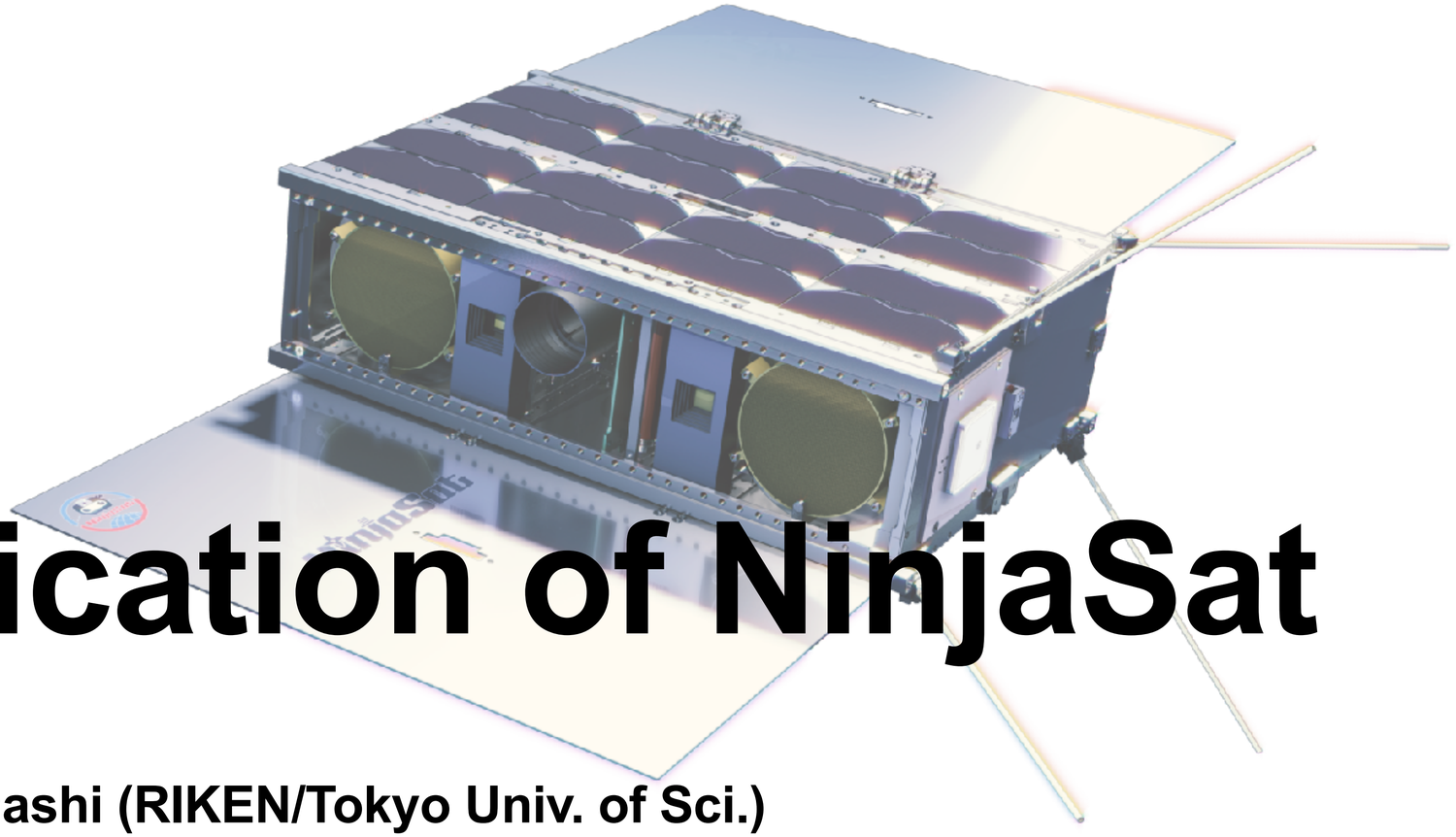


Timing verification of NinjaSat

Takuya Takahashi (RIKEN/Tokyo Univ. of Sci.)

N. Ota (RIKEN/Tokyo Univ. of Sci), T. Tamagawa (RIKEN), T. Enoto (Kyoto Univ.), T. Kitaguchi, Y. Kato, T. Mihara (RIKEN),
W. Iwakiri (Chiba Univ.), M. Numazawa (Tokyo Met. Univ.), T. Takeda (Hiroshima Univ.), C. P. Hu (Natl.Chnghua Univ. of Edu.), Y. Zhou,
K. Uchiyama, Y. Yoshida, S. Hayashi, A. Jujo, S. Watanabe, A. Aoyama, S. Iwata, K. Yamasaki (RIKEN/Tokyo Univ. of Sci), T. Kita (Chiba Univ.),
H. Sato (RIKEN/Shibaura Inst. Tech.), H. Takahashi (Hiroshima Univ.), H. Odaka (Osaka Univ.), T. Tamba (ISAS/JAXA), K. Taniguchi (Waseda Univ.)

the 17th IACHEC meeting 2025-05-15

NinjaSat

Objectives

- Long-term monitoring of the bright source.
- Multi-wavelength observation.
- Follow-up observation of the transient.

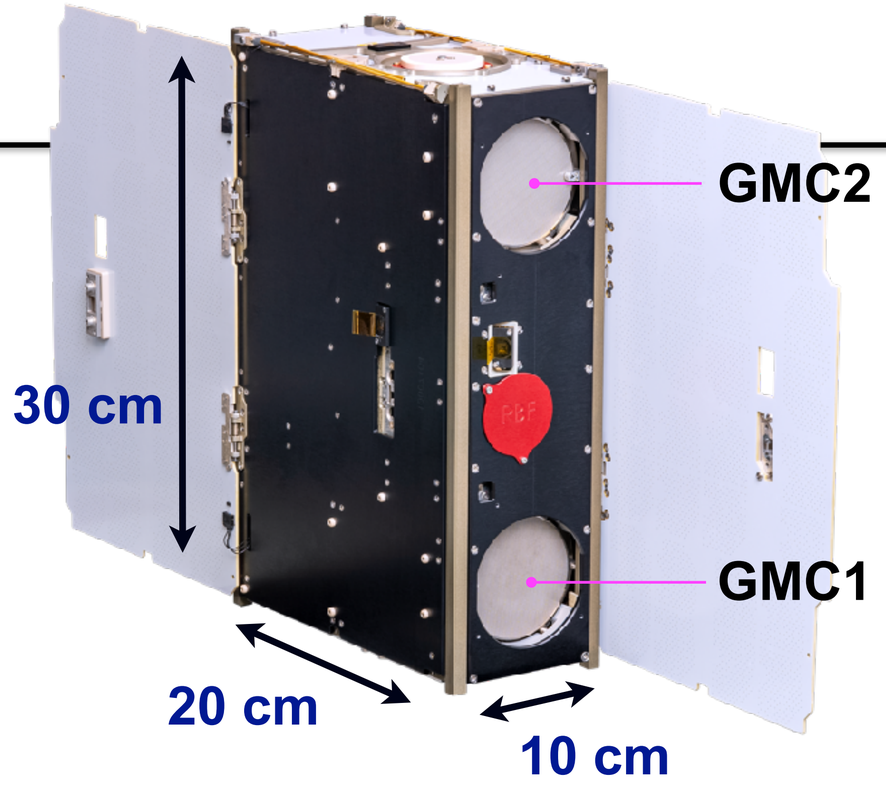
Satellite Bus

- Sun-synchronous polar orbit (~95 minutes/orbit).
- Get precise position and time from GPS receiver (NMEA format).

