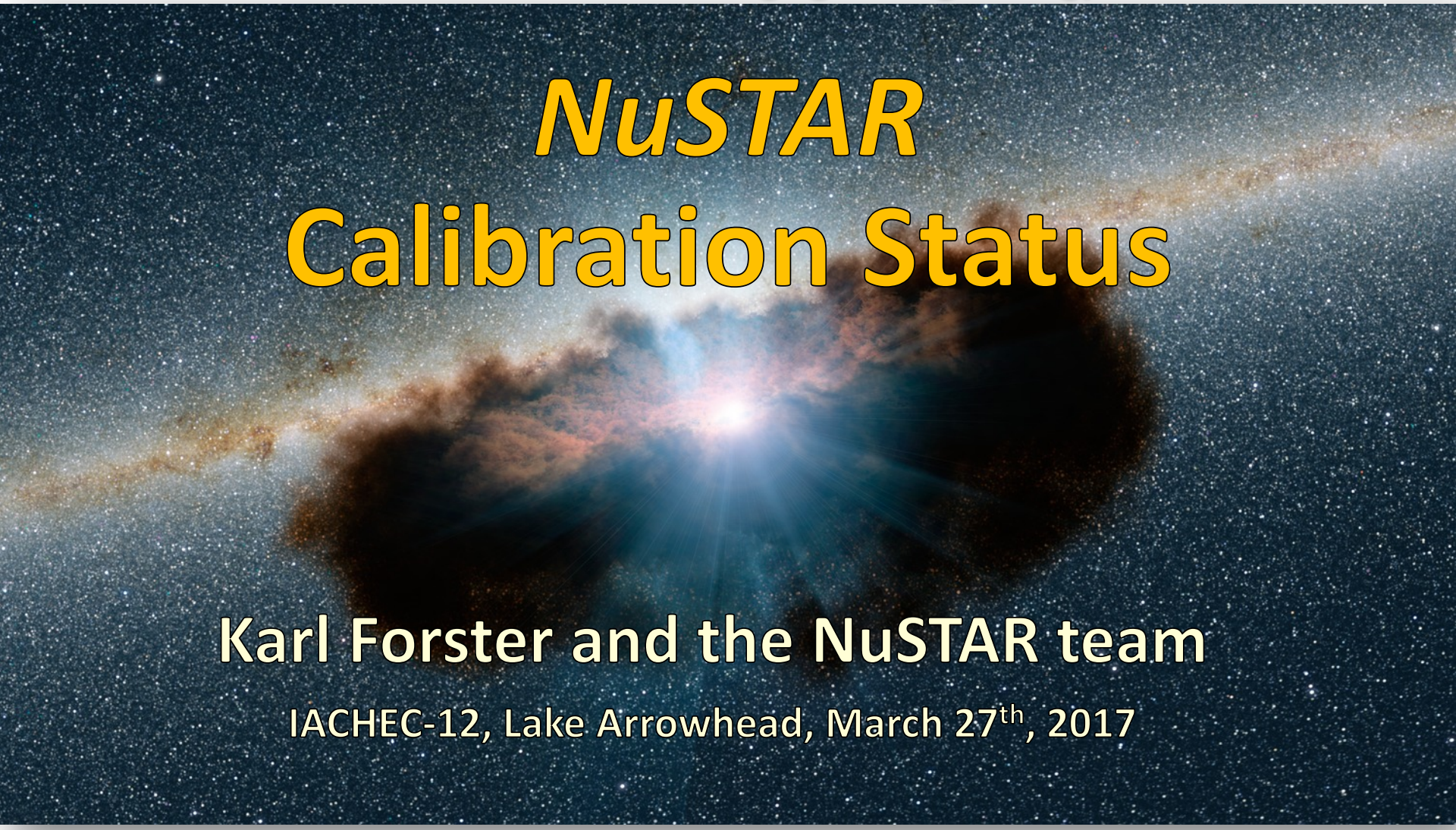


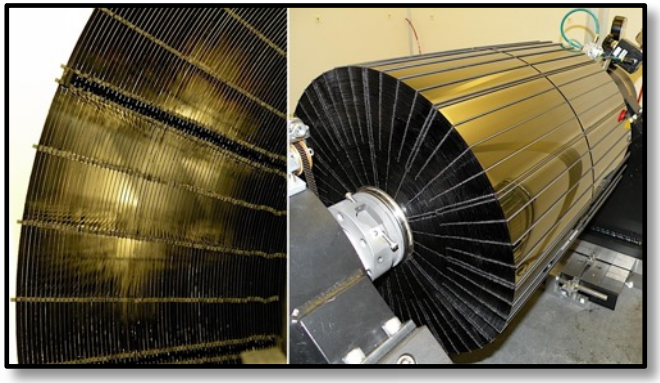
NuSTAR Calibration Status

