993 from temperature data arising from two equilibrium attitudes. That model, based on only four OTA temperature sensors, was compared with the focus data throughout the attitude-based model development and is remarkably successful, considering its mathematical simplicity. Since it was based on data from two attitudes, and that those attitudes were held long enough for a near-equilibrium condition, it seemed likely that a better, though more complex model could be developed, constrained by the larger amount of focus data now available covering a variety of attitude histories.

The OMS system saves various OTA temperatures from the telemetry in addition to the four light-shield temperatures in a separate set of files. The OTA temperatures for the first third of 1997 were extracted and plotted for visual exploration for any which might have a time dependence related to attitude and orbital phase. A subset of temperatures were selected for use in a fitting program.

Truss temperature differences, front shield, light shield and aft shroud temperature-sensor means showed activity, some with orbital-period modulation and all with some longer-term changes. The phases of those with orbital-period components showed some changes which suggested they might carry additional information. The behavior of the temperature data was initially explored with only a trial-and-error loop to test the behavior of various sub-groups of temperatures and functions as the functions of temperature were built up.

A fitting process evolved which combines least-squares fitting for coefficients of the various functions of temperature means with a trial-and-error loop for variations of any parameter in the functions. The focus observations were represented as the sum of a constant, and 6 functions of various temperature-sensor means. The least-squares solution solves for the constant and 6 coefficients of the functions for each trial value of a parameter, in a series of trial values. The RMS of the residuals for each of a parameter value series was stored and the parameter value adopted which yielded the best fit. The optimization proceded iteratively with each parameter re-optimised more than once after the others had been optimized. As the temperature-based model was developed it became apparent that the four aft light-shield temperature model could be improved and the attitude model was equalled and then surpassed for the the intensive observational focus data in 1997.

Phases or time shifts were found for three of the temperature data means. One of the components was the mean of the aft light-shield temperatures with a slight modification of the Bély formula to difference against a mean of two orbits rather than one and to leave the scale factor free for the least squares solution to determine. Initial explorations of models using separate aft light-shield temperature sensors did not improve the model, but more exploration might bring improvement since the four temperatures do behave somewhat differently. The temperature-based model need not include the variation of the solar intensity or the HST orbital precession since the model is using the telescope temperatures which are already affected by the solar variation and precession.

The "full temperature-based" model is the sum of the modified light-shield four-temperature formula, and five other OTA temperature functions. A solution for the interval from late 1996 to 1998.2 yielded a coefficient for the aft light-shield temperature function 12 times larger than its formal error from the least squares solution, showing that it is carrying the largest component of the focus behavior. The next most significant of the terms are: the truss axial difference means, 6 times its formal error (6σ); the forward shell, 3.5 σ; mean light-shield temperatures with phase shift: 1.5σ, the aft shroud, 0.4 σ; and the truss diametric differences, 0.8 σ. The latter coefficients are marginal and may be dropped if future data does not support their validity. Large time delays were found in the optimization process for the truss axial and diametric difference means.

Fig. 6 shows the temperature-based model values for the 1997 intensive focus data versus the focus observations and the very high correlation of the new temperature-based model with the focus data. The RMS for the focus data in this range is 2.0 microns. The RMS of the model fit to the focus data is 0.6 microns of secondary mirror position.