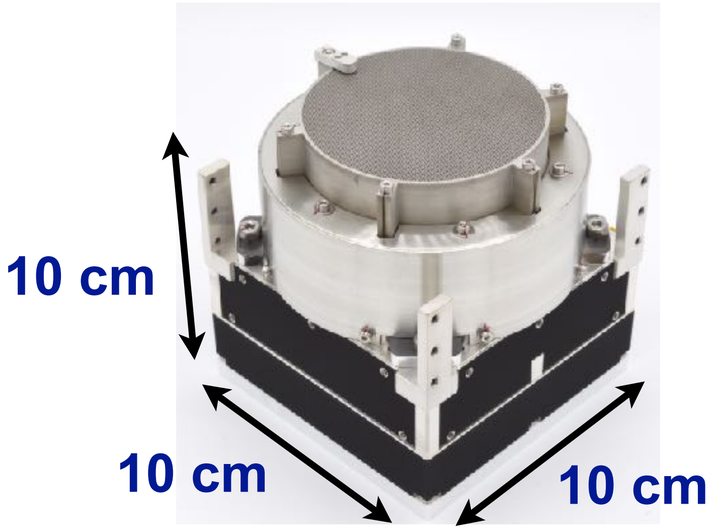
Gas Multiplier Counter: GMC

- Energy range: 2–50 keV
- Effective area: 16 cm² /GMC (@ 6 keV)
- Time resolution: 61 μs

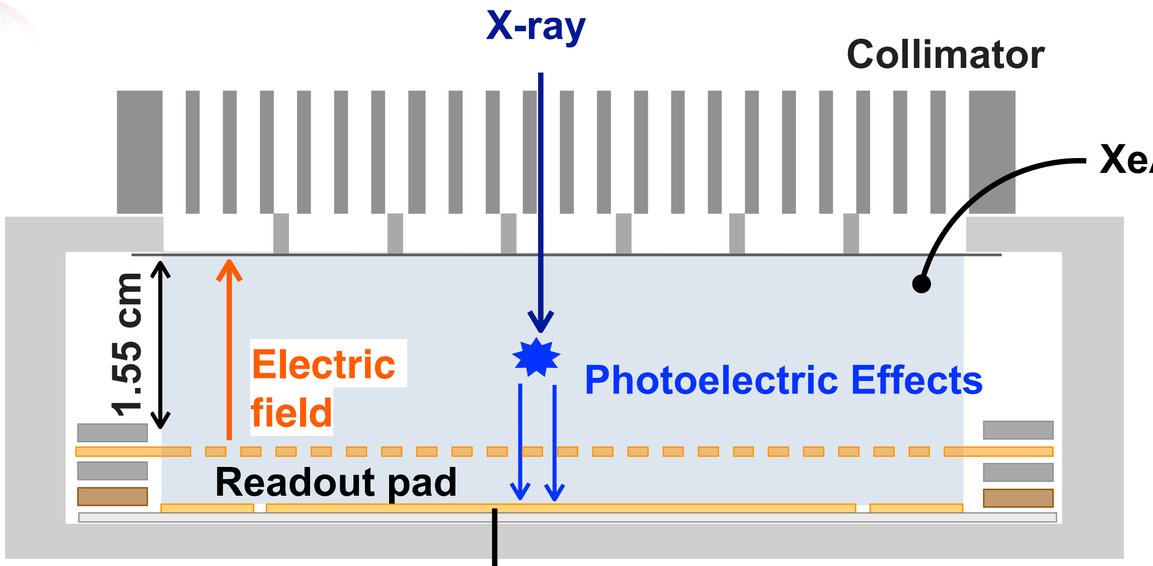
I will introduce how accurate the GMC timing can be.



GMC



GMC X-ray detection and time tagging

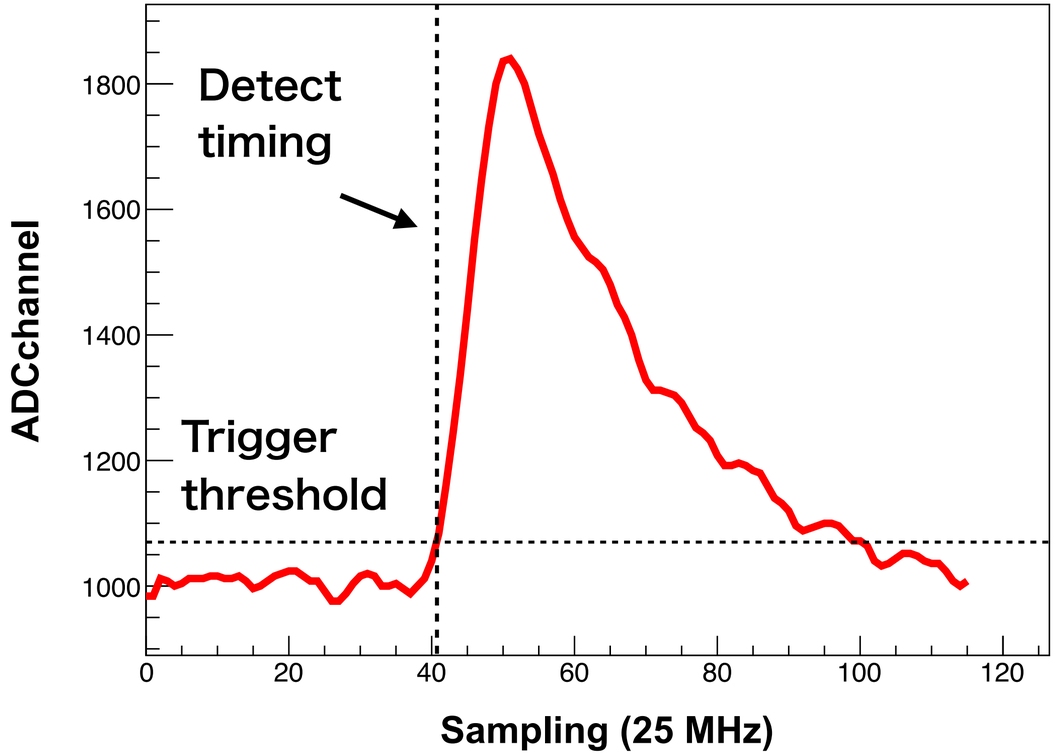


Analog process
(preamplifier=> high pass filter=> main amplifier)

Fast ADC
(2 V / 12 bit, 25 MHz)

FPGA
Time counter

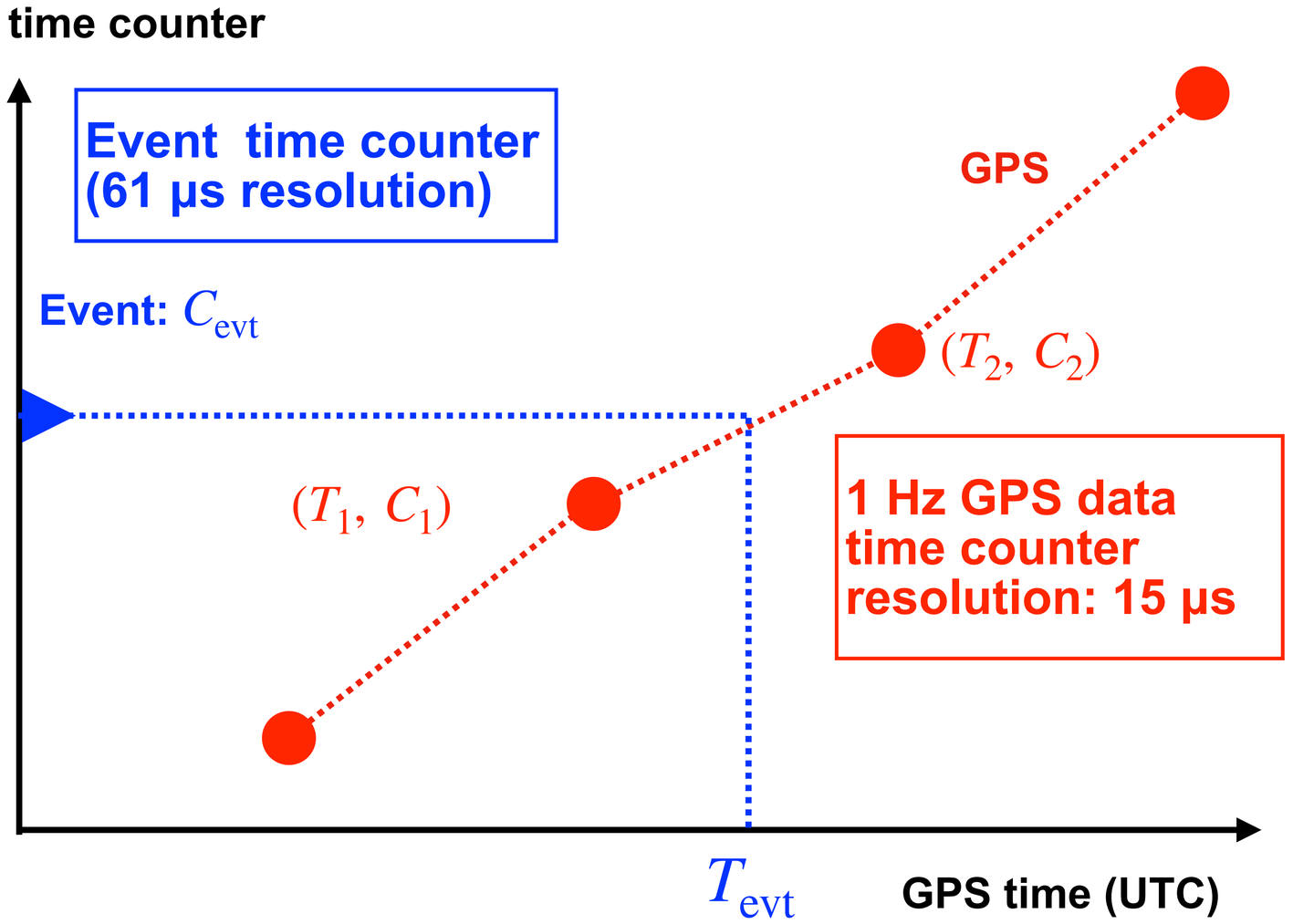
Tag the time counter value with 61 μs resolution (1 s / 2^{14}).