Karl Forster and the NuSTAR team

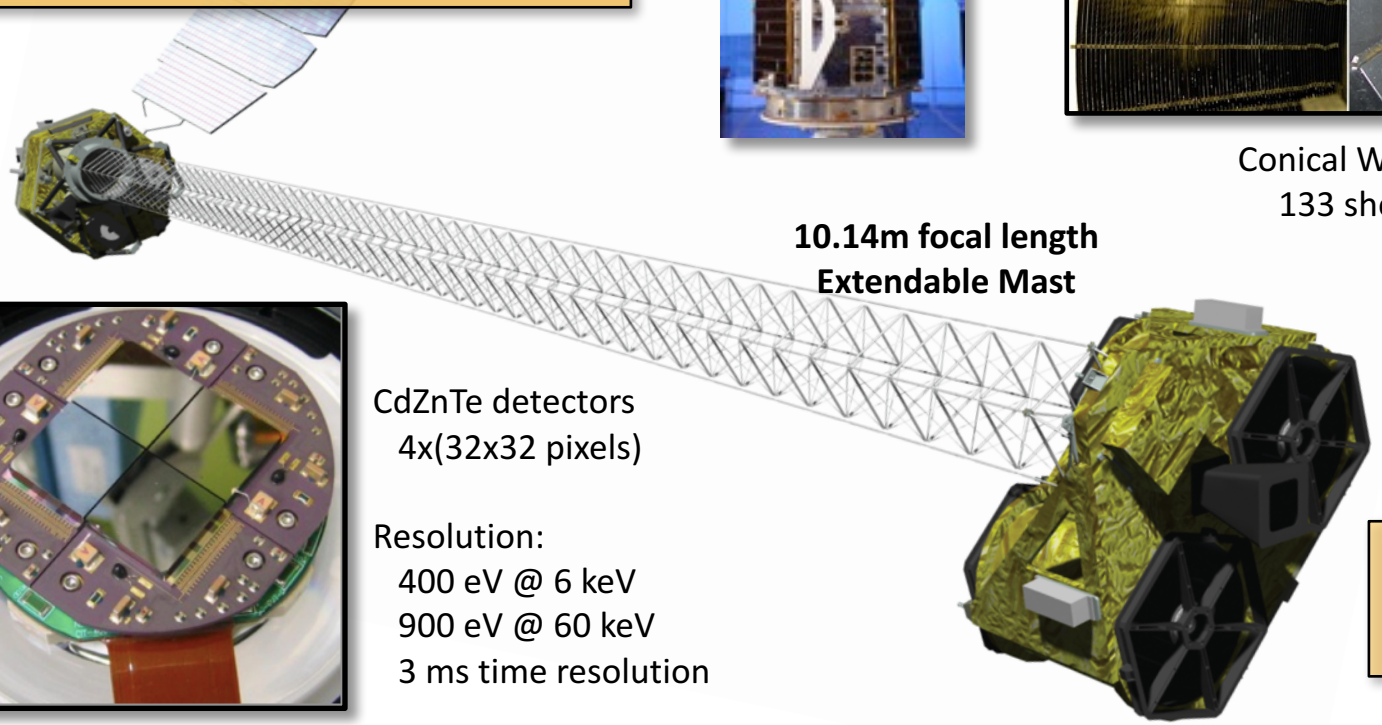
IACHEC-12, Lake Arrowhead, March 27th, 2017

