Lessons learned from Hitomi Calibration

Rob Petre
(NASA / GSFC)

With thanks to the Hitomi team

Goals

- Present top level view of lessons learned during the process of calibrating the Hitomi instruments
- Examples of specific lessons regarding instruments are mentioned, but the primary goal is to critique the process for planning and executing the calibration, primarily in flight
- This is the first of a number of Hitomi talks; others will focus on specific instruments

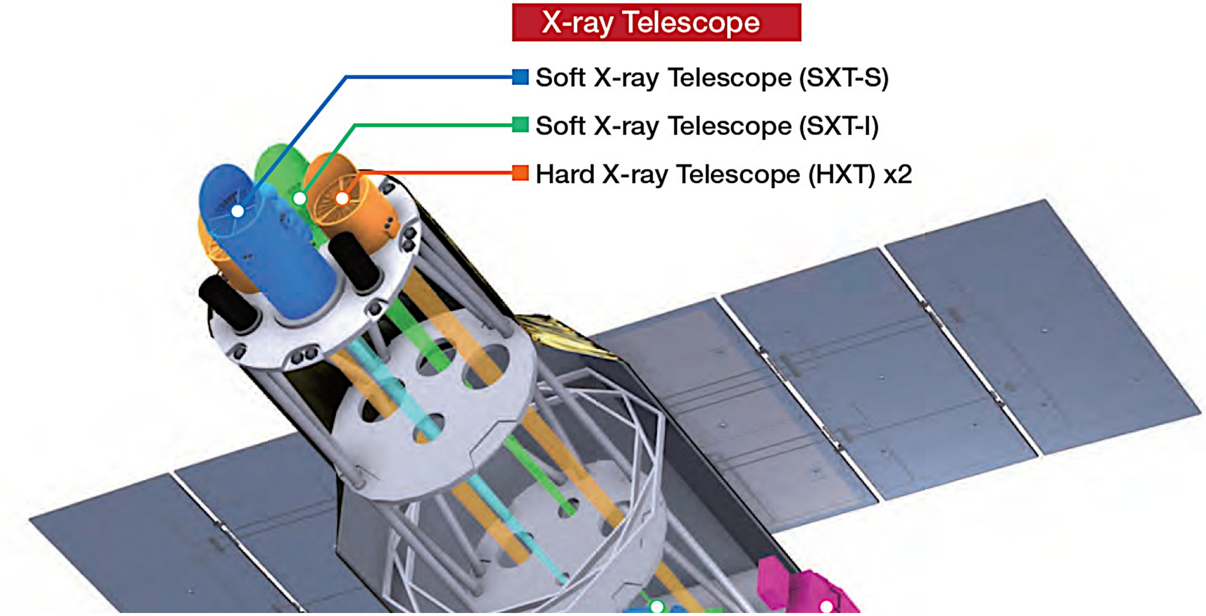
Disclaimer

This is a subjective view of the Hitomi calibration process and plans. While it includes contributions from the members of the instrument team (who I thank for their input), the opinions expressed here are mine.

Background

- Hitomi was launched on February 17, 2016
- An attitude control failure resulted in the loss of the mission just 37 days later (one year ago yesterday).
- By the time of the failure, all of the instruments had been turned on, and had performed "first light" observations, but the formal calibration program had barely begun
- This is especially true for the SXS, whose gate valve had not yet been opened

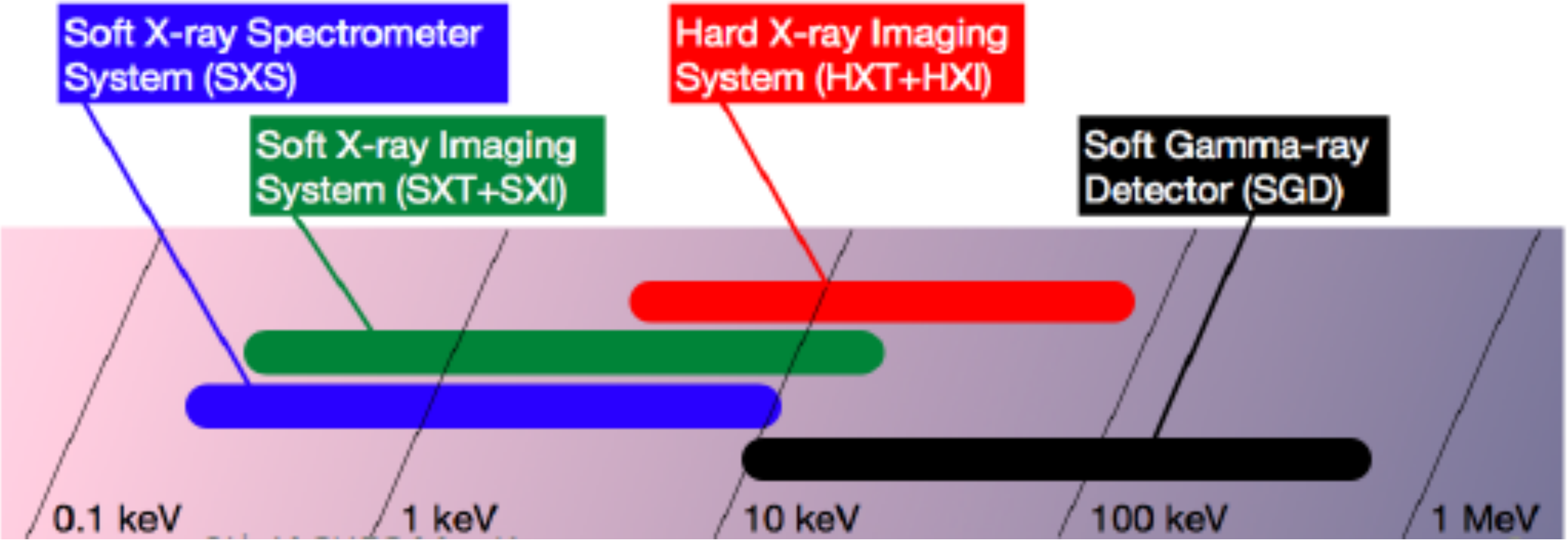
Hitomi – Eye to the Universe!



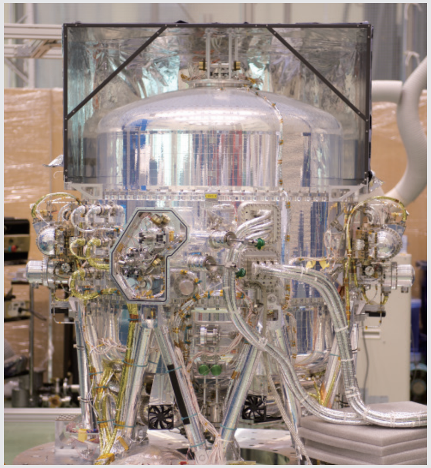
Study structure and evolution of the Universe

Study matter in extreme environments

- Black holes

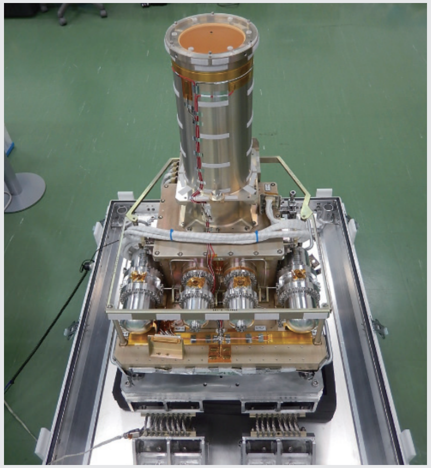


Soft X-ray Spectrometer (SXS)



Uses US-led technology called microcalorimetry. Includes multiple stages of coolers to lower the temperature of the sensor to near absolute zero (-273.15 degrees C). By measuring the slight increase in temperature from incoming X-ray photons, it is capable of measuring the X-ray energy in never before achieved high resolution. The most highly anticipated device on ASTRO-H by scientists.

