The Quality and Stability of Chandra Telescope Pointing and Spacial Resolution

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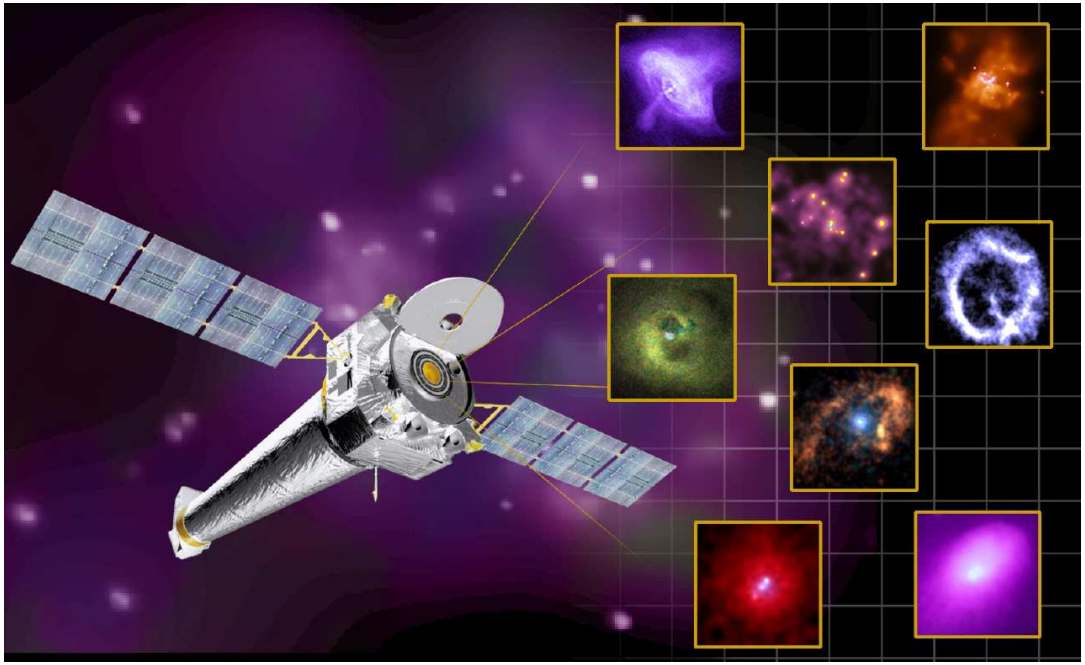

Chandra X-ray Observatory

- Revolutionized the X-ray astronomy as being the first, and so far the only, X-ray telescope achieving sub-arcsecond resolution.
- Comprised of three principal elements: the High Resolution Mirror Assembly (HRMA), Pointing Control and Aspect Determination (PCAD) system, and the Science Instrument Module (SIM).
- To achieve and retain the unprecedented imaging quality, it is critical that these three principal elements to stay rigid and stable for the entire life time of the Chandra operation.

Chandra Focal Point, Optical Axis, and Aimpoint

Definition:

- Focal Point: Point on the focal plane where the sharpest PSF is located.
- Optical Axis: Axis that perpendicular to the focal plane at the Focal Point.
- Aimpoint: Point on the focal plane where the image of a source with zero Y and Z offsets is located.

Measuring the telescope Optical Axis and Aimpoint positions on the detectors can determine the stability of the telescope.

Chandra Attitude Control and Fiducial Transfer System

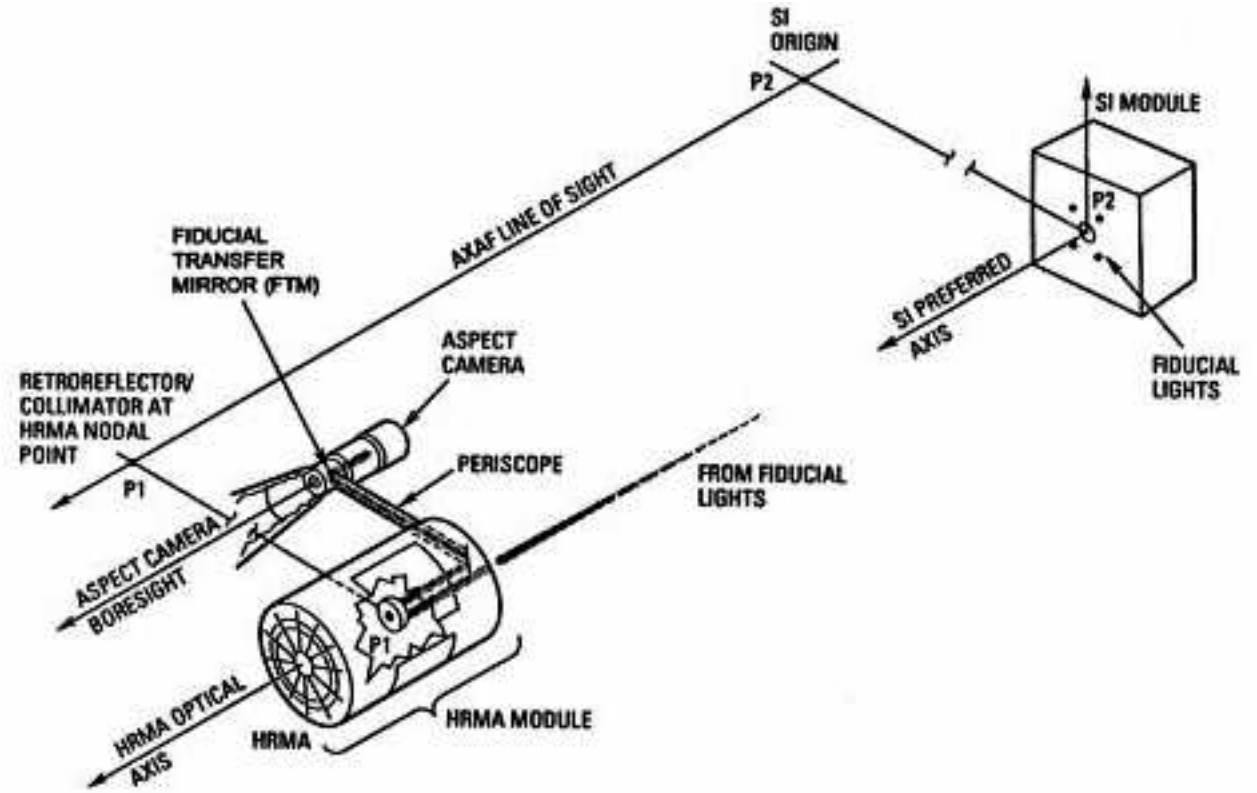

Figure 1: Chandra Pointing and Fiducial Transfer System. (POG.11: Figure 5.3.)

- Target position: RA_targ and Dec_targ in the data header, requested by the observer.
- ACA attitude (Aspect Camera Assembly pointing): Quaternions in the ACA database, command position computed from the RA_targ and Dec_targ, with an 89.6″ offset.
- Telescope attitude (HRMA pointing): RA_pnt and Dec_pnt, computed mean pointing of the observation, with ∼97″ offset from ACA attitude, and ∼17″ from the target position.

Chandra Pointing: Target Position, Telescope and ACA Attitude

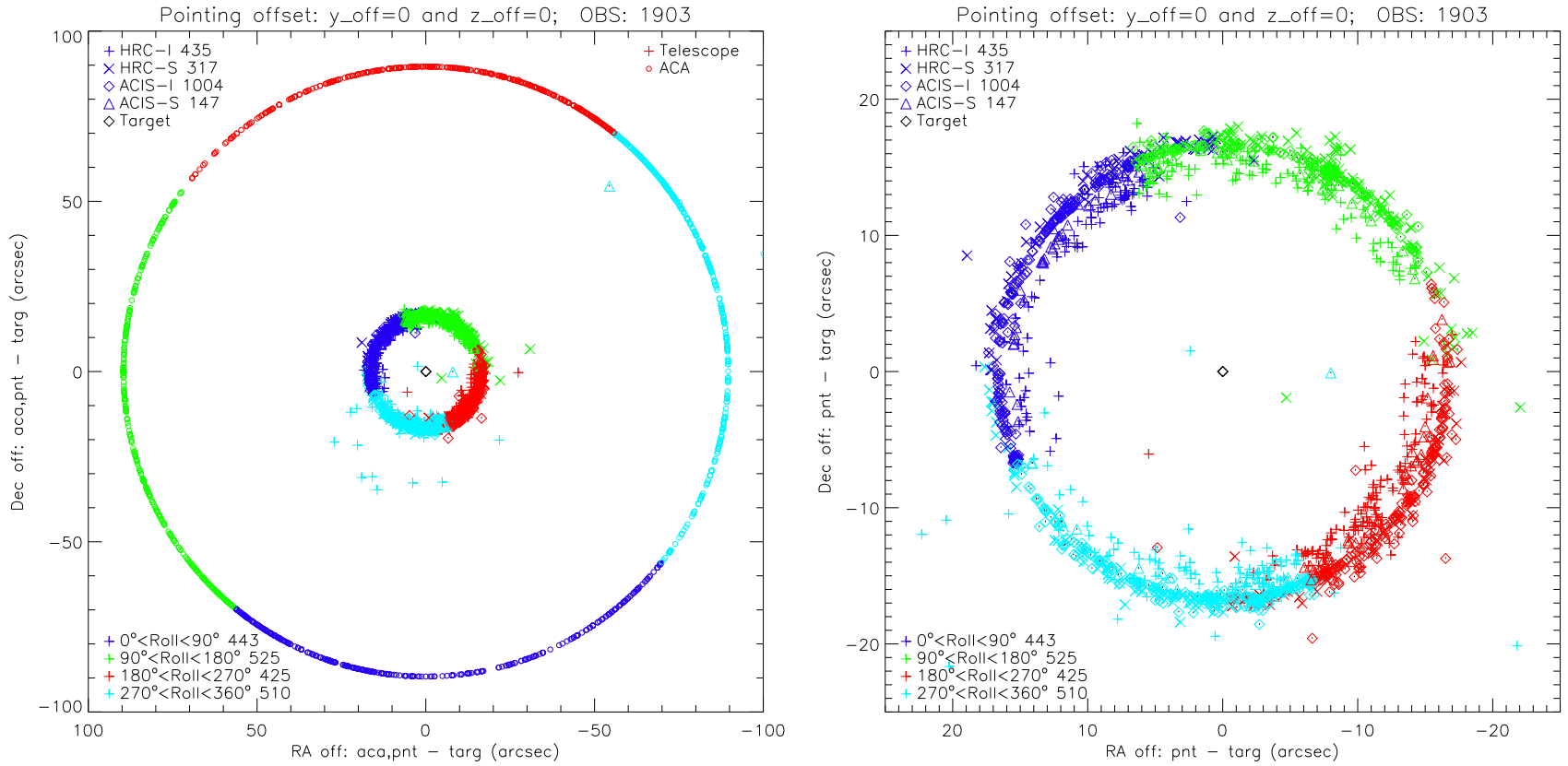

Figure 2: Chandra Pointing: Left panel shows, for given target positions (RA_targ, Dec_targ, specified by observers) at the center of the diagram, the ACA pointings (control command) as a big circle. Four colors separate roll angles into four quadrants. The offset between the requested target position and the commanded ACA attitude is 89.6″. Right panel is a zoomed in version of the left panel. It shows the actual telescope (HRMA) pointings (RA_pnt, Dec_pnt in the data header) wrt the target at the center. Four symbols indicate four detectors. There is a misalignment of ∼17″ between the target position (aimpoint on the detector) and the HRMA pointing. The misalignment between HRMA and ACA attitude is ∼ 97″.

