# USING THE TYCHO CATALOGUE FOR AXAF: GUIDING AND ASPECT RECONSTRUCTION FOR HALF-ARCSECOND X-RAY IMAGES

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ABSTRACT

AXAF, the *Advanced X-ray Astrophysics Facility* will be the third satellite in the series of great observatories in the NASA program, after the Hubble Space Telescope and the Gamma Ray Observatory. At launch in fall 1998, AXAF will carry a high resolution mirror, two imaging detectors, and two sets of transmission gratings (Holt 1993). Important AXAF features are: an order of magnitude improvement in spatial resolution, good sensitivity from 0.1–10keV, and the capability for high spectral resolution observations over most of this range.

The Tycho Catalogue from the Hipparcos mission will serve as a primary part of the AXAF Guide and Aspect Star Catalog (AGASC), particularly as merged with other star catalogues. Incorporation of the Tycho Catalogue into AGASC will provide: (1) accurate positions and magnitudes for target acquisition and guiding; (2) the colours necessary for magnitude transformations to the AXAF Aspect Camera (ACA) system; (3) high internal astrometric accuracy for half-arcsecond post-facto image reconstruction; and (4) an external astrometric system that will tie AXAF X-ray image astrometry into the best positional system expected well beyond the mission lifetime and into the next millennium.

Key words: space astrometry; X-rays.

## 1. INTRODUCTION

The AXAF X-ray telescope, after launch in fall of 1998, will follow an elliptical high-earth orbit (140 000 km) allowing uninterrupted observing intervals of more than 48 hours. AXAF's four nested mirror pairs in Wolter type 1 geometry have a focal length of 10 m. The largest mirror's diameter is 1.2 m (see Figure 1). Small reflection angles and iridium coating improve high energy mirror response, while improved grinding and polishing techniques yield a final spatial resolution of 0.5 arcsec (Van Speybroeck 1987). The combination of high resolution, large collecting area, and sensitivity to higher energy X-rays will make it possible for AXAF to study faint sources, sometimes strongly absorbed, in crowded fields.

High resolution imaging and/or fast timing measurements are enabled by the High Resolution Camera (HRC; Kenter 1996). Advances over the high resolution imagers of Einstein and ROSAT include smaller pore size, larger microchannel plate area, lower background, energy resolution, and charged particle anticoincidence.

The AXAF CCD Imaging Spectrometer (ACIS; Garmire 1997) is a CCD array for simultaneous imaging and spectroscopy ($E/\Delta E = 20 - 50$) over almost the entire AXAF bandpass with high quantum efficiency and low read noise. Pictures of extended objects can be obtained along with spectral information from each element of the picture. The ACIS-I array comprises 4 CCDs arranged in a square which provide a $16 \times 16$ arcmin$^2$ field. The ACIS-S array has 6 CCDs of the same type, lined up in a $1 \times 6$ configuration. Although ASCA carries a similar CCD array, its mirror limits the spatial resolution to $\sim$2 arcmin.

There are two transmission grating spectrometers for use with either the HRC or ACIS detectors. One set is optimized for low energies (LETG) and the other for high energies (HETG), providing resolving powers from 100–2000 (e.g. Flanagan 1996).

## 2. ASPECT DETERMINATION

The AXAF Aspect Camera Assembly (ACA), a 10.4 cm, f/9.5 R-C optical reflector with two swappable 1024$^2$ CCDs, measures the image positions of up to 8 selected target stars in its ($1.4 \times 1.4$ deg$^2$) field of view. The AXAF on-board computer uses gyro attitude data and ACA stellar image centroids for real-time pointing control and attitude determination, using positions and magnitudes from the AXAF Guide and Aspect Star Catalog. The absolute celestial pointing accuracy of the spacecraft is required to be $<$ 30 arcsec (99 per cent of the time, in any 1 s interval). Post-facto aspect determination is required for observations over 100 s to compensate for the apparent motion of the X-ray image on the focal plane of the science instruments. The aspect solution as a function of time provides for an RMS image diameter smaller than 0.5 arcsec within the central 5 arcmin field-of-view, increasing to 2 arcsec at a radius of 20 arcmin.