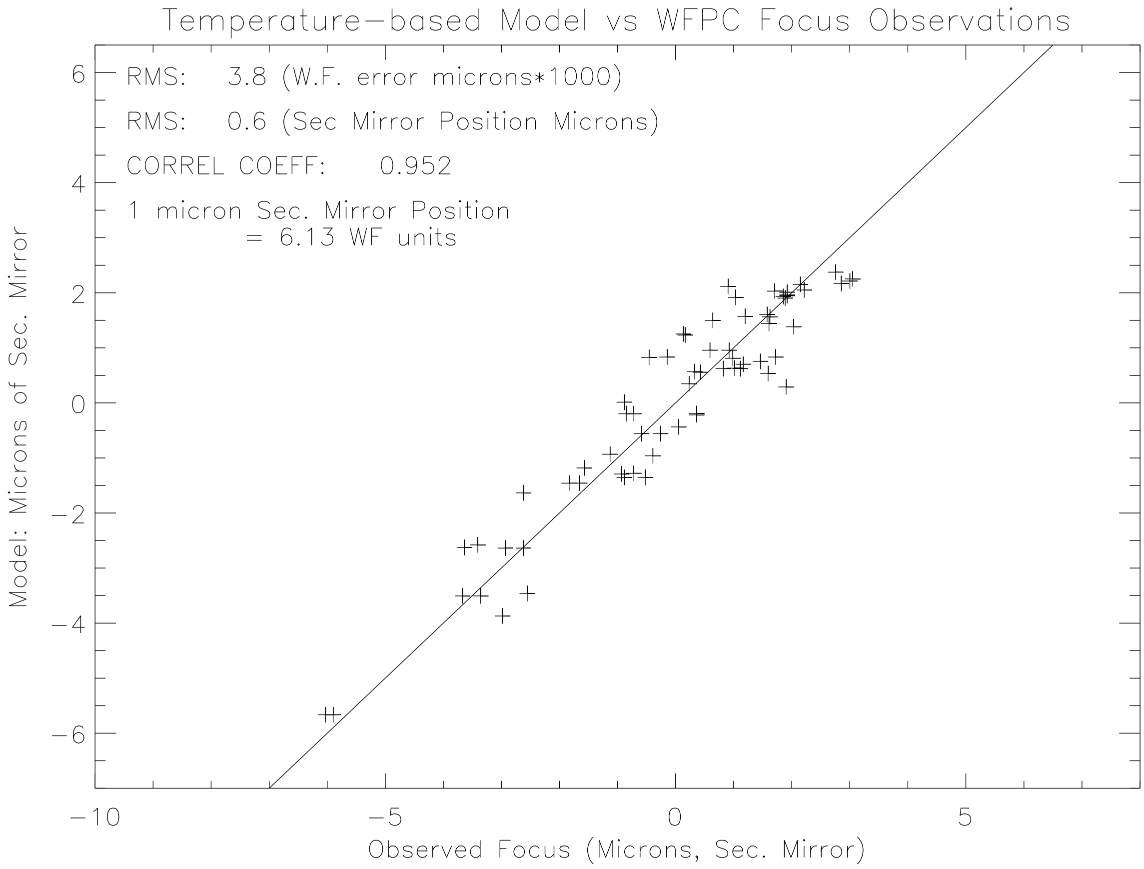

Fig. 6. The correlation of the temperature-based model with the observations of focus for an interval of a month of intensive focus observations in 1997.

The error of the focus-position observations is not well determined, but is estimated to be near 0.5 microns, so it is possible that there is not much room for improvement of the model. Temperatures have been extracted back to 1995.0 from OMS tapes for fitting across over 3 years of focus data. As for all three types of models the fitting error for 1995.0 to 1998.2 is appreciably larger: 1.0 microns secondary mirror position and 1.4 for the

4-temperature model.

5 Focus Data

WFPC2 focus observations were provided by the STScI Science Support Division (SSD) from a focus monitoring program used to determine the time and amount of secondary mirror moves to compensate for OTA GE contraction. After the first servicing mission (SM1) at the end of 1993, the corrected PSFs in FOC, FOS and WFPC2 were much smaller and more capable of revealing the changes in focal length. Most of the focus observations since early 1994 have been on the same target with WFPC2 and the location of the focus has been determined with an optical analysis program from the PSF of a single star, imaged with the Planetary Camera image sensor.

As noted earlier, the focus data for 3 months after SM2 were used to develop the first attitude-based focus model. There were about 90 points, from about 30 orbits, a much denser coverage than in any similar-length interval of the preceding 3 years. Some of the data after SM2 is in groups of two in a single orbit, a few have 3 or 4 points in an orbit and a few orbits with data followed in close succession, as shown in Fig. 5. However in the same interval of time nearly 1500 HST orbits occurred; thus even in that time span focus coverage is extremely sparse in view of the great variety of attitude combinations and sequences in a time interval of that length. There are limiting factors in the acquisition of focus data. Generally, dedicated telescope time is required. Only images in the PC part of WFPC2 carry enough resolution of the PSF for determination of the focus position. Field stars from science observations may be unresolved doubles and few field stars appear with correct exposure and sufficient isolation from surrounding images.

Although the full focus data set includes over 200 points, it covers 4.2 years. The time interval spanned by the data is nearly 25,000 HST orbits. The focus data in 1994, 95 and 96 is especially sparse; about 60% of the focus data is post SM2. As the time spans for model fitting are lengthened, the fitting errors of the models become progressively larger. This is true consistently for all three models, which suggests that at least some of the cause is not within the models. There may be less observational homogeneity in the early years and other unknown systematic effects may be at work. The residuals from long-interval solutions seem to show some systematic drifts on the scale of substantial fractions of a year.