On-orbit calibration of the Optical Axis

The HRC-I and HRC-S gain maps were calibrated by using raster scans of Y and Z offset with bright point sources (HR 1099 and Ar Lac). These calibration data are used to determine the position of the Chandra Optical Axis.

Optical Axis Calibration data

Detector: HRC-I

Date	Source	Sim-Z (mm)
1999-09-02	HR 1099	91.8655
1999-10-03	Ar Lac	126.9855
1999-12-09	Ar Lac	126.9855
2000-12-12	Ar Lac	126.9855
2002-01-26	Ar Lac	126.9855
2003-02-22	Ar Lac	126.9855
2004-11-25	Ar Lac	126.9855
2005-09-27	Ar Lac	126.9830
2006-09-20	Ar Lac	126.9830
2007-09-17	Ar Lac	126.9855
2008-09-07	Ar Lac	126.9830
2009-09-24 (Scheduled)	Ar Lac	126.9830

Detector: HRC-S

Date	Source	Sim-Z (mm)
2000-12-20	Ar Lac	250.4660
2001-05-14	Ar Lac	250.4660
2002-01-26	Ar Lac	250.4660
2002-08-09	Ar Lac	250.4660
2003-02-22	Ar Lac	250.4660
2003-09-01	Ar Lac	250.4660
2004-02-09	Ar Lac	250.4660
2004-11-28	Ar Lac	250.4660
2005-02-10	Ar Lac	250.4660
2005-09-01	Ar Lac	250.4660
2006-03-20	Ar Lac	250.4660
2006-09-21	Ar Lac	250.4660
2007-09-21	Ar Lac	250.4660
2008-09-02	Ar Lac	250.4660
2009-09-26 (Scheduled)	Ar Lac	250.4660

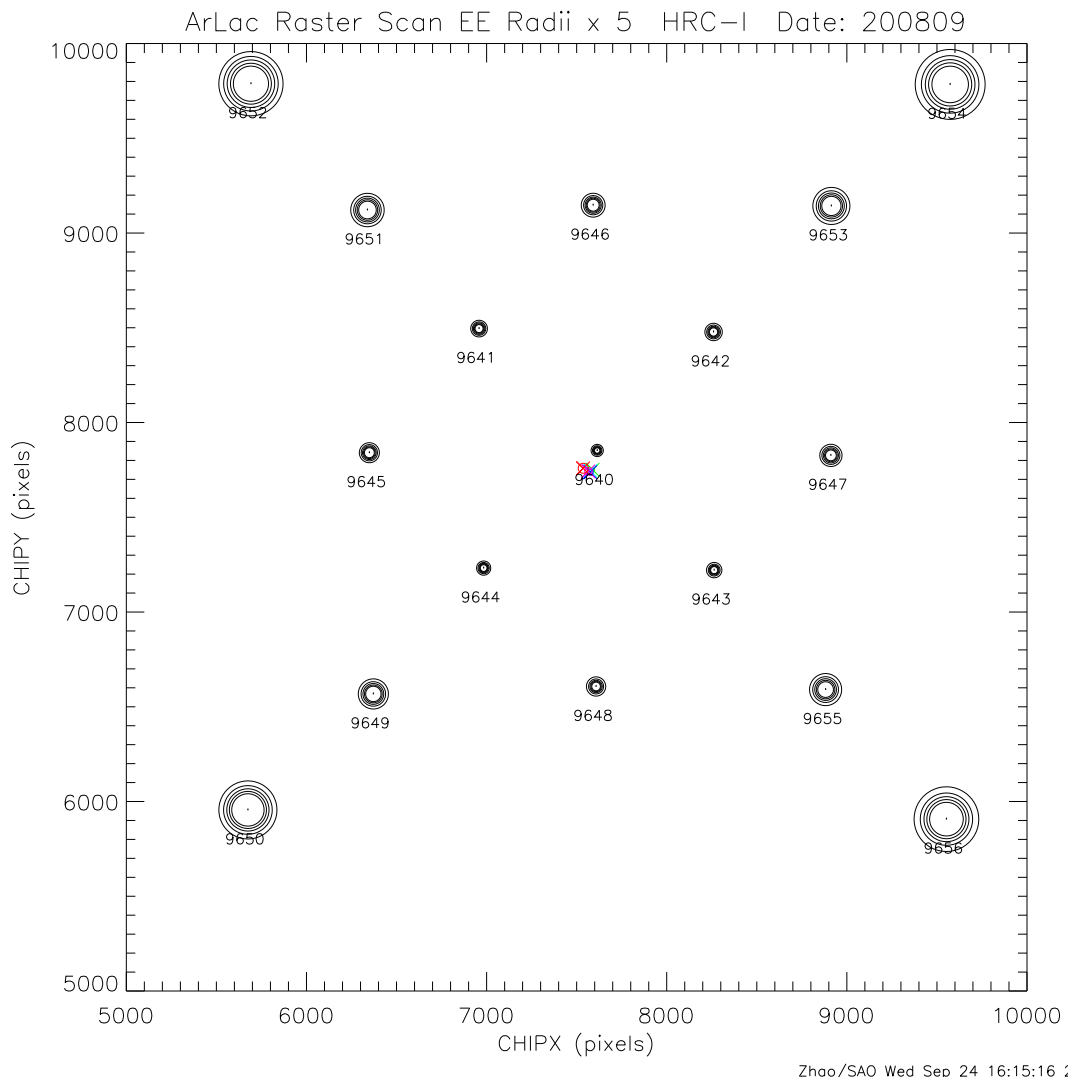

Figure 3: HRC-I raster scan of Ar Lac with 1ks exposure time for each point, except the center point which is 3ks (Date: 2008-09-07). Circles around each observation point are the 50%, 60%, 70%, 80%, 90% encircled energy circles × 5.

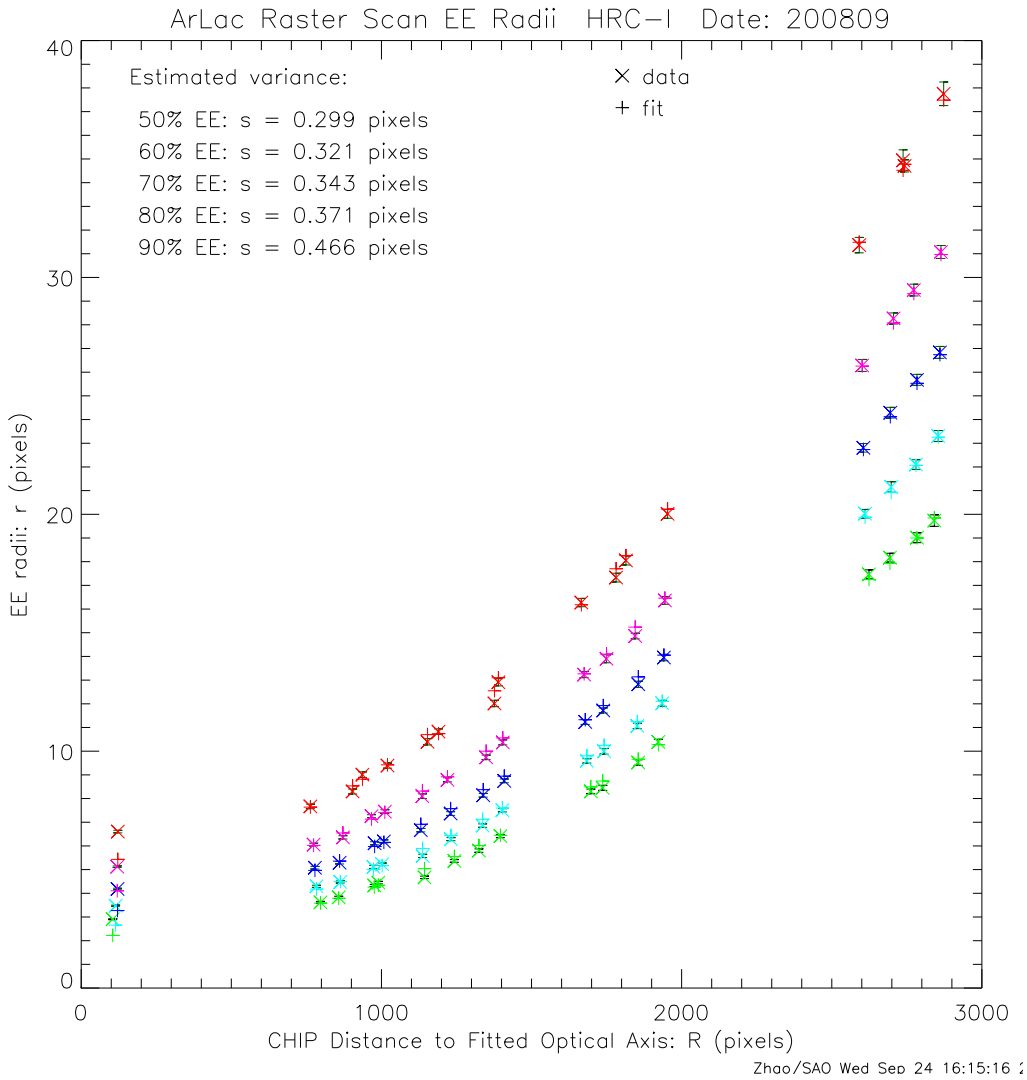

Figure 4: Quadratic fit of HRC-I raster scan data of Ar Lac (Date: 2008-09-07).

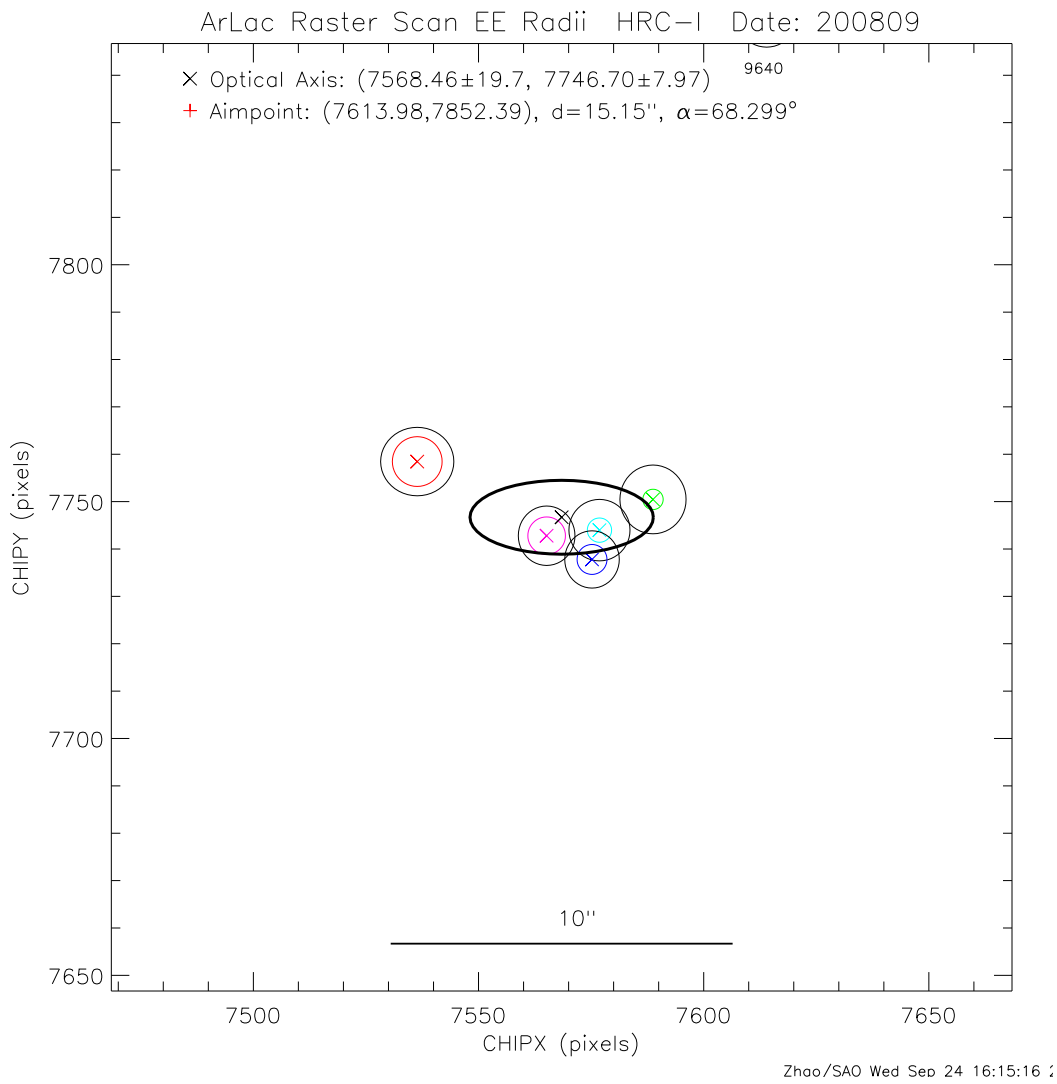

Figure 5: Optical Axis and Aimpoint position on HRC-I, based on raster scan observation of Ar Lac made on 2005-09-17. The Optical Axis is the weighted average of five EE (50% – 90%) measurements, at the center of the error ellipse.

