ATHENA

Using Lessons Learned from *Hitomi* to Develop the *Athena* In-Flight Calibration Plan

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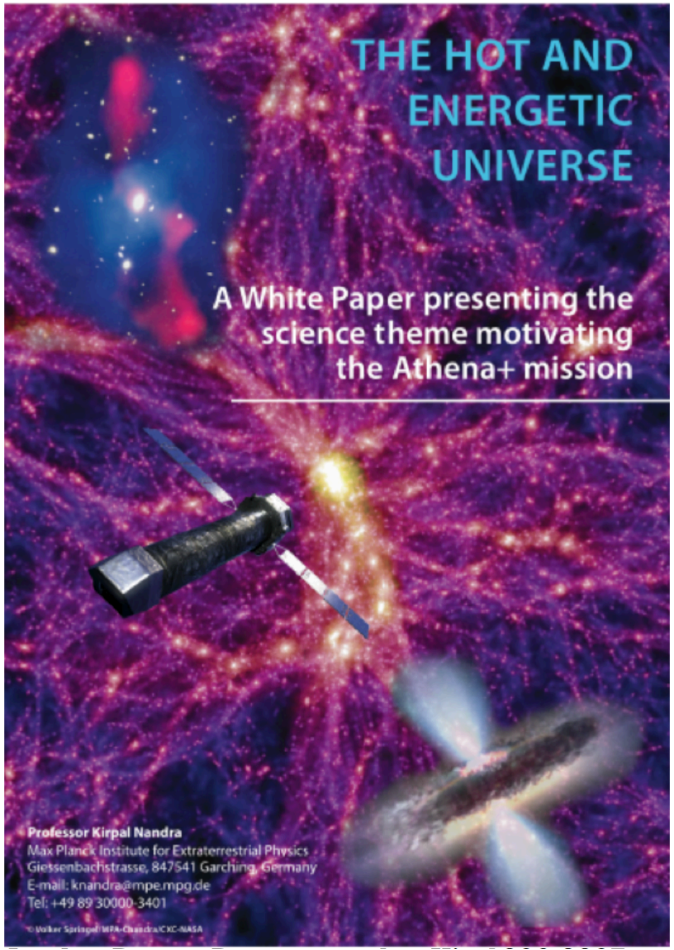
On behalf of the *Athena* Calibration Group

The Hot and Energetic Universe

- **The Hot Universe:** How does the ordinary matter assemble into the large-scale structures we see today?
  - 50% of the baryons today are in a hot ($>10^6$ K) phase.
  - There are as many hot baryons in clusters as in stars over the entire Universe.

- **The Energetic Universe:** How do black holes grow and influence the ISM, IGM and ICM around them?
  - Building a SMBH releases ~30x the binding energy of its host galaxy.
  - 15% of the energy output in the Universe is in X-rays.

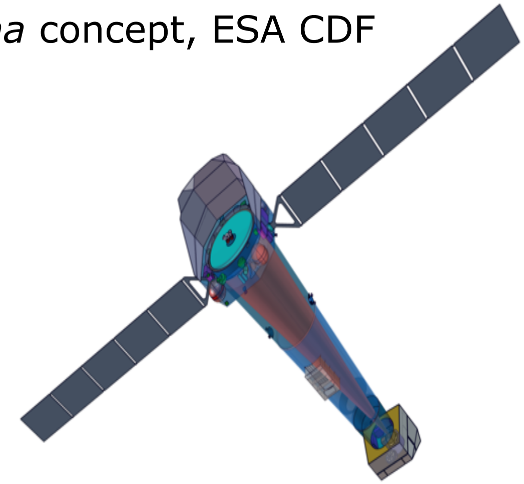


Nandra+ (2013)

Athena Mission Profile

- Single telescope, Silicon Pore Optics (SPO) technology, 12m focal length, ~1.4m^2 area @1 keV.
- **WFI** (Active Pixel Sensor Si detector): wide-field (40'x40') spectral-imaging, CCD-like energy resolution (~150 eV @6 keV).
- **X-IFU** (micro-calorimeter): 2.5 eV energy resolution, 5' diameter field-of-view, ~5" pixel size.
- Movable mirror assembly to switch between instruments in the focal plane.
- Defocusing capability increases count rate dynamical range.