On the interval from 1995.0 to 1998.2 where temperatures are available for comparisons of all 3 models, the full-temperature model does best on the whole interval and sub-intervals, and the attitude-based model does less well, and the 4-temperature model least well. The comparisons fluctuated with different time intervals, but the behaviour could be roughly characterized by steps of 10 to 20% improvement, from 4-temperature to attitude-based models and from attitude-based to full-temperature models.

6 Determination of OTA Shrinkage With the Help of Focus Models

The focus data passed into the model development described above had been adjusted for systematic changes over time in the OTA. The OTA GE shrinkage is a long-term monotonic process continuing since HST launch. The shrinkage across 4 years is 3 or 4 times as large as the focus excursions due to orbital effects. Although much of the focus change due to shrinkage is compensated by occasional secondary mirror moves, the focus drift continues between each mirror move. The drift in each time segment must be removed from the raw focus data before it is used as input to a focus model. By now most of the shrinkage has been completed and the change across several months is comparable to the oscillatory attitude effects on focus. If at both ends of a time interval under study for shrinkage effects, some focus observations should happen to be made at opposite extremes of the focus excursions caused by attitude, the two effects could become confused. Determination of the amount of secondary mirror compensation needed can be aided by first removing a model for the attitude-driven part of the focus change.

Throughout the 4.2 years of focus data there have been seven adjustments of the HST secondary mirror to compensate for OTA shrinkage. Fig. 7 shows the focus data with the times of mirror move marked by vertical lines.

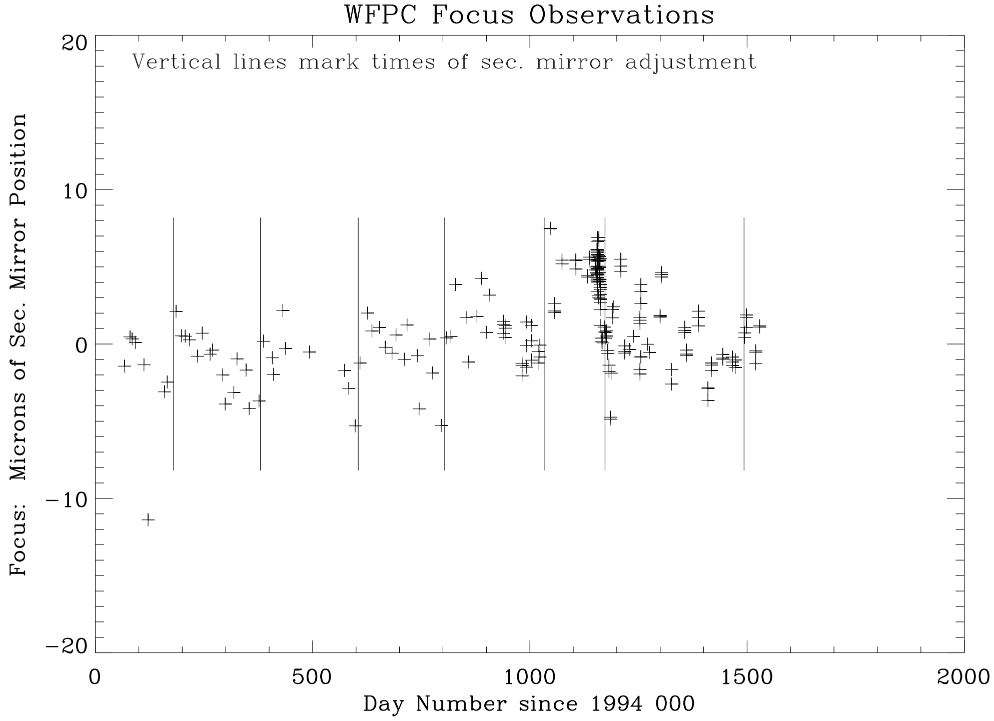

Fig. 7. Focus data since SM1. The point at -12 microns is a valid observation; it the same point shown in Fig. 4b.

The very low point for day 121 is a valid observation and is due to most of a day of sun-angle near 180°. The model represents it well as can be seen in Figs. 4b and 9. In most of the intervals in Fig. 7 the downward trend of points is apparent, due to OTA GE shrinkage. The mirror move at day 1033 appears to have been a slight over-correction.

In Fig. 8 the mirror moves have been applied cumulatively to show the focus data as it would have appeared if no secondary mirror moves had been made. The fit to the shrinkage effect is a negative exponential in time.