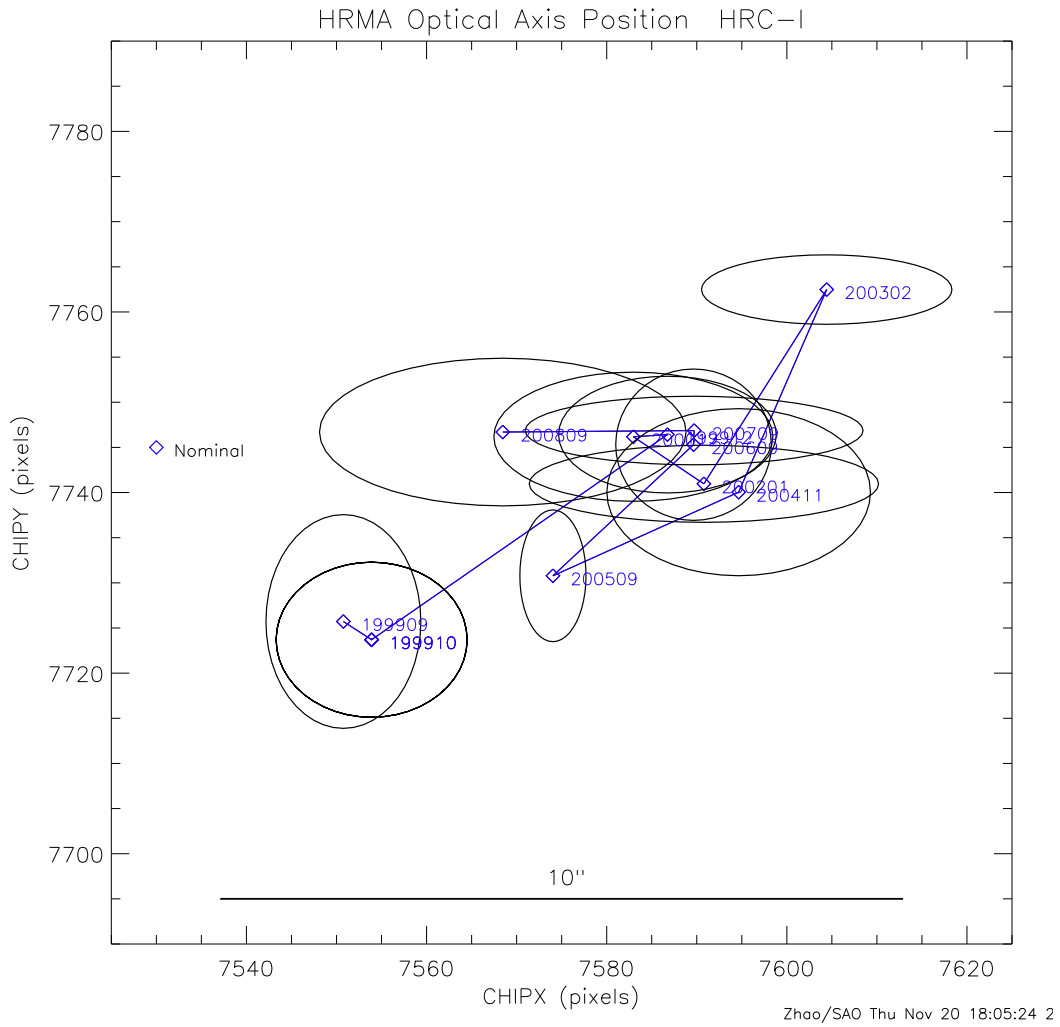

Figure 6: Optical Axis positions from all the HRC-I measurements on CHIP coordinates. The drift of the Optical Axis is more like a random walk within 10″.

On-axis Target Chip Position and Aimpoint

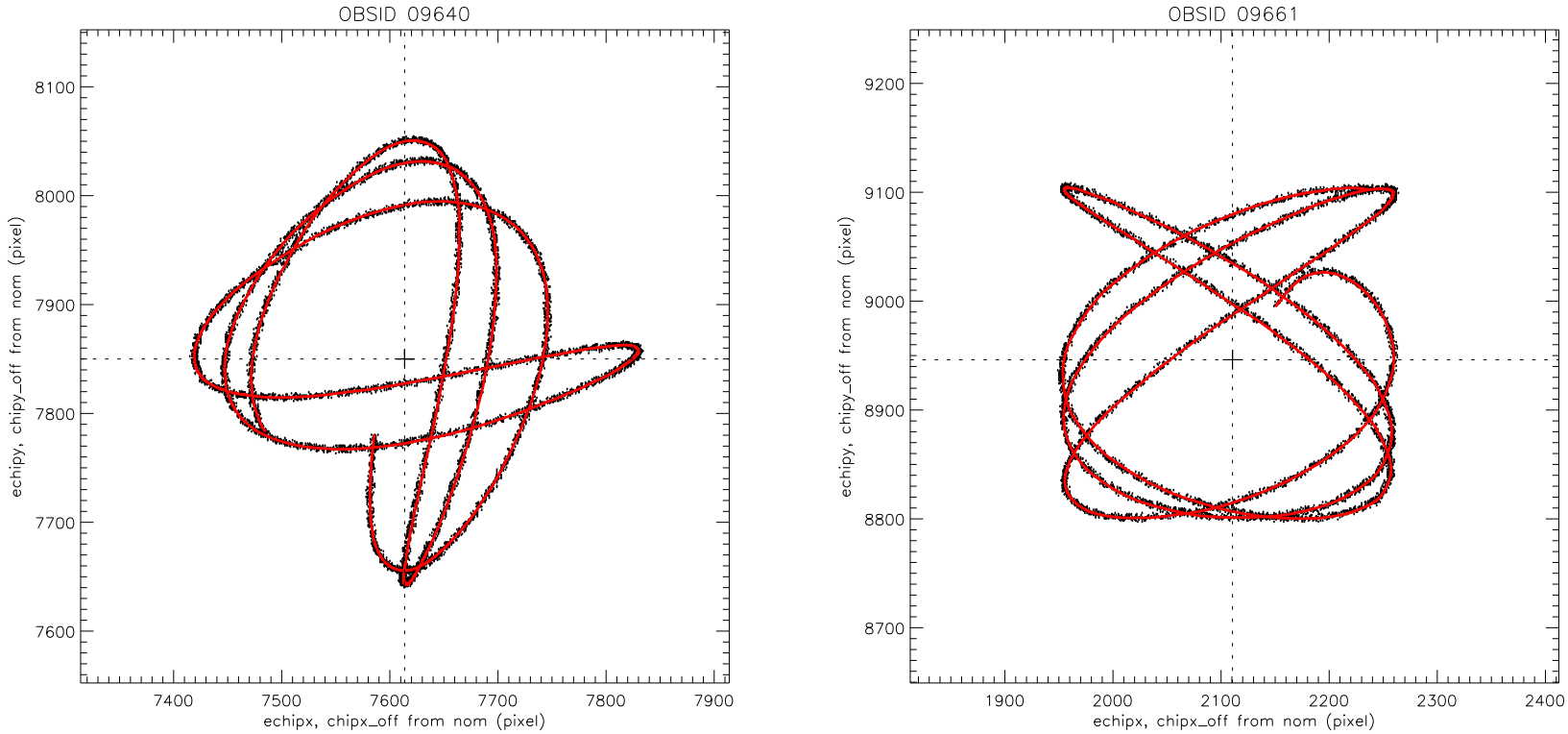

Figure 7: On-axis Target Chip Position and Aimpoint. ArLac observation (3ks) with HRC-I (left) and HRC-S (right) on chip coordinates. Data (black dots) are registered on the chip as a dither pattern (a Lissajous figure). The overlay red curve is the deduced from the RA and Dec offset wrt the telescope pointing in the aspect solution file. The cross in the center is the aimpoint.

Chandra Optical Axis and Aimpoint Positions on HRC-I

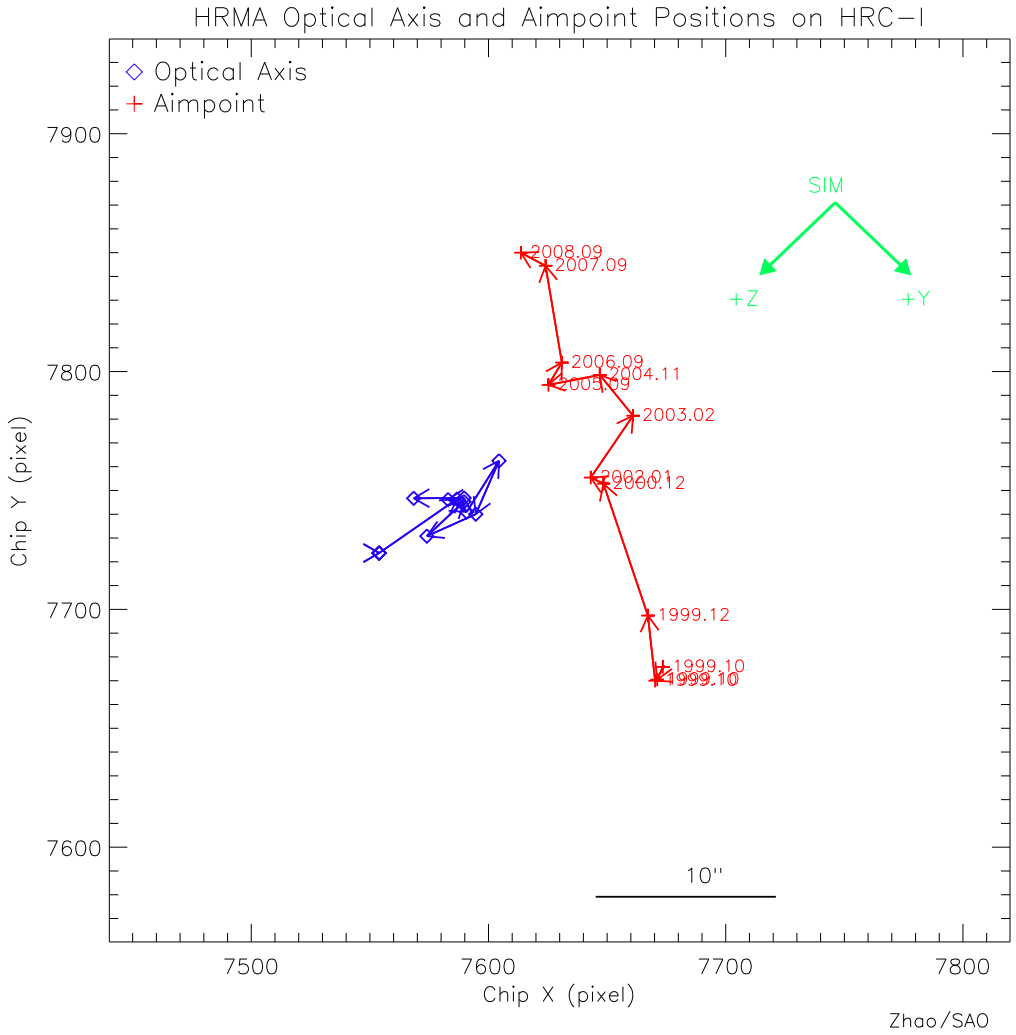

Figure 8: Optical Axis and Aimpoint positions from all the HRC-I measurements on CHIP coordinates. The Aimpoint has drifted by more than 24″ in the -Y and -Z direction of the SIM coordinates. But the two points were never more than 16″ apart.

