CHANDRA
X-ray Center 60 Garden St., Cambridge Massachusetts 02138 USA

MEMORANDUM

Date: October 29, 2002
From: Diab Jerius
Subject: Comparison of on-axis Chandra Observations of AR Lac to SAOSAC Simulations
Version: 1.9

Abstract

I compare the PSF of an on-axis Chandra HRC-I observation of AR Lacertae with a model produced by SAOSAC. The observed data were corrected for small systematic errors in event positions not removed by the standard CXC pipeline processing. One thousand realizations of the observation were generated to investigate systematic uncertainties in the simulations. The radially averaged count densities (profiles) and the fractional encircled energy relations of the observations and simulations were computed and compared, and indicate excellent agreement between the data and the model. This work is an extension of previous work done on verifying the SAOSAC model of the CXO's PSF [1], using a more refined method of correcting for the HRC-I position errors and studying in greater detail the systematic uncertainties in the simulations.

1 Introduction

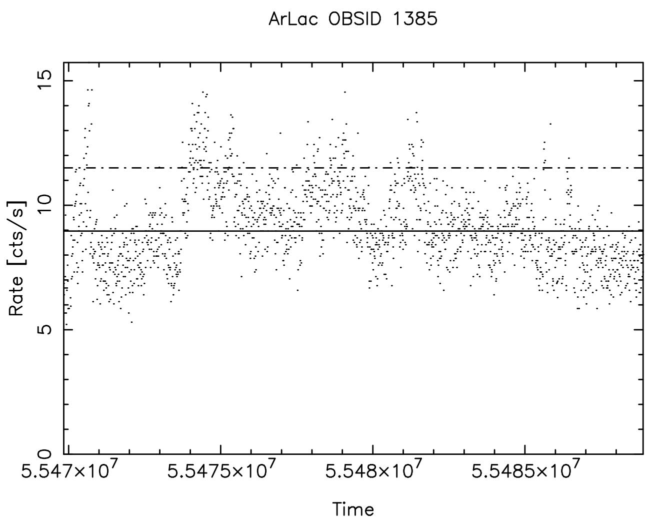
SAOSAC is a suite of tools which, along with an extensive library of calibration data, define the "official" model of the Chandra optics and their supports (the High Resolution Mirror Assembly, or HRMA). The model is composed of a set of algorithms defining how photons propagate through the optical system as well as data which describe the properties of the materials and their physical placement and alignment. In general the algorithms are static; the data have been updated to better reproduce the actual performance of the optics.

Even though the HRMA was extensively calibrated prior to launch of the spacecraft, the calibration could not (and was not expected to) describe all aspects of the optics' performance. Instead, the calibration focussed on those areas which would provide measurements of globally important behavior (such as mirror effective area) and would provide a sensitive challenge to the models. As an example, it was impossible to measure the two-dimensional PSF at every point in the focal plane. Having measured it at several positions and verifying that the model was in good accord with the measurements provides assurance that the model is able to accurately describe the PSF elsewhere.

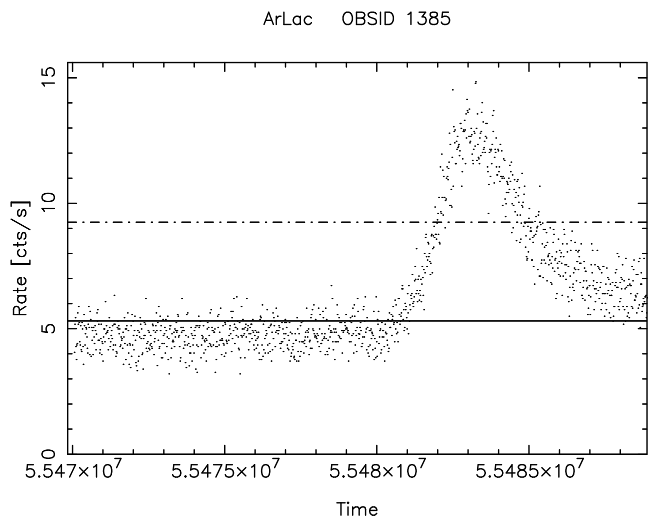
The models are especially important in that they provide a means of translating the optics' measured performance in non-ideal conditions (one-G gravitational field with a source at 0.5 km) to that in a zero-G environment with sources at infinity. Since the models successfully reproduced the ground calibration results, there is good reason to trust their on-orbit predictions, but it's still nice to verify them.