Timing calibration

- The GPS module receives absolute time from GPS satellites.
- Using the GPS pulse-per-second (PPS) signal, **GMC time counter and GPS time are synchronized. (15 µs resolution)**
- Linearly interpolating GPS data yields the absolute detection times of events.

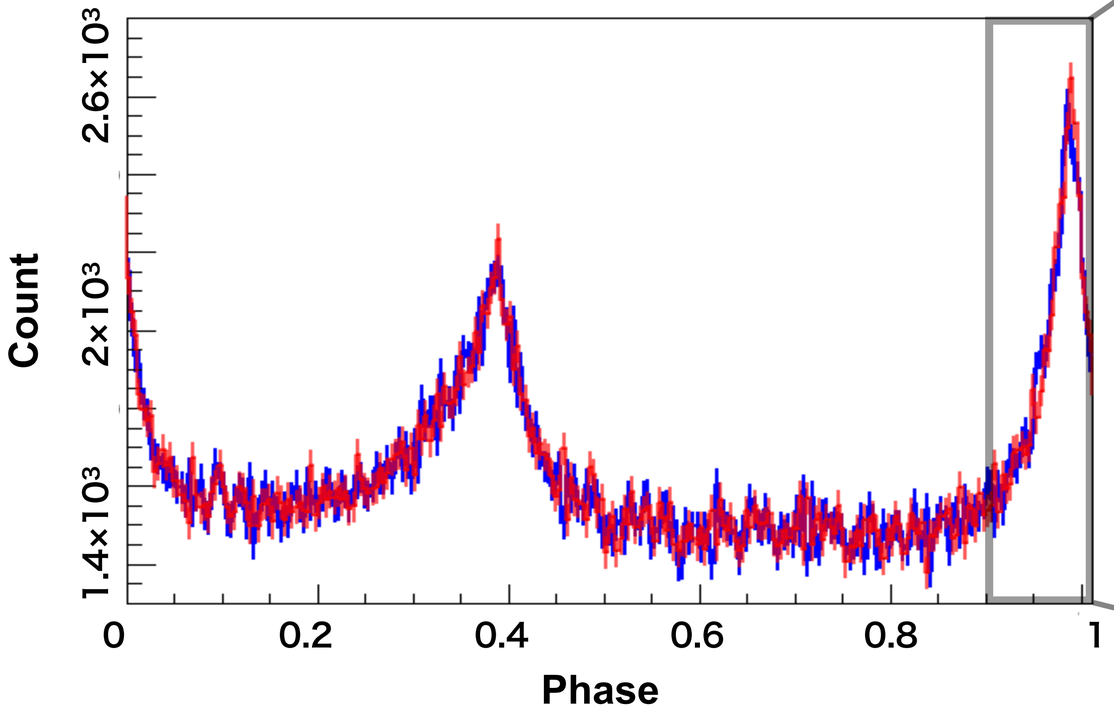
$$T_{\mathrm{evt}} = T_1 + \frac{T_2 - T_1}{C_2 - C_1} \times (C_{\mathrm{evt}} - C_1)$$



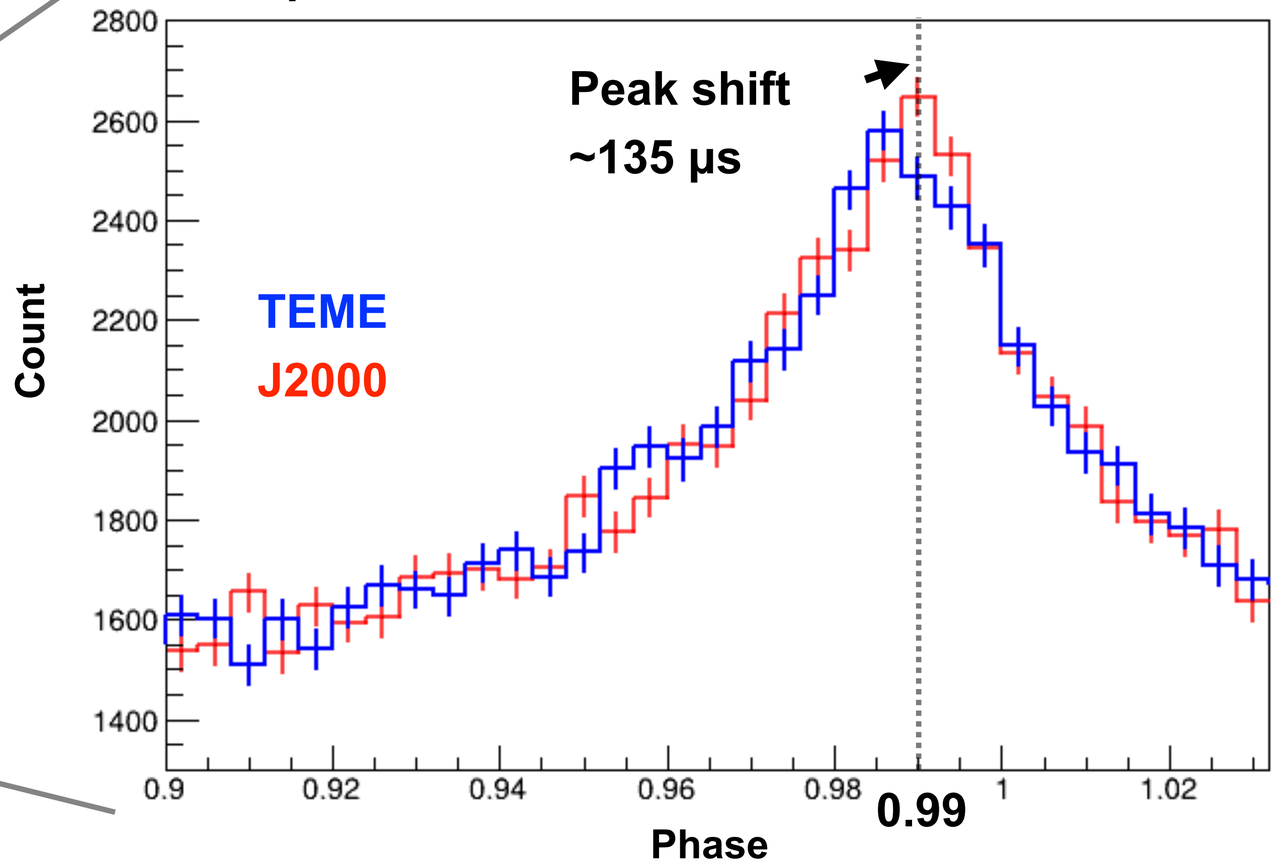
Correction of position coordinates

- ✦Position coordinate should be J2000 for deriving pulse profile
- ✦But not in the IACHEC2024 presentation (we used TEME).