STF (SIM Translation Frame) Shift Relative to FC (Focal Coordinate)

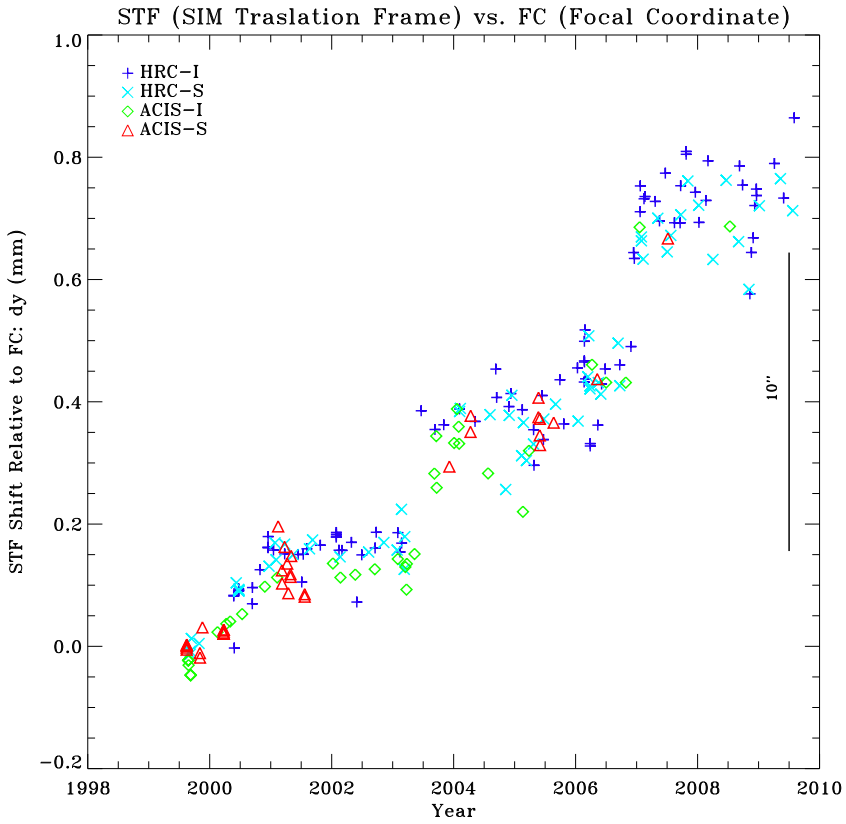

Figure 9: STF dy drifted about 0.9mm (18″) since launch.

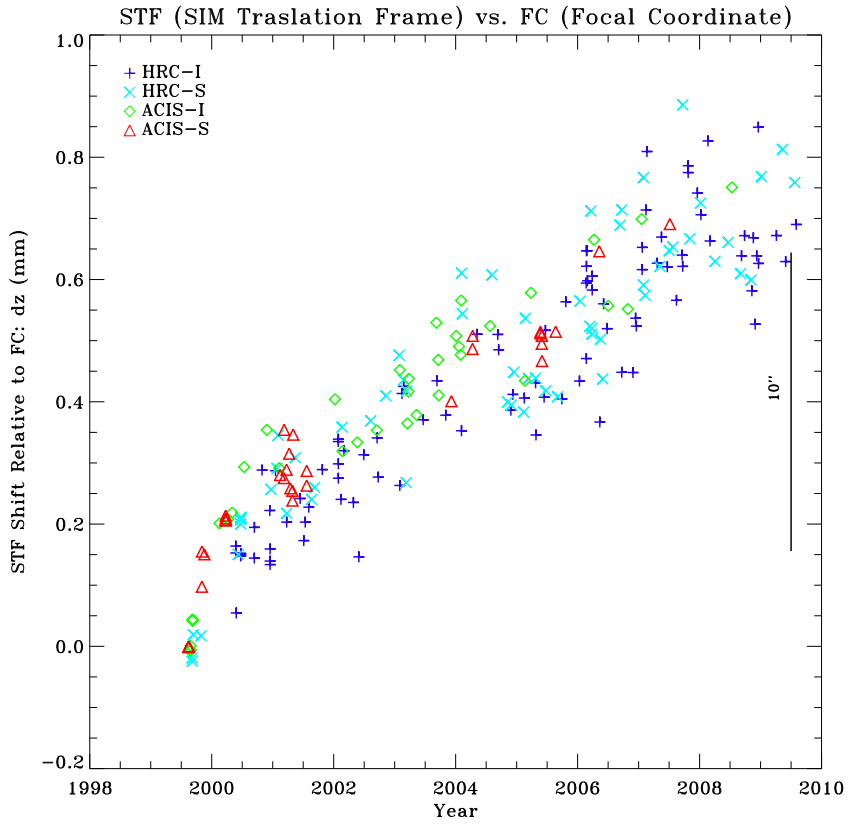

Figure 10: STF dz drifted about 0.9mm (18″) since launch.

STF (SIM Translation Frame) Shift Relative to FC (Focal Coordinate)

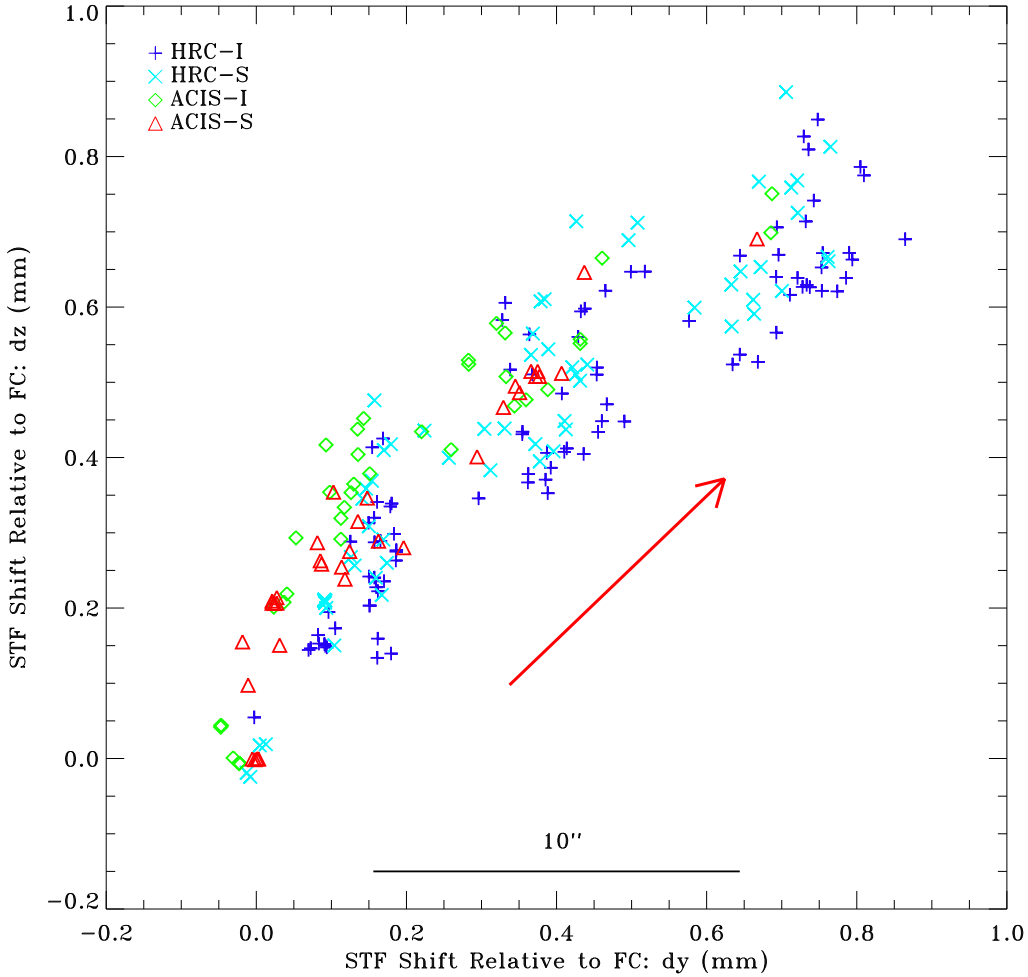

Figure 11: STF drifted about 1.2mm (24″) in +SIM-Y and +SIM-Z direction since launch.