Athena concept, ESA CDF



- Metrology system to achieve a reconstructed astrometric error ≤1" (3σ).
- **Launch 2028+**, Ariane 6.4, L2 halo orbit (TBC).
- Nominal lifetime 4 years + extensions.

Calibration Strategy: Playing the "Long Game"

- Observatory won't launch for at least a decade, so plenty of time to formulate the best possible in-flight calibration plan.

- Objectives are twofold:

  1. To allow science needs to set calibration requirements;

  2. To create the most efficient, effective in-flight calibration plan to address our derived calibration requirements.

- Strategic thinking required to accomplish these objectives:

  - Need to know mission requirements (flowdown from science requirements), e.g., A_{eff}.
  - Need to know accuracy with which these must be known in-flight in order to generate reliable scientific results.
  - Need to identify astrophysical sources to use in determining these on-orbit.
  - Need to estimate the uncertainties/precisions involved in making these measurements and the exposure times needed to get within these uncertainties.

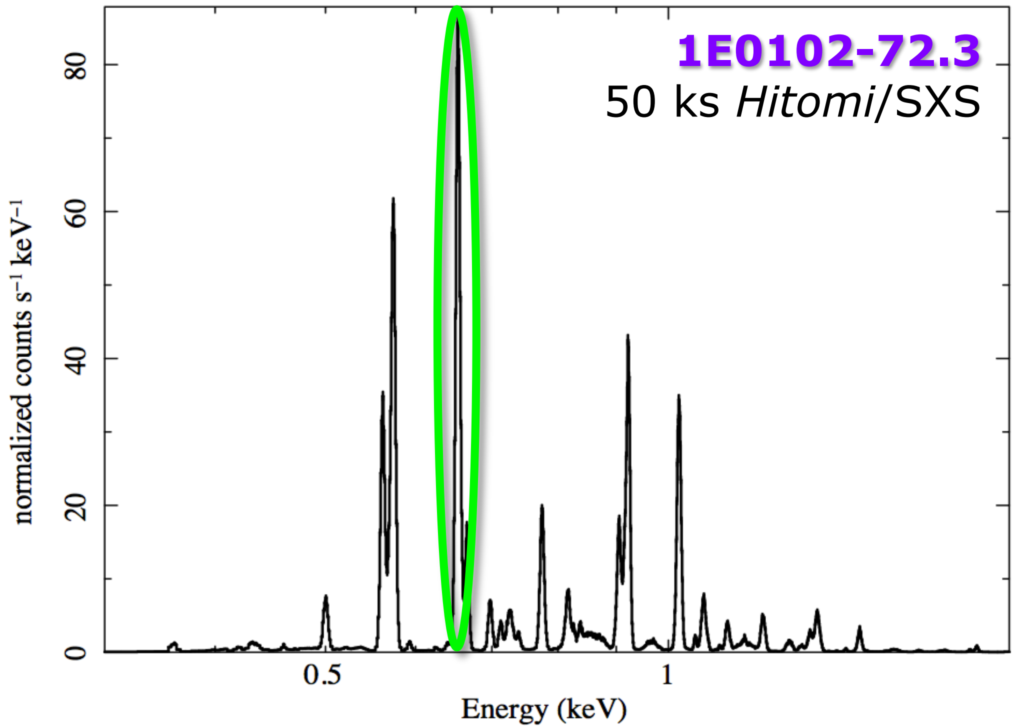
Planning for *Hitomi* In-Flight Calibration

- Although extensive work was done prior to launch on defining the in-flight calibration targets, their necessary exposure times and observing strategy, the resulting plan could have been developed more thoughtfully and effectively with additional time.