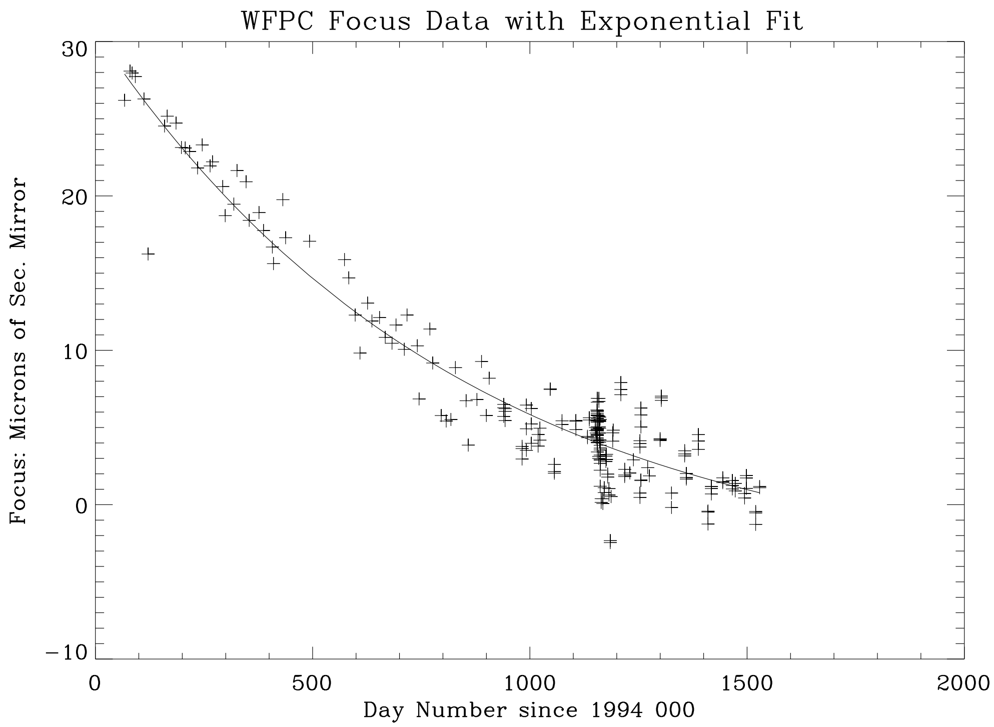

Fig. 8. The focus data since SM1 with the secondary mirror moves restored. The low point at day 121 is a valid observation; it the same observaion shown in Fig. 4b.

The data reveal the exponential shrinkage of the OTA. The line is a fit for ordinate constant, coefficient of the exponential, negative exponent in time, and zero-point in time. The dispersion of the residuals is due to the focus changes resulting from thermal effects, focus measurement errors and perhaps some long-term systematic effects. The residuals relative to the exponential fit shown in Fig. 8 are the focus-change data which the focus models attempt to represent. It is data which ideally shows only focus deviations as would have been seen if there were no shrinkage of the OTA.

Fig. 9 shows the data of Fig. 8. with the attitude-based focus model fit across 4.2 years subtracted from the data. The exponential is now more clearly defined, but unfortunately much unmodelled scatter remains in a fit across an interval as long as 4.2 years. However, subtraction of the focus model has “fixed” the large negative observation at day 121.