Chandra Aimpoint Drifts on Four Detectors in SIM Coordinates

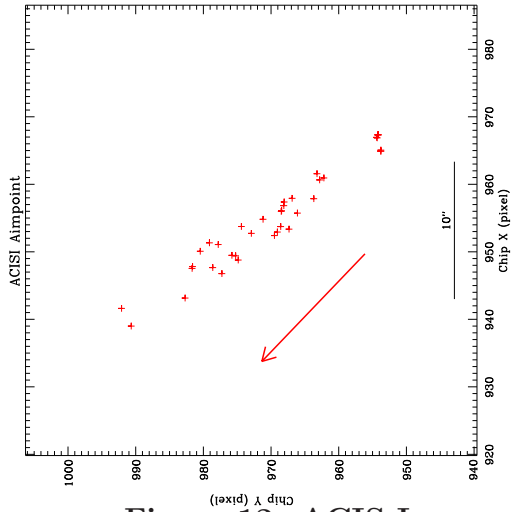

Figure 12: ACIS-I

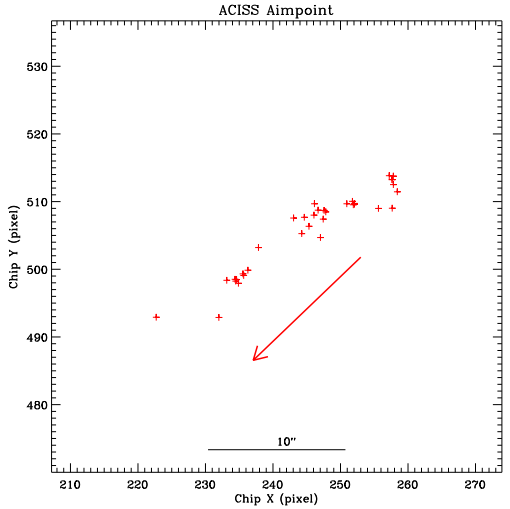

Figure 13: ACIS-S

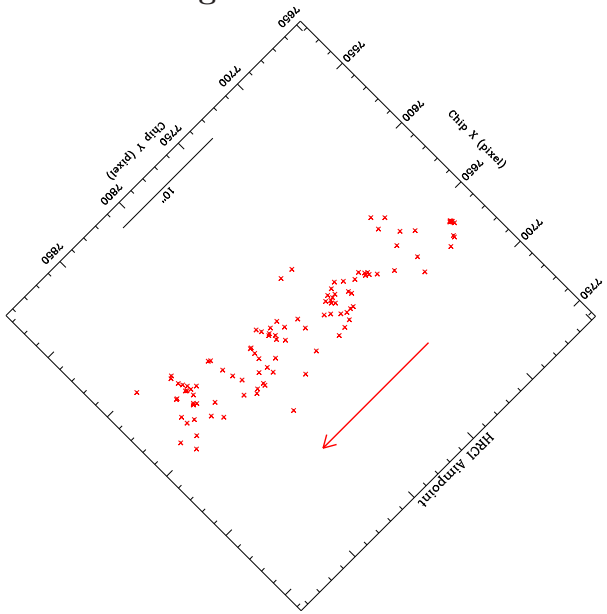

Figure 14: HRC-I

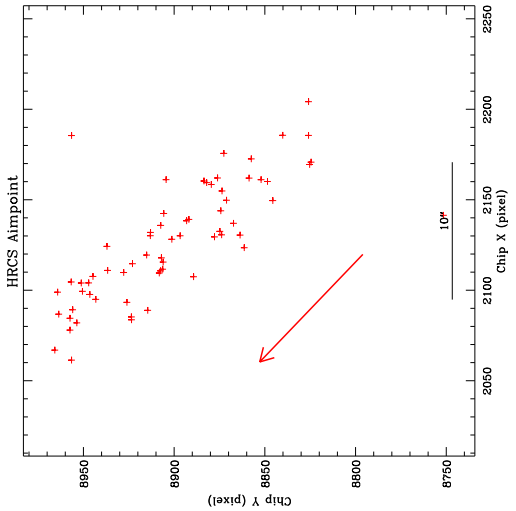

Figure 15: HRC-S

Chandra Optical Axis and Aimpoint Positions on HRC-S

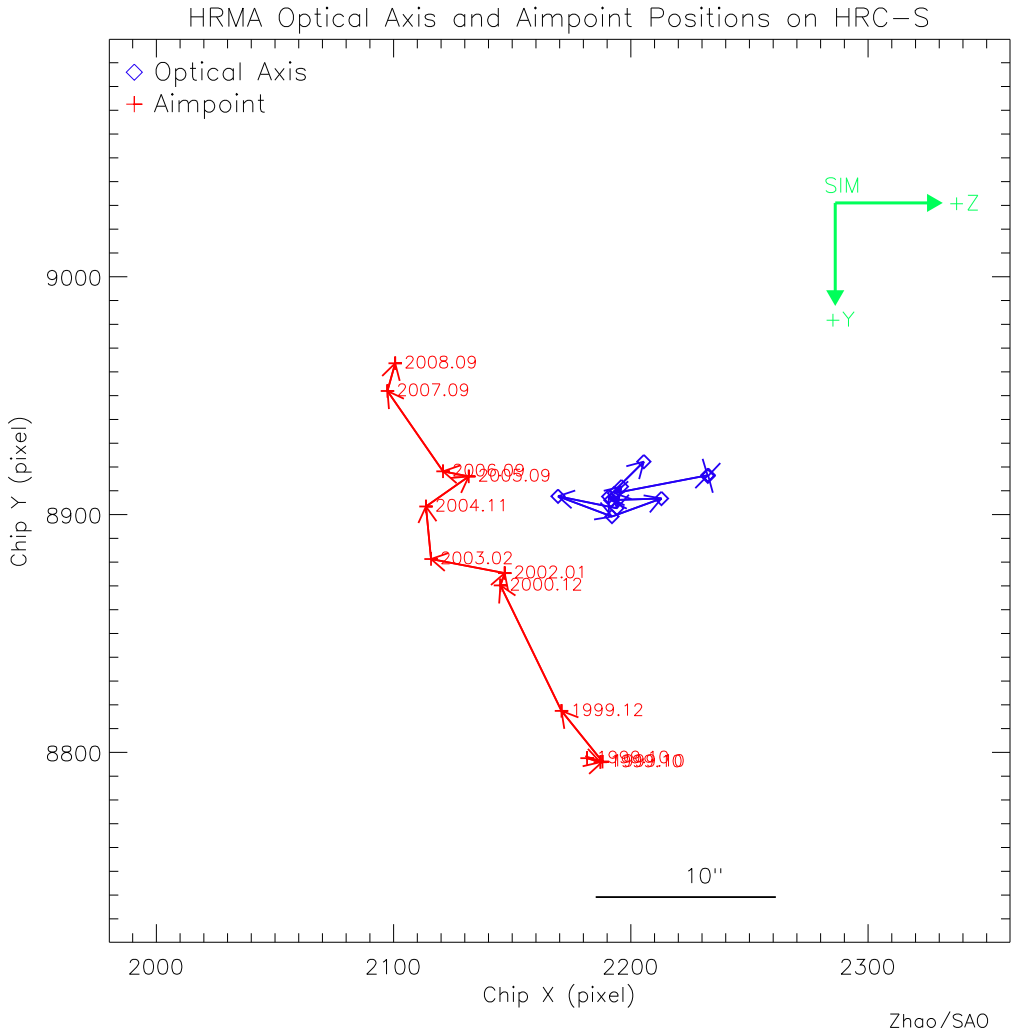

Figure 16: Chandra Optical Axis and Aimpoint positions on HRC-S, transformed from the HRC-I measurements.

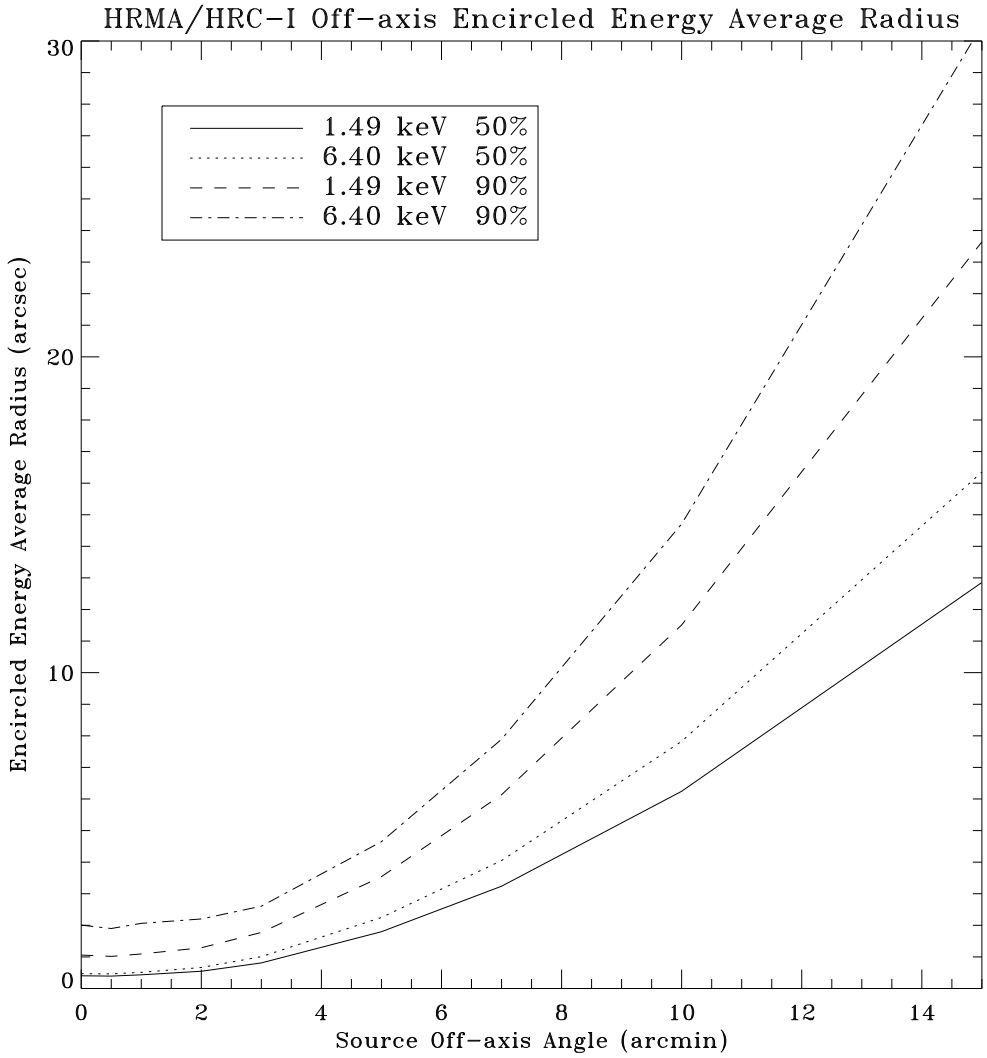

Figure 17: The HRMA/HRC-I Encircled Energy as a function of off-axis angle (POG.11: Figure 4.12). It shows that the current small separation ($< 15''$) between the Optical Axis and the Aimpoint does not degrade the onaxis target PSF on the HRC.

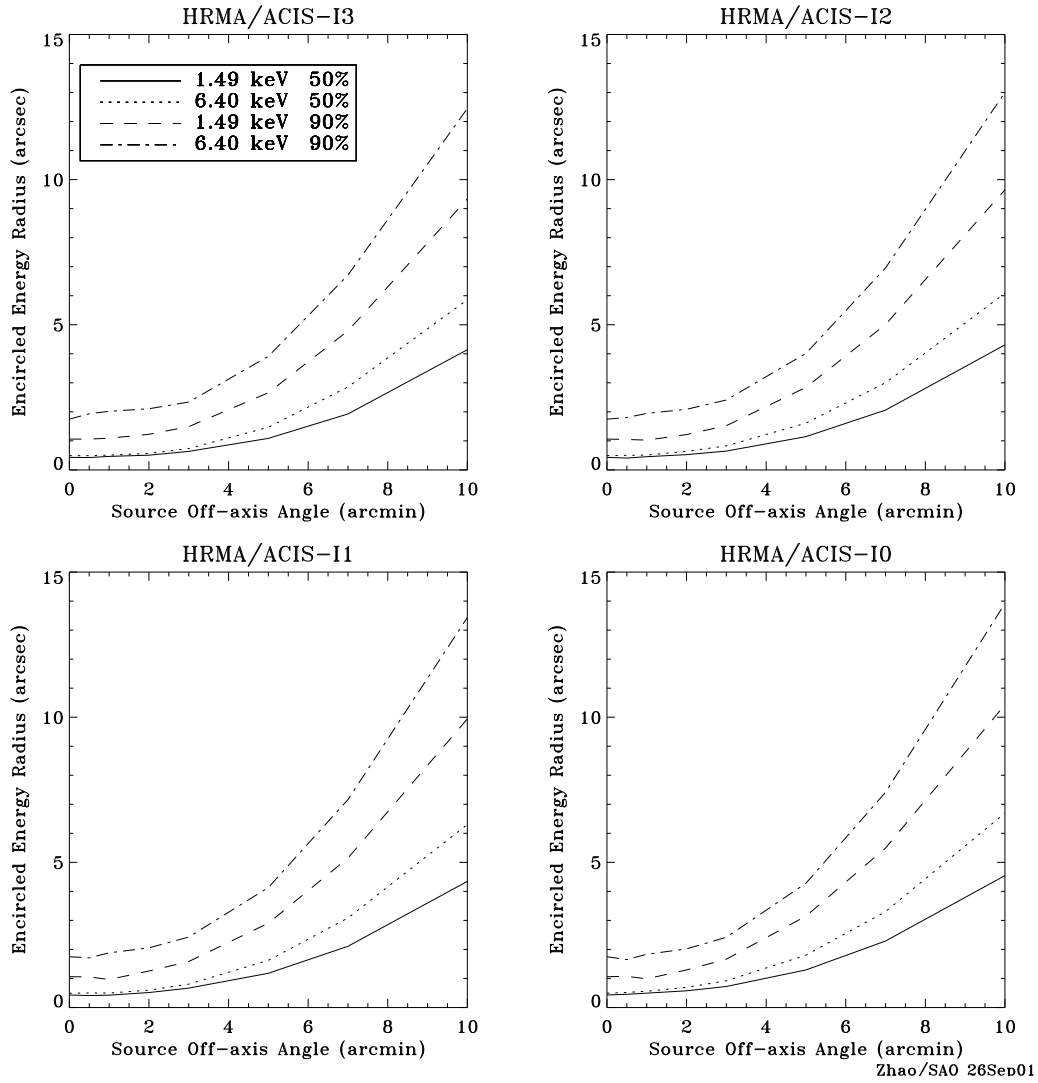

Figure 18: The HRMA/ACIS-I Encircled Energy as a function of off-axis angle (POG.11: Figure 4.13). It shows that the current small separation ($< 15''$) between the Optical Axis and the Aimpoint does not degrade the onaxis target PSF on the ACIS.