NuSTAR Observatory

- NASA small explorer astrophysics mission
- PI Fiona Harrison (Caltech)
- Partners: ASI, ASDC, DTK, HEASARC
- Launched on June 2012, 620 km, 6° orbit
- Orbital-ATK LeoStar-2 spacecraft bus



Conical Wolter-I approximation
133 shells (43 W/Si, 90 Pt/C)
HPD = 1 arcminute
FOV = 12’ x 12'



10.14m focal length
Extendable Mast

CdZnTe detectors
4x(32x32 pixels)

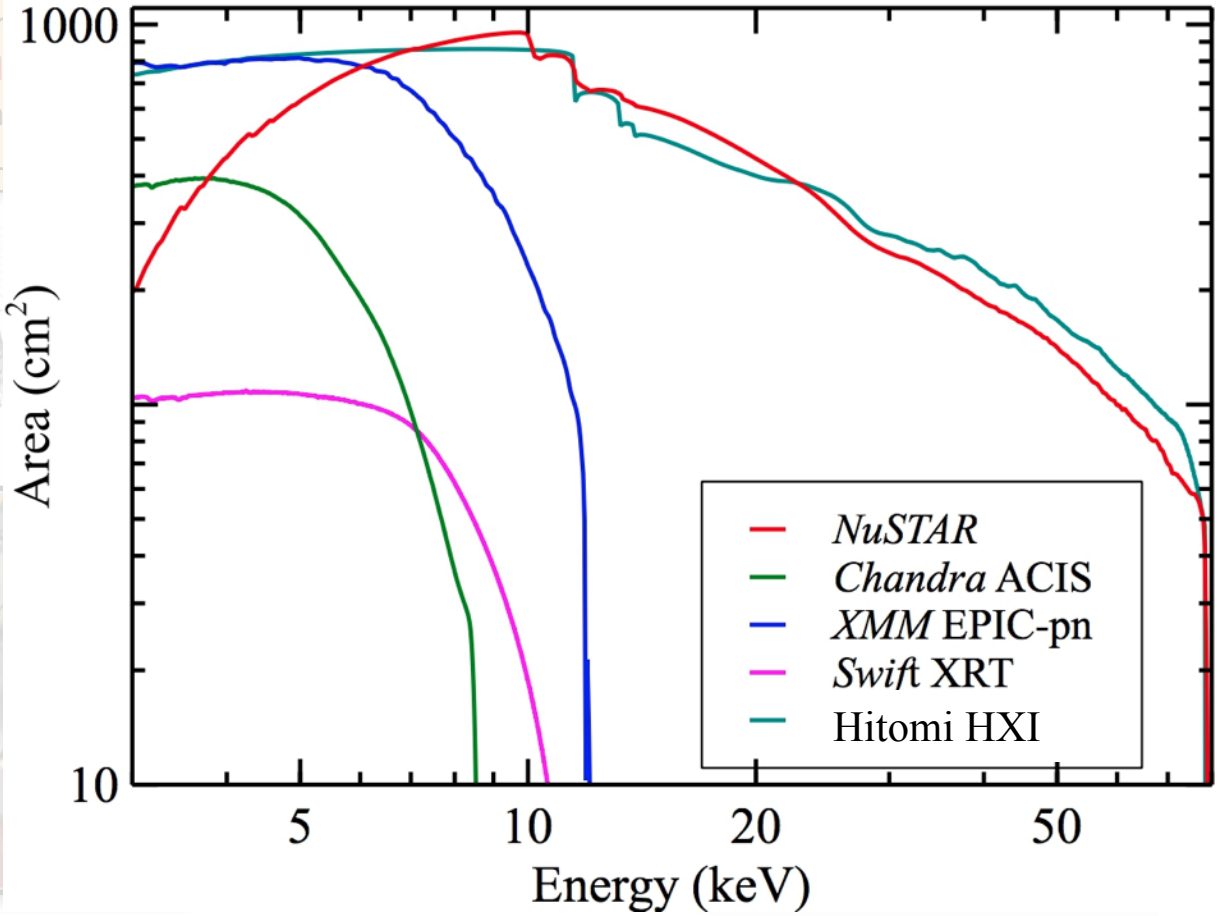
Resolution:
400 eV @ 6 keV
900 eV @ 60 keV
3 ms time resolution

