Chandra X-ray Observatory Optical Axis, Aimpoint and Pointing Stability

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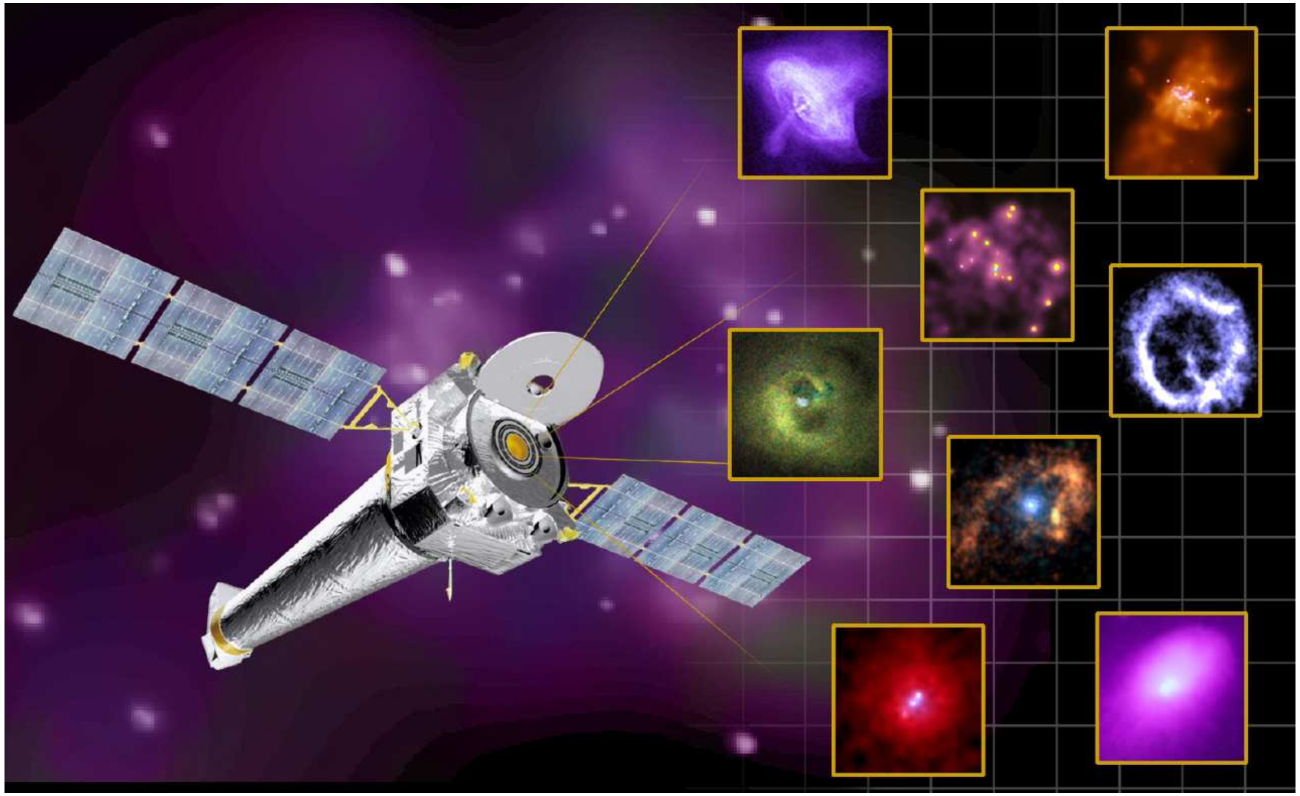

Chandra X-ray Observatory

- This year (2019) is Chandra's 20th anniversary of very successful scientific exploration.
- Chandra revolutionized the X-ray astronomy as being the first, and so far the only, X-ray telescope achieving sub-arcsecond resolution.
- Chandra has 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.

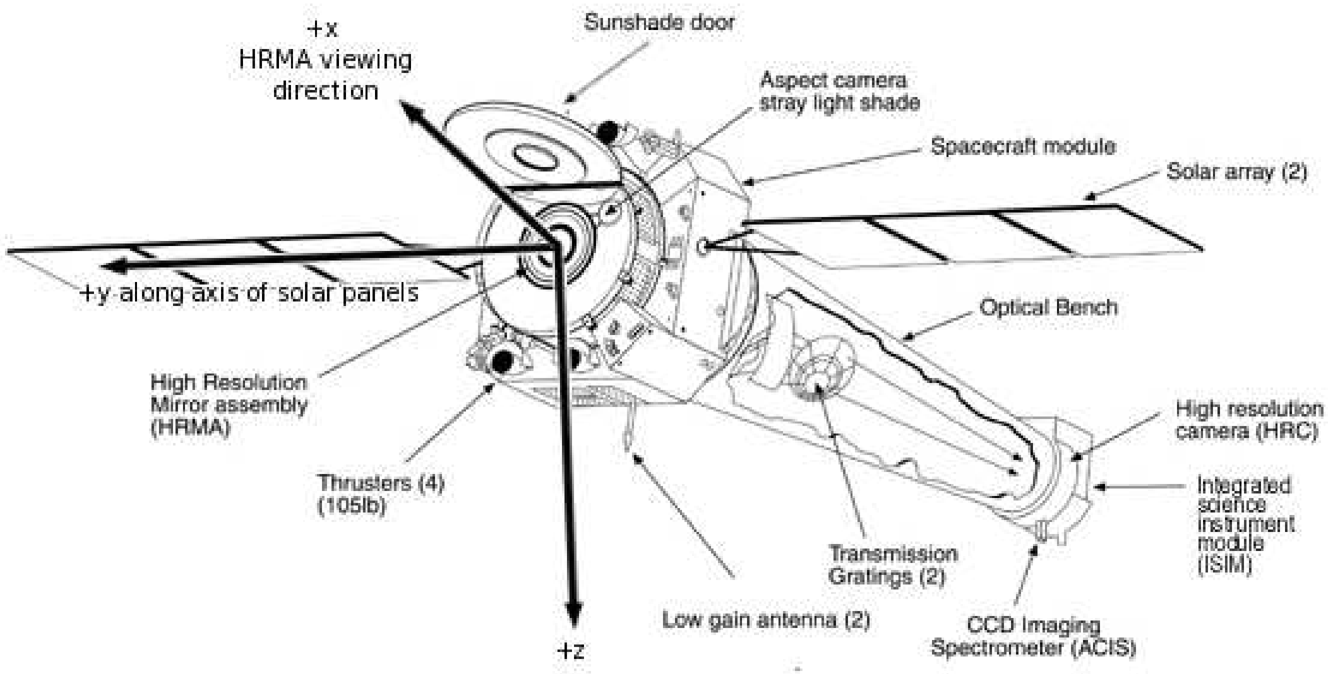

Figure 1: Chandra X-ray Observatory with certain subsystems labeled.

Chandra Optical Axis and Aimpoint

- **HRMA Optical Axis:** A straight line passing through the geometric center of the four nested parabolic and hyperbolic surface mirror pairs and the HRMA focal point.
  - HRMA Focal Point: Point on the focal plane where the sharpest PSF is located.
  - HRMA Focal Plane: An imaginary plane perpendicular to the HRMA optical axis and intersecting it at the focal point.
- **HRMA Aimpoint:** Point on the focal plane where the image of an on-axis target is located.
  - Effective Aimpoint: Location on each detector where the image of an on-axis target actually landed. Effective aimpoint is not fixed and it actually drifts during the mission.
  - Default Aimpoint: Fixed chosen locations on detectors to avoid the chip gaps and node boundaries while still maintaining the optimal PSF. Before cycle 18, default aimpoints on ACIS-I and ACIS-S were managed by setting certain pointing offset annually to compensate the slow drift of the effective aimpoint. Starting with Cycle 18 observations, a permanent default aimpoint is chosen for each detector, which is set dynamically.

For ideal mirrors, the optical axis intersects the focal plane at the best focus which is both the focal point and the aimpoint. For the actual HRMA, the focal point and the aimpoint are not the same, although they differ only slightly. With respect to a preset coordinate system associated with each detector, the positions of both points have been drifting slowly since launch. To monitor and measure the telescope Optical Axis and Aimpoint positions on the detectors can determine the stability of the telescope.

