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 decommissioning (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

---

**PKS2155-304**

- Suzaku
- Chandra
- Swift
- NuSTAR
- XMM-Newton

---

**3C 273**

- Suzaku
- Chandra
- Swift
- NuSTAR
- XMM-Newton

---

20 April 2015
NuSTAR Calibration Status - Karl Forster
IACHEC 2015 - Beijing, China
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!
“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
• 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
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
Effective Area
- Multiple observations of Crab nebula
- Assume $\Gamma = 2.1$ in 3-78 keV range
- Measure $N_H = 2.224 \times 10^{21} \text{ cm}^{-2}$
  - 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 $^{155}\text{Eu}$ 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