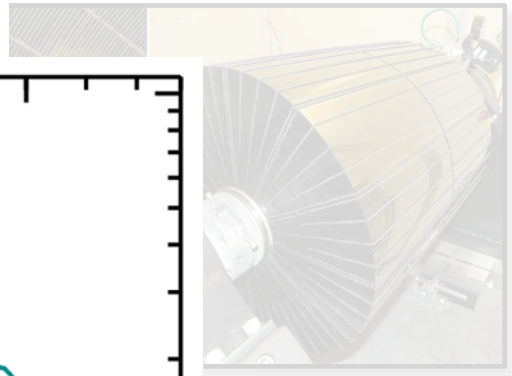
- No consumables
- Single string
- 10 year lifetime

NuSTAR Observatory

- NASA small explorer astrophy
- PI Fiona Harr
- Partners: ASI
- Launched on
- Orbital-ATK L

Energy Range: 3 – 78 keV





lter-I approximation
ls (43 W/Si, 90 Pt/C)
HPD = 1 arcminute
FOV = 12’ x 12'

No consumables
Single string
10 year lifetime

Calibration update

- Observatory status is green – no anomalies in 2016/17
- Monitoring of change in detector gain indicates continued trend of ~1% degradation / year

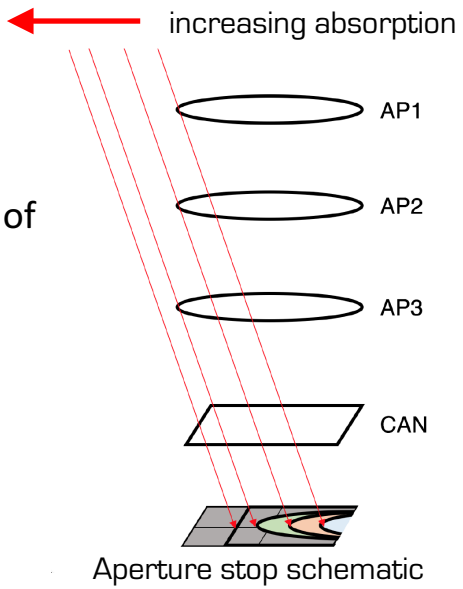
2016 calibration news

- Calibration observations measuring stray light from the Crab in 2015/16 used to update detector absorption parameters
  - Removed residual feature of order few % seen at ~3.5 keV in observations of bright, soft X-ray sources
  - CALDB release June 2016
- Using NuSTAR as a collimator provided a new measurement of the instantaneous absolute Crab flux.
  - Using ground calibrated detector responses only
    - Known to better than 1% above 5 keV
- Absolute Crab flux measured to an accuracy of better than 4%
  - Madsen et al. 2017 (ApJL accepted)
  - Crab stray light monitoring observations planned throughout the year
- More details in Kristin's presentation this afternoon
  - session II-b in Violet room

Calibration update

2016 calibration news – cont.

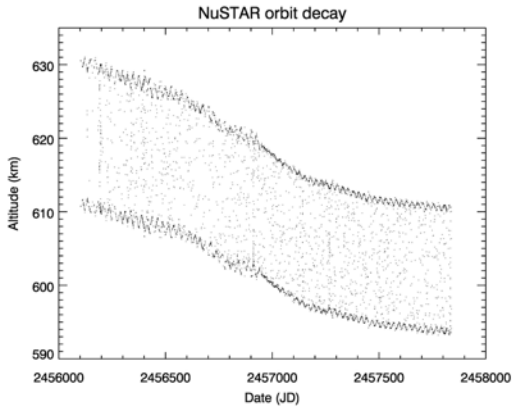
- Detailed investigation of the observational artifacts
  - Ghost-rays and stray-light characterized in detail
  - Absorbed stray light measurements by various combinations of aperture stops
    - Ask Kristin "where's the Sn-man"



