Timing calibration of the CubeSat X-ray observatory NinjaSat

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NinjaSat overview

Observation purpose

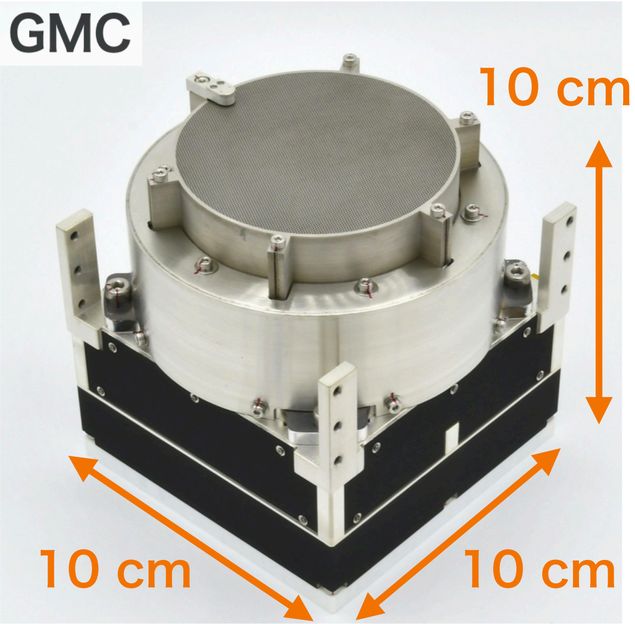
- Long-term monitoring of bright X-ray sources.
- Follow-up observations of unexpected objects.
- Multi-wavelength observations in conjunction with radio and optical window.

Satellite bus

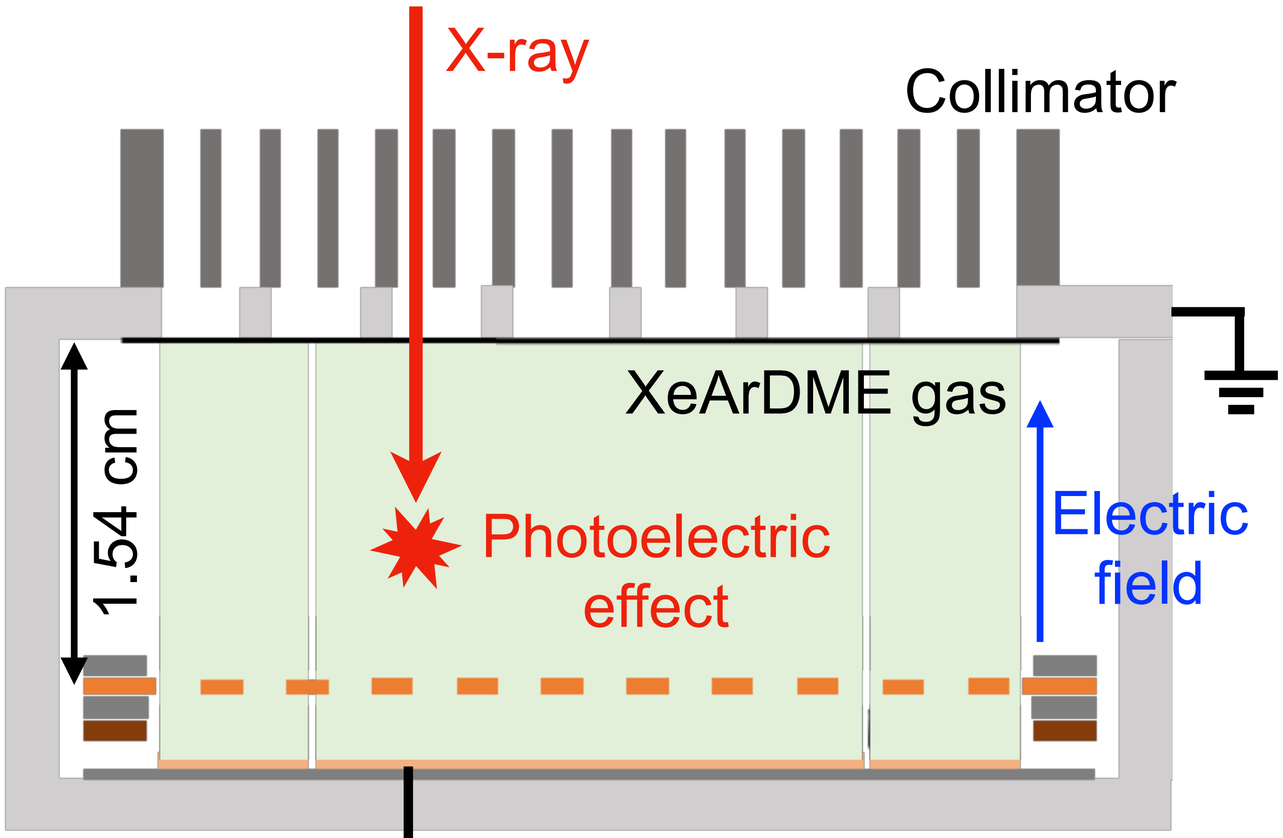
- Mass: 8 kg, Power: 16 W.
- Sun-synchronous polar orbit at an altitude of 530 km (orbital period: 95 minutes).
- Receive absolute time and location information from GPS satellites (NMEA format).

