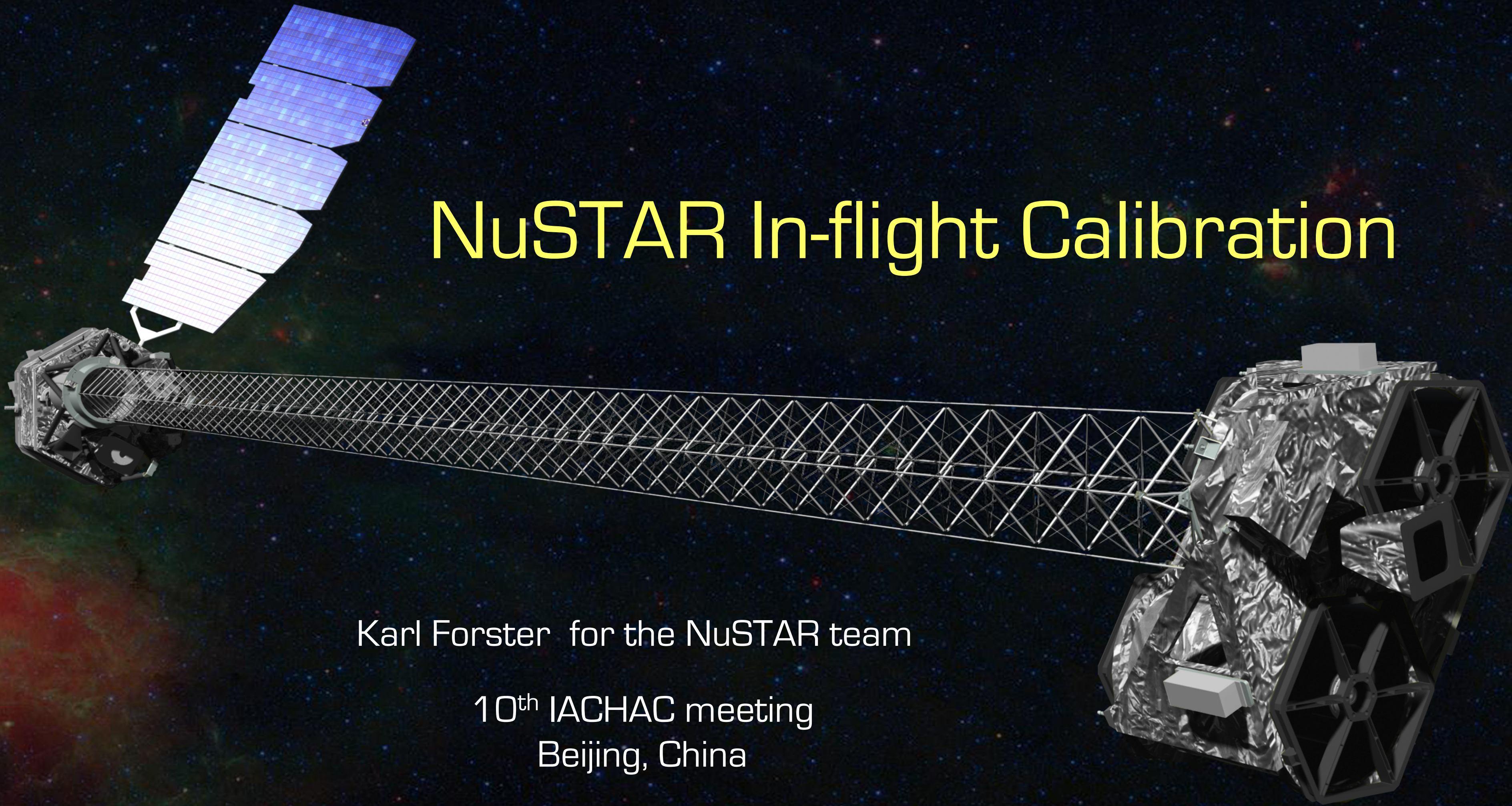
NuSTAR In-flight Calibration



Karl Forster for the NuSTAR team

10th IACHAC meeting
Beijing, China

3 phase in-flight calibration

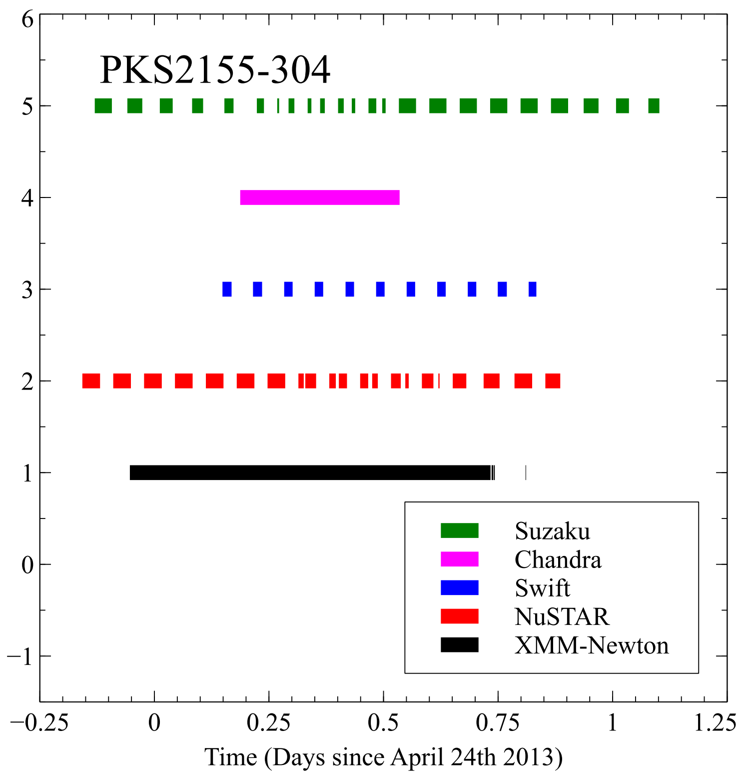
- After attending IACHEC meeting(s), ground calibration, launch, & spacecraft bus checkout

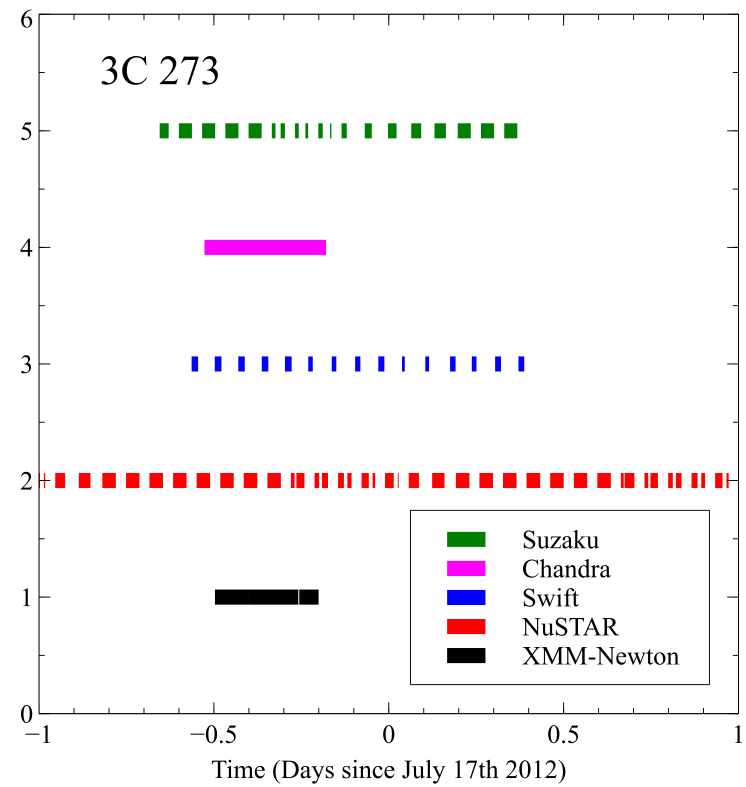
1. Internal (detector) calibration
   - Mission specific dependent on instrument(s)
     - e.g. radioactive source deployment, no optics or pointing
   - Possibly merged with spacecraft bus checkout
2. Observe Celestial source(s) to calibrate:
   a. Observatory Pointing
   b. Optics response
   c. Timing
   d. Polarimetry
   - Time limitation/pressure before announcement of start of science mission
3. Continued calibration refinements
   - Neverending story, even after decomissioning (ala Einstein)
   - Coordinated multi-mission observations can help set absolute normalization
   - There will be no detailed agreement between observatories

