Planning in-flight calibration for XRISM

Eric D. Miller (MIT) for the XRISM Team
IACHEC April 2021 Plenary Sessions
XRISM Science Meeting 2, Ehime University, Japan, October 2019
Outline

• Overview of the XRISM mission and instruments
• In-flight calibration planning team organization and guiding principles
• Calibration target list
• Specific in-flight calibration tasks and strategies

• Discussion
Science goals

XRISM is the “X-Ray Imaging and Spectroscopy Mission”: High-spectral-resolution imaging spectrometer across a broad X-ray band

1. Formation and evolution of structure in the Universe
   - How do cluster mergers turn gravitational energy into thermal energy?
   - How much energy is distributed in ICM motion?

2. Circulation of baryonic matter in the Universe
   - How do supernova and AGN feedback distribute heavy elements?

3. Transport and circulation of energy in the Universe
   - How do galaxies and their supermassive black holes evolve together?
   - How do AGN and X-ray binary accretion flows and winds work?

4. New astrophysics
   - SNR plasma diagnostics, validation of laboratory measurements, dark matter.

XRISM will greatly expand a new era of spatially resolved X-ray spectroscopy begun by Hitomi.
Mission

- XRISM is led by JAXA, with contributions from NASA and ESA
- 3-year nominal mission + cryogen-free mode
- Low Earth orbit, $i = 31^\circ$
- Launch in JFY 2022 (Apr 2022–Mar 2023)
  - 0–3 months: initial phase (commissioning)
  - 3–9 months: calibration + PV phase
  - 9+ months: GO phase

<table>
<thead>
<tr>
<th>Instrument</th>
<th>FOV</th>
<th>PSF (HPD)</th>
<th>$\Delta E$ (FWHM @6 keV)</th>
<th>Energy band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolve</td>
<td>3’ × 3’</td>
<td>&lt;1.7’</td>
<td>7 eV (goal 5 eV)</td>
<td>0.3–12 keV</td>
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<tr>
<td></td>
<td>(6 × 6 pixels)</td>
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<tr>
<td>Xtend</td>
<td>38’ × 38’</td>
<td>&lt;1.7’</td>
<td>&lt; 250 eV at EOL (&lt; 200 eV at BOL)</td>
<td>0.4–13 keV</td>
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</table>
• High-resolution imaging spectrometer, based on Hitomi SXS, including X-ray Mirror Assembly (XMA).

• Detector must be cooled to 50 mK.

• Flight detector has been integrated with flight dewar at SHI in Japan and is undergoing testing.

• Flight XMA in testing and calibration at GSFC.
### Resolve requirements

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<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Hitomi Values</th>
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<tbody>
<tr>
<td>Energy resolution</td>
<td>7 eV (FWHM)</td>
<td>5.0 eV</td>
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<td>Energy scale accuracy</td>
<td>± 2 eV</td>
<td>± 0.5 eV</td>
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<tr>
<td>Residual Background</td>
<td>2 x 10^{-3} counts/s/keV</td>
<td>0.8 x 10^{-3} counts/s/keV</td>
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<tr>
<td>Field of view</td>
<td>2.9 x 2.9 arcmin</td>
<td>same, by design</td>
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<tr>
<td>Angular resolution</td>
<td>1.7 arcmin (HPD)</td>
<td>1.2 arcmin</td>
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<tr>
<td>Effective area (1 keV)</td>
<td>&gt; 160 cm²</td>
<td>250 cm²</td>
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<tr>
<td>Effective area (6 keV)</td>
<td>&gt; 210 cm²</td>
<td>312 cm²</td>
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<tr>
<td>Cryogen-mode Lifetime</td>
<td>3 years</td>
<td>4.2 years (projected)</td>
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<tr>
<td>Operational Efficiency</td>
<td>&gt; 90%</td>
<td>&gt; 98%</td>
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Xtend