ACIS FLIGHT FOCAL PLANE

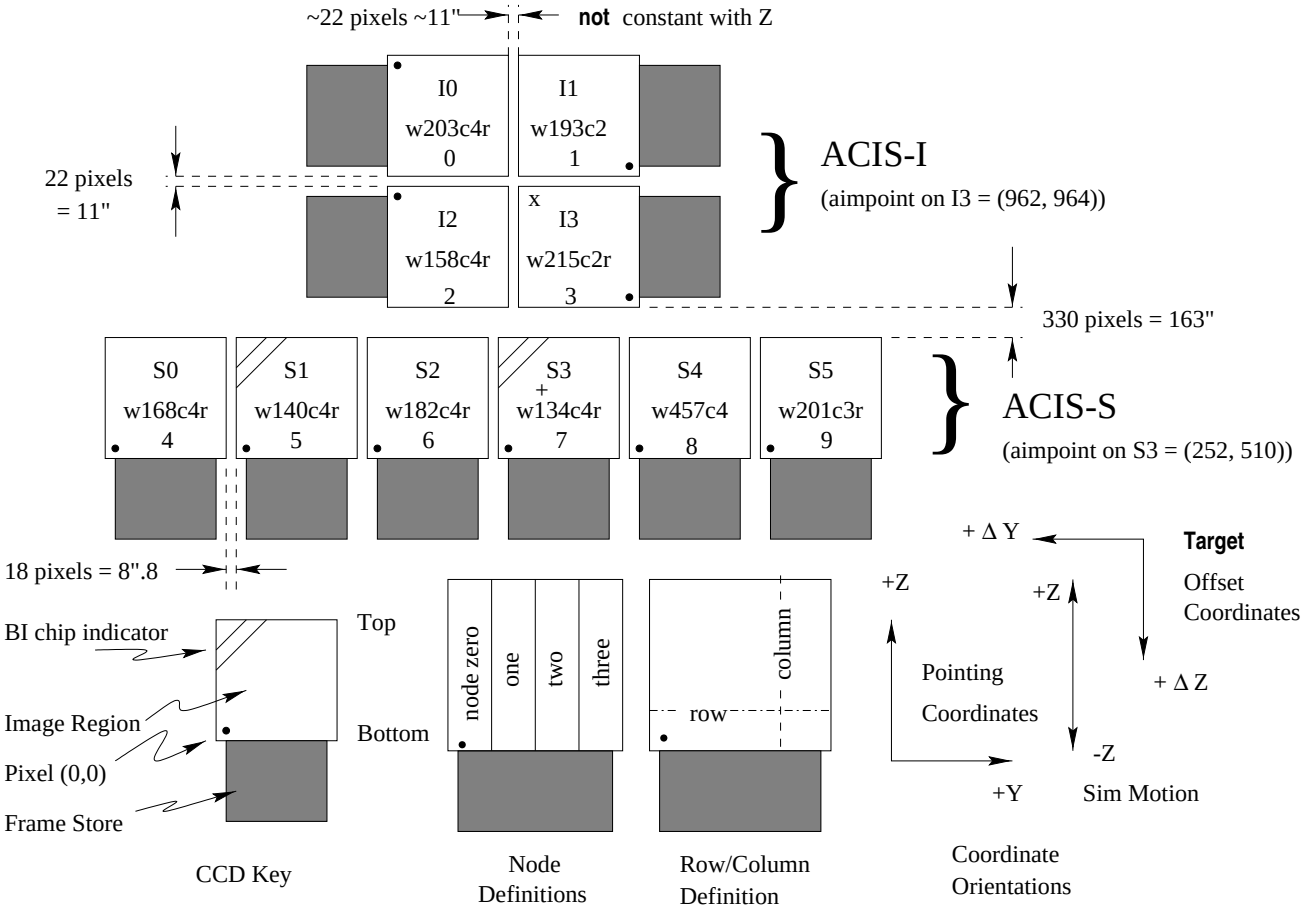

Figure 19: The ACIS focal plane layout (POG.11: Figure 6.1).

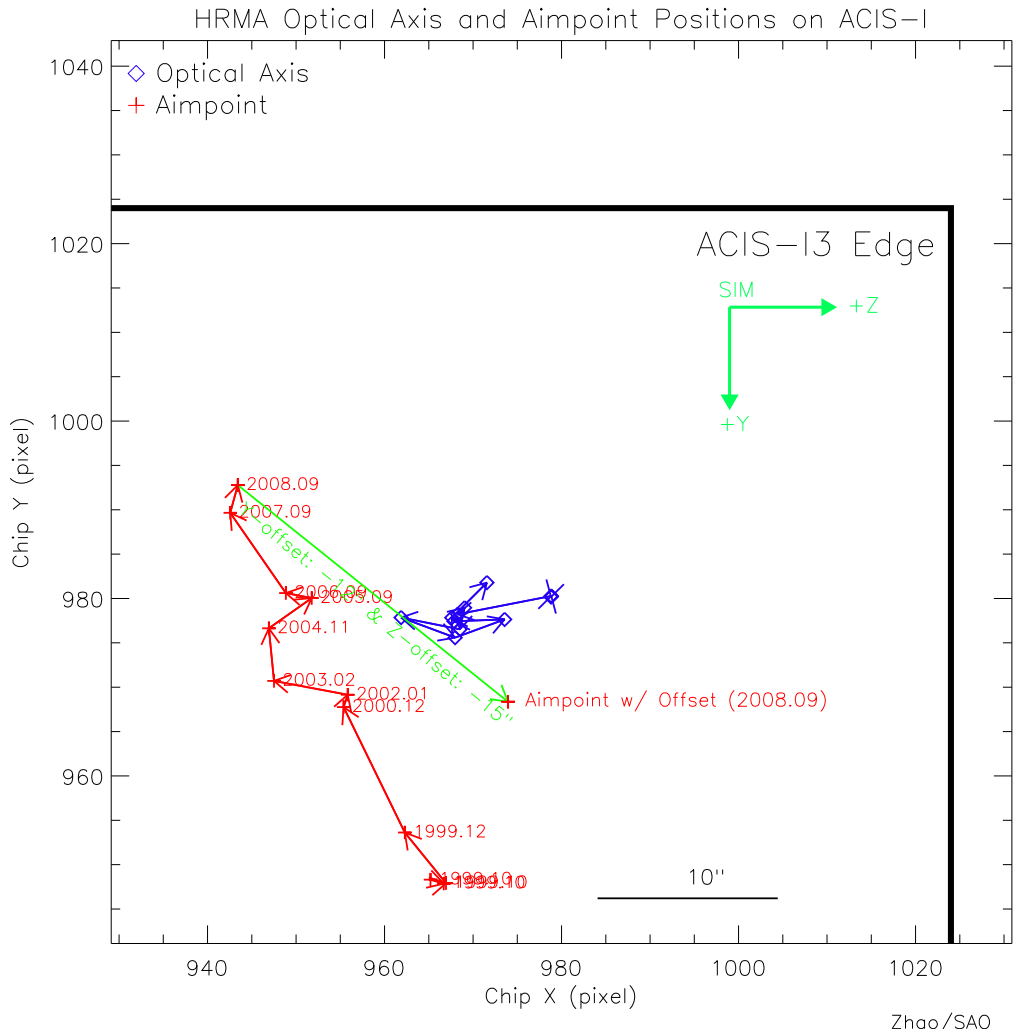

Figure 20: Chandra Optical Axis and Aimpoint positions on ACIS-I, transformed from the HRC-I measurements. A large shift of $\sim 10''$ in December 2006 was caused by the Aspect Camera Assembly (ACA) primary focal plan CCD cool down from -15°C to -20°C. This sudden shift brought the aimpoint very close to the ACIS-I3 chip boundary. As it continue to drift towards the boundary, the dither pattern ($16''$ peak-to-peak) will soon fall out of the chip. Therefore a default target pointing of Y-offset $= -15''$ and Z-offset $= -12''$ was implemented to bring the aimpoint away from the chip boundary and also closer to the optical axis. Later when the ACA warmed up, the aimpoint drifted back $\sim 4''$.

Chandra Optical Axis and Aimpoint positions on ACIS-S

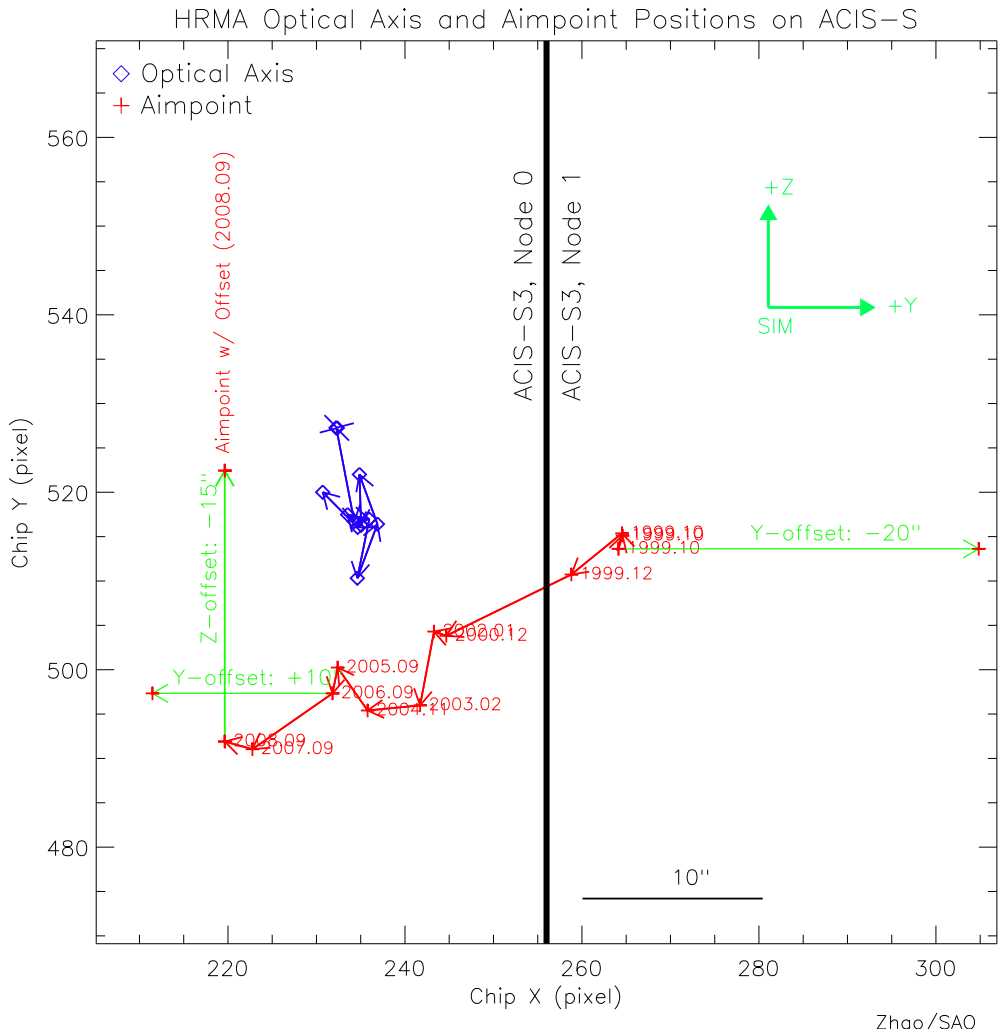

Figure 21: Chandra Optical Axis and Aimpoint positions on ACIS-S, transformed from the HRC-I measurements. Because of the aimpoint drift, the default target pointing offset for ACIS-S observations has been implemented three times to avoid the dither pattern falls on the node boundary: 1) Y-offset=$-20''$ in Oct. 1999; 2) Y-offset=$+10''$ in Sept. 2005; and 3) Z-offset=$-15''$ in Jan. 2007. The last one is to put the target pointing closer to the Optical Axis.