IACHEC Coordinated observations

(Madsen et al 2015)

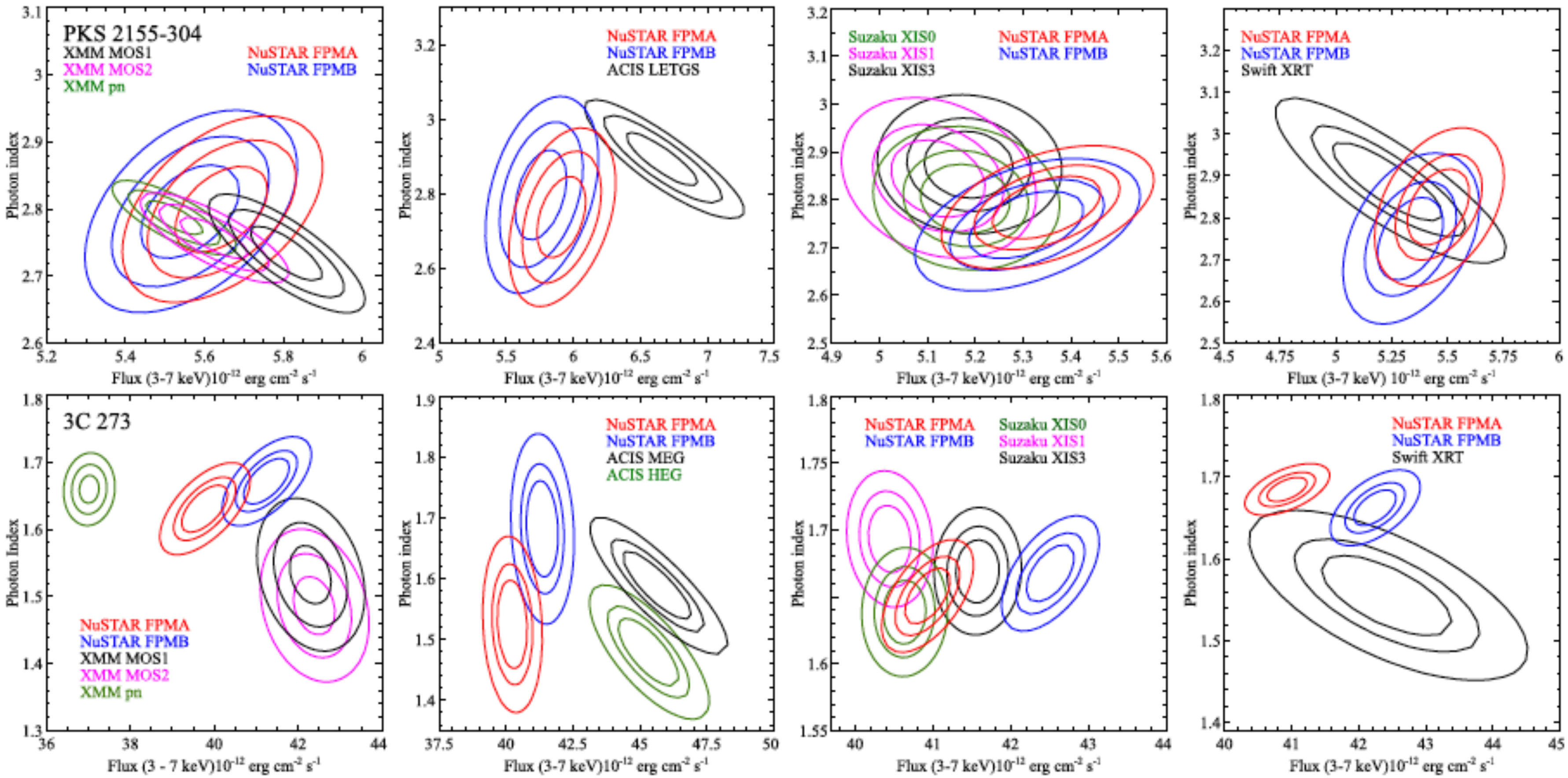
- Analyze instrument pairs
- Matched START and STOP times of the limiting observation
  - ignoring SAA and occultation