- Wide-field X-ray CCD imager, based on Hitomi SXI, including XMA.
  - 4 × 200-µm thick BI CCDs
    - Good QE at soft and hard energies.
    - Low particle background.
    - 38’×38’ FOV allows detection of sources that might contaminate Resolve FOV, and monitoring for transients.
- Flight detector undergoing testing and calibration at Osaka U., MHI, and TKSC in Japan.
- Flight XMA in testing and calibration at GSFC.
• Ground calibration is underway, but things can change after launch and on-orbit.
  Porter+2020, Midooka+2020, Nakajima+2020, Yoneyama+2020

• In-flight calibration plan must:
  - Identify and prioritize calibration requirements for the instruments aboard XRISM;
  - Identify calibration targets and observing strategies;
  - Perform feasibility simulations.

• Calibration challenges for Resolve:
  - Unprecedented combination of spectral resolution, spectral coverage, and effective area.
  - Field of view ~ point spread function.

• Calibration challenges for Xtend:
  - Imaging fidelity over 38’ FOV.
  - Increased hard-band response compared to other X-ray CCD instruments.
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<tr>
<th>Role</th>
<th>Members</th>
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<tbody>
<tr>
<td>Chair</td>
<td>Eric Miller *</td>
</tr>
<tr>
<td>Co-chair</td>
<td>Makoto Sawada *</td>
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<tr>
<td>Resolve Instrument Team</td>
<td>Megan Eckart, Caroline Kilbourne, Maurice Leutenegger, Scott Porter</td>
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<tr>
<td></td>
<td>Masahiro Tsujimoto, Cor de Vries, Takashi Okajima, Takayuki Hayashi</td>
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<tr>
<td></td>
<td>Keisuke Tamura, Rozenn Boissay-Malaquin</td>
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<tr>
<td>Xtend Instrument Team</td>
<td>Hironori Matsumoto, Koji Mori</td>
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<td></td>
<td>Hiroshi Nakajima, Takaaki Tanaka</td>
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<tr>
<td>Science Operations Team</td>
<td>Yukikatsu Terada, Mike Loewenstein, Tahir Yaqoob</td>
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<tr>
<th>Office</th>
<th>Members</th>
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<tr>
<td>Science Management</td>
<td>Makoto Tashiro, Richard Kelley, Rob Petre</td>
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<tr>
<td>Management Office</td>
<td>Matteo Guainazzi *, Brian Williams, Hiroya Yamaguchi</td>
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<tr>
<td>Science Team</td>
<td>Marc Audard, Ehud Behar, Laura Brenneman, Lia Corrales</td>
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<td></td>
<td>Renata Cumbee, Teruaki Enoto, Liyi Gu</td>
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<tr>
<td></td>
<td>Edmund Hodges-Kluck, Yoshitomo Maeda, Maxim Markevitch *</td>
</tr>
<tr>
<td></td>
<td>Paul Plucinsky, Katja Pottschmidt, Aurora Simionescu *</td>
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* IFCP sub-group lead.
IFCP team organization

• Broad membership drawn from Instrument Teams, Science Operations Team, and Science Team.
• Ensures necessary technical and astrophysical background to understand limits imposed by instrumentation and celestial sources.
• Ensures that all interested parties have a stake in proper calibration to reach the desired science goals.
• Greatly expands the workforce available to run complex simulations of different calibration strategies and review possible targets.
IFCP guiding principles

• Build in flexibility
  - Identify secondary calibration targets well in advance of launch in case of schedule changes.

• Plan ahead
  - Perform simulations of observations and strategies well before launch.
  - Learn from previous experience to prepare contingency plans (e.g. molecular contamination monitoring and calibration).

• Use the community
  - Capitalize on experience of IACHEC*, including standard candle definitions and multi-mission observation coordination.
  - XRISM IFCP borrows heavily from Hitomi IFCP, but with fewer instruments.

* International Astronomical Consortium for High-Energy Calibration, iachec.org
Calibration requirements are derived from mission science goals by the Instrument Teams.