Soft X-ray Imager (SXI)

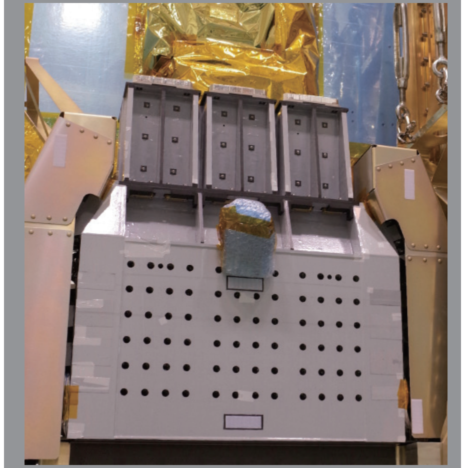


X-ray camera that achieves wide field of view of 38 arcmin by arranging 4 large X-ray CCDs together. Simultaneously implements X-ray imaging and spectrometry of sources in soft X-ray band. Located inside the satellite at the focal plane of SXT-I.

Hard X-ray Imager (HXI) x2

Camera that observes sources in hard X-ray with energy 5 keV and higher using silicon and Cadmium Telluride semiconductors. Located at the focus of the HXT with 12m focal length, which is realized by the extensible optical bench (EOB) that gets deployed in orbit.

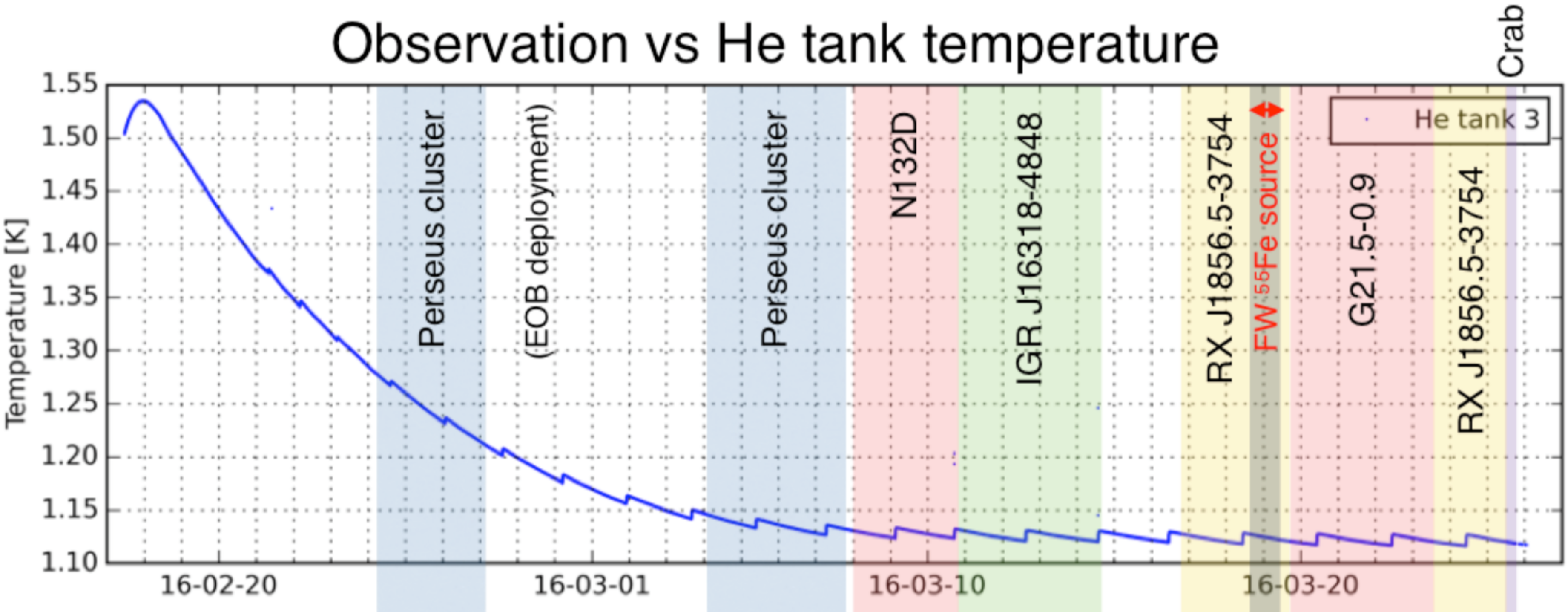
Soft Gamma-ray Detector (SGD) x2



High sensitivity gamma-ray detector layered with semiconductor detectors and using Compton camera theory. Cannot image sources since it does not use a telescope, but anticipated to reveal high energy phenomena by detecting soft gamma-rays with higher energy than X-ray.

