Using Lessons Learned from *Hitomi* to Inform the *ATHENA* In-Flight Calibration Plan

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Introduction: The *Hitomi* mission flew a unique set of four very different instruments, including a micro-calorimeter and soft X-ray imager, a hard X-ray imager and a soft Gamma-ray detector. As such, the in-flight calibration plan had to be carefully thought out, taking into account not just the needs of each instrument on its own, but also how best to cross-calibrate them with each other and with instruments on existing X-ray missions. Proposed astrophysical targets were selected largely based on IACHEC research. They were then vetted through a systematic, iterative analysis of simulated spectra using fiducial responses provided by the instrument teams and spectral models culled from the IACHEC and the literature. This process yielded valuable insights on the expected calibration tolerances of each instrument and the mission as a whole. Though the *Hitomi* mission was unfortunately brief, we can adapt the techniques used and lessons learned in formulating and vetting its in-flight calibration plan to future missions. *ATHENA* will also fly both a micro-calorimeter and an imaging CCD detector, and we are currently in the process of developing its in-flight calibration strategy. Here I describe our methods and their *Hitomi*-based heritage.

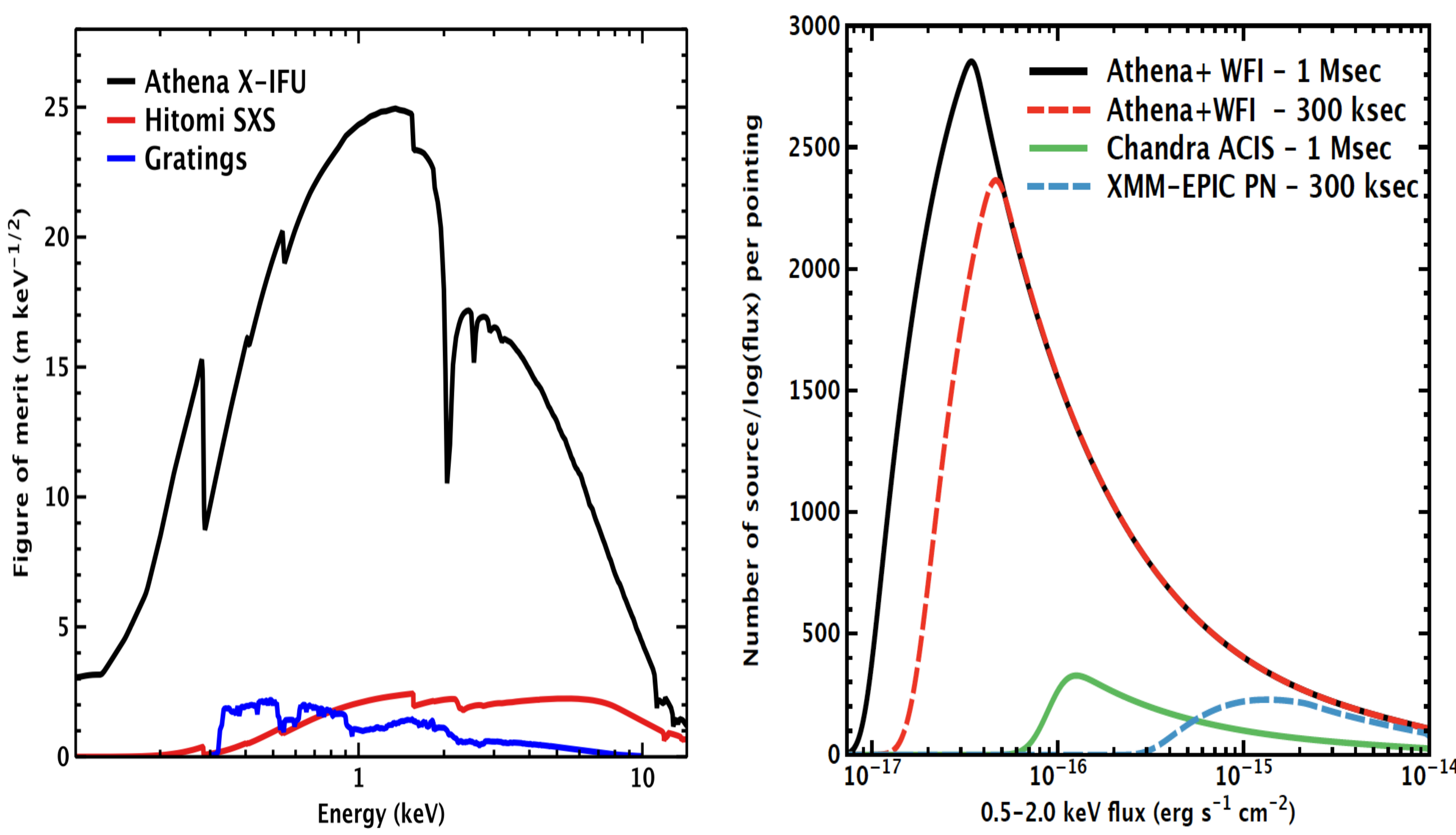


Figure 1*:* *ATHENA* will fly both a micro-calorimeter (X-IFU, above left) and a wide-field imager (WFI, above right) detector. Both instruments will offer order-of-magnitude improvements upon existing X-ray instrumentation, enabling the observatory to conduct both large-scale imaging surveys and detailed spectroscopy of individual sources. We list select instrument requirements in Table 1 below, as well as the associated precision with which each must be calibrated.

Table 1: *ATHENA* Mission Requirements and Calibration Needs

Parameter	Requirements	Calibration Precision
Energy range/scale (on-axis)	0.3-7 keV 0.2-10 keV	0.4 eV (X-IFU) <10 eV (WFI)
Gain	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 @ 6 keV, 0.25 m^2 @ 1 keV	5% (X-IFU) 4% (WFI)
Relative effective area (off-axis)	1.4 m^2 @ 6 keV, 0.25 m^2 @ 1 keV	5%
Relative effective area (fine structure)	1.4 m^2 @ 6 keV, 0.25 m^2 @ 1 keV	1%+TBD
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% (X-IFU) 1% (WFI)
Timing Resolution	10 μs (X-IFU)	1% (X-IFU)

Assessing Calibration Tolerances and Necessary Exposure Times

Hitomi Method:

1. Identify a source for each calibration activity (multiple preferred to ensure source visibility; see Table 2).
2. Use "standard candles" whenever possible (e.g., IACHEC).
3. Try to find sources that satisfy multiple calibration goals.
4. Using spectral analysis software (e.g., XSPEC), input a model of the reference source used to derive a particular calibration requirement (see Figure 2).
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.
7. To determine needed exposure time to reach required calibration precision, repeat the exercise for a variety of exposure times (see Figure 2).