Tashiro+2018, Tashiro+2020, Eckart+2018

Table 1. XRISM calibration requirements to be verified in flight.\textsuperscript{a}

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Resolve</th>
<th>Xtend</th>
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<tbody>
<tr>
<td>Energy scale</td>
<td>2 eV for each pixel</td>
<td>5% (1 keV)</td>
</tr>
<tr>
<td></td>
<td>\begin{itemize}</td>
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<tr>
<td></td>
<td>\item [1 eV (0.05–12 keV), 3 eV (12–25 keV)]</td>
<td>\item 0.3% (6 keV)</td>
</tr>
<tr>
<td>Energy resolution (FWHM)</td>
<td>1 [0.5] eV for each pixel\textsuperscript{b}</td>
<td>10% (1 keV)\textsuperscript{c}</td>
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<tr>
<td></td>
<td>\begin{itemize}</td>
<td>\begin{itemize}</td>
</tr>
<tr>
<td></td>
<td>\item [2 eV (12–25 keV)]</td>
<td>\item 5% (6 keV)\textsuperscript{c}</td>
</tr>
<tr>
<td>Abs. eff. area on-axis\textsuperscript{d}</td>
<td>10% [5%]</td>
<td>10% [5%]</td>
</tr>
<tr>
<td>Abs. eff. area off-axis\textsuperscript{d}</td>
<td>10% [5%] within 5’</td>
<td>15% [10%] within 10’</td>
</tr>
<tr>
<td>Rel. eff. area on-axis\textsuperscript{d}</td>
<td>5% [3%] [5% (12–25 keV)]</td>
<td>5% [2%]</td>
</tr>
<tr>
<td>Rel. eff. area &lt; 2° off-axis\textsuperscript{d}</td>
<td>5% [3%] [5% (12–25 keV)]</td>
<td>10% [5%]</td>
</tr>
<tr>
<td>Rel. eff. area 2°–5° off-axis\textsuperscript{d}</td>
<td>10% [10% (12–25 keV)]</td>
<td>10% [5%]</td>
</tr>
<tr>
<td>Rel. eff. area &gt; 5° off-axis\textsuperscript{d}</td>
<td>N/A</td>
<td>10% [5%]</td>
</tr>
<tr>
<td>Rel. eff. area fine structure\textsuperscript{d}</td>
<td>5% in 1 eV bins around C, N, O K edges\textsuperscript{e}</td>
<td>15% at Si K edge</td>
</tr>
<tr>
<td>PSF on-axis\textsuperscript{f}</td>
<td>5% [3% (0.3–25 keV)]</td>
<td>10%</td>
</tr>
<tr>
<td>PSF off-axis\textsuperscript{g}</td>
<td>5% [5% (12–25 keV)]</td>
<td>10% [10%]</td>
</tr>
<tr>
<td>Absolute timing\textsuperscript{h}</td>
<td>1.0 ms</td>
<td>10 ms</td>
</tr>
<tr>
<td>Relative timing\textsuperscript{h}</td>
<td>0.5 ms</td>
<td>TBD</td>
</tr>
<tr>
<td>Aimpoint</td>
<td>Difference in the aimpoint and optical axis known to 30”</td>
<td></td>
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IFCP boundary conditions

• Available calibration time
  - Commissioning phase: 0 Msec
  - Calibration and PV phase: 
    \[ \frac{1}{12} \text{mo} + (0.05 \times 6 \text{mo}) \times 0.43 = 1.4 \text{ Msec} \]
  - GO phase: 
    \[ (0.05 \times 12 \text{mo}) \times 0.43 = 0.7 \text{ Msec} \]

• Visibility constraints
  - 90-minute low-Earth orbit, 90°±30° Sun angle
  - Most sources are visible 2x per year, short windows for Ecliptic sources, high-Ecliptic latitude sources are always visible.
  - Roll constraints affect extended sources, raster scans, PSF measurements.