The ideal observation for verification of the predicted on-orbit PSF would enjoy the following characteristics:

- the object would be a known point source, with no intervening astrophysical dust
- the object would have a fairly flat spectrum;



(a) Background Count Rate



(b) Source Count Rate

Figure 1: Count Rates. The source and background rates cannot be directly compared because the sampled regions have different areas.

- the object would have a count rate which would neither saturate telemetry, overwhelm the detector, nor destroy it;
- the detector used would have good energy sensitivity.

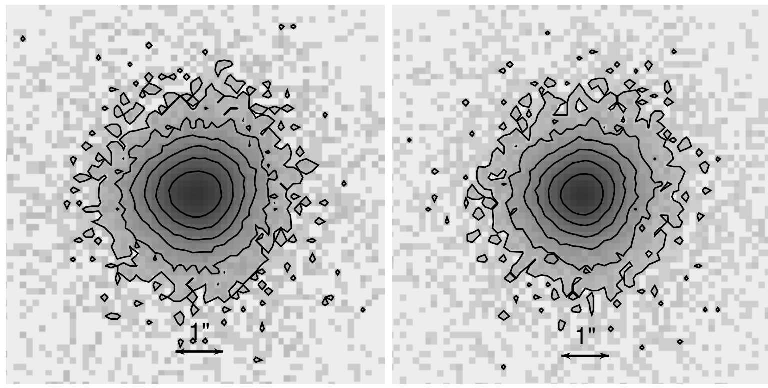
Fate hasn't been that kind, so what we actually get to work with is AR Lacertae, a star which appears to have no extended X-ray emission due to a dust halo, is spectrally soft, and which has been observed with HRC-I, which has no energy resolution, but has reasonable angular resolution. AR Lac is too bright for ACIS, which in any case has much worse angular resolution.

2 The Observation

AR Lac was observed with the HRC-I on 1999-10-05T00:16:23 for approximately 18.8 ksec (OBSID 1385), resulting in approximately 124000 source events. Version 004 of the processed data was used. Fig. 1 shows the count rates in a background region and in the source during the course of the observation. The background was fairly uniform, while the source had a strong outburst (which does not affect this analysis).

An image of the event list is shown in Fig. 2(a). There is a marked elongation in the core – the mirror PSF is not expected to have this structure. There are a number of possible explanations for it:

1. incomplete correction for telescope motion during the observation (aspect);
2. the result of a detector artifact;
3. or, the actual mirror PSF (horrors).



(a) 'Raw' (b) 'Corrected'

Figure 2: AR Lac, linear contours

The first possibility can be diagnosed by a study of the motion of event positions (in sky coordinates) as a function of time. This is shown in Fig. 3. There are marked excursions of up to $0.5''$.

These are *unlikely* to be due to aspect [2], but *are* consistent with an error in the HRC-I event positions [3]. Additional studies [4] indicate that the relationship between the excursions and the detector coordinates of the events are related in such a manner as to exclude an optics origin.

To provide a more quantitative depiction of the effect of the excursions, the events were divided into groups by event time, with each group spanning 25 seconds. The centroid (in sky coordinates) of each group was determined – the resulting distributions are shown in Fig. 4. Without a correction for this behavior, it adds a blur component to the measured PSF equivalent to that of the nominal aspect error, resulting in a significant degradation of performance.

2.1 "Correcting" the data

Until the HRC PI team determines the cause and solution to the fine position artifacts described above, one has to perform *ad hoc* corrections. I have done this by fitting the sky position of the image center with time and subtracting that from the data. Because the excursions are complex and not easily reducible to a simple analytical form, I chose to divide the events into groups by time and fit them piecewise with polynomials. In order to insure that the resultant polynomials were somewhat continuous, I fit overlapping segments in time. The approach was as follows:

1. An initial centroid for the image was determined using a 3σ clipping algorithm. Events outside the final clipping radius were excluded from the subsequent analyses. This removes most, but not all background events.

2. The events were divided into segments by time, with each segment spanning 100 seconds. This is a somewhat *ad hoc* value, based upon visual inspection of the time scale of the image center motion. It is a large enough interval that the polynomial fit will represent the motion of the image centroid, rather than the scattering of the events due to the PSF.