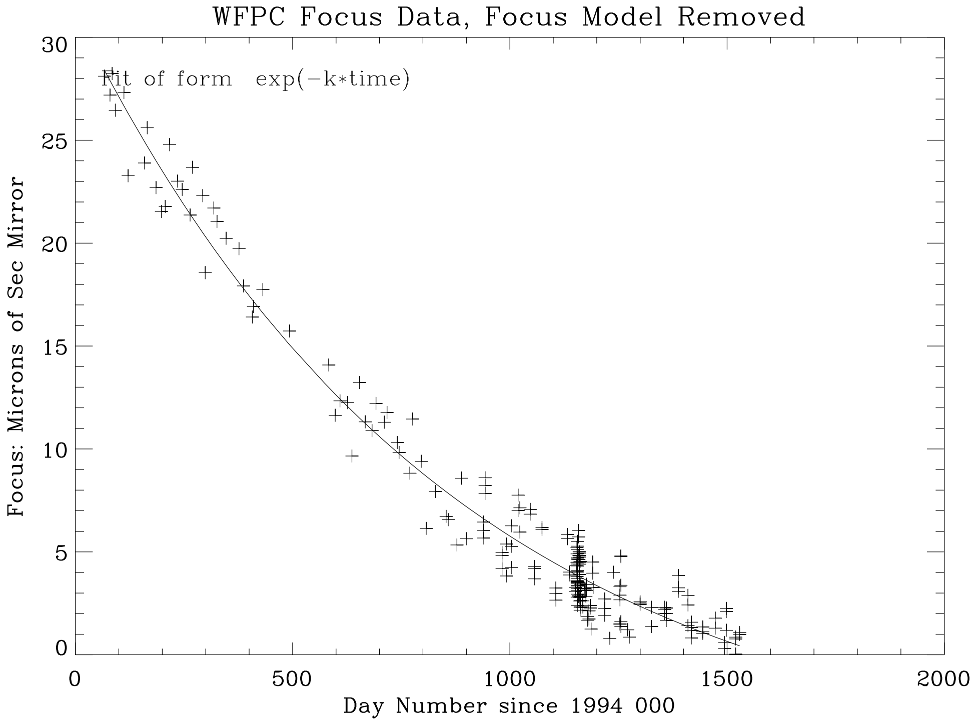

Fig. 9. The focus data with secondary mirror moves restored and the attitude-based focus model removed. The point which fell very low on day 121 in Figs. 7 and 8 has been brought up to the other residuals by the model.

A thorough analysis requires an iterative approach to determination of the exponential function and the focus models. An estimate of the shrinkage function must first be made with the shorter-term variations unmodelled as in Fig. 8. Then models may be developed with this approximate shrinkage function removed. With a model of the short-term variation removed a better exponential shrinkage function can be found, leaving better residuals for fitting by the short-term variation models. Because of the long time range of over 4 years for the shrinkage model, this process converges after one interation. The first iteration brought a reduction of a few percent in the RMS of the model fit across 4.2 years.

7 Focus Ephemerides

The attitude-based model has the advantage that it can generate focus deviations where temperature data is missing, or it can predict focus deviations to be expected from a future HST calendar. A tool has been set up for generating a focus "ephemeris" for a week in the future from a Mission Schedule (.RMS file) which is usually available for a week or more before execution on the telescope. A focus model for a future week, such as Fig. 3, could be used to avoid particularly large focus excursions which might be harmful to observations unusually sensitive to focus deviation.

The predictive capability of the attitude model might be used to give a relationship between combinations of sun-angle and off-normal roll and the deviation of focus to be used as a guide for avoiding large focus effects in future calendars. Fig. 10 shows the dependence of focus on combinations of equilibrium (long-duration) values of sun-angle and off-normal roll. In general, any long-term (half day or more) extreme of sun-angle and off-nominal roll will cause large focus excursions. The values of the function in the plot are given in Table 1. The figure illustrates the direct relation of focus and attitude. Time-delays are eliminated because the model originates in equilibrium states. The zero-point of each model component function is not defined. The data should be regarded in a relative sense, that is showing the difference in focus between attitude combinations. Fig 10. was generated by the model from sun-angle – roll combinations which were fixed for long time periods so that the functions would reach a constant value. In a real situation the focus deviations of Fig. 10 could have a large orbit-period amplitude variation superimposed if the target lies at low orbital latitude for maximum occultation time and at moderately large sun-angle for approximate alignment with day phase.

Table 1: Focus change due to equilibrium sun-angle and off-normal roll attitudes.

unit: Secondary Mirror Position in Microns

—- Sun-angle (Degrees) —–

Off-N. Roll	60.0	80.0	100.0	120.0	140.0	160.0	180.0
(degrees) 0	−0.9	0.0	0.0	−0.9	−2.7	−5.1	−7.8
5	−0.7	0.3	0.3	−0.7	−2.4	−4.8	−7.5
10	−0.4	0.6	0.6	−0.4	−2.1	−4.5	−7.3
15	−0.1	0.9	0.9	−0.1	−1.9	−4.3	−7.0
20	0.2	1.1	1.1	0.2	−1.6	−4.0	−6.7
25	0.5	1.4	1.4	0.5	−1.3	−3.7	−6.4
30	0.8	1.7	1.7	0.8	−1.0	−3.4	−6.1

