IACHEC Timing WG report

Presented by
Yukikatsu Terada (Saitama U. & JAXA)
Timing WG members (Nov 2021)

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Felix Fuerst (XMM-Newton),
Simon Rosen (XMM-Newton),
Vinay Kashyap (Chandra),
Arnold Rots (Chandra),
Amy Lien (Swift),
Giancarlo Cusumano (Swift),
Guillaume Belanger (INTEGRAL),
Volodymyr SAVCHENKO (INTEGRAL),
Lucien Kuiper (INTEGRAL),
Xiaobo LI (HXMT),
Gulab Dewangan (Astrosat),
Dipankar Bhattacharya (Astrosat)
Michael Freyberg (eROSITA),
Makoto Sawada (XRISM),
Takaaki Tanaka (XRISM),
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Timing WG communication

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SLAC:  iachec.slack.com  #timing
Wiki:  https://wikis.mit.edu/confluence/display/iachec/Timing

→ Please contact Yuki to join ML; terada@mail.saitama-u.ac.jp
Goal of the Timing WG

1. Share information on Timing calibration methods/protocol, lessons learned (to enhance timing capability)
   - Suzaku, Hitomi (2017, 2018, 2019)
   - HXMT(2018), Astrosat
   - eROSITA
   - Future missions (XRISM, Athena, etc)

2. In-orbit timing calibration plan/observations/studies
   - Discussion on calibration plans for near future missions
   - Perform timing coordinated observations // Coordinated Observation WG
   - Analyses of GO coordinated observations (using archive data) // with Cal. Stat. WG

3. Studies on Timing products
   - Systematic studies on the effects for timing products (power spectrum, light curve etc) by the detector’s behavior (dead time, grade selection of calorimeter etc)
   - Timing Tool // collaboration with Cal. Stat. WG
Activities in 2020-2021

Timing WG telecom
- 28 April 2020
- 15 Sep 2020
- 20 April 2021
- 12 May 2021
- 13 Oct 2021

Meeting notes (PDF) are available on the timing WG wiki page
https://wikis.mit.edu/confluence/display/iachec/Timing

Major activities
1. Summary of timing calibration/performance of multiple missions (Goal 1)
   update
2. Systematic study of Crab timing using archive data among instruments (Goal 2)
   update
3. Effects of dead time / grade selection etc on timing products (Goal 3)
   new/to be active soon
# 1. Summary of timing calibration/performance

Organizer: Yuki Terada
Output: see https://wikis.mit.edu/confluence/display/iachec/Timing

Instruments:
- RXTE PCA, HEXTE (calibration target; updated)
- Chandra ACIS, HRC
- XMM-Newton EPIC-PN, EPIC-MOS
- INTEGRAL SPI, IBIS
- Swift BAT, XRT
- Suzaku XIS, HXD
- NuSTAR FPM
- Fermi LAT, GBM
- AstroSat LAXPC, CZTI
- Insight-HXMT (Newly added)
- Hitomi SXS, SXI, HXI, SGD
- NICER XTI
- SRG eROSITA
- XRISM Resolve, Xtend

Update from May 2021
# 1. Summary of timing calibration/performance

Columns on the table:
- Science Requirement Absolute Time (Requirement & Goal)
- Timing System Design (GPS yes/no, Clock Stability)
- Timing Calibration Status (Timing offset, deviation, notes)
- In-orbit Timing Calibration Targets
- Reported Issues
- Reference

Note:
- The values on the table come from the various published papers; i.e., they do not come from a systematic study like item #2.
  - The definition of the timing accuracy and offset are different among instruments. For example, some instruments refer the radio arrival time, but others refer the absolute timing.
- The detail description is available in the “note” column.
  (we are gathering information, still)
- We plan to keep maintenance of this summary table.
### Update from May 2021

