

Pulsar backend for 21CMA: implementation and progress

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1. 21CMA



1.1 21CMA



Figure 1: Bird-view of some station of
21CMA East-West arm

- Main goal: Epoch of Re-ionization (EoR); Pulsar and Transients
- Frequency: up to 50 – 350 MHz
- 81 hexagon-shaped stations

1.2 21CMA Pulsar Backend

- 21CMA 脉冲星终端的研发工作是 **平方公里阵列射电望远镜 (SKA) 专项 SKA 脉冲星搜寻预研项目 (负责人: 朱炜玮)** 的一部分
- 21CMA 脉冲星终端的研发工作还得到了以下项目与课题的支持:
 - 平方公里阵列射电望远镜 (SKA) 专项 脉冲星测时和检验引力理论项目 (负责人: 李柯伽)
 - 平方公里阵列射电望远镜 (SKA) 专项 面向宇宙再电离探测的低频实验与观测项目 21CMA 观测与多波束技术课题 (负责人: 顾俊骅)

1.2 21CMA Pulsar Backend

Parameter	Value
Antenna	
# of Station	20 (short-term), 81 (long-term)
Station Diameter	16 m
Effective Diameter	~ 50 m (short-term), ~ 100 m (long-term)
Sample Board	
Sample Rate	800 Msps (effective)
Bit Width	8 bit
Multi-board Synchronization	$\lesssim 0.1 \times$ sample time
Beamform Pipeline	
Frequency Coverage	50 – 350 MHz (with efficiency limitation of antenna)
# of Channel	arbitrary, typically 65536
Frequency Resolution	selectable, typically 6 kHz
Time Resolution	selectable, typically 163.84 us
Beamformed File Format	SIGPROC filterbank; raw voltage
Coherent Dedispersion	supported, by beamformed raw voltage + DSPSR

Table 1: Specifications of 21CMA & its pulsar backend

2. Pulsar Backend for 21CMA: Data Acquisition

2.1 Hardware: sample boards for pulsar backend

- Sample board migration: SNAP → AiSense PG390 → RFSoc

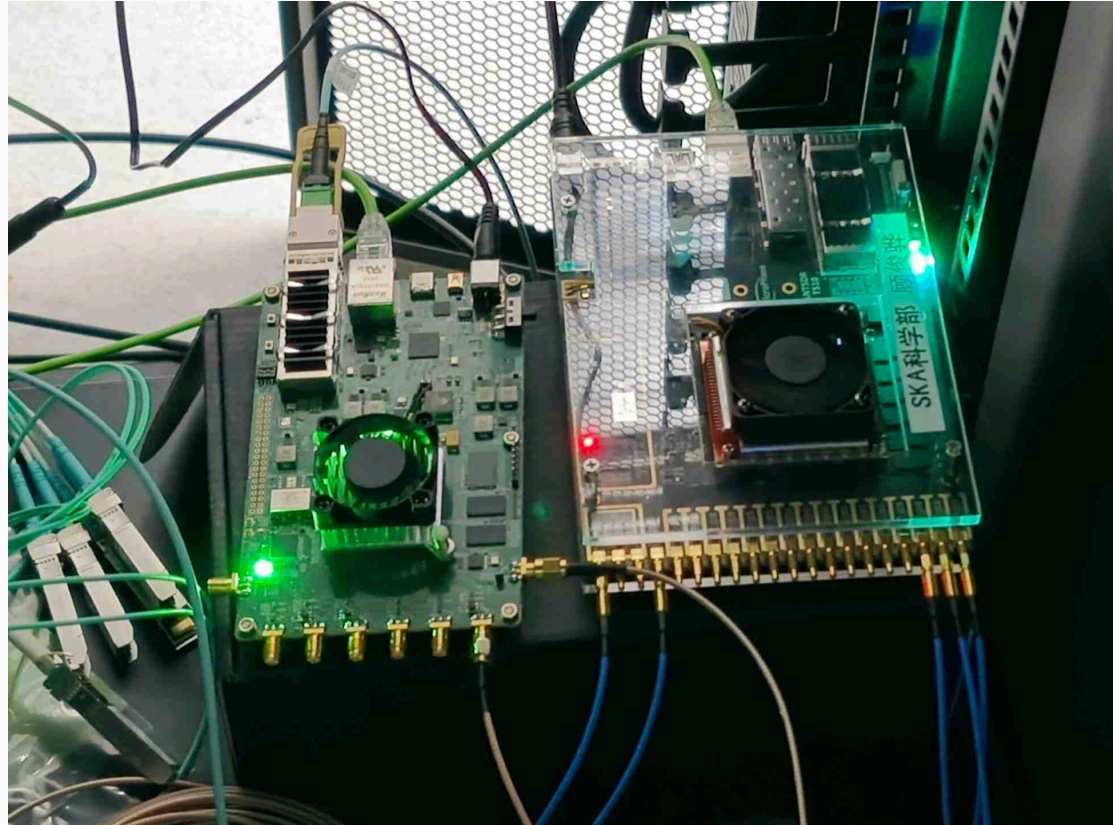


Figure 2: Two RFSoc-based sample boards being tested, for North-South arm.

2.2 Firmware: RFSoc-based data acquisition system

- implementation details in arXiv: 2607.01975; submitted to RAA
- firmware available at https://github.com/fxzjshm/rfsoc_data_acquisition

2.3 Test: multi-board synchronization

- enabled automatic multi-board synchronization, no manual calibration for sample boards
- enabled deterministic latency (relative to atomic clock), may reduce timing noise
- signal delay in lab test: 0.16 ± 0.14 ns, one magnitude lower than sample time 1.25 ns

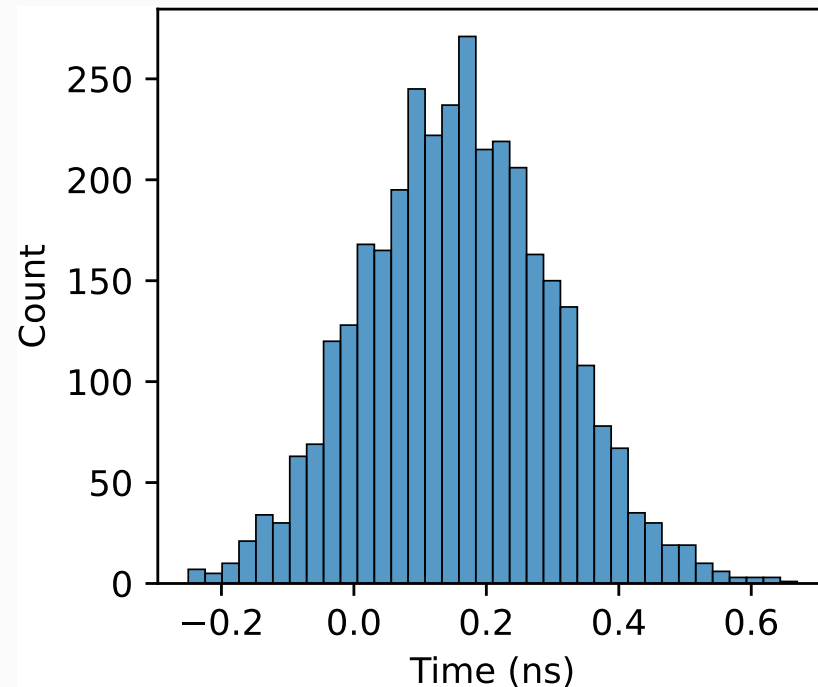


Figure 3: Histogram of time delays of 3462 multi-board synchronization tests in lab