Chandra Pointing Control and Aspect Determination (PCAD) System

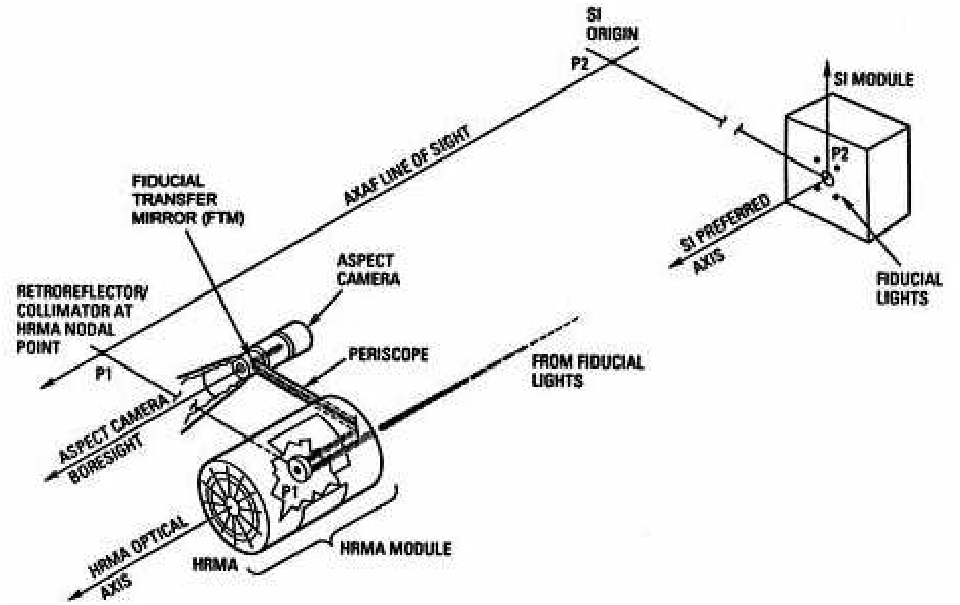

Figure 2: Chandra Pointing and Fiducial Transfer System. (POG.21: Figure 5.3.)

- Aspect camera assembly (ACA) – 11.2 cm optical telescope, two CCD detectors.
- Fiducial light assemblies (FLA) – LED lights on each detector are imaged in the ACA.
- 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 image coordinates are determined by the stars and LEDs imaged by the ASA.

Chandra Detectors and Aimpoints

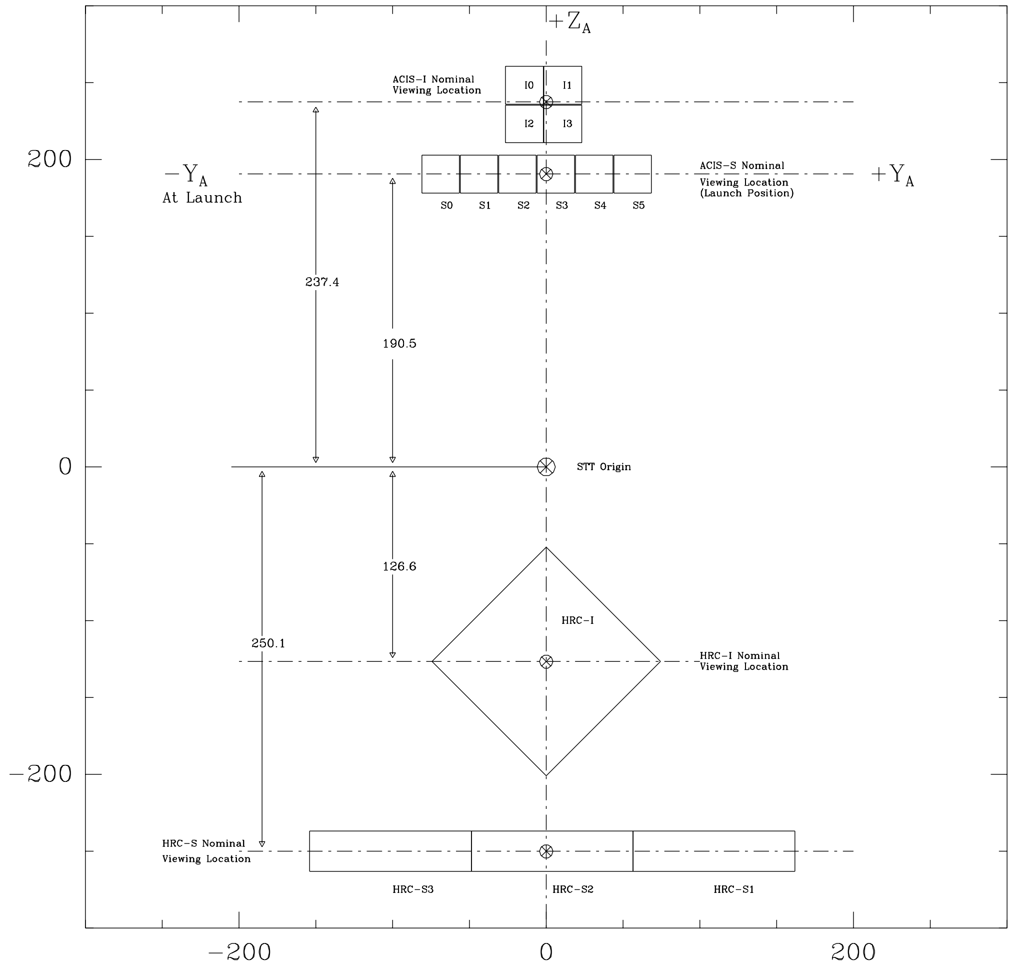

Figure 3: Chandra Detectors Layout (viewing from the HRMA towards the detectors): The SIM Translation Table shows the flight focal plane instrument to scale (in mm, coordinate system is AXAF-STT-1.0). SIM +Y is in x-axis; SIM +Z is in y-axis. ⊗ on each detector marks the aimpoint position with nominal SIM-Z and zero pointing offset. (POG.21: Figure 4.24)