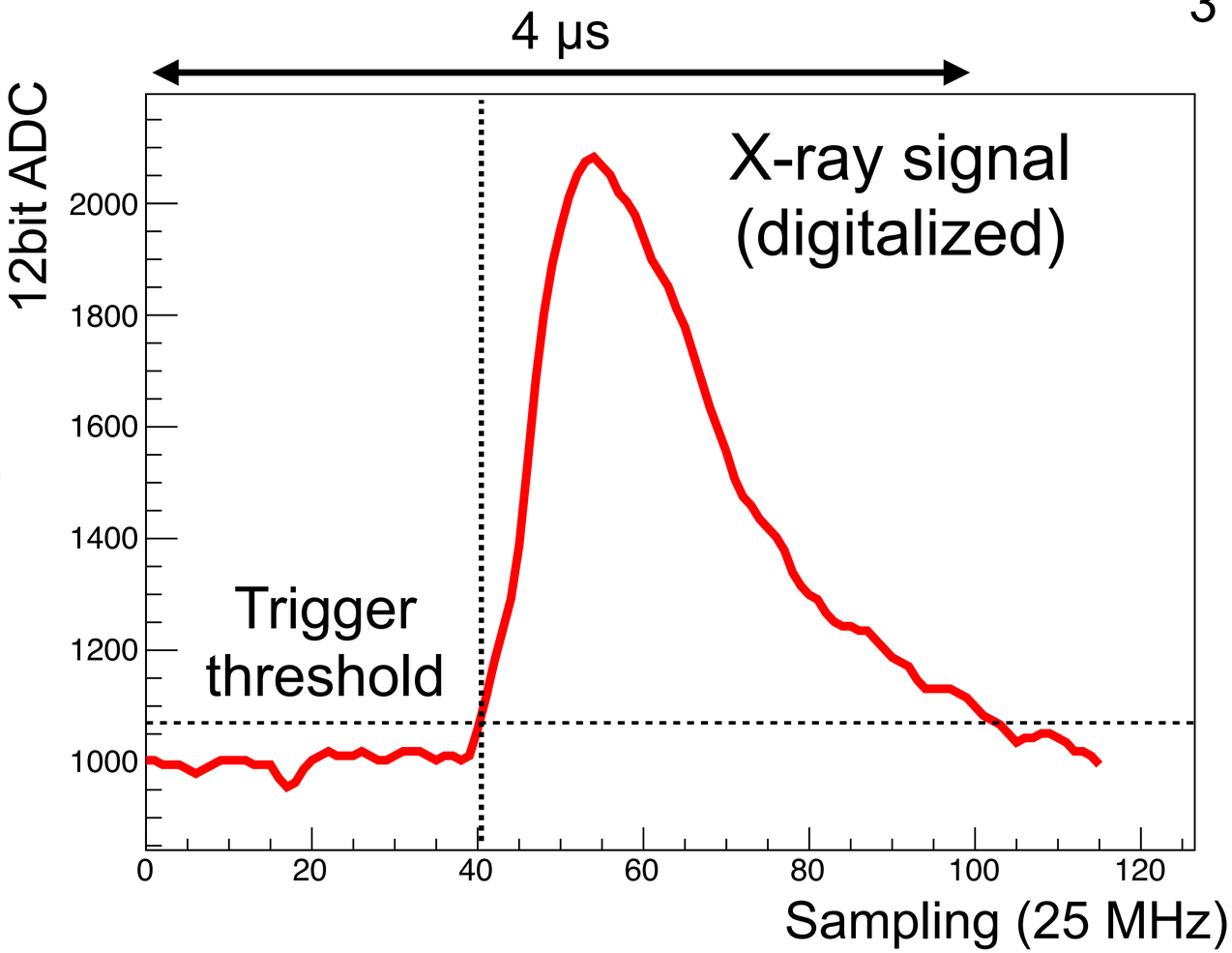
Gas Multiplier Counter: GMC

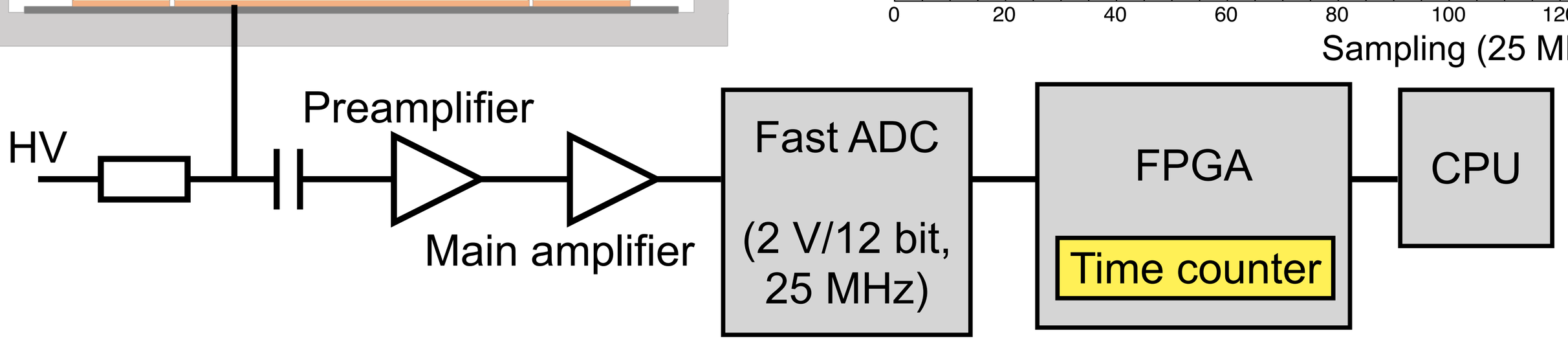
- Energy band: 2-50 keV
- Effective area (total of 2 units): 32 cm^2 @ 6 keV
- Time resolution of X-ray detection: 61 μs.
  => X-ray timing measurements with ms accuracy.