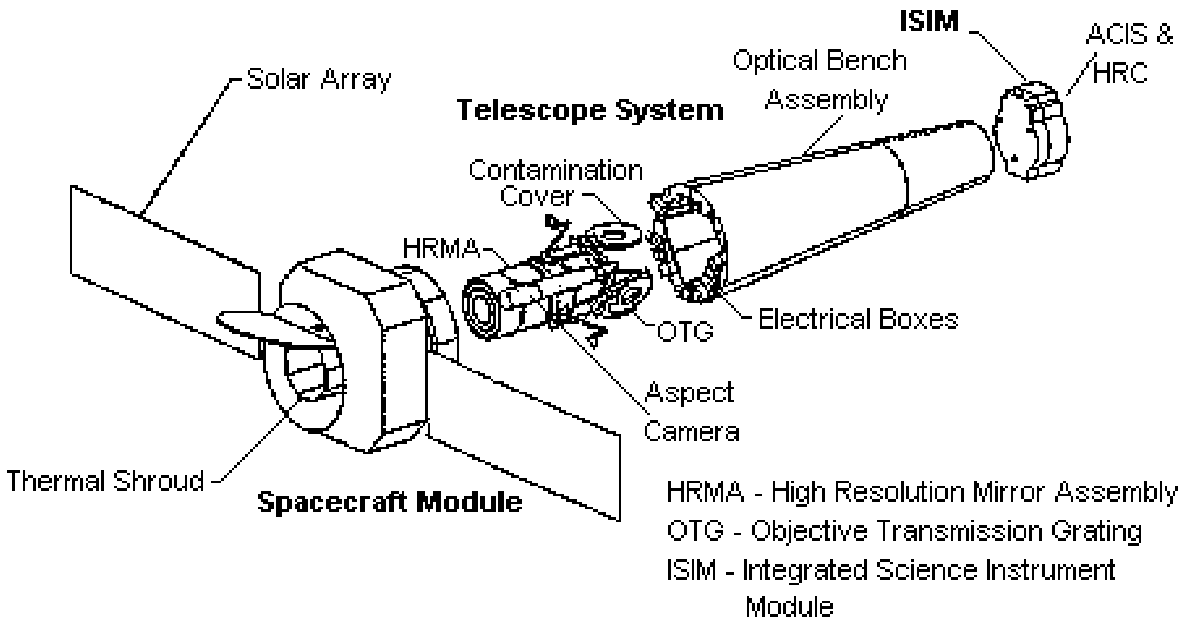


*Figure 1. A schematic of the Advanced X-ray Astrophysics Facility (AXAF) telescope system.*

Using the gyros and aspect camera data, the aspect solution provides an accuracy of < 1 arcsec relative to reference star locations, once per integration (1, 2, or 4 s). For accurate stellar centroids at the CCD plate scale of 5 arcsec per pixel, the camera is defocused, yielding a FWHM of a star image of about 9 arcsec. Tolerable centroiding errors for stellar images result when reference star magnitudes *in the instrumental 'ACA' system* are brighter than $m_{ACA} = 10.2$. The ACA bandpass is broad, peaking near 7000Å (Figure 2).

For the star catalogue, we determine the conversion from common published magnitudes to the AXAF Camera CCD magnitude $m_{ACA}$ as a function of colour by convolving the ACA bandpass with the Bruzual-Persson-Gunn-Stryker stellar spectrophotometric atlas (Gunn & Stryker 1983). The zero-point for each filter was established by convolution of the bandpass with a mag=0 spectrum of type G0V (BD+26 3780, normalized to $V = 0$). The relation goes severely non-linear redder than $(B - V) = 1.4$ (see Figure 3). A reasonable fit is achieved for the entire colour range as follows:

$$m_{ACA} = V + 0.283 - 0.58(B - V) + 0.23(B - V)^2 - 0.21(B - V)^4$$

## 3. REQUIREMENTS FOR THE AXAF STAR CATALOGUE

The *AXAF Guide/Aspect Star Catalog (AGASC)*, when finished, should contain enough stars to detect with the Aspect Camera a minimum of 5 stars suitable for an astrometric solution, 95 per cent of the time, anywhere on the sky. This requires a star density of 5.11 deg$^{-2}$ to an instrumental magnitude of