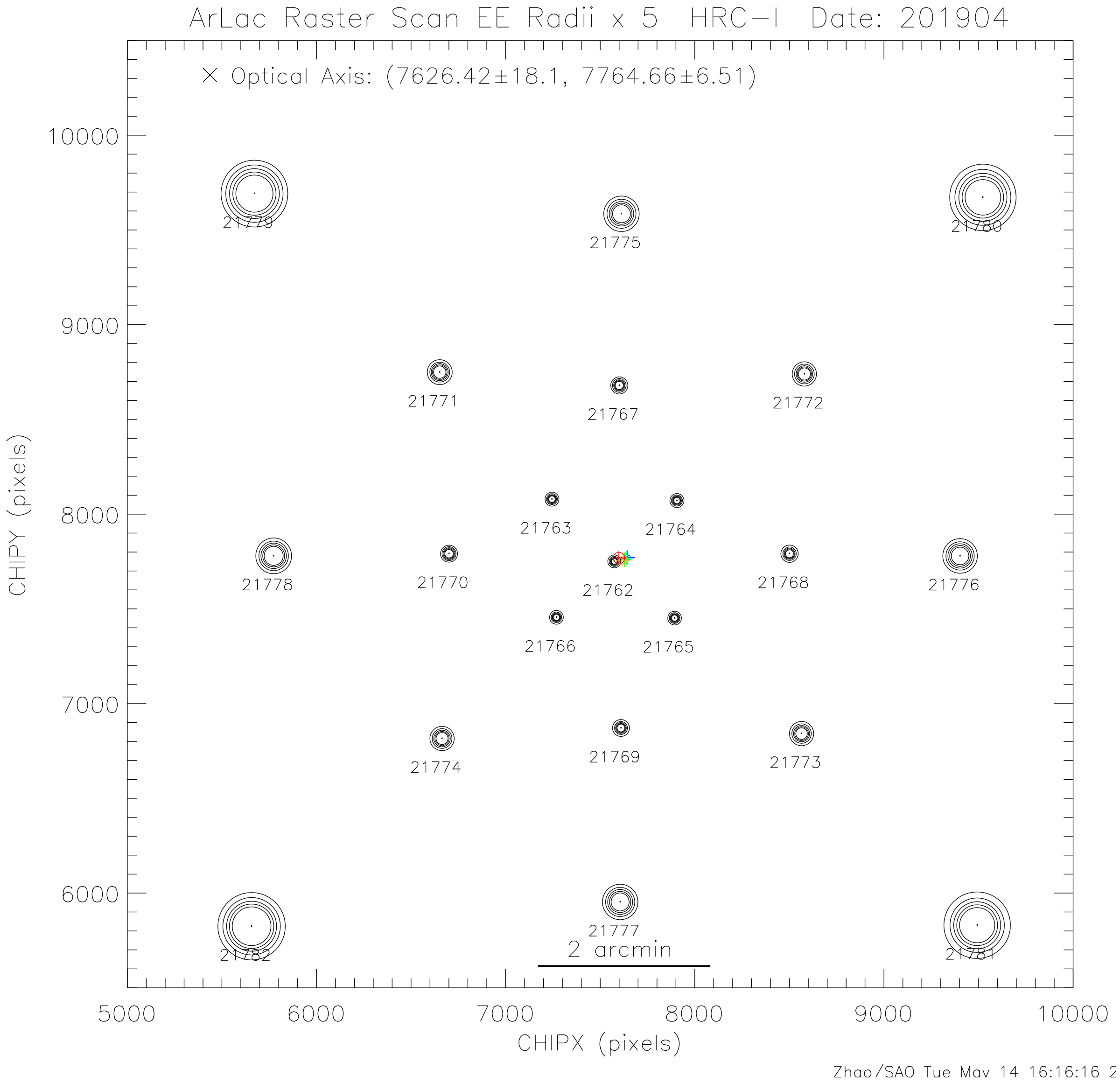

Figure 4: HRC-I raster scan observation of Ar Lac in chip coordinates. Circles around each observation point have the 50% – 90% encircled energy radii × 5. The data are fit to a 2-D quadratic function to find the optical axis. Data taken in April 2019. The numbers under the circles are the OBSIDs of the observations.

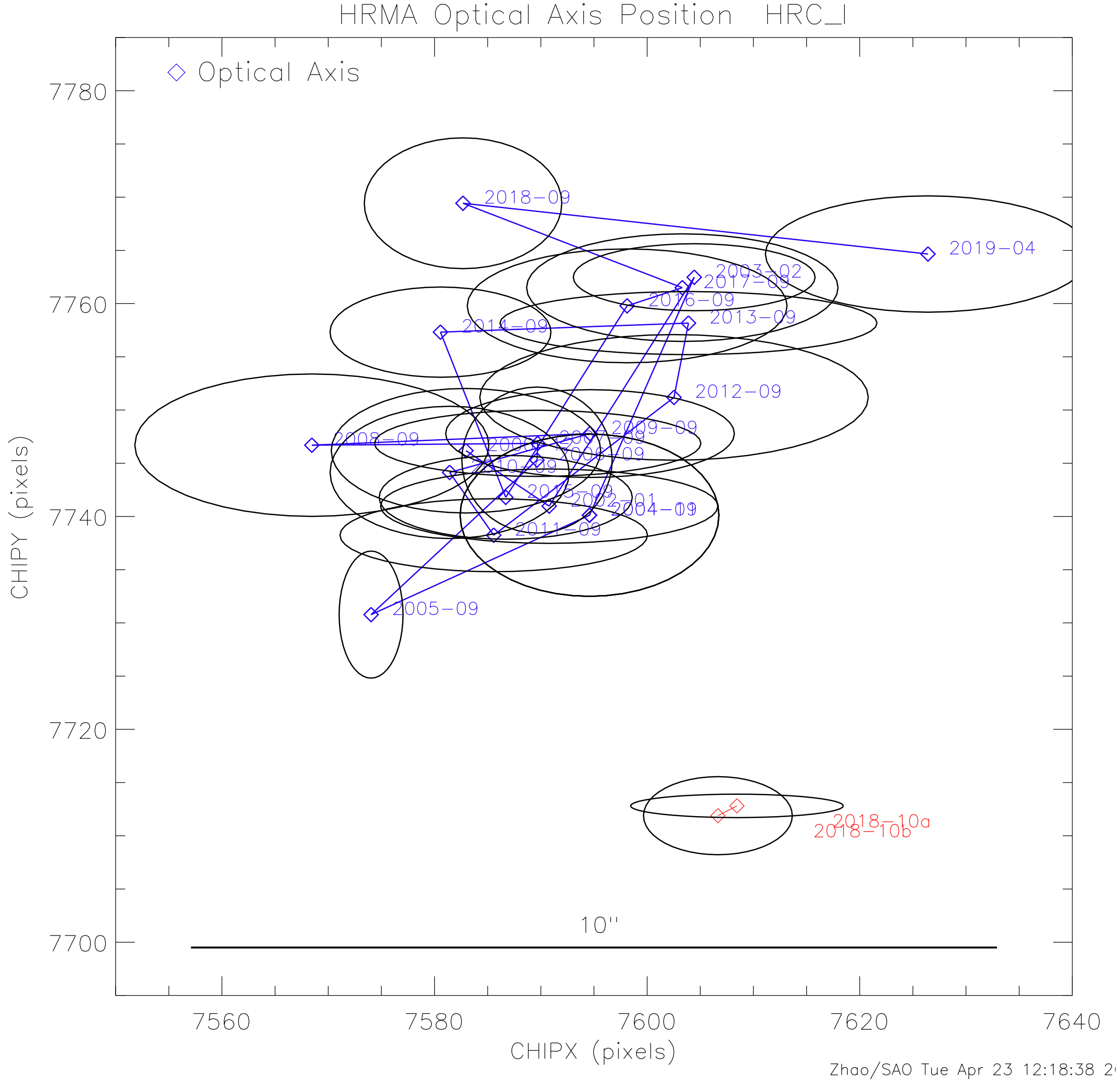

Figure 5: Chandra optical axis positions on HRC-I since launch. Each position (blue diamonds) is labeled by the year–month. The ellipse around each position is the $1-\sigma$ measurement error ellipse for that given year. The drift of optical axis position is consistent with the measurement errors. The optical axis position is very stable and well within a 10″ region. Since year 2000, the optical axis drift was well within a 6″ region. (POG.21: Figure 4.25). The two red diamonds at the lower-right corner were measured immediately after the safe mode 2018. The April 2019 measurement is slightly to the right of the previous years' measurements.