—————————————

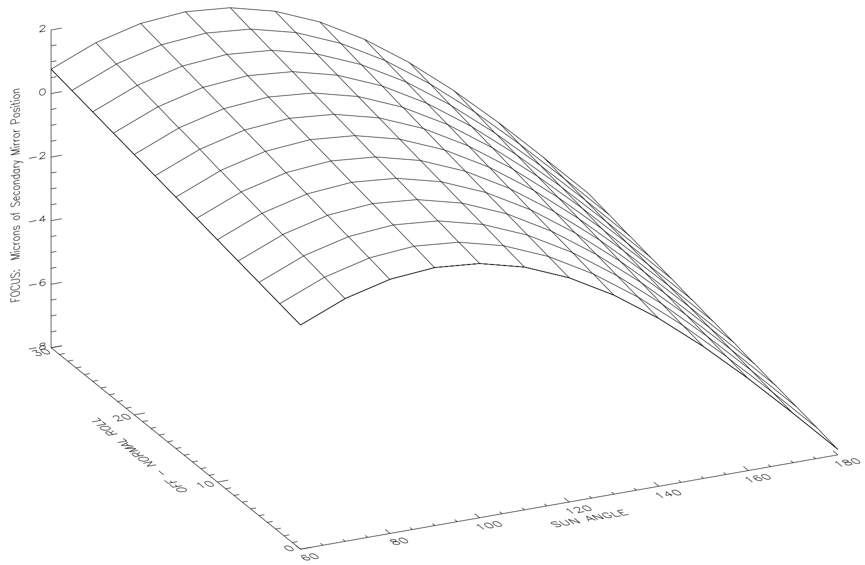

Fig. 10. The dependence of focus on combinations of equilibrium values of only sun-angle and off-normal roll.

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A focus model can have use for analysis of data from HST instruments. Images are somewhat degraded when the focus excursions are at their extremes, and knowledge of how far off correct focus the telescope was at the time of exposure of an image could provide the basis for the choice of a PSF for image deconvolution. In some cases it may suggest how much throughput was degraded at a very small aperture of size comparable to the PSF. In other cases it may help isolate internal instrument changes affecting focus.

A tool has been set up to generate files covering the entire time since 1994.0 on a five-minute time grid, containing the attitude-based focus model, along with the four-temperature model and the full temperature model from 1995.0 where extraction of temperature data began. Time tags are given in year-day-hour-minute form and in Modified Julian Day. The units are in microns of secondary mirror position, not the actual change in the primary focus position. A change in secondary mirror position of one micron changes the telescope prime focus by 110 microns. Data is only provided for the time intervals when the telescope has target visibility. Each of the files spans a nominal quarter year. The generation of the files for the multi-year time span is automated and will allow improvements and additional model features to be included easily for replacement of the previous files.

Explanation of the contents of the focus model files and guidance for their use are now on a website maintained by SSD:

http://www.stsci.edu/ftp/instrument_news/Observatory/focus/focus2.html

The following disclaimer appears at the top of each file:

"The following file contains three models for focus change in the HST prime focus. The first one was derived early in the life of HST by Pierre Bely of SESD and is based on four temperature sensors in the light shield near the secondary mirror spider (SESD document: SESD-93-16). The second model is based on HST attitude information from the Mission Scheduler files, and uses a model developed in the SESD Engineering Team to fit a sparse set of observations of focus positions from WFPC2 images as determined by the Science Support Division. The attitude-based model represents the large excursions of the focus somewhat better than the four-temperature model. The attitude-based model requires information reaching back a day before the time of model generation, so the first day of each file has no model variation in the second model column. The third model is based on a large number of temperature sensors throughout the telescope, including the four sensors in the first model, and has been representing the observations somewhat better than the other two models.

The attitude-based model is based on commanding information and thus can predict the focus before telemetry is received, or fill in a model where temperature telemetry has been lost. Development of the models is expected to continue. They should be regarded as an aid to analyses requiring focus information, not as a completely reliable and finished product.

- J. Hershey, D. Mitchell SESD Eng. Team"

8 Acknowledgements

Dana Mitchell, ET lead, suggested the study of the focus changes; X. Liu, W. Sawchuck and E. Lee provided much help with OMS, RMS files, and OMS tape archive access.

The 1993 work of Pierre Bély of the STScI SESD revealed the close link between the aft light-shield temperatures and focus change, and provided the functional form which has served for the study of breathing effects since early 1993. The SESD Document: SESD-93-16 (June, 1993), has served as the starting point for the present study.

Matt Lallo has provided the focus observations from SSD and much help and checking of the model files, as well as setting up the website for the users of focus models.