#### The Table (1/3)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RXTE/PCA</td>
<td>10 µsec</td>
<td>none</td>
<td>Calibrated: &lt; 3.4 µsec</td>
<td>Calibration: Spitzer-based calibration against ground timing standards, including ground time assignment error.</td>
<td>PSR B1913+60-2400 µsec</td>
<td>Timing Budget: Hazbuda et al. 2008 (<a href="https://doi.org/10.1088/0004-637X/68/1/26">10.1088/0004-637X</a>)</td>
</tr>
<tr>
<td>RXTE/HETE</td>
<td>10 µsec</td>
<td>none</td>
<td>See above</td>
<td>Event by event has 7 ± 1 µsec resolution. <em>the HETE absolute time reference is accurate within a fraction of a millisecond.</em> (<a href="https://doi.org/10.1088/0004-637X/68/1/26">10.1088/0004-637X</a>)</td>
<td>delay 0-1 µsec (corrected?)</td>
<td>None</td>
</tr>
<tr>
<td>Chandra/ACIS</td>
<td>0.206 s/25 s (one micron frame start time)</td>
<td>0.001 s (synchronize minor frame start)</td>
<td>3.2 µsec</td>
<td>No (sync, DSN)</td>
<td>280 ± 6 µsec</td>
<td>None</td>
</tr>
<tr>
<td>Chandra/HRC</td>
<td>16 µsec</td>
<td></td>
<td>4 ± 4 µsec</td>
<td>No</td>
<td>4 ± 4 µsec</td>
<td>None at present</td>
</tr>
<tr>
<td>XMM-Newton/EPIC-PN</td>
<td>1 ms</td>
<td>none</td>
<td>-</td>
<td>Note: Timing = 308 ± 16 µsec, Burst = 387±13 µsec. Timing mode is affected by pile up.</td>
<td>None currently</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Note: XMM-Newton EPIC MOS was deleted from the table.</td>
<td>No</td>
<td>None</td>
</tr>
</tbody>
</table>
### Update from May 2021

**The Table (2/3)**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Requirement</th>
<th>Note</th>
<th>9 x 10^{-9} s/s (measured)</th>
<th>1 x 10^{-9} s/s (ground)</th>
<th>Clock offset from X-ray mission and the HDG in the simultaneous observation of Crab.</th>
<th>Crab pulsar (annual)</th>
<th>Crab pulsar (annual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTEGRAL/SPI</td>
<td>No science requirement defined</td>
<td>No (time, ground)</td>
<td>1.9 x 10^{-9} s/s</td>
<td>Not confirmed</td>
<td>N/A</td>
<td>0.25 (0.21-0.3; 95% C.L.)</td>
<td>N/A</td>
</tr>
<tr>
<td>INTEGRAL/IBIS</td>
<td>No science requirement defined</td>
<td>No (time, ground)</td>
<td>5 x 10^{-9} s/s</td>
<td>Calibrated: ~50 µs</td>
<td>Calibrated: ~50 µs</td>
<td>~70 µs</td>
<td>~70 µs</td>
</tr>
<tr>
<td>Swift/BAT</td>
<td>100 ms</td>
<td>100 µsec</td>
<td>~5.57 x 10^{-8} s/s</td>
<td>Uncalibrated:term of seconds</td>
<td>Uncalibrated: N/A</td>
<td>01 µsec</td>
<td>Offsets for PSR J0737-3039 and the HDG in the simultaneous observation of Crab.</td>
</tr>
<tr>
<td>Swift/BAT</td>
<td>~ 10 ms</td>
<td>No</td>
<td>~270 µs</td>
<td>Clock measurements made by mission operations &amp; ground station, and applied as calibration when beaming.</td>
<td>Crab pulsar</td>
<td>None of present</td>
<td>None of present</td>
</tr>
<tr>
<td>SuzakuXMM</td>
<td>No science requirement defined</td>
<td>No (time, ground)</td>
<td>1 x 10^{-9} s/s</td>
<td>Not confirmed</td>
<td>N/A</td>
<td>0.015 (0.010, 0.2; 1% C.L.)</td>
<td>Y. Torii et al 2008 (10.1088/0004-637x.673.2.1021)</td>
</tr>
<tr>
<td>Suzaku HDG</td>
<td>~ 10 µsec</td>
<td>0.130 µsec</td>
<td>0.130 µsec</td>
<td>0.130 µsec</td>
<td>0.130 µsec</td>
<td>0.130 µsec</td>
<td>0.130 µsec</td>
</tr>
<tr>
<td>NuSTAR/FPM</td>
<td>Should be 100 ms</td>
<td>Min.</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>0.05 µs (1-sigma)</td>
<td>Crab pulsar (annual)</td>
</tr>
<tr>
<td>Fermi/LAT</td>
<td>-111 ±4 µs</td>
<td>57 µs</td>
<td>9 years of LAT data; see also fic 334, 60 (2011)</td>
<td>9 years of LAT data; see also fic 334, 60 (2011)</td>
<td>9 years of LAT data; see also fic 334, 60 (2011)</td>
<td>Crab pulsar</td>
<td>~394 µs using 0.25 s/50 s (Bachetti et al prep)</td>
</tr>
<tr>
<td>Fermi/GBM (HDG)</td>
<td>-222 ±4 µs</td>
<td>56 µs</td>
<td>100-300 keV band; data from Nov 2012</td>
<td>100-300 keV band; data from Nov 2012</td>
<td>100-300 keV band; data from Nov 2012</td>
<td>Crab pulsar</td>
<td>~394 µs using 0.25 s/50 s (Bachetti et al prep)</td>
</tr>
</tbody>
</table>