• Bright source limits
  - Resolve encounters issues with >10mCrab sources: reduced high-res fraction due to pulse overlap, electrical cross-talk degrading resolution, dead time from PSP overload. XRISM Bright Sources Study Group (“The 1 Crab Club”), Lead: E. Hodges-Kluck
  - Xtend suffers pile-up for >1mCrab sources. Tamba+2021
### Some calibration must be done early.
1. Determination of the boresight and optical axis position of both instruments.
2. Verification of the accuracy of time assignment.
3. Verification of the accuracy of the Resolve energy scale and resolution.
5. First characterization of the overall effective area calibration.

### Target visibility and flexibility are key!
Some calibration must be done early.

1. Determination of the boresight and optical axis position of both instruments.
2. Verification of the accuracy of time assignment.
3. Verification of the accuracy of the Resolve energy scale and resolution.
5. First characterization of the overall effective area calibration.

Target visibility and flexibility are key!
IFCP Team has ~30 people. That’s a lot.

Sub-groups defined for detailed work.
- Review specific XRISM in-flight calibration requirements.
  - Review Hitomi IFCP to identify changes:
    - New or stricter requirements for XRISM.
    - New or different operational constraints placed on XRISM compared to Hitomi.
    - Elimination of hard X-ray instruments.
    - New science goals for XRISM.
- Perform simulations and plan strategies.
Resolve energy scale and spectral response

\(^{55}\)Fe-illuminated calibration pixel for overall energy scale, LSF trend.

\(^{55}\)Fe filter wheel position to illuminate all pixels, 1 ct/s/pix @ 6 keV.

Modulated X-ray Source (MXS) can be pulsed at 1–3% duty cycle, 1–3 cts/s/pix

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Resolve energy scale and spectral response

- Coronal stars for on-axis energy scale, LSF < 5 keV. Exposure times driven by LSF calibration.

Simulations by M. Audard
Resolve energy scale and spectral response

- Capella raster scan to uniformly illuminate all Resolve pixels.
- Obtain >1000 counts in two Fe L lines (0.72 and 0.82 keV).
- Two modes (normal/forced mid-res) × three operating temperatures.

Total time allocation 43 ks × 5 = 215 ks (+ on-axis 50 ks)

Simulations by M. Guainazzi
• Bright blazars (3C273, PKS2155) for on-axis effective area (absolute and relative).
• Variable, so must be observed simultaneously with other instruments, especially NuSTAR.
All filter and gate valve combinations must be calibrated for Resolve.

Xtend must use a fainter source than Resolve due to pile-up, like 1ES0033.

Observe E0102 to compare continuum-dominated and line-dominated sources, monitor contamination.

Observe RXJ1856 to monitor contamination.
Xtend effective area off-axis

- 4×10 ksec raster scan of “peaky cluster” for Xtend XMA off-axis vignetting and optical axis.

Simulations by A. Simionescu
• Resolve timing requirements are 1.0 ms absolute, 0.5 ms relative.
• Includes allocations for instrument and spacecraft.
• Crab pulsar is best source, but other sources can calibrate absolute timing if visibility is bad.

![Crab](image1)
![PSR B0540](image2)

### Figure 6. Required exposure times for the Resolve absolute timing calibration.

Contours show the exposure time \( t_{\text{exp}} \) required to achieve statistical uncertainty on the pulse peak phase of \( t \sim 100 \mu s \), which is a function of the peak count rate \( r_{\text{peak}} \) and peak width \( \sigma_{\text{peak}} \) of a pulsar. Dots show order estimation for candidate pulsars with a Gaussian approximation of pulse profiles. Only high-resolution (H-res) events are considered.