Crab pulsar (MJD 60411)
Apply Jodrell Bank Observatory (JBO) radio phases.



Main peak: 0.9~1.03 Phase



After the correction, the Main peak appears in exact phase.

Increased orbit data recording interval

Planetary ephemeris DE430 is standard for timing analysis.

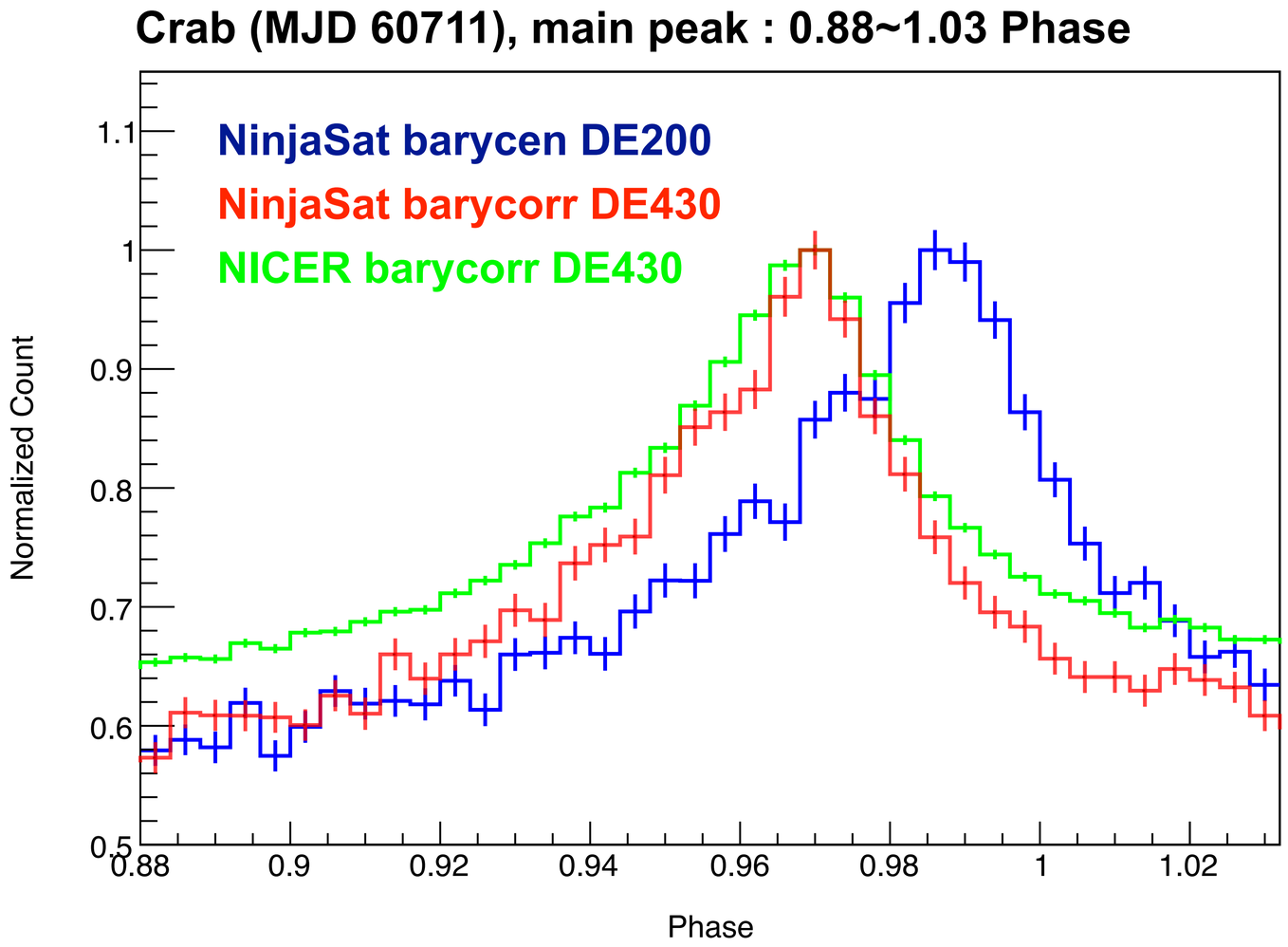
Before (2024 IACHEC meeting)

- ✦Recording interval of orbit data: **60 s**
- ✦Couldn’t use DE430.

After (2024 8/23~)

- ✦ Recording interval changed to **15 s.**
- ✦**'barycorr' can now be used.**
- ✦**Able to use the latest ephemeris.**

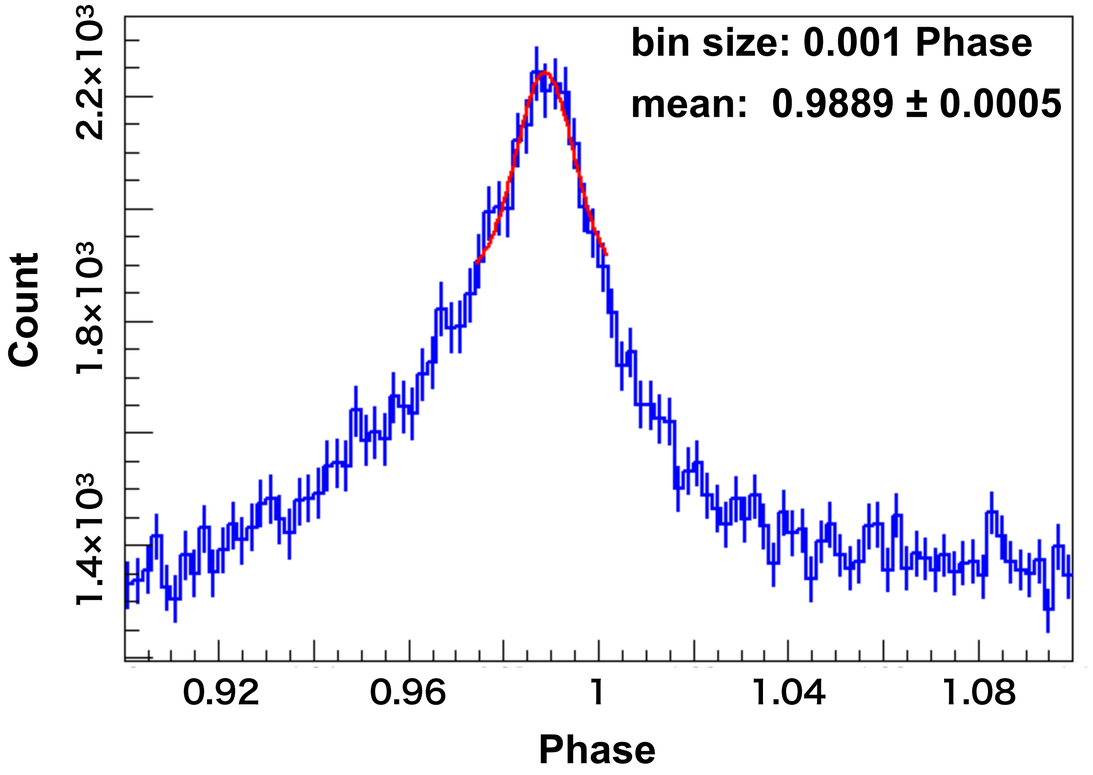
The pulse phase is consistent with that of the NICER using DE430.