Feb 17 2016

Hitomi post-launch timeline

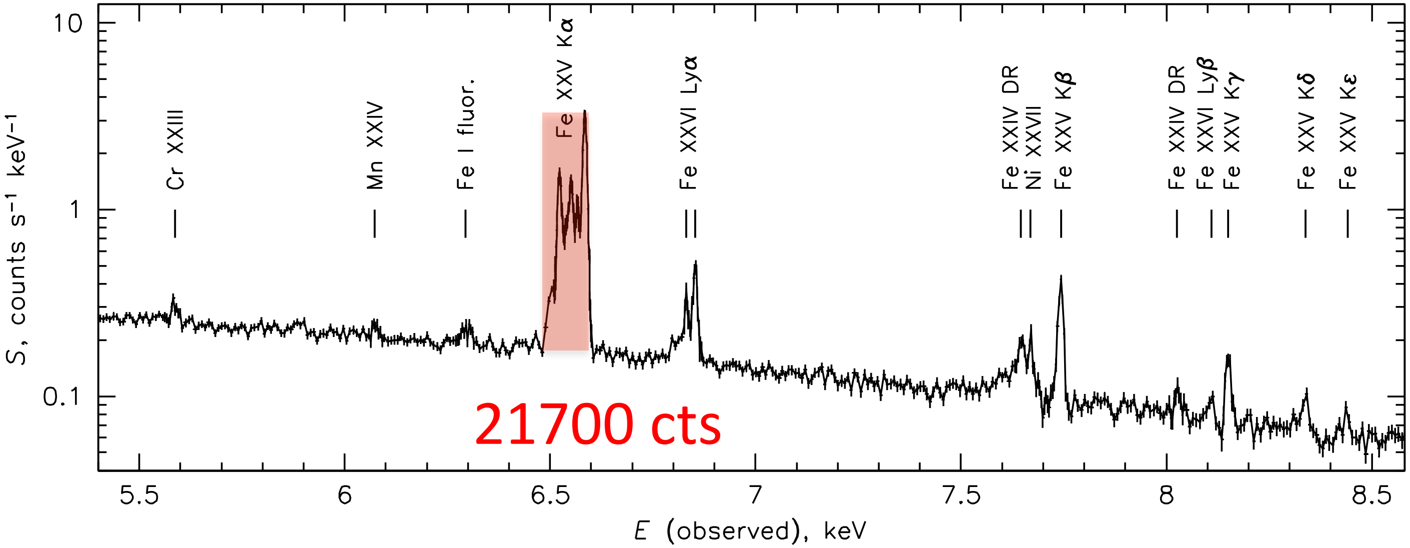


The Hitomi instruments never really attained nominal operating mode

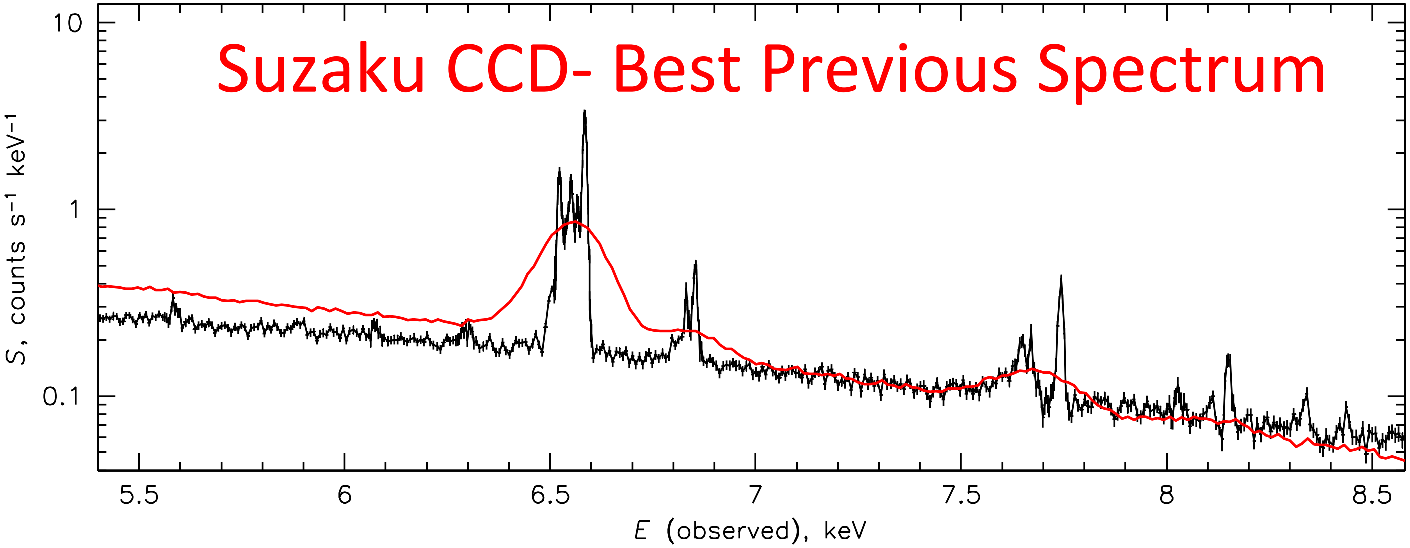
Calibration of Hitomi

- The Hitomi instruments had been calibrated to varying degrees on the ground
- Some essential calibration activities were not possible until after launch
  - End-to-end calibration of SXS, SXI, HXI (mirrors + detectors)
  - Pretty much everything on the SGD
- The Hitomi team had developed a comprehensive in-flight calibration plan (presented at previous IACHEC meetings) – or so we thought
  - Upcoming talks will describe the calibration of the various instruments
  - Given the limited data and discovery of instrument issues post launch, the actual calibration turned out to require a substantial (at times heroic) effort. **The instrument teams are to be commended!**
  - For the most part, the calibration requirements for all instruments were met, and some (most notably the SXS) exceeded.
  - Most importantly, the calibration, however limited, nevertheless made possible roughly a dozen scientific results, some of them transformational

Residual instrumental background ~16 cts



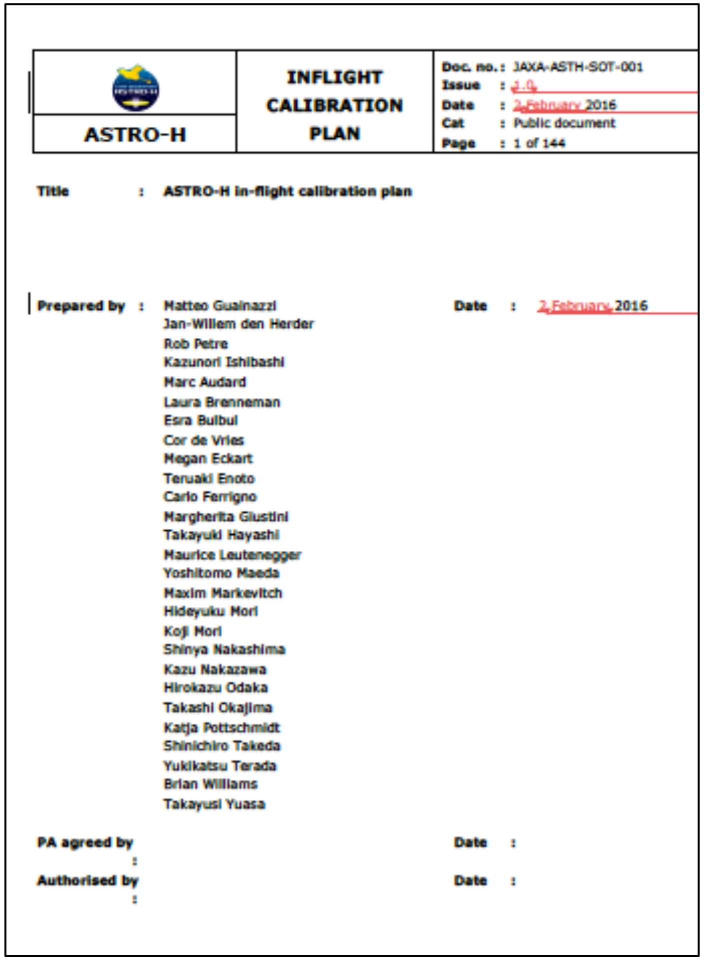
21700 cts



Suzaku CCD- Best Previous Spectrum

Full array

Hitomi In-flight Calibration Plan



ASTRO-H

INFLIGHT CALIBRATION PLAN

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Page : 1 of 144

Title : **ASTRO-H in-flight calibration plan**

Prepared by : Matteo Guainazzi
Jan-Willem den Herder
Rob Petre
Kazunori Ishibashi
Marc Audard
Laura Brenneman
Esra Bulbul
Cor de Vries
Megan Eckart
Teruaki Enoto
Carlo Ferrigno
Margherita Giustini
Takayuki Hayashi
Maurice Leutenegger
Yoshitomo Maeda
Maxim Markevitch
Hideyuku Mori
Koji Mori
Shinya Nakashima
Kazu Nakazawa
Hirokazu Odaka
Takashi Okajima
Katja Pottschmidt
Shinichiro Takeda
Yukikatsu Terada
Brian Williams
Takayusi Yuasa

Date : 2 February 2016

PA agreed by : **Date** :

Authorised by : **Date** :

- Prior to launch, the Hitomi team developed a comprehensive in-flight calibration plan
- The goal of this plan was to convert Hitomi from a spacecraft containing four distinct instruments into an observatory
- Developed in parallel with definition of operations team
- Substantial effort involving instrument teams, software team, and calibration advisory board

In-Flight Plan Development Methodology

- Planning being performed by calibration coordination team, with input from instrument teams and SWG
- Build a plan that assumes successful ground calibration, but allows for complete on orbit calibration
- Identify source for each calibration activity (multiple preferred to ensure visibility)
- Use "standard candles" when possible (IACHEC favorites like 3C 273, E0102, etc.)
- Try to find sources that satisfy multiple goals
- Determine needed exposure via simulation
- Perform perturbation exercise to determine what happens in the case of off-nominal performance
- Need plan that fits in available time:
  - Satellite/Instrument checkout (3 months). Primary aim is to bring observatory to operational readiness but we can select sensible targets. Maximum effective observing time is 3.5 Ms (45% observing efficiency)
  - Science Working Group (6 months, 90% SWG time and 10% observatory time). We assume that a significant part of the observatory time (say 7% of total 6 months) is inflight calibrations. This gives for the PV phase 0.5 Ms.
  - Next phases (assume 5% calibration time). 0.7 Ms/year
- Establish priority scheme to ensure most critical observations done during calibration time and to enable flexibility on orbit

Calibration requirements - I.

Summary from the SCT “Calibration Control Table”: `http://www.astro.isas.jaxa.jp/next/astroh-sct/wiki/index.php?cal_control_table`

	SXS(+SXT)	SXI(+SXT)	HXI(+HXT)	SGD
Boresight stability	<2 arcmin	<2 arcmin	<1 arcmin	N/A
X-ray axis	2 arcmin	2 arcmin	1 arcmin	TBD
Astrometry/plate scale	2x10^{-4}	2x10^{-4}	1x10^{-4}	N/A
Energy scale uniformity (Knowledge of gain v. E)	1 eV; 0.2 eV goal	0.1%	3%; 0.5% goal	5%; 3% goal
Energy scale stability (Short term gain variability)	0.5 eV; 0.2 eV goal	0.2%; 0.1% goal (on axis)	5%, 3% goal	5%, 3% goal
Energy resolution	1.6 eV; 0.2 eV goal	5%; 3% goal	5% or 1 keV; 3% goal	5%; 3% goal
Energy redistribution	10%, 1% goal	10%, 1% goal	10%, 1% goal	10%, 1% goal
HPD; 90% PD on axis	10%; 5% goal (0.3-12 keV)	20% (0.3-12 keV)	20% (5-70 keV)	
Absolute effective area: broad band	10%; 5% goal	11%; 7% goal	10%; 5% goal	15%; 8% goal
Absolute effective area: broad band off-axis	N/A	15%; 10% goal	15%; 10% goal	
Relative effective area: broad band	5%; 2% goal	5%; 2% goal	5%; 2% goal	15%; 8% goal
Relative effective area:	N/A	10%; 5%	10%; 5%	

Calibration requirements - II.