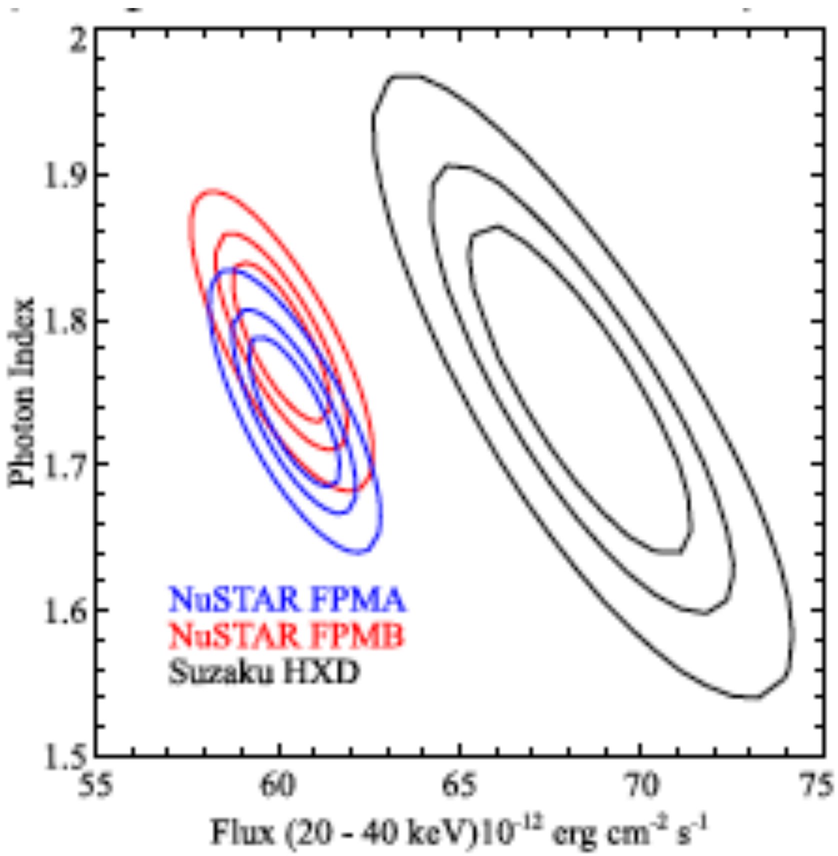


Evaluate coordinated observations

- Errors on simultaneous model fits



Some will not agree…



- Which do you “believe”?
- Publish best evaluation of systematic errors
  - NuSTAR Absolute normalization
  - adjustment (+15% area = -15% flux) based on IACHEC cross calibration observations