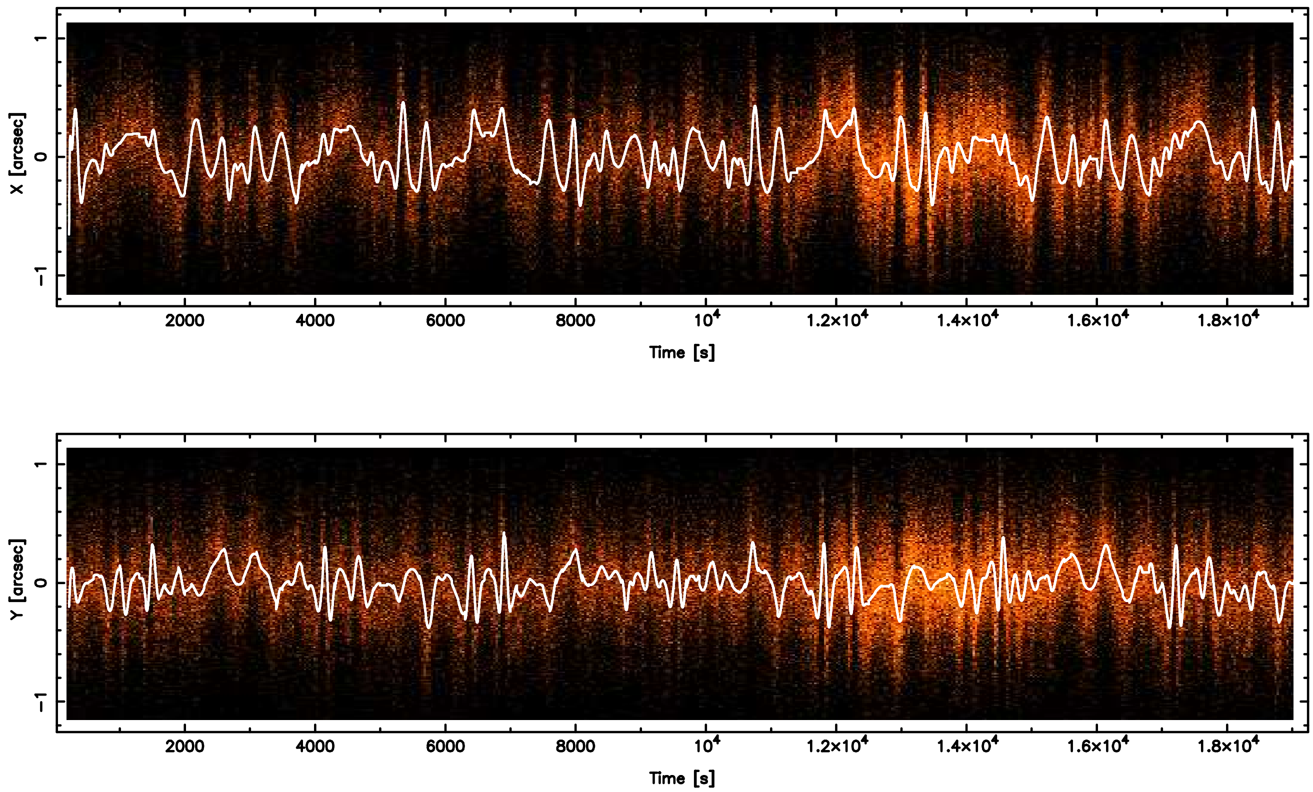


Figure 3: Motion of image centroid. The lines are polynomial fits to the average event position.