Summary from the SCT “Calibration Control Table”: `http://www.astro.isas.jaxa.jp/next/astroh-sct/wiki/index.php?cal_control_table`

	SXS(+SXT)	SXI(+SXT)	HXI(+HXT)	SGD
Relative effective area: Fine structure	<2% around O, Si and Fe edges; goal <1%	15% around Si edge	N/A	N/A
Contamination	10%; 5% goal	10%; 5% goal	N/A	N/A
Pixel-pixel uniformity	QE 5%; gain 0.3 eV	3%	5%; 1% goal	N/A
Stray light	10% @ 4xFOV	10% @ 4xFOV	10% @ 4xFOV	N/A
Background reproducibility (flux)	10%	5%	5%; 3% goal	5% goal
Background reproducibility (image)	N/A	N/A	10%; 5% goal	N/A
Polarization (MDP)	N/A	N/A	N/A	10%
Dead time estimation	10%; 5% goal	TBD	10%; 5% goal	10%; 5% goal
Timing (absolute)	10 ms; 80 µs goal (design) 200 µs 30µs goal (science)	61.0352µs= 2^{-14} s goal (design) 200 µs 30µs goal (science)	60 µs goal (design) 200 µs 30µs goal (science)	60 µs goal (design) 200 µs 30µs goal (science)
Timing resolution (relative)	5 µs	61.0352 µs[1]	25.6 µs	25.6 µs
Instrument specific	Filters: BB effective area with filters 10%; 5% goal	Effective area, spectral performance of all modes	Cross instrument effective area 5%	Cross instrument effective area 10%

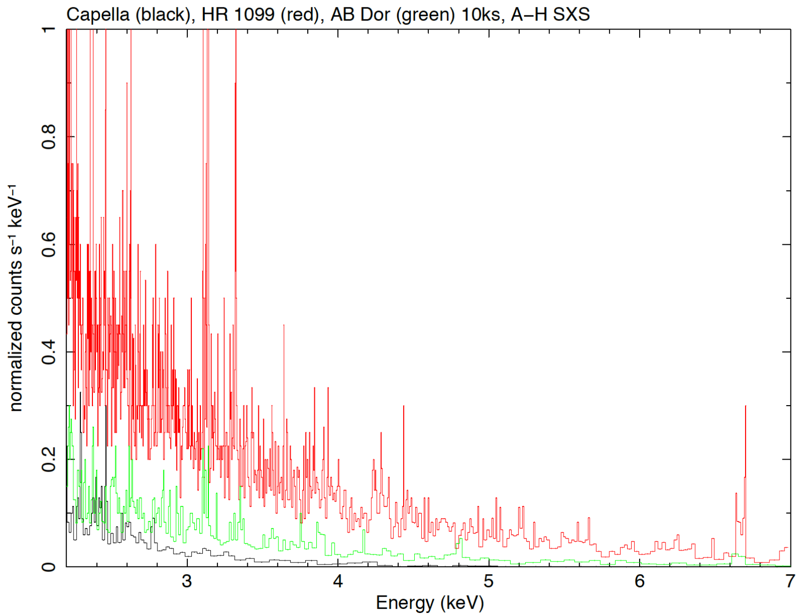
Sources for effective area and timing

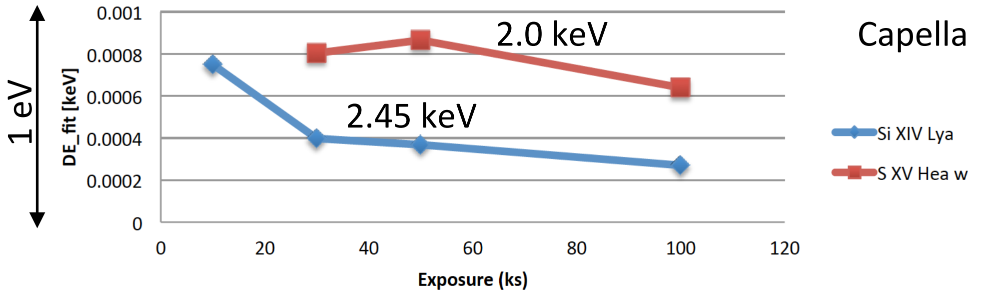
(Sources listed in priority order. In brackets the exposure time in ks)

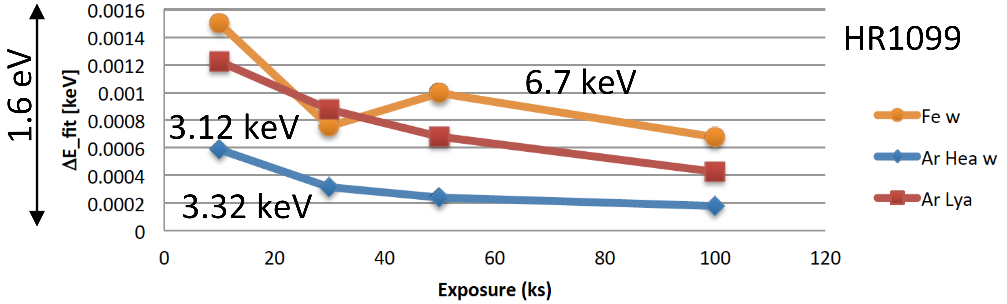
	SXS GVC	SXS GVO	SXI	HXI	SGD
Effective area on-axis	3C 273 (75) Centaurus A (75) PSR1509-58 (75)	3C 273 (75) Centaurus A (75) PKS2155-304 (75) PSR1509-58 (75)	3C 273 (75) 1ES0033+595 (75)	3C 273 (75) Centaurus A (75) PKS2155-304 (75) PSR1509-58 (75)	Crab (10) Cyg X-1 (40) Centaurus A (40)
Effective area off-axis	NA	NA	Abell1795 (180) Abell3571 (180)	G21.5-0.9 (240) Crab (60)	NA
Effective area (fine structure)	3C 273 (75), 4U0614+091 (30)	3C 273 (75), 4U0614+091 (30)	NA	NA	NA
Contamination (on-axis)	NA	1E0102-72 (60) RXJ1856-3754(120)	1E0102-72 (60) RXJ1856-3754(60)	NA	NA
Contamination (off-axis)	NA	NA	Vela SNR (60) Cygnus Loop (80)	NA	NA
Timing	B1509-58 (40)	B1509-58(40)	HMXRB and/or MCVs from PV (**40**)	B1509-58 (40) Crab (40)	Crab (40)

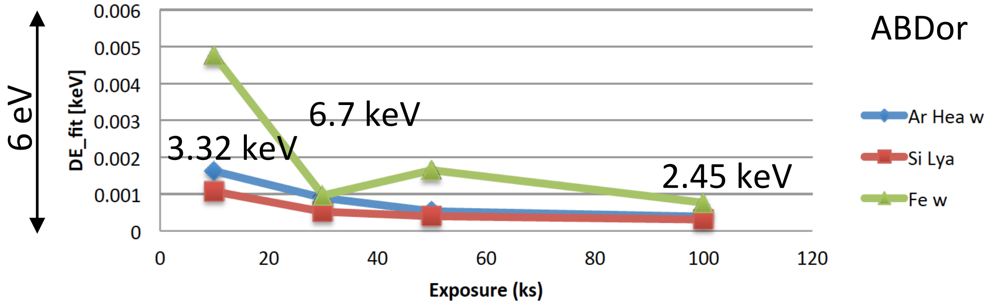
Similar charts for Energy scale, LSF/RMF, instrument specific needs

IFCP simulations example - SXS energy scale









- Requirement: 1 eV (goal: 0.2 eV)
- **30 ks** on **Capella** (no GVC)
- **50 ks** on **HR1099** (GVC)
- *Similar exposure times* for *ABDor* or *Sigma Gem*
- Satisfy resolution requirements as well
- Variable sources! Stay on the safe T_{exp} side

Limitations imposed by truncated mission

- SXS never achieved equilibrium, other instruments were in the early commissioning stages
  - The gate valve was closed
  - Unable to make full use of SXS calibration sources
  - calibration pixel available
  - limited illumination by Fe^{55} through gate valve
  - MXS unavailable
- No official SXS calibration targets were viewed
  - Calibration was to commence after gate valve opening
- Limited calibration of other instruments