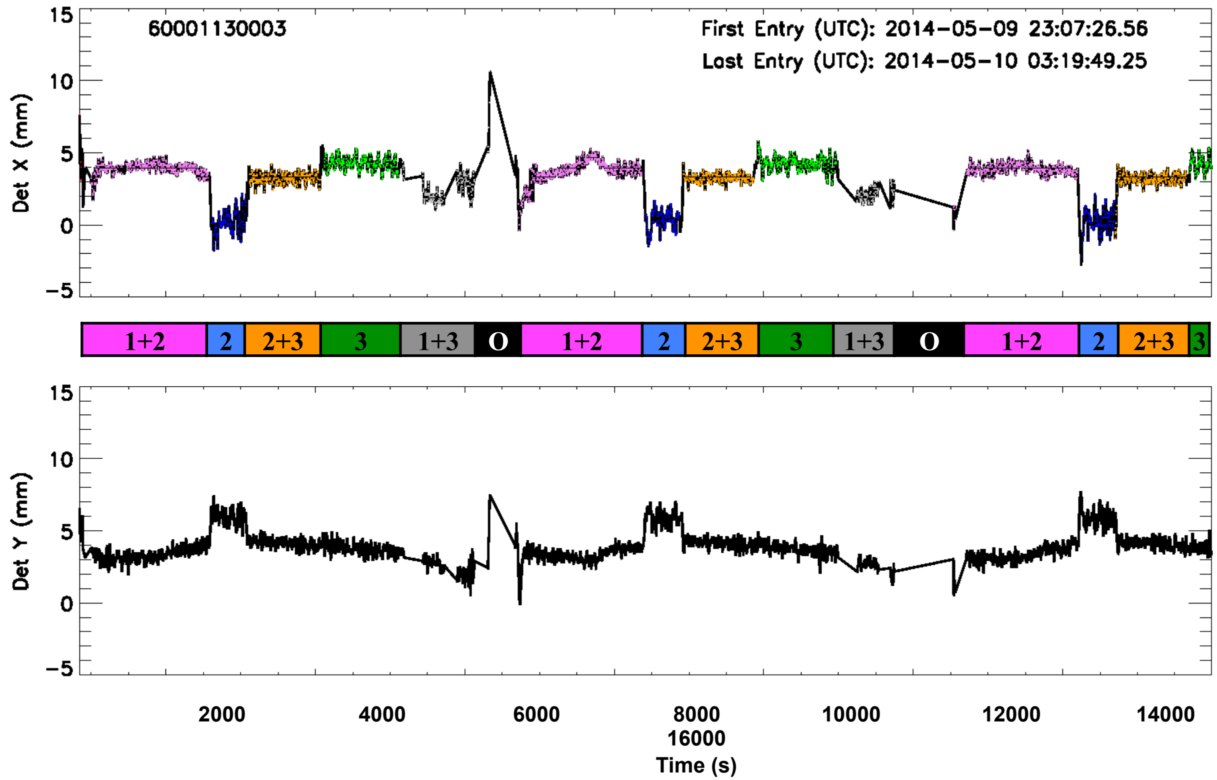
Test systems & procedures

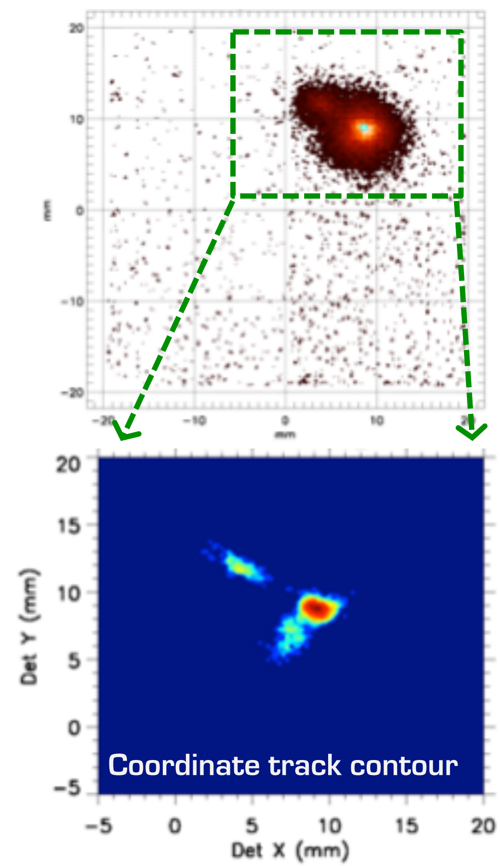
- Develop calibration plan documentation
  - Based on experience from instrument lab testing and ground data system testing
  - Operation readiness training
- Development of data analysis software
- Comprehensive performance tests
  - Include full path of science operations:
    - Target planning
    - Command sequence generation (constraint checking)
    - Upload
    - Data recovery, processing, archiving
  - Results will inform your calibration plans
- Sit back and enjoy the launch!