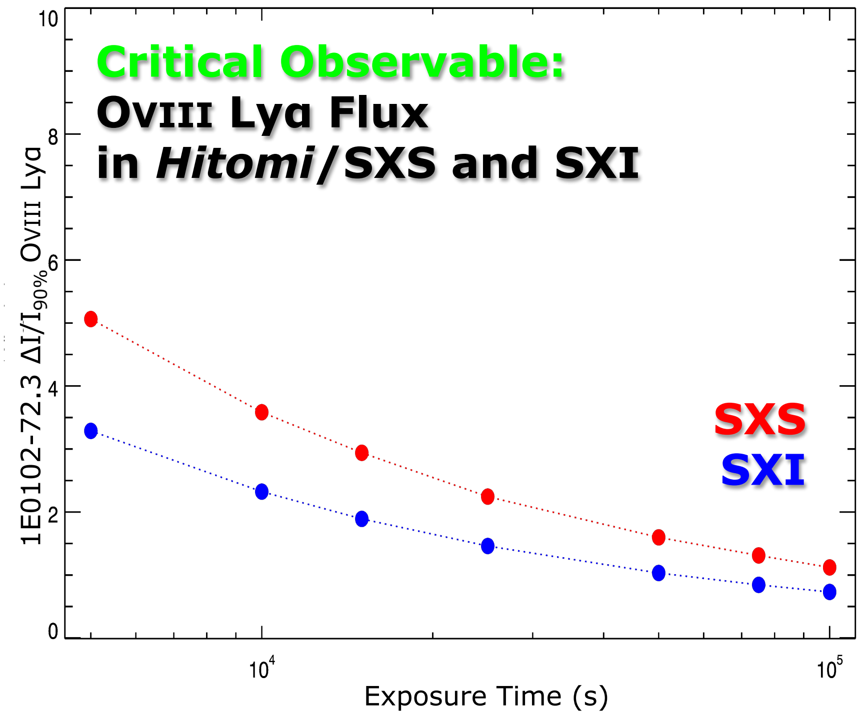
- The method for formulating this plan was as follows:

  1. Identify a target for each calibration activity (multiple preferred to ensure source visibility).
  2. Use "standard candles" whenever possible (IACHEC database).
  3. Try to find sources that satisfy multiple calibration goals.
  4. Using spectral analysis software (e.g., XSPEC) or a simulator (e.g., SIXTE, SIMX), input a model of the reference source taken from the literature.
  5. Create simulated spectra using the input model and nominal instrument response and background files.
  6. Fit the input model to the simulated data, generating 90% uncertainties on the parameter(s) that address the calibration requirement in question. Repeat 10 times and take the average of the distribution to get the most reliable result.
  7. Repeat the exercise for a variety of exposure times.