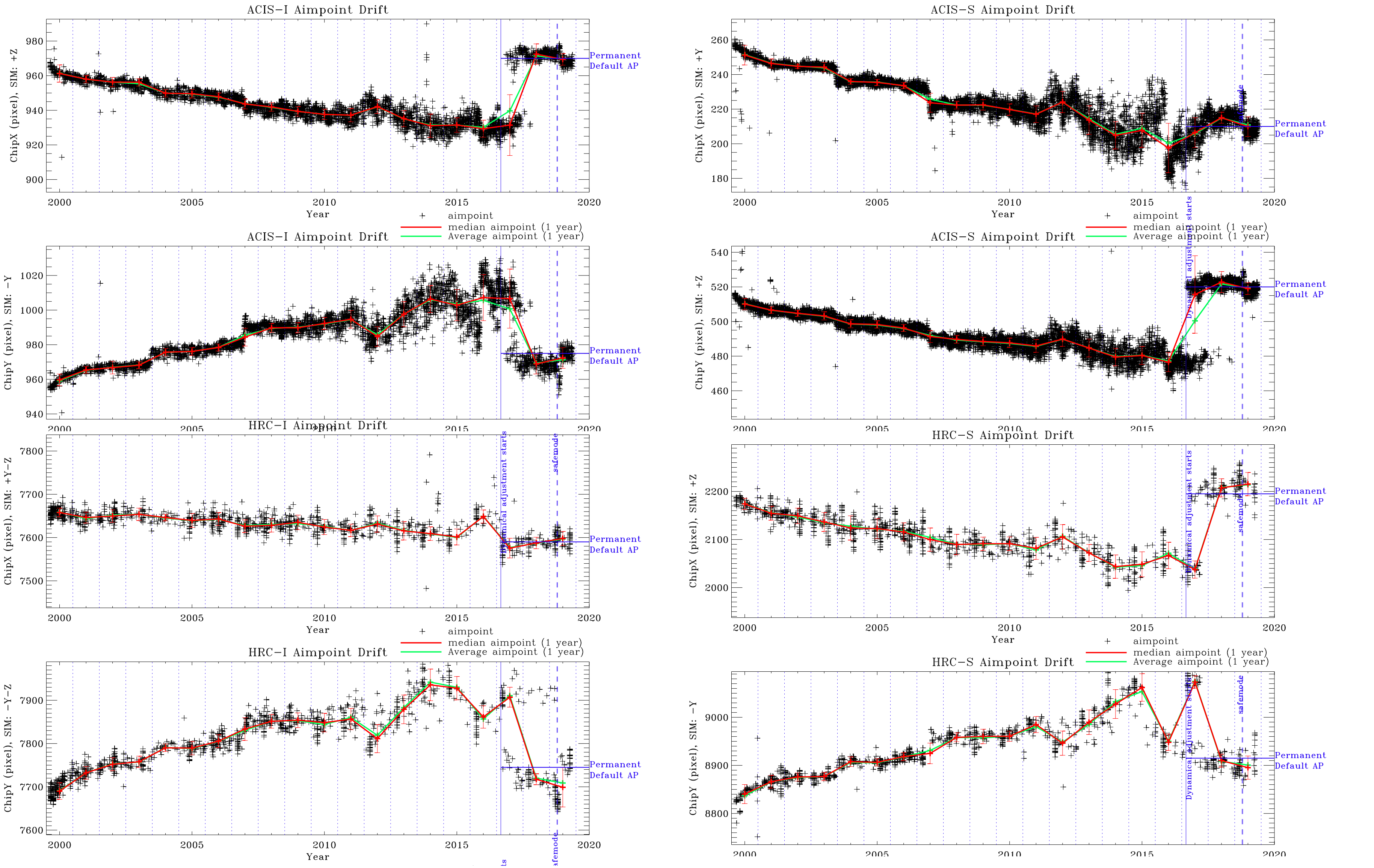

Figure 6: Chandra detectors aimpoint position as a function of time. Solid red (green) lines show the median (average) aimpoint drift in 12 months bins, separated by vertical dotted blue lines. Solid horizontal and vertical blue lines at the right side of the figures indicate the permanent default aimpoints and the date of their implementation (August 26, 2016).

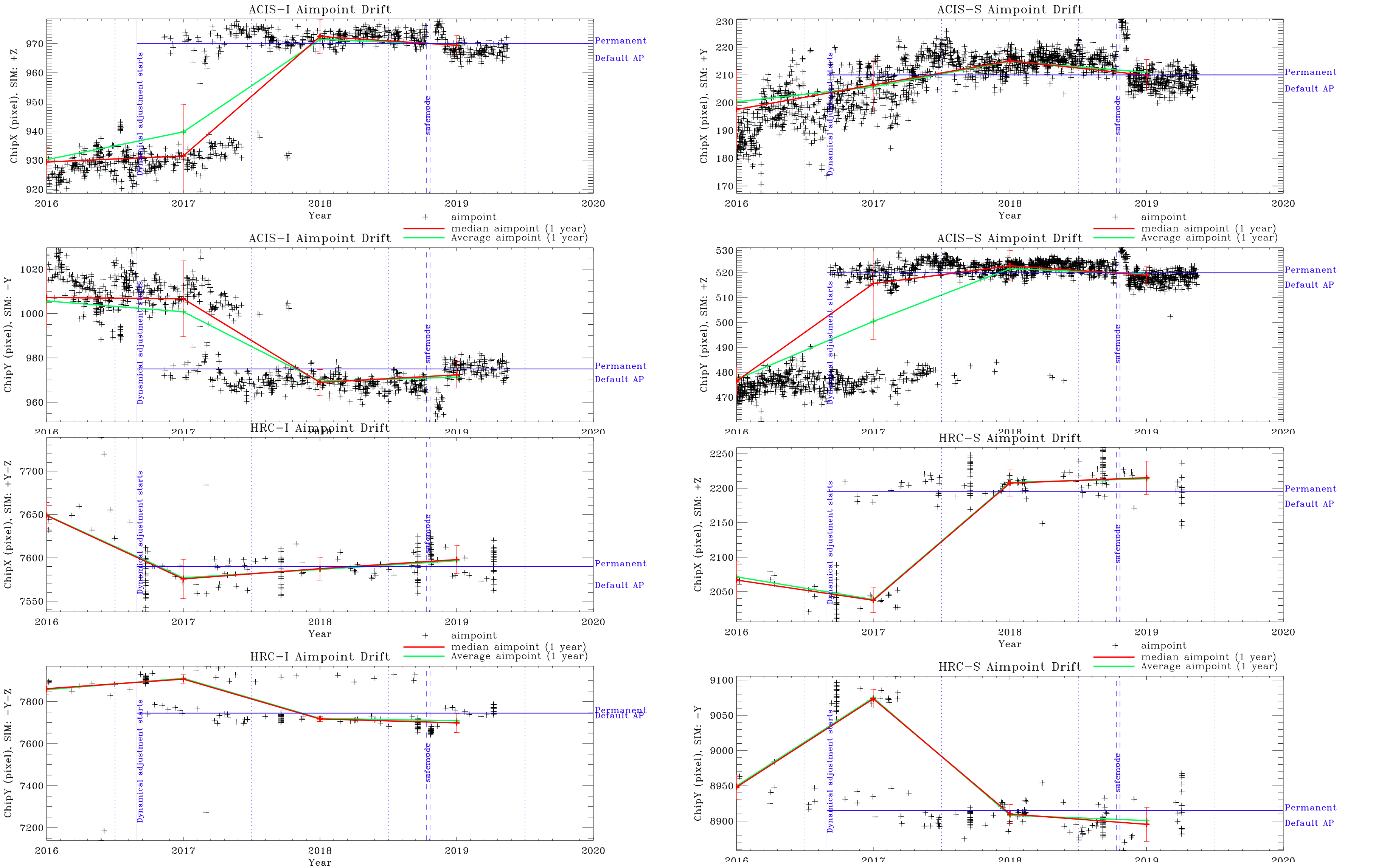

Figure 7: Chandra detectors aimpoint position since 2016. Solid horizontal and vertical blue lines at the right side of the figures indicate the permanent default aimpoints and the date of their implementation (August 26, 2016). Double vertical dashed lines indicate the safemode in October 2018.

Optical Axis and Permanent Default Aimpoint

The current optical axis with their standard deviation (σ), and the permanent default aimpoint with their error boxes are listed in Table 1. These numbers are used in *CIAO* (Chandra Interactive Analysis of Observations) and *ObsVis* (The Chandra Observation Visualizer).

On-axis targets will be imaged near the default aimpoint and inside the error box on each detector. Observers should use this table to check their target location and may request different pointing offset based on their sources to maximize the scientific return. If the observer does not request a specific pointing offset, their target will be put near the default aimpoint.

Figures 8 and 9 show the optical axis and permanent default aimpoint with their error boxes on the four detectors.

Table 1: Chandra Optical Axis and Permanent Default Aimpoint Positions

Detector	SIM-Z (mm)	Optical Axis (pixel)		Permanent Default Aimpoint (pixel)		Error Box without dither (pixel)	Error Box with dither (pixel)	Chip
		ChipX(σ)	ChipY(σ)	ChipX	ChipY			
ACIS-I	−233.587	964.9(2.5)	984.3(2.5)	970	975	$12'' \times 16''$ (24.4 × 32.5)	$28'' \times 32''$ (56.9 × 65.0)	I3
ACIS-S	−190.143	227.9(2.5)	513.2(2.5)	210	520	$16'' \times 12''$ (32.5 × 24.4)	$32'' \times 28''$ (65.0 × 56.9)	S3
HRC-I	126.983	7582.7(11.0)	7769.4(7.3)	7590	7745	$16'' \times 12''$ (121.4 × 91.1) SIM [Y,Z]	$56'' \times 52''$ (425.0 × 394.7) SIM [Y,Z]	
HRC-S	250.466	2178.0(9.4)	8935.7(9.4)	2195	8915	$12'' \times 16''$ (91.1 × 121.4)	$52'' \times 56''$ (394.7 × 425.0)	S2