Nevertheless, the Hitomi calibration accuracy largely met and, in some area, exceeded the requirements

Lessons learned - planning

- Have a well defined and reviewed plan; buy in from all instruments and mission leadership
  - Plan should take into account limitations of ground calibration program
  - Use simulations to determine observing times and strategies
  - Take advantage of prior experience (i.e., IACHEC)
- Make sure the entire team agrees on the goals of the calibration activity. Hitomi team members had two somewhat conflicting viewpoints:
  - "goal oriented" calibration – determining the right numbers to put into the caldb
  - "physics oriented" calibration – obtaining a quantitative understanding of how the instruments perform
- For multi-instrument missions cross calibration can be a challenge: mutually exclusive requirements like SXI count rate limit; broad wave band coverage
- Build flexibility into the plan – "A list" sources might not be visible when needed
- No calibration plan can address all contingencies
  - Ideally, your mission lasts long enough so that the calibration plan can be executed

Lessons learned - organization

- Have clear, proactive leadership of the calibration effort. Role is to make sure all calibration issues are addressed, that cross instrument coordination occurs (mirror – detector and across systems). Make sure the leader is someone people will listen to.
  - We had this prior to launch during the development of the in-flight plan, but in-flight organization was not fully developed when the mission ended.
- Assign teams to cross instrument and instrument/spacecraft issues (alignment and timing).
- Like it or not, the heavy lifting has to be done by IT scientists who know best how the instrument works. Need to keep them communicating with the rest of the team.
- "Calibration scientists" need to be embedded with instrument teams well in advance of launch; can't expect neophytes to be useful to address subtleties
  - A number of non-IT scientists had been assigned to assist the instrument teams with calibration tasks. These assignments were made just prior to launch, and the scientists were exposed to the software tools just prior to launch. They therefore were not ready to assist, especially when the mission did not proceed nominally.

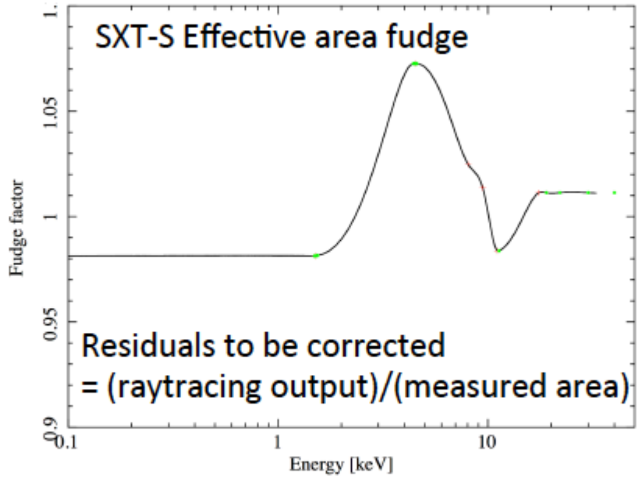
Lessons learned from in-flight calibration - 1

- Having an extensive ground calibration campaign is essential
  - Allowed better understanding of the SXS performance
  - Additional mirror calibration might have been useful to resolve residual issues
- Don't rely on instrument models that can't be confirmed via flight data, or expect "fudge" to happen
- Doesn't matter how much you calibrate – you're going to need more – either instruments work differently from what is expected, or they show unanticipated capability
  - SXS gate valve was never opened
  - SXS hard X-ray response
  - SXI cosmic ray echoes and light leak

“Fudge” happens

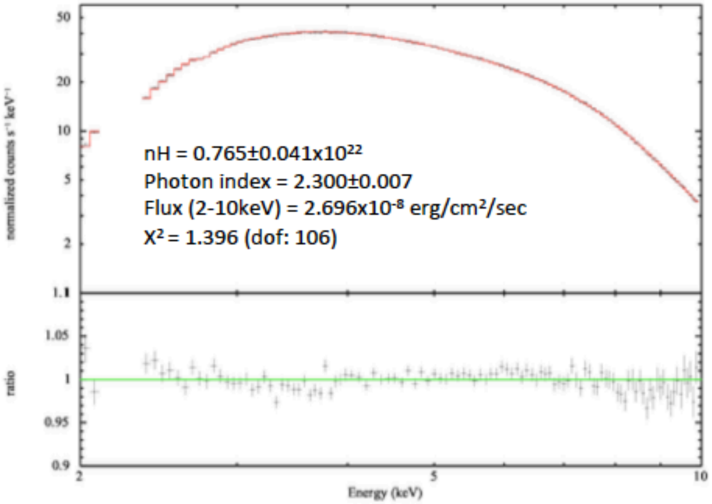
Effective area uncertainties (fudge factor)

The fudge factor is applied to reduce residuals between raytracing output and measured data

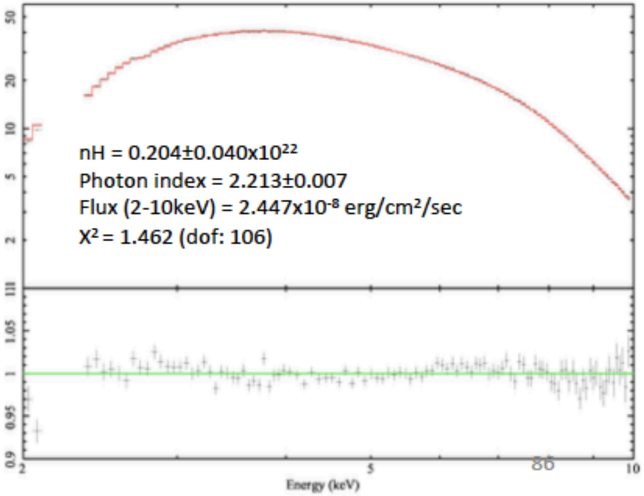

SXT-S Effective area fudge

Residuals to be corrected
= (raytracing output)/(measured area)

Crab spectrum WITHOUT fudge factor


nH = 0.765±0.041x10²²
Photon index = 2.300±0.007
Flux (2-10keV) = 2.696x10⁻⁸ erg/cm²/sec
X² = 1.396 (dof: 106)

Crab spectrum WITH fudge factor

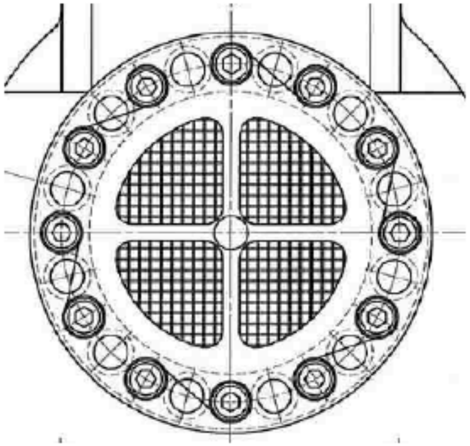

nH = 0.204±0.040x10²²
Photon index = 2.213±0.007
Flux (2-10keV) = 2.447x10⁻⁸ erg/cm²/sec
X² = 1.462 (dof: 106)

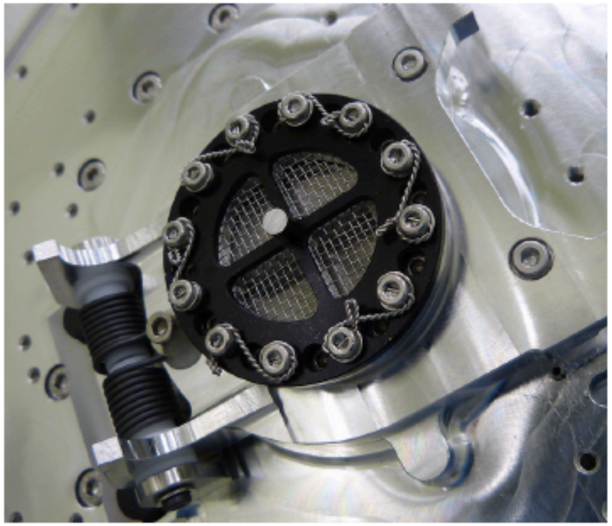
“Fudge” is an unfortunate choice of terminology – “correction factor” would be better