Chandra On-axis PSF: Comparing Observation with simulations

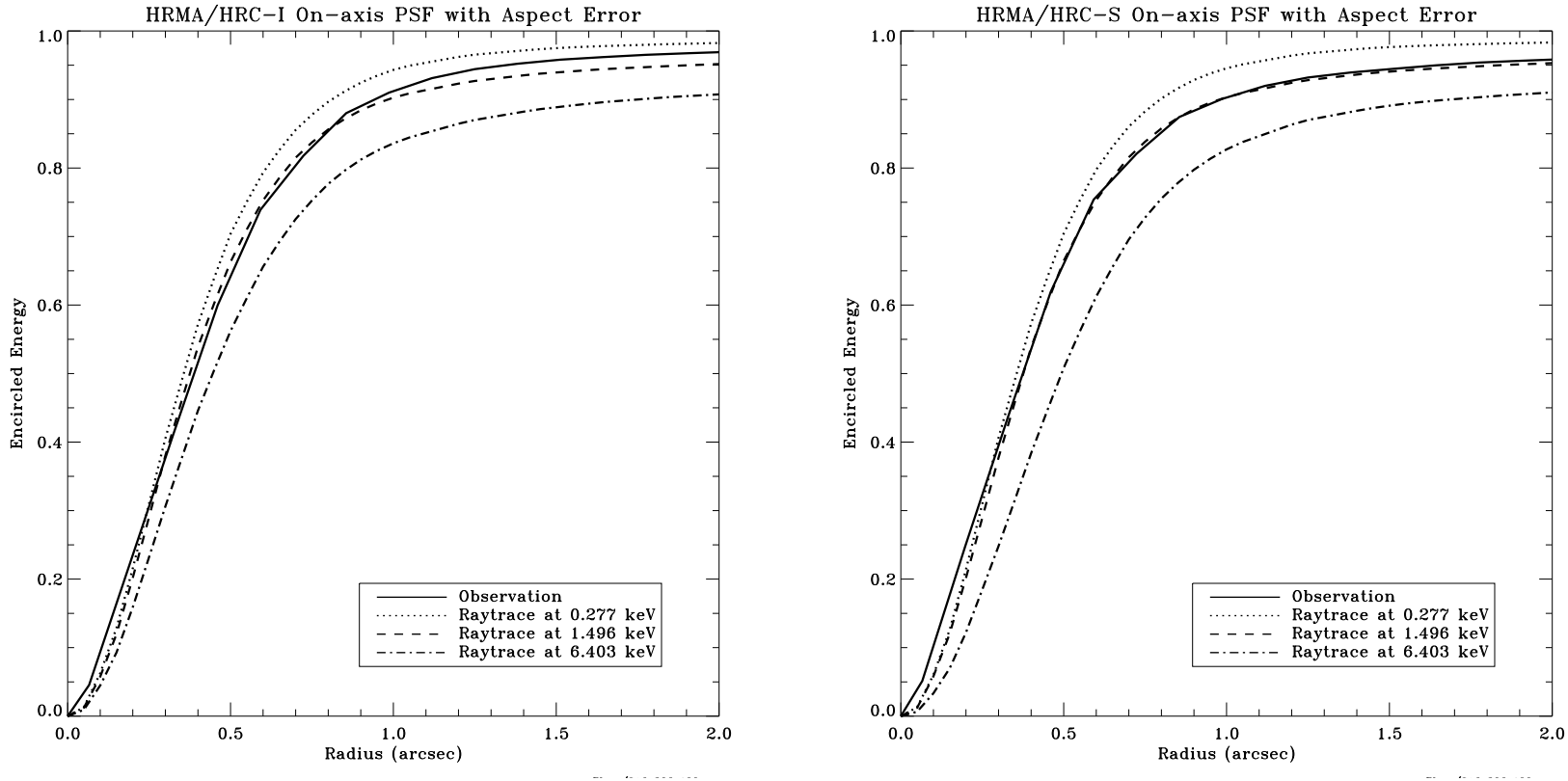

Figure 22: The HRMA/HRC-I (left) and HRC-S (right) on-axis fractional encircled energy as a function of angular radius from point sources (Ar Lac on HRC-I and LMC X-1 on HRC-S, observed immediately after Chandra launch in September 1999) compared with raytrace simulations for an on-axis point-source at selected X-ray energies, including the aspect uncertainties and the HRC pixelization effects. The data agree very well with the simulation. 50% encircled energy are within 0.4″ radius. (POG.11: Figures 4.18 &4.19)

Chandra On-axis Point source (ArLac) HRC-I Images

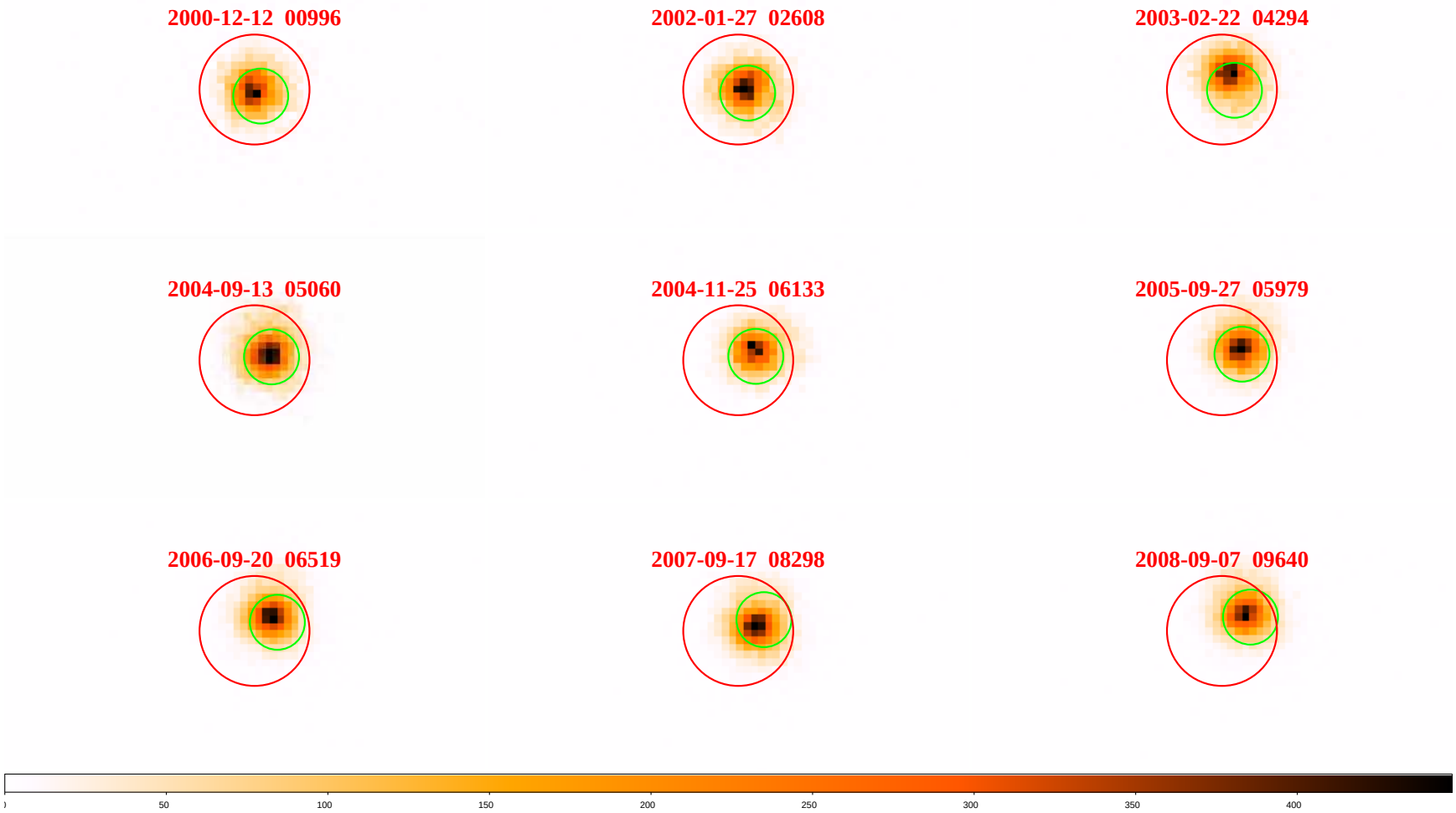

Figure 23: Chandra On-axis Point source (ArLac) HRC-I images in the past decade. The red circle ($1''$ radius) is centered at its J2000 coordinate (RA_targ, Dec_targ). The green circles ($0.5''$ radius) are centered at the predicted positions at different observing times, based on its proper motion: δRA=$-0.05248''/yr$, δDec=$0.04788''/yr$. The image quality stays the same, and the pointing is very accurate.