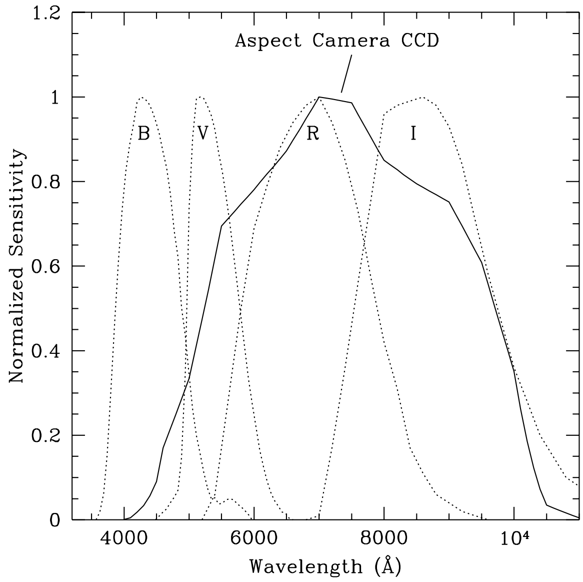


*Figure 2. The approximate bandpass of the Aspect Camera CCD (solid line) is plotted over bandpasses of common optical filters, B, V, R, and I (dashed lines). All these filter transmission curves are normalized to peak at unity.*

$m_{ACA} = 10.2$, using the end-of-life field-of-view of 1.79 deg$^2$. To attain this goal, we need a catalogue with both magnitudes and colours.

'Spoiler stars' are those which may degrade the astrometric solution obtained from a nearby star used for guiding or aspect. Red stars fainter than 10.2 mag in their published bandpass, but brighter than 10.2 mag

*Table 1. A quick reference for the AXAF imaging and spectroscopic capabilities using the HRC or ACIS.*

| | HRC-I | HRC-S | units |
|---|---|---|---|
| FIELD of VIEW | $31 \times 31$ | $7 \times 97$ | arcmin |
| SPECTRAL RANGE | $0.1 - 10$ | | keV |
| SPATIAL RESOLUTION | $< 0.5$ | | arcsec |
| TIME RESOLUTION | 0.016 | | $\mu$s |
| SENSITIVITY | $10^{-15}$ | | erg $cm^{-2}s^{-1}$ |
| for powerlaw point source, | $t = 300$ks, | and , $= 1.4$ | |
| | ACIS-I | ACIS-S | |
| FIELD of VIEW | $17 \times 17$ | $8.5 \times 51$ | arcmin |
| SPECTRAL RANGE | $0.5 - 8$ | | keV |
| PIXEL SIZE | $< 0.5$ | | arcsec |
| SENSITIVITY | $10^{-14}$ | | erg $cm^{-2}s^{-1}$ |
| for powerlaw point source, | $t = 100$ks, | and , $= 1.4$ | |

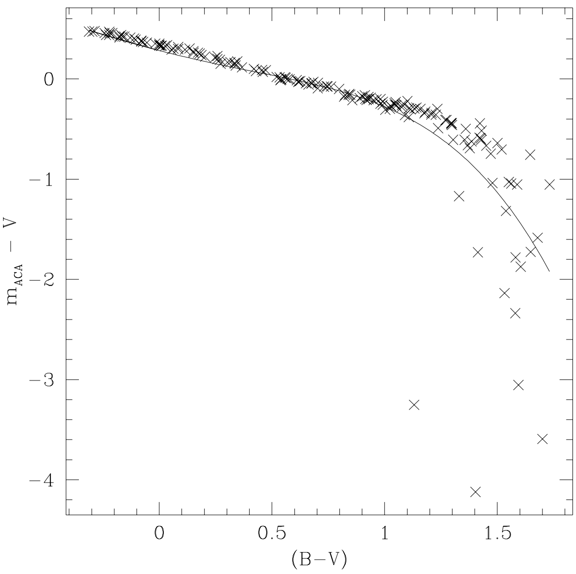


*Figure 3. The predicted difference between the AXAF Aspect Camera magnitude $m_{ACA}$ and Johnson V mag, as a function of colour (Johnson $B-V$).*

in the (red-sensitive) instrumental ACA system are a particular danger. Given the transformation between $V$ and $m_{ACA}$, the reddest expected stars have $(V - m_{ACA})$=3.6. Including an error budget of 0.7 mag in colours and transformations, the AGASC should be as complete as possible, with colours, to $V \approx 14$.

Accurate star positions (either of recent epoch or including proper motions) are required to meet the top level AXAF requirement that X-ray photons can be assigned *absolute* sky coordinates accurate to better than 1 arcsec. Proper motions are clearly required to attain this. Parallax data are also necessary, since parallaxes are not random, and in many cases will exceed position errors.