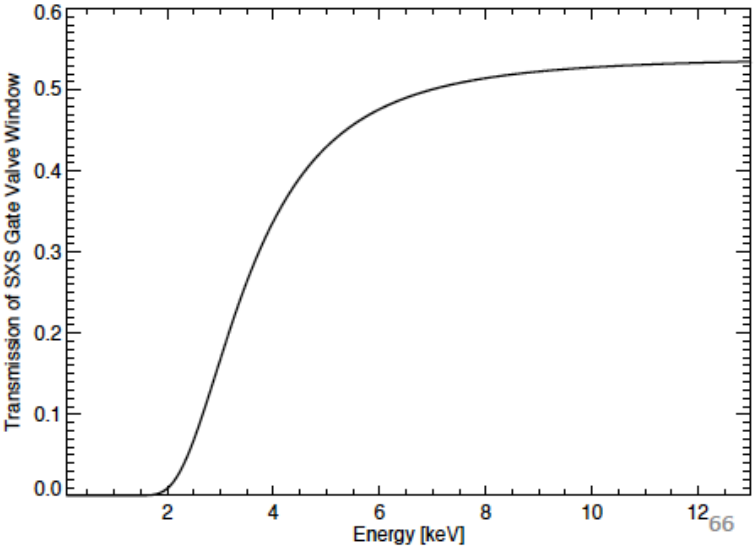
The SXS gate valve

Be window: ~282 µm thick
Window support structure:
0.2 mm-thick stainless mesh (71% open)
2 mm-wide, 6 mm-thick Al cross

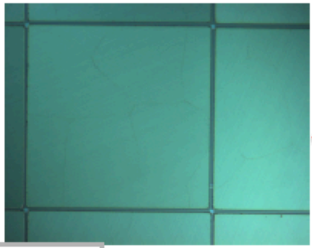
Intended for ground tests and commissioning phase only; X-ray transmission not calibrated; transmission estimates based on Be thickness, mesh geometry, and raytrace calculations of support cross.





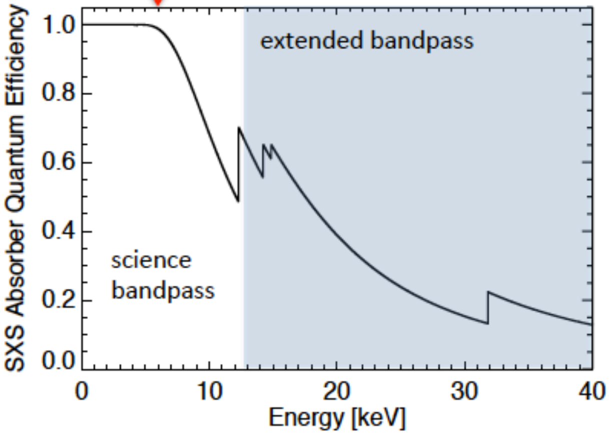


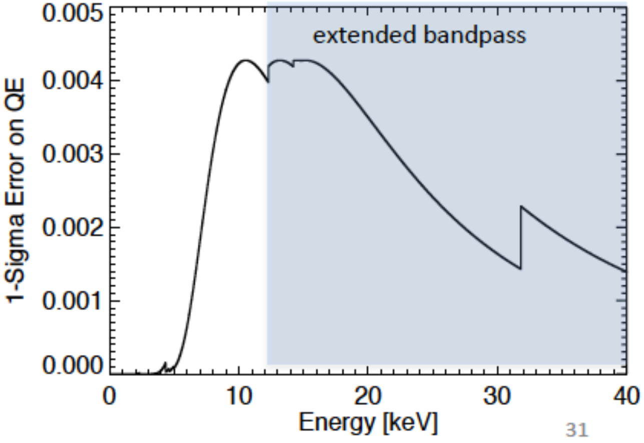
SXS extended response



Fill fraction = 97%
measured absorber size, compared to pixel pitch

Absorber x-ray stopping power: measured HgTe absorber weight and area. **Areal density = 85.7 ± 1 μg/mm^2.**
Implies thickness of d~10.5 ± 0.1 μm.
Assume nominal stoichiometry column number density of HgTe.



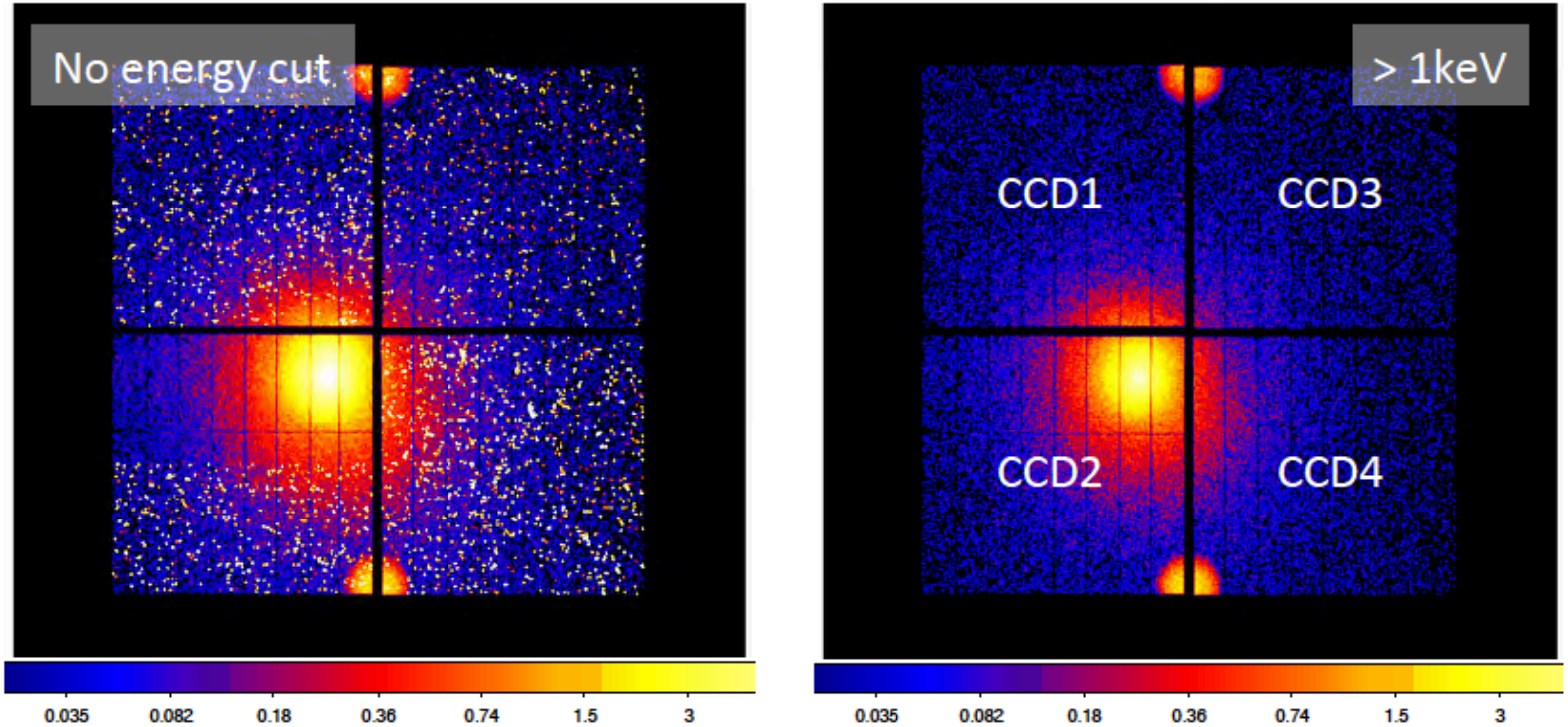


Extended bandpass was critical for distinguishing NGC 1275 from cluster; but little effort was spent calibrating the band (outside the mission requirements)