Aperture stop schematic

Calibration observations for 2017

- IACHEC campaign on 3C 273 in June
- Bullet cluster investigation of background modeling
- Pulsar observations to improve timing accuracy
- Dust scattering halos
  - Investigation of nearby binaries
    - See Kristin's talk this afternoon



Orbit decay slowed in 2016

- Early Solar minimum
- Mission lifetime ~ 10 more years

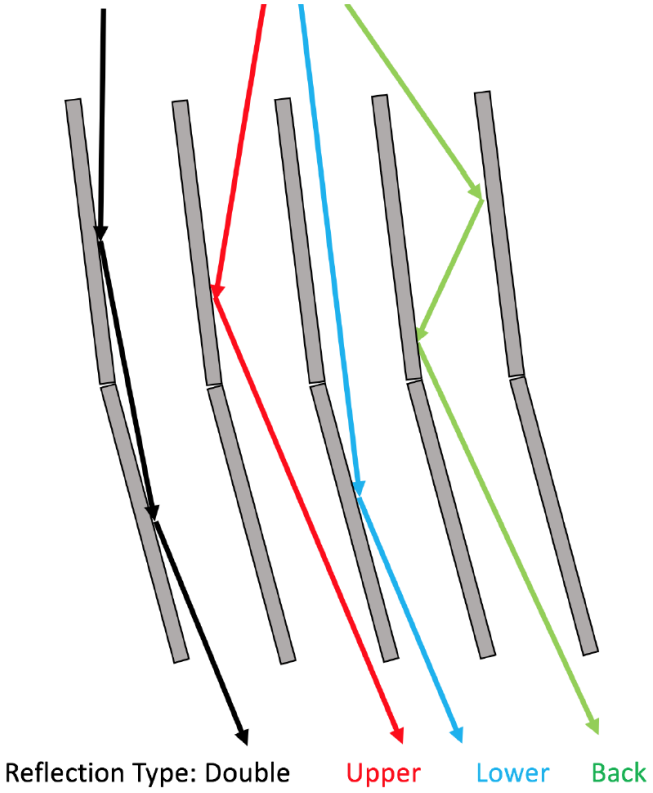
Bullet nod & shuffle

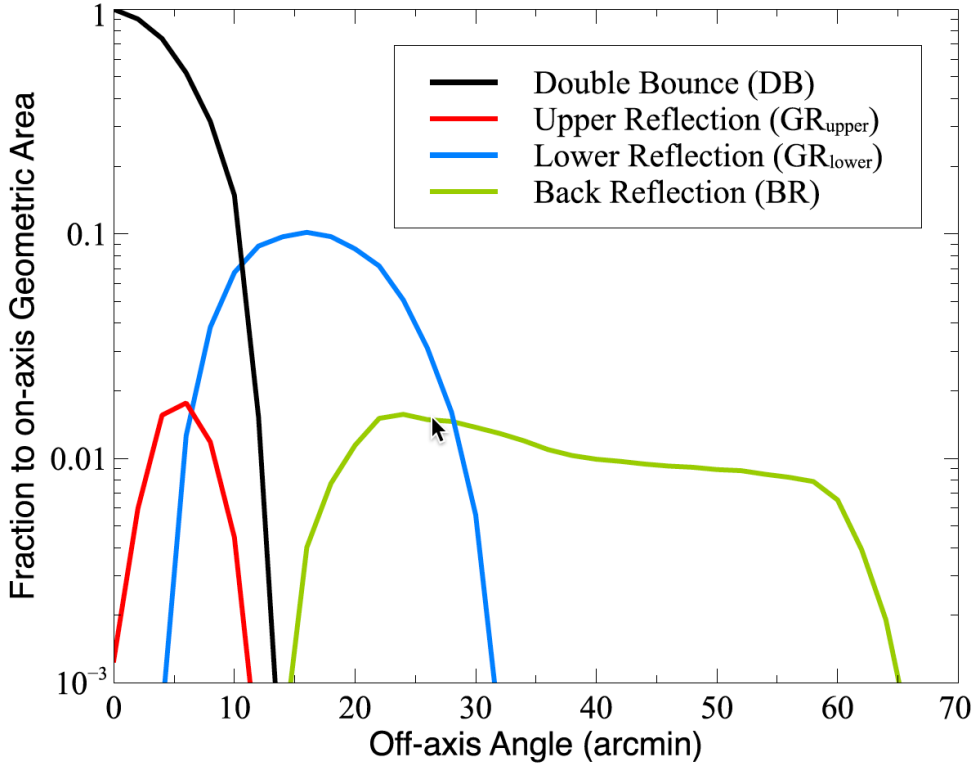
Kristin Madsen and Daniel Wik

- Background estimation problematic for sources that fill the field of view
- NUSKYBGD was developed to model the instrumental and aperture background
  - Systematic uncertainties remain in model
- So a new observing style was developed to measure the Bullet galaxy cluster and nearby background emission
  - Aims to confirm NUSKYBGD accurately accounts for the aperture background component
  - Potentially free of systematic uncertainties inherent in the use of NUSKYBGD
- In February 2017 the Bullet cluster and an annulus around the cluster were observed for 44 orbits each
  - 1 orbit on the Bullet cluster followed by 1 orbit exposure 45 arcmin away
- 45 arcmin annulus was chosen to minimize ghost ray reflection from Bullet cluster
  - > 2 degree away then stray light from the Bullet will enter the aperture at some PA
- Observatory Position Angle and Solar aspect angle were within ~1 degree for all exposures