2.4 Initial results: single station pulsar observation

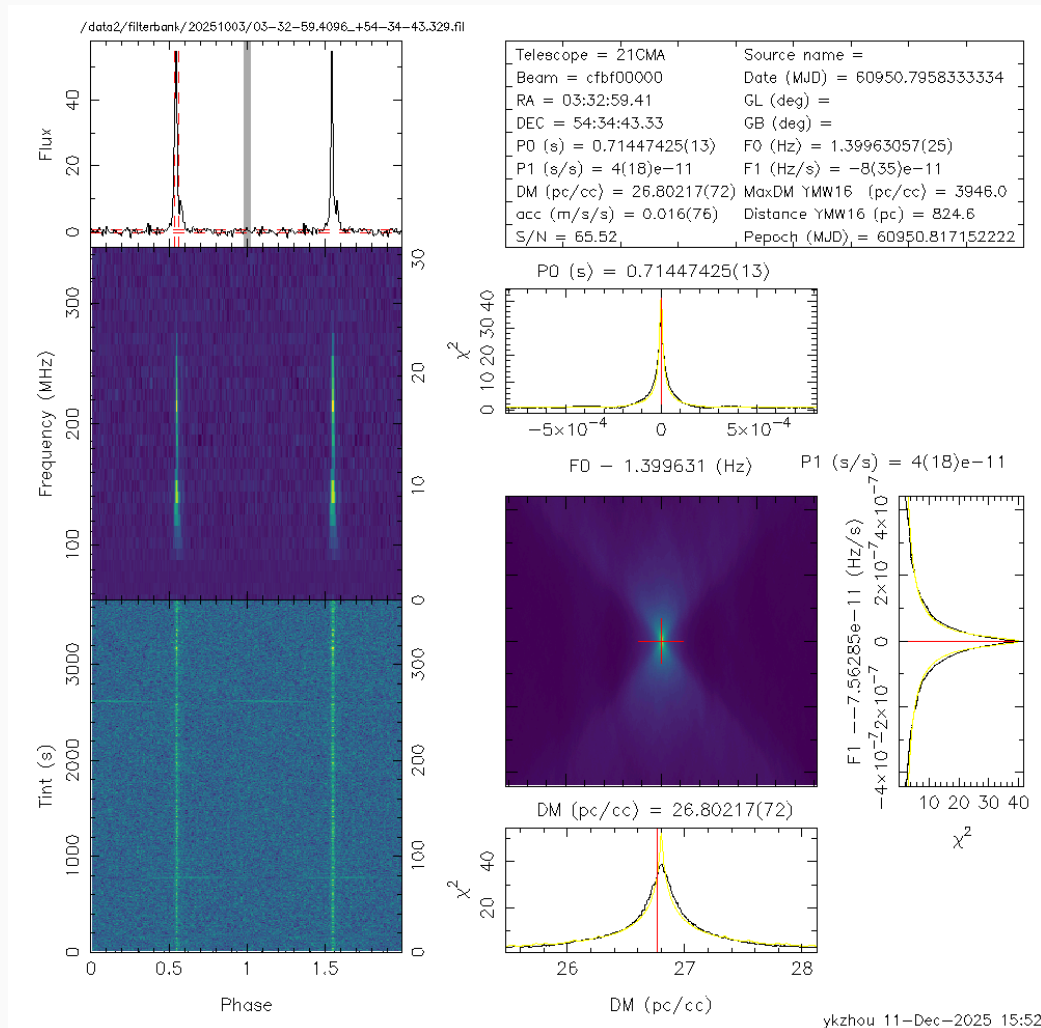


Figure 4: Single station (S13), 1 hour observation to PSR B0329+54 on 2025.10.03

3. Pulsar Backend for 21CMA: Beamformer

3.1 Implementation of Beamforming

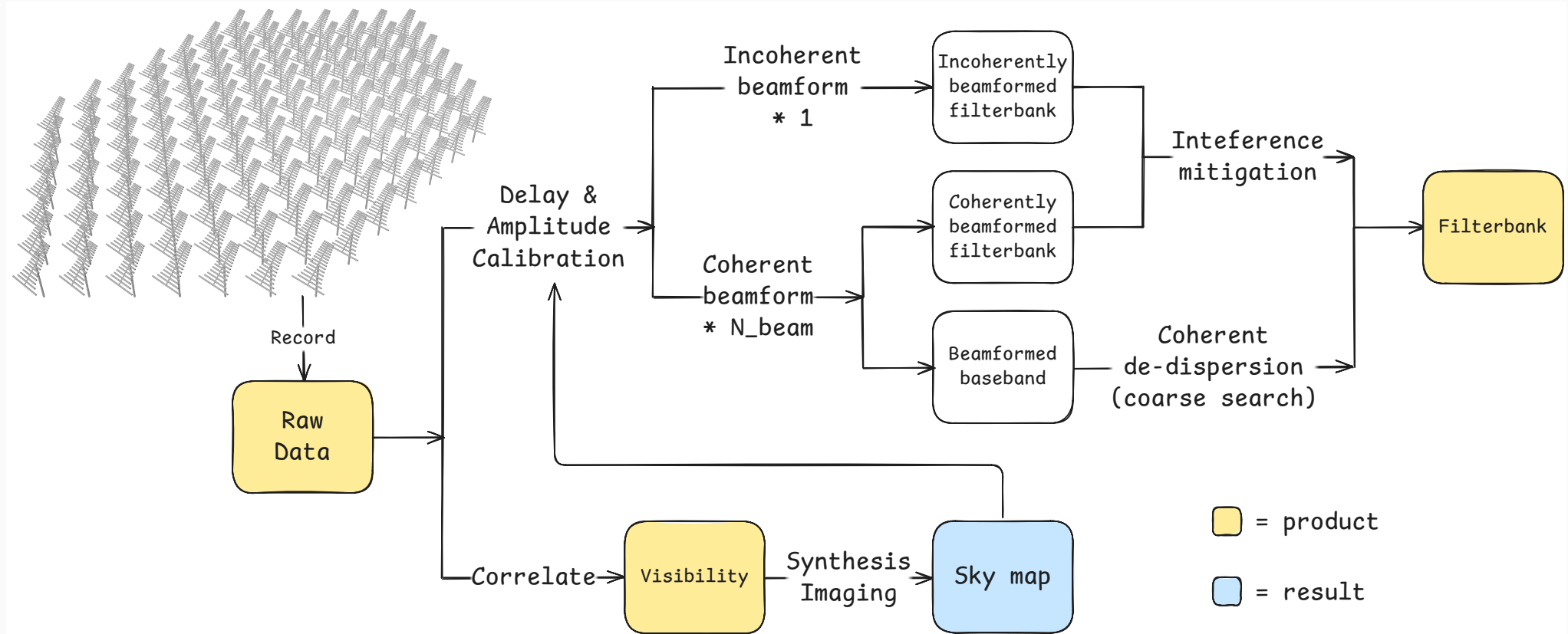


Figure 5: Diagram of product generation in 21CMA pulsar backend

- Geometry delay code from Ord et al. (2019), RFI mitigation method from Roy et al. (2018)

3.1 Implementation of Beamforming

- Pipeline is GPU-based, to accelerate processing 20×0.8 GB/s raw data
- Code is independent of GPU vendors with AdaptiveCpp as compatible layer