Example: Monitoring Contamination Buildup

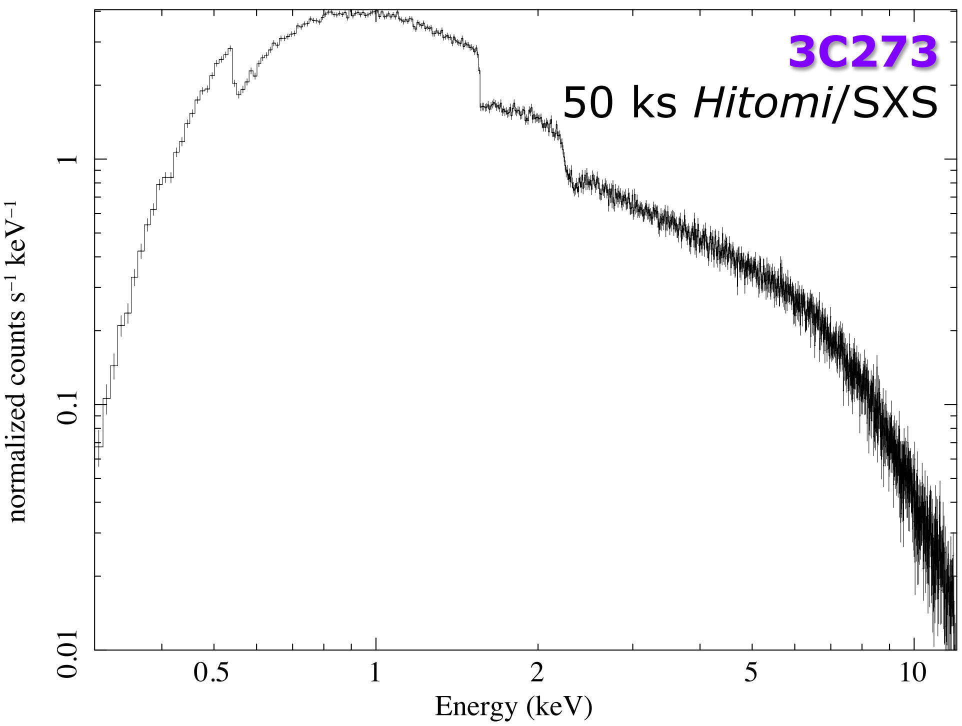


Extended Source: 40″ diameter
Plucinsky et al. (2014) model

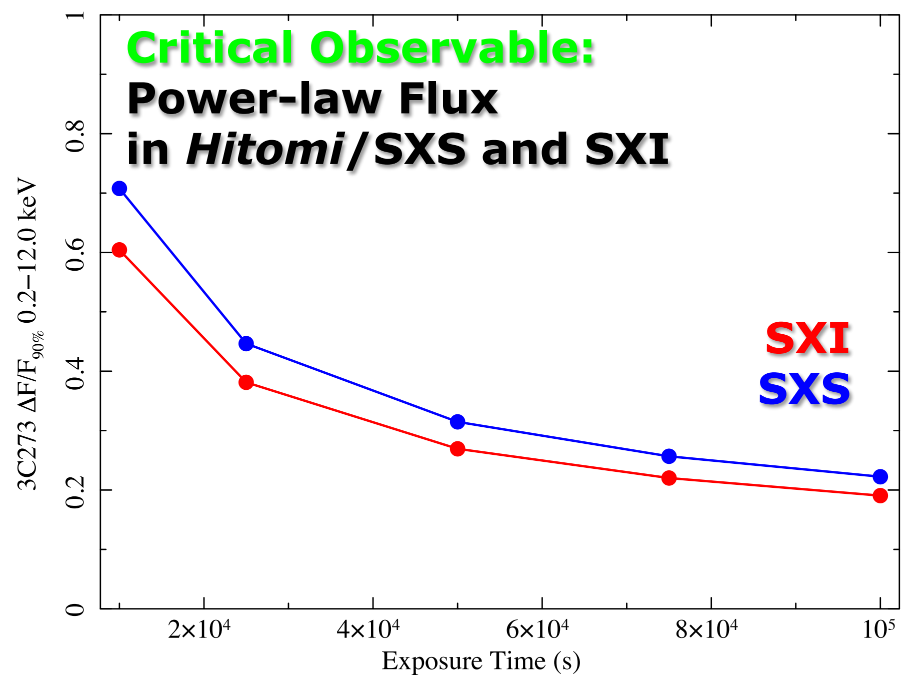


Supernova remnants have a wealth of emission lines whose fluxes can be used to trace the buildup of contamination on the detector over time. The model for 1E0102-72.3 (above) was used to create *Hitomi*/SXS and SXI simulations for a variety of exposure times (right) in order to assess the minimum exposure required to reach the calibration goal.