- The annulus was built up over 8 days, 44 positions provided multiple overlapping exposures of the same position on the sky
  - Created a Bullet cluster and background exposure of 160 ks each

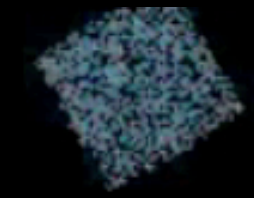
Bullet nod & shuffle

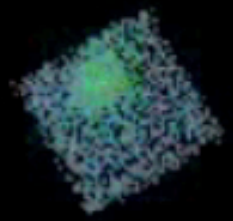
Kristin Madsen and Daniel Wik





Madsen et al. 2017 in prep





Timing Calibration

Matteo Bachetti, Craig Markwardt, Eric Gotthelf

- Accurate time of arrival of events requires the use of a clock correction file as part of FTOOL *barycorr*
- Corrections to the spacecraft clock applied during ground station passes
- Drifts are usually +/- 10ms from true (GPS) time
  - Database of clock adjustments provided by the MOC
- Interactive tool is used to fit a piecewise spline interpolation between the spacecraft clock corrections
  - Keeps relative accuracy to within +/- 2ms
  - Monthly updates to clock correction file released as CALDB updates
- Large unphysical variations were discovered in the clock correction file in 2016
  - During analysis of some pulsar observations (user community)
- A new fit to the data was performed, using only data from primary ground station
  - Data from backup ground stations (KSAT Singapore, USN Hawaii) only used for periods of Malindi station downtime
- Updated clockfile released 2016-12-07, significant improvement in the stablity of clock correction