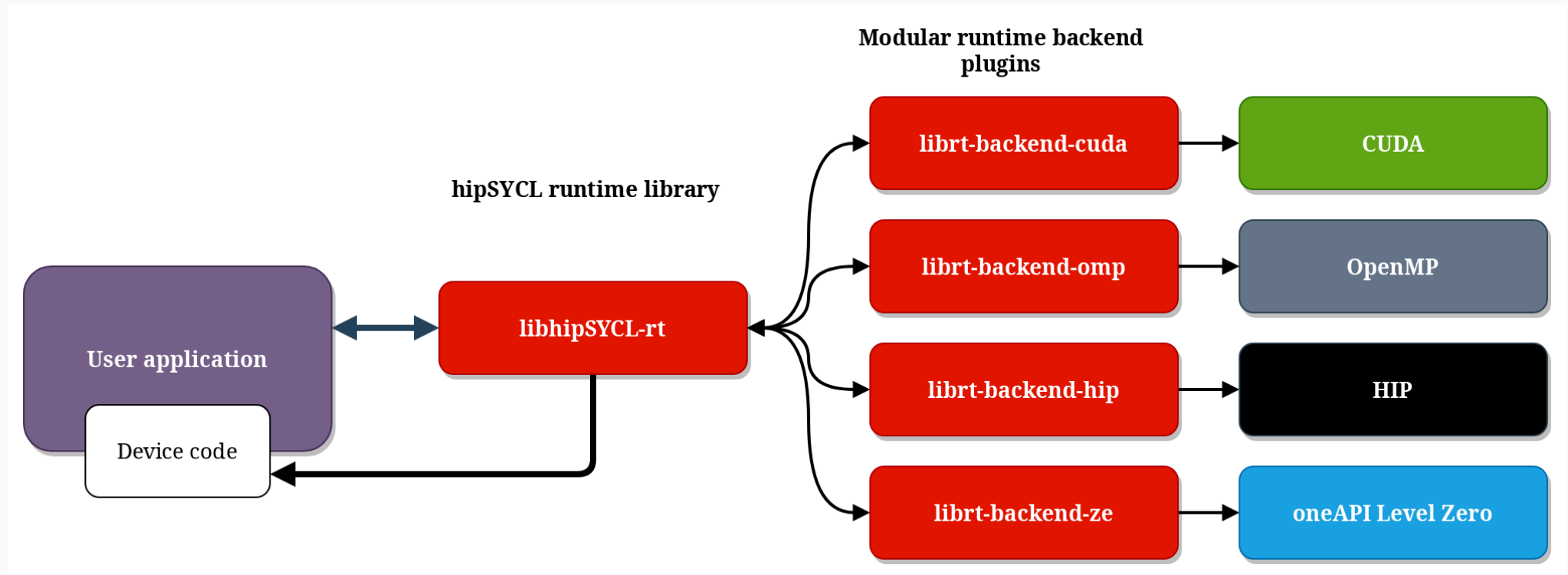
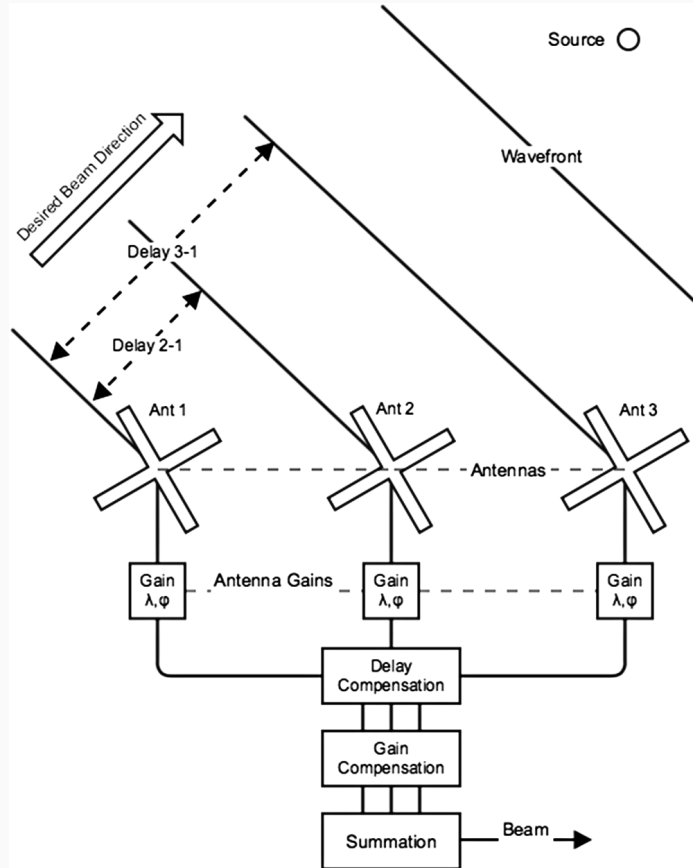


Figure 6: Diagram of runtime of AdaptiveCpp a.k.a. hipSYCL (Alpay and Heuveline 2023)

3.2 Initial results: multi-station delay calibration



- requirement:
 - digitize all station + process them
 - calculate geometry delay
 - calibrate cable delay
 - calibrate amplitude

Figure 7: Schematic of beamforming (Ord et al. 2019)

3.2 Initial results: multi-station delay calibration

- cable delay calibrated using Cas A and Cyg A, residual mostly less than $\frac{1}{4}\lambda$