Optical Axis and Permanent Default Aimpoint

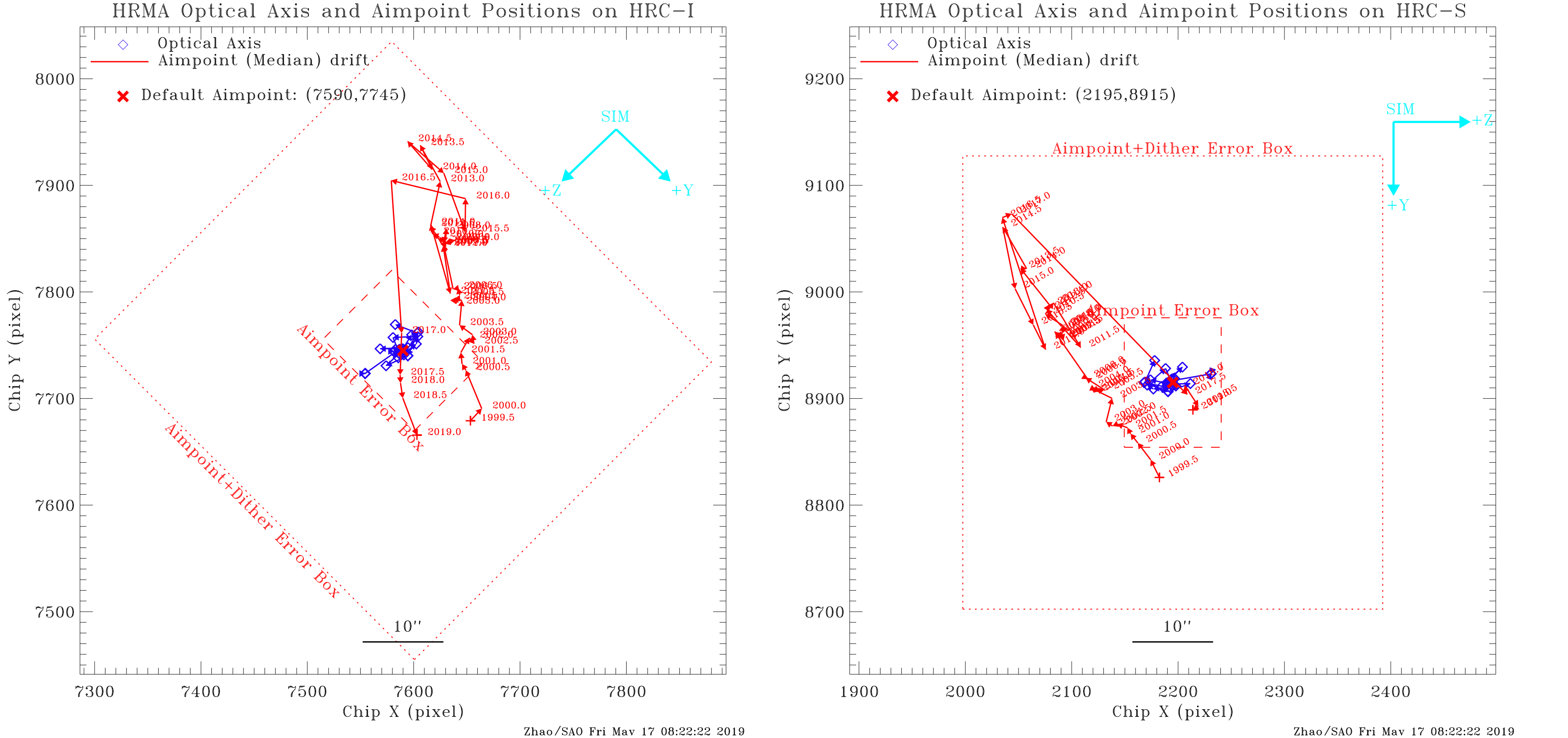

Figure 8: Median aimpoint in 6 months bins (red arrows) and optical axis (blue diamonds) drifts on HRC-I (left) and HRC-S (right). While the optical axis are relatively stable, aimpoint has been drifting towards the SIM [-Y,-Z] direction since launch, with several short-term jitters and reversals. Starting in Cycle 18, permanent default aimpoints are chosen for each detector (red $\times$). Dynamical adjustment are implemented (since August 26, 2016) using the recent ACA/HRMA alignment data during the PCAD attitude planning process. The small box (red dashed line, $16'' \times 12''$, or 121.4×91.1 pixels in SIM [Y, Z]) centered at the aimpoint is the error box of the aimpoint center, i.e. an on-axis target can be anywhere inside this box. The large box (red doted line, $56'' \times 52''$, or 425.0×394.7 pixels in SIM [Y, Z]) is the error box of aimpoint with dither.

Optical Axis and Permanent Default Aimpoint

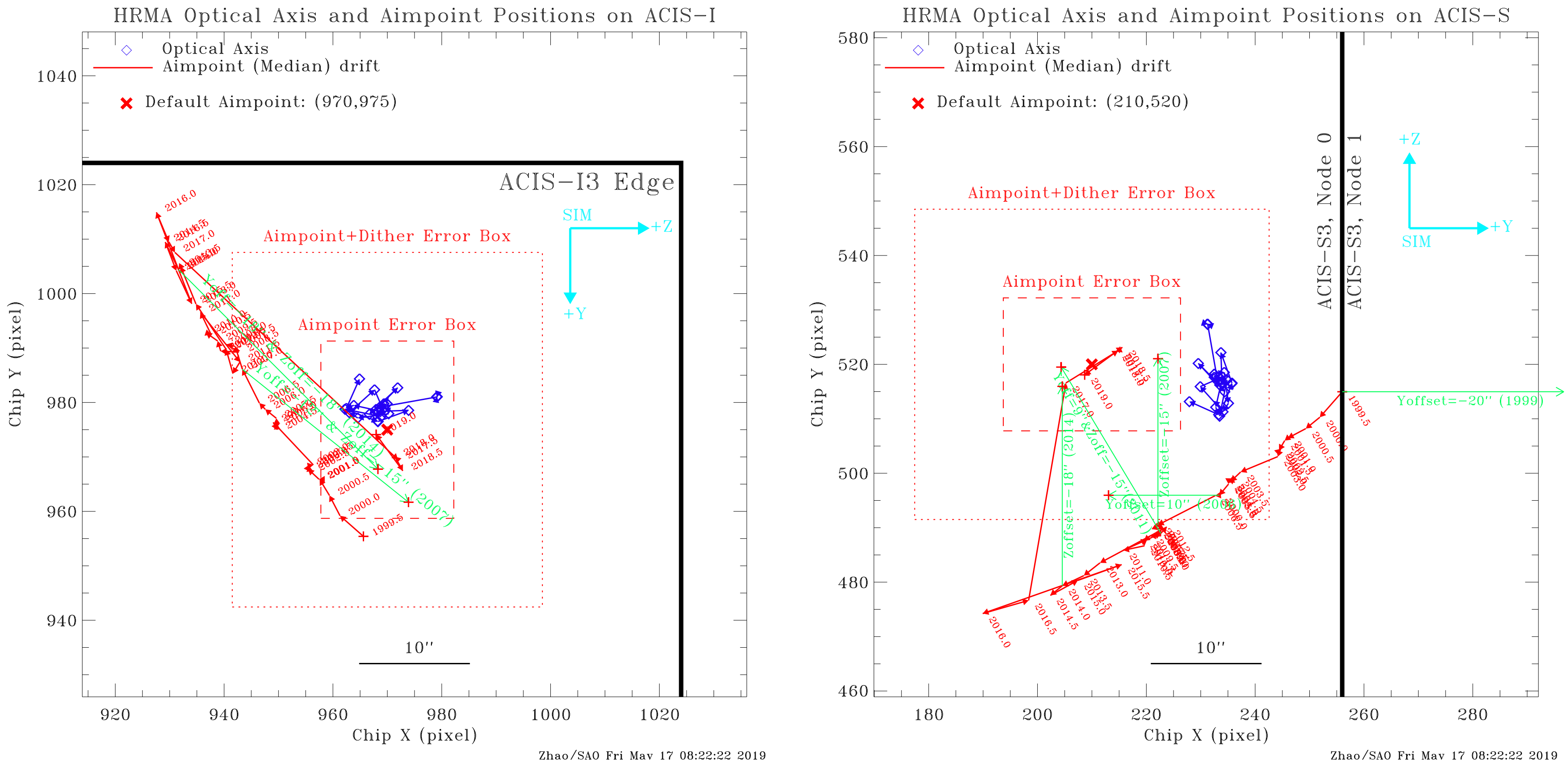

Figure 9: Median aimpoint in 6 months bins (red arrows) and optical axis (blue diamonds) drifts on ACIS-I (left) and ACIS-S (right). Before Cycle 18 (2017), default offsets were implemented for ACIS to adjust the aimpoint to near the optical axis and to avoid the aimpoint falling off the chip or crossing the node boundary $0|1$, indicated by green arrows. Starting in Cycle 18, a permanent default aimpoint is chosen for each detector (red $\times$). Dynamical adjustment are implemented (started on August 26, 2016) using the recent ACA/HRMA alignment data during the PCAD attitude planning process. The small box (red dashed line, $12'' \times 16''$, or 24.4×32.5 pixels) centered at the aimpoint is the error box of the aimpoint center, i.e. an on-axis target can be anywhere inside this box. The large box (red doted line, $28'' \times 32''$, or 56.9×65.0 pixels) is the error box of aimpoint with dither.