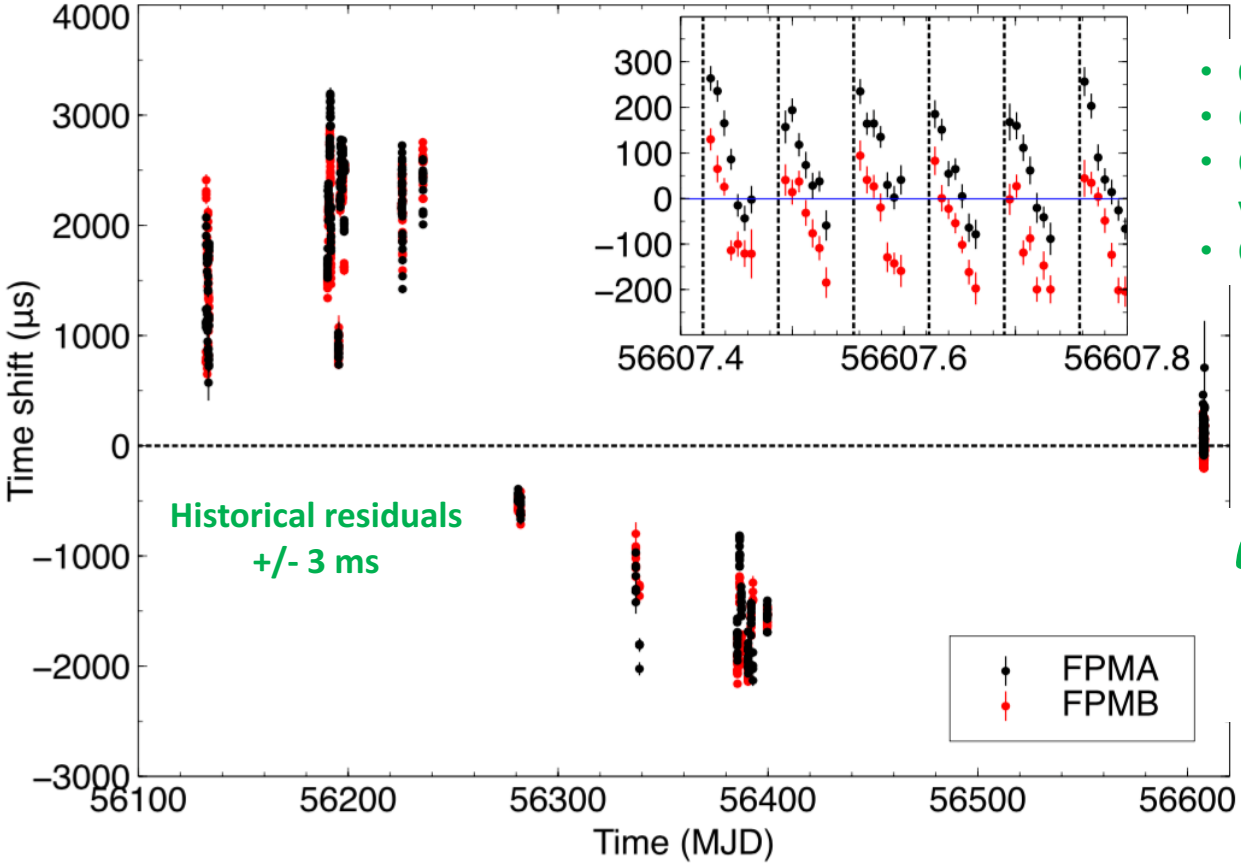
Timing Calibration

Matteo Bachetti, Craig Markwardt, Eric Gotthelf

- Previously confirmed accuracy of relative timing to be +/- 3ms
  - Using Crab calibration data
- Absolute accuracy of event times found to be 1 +/- 2ms compared to measurements by Swift-XRT
  - Based on simultaneous observations of PSR B1509-58
- However residual drifts are seen in Crab data
  - 400 μs over an orbit
  - Due to residual temperature sensitivity of spacecraft crystal oscillator
    - Impacts analysis of pulsars with periods shorter than ~3ms
- Scale linearly with temperature of clock housing
  - ~0.4ppm over 6 ºC observed temperature range
  - Spacecraft clock uses a temperature compensated crystal oscillator

Timing Calibration

Matteo Bachetti, Craig Markwardt, Eric Gotthelf



- **October 2013 observation**
- Clear shift by +/- 400 μs
- Originating in clock frequency variations
- Orbital timescales

Can we do better than mission requirement of +/- 3 ms ?