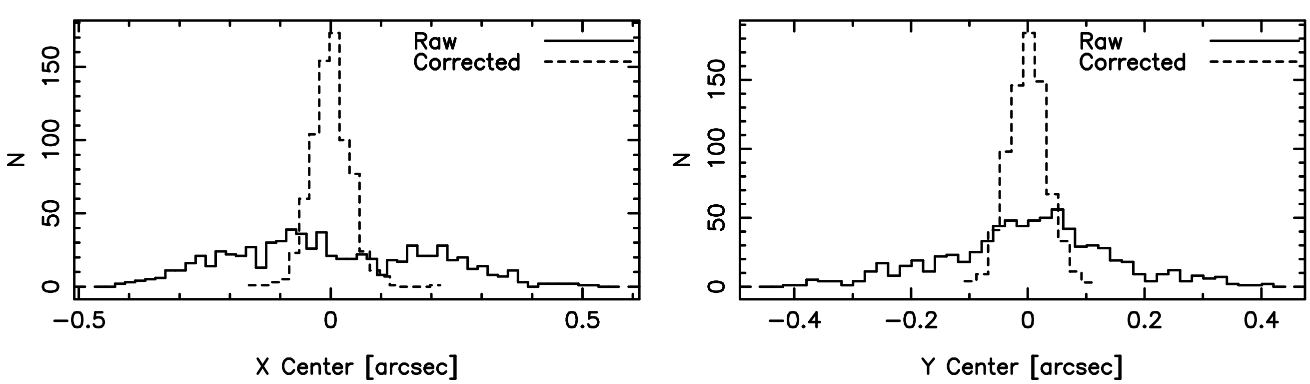


Figure 4: Distribution of image centroids (determined every 25 seconds) about the mean image center.

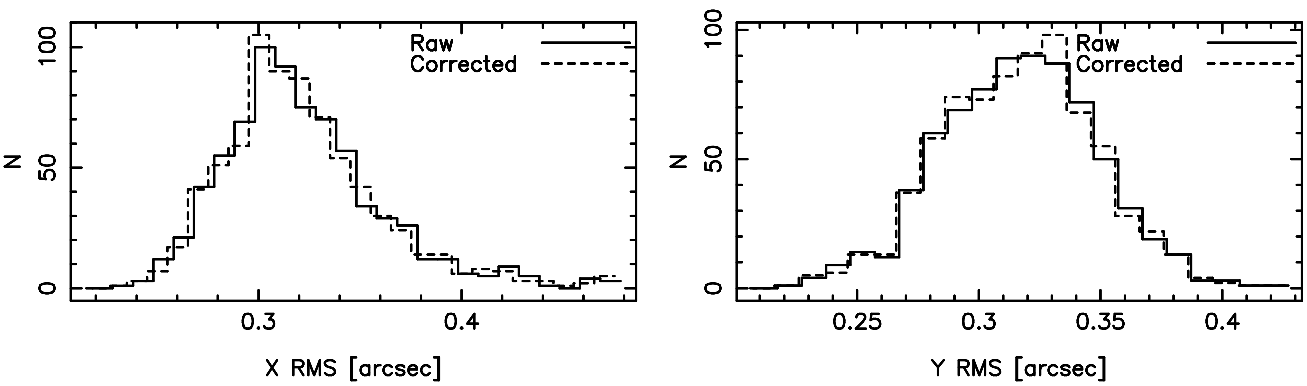
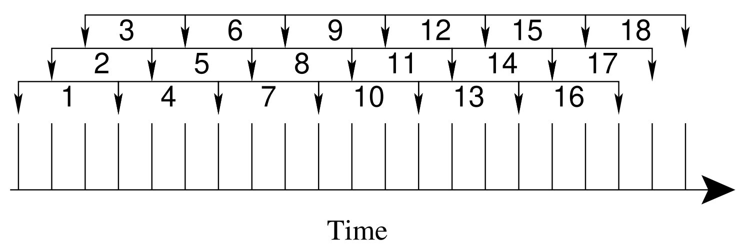


Figure 5: The distribution of the RMS of the event positions in 25 second time slices.

3. The segments were combined into groups of three segments such that each group overlapped two other groups:



4. The sky positions of the events in each group were fit independently as a function of time with up to a 10^{th}order polynomial. The polynomials were evaluated at the recorded time for the events in the middle segment of each group and subtracted from the events' positions. The solid lines in Fig. 3 are the evaluated polynomials.

The results can be seen in Figs. 2(b) and 4. (The companion to Fig. 3 is quite boring and is not shown).

While the correction certainly seems to remove the image center motion, does it affect the image properties? Figs. 5 and 6 show the distribution of estimates of the PSF width as measured in 25 second bins before and after the correction. Fig. 5 shows the distribution of the RMS of the event positions, while Fig. 6 shows the distribution of the range between the first and last quartile of the event positions.

Kolmogorov-Smirnov tests (see Table 1) of the raw and corrected distributions indicate they are drawn from the same distributions. This indicates that the correction has not affected the basic image structure.