…best laid plans…

- "Stuff" happens after launch
  - Instrument calibration is absolutely the least important aspect of in-orbit checkout
- Be prepared to adjust plans on short notice
  - There may be windows where some calibration procedures can be brought forward
- Pressure will be present to obtain an image… any image… as soon as possible
  - E.g. NuSTAR press release of Cyg X-1

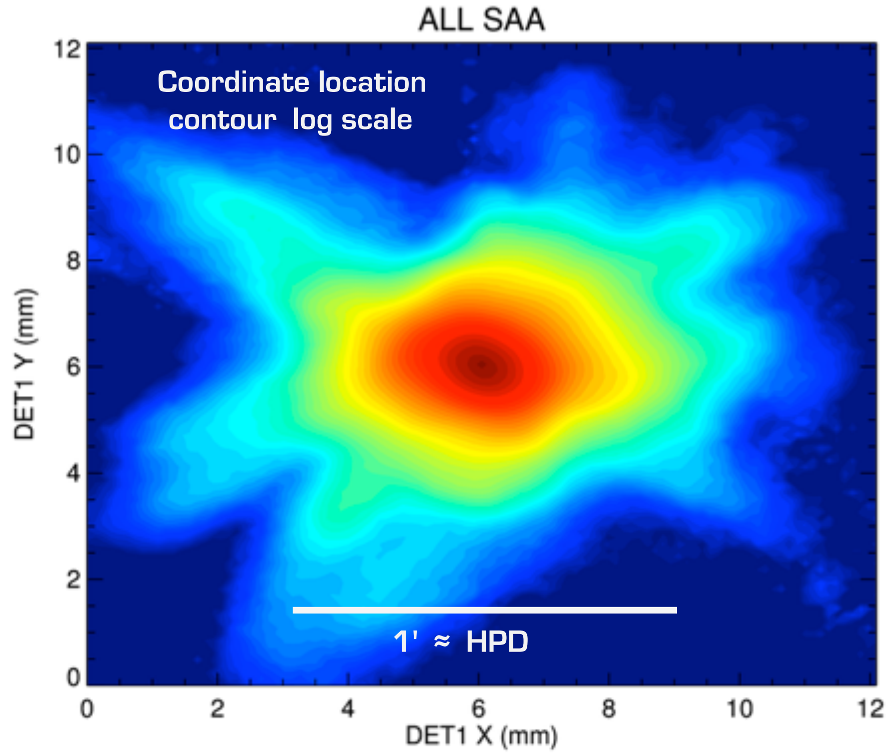
Attitude control alignment

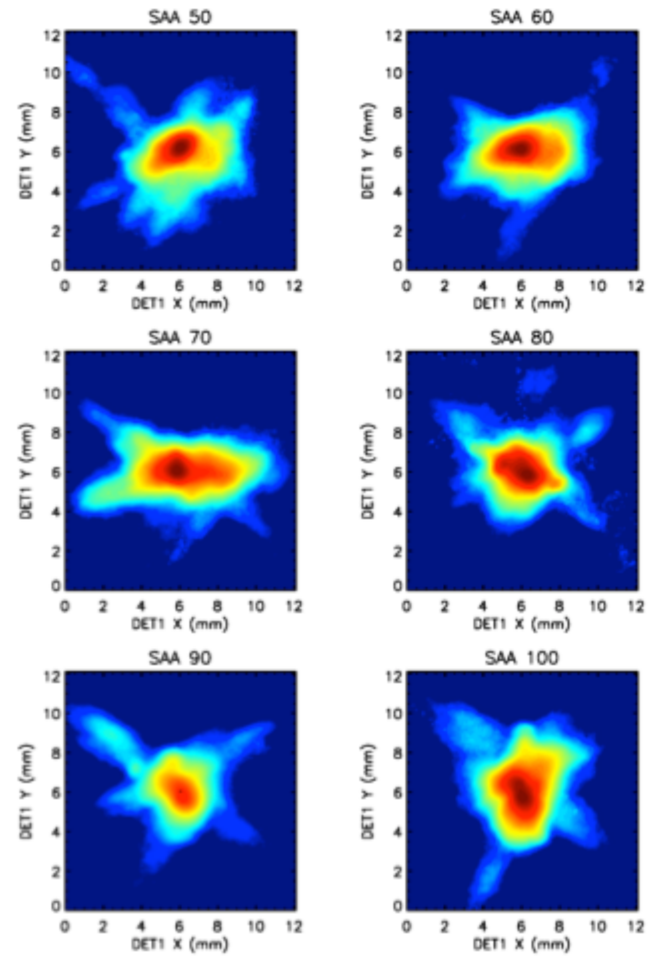




- Spacecraft ACS solution from 3 Camera head units (CHU)
  - CHU123 alignment changes with Solar illumination
  - Thermal flexing of camera mounts
- Causes the FOV to move by up to 3' during some observations
  - Depending on which combination of CHU are "driving" the ACS when the target is un-occulted

Attitude control alignment





- Size and direction of offsets are Solar aspect angle dependent
- 90% of on-target time places target within ±1.5mm (30") of centroid of motion
- Operations adjustment needed to place centroid of motion at optimal location on the focal plane

NuSTAR Calibration

- Effective Area
  - Multiple observations of Crab nebula
  - Assume $\Gamma = 2.1$ in 3-78 keV range
  - Measure $N_H = 2.224 \times 10^{21}$ cm^{-2}
    - normalized using 3C 273 measurement
- Absolute normalization uses cross-calibration observations
  - ***IACHEC organized simultaneous observations of PKS 2255-301 & 3C 273***
  - Simultaneous modeling of data from *NuSTAR* and *Chandra, XMM-Newton, Swift, & Suzaku*
- Vignetting response
  - 39 observations of Crab at multiple off axis angles in 2012 & 2013
    - Uses piece-wise linear spline function to modify ground calibration model
    - Model corrections for energy dependence including ghost-rays (single bounce) and aperture stop
- PSF calibration
  - Multiple observations of bright point sources
    - Cyg X-1, Vela X-1, GRS 1915+105, GS 0834-430, Her X-1
- Detector gain calibration
  - Uses deployable calibration source ^{155}Eu deployed in June 2012 and January 2015