Comparison of the TOAs of the Crab pulses and expected arrival times calculated through the Jodrell Bank Monthly Ephemeris

Timing Calibration

Matteo Bachetti, Craig Markwardt, Eric Gotthelf

- Model the temperature clock frequency variations frequency using the
- Calibrate using PSR B1821-24
  - 3ms pulsar in M28, very sharp pulse profile
  - Bright enough to measure in one orbit
- Follow transition from Sunlight to shadow in each orbit to track the variations in the pulse
  - Observations scheduled for 2017 April and September
  - Solar aspect angle +/- 90 degrees
  - Illuminate different sides of the spacecraft
- Model pulse variations with measured temperature of clock housing
  - Telemetry is recorded but not yet delivered to the SOC
- Goal is to provide an additional clock correction for the entire mission
- Preliminary models indicate that this method may improve relative timing to as small as a few μs

Timing Calibration

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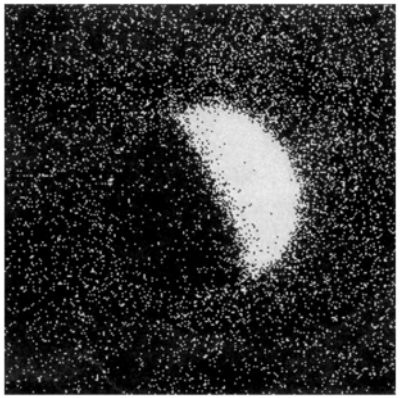
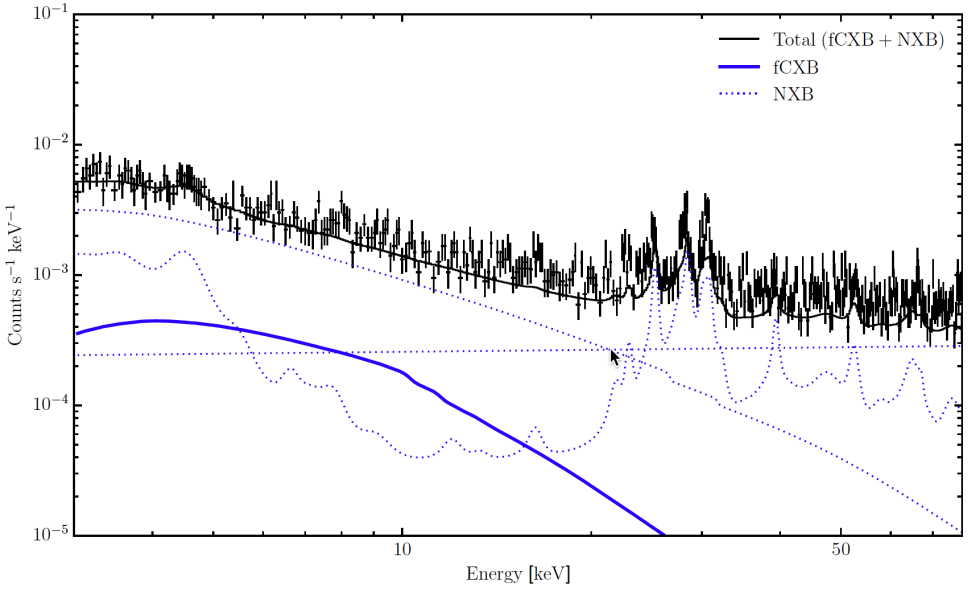
The Moon and the CXB

George Lansbury, Brian Grefenstette

- NuSTAR Legacy Survey to measure the normalization of the Cosmic X-ray Background
- Using the Moon as a “shutter”
- Track the Moon while it oscillates (parallax) over 4º of sky
  - Building up a 200 ks exposure
- Observation planed for 2017 April



ROSAT image of the Moon (Schmitt et al. 1991).



- Simulated NuSTAR spectrum
- 100 ks exposure
- fCXB = focused CXB
- NXB = non X-ray background
  - Aperture background
  - Reflected Solar X-rays
  - Instrument Compton-scattered continuum
  - Instrument emission lines

Summary