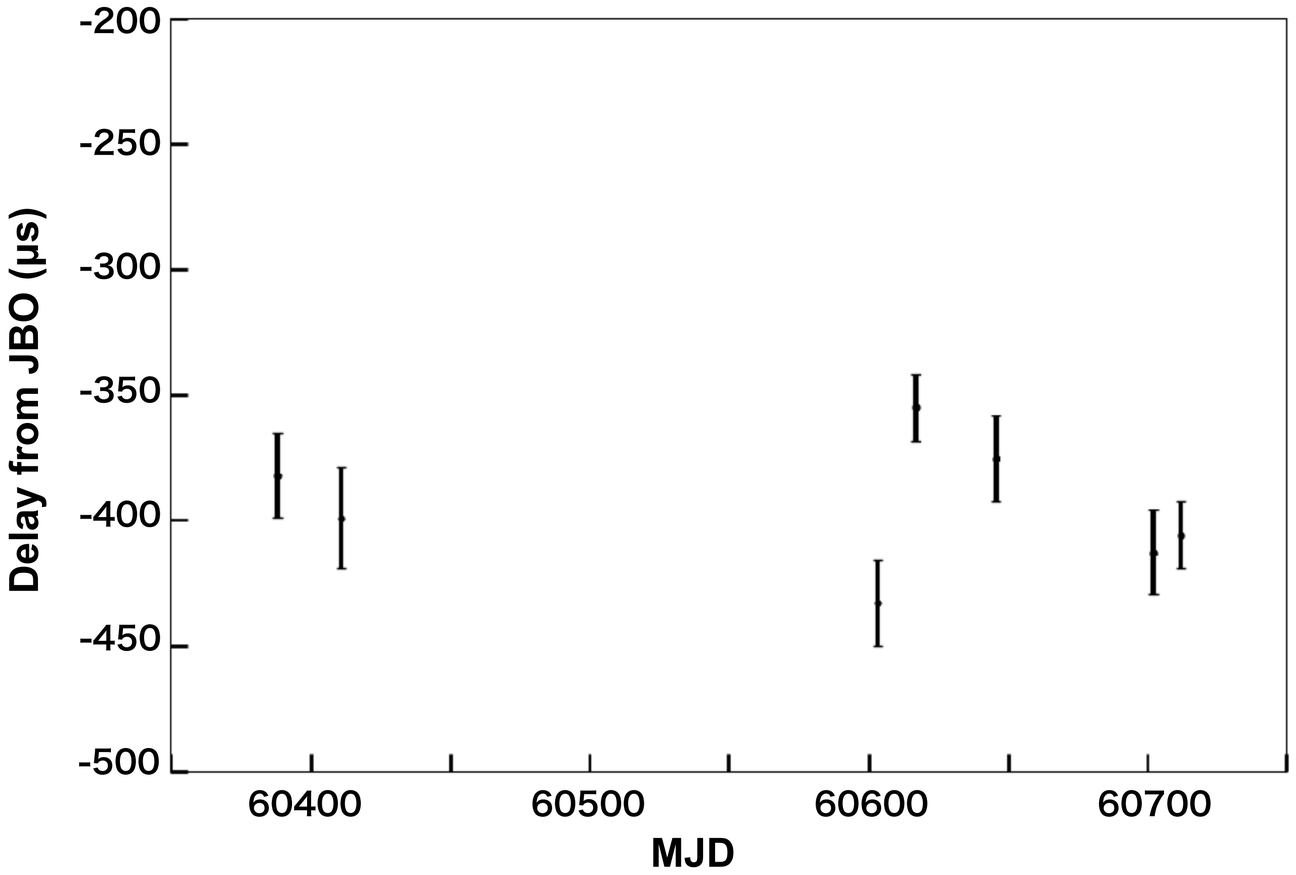


Long-term absolute timing accuracy

- ✦NinjaSat Regularly observe Crab pulsar.
- ✦Check absolute timing accuracy using the JBO Crab ephemeris.
- ✦NinjaSat pulse detection delay from JBO is about 400 μs.

Crab pulse main peak fit (MJD 60646)





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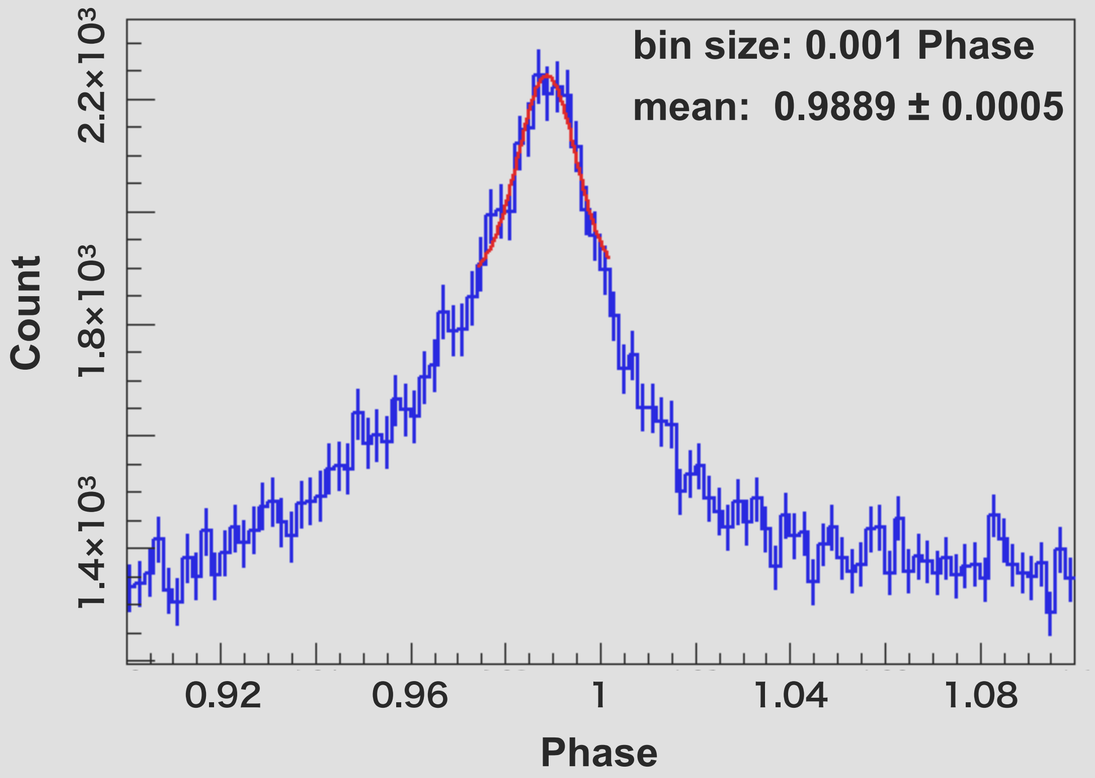
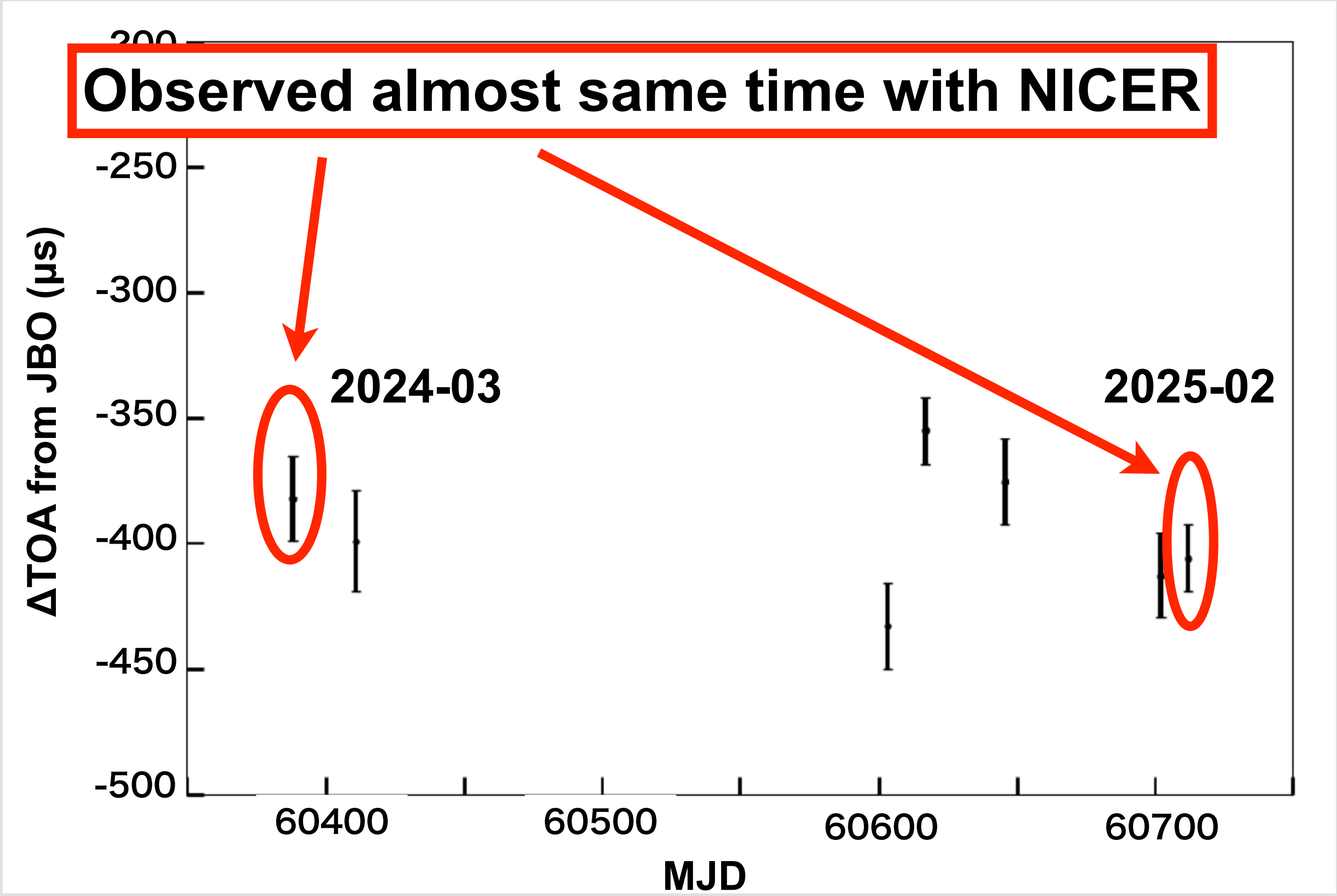