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**References:**

- L. Kaiser 2003 (10.1051/0004-6361:20031351)
- L. Kaiser 2018 (10.1007/s10909-017-3211-7)
- Continue.
### The Table (3/3)

**Update from May 2021**

| Fermi/GBM (Na) | AstroSat/LAACPC | None-defined | Yes (offline referral) | 4 usec rms after GPS synchronization | 318 ±70 μs | 110 μs (rms) | The offset is with respect to Fermi-LAT ephemeris | Crab Pulsar (with Radio) | None at present | D. Bhattacharya 2017 (0.10769432504517985x) | (Bos et al in prep)
|----------------|-----------------|--------------|------------------------|-------------------------------------|------------|-----------|-----------------------------------------------|-------------------------|-------------|-----------------------------------------------|-------------------------|
|                | AstroSat/CZTI   | None-defined | Yes (offline referral) | 3 usec rms after GPS synchronization | 4660 ±70 μs | 83 μs (rms) | The offset is with respect to Fermi-LAT ephemeris | Crab Pulsar (with Radio) | None at present | D. Bhattacharya 2017 (0.10769432504517985x) | (Bos et al in prep)
|                | Insight-HEXT/E | None-defined | Yes (offline referral) | 3 x 10^12 s/s | 24.7 s | 12.1 s (rms) | The offset is with respect to NICER | Crab (with NICEER) | None at present | Y. Sun et al. 2021 [https://arxiv.org/abs/2105.04739](https://arxiv.org/abs/2105.04739) |
|                | Insight-HEXT/L | None-defined | Yes (offline referral) | 10.1 μs | 8.6 μs | The offset is with respect to NICER | Crab (with NICEER) | None at present | |
|                | Hitomi/SXS, S1K, XOL, SOD | 350 usec | 35 usec | Yes | 0.011μsec (SPSR) | <3 μsec | <3 μsec | The offset is with respect to NICER | Crab (with radio) | absolute timing accuracy is much larger than expected on ground (3 μsec) | Y. Tanaka et al. 2018 (0.10701714145.4.1.02506)
|                | NICER/XTI | 100 ns (RMS) | none | Yes | N/A | Uncalibrated 1 second | Calibrated: Approx 3 μs based on Crab | 100 ns (RMS) (requirement) | The NICER XTI timing system was calibrated on ground using an end-to-end system, with GPS simulator and precision X-ray pulse generator. Detector + system time delays of ~400 μs are included in the calibration. Combined error/nominal terms tends to be ~100 μs (including GPS, X-ray detector + system time delays). Absolute timing offset values depend on the definition of absolute timing. See supplementary material of this paper [https://openaccess.as.arizona.edu/content/37/205/318/147](https://openaccess.as.arizona.edu/content/37/205/318/147). Figure 312 and 313 (p.33-34) for the NICER Crab X-ray main peak monitoring. At this stage, it is not clear whether the fluctuation of the peak phase is due to the instrumental effects or due to intrinsic of the pulsar. | Crab Pulsar (PSR D0531−21) | Precise 1-second offset in on-board timescales due to flight software bug (corrected using TINEZERO) in pipeline-processed RT3 data files. See [NICEER data](https://k2scics.arizona.edu) for details | Marriotti et al. (in prep)
|                | eROSITA | XMM-Newton | 1 usec | none | Yes | Same as Hitomi | <1 μs | <1 μs | The values (~1 μsec) are the requirement including both offset and deviation | (under discussion) | See in-flight Calibration Plan in IACTWG 2021 virtual meeting, [xmm_fmu_iaactwg_20210416.pdf](xmm_fmu_iaactwg_20210416.pdf) | |
|                | XMM-Newton | 10 usec | none | Yes | <10 μs | <10 μs | The mission requirement values. | (under discussion) | | | | | |
Fig. Timing Calibration status (offset ± deviation)