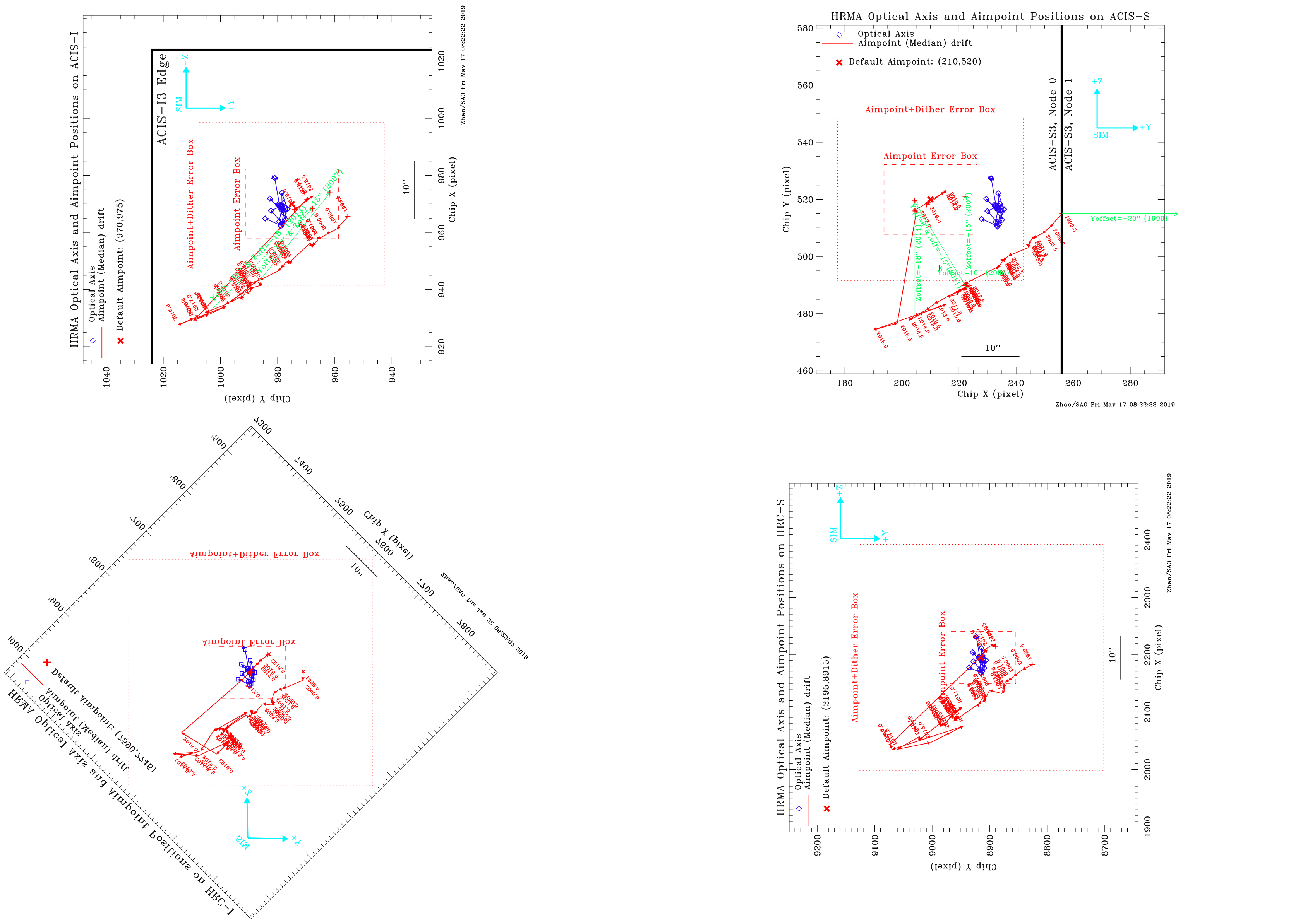

Figure 10: Permanent aimpoint (red ×) and optical axis (blue diamonds) on four detectors in SIM coordinates.

Chandra Safe Mode 2018

- On October 10, 2018, Chandra entered safe mode, the telescopes instruments were put into a safe configuration, critical hardware was swapped to back-up units, the spacecraft pointed so that the solar panels got maximum sunlight, and the mirrors pointed away from the Sun.
- On October 15, it was determined that the safe mode was caused by a glitch in one of Chandra's gyroscopes resulting in a 3-second period of bad data that in turn led the on-board computer to calculate an incorrect value for the spacecraft momentum.
- On October 21, Chandra returned to science observations after the team successfully carried out a procedure to enable a new gyroscope configuration for the spacecraft.
- During the safe mode, the HRMA mirror cavity temperature was warmed up to as high as 75°F, from the nominal temperature of 70°F.
- After the safe mode, science observations resumed while the HRMA temperature was still at ∼72°F. Then the temperature continued to cool down to its nominal value of 70°F.
- The first operations during the cool down was a series of HRC-I observations of HR1099, a RS CVn binary star, to check if the safe mode affected the Chandra aimpoint and optical axis.
- The aimpoint jumped about +6.5 aresec in SIM-Y and +3.0 aresec in SIM-Z directions after the safe mode (see Figures 7). After the HRMA temperature returned to normal, the aimpoints on all four detectors were again back to their default positions.
- Figure 5 shows the Chandra optical axis positions measured during the HRMA cool down (red diamonds) with all the measurements since launch (blue diamonds). The two measurements (2018-10a) and (2018-10b) were made on Oct. 22 and 23, 2018, respectively. They are very close to each other ($\sim 0.3''$) and only a few arcsec away from all the previous measurements.
- The optical axis was measured again using the ArLac in April 2019.