Lessons learned from in-flight calibration - 2

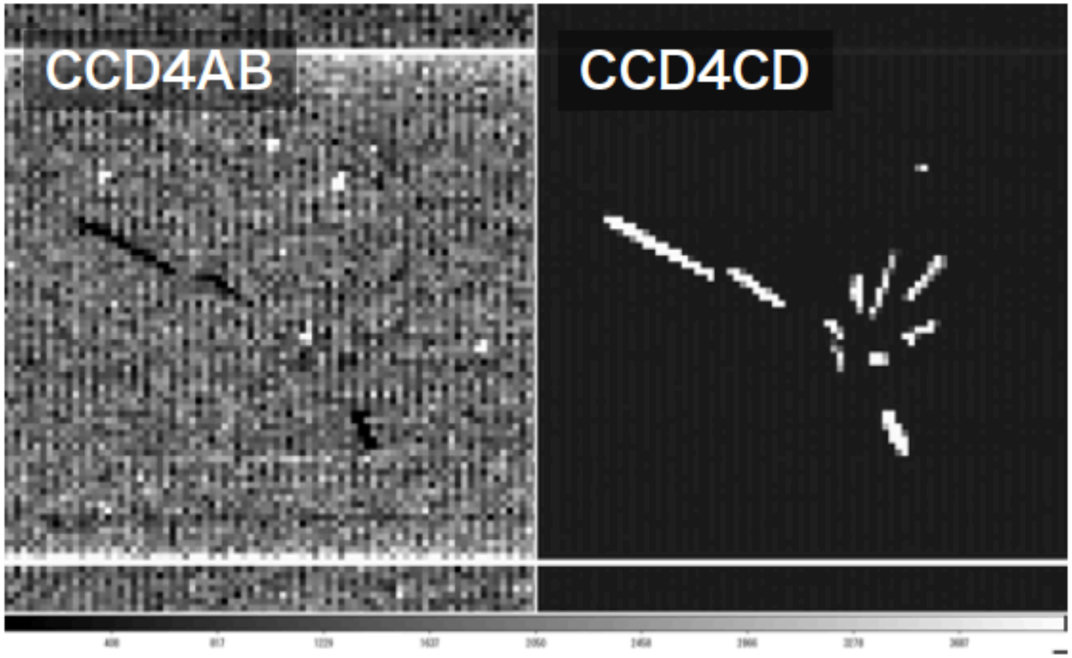
- Instruments with new capabilities will reveal previously unknown aspects of even the best-characterized cosmic calibration sources (e.g., the IACHEC list). Separating out these new aspects complicates in-flight calibration (but leads to scientific results).
  - In the absence of true X-ray "standard candles," what else can we use?
  - This issue could be mitigated by a comprehensive ground campaign. But such a campaign is expensive, and still would not address instrument features that only show up in orbit
- Document at all stages of calibration. Hard/impossible to reconstruct what calibrations were (and weren't) performed after the fact.
- Especially in the initial calibration phase, close cooperation between not only hardware teams (detector and mirror people) but also hardware and software teams was essential to reflect the latest calibration and distribute the results to users. Thus, meetings with both team members worked well in terms of real-time information sharing.

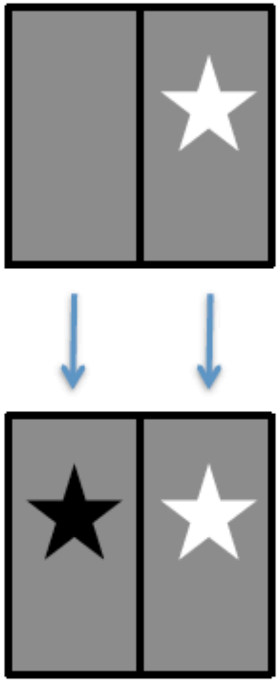
Image of Perseus Obs.



- Apparently “false” events seen all over the region except for CCD2CD (on-axis segment)
- “false” events dominate the spectrum below 1keV

Negative pulse height due to cross talk




actually happened

cross talk during readout

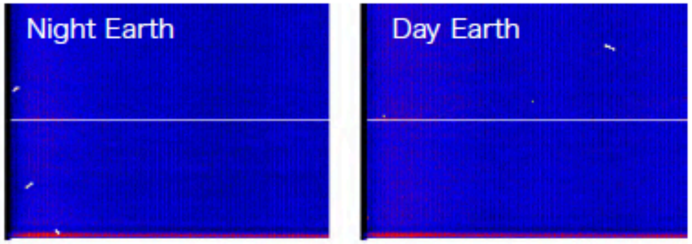
recorded

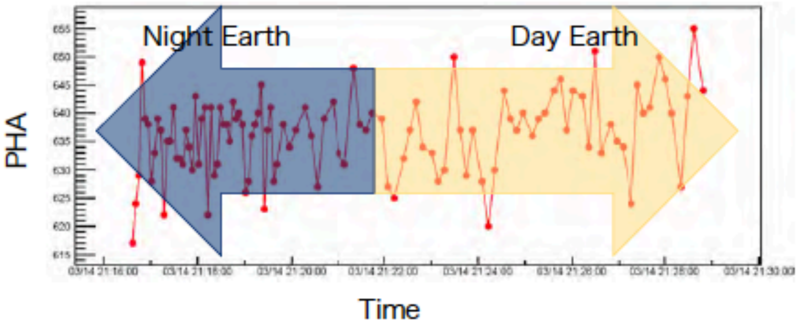
- 2 readout for 1 CCD
- Negative pulse height pixels are seen in the same position but in the neighboring segment of very high pulse height pixels (e.g., Cosmic-rays) due to cross talk

Instrument specific lessons learned (a sampling)

- Timing calibration was well planned, and well executed (Terada talk)
  - Synchronization using SpaceWire worked well
  - Helpful to have ground measurements of timing precision of components plus end-to-end measurements
  - Same software was used on board and on ground
  - Simultaneous X-ray and radio observation of Crab allowed verification
- SXI light leak resulting from internal reflections of bright earth through spacecraft holes for HXI light path
- SXI cosmic ray echos
- Despite unexpected contributions, it was still possible to calibrate the HXI background
  - Low efficiency below 10 keV in Si strip detectors SiO_2 layer on surface of the Si detector distorts electric field in the detector, and also acts as a passive absorber. Both of these suppress the detection efficiency in lower energies (~50%@5 keV).
  - Activation background was higher than the pre-launch estimation.