- Blue: offset from Crab radio MP
- Red: absolute timing offset

Note:
- the definitions of the offset are different (described in the “Notes” column).
- offset from radio has energy dependency
Ref) The energy dependency of the intrinsic timing delay from the radio main pulse of Crab

Molkov, Jourdain, Roques 2010
Fig. Timing Calibration status (deviation) ;
# Summary of Timing Calibration Objects

<table>
<thead>
<tr>
<th>In-orbit calibration objects</th>
<th>Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crab</strong></td>
<td>Chandra/HRC,</td>
</tr>
<tr>
<td></td>
<td>XMM-Newton/EPIC-PN,</td>
</tr>
<tr>
<td></td>
<td>Swift/BAT, Swift/XRT,</td>
</tr>
<tr>
<td></td>
<td>Suzaku HXD,</td>
</tr>
<tr>
<td></td>
<td>NuSTAR/FPM,</td>
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<tr>
<td></td>
<td>AstroSat/LAXPC,</td>
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<td></td>
<td>AstroSat/CZTI,</td>
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<td></td>
<td>Hitomi/SXS,</td>
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<tr>
<td></td>
<td>Hitomi/HXI,</td>
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<tr>
<td></td>
<td>Hitomi/SGD,</td>
</tr>
<tr>
<td></td>
<td>NICER/XTI,</td>
</tr>
<tr>
<td></td>
<td>HXMT</td>
</tr>
<tr>
<td><strong>PSR B1937+21</strong></td>
<td>Chandra/HRC,</td>
</tr>
<tr>
<td></td>
<td>NuSTAR/FPM,</td>
</tr>
<tr>
<td></td>
<td>NICER/XTI</td>
</tr>
<tr>
<td><strong>PSR B1821-24A</strong></td>
<td>RXTE/PCA</td>
</tr>
<tr>
<td></td>
<td>NuSTAR/FPM,</td>
</tr>
<tr>
<td></td>
<td>NICER/XTI</td>
</tr>
<tr>
<td><strong>PSR B1509-58</strong></td>
<td>Suzaku/HXD</td>
</tr>
<tr>
<td><strong>GRB</strong></td>
<td>AstroSat/CZTI</td>
</tr>
<tr>
<td><strong>A0535+262, Her X-1, etc</strong></td>
<td>Suzaku/XIS</td>
</tr>
</tbody>
</table>
#2. Comparison of Crab ephemeris

Organizer: Matteo Bachetti

Purpose:
1. Systematic-timing cross-calibration of instruments using archive data.
2. Systematic check of Timing delay of the Crab main pulse between the X-ray and Radio.

Note: please see also the presentation by L.Kuiper in 13th IACHEC 2018.

Status:
1. We start gathering barycenter event files of the missions;
   - XMM-Newton
   - Suzaku
   - NuSTAR
   - Astrosat
   - Hitomi
   - Swift
   more missions/instruments will be added.
2. Matteo prepared the code to check ephemeris of multiple missions.
   Quick-look result was updated (next page).
   We still gather the event files (or folded light curve) for the study.
3. We see several outliers, which may be due to ground station issues;
   “Known issues” will be also listed ← we are gathering the information.
Quick-look results of systematic timing study with Crab © Matteo Bachetti

Plot on 15 Oct 2021
#3 Effects of DAQ behavior on timing products

Organizer: TBA (Yuki)

Purpose:
- check the effect of the following detector’s behavior on folded light curve/power spectrum, delta-time spectrum, etc
  - a. Time resolution of instruments
  - b. Absolute timing accuracy
  - c. Dead time (and/or grade selection for calorimeter)
  - d. Background events
  - e. Good time interval etc

Notes:
- Previous works exist on pile-up (Chandra, Suzaku), dead time (NICER, NuSTAR), and time resolution (Hitomi) etc.

Status:
- To be active soon!
Please join the WG if you are interested in.

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