3 Simulations

The observation was simulated using SAOSAC and the `orbit_XRCF+tilts_04` configuration. AR Lac was modeled as a point source $0.29'$ off-axis, at an azimuth (in mirror spherical coordinates) of $203.8°$. The model spectrum [5] is shown in Fig. 7. Residual blur due to uncertainties in the aspect correction was modeled by convolving the events with a Gaussian with $\sigma = 0.11''$ blur. The HRC-I was modeled by convolving the events with a Gaussian with a FWHM of 20μm, binning them on a 6.4294μm grid. The detector QE was taken from the Chandra CALDB, `hrciD1999-07-22qeN0003.fits`.

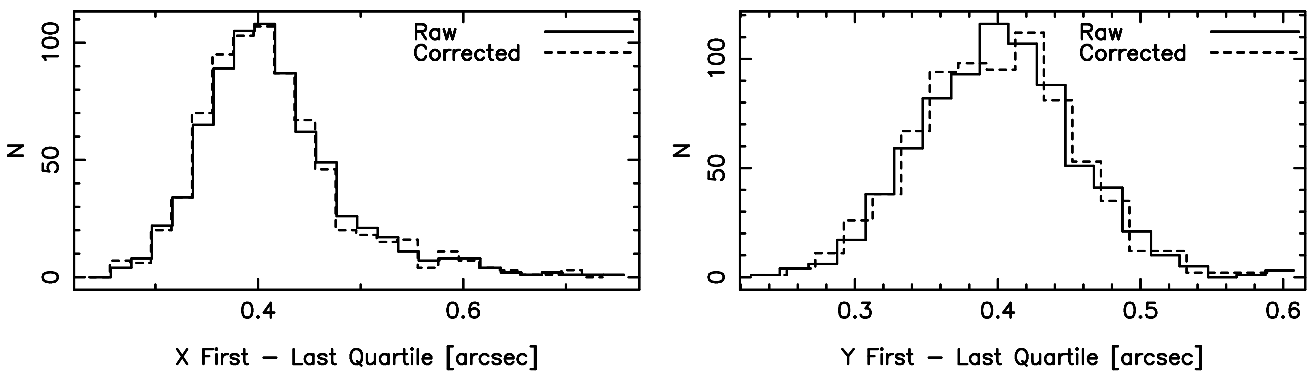


Figure 6: The distribution of ranges bounding the central 50% of the events, in 25 second time slices

A single raytrace (or observation for that matter) samples only a small fraction of the optical system. To examine consistency between the model and the observation, it is important to both densely sample the optical system and to compare data of similar statistical uncertainties. This was done by generating 1000 simulations with a number of events similar to that of the observation.

4 Comparison of Simulations to the Observation

Two metrics were extracted from the simulations and the observation: 1) the radii enclosing given fractions of the total energy (the encircled energy function); and 2) a radially averaged PSF profile. The two most important aspects in their production are center determination and background subtraction.

The center of the event distributions (both observed and simulated) was determined via an iterative σ-clipping algorithm. The background in the observation was determined as follows:

1. The events were sorted by radius into bins containing 50 events.
2. The cumulative sum of the bins was fit to the function $K + b\pi r^2$ in an annulus of inner and outer radii of $200''$ and $400''$. The annulus is far enough out that it does not contain a significant number of source events. It is also free of other objects.

The resultant background agrees well with simply counting the events in the background annulus.

The encircled energy function was determined as follows:

Table 1: K-S Results for comparisons of corrected and raw image widths.

Coord	Statistic	Max. Distance	Q
X	RMS	0.027111	0.944588
X	Lq-Fq	0.030318	0.879058
Y	RMS	0.026136	0.959034
Y	Lq-Fq	0.031398	0.851414