GMC X-ray detection flow

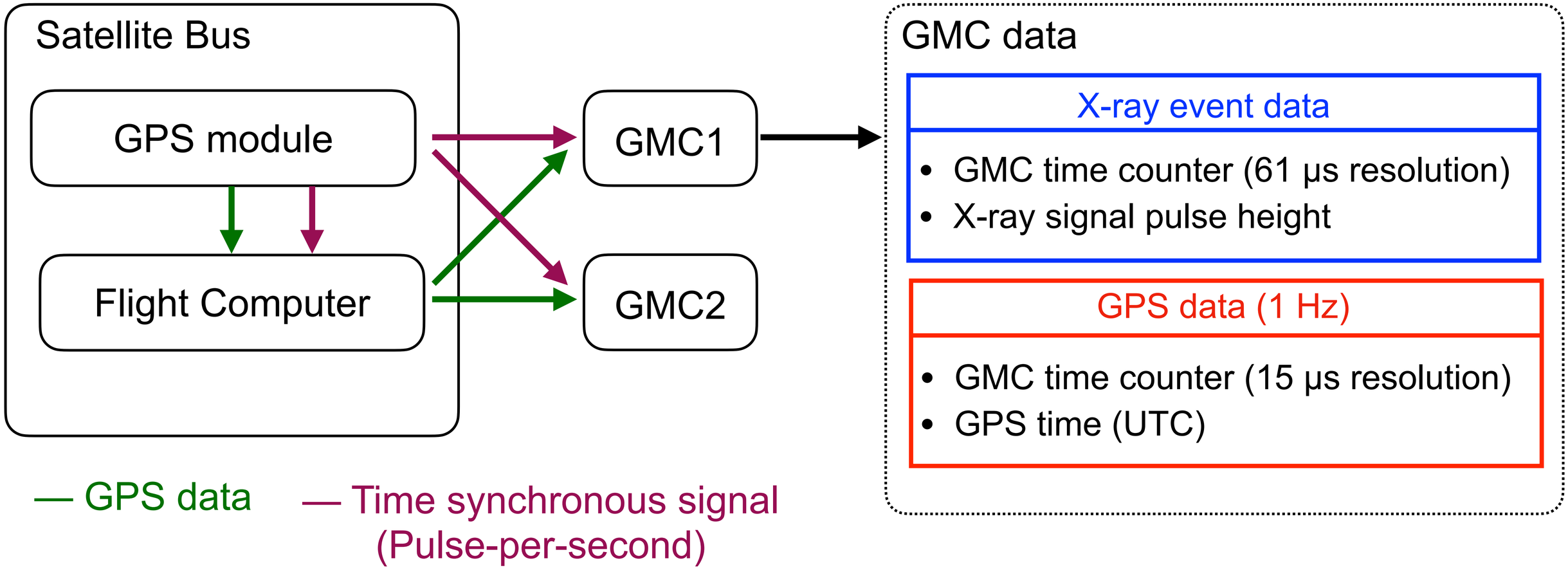






Time assignment system on the satellite

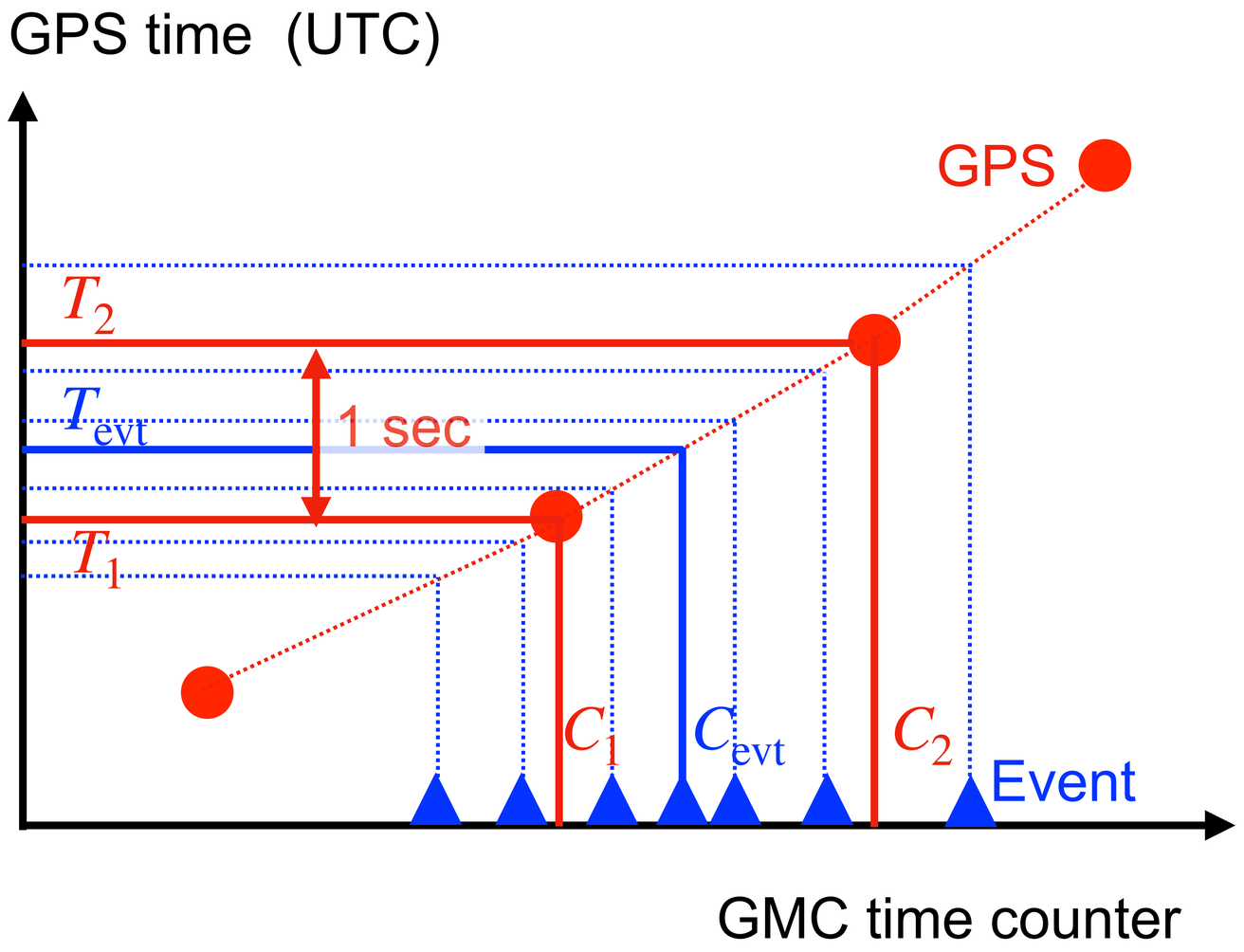
- GMCs measure times of X-ray events with an internal time counter (61 μs resolution).
- GPS module receives absolute time from GPS satellites and stores it in the Flight Computer.
- GMC time counter and GPS time are synchronized by Pulse-per-second signal.



Time assignment system on ground

- Interpolate GPS absolute time acquired in synchronization with the GMC time counter.
- Absolute time information are assigned to X-ray events.

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

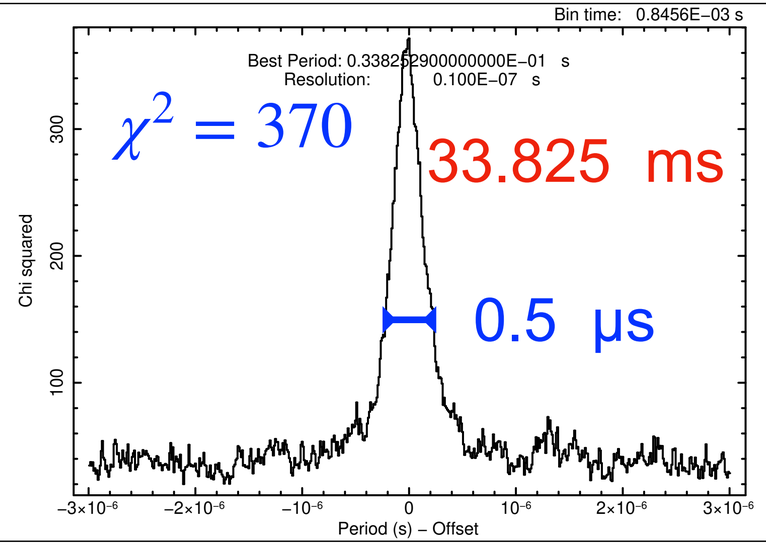


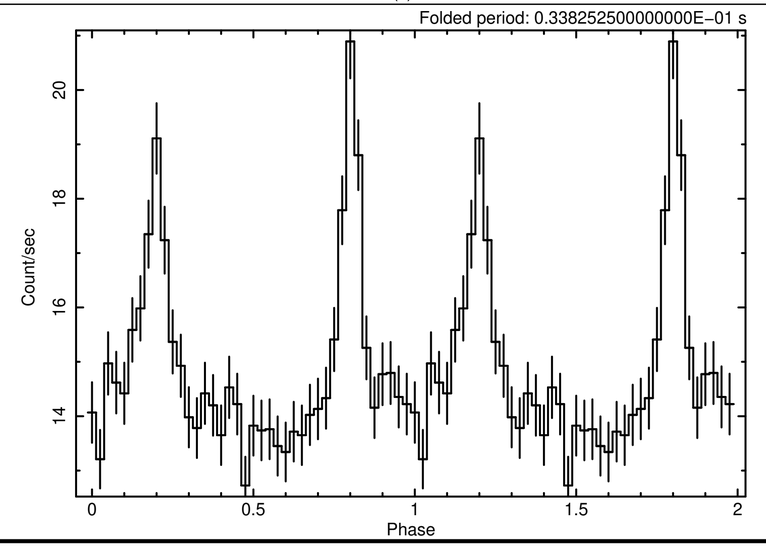
Demonstration of periodic signal profile

Pulse profile examples of **~1 ksec** observation data of pulsars.