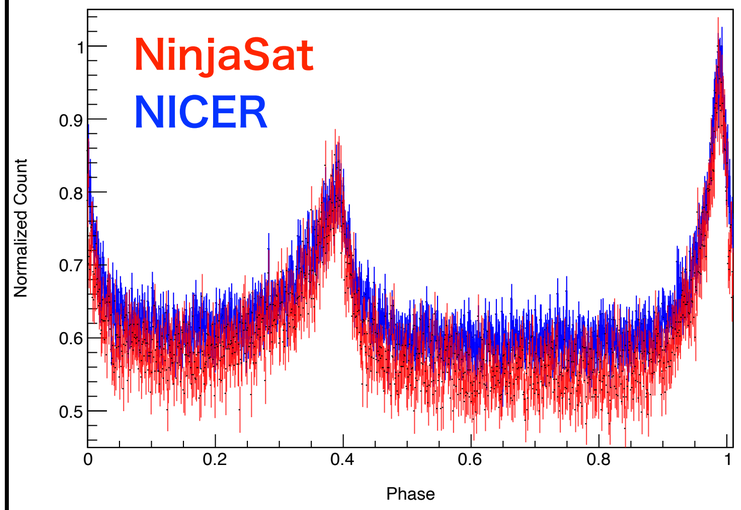
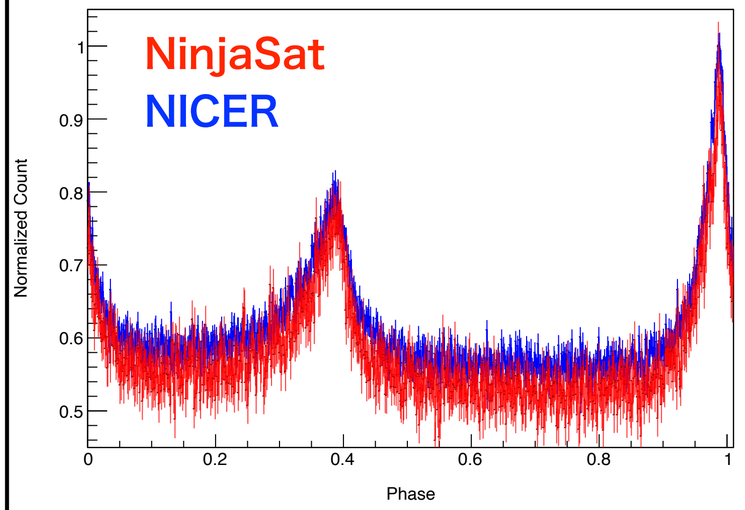
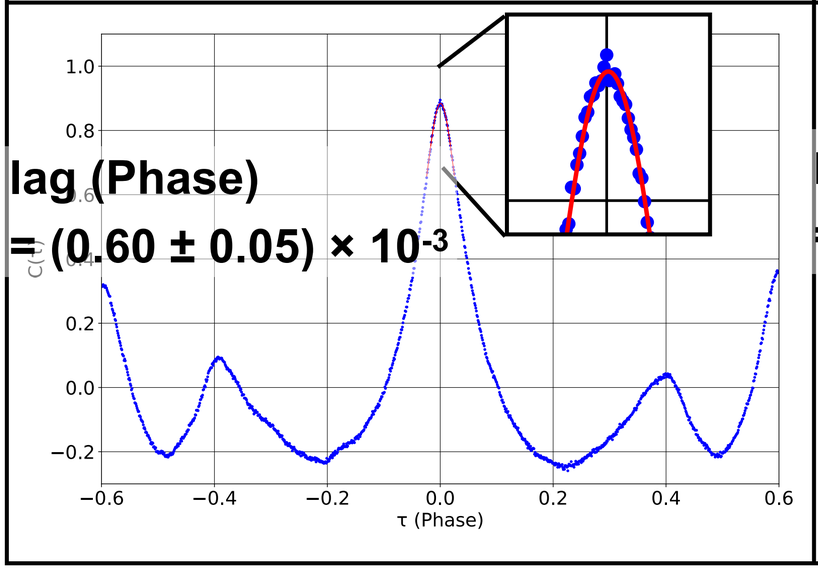
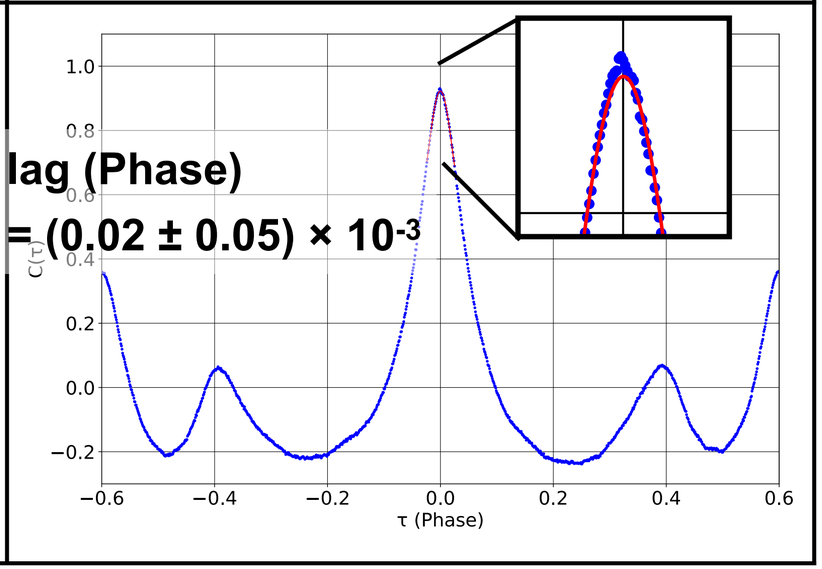
Timing verification with NICER

Pulse profile of Crab pulsar ➔

- ✦ Bin size: 1/1000 of pulse period (~33.8 μs)
- ✦ Energy range: 2–12 keV
- ✦ Folding with JBO Crab ephemeris

Calculate cross-correlation ➔

NinjaSat event time resolution = 61 μs (~2 × 10^{-3} Phase)

MJD 60387	MJD 60711
	
	