Example: Calibrating Effective Area



Compact Point Source
Yaqoob et al. (1994) model



Mildly absorbed AGN have spectra closely resembling a power-law over the SXS and SXI bands, so they make for simple effective area calibrators. The model for 3C273 (above) was used to create *Hitomi*/SXS and SXI simulations for a variety of exposure times (right) in order to assess the minimum exposure required to reach the calibration goal.

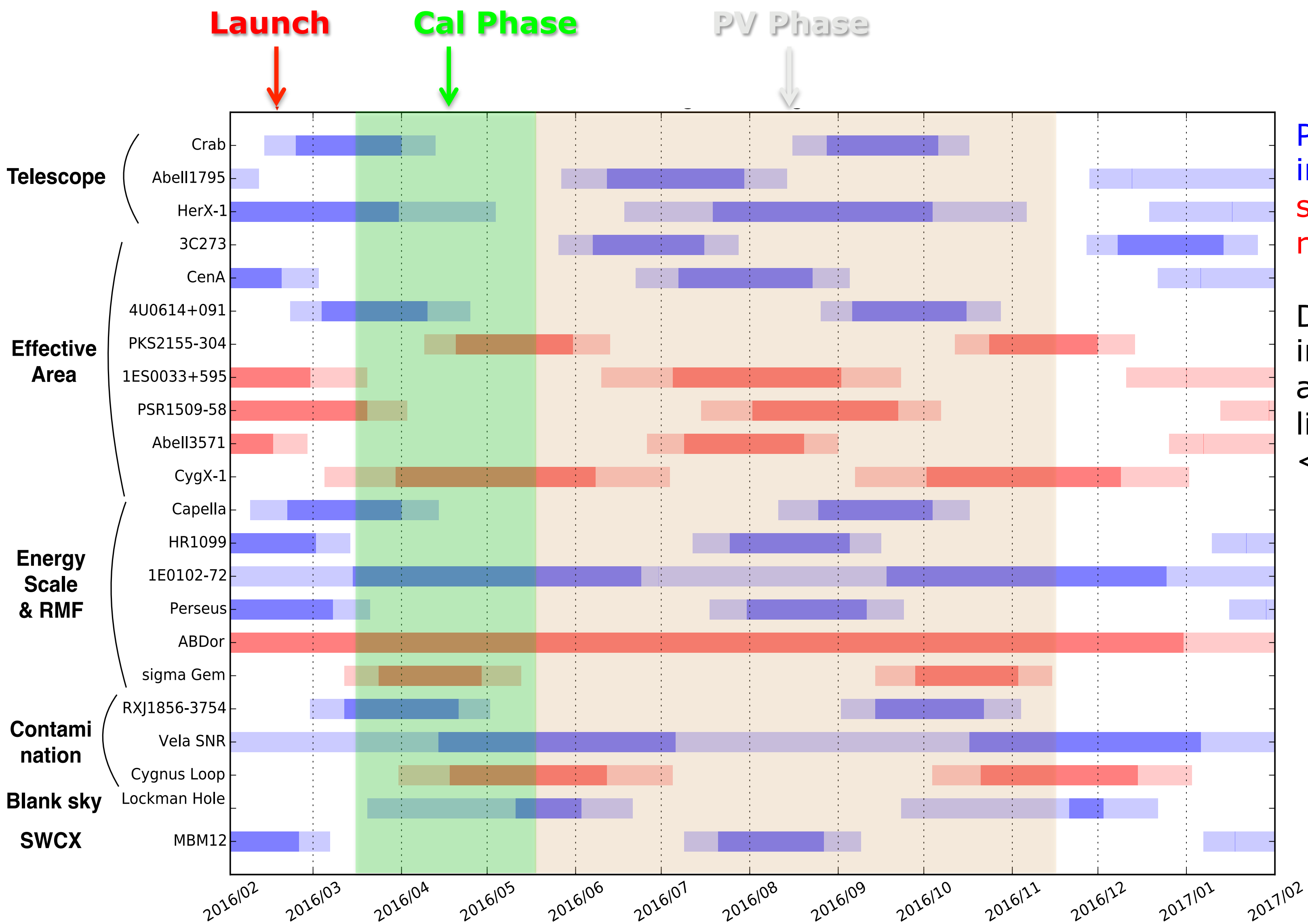
Hitomi In-Flight Calibration Targets

Parameter	SXS (GVC)	SXS+SXT-S (GVO)	SXI+SXT-I
Energy scale (on-axis)	HR1099(50) ABDor(50) CP, FW, MXS	Capella(30) HR1099(50) ABDor(50) σGem(50) CP, FW, MXS	Perseus (140) 1E0102-72 (15)
Gain (short-term stability)	CP, MXS	CP	CP
LSF	FW(10), MXS(1) HR1099(50) ABDor(50)	FW(10), MXS(1) Capella (30) HR1099 (50)	*See Energy scale (on-axis)*
Effective area (on-axis)	3C273(25) CenA(25)	3C273 (75) CenA (75) PKS2155-304 (75) PSR1509-58 (75)	3C273 (*see SXS*) 1ES0033+595 (75)
Effective area (off-axis)	NA	NA	Abell478 (100) Abell1795/2029 (100)
Effective area (fine structure)	NA	3C273 (75), 4U0614+091 (75)	NA
Timing	PSRB1509-58 (TBD) PSRB1821-24 (TBD)	PSRB1509-58 (TBD) PSRB1821-24 (TBD)	PSRB1509-58 (TBD) PSRB1821-24 (TBD)
Stray light	NA	Crab (90)	Crab (90)
Background	NA	North Polar Spur (100)	TBD

Primary targets in blue, secondaries in red.

Exposure times in parentheses are in ks.

Hitomi Calibration Target Visibility



Primary targets in blue, secondaries in red.

Dark shading indicates sun angles <20°, light indicates <30°.

Takeaways from *Hitomi* Work

The good:

- An efficient plan was developed with well-justified exposure times.