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

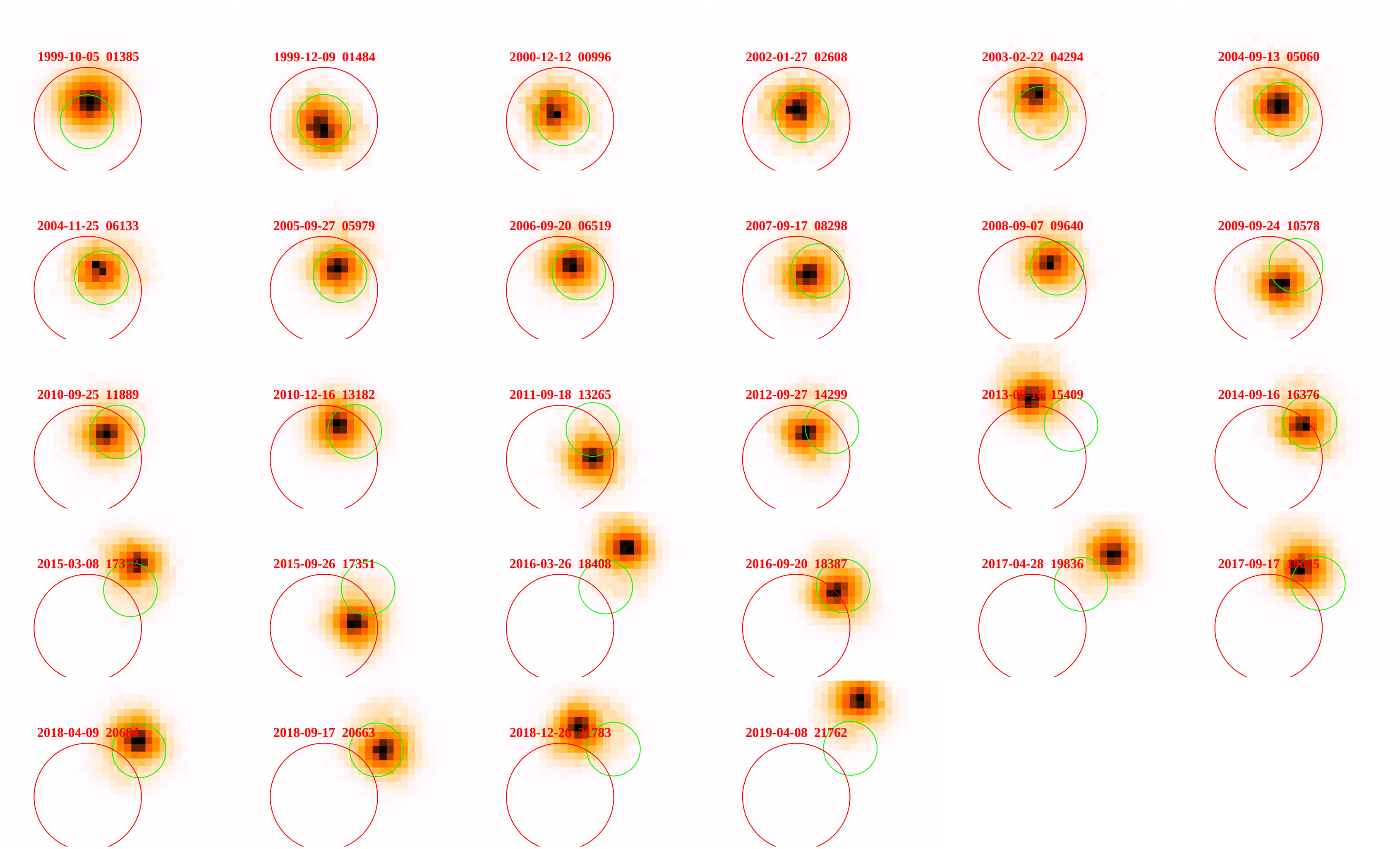

Figure 11: Chandra On-axis Point source (ArLac) HRC-I images since launch. The red circle ($1''$ radius) is centered at its J2000 coordinate (RA_targ=332.170000°, Dec_targ=45.742306°). The green circles ($0.5''$ radius) are centered at the predicted positions at different observing times, based on its proper motion: $\delta RA = -0.05248''/yr$, $\delta Dec = 0.04788''/yr$. The image quality stays the same.

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

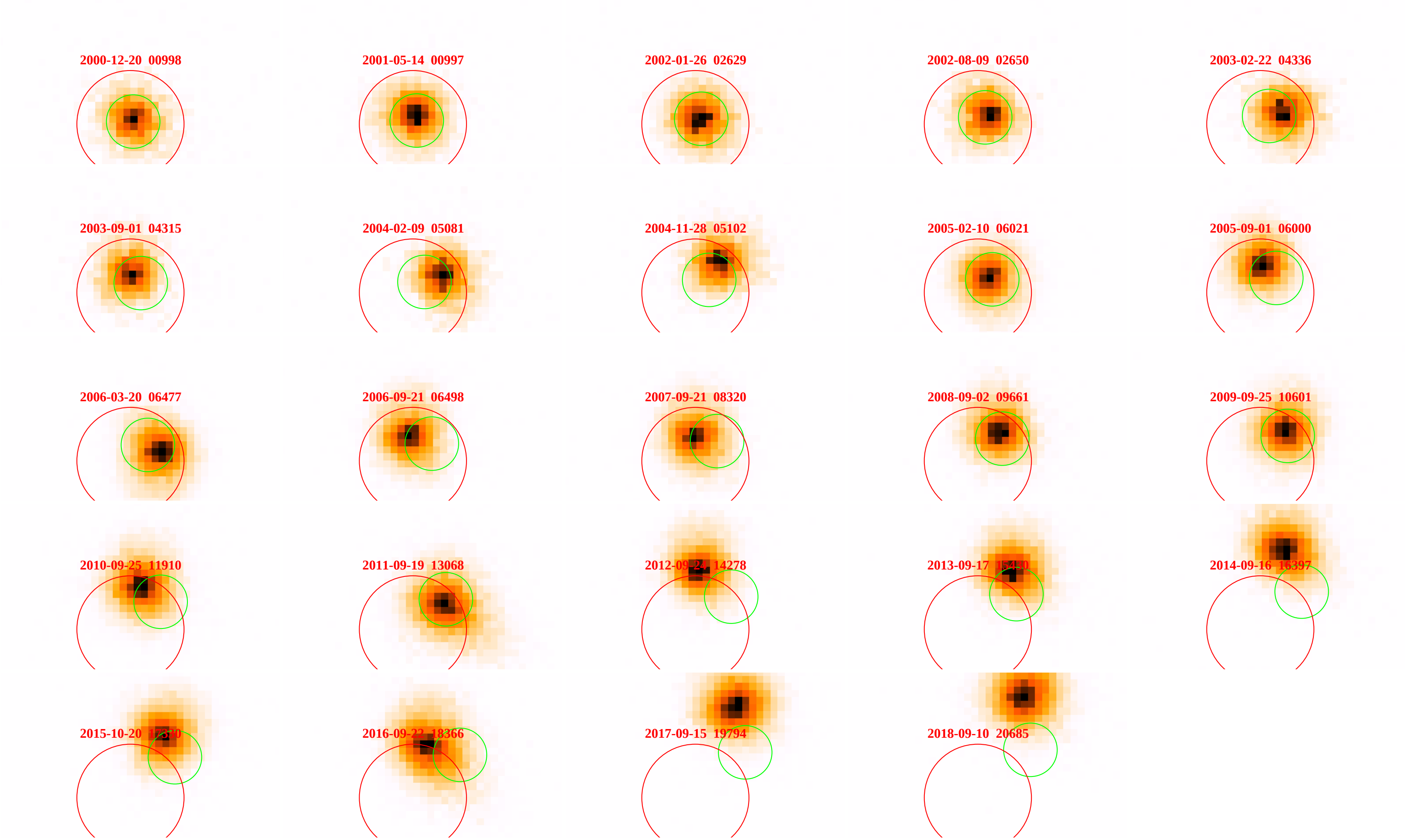

Figure 12: Chandra On-axis Point source (ArLac) HRC-S images since launch. The red circle ($1''$ radius) is centered at its J2000 coordinate (RA_targ=332.170000°, Dec_targ=45.742306°). The green circles ($0.5''$ radius) are centered at the predicted positions at different observing times, based on its proper motion: $\delta RA{=}{-}0.05248''/yr$, $\delta Dec{=}0.04788''/yr$.