## 4. AGASC1.1 = Hubble + PPM

The Hubble Space Telescope Guide Star Catalog (GSC1.1), constructed to support the operational need of the Hubble Space Telescope for off-axis guide stars, contains 18 819 291 objects in the range 7–16 mag, of which more than 15 million are classified as stellar. GSC photometry is given in the natural systems defined by the individual plates in the GSC collection (generally J or V), and photometric uncertainties are typically 0.3 mag.

The Positions and Proper Motions (PPM) Catalogue provides magnitudes, stellar spectral types, and proper motions for stars down to $V \sim 10$ mag, for about 400 000 stars.

Matching the catalogues, and incorporating proper motions, we find an optimal *positional matching* tolerance of 10 arcsec. To that separation, 99.7 per cent of PPM stars are matched. We then perform a *magnitude matching*, with a liberal tolerance of $\pm 2$ mag. Using the PPM spectral types, we obtain $(B - V)$ colours by interpolation, and express the conversion to $V$ via a single coefficient $\alpha$, where $m_{GSC} = V + \alpha(B-V)$ is used when the PPM mag is visual, or $m_{GSC} = B + (\alpha - 1)(B-V)$ is used when the PPM mag is photographic.

The surface density of objects matched between the GSC1.1 and PPM with $m_{ACA} \leq 10.2$, is 10.6 $deg^{-2}$ for $|b| < 10°$, and 4.9 $deg^{-2}$ for $|b| > 80°$. This latter surface density is still slightly low for AXAF mission requirements.

## 5. AGASC1.2 = Hubble + PPM + TYC

Colours are still needed for the majority of stars in AGASC1.1, since merging with the PPM provided colours (from spectral types) for only the brightest 2 per cent of the GSC1.1 to $V = 14.5$ mag. Also, PPM-derived colours are probably very uncertain, since they are interpolated from listed Spectral Types with no reddening information. Merging the Tycho Catalogue with the existing AGASC1.1 (Hubble +

PPM data, in AXAF format—see below) will provide reliable colours for 1 058 332 stars, nearly complete to $V \leq 10.5$ mag. In the current error budget, using the highly accurate Tycho star positions (versus the GSC 1.1) should improve the absolute aspect by 30 − 50 per cent.

Astrometric errors for Tycho stars ($\sim 0.025$ arcsec), are of the same order as parallaxes expected for many bright ($V \sim 8$) stars typically selected by the AXAF Star Selection Algorithm. Since parallax is additive, it will dominate absolute position errors unless incorporated in the AXAF image aspect solution.

The *AXAF Guide/Aspect Star Catalog* version 1.2 (AGASC1.2), will be produced in FITS format files, divided into 9537 small regions on the celestial sphere. The regions scheme is identical to that of the Hubble Space Telescope Guide Star Catalog (GSC1.1), so that regions files contain about 2000 objects each. AGASC1.2, however, will offer more information, totaling about 2.6 Gbytes.

The data format for each star allows for inclusion of positional data (right ascension and declination, proper motion and parallax), photometry (a catalogue magnitude, two colours, and an estimated AXAF aspect camera magnitude), as well as flags for variability and multiplicity, and quality codes based on proximity and brightness of nearby stars.

## 6. CONCLUSIONS & FUTURE UPDATES

The next *AXAF Guide/Aspect Star Catalog* (AGASC1.2) will be used for pointing control and attitude determination and for aspect reconstruction of timed X-ray events to form 0.5 arcsec X-ray images with absolute positions good to $< 1$ arcsec.

AGASC1.2 will incorporate the *best* measurements (based on lowest quoted error) for photometry, positions, proper motions, and parallax for all stars from (1) the Hubble Guide Star Catalog (GSC1.1); (2) the Positions and Proper Motions Catalogue (PPM); and (3) the Tycho Catalogue (TYC).

Systematic errors may be reduced in the future by basing the catalogue on the GSC1.2, which will use a PPM/AC (and eventually, a TYC) reference frame for re-reduction of plate solutions. Actual $m_{ACA}$ data from the AXAF Aspect Camera may also be included for previously-observed stars. These may in turn be used for on-orbit recalibration of the $m_{ACA}$(V) relation as a function of colour. Colours for fainter stars may be incorporated from the USNO catalogues, complete in the range $12 < V < 19$ mag.

AXAF Science Center HomePage:
http://asc.harvard.edu/

## 7. ACKNOWLEDGEMENTS

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