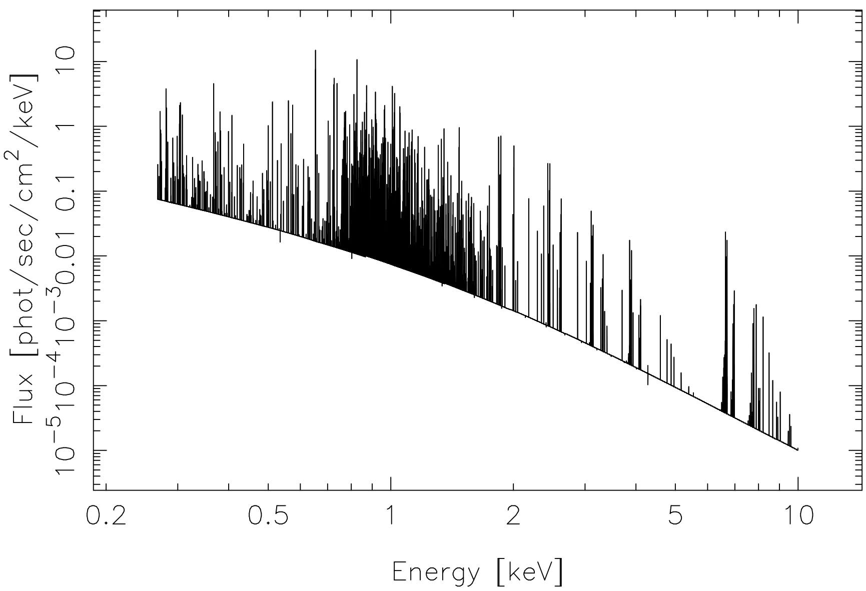


Figure 7: Model AR Lac spectrum used in simulations.

1. The background, *b*, was subtracted from the cumulative sum. The sum was truncated at the first bin where it stopped growing monotonically (the sign of either an overestimate of the background or where the source counts are negligibly small compared to those of the background and the Poisson noise in the local background event density has led to over-subtraction of the background).
2. The sum was rebinned in bins of 500 counts, to improve the error estimate, and normalized.
3. The radii of the circular apertures enclosing requested values of the fraction of the total counts were interpolated from the sum.

Fig. 8 shows the encircled energy functions for the corrected and raw observed events, as well as their differences. As expected, the corrected PSF shows a narrower profile.

The radially averaged PSF was evaluated at the radii determined for the encircled energy function. The results are shown in Fig. 9

Note that for both the encircled energy functions and the radial profiles the *randomized* event location was used, not the center of the pixel. This adds a slight broadening to the PSF, as it essentially assumes a flat distribution of flux across the pixel, rather than the gradient which actually occurs. Bear this in mind when looking at the sub-arcsecond results in the plots.

The simulated event lists were analyzed similarly (although since no background was added, the background subtraction step was not performed). The same radii used to determine the PSF for the observations were used for the simulations.

Fig. 10 shows a comparison of the encircled energy function for the simulations and the corrected observation. The horizontal error bars indicate the range encompassed by 95% of the simulations; the points are the corrected observation. The agreement is quite good, except at the higher fractions, where the simulated radii vary widely. This is due to the low number of counts in the outermost edges of the PSF. There is a tendency at these higher fractions for the models to predict lower radii than is shown by the observation. This is an indication either that

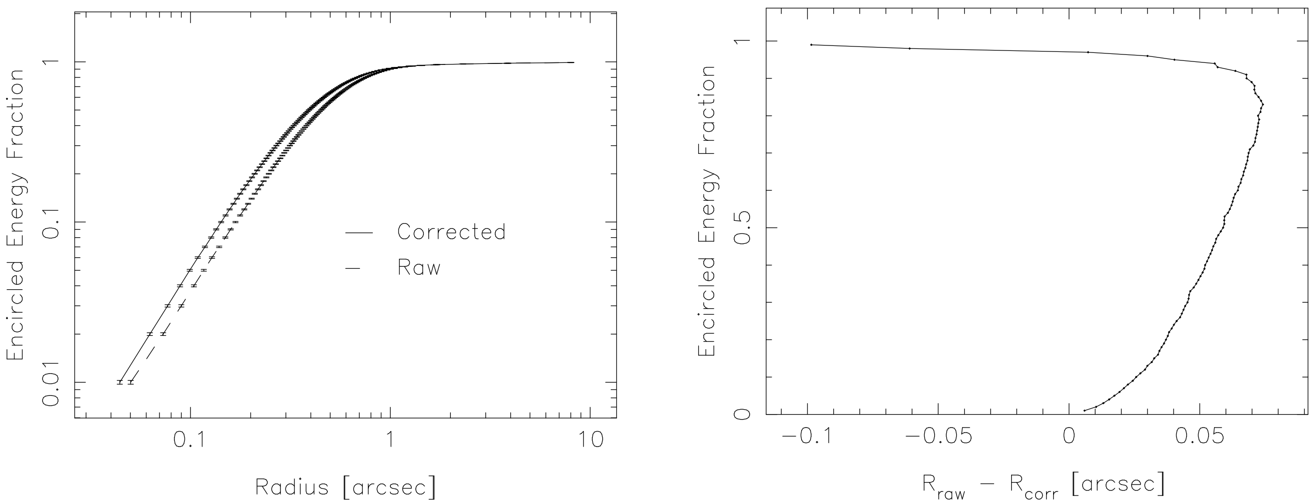


Figure 8: Encircled energy functions and their differences for the corrected and raw observed events.