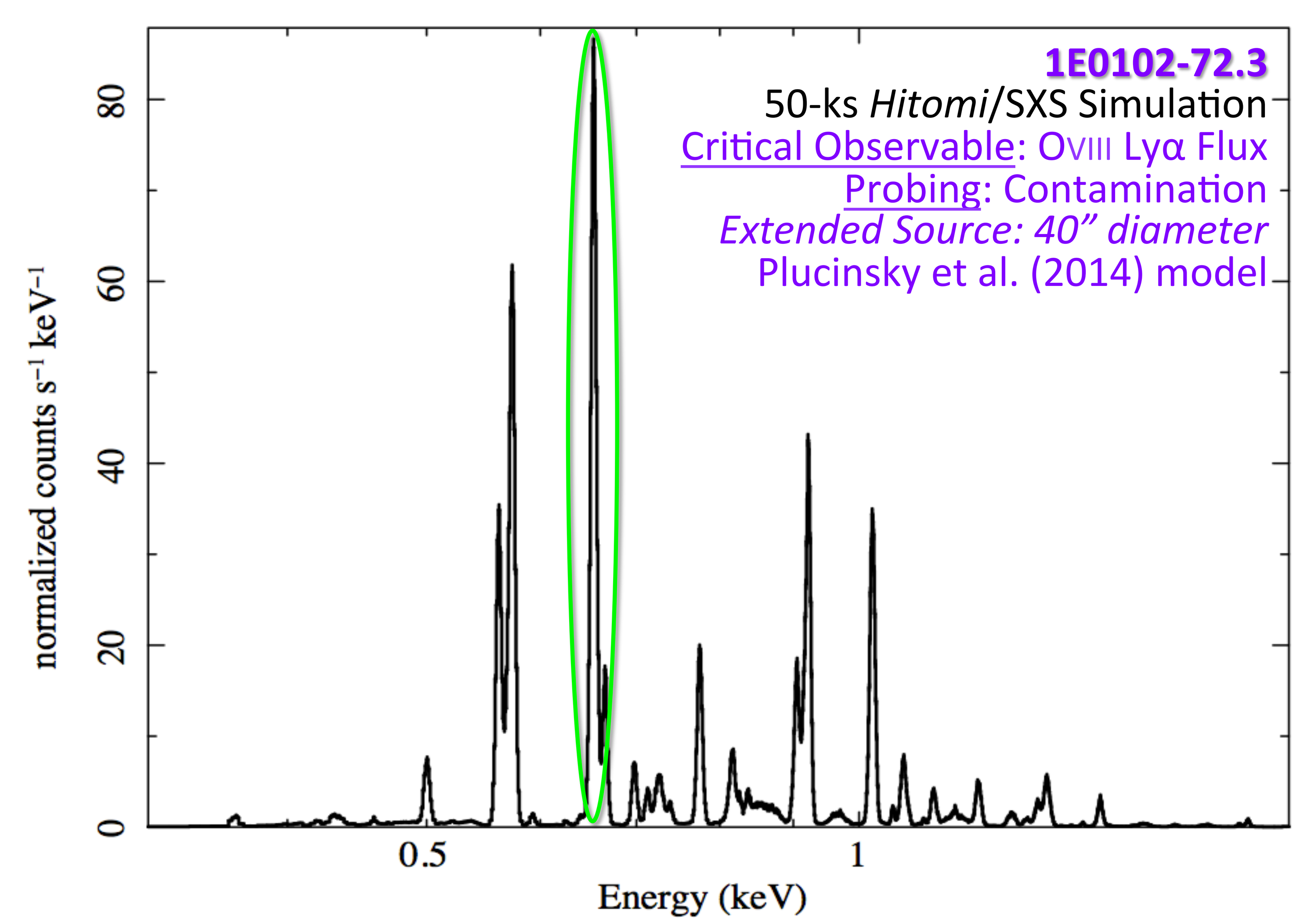