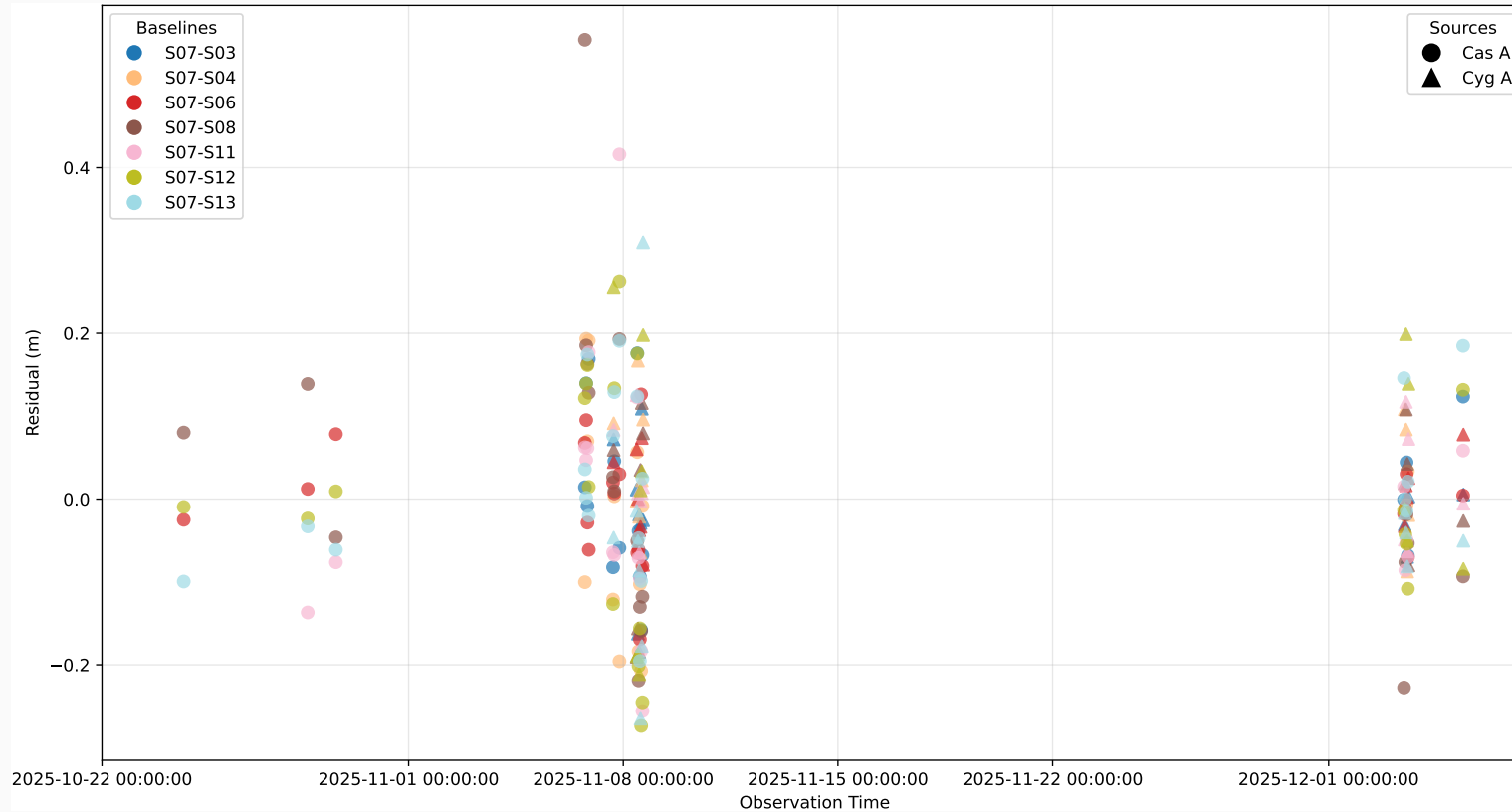


Figure 8: Residuals of fitted observed signal delays using geometric delay + cable delay