- Primary and secondary targets were vetted through thorough simulation work.
- Visibility was taken into consideration when prioritizing targets and constructing observing strategy.

The bad:

- Calibration requirements were handed down by the Instrument Teams and the Software and Calibration Team without strong justification, rather than being empirically validated.
- Method only assessed statistical uncertainties, **NOT** systematics.
- Efficacy of this method was never tested due to the untimely loss of the mission.

Planning for *Athena*: a Better Approach

The ideal approach is to start with the *science objectives and requirements* ➔ *mission requirements* ➔ *calibration requirements* that are needed in order to achieve the science objectives, taking telescope and instrument performance uncertainties into consideration.

The method for formulating the in-flight calibration plan is therefore composed of three parts:

- **Determine the degree of calibration accuracy required on mission parameters of interest (e.g., A_{eff}) in order to achieve science objectives.**
- **Identify candidate astrophysical targets that can be used to perform calibration observations on-orbit.**
- **Using the accuracy derived in #1 above as a threshold, derive the needed exposure time on a given candidate calibration target through iterative simulations and analysis.**

Planning for *Athena*: a New Approach

esa

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From *Hitomi*

- **Using the accuracy derived in #1 above as a threshold, derive the needed exposure time on a given candidate calibration target through iterative simulations and analysis.**