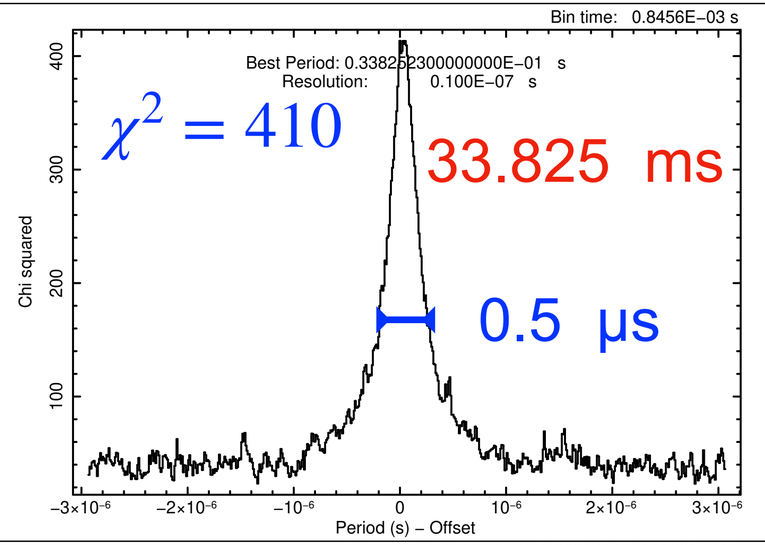
Crab pulser (MJD 60362)

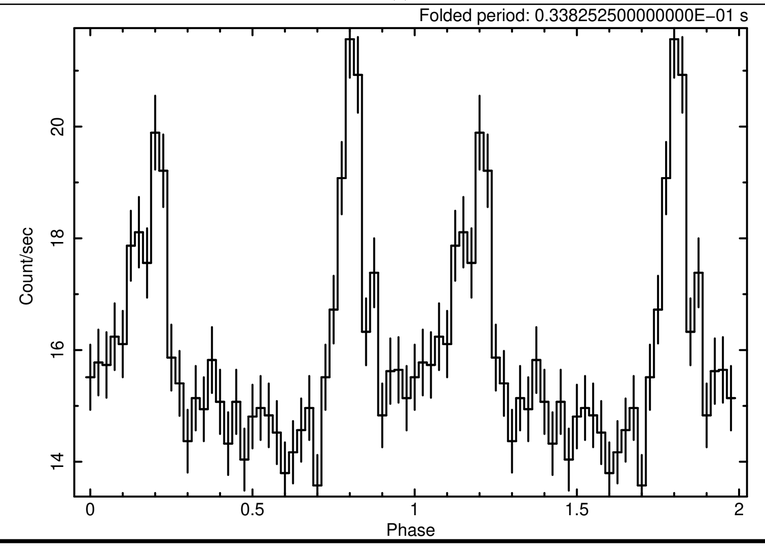
GMC1



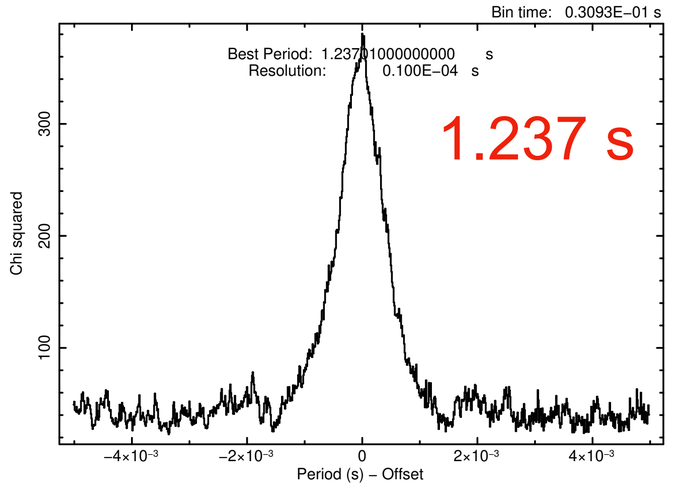


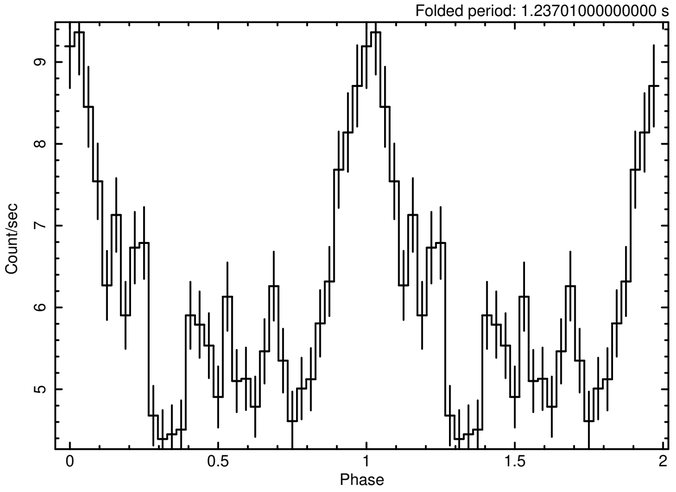
GMC2





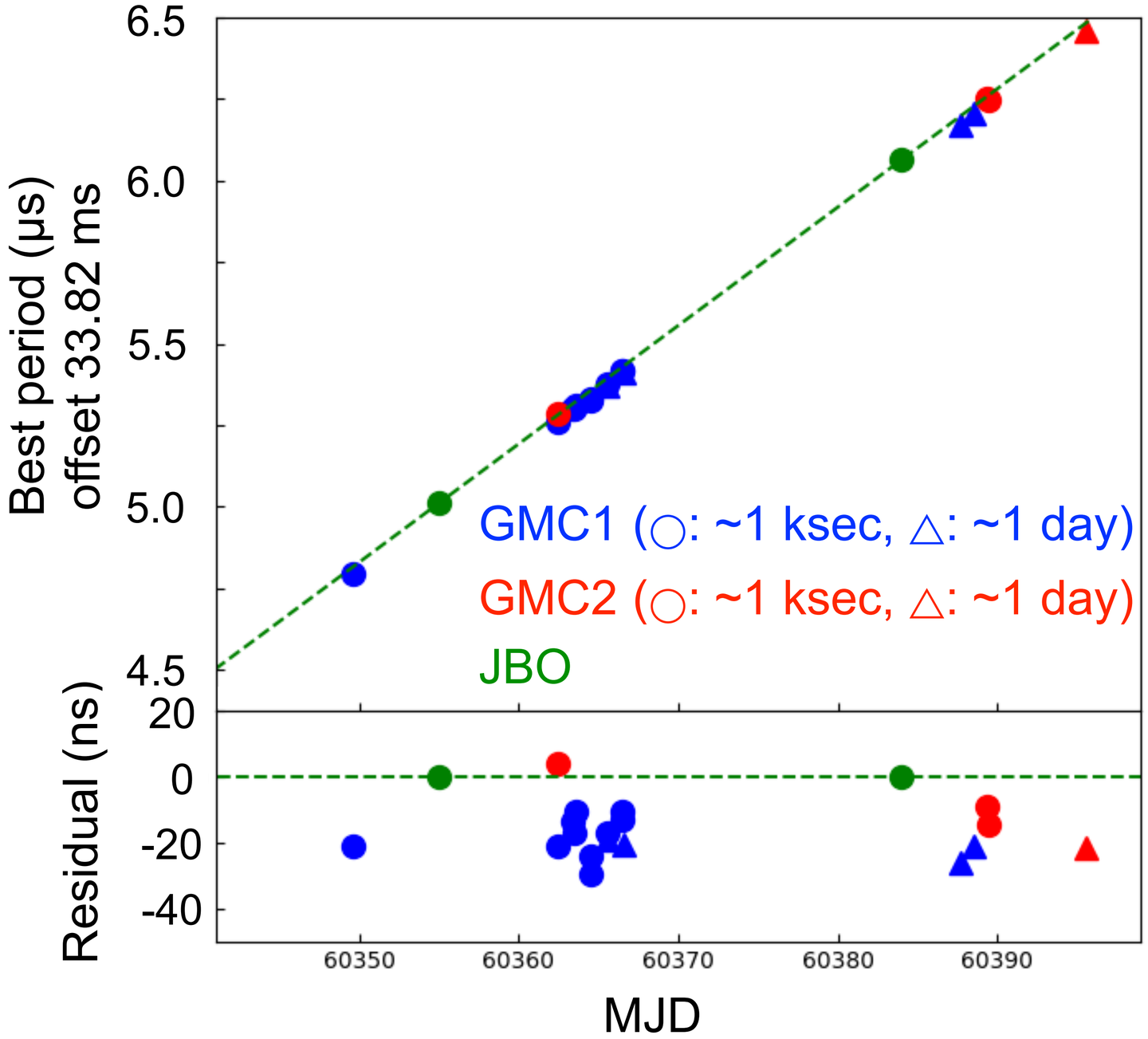
Her X-1 (MJD 60427)