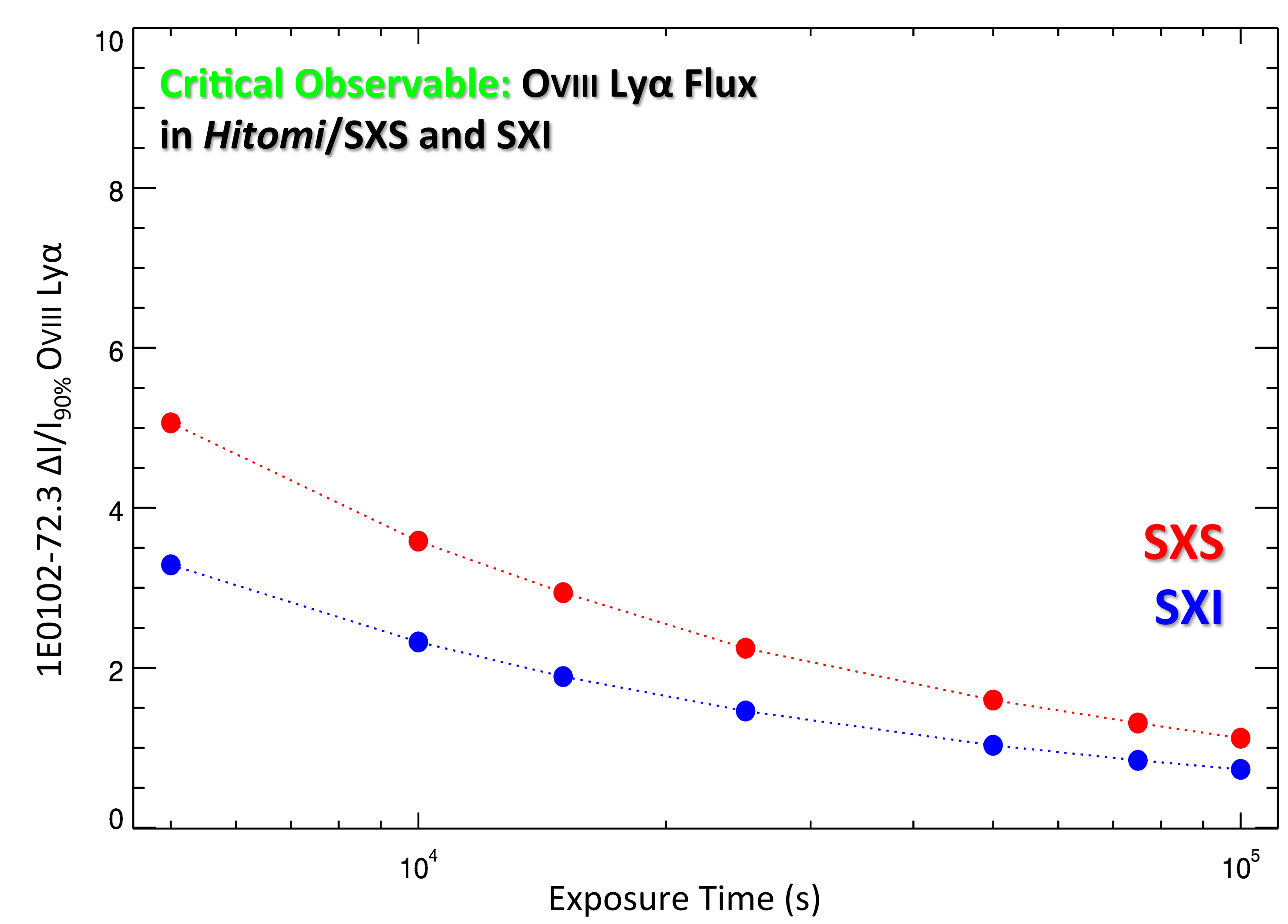