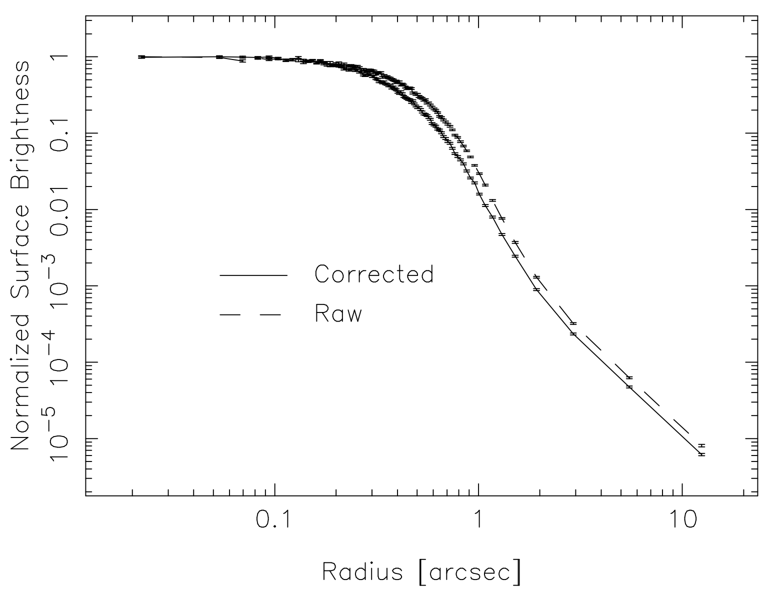


Figure 9: Radial profiles of the raw and corrected observation

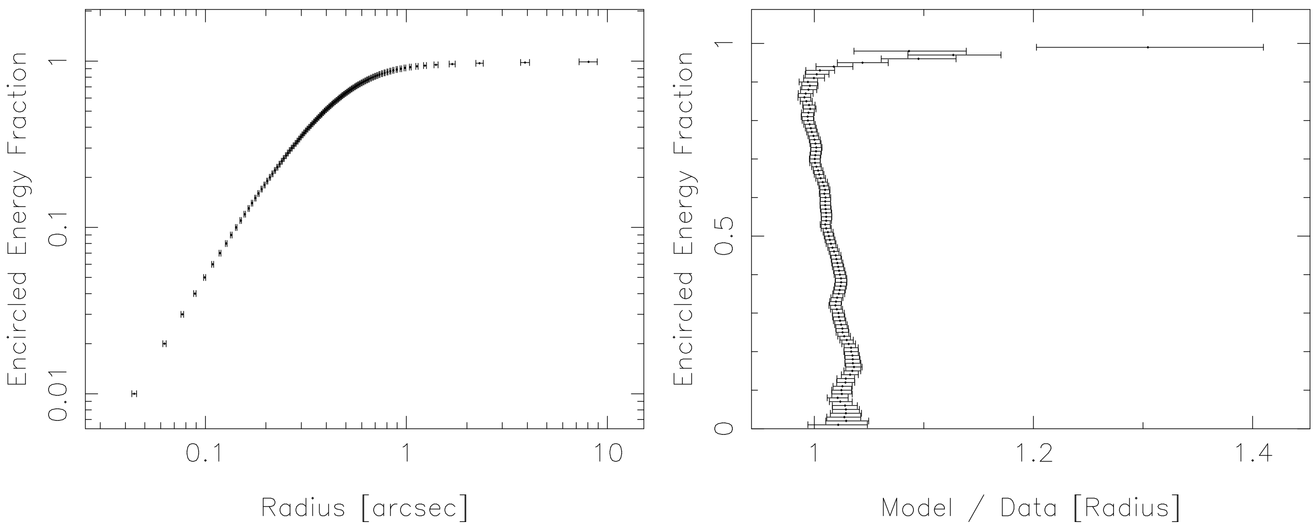


Figure 10: Comparison of simulated and observed encircled energy functions. The horizontal error bars indicate the range encompassed by 95% of the simulations. (a) The points are the observational data. (b) The points are the ratio of the median of the results of the simulations to the observational data.

the known underestimation of the mirror scattering is a more important component at the low energies of AR Lac then expected, or that the AR Lac observation is not sampling the "median" part of the optics. Without a good deal more data, it is not possible to evaluate either of these explanations.