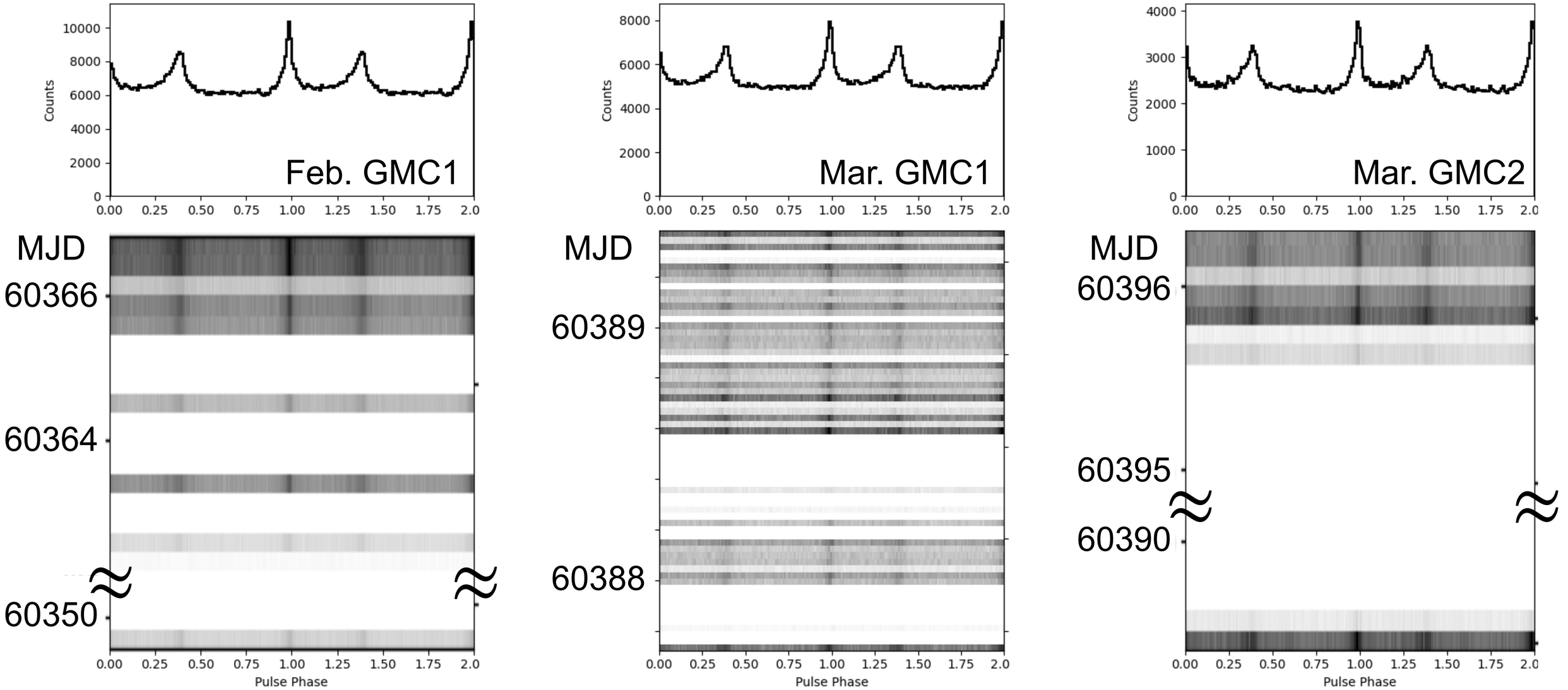
Relative timing verification

- Compare measured crab pulsar period with Jodrell Bank Observatory (JBO) radio observation data.
- GMCs and JBO data are consistent within 50 nsec.
- GMCs can measure relative period enough accurately.