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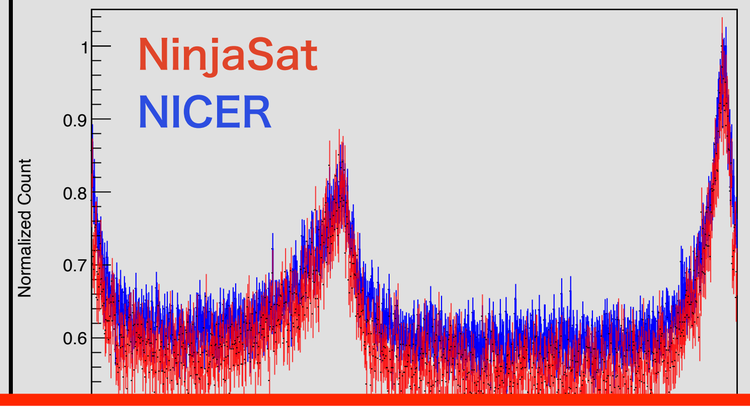
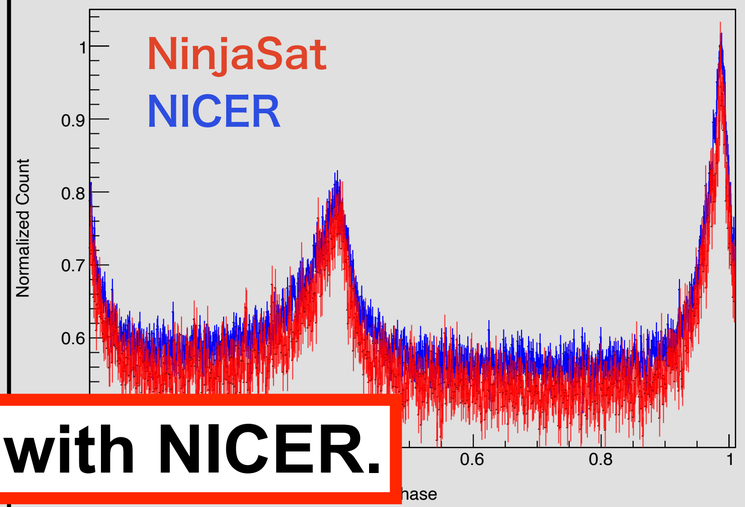
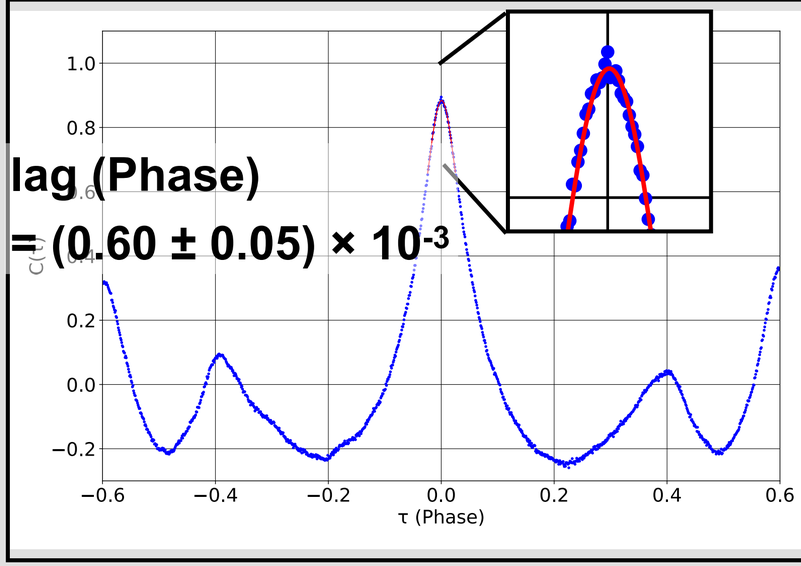
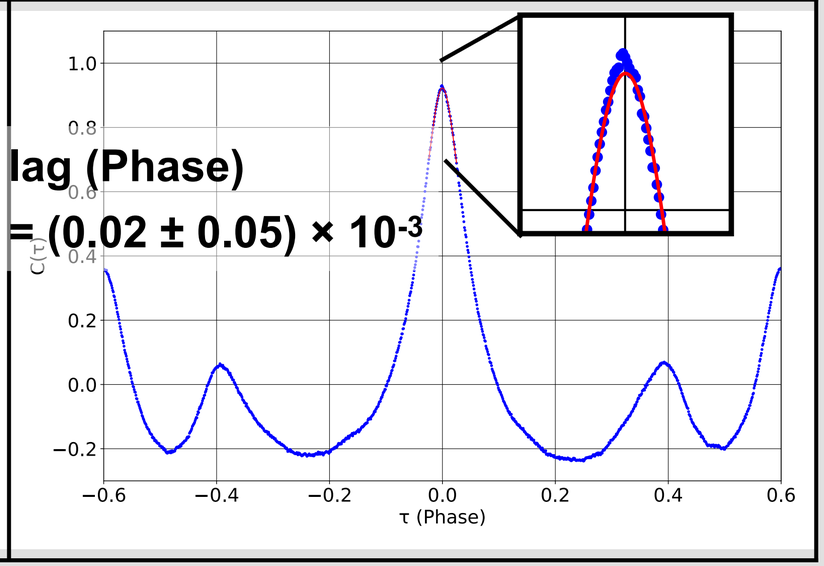
	

NinjaSat's absolute timing is consistent with NICER.

Calculate cross-correlation ➔

NinjaSat event time resolution
= 61 μs (~2 × 10^{-3} Phase)