3.3 Initial results: multi-station pulsar observation

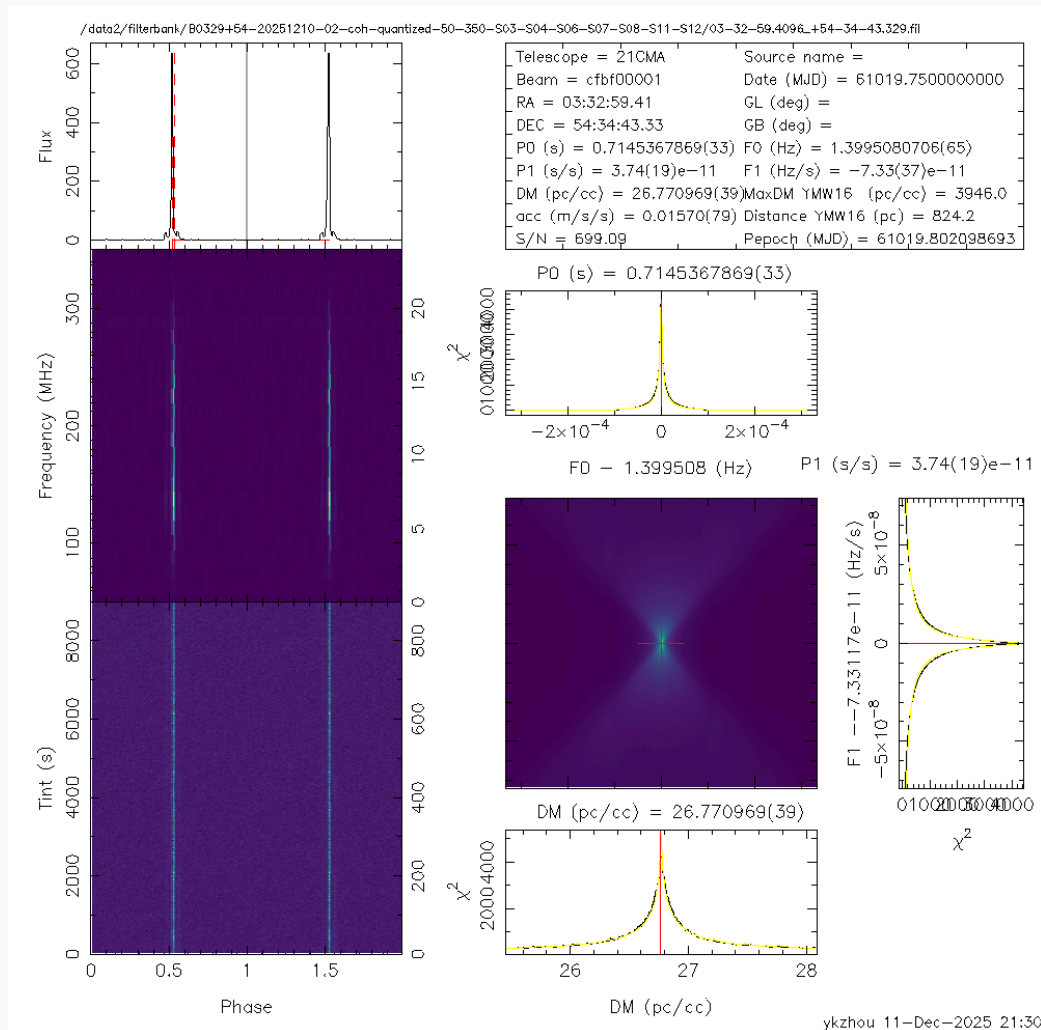


Figure 9: 7 stations, 2.5 hours observation of PSR B0329+54 on 2025.12.10

3.3 Initial results: multi-station pulsar observation

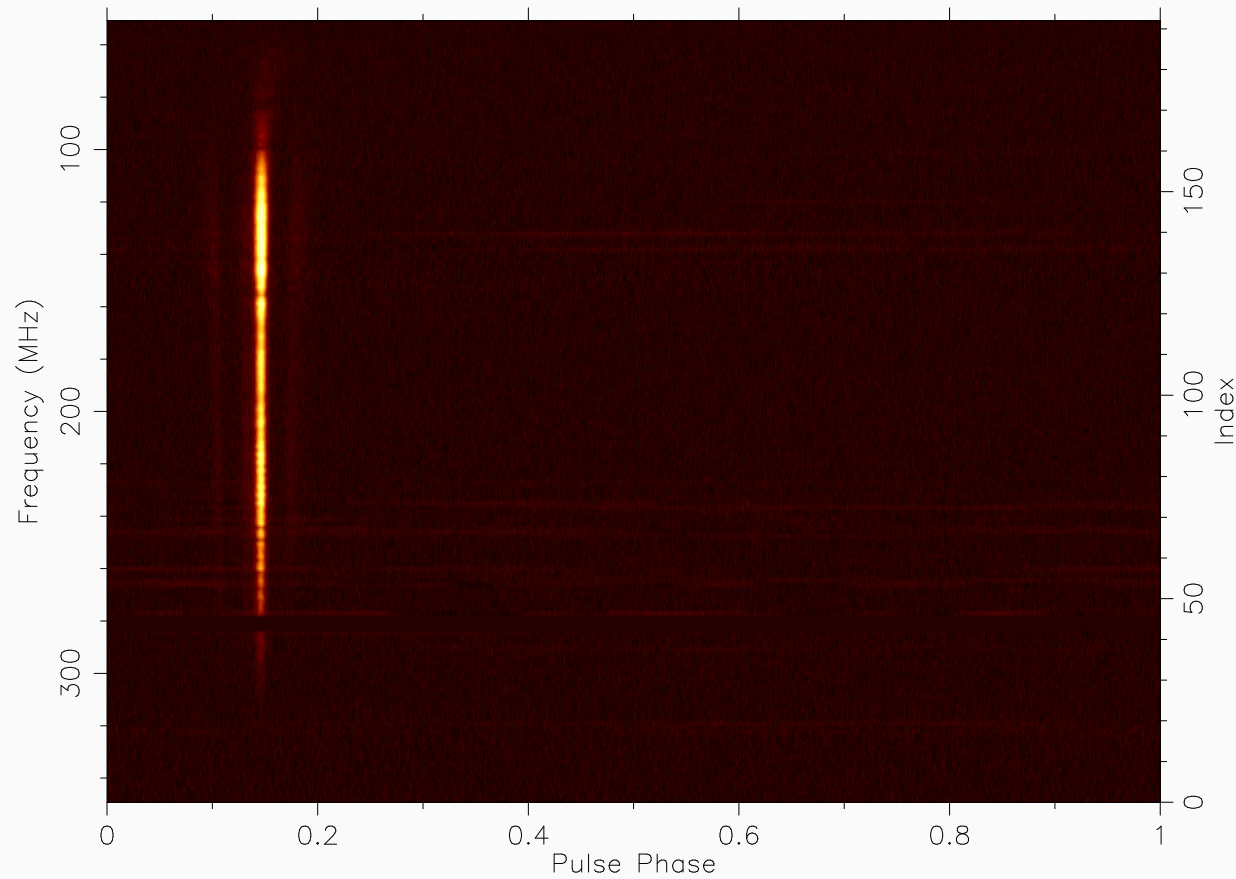


Figure 10: 7 stations, 2.5 hours observation of PSR B0329+54 on 2025.12.10

3.4 Initial results: pulsar timing

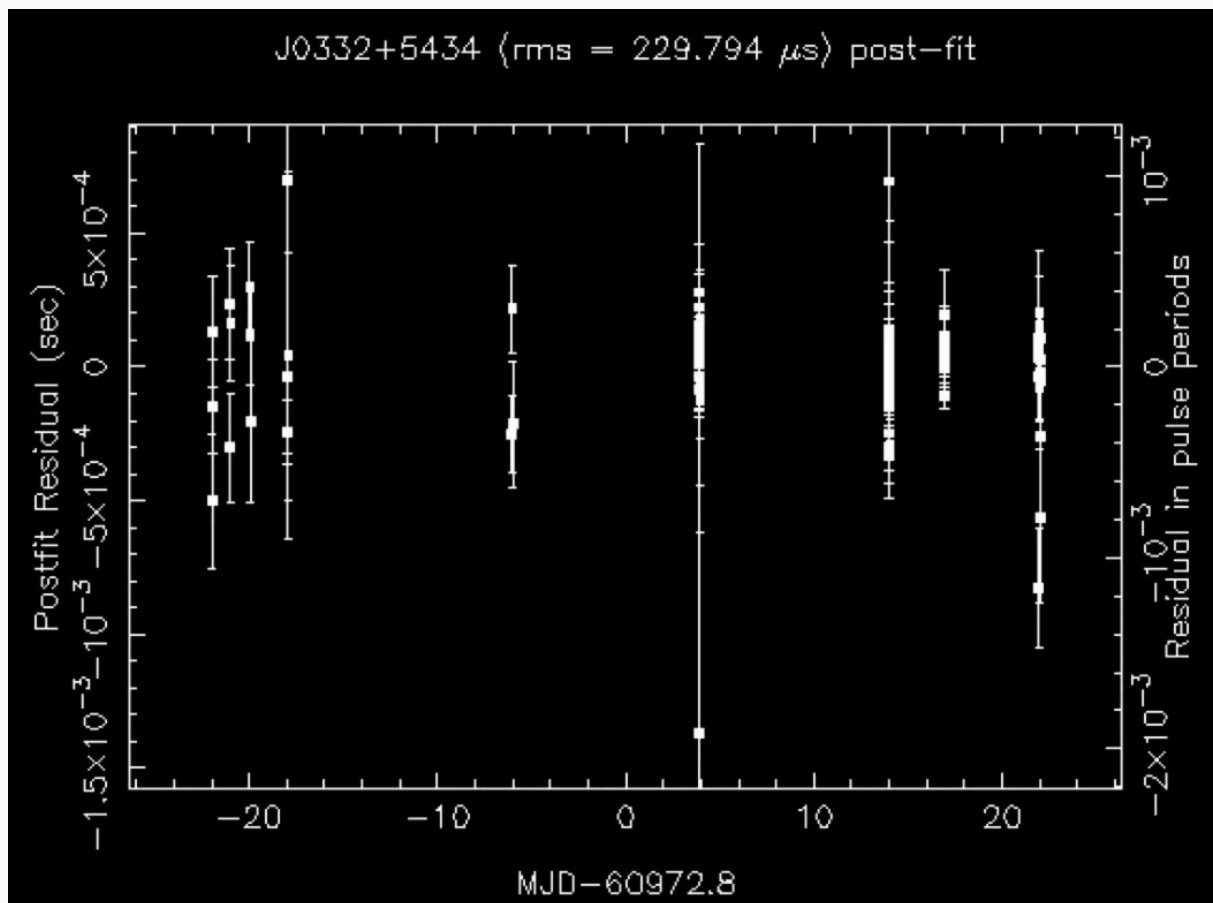


Figure 11: PSR B0329+54 timing, 2025.10 – 2025.11, credit: Heng Xu

3.5 Initial results: multi-station sky coverage

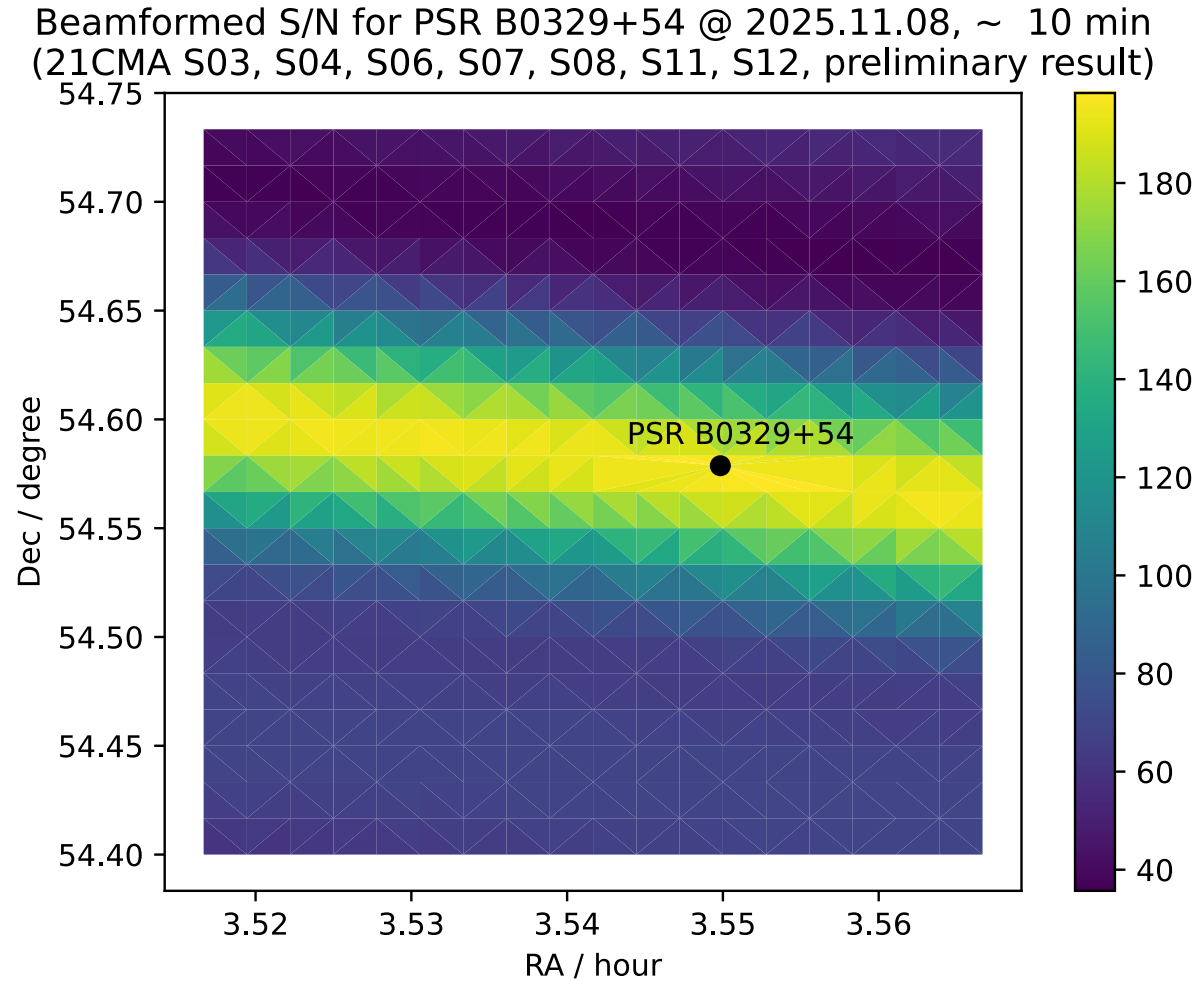


Figure 12: 7 stations, 10 min observation around PSR B0329+54 on 2025.11.08

3.6 Initial results: two pulsars simultaneously in single observation

- Verify multibeam capability by detecting two pulsars in one observation

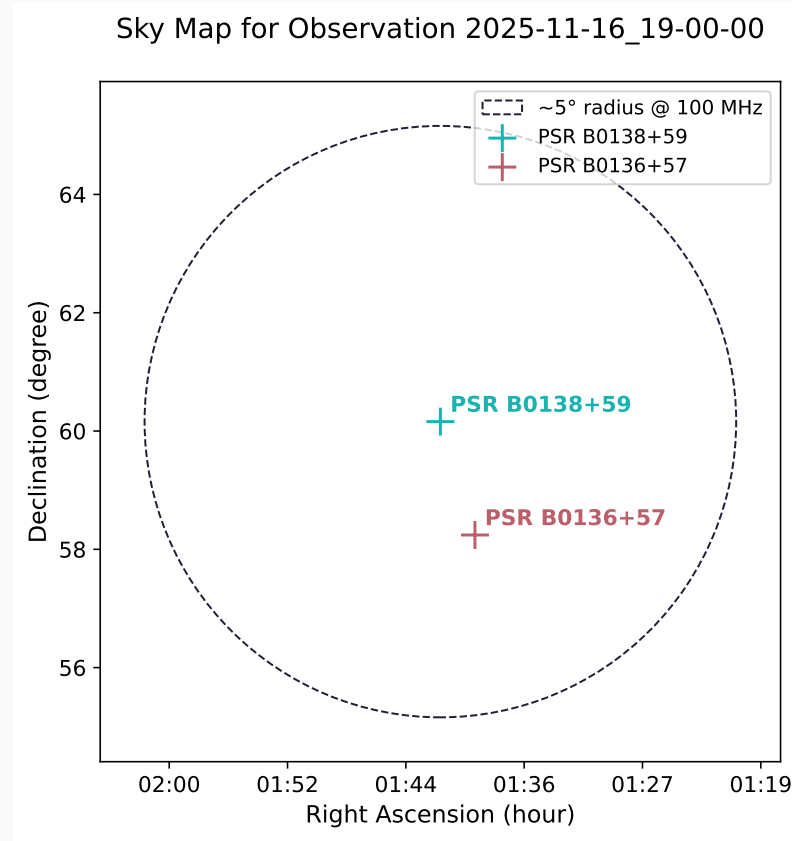


Figure 13: Sky map for observation on 2025.11.17