From the visibility perspective (Figure 1), PSR B0540–69 is the best; it is visible throughout the year. The three NuSTAR targets, if combined, also cover most of the year with an overlap with the Crab pulsar. Note that, in the above evaluation, only the primary goal, the absolute timing calibration using high-resolution (H-res) grade events, is considered. The backup targets (e.g., 1 mCrab) are not bright enough to calibrate the Resolve relative timing, especially the grade dependence (having sufficient non-high-res branching ratio requires a source to be \( \geq 100 \text{ mCrab} \)), or to cross-calibrate the Xtend timing using the out-of-time events technique. Therefore, additional calibration using, e.g., the MXS for Resolve and an accreting pulsar for Xtend may also be needed. As a next step of the planning, more accurate exposure-time estimation based on simulations is ongoing and discussion on coordinated observations is to be initiated soon.

### 4.6 Science Calibration

XRISM, like missions before it, will open up an unexplored arena in X-ray astrophysics, and we already saw from Hitomi that it will challenge the fidelity of the very tools we need to understand the data. We have adopted the concept of “science calibration” observations as a category of targets that, while they do not address a formal instrumental calibration requirement, and may not be as interesting astrophysically as other PV-phase targets, have the potential to greatly improve the science return of the mission. Examples of such observations being considered are presented below.

#### 4.6.1 Atomic Modeling

Large uncertainties on atomic constants (e.g., transition energies, cross sections) will lead to unacceptable errors on scientific results obtained from the observed spectra. There is an increasing demand that the spectral models and their atomic data should be sufficiently tested during the early mission phase, using observations of selected objects that contain relevant information for the atomic physics quantities. There have been discussions in the...
“Science calibration” targets are valuable for enabling the best XRISM science or performance, but do not directly address instrument calibration.
- Enhance PV or GO phase science.
- Require early observations (PV phase) to be of most use.
- Enable or enhance science return on multiple categories of objects.

Calibration of X-ray spectral models
- transition energy, line emissivity, ionization balance
- NGC 1550: 1.3 keV, L-shell lines of FeXX–FeXXIV, K-shell lines of O to Si.
Summary

• XRISM in-flight calibration plan builds on lessons learned.
• Team members have been performing simulations, planning strategies.
• Preliminary target list has been compiled, final simulations are underway and observing strategies are being planned.

• Thanks to hard work on ground calibration by instrument teams, we expect smooth in-flight verification, but we will be prepared!
• Tashiro+2020, “Status of x-ray imaging and spectroscopy mission (XRISM).”
  Proc. SPIE 11444, Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, 1144422

• Porter+2020, “Initial ground calibration of the Resolve detector system on XRISM.”
  Proc. SPIE 11444, Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, 1144424

• Midooka+2020, “X-ray transmission measurements of the gate valve for the x-ray astronomy satellite XRISM.”
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Resolve energy scale and spectral response

Extended gain and LSF calibration using two-photon events!

Credit: S. Porter (GSFC)
Xtend energy scale and spectral response

- Strategy from Suzaku XIS: field-filling stable line sources.
  - Perseus Cluster @ 6 keV
  - Cygnus Loop @ < 2 keV
- Xtend has 4x the FOV of XIS.
  - Outer regions are expensive to calibrate.
  - But aimpoint will be self-calibrated by any line source thanks to Resolve!

<table>
<thead>
<tr>
<th>Case</th>
<th>Gain uncertainty</th>
<th>$t_{\text{exp}}$ (ks)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>7 eV @ $r &lt; 8'$, 18 eV @ $8' &lt; r &lt; 15'$, 60 eV @ $r &gt; 15'$</td>
<td>80</td>
<td>Observed only on-axis to reach the same gain uncertainty as Suzaku/XIS.</td>
</tr>
<tr>
<td>Case II</td>
<td>7 eV on-axis chip, 8 eV neighbor chips, 9 eV opposite chips</td>
<td>320</td>
<td>Observed on each chip for the same exposure time and goal as Case I. Off-axis chips have higher uncertainty due to vignetting.</td>
</tr>
<tr>
<td>Case III</td>
<td>7 eV everywhere</td>
<td>640</td>
<td>Observed on each chip for exposure time that scales with vignetting, to reach the Suzaku/XIS gain uncertainty at all FOV locations.</td>
</tr>
</tbody>
</table>