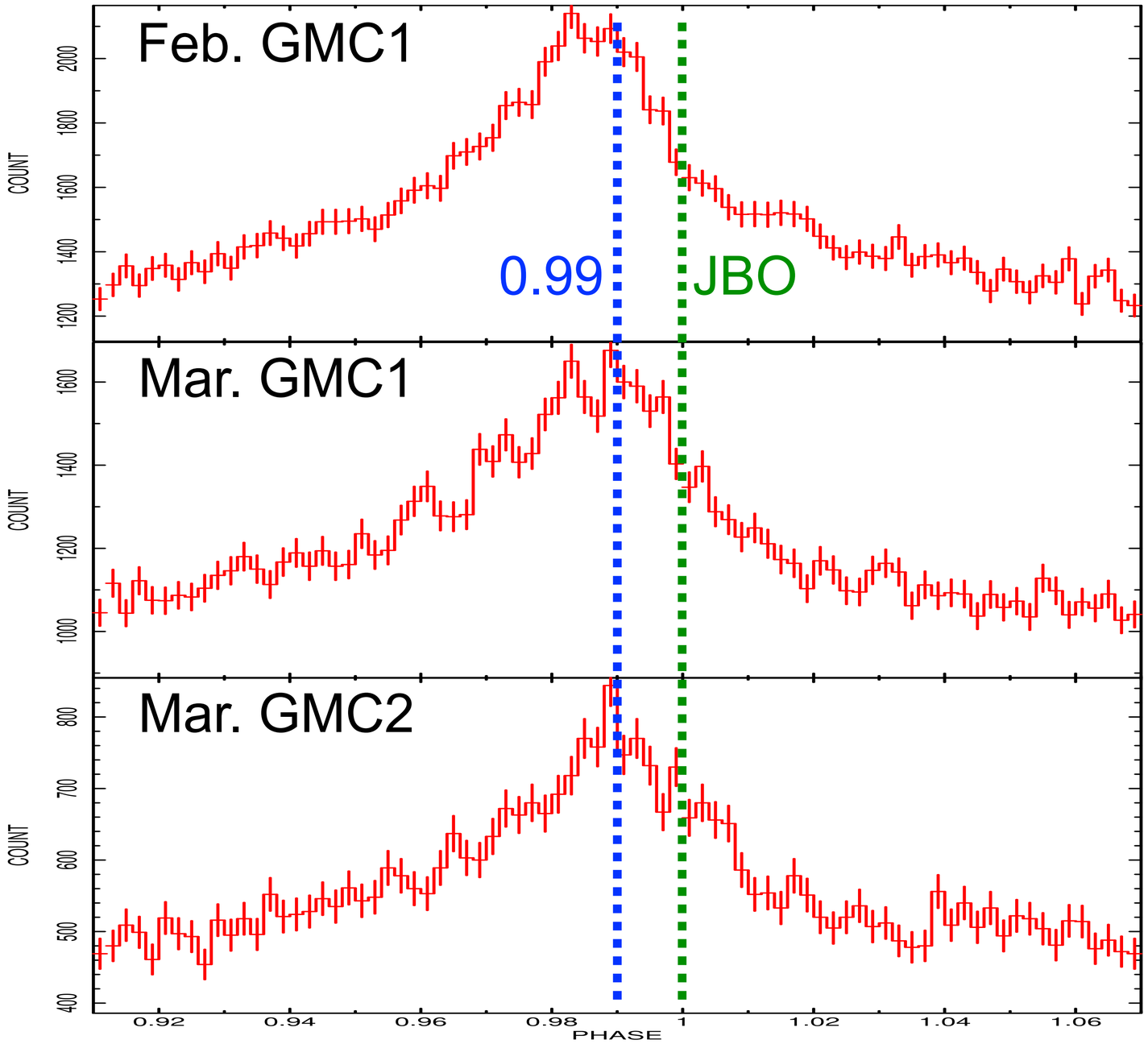
Absolute timing verification

- Add photon phase to Crab pulsar X-ray events detected by GMC based on JBO radio data.
- Primary peak phases are around 1.0 during the entire (February and March) observation.



Absolute timing verification

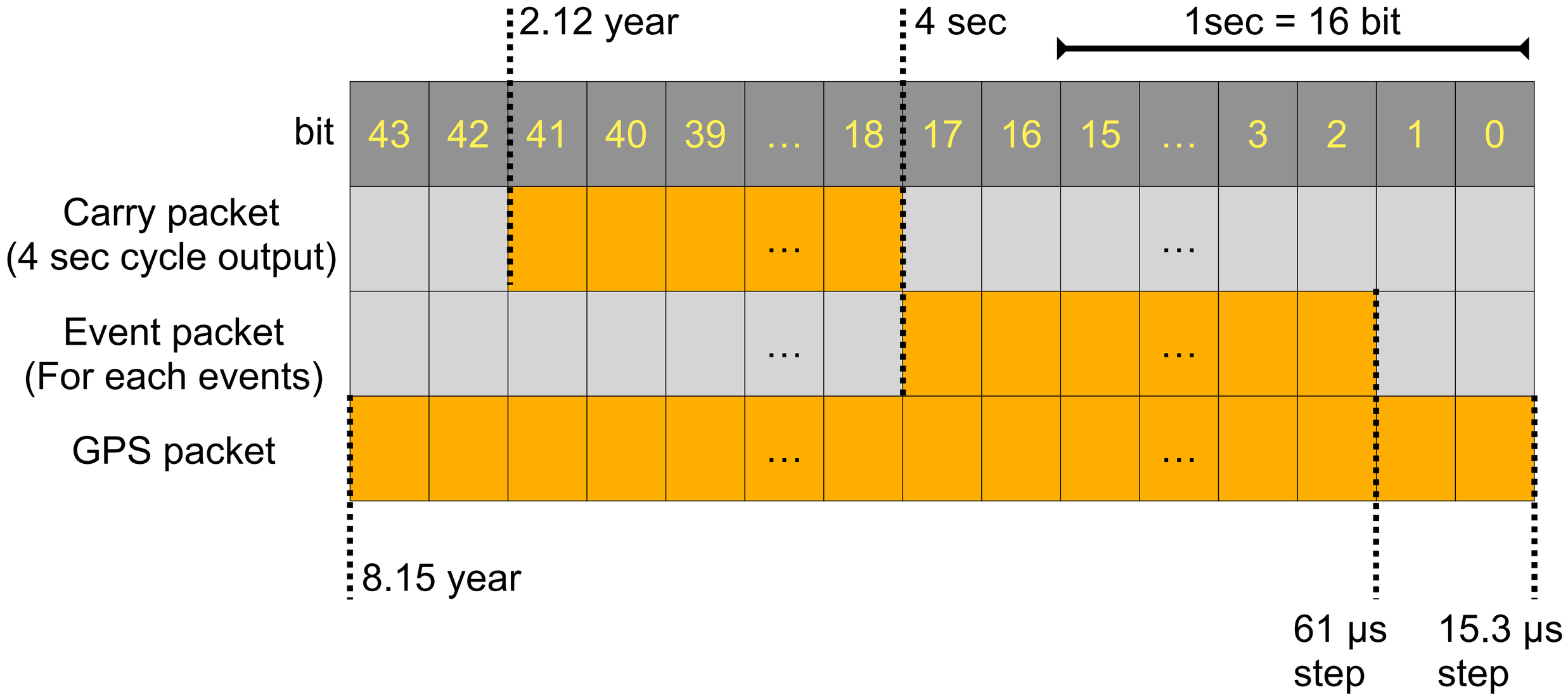
- The phases of the primary peak are distributed in 0.98–0.99.
- The pulse peak in X-rays is known to precede that in the radio band by 0.01 phase (0.34 ms) [Enoto et al. 2021]
- GMCs measurement accuracy of absolute time ~ 0.34 ms.