- Timing calibration
  - On-board time reference uses temperature compensated crystal oscillator 24 MHz
  - Routinely correlated with ground time references (referenced to UTC via GPS)
  - Timing performance characterized using observations of pulsars in Crab and B1509-58
  - System performance accuracy of 3 ms
- **See NuSTAR observatory calibration paper** **(Madsen et al. 2015 arXiv :1504.01672v1)**

Summary of NuSTAR calibration status

- ARF - *completed*
  - ARF revisions:
  - 2013-08-04 CALDB version 20130509
    - Based on 1st Crab calibration
  - 2013-11-25 CALDB version 20131007
    - Absolute normalization adjustment (+15% area, -15% flux) based on IACHEC cross calibration observations
  - 2014-01-17 CALDB version 20131223
    - Revised Crab high energy calibration
- PSF – *completed*
- Detectors – *completed*
  - Gain/CLC revisions:
  - CALDB version 20140414: Corrections for some high-grade events
  - CALDB version 20150316: Time dependent gain calibration
- Background – *Understood and managed*
  - QA & NuSTARDAS screening

Lessons learned...

- Keep observation planning system simple and flexible
  - Scientists with a new instrument will not stick to pre-launch plans
  - E.g. 10 x more ToOs then pre-launch plans
- Fix what you can before launch but when on-orbit...
  - Plan to continue developing data processing software
  - Perform science “mode” observations as early as possible
    - don't wait for calibration to be completed
  - Keep in mind that operations budgets will continue to shrink
  - There will always be surprises (SAA sensitivity, ACS performance)
- Space observatories are a finite resource
  - Difficult to fix anything after launch ($$$)
  - Systems are developed according to baseline mission requirements
  - Don’t include any ‘hard-coded’ limitations based on duration of baseline mission
- Management will expect operations improvements
  - and funding agencies will expect lower operations costs