3.6 Initial results: two pulsars simultaneously in single observation

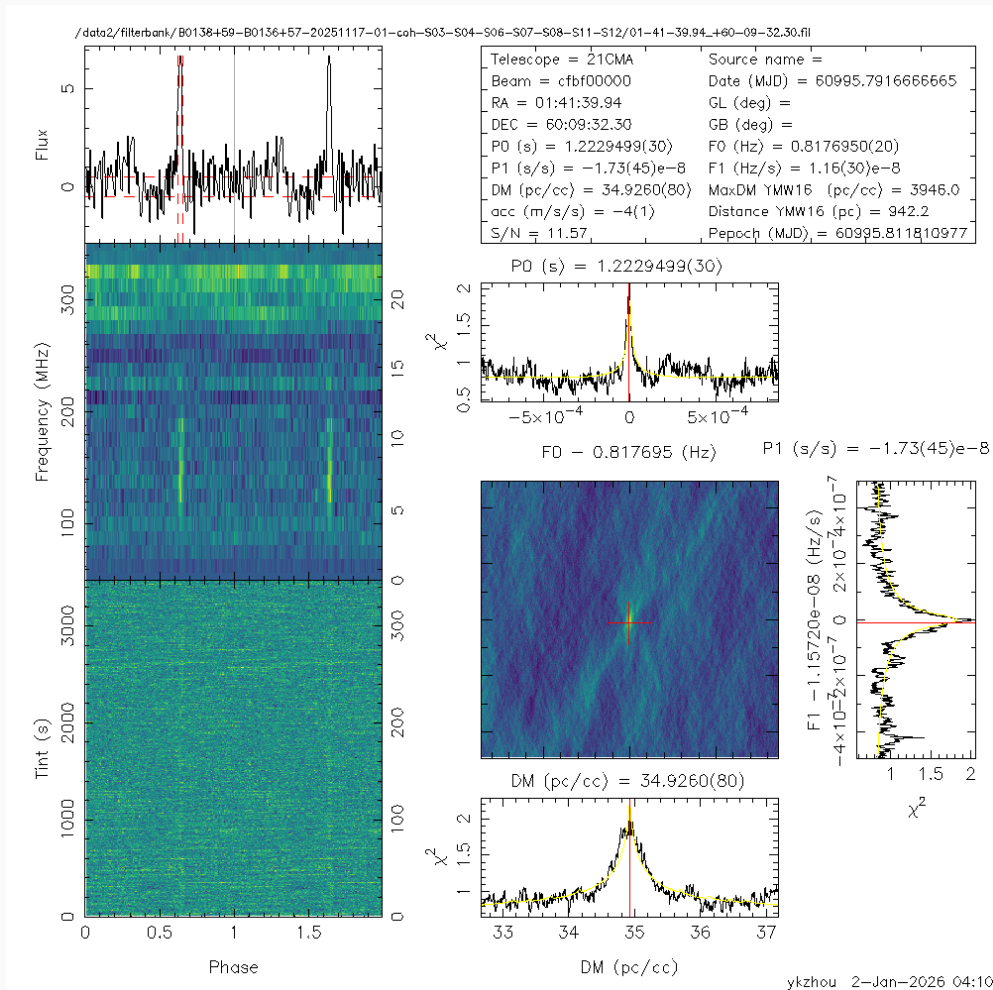


Figure 14: PSR B0138+59 on 2025.11.17

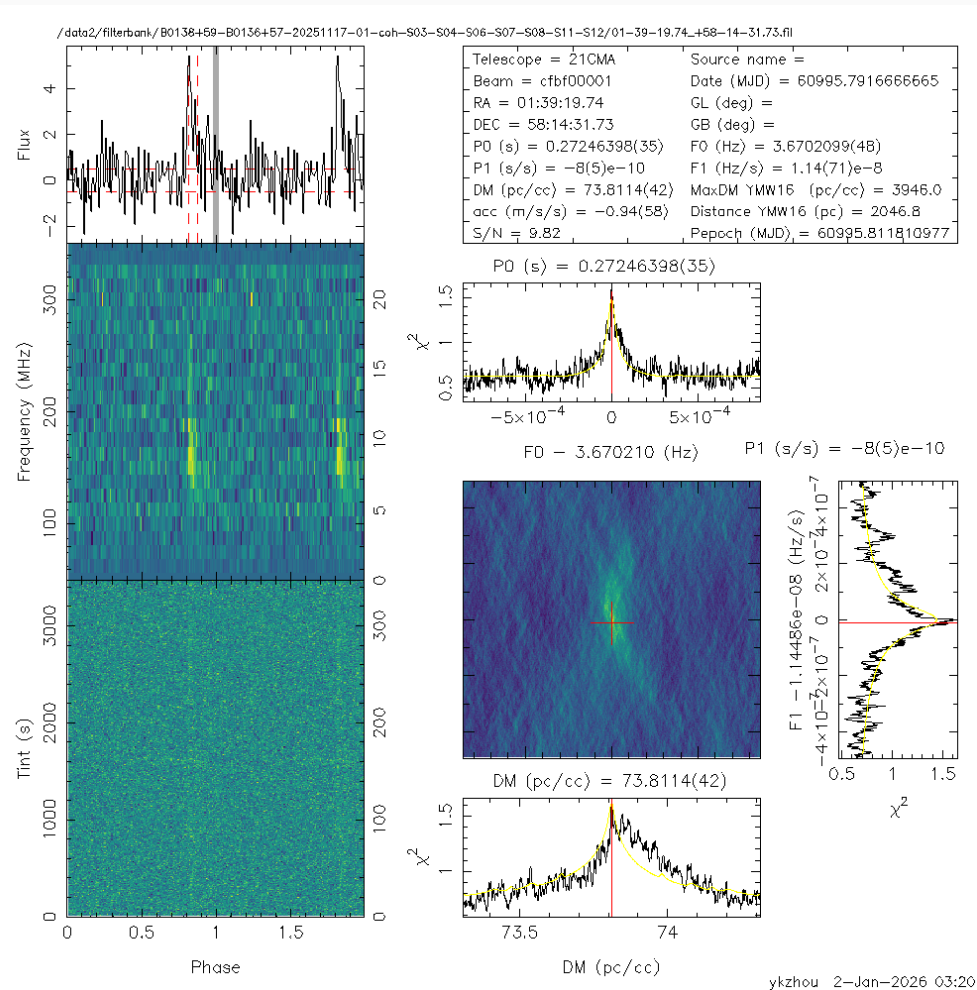
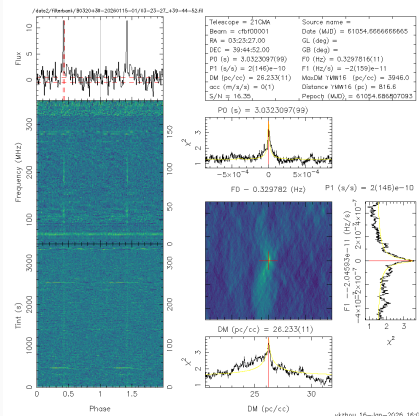
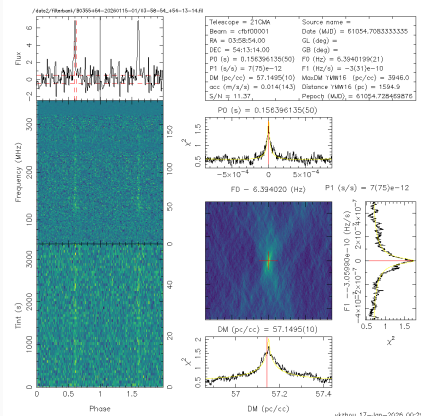


Figure 15: PSR B0136+57 on 2025.11.17

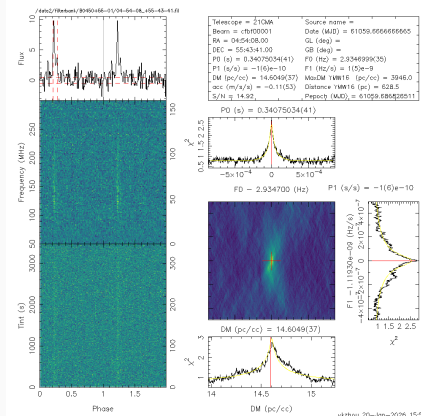
3.7 Initial results: more trials



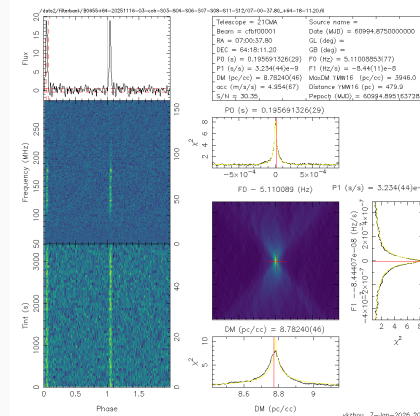
(a) PSR B0320+39



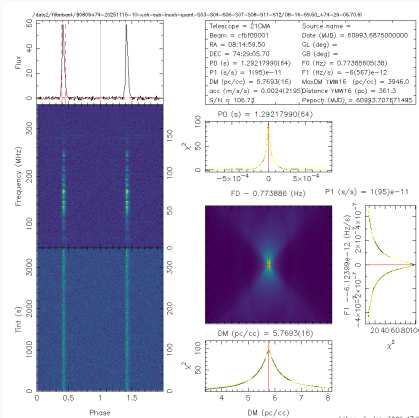
(b) PSR B0355+54



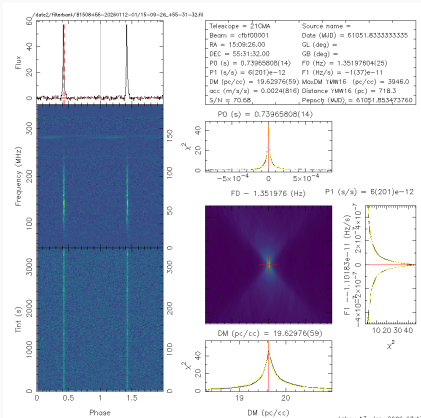
(c) PSR B0450+55



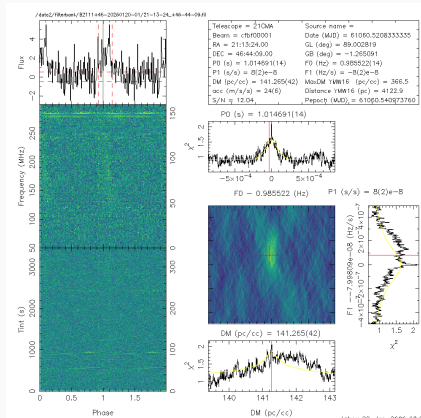
(d) PSR B0655+64



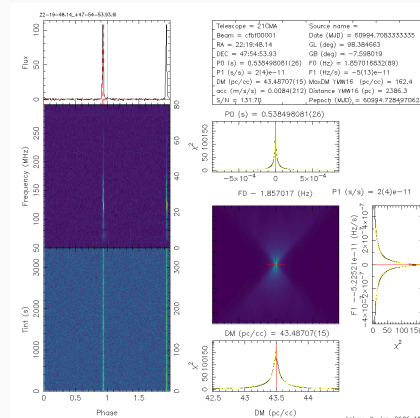
(e) PSR B0809+74



(f) PSR B1508+55



(g) PSR B2111+46



(h) PSR B2217+47

Figure 16: More pulsars detected on 21CMA

3.7 Initial results: more trials

- Tried and succeeded:
 - ~ 15 pulsars detected
 - wideband mode change of PSR B0329+54
 - in collaboration with YNAO (Faxin Shen, Zhixuan Li et al., in prep.)
- Tried but no progress yet:
 - millisecond pulsars for Pulsar Timing Array (e.g., PSR J0218+4232, PSR J1125+7819)
 - Fast Radio Bursts (e.g., FRB 20240209A, FRB 20250924A)
 - Long Period Transients (e.g., LPT J1634+44)
- Future Possibilities
 - low frequency widefield wideband pulsar search
 - accurate dispersion measurement
 - interstellar medium, scintillation; ionosphere

4. Conclusion & Plan

4. Conclusion & Plan

- 21CMA Pulsar Backend
 - Data acquisition system:
 - RFSoc-based, 20×800 Msps, 8 bit; arXiv: 2607.01975, submitted to RAA
 - Beamforming pipeline:
 - verified multibeam capability
 - ~ 15 pulsars detected
 - more stations in progress for better signal-to-noise ratio
 - millisecond pulsars, fast radio bursts, long period transients in progress

Thank You!