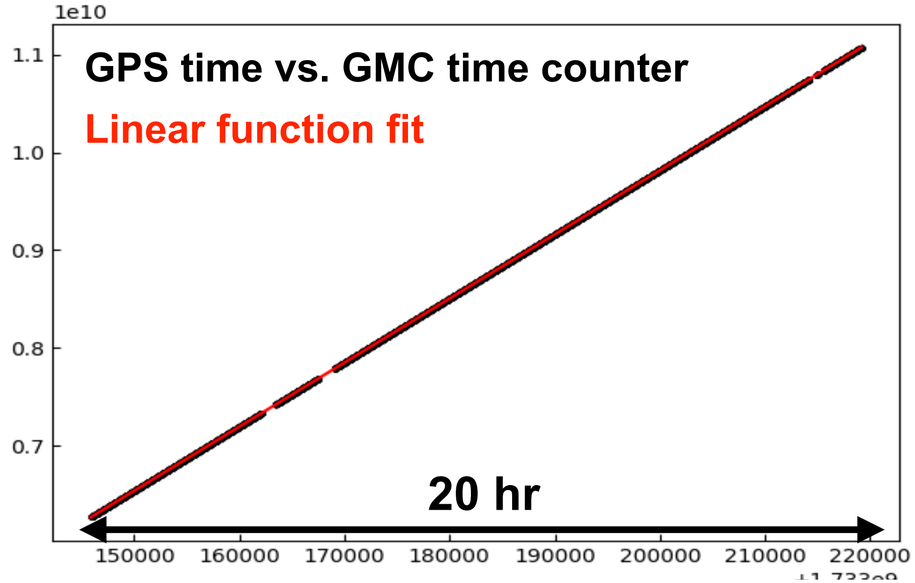
	

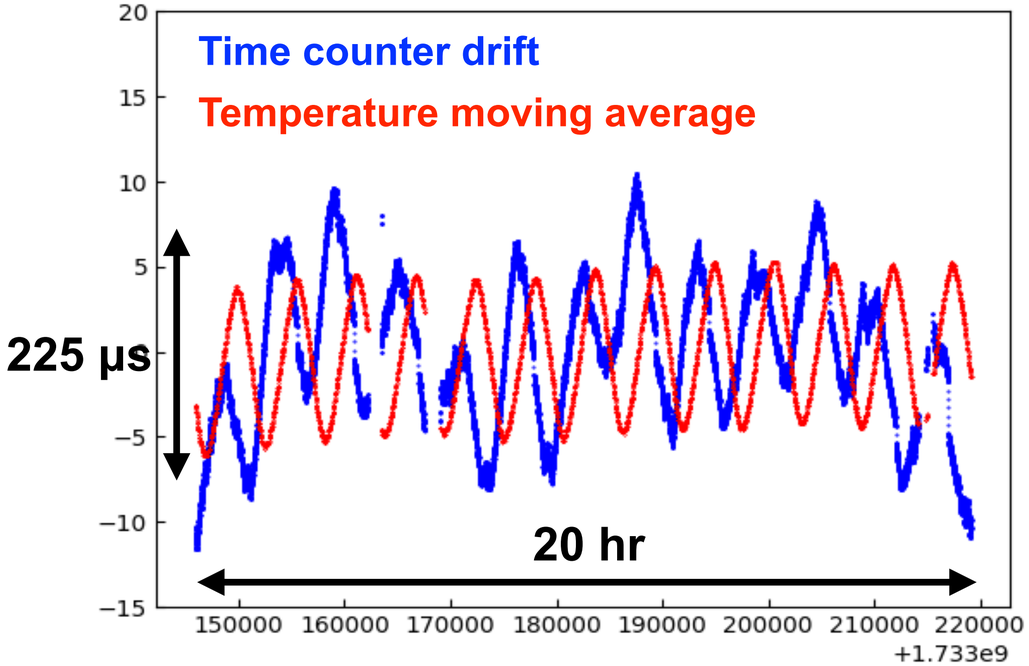
Correct time counter drift

- GPS data is not available about 4 times per month for 10 min - 20 hr due to module latch-up.
- Timing may not be accurate during the lack of GPS data.

Giving accurate time with only start-end GPS data.

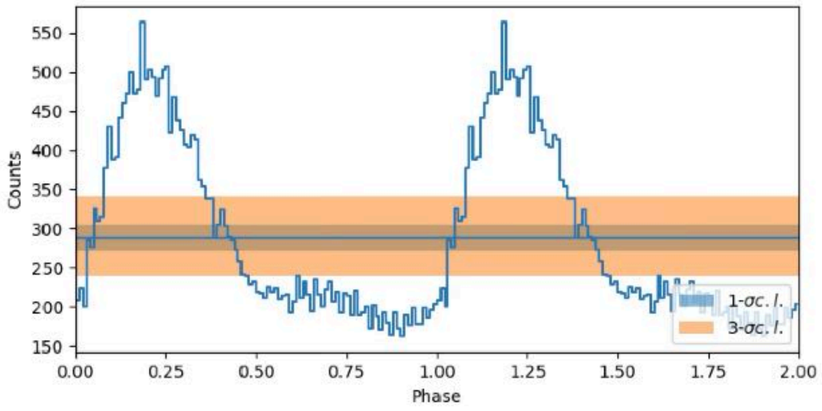
- Linear function fit of
  GPS time vs. GMC time counter
- The residual plot shows time counter drift.
- Drift width is ~225 μs, and has correlation with GMC board temperature modulation

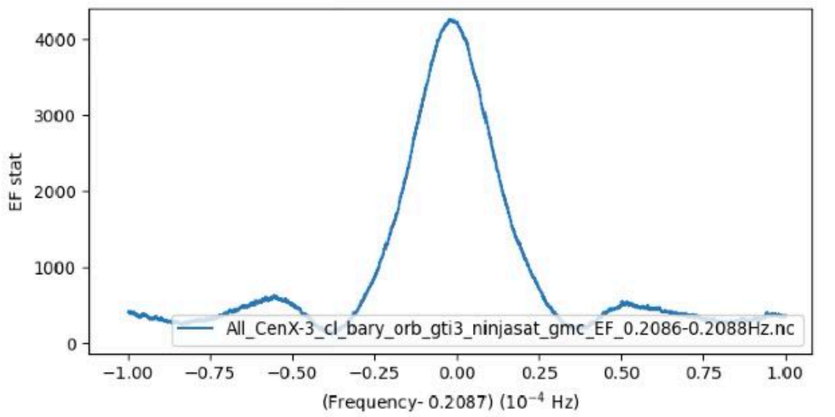


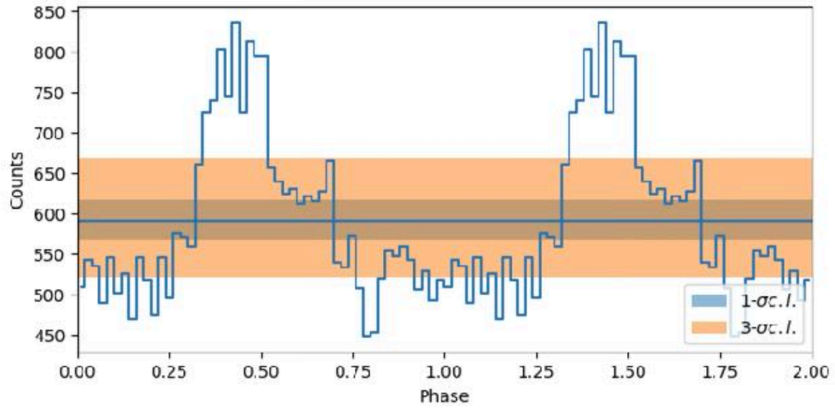


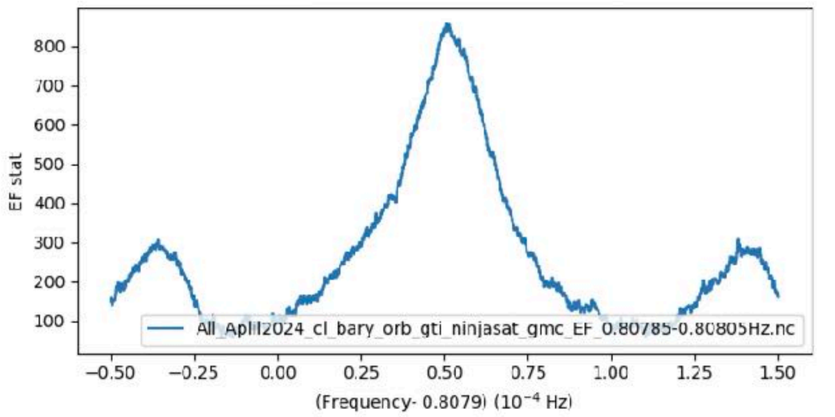
Other NinjaSat timing observations

Cen X-3, 4.79 s pulse	Her X-1, 1.24 s pulse
MJD 60652, **~2.86 ks data**	MJD 60429, **~7.06 ks data**

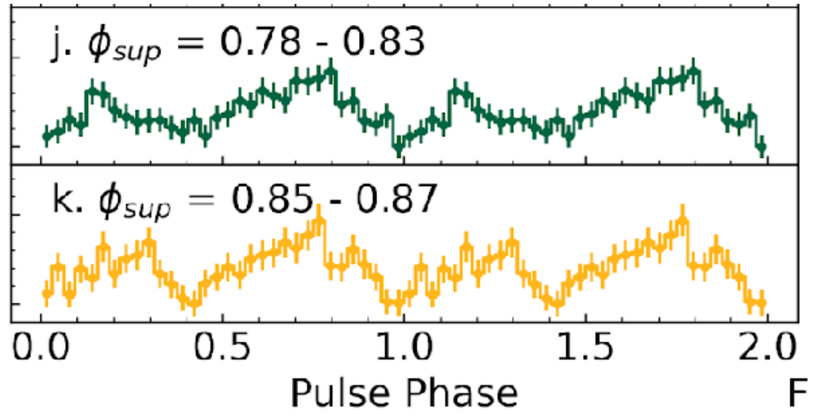








SMC X-1, 0.70 s pulse



Detected the pulse even in low state (~10 mCrab).

Observations covered the entire superorbital modulation.

Summary

✦NinjaSat is a 6U X-ray observatory with two Gas Multiplier Counters (2–50 keV).

✦An on-board GPS module obtains absolute time every second.

✦The recording interval was changed to 15 s, and **able to use DE430.**

✦Crab pulsar is regularly observed for timing calibration.

✦**Absolute timing is consistent with NICER.**

✦Time counter Drift correction is in progress.