Summery

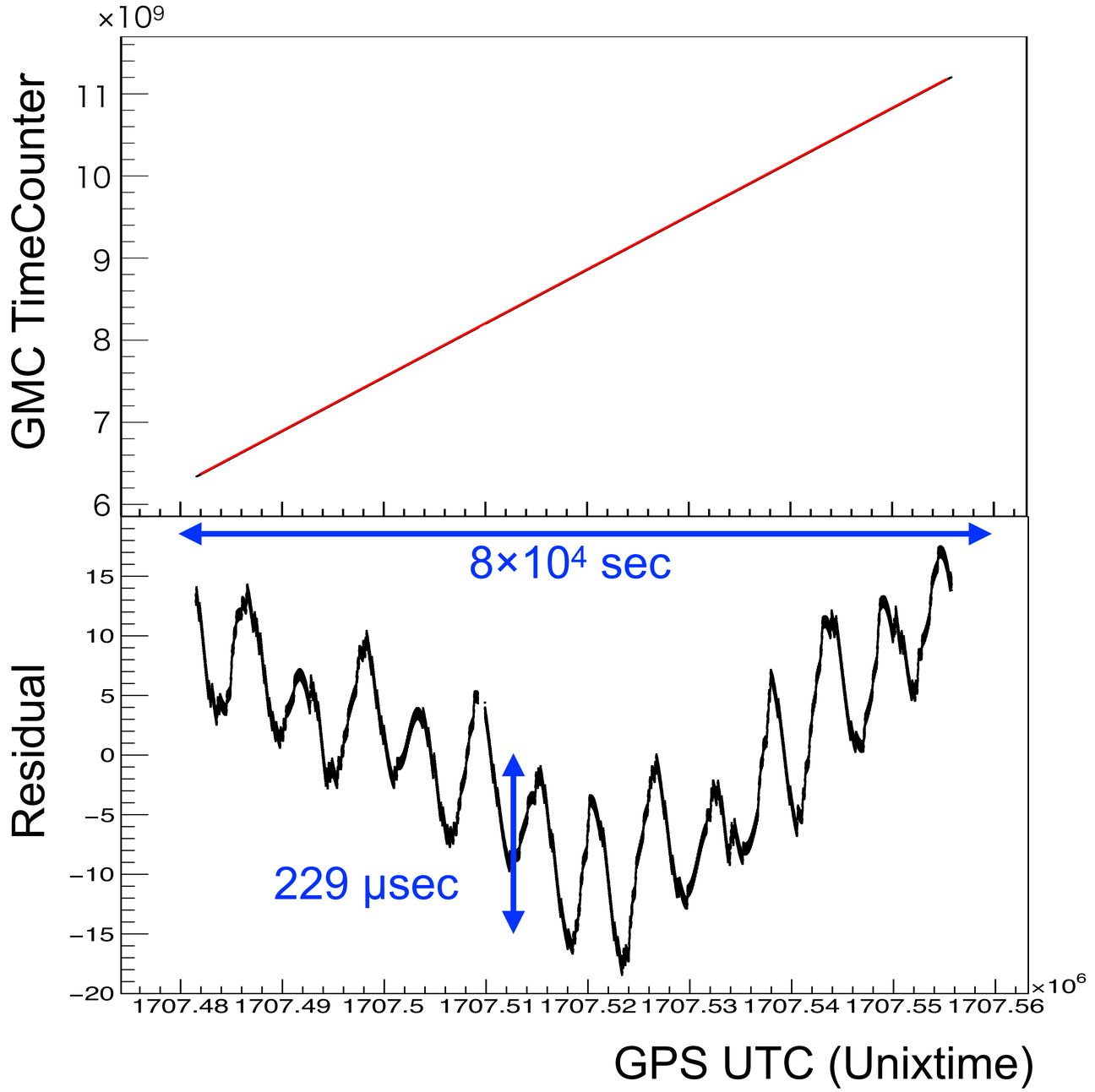
- NinjaSat aims to measure X-ray timing with ms accuracy.
- The X-ray detector GMC onboard NinjaSat measures X-ray arrival time with a time counter with 61 μs resolution. GPS receiver is also onboard and GPS data is used for time assignment.
- Crab pulser periods measured by GMCs are consistent with JBO radio band observation within 50 nsec. GMCs measure relative timing with the required accuracy.
- From ephemeris analysis based on JBO Crab Pulsar observation data, the absolute time measurement accuracy of GMCs ~ 0.34 ms.

Detail of GMC Time Counter data



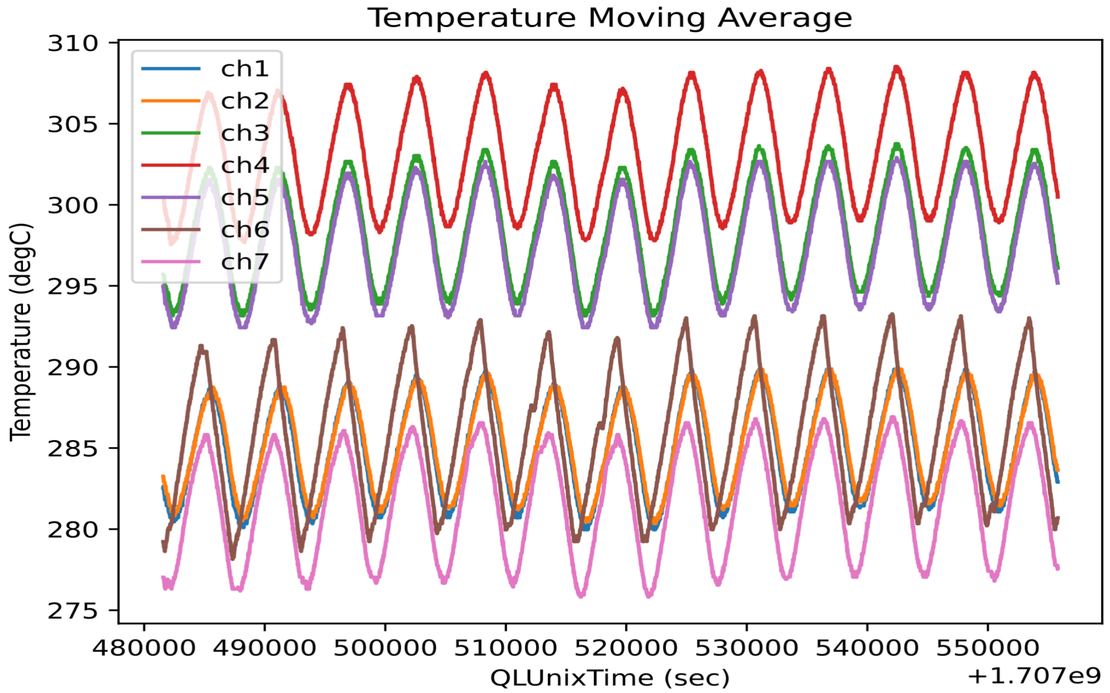
GMC Time Counter drift

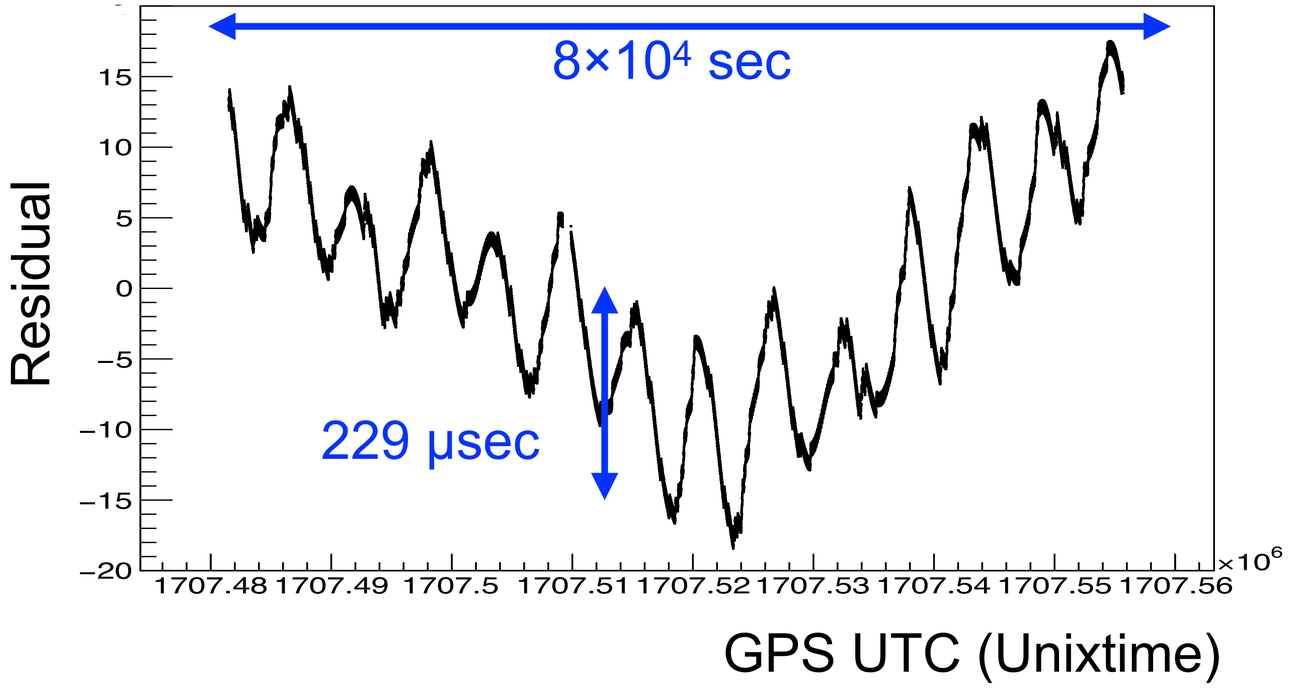
- Linear function fit of the GPS time and the GMC time counter
- The residuals plot shows drift with amplitude of hundred μsec.
- If GPS fails to acquire for a long time (several tens of minutes), a simple linear completion of the X-ray event times will cause a deviation.