5. Backup Slides

5.1 21CMA

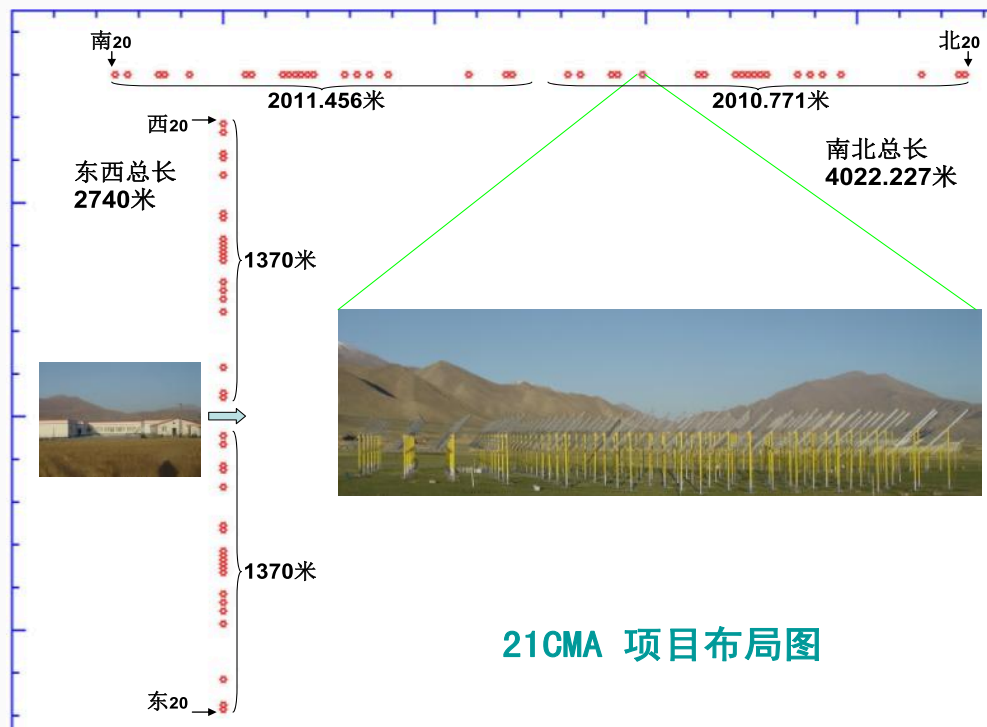


Figure 17: 21CMA station geometry positions (Zheng et al. 2015, Zheng et al. 2016, Wu 2019)

- Main goal: Epoch of Re-ionization (EoR); Pulsar and Transients
- Frequency: up to 50 – 350 MHz
- 81 hexagon-shaped stations

5.2 In-station Analog Beamformer



Figure 18: Two stations with remote-controlled signal delay tuners installed.

- Remote-controlled signal delay tuner installed on each antenna
- Can tune delay of each antenna individually to alter field of view
- Refer to Prof. Kejia Lee's talks

5.3 Hardware: Sample Boards

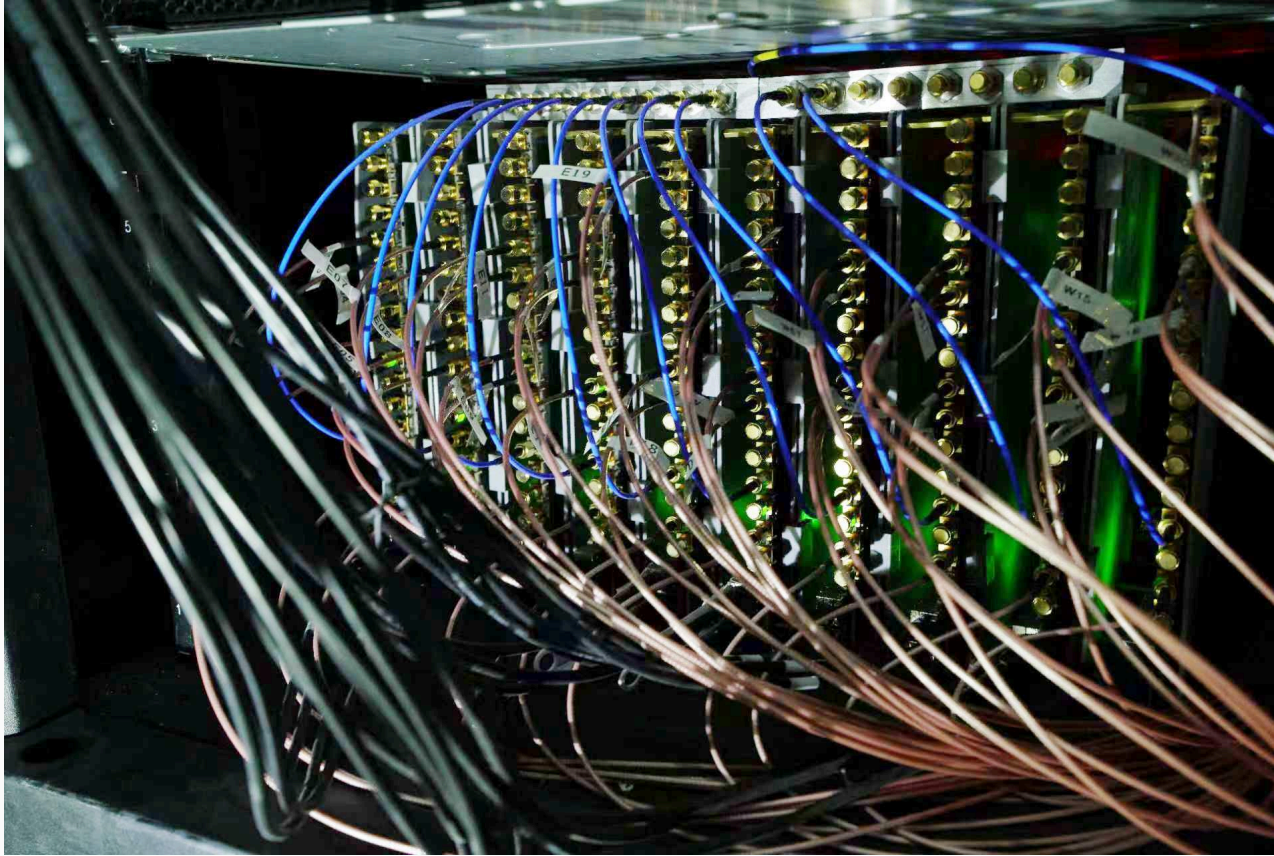


Figure 19: 10 