Figure 2: Supernova remnants have a wealth of emission lines whose fluxes can be used to trace the buildup of contamination on the detector over time. The model for 1E0102-72.3 (above) was used to create *Hitomi*/SXS and SXI simulations for a variety of exposure times (below) in order to assess the minimum exposure required to reach the desired statistical calibration precision.



Improving on the *Hitomi* Strategy

ATHENA Method:

1. *Hitomi* sources identified for SXS, SXI calibration can be largely repurposed (see Table 2).
2. Using response matrices based on the telescope ray-tracing code or an end-to-end simulation tool, simulate a spectrum of this model for the exposure time required, as listed in the Mock Observing Plan.
3. **Perform multiple simulations, each time perturbing the nominal effective area of the telescope slightly (according to a Gaussian perturbation model) to create a new response file.**
4. Fit the input model to each simulated dataset and record the flux (or normalization) parameter and its uncertainty measured to 90% confidence.
5. Plot the results showing the flux and its uncertainty vs. the magnitude of the perturbation in effective area in order to determine the maximum perturbation that can be tolerated while still measuring the source flux to the required accuracy and precision.

Table 2: *Hitomi* In-Flight Calibration Source Candidates

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

CP=Calibration Pixel, FW=Filter Wheel, MXS=Modulated X-ray Source, IMXS=Indirect Modulated X-ray Source, AM=HXI ^{241}AM source, NXB=Non X-ray Background, TP=Test Pulse, GVC=Gate Valve Closed, GVO=Gate Valve Open, NA=Not Applicable. Blue indicates primary targets, red indicates secondary/back-up targets.

Conclusions and Lessons Learned:

- A robust and thorough ground calibration campaign is essential for success:
  - Allows for better understanding of instrument performance;
  - Can help resolve residual issues noted during in-flight calibration.
- Don't rely on instrument models that can't be confirmed with flight data.
- Instruments with new capabilities will reveal new aspects of observed calibration sources, even "standard candles."
- Thorough documentation of all ground and in-flight calibration efforts is essential.
- Close collaboration between hardware and software teams involved in the calibration effort is also critical.
- The goal of in-flight calibration efforts prior to launch should be to create a well-informed plan that includes contingencies and redundancies in target selection.
- Establish priority scheme to ensure that the most critical observations are done first.
- Surprises will happen, so flexibility is necessary during in-flight calibration efforts with regard to data analysis and scheduling!