GMC Time Counter drift

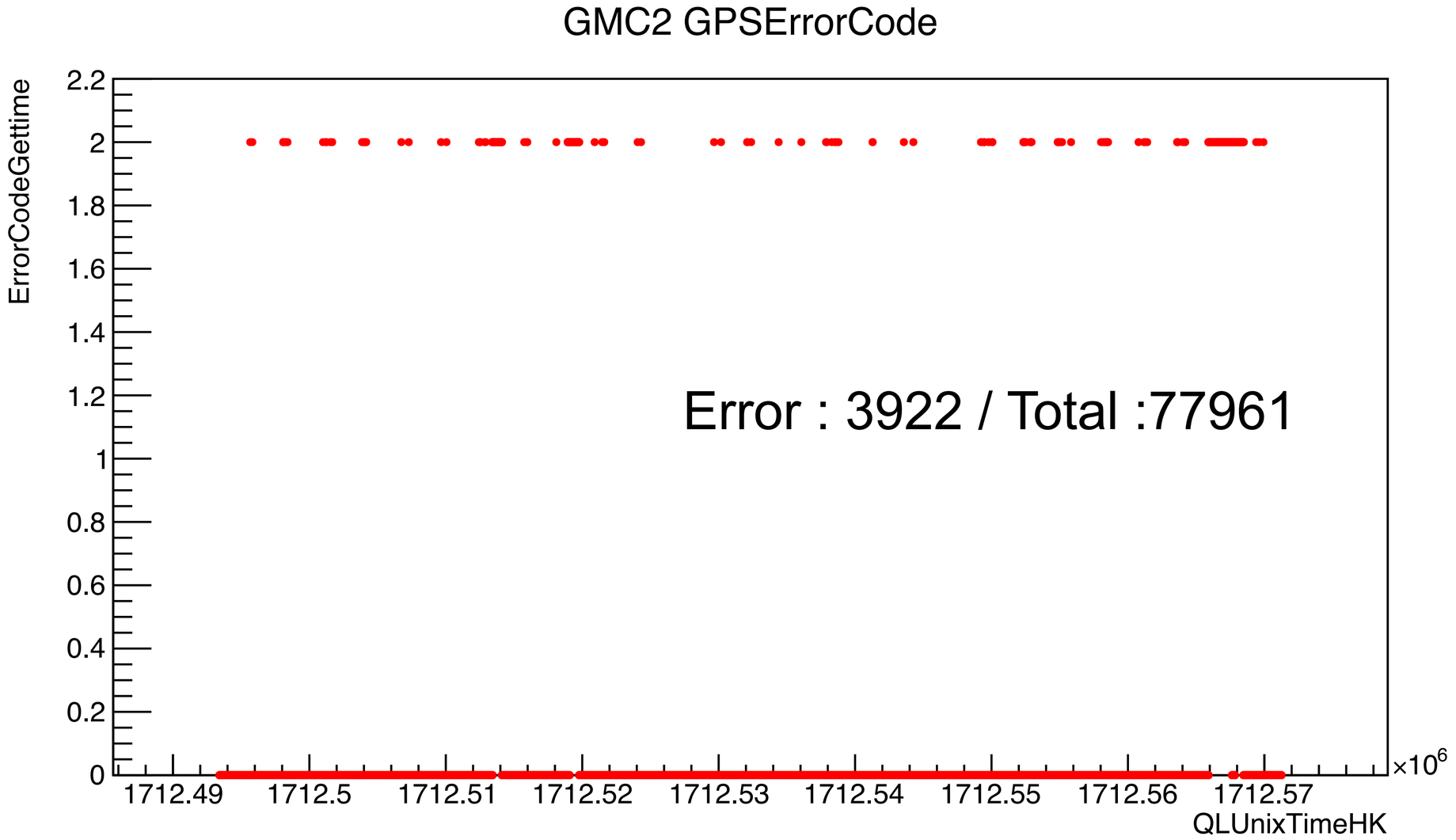
- One possible cause of the drift could be temperature fluctuations of the oscillator on the electronic board.
  (Details have not yet been investigated.)
- Temperature fluctuation has an oscillation amplitude of 10-15˚C in an orbital period of 95 min.





GPS acquisition success rate

An example of the percentage of successful GPS acquisitions in a day.
1-2 hours of failure in a day (~ 80–90% success).

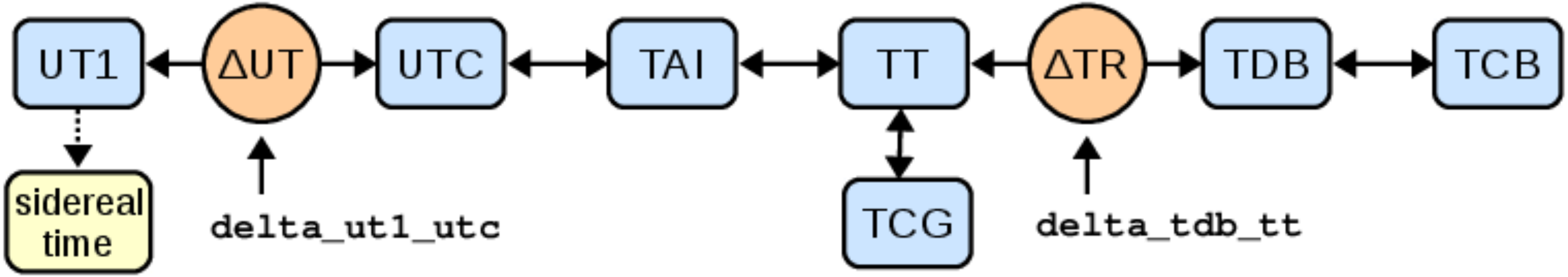


NinjaSat mission time system

Refer NICER TIME system

MJDREFI = 56658 / [d] MJD reference day (2014-01-01T00:00:00)
MJDREFF = 0.00077759259259259 3 / [d] MJD reference (fraction of day)
TIMESYS = 'TT ' / Reference time system

Convert time system using astropy.time



https://docs.astropy.org/en/stable/time/

NICER X-ray pulse profile and Radio pulse

Enoto et al. 2021