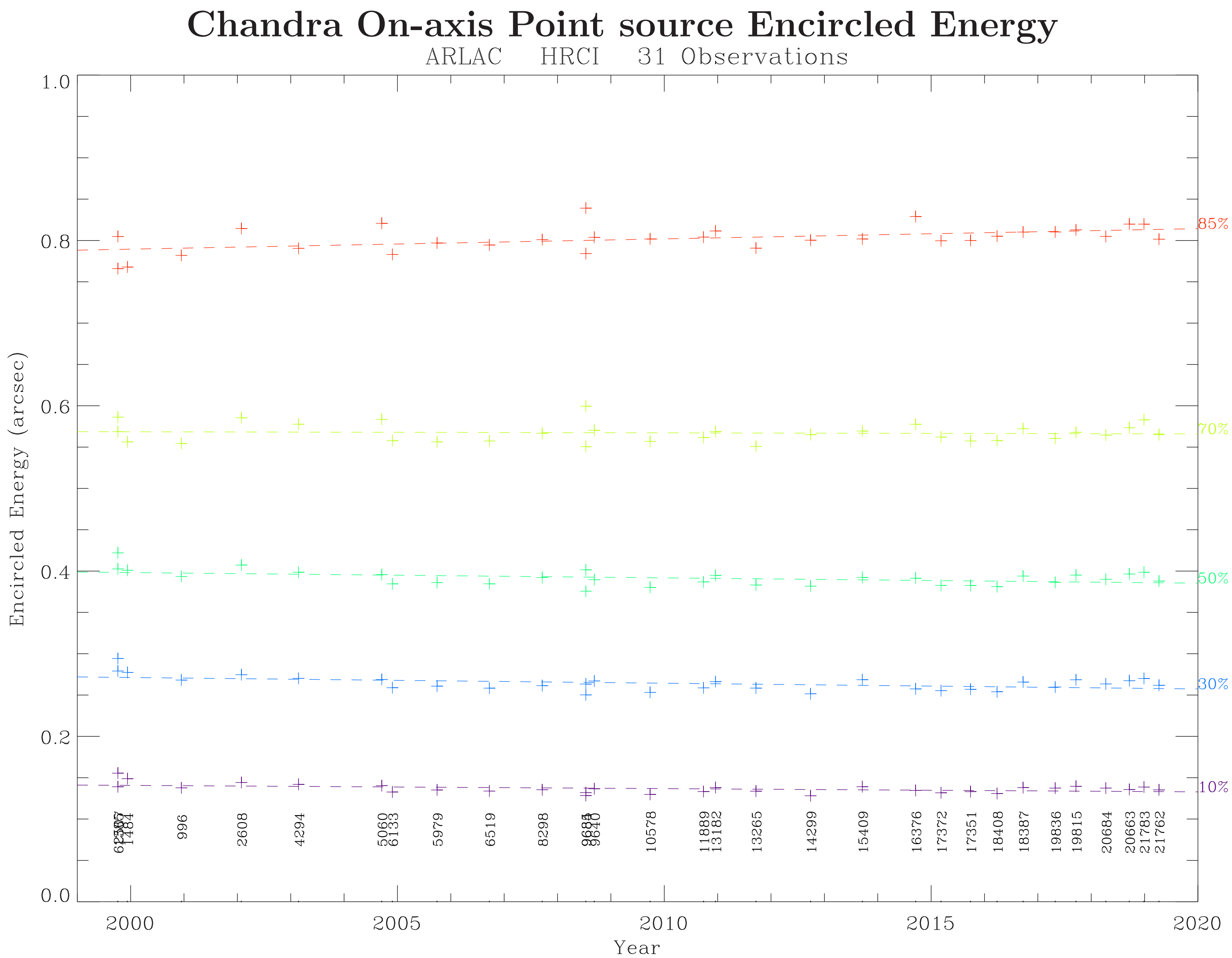

Figure 13: Chandra On-axis Point source (ArLac) HRC-I encircled energy radii since launch. The encircled energy radii almost stay the same.

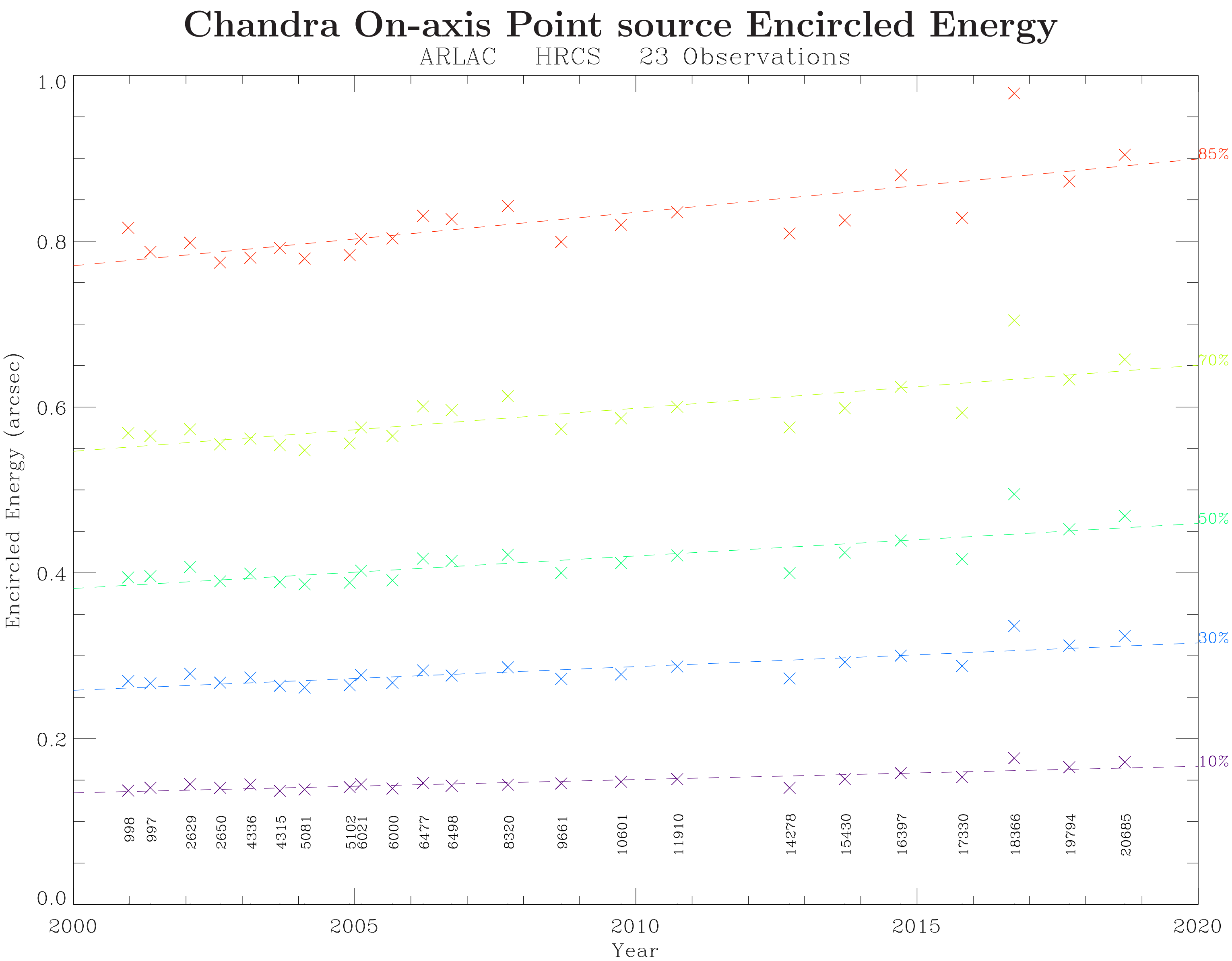

Figure 14: Chandra On-axis Point source (ArLac) HRC-S encircled energy radii since launch. The encircled energy radii has a trend of increasing since 2006. This seems to be a detector issue, which is currently under investigation.

Summary

- To achieve and retain the unprecedented imaging quality, it is critical that three Chandra principal elements (HRMA, PCAD and SIM) to stay rigid and stable.
- Measuring the Chandra Optical Axis and Aimpoint positions on the detectors can determine the stability of the telescope and optimize its performance.
- From launch until 2016, the aimpoint was drifting towards the SIM [−Y,−Z] direction, for about $30''$, with several short-term jitters and reversals.
- The optical axis position has been relatively stable. Its random walk like movement is well within a $10''$ region. This indicates that the optical bench is rigid and stable, and hence the integrity of the telescope.
- The Aimpoint drift is caused by the alignment change between the ACA and the HRMA. Its long term change is due to the aging and relaxing of the material. Its short term change is usually associated with the thermal stability in the ACA housing.
- The relative position between the optical axis and aimpoint was changing due to the aimpoint drift. But at no time these two were more than $27''$ apart, which is very small and doesn't cause any degradation of the PSF. The Chandra imaging quality has stayed the same.
- The Chandra telescope pointing has always been stable and accurate since launch.
- Starting in Cycle 18, a permanent default aimpoint is chosen for each detector, which is set dynamically using the recent ACA/HRMA alignment data.
- The safe mode in October 2018 caused the HRMA temperature to rise to 75°F. This caused the aimpoint to jump a few aresec. After the HRMA temperature returned to normal, the aimpoints on all four detectors were again back to their default positions.
- The Chandra PSF has stayed the same since launch.