A comparison of the radial profiles for the simulations and the corrected observation is shown in Fig. 11. The vertical error bars indicate the range encompassed by 95% of the simulations; the lines are the corrected observation. The agreement is in general good, although the simulations tend to be broader between $0.5''$and $1''$. The simulations have a fairly large 95% range, but their standard deviations (not shown) are consistent with Poisson statistics in the counts per bin ($\pm 3\%$for the inner most radii). The source of the ringing exhibited by the simulations is unknown and under investigation.

5 Conclusions

After the *ad hoc* corrections to the events' positions to compensate for the artifacts in HRC-I position reconstruction, I find excellent good agreement between the SAOsac model and the observations. The encircled energy radii are predicted to better than 5%, while the radial profile predicts the surface brightness to within 15%. The most significant deviations in the latter occur in a region where the model exhibits ringing; this is under investigation.

References

[1] "Orbital measurement and verification of the Chandra X-ray Observatory's PSF," D. Jerius et al., 2000 Proc. SPIE 4012.

[2] T. Aldcroft, private communication.

[3] M. Juda, `http://hea-www.harvard.edu/~juda/memos/hrc_blur/hrc_blur.html`.

[4] M. Juda, private communication.

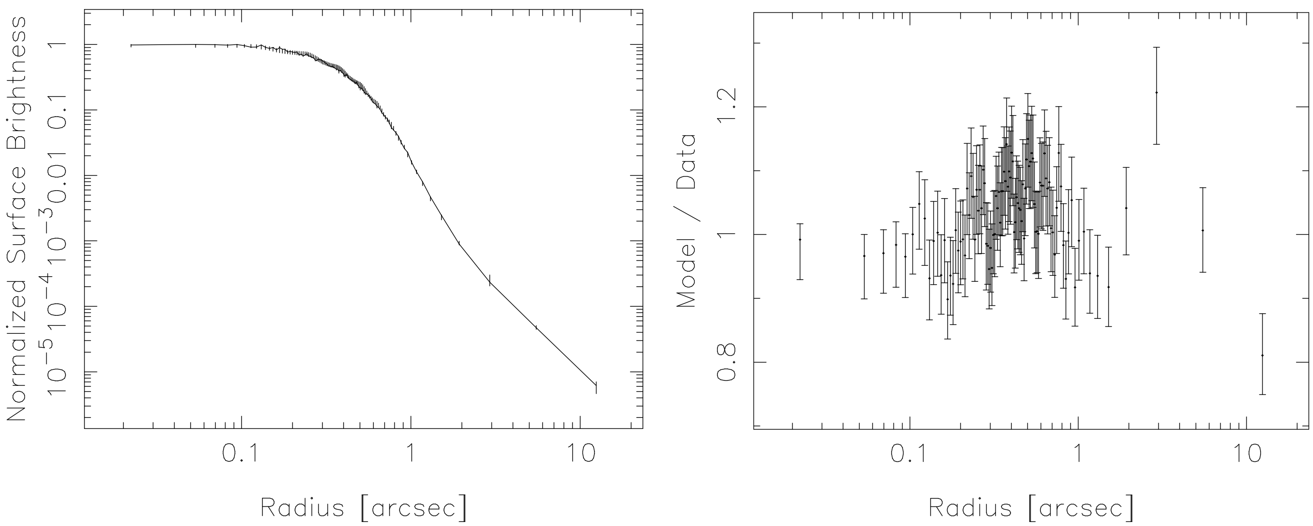


Figure 11: Comparison of simulated and observed radial profiles. The vertical error bars indicate the range encompassed by 95% of the simulations. (a) The line is the observational data. (b) The points are the ratio of the median of the results of the simulations to the observational data.

[5] J. Drake, private communication.