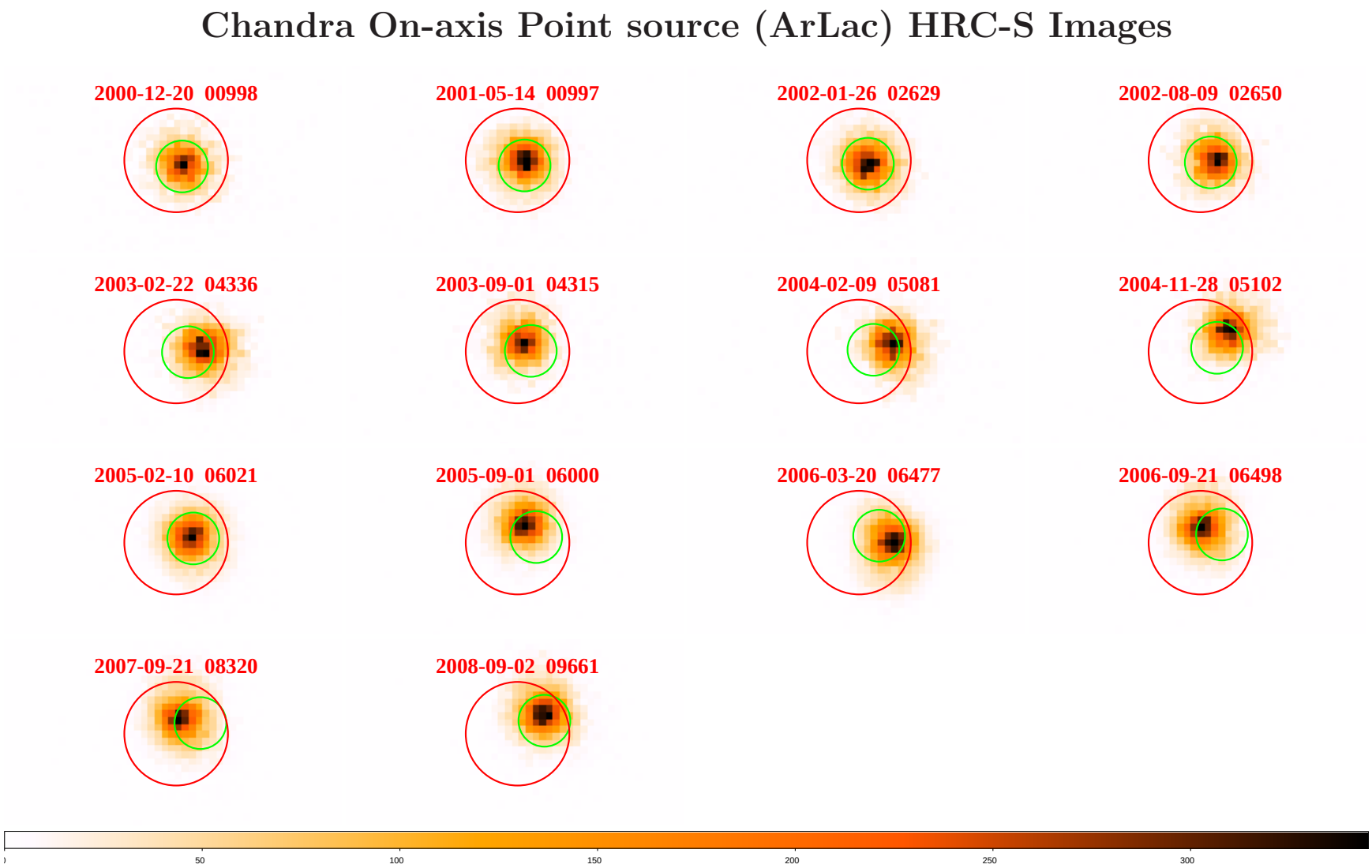

Figure 24: Chandra On-axis Point source (ArLac) HRC-S images in the past decade. The red circle ($1''$ radius) is centered at its J2000 coordinate (RA_targ, Dec_targ). The green circles ($0.5''$ radius) are centered at the predicted positions at different observing times, based on its proper motion: δRA=$-0.05248''/yr$, δDec=$0.04788''/yr$. The image quality stays the same, and the pointing is very accurate.

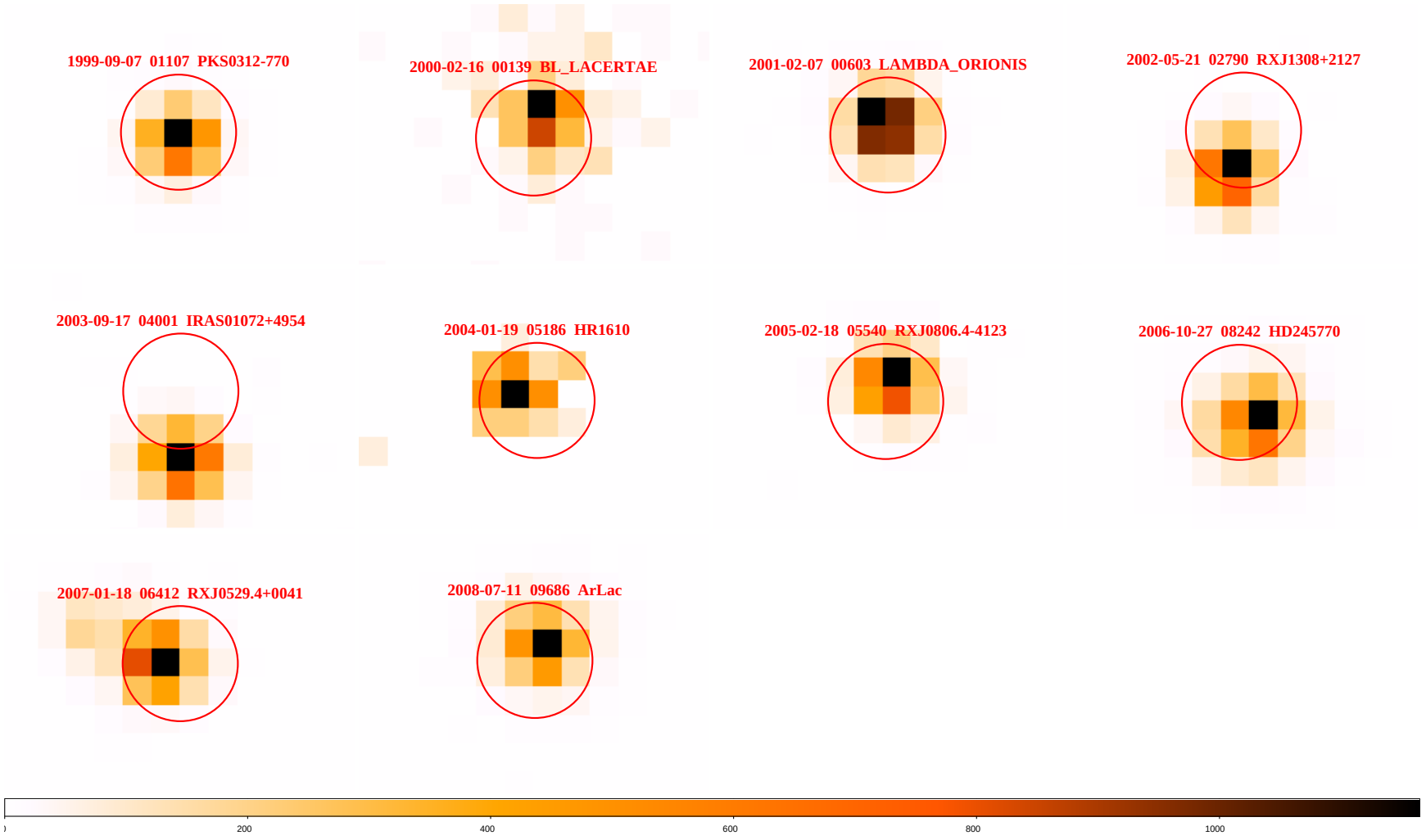

Figure 25: Chandra On-axis Point source ACIS-I images in the past decade. The red circle (1″ radius) is centered at ACIS-I3 aimpoint.

Chandra On-axis Point source ACIS-S Images

Figure 26: Chandra On-axis Point source ACIS-S images in the past decade. The red circle (1″ radius) is centered at ACIS-S3 aimpoint.

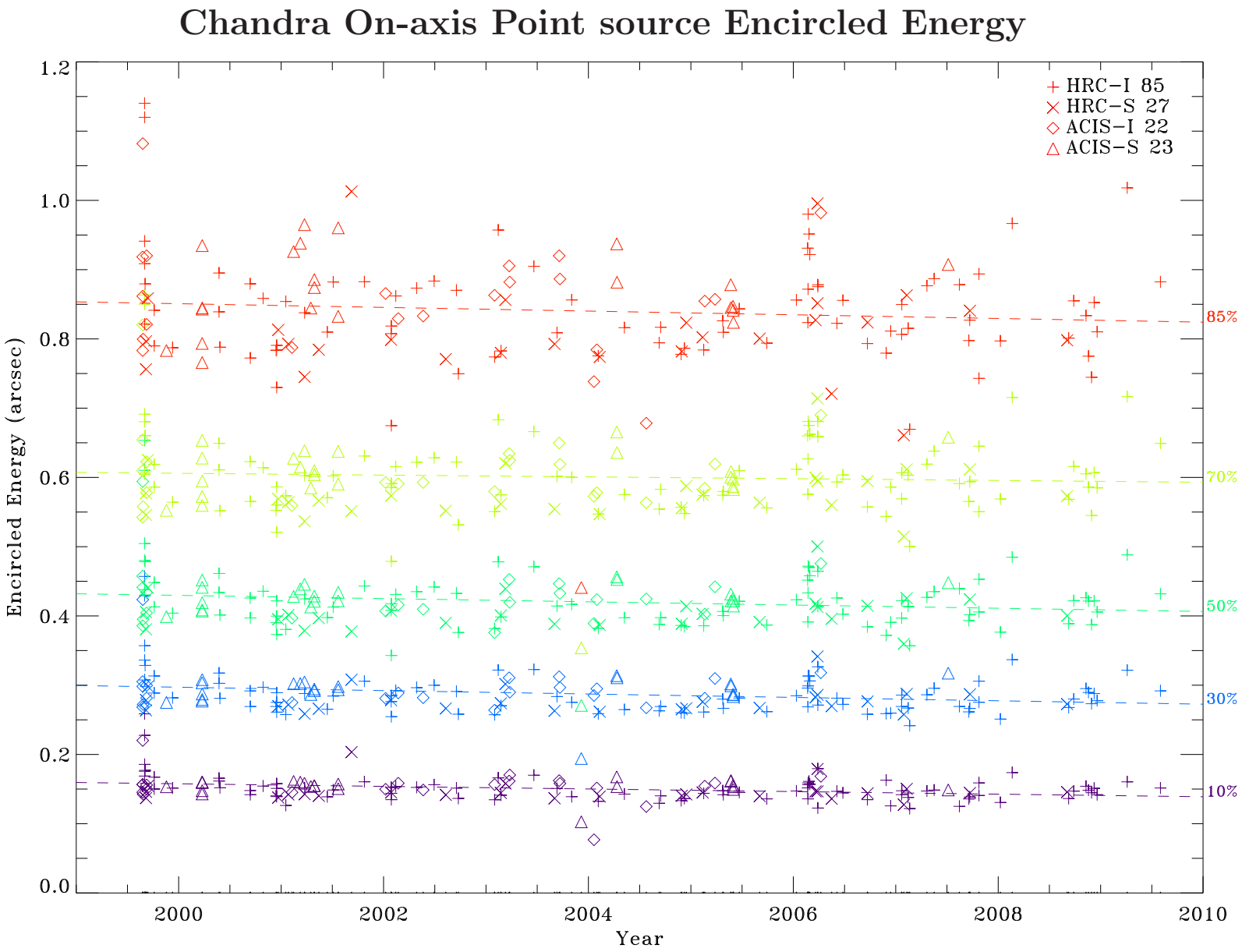

Figure 27: Chandra On-axis Encircled Energy of point sources on all four detectors. The EE did not change since launch. i.e. the Chandra image quality (PSF) stays the same with superb spacial resolution.

Summary

- In the past decade, the Chandra optical axis has been drifting like a random walk within 10″ range. This relatively small drift indicates that the optical bench (connection the HRMA and SIM) and SIM itself are very stable.
- The Chandra aimpoint has been drifting in the -Y and -Z direction of the SIM coordinates by more than 24″. This consistent directional drift of the aimpoint indicates that relative alignment between the aspect system and the telescope has been changing constantly in one direction. This is especially true when there is a sudden change in the ASA system such as the CCD cool down.
- Despite the above drifts, the optical axis and the aimpoint were never more than 16″ apart anytime during the Chandra operation. This small separation causes no degradation on the PSF of the on-axis targets.
- The directional drift of the aimpoint causes the change of the default offset for the on-axis target pointing on both ACIS-S and ACIS-I from time to time, to avoid the dither falling on the node boundary or off the chip.
- The Chandra imaging quality (i.e. PSF and spacial resolution) has been the same since launch.
- The Chandra telescope pointing has always been stable and accurate in the first decade.
- WE ARE LOOKING FORWARD TO THE SECOND SUCCESSFUL DECATE OF THE CHANDRA X-RAY OBSERVATORY!