Nominal *Athena* Calibration Needs

Parameter	Requirements	Calibration Accuracy
Knowledge of gain	0.3-7 keV 0.2-10 keV	0.4 eV (X-IFU) <10 eV (WFI)
Knowledge of pixel-to-pixel gain uniformity	0.3-7 keV	<0.5 eV (X-IFU)
LSF	2.5 eV @ 6 keV (X-IFU) <150 eV@ 6 keV (WFI)	0.15 eV (X-IFU) <10 eV (WFI)
Relative effective area (on-axis)	1.4 m^2 @ 1 keV, 0.25 m^2 @ 6 keV	5% (X-IFU) 3% (WFI)
Relative effective area (off-axis)	1.4 m^2 @ 1 keV, 0.25 m^2 @ 6 keV	5% (WFI)
Relative effective area (fine structure)	1.4 m^2 @ 1 keV, 0.25 m^2 @ 6 keV	1%+TBD (X-IFU)
Stray Light	<2 x 10^{-3} cts/s/cm^2/keV	5%
Background (non-focused, charged particle)	<2 x 10^{-3} cts/s/cm^2/keV	2%
Contamination	10%	2%
Relative Timing Resolution	10 µs (X-IFU) 5000/80 µs (WFI)	1% (X-IFU; deadtime) TBD (WFI)

Validating the Calibration Requirements

We plan to validate the *Athena* calibration requirements by comparing them against the science requirements of the mission, which have been derived from the science objectives through simulation work by the topical panels. We will undertake this process with a two-tier approach:

Tier 1: **Assessing statistical uncertainties**

1. Using the Mock Observing Plan, identify an astrophysical source, spectral model and exposure time used to derive a given L1 science requirement (e.g., determine black hole spin of MCG—6-30-15 to $\Delta a \leq 10\%$).
2. Generate an array of 1000 response matrices by perturbing the original matrix (obtained from ray-tracing) with a Gaussian function having μ_{cal} = nominal value of parameter (e.g., A_{eff}), σ_{cal} = nominal calibration uncertainty.
3. Simulate a spectrum for the input model with each response, then fit that spectrum with the input model and measure the uncertainty on the spin to 90% confidence.
4. Calculate the standard deviation (σ_a) of the distribution of the spins measured in the previous step and compare with the L1 requirement (Δ_{max}).
5. Iterate with different values of σ_{cal}, if needed, until $\sigma_a \leq \Delta_{max}$.

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Tier 2: **Assessing systematic uncertainties**

1. For a pre-defined set of input parameters (P_i) describing the telescope A_{eff}, establish the predicted distribution of systematic uncertainties of the P_i, e.g., the distribution of expected accuracy in the alignment of the mirror modules or of the accuracy in the calibration of the reflectivity.
2. Generate 1000 Monte Carlo realizations of the response, $R_{P,j}$, based on the P_i set, assuming the statistical distribution defined in the previous step.
3. Simulate a spectrum for the input model with each response, then fit that spectrum with the input model and measure the uncertainty on the black hole spin to 90% confidence.
4. Calculate the standard deviation σ_a of the distribution of the spins calculated in the previous step and compare it with the L1 requirement (Δ_{max}).
5. Iterate with different P_i distributions, if needed, until $\sigma_a \leq \Delta_{max}$.

Moving Forward: Making Use of Lessons Learned from *Hitomi*

- Once the calibration requirements have been validated, we can use our efforts from *Hitomi* to generate an in-flight calibration plan for use during commissioning and for the baseline mission.

- The goal of in-flight calibration efforts prior to launch should be to create a well-informed, efficient plan that includes contingencies and redundancies in target selection.

- Establish priority scheme to ensure that the most critical observations are done first.

- Close collaboration between hardware and software teams involved in the calibration effort is also critical.

- Surprises will happen, so flexibility is necessary during in-flight calibration efforts with regard to data analysis and scheduling!

Conclusions

1. Calibration requirements should be derived empirically from the science and mission requirements, addressing both statistical and systematic uncertainties.

2. We plan to address statistical uncertainties by performing simulations with an array of response functions derived from the nominal mission response by perturbing it with, e.g., a Gaussian function.

3. We plan to address systematic uncertainties by performing simulations with an array of Monte Carlo realizations of the nominal mission effective area, varying physical system parameters such as mirror reflectivity.

4. This method can be applied to *XARM* in-flight calibration as well: very similar instrument characteristics to both *Athena* and *Hitomi*.