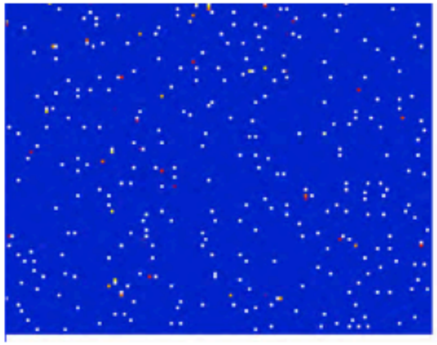
Optical Blocking and Light Leak

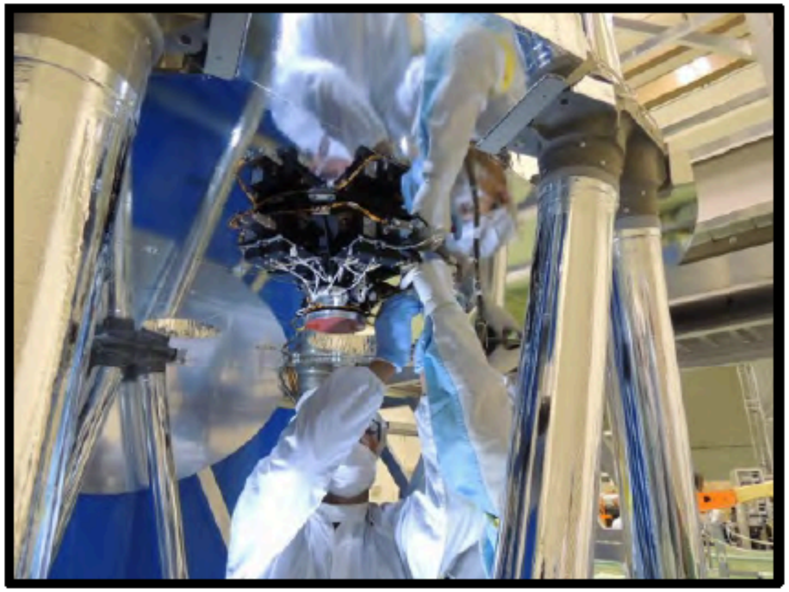




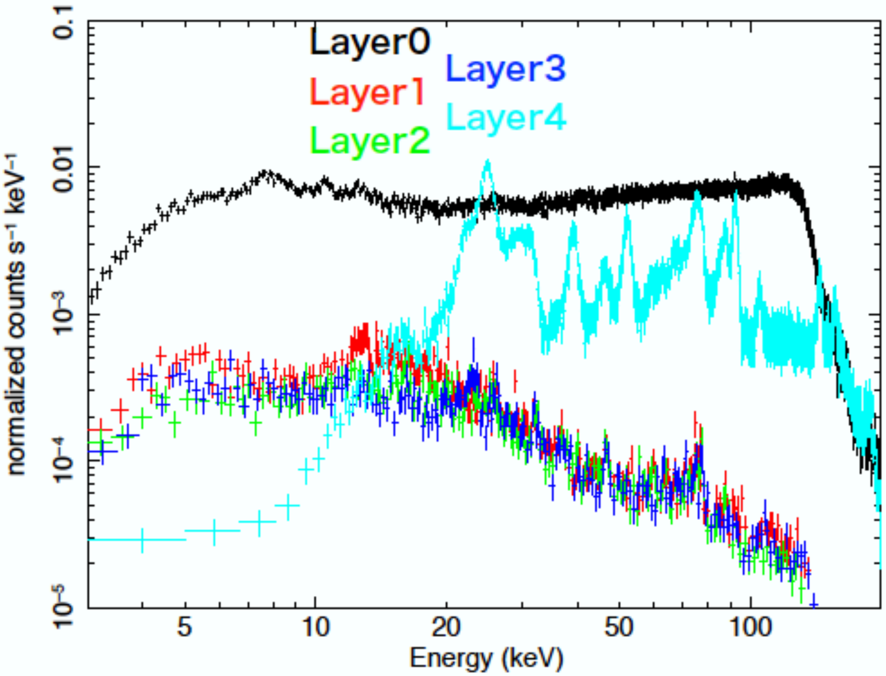
- Two expected light paths:
  - mirror (through thermal shield) to CCD
  - vent pipe (reflections several times) to CCD
- These optical lights are well blocked by CBF and black nickel plating inside the vent pipe.

- In a certain period (not night and day earth), we found light leak events which are possibly due to reflected optical lights from the bottom of the lower plate.



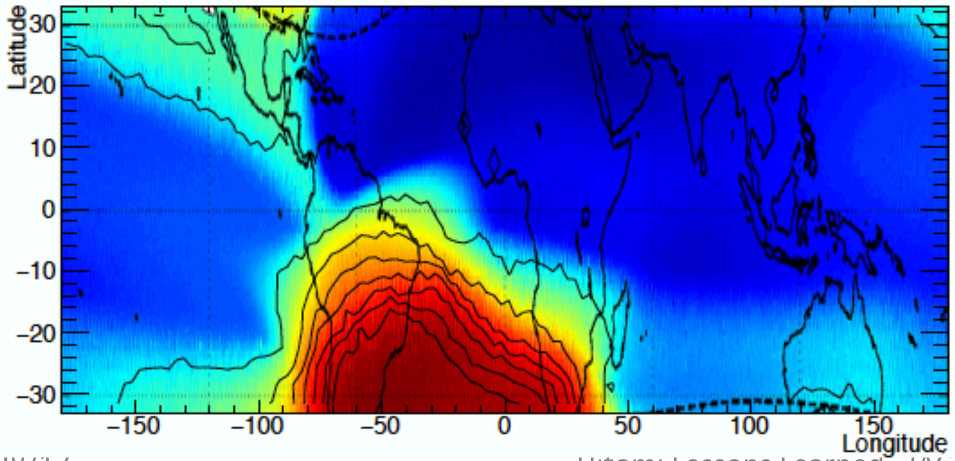


Electron background in Si top layer



- Background in Si top layer (black) is unexpectedly high
  - High energy but low penetrating power
  - The background distribution is consistent with the electron distribution (>93 keV) observed by DEMETER/IDP in orbit

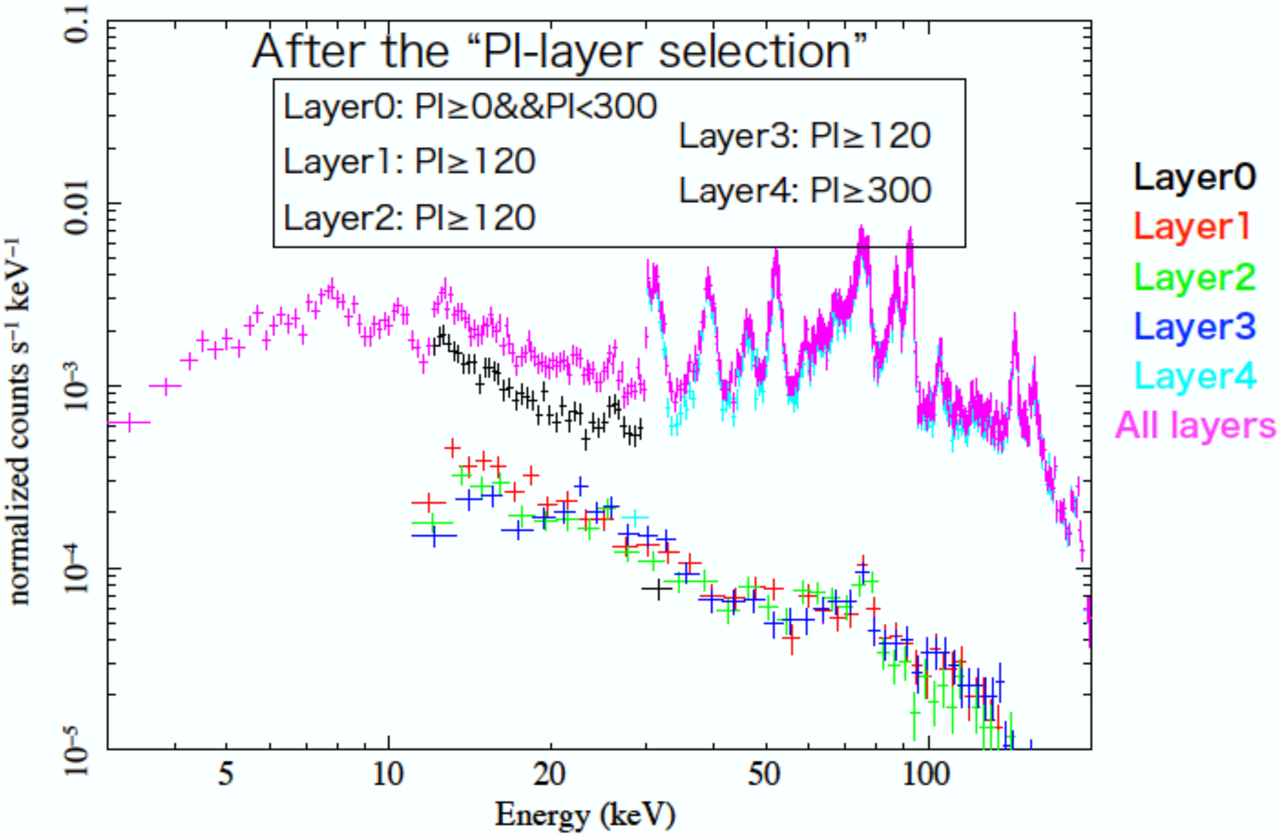
➡ **This originates from low energy albedo electrons**



color map: Observed by DEMETER (Whittaker et al. 2013)
contour: Distribution of HXI Si top layer background

Background after satellite position selection

- By the satellite position selection (defined as “SAA2_HXI” column in EHK), the background of Si top layer is reduced to 10% of the background with no selection.



- These screening criteria were applied from 2nd processing

Final thoughts

- Calibration must be an integrated effort of IT, operations team, software team from the start; coordination must continue into the mission
- For missions like Hitomi, must take global view of calibration – calibration of instruments must fold into the calibration of an observatory
- Can't have enough ground calibration, but can't expect to be able to cover all non-standard configurations
- Have well considered plan that includes contingencies
  - Make use of collective wisdom of team and community
- Expect surprises
  - Celestial calibration sources will provide surprises ("too much science" in Perseus first light observation)
  - Instrument will not behave as on ground
  - Instrument could out-perform requirements
- We will be ready for the X-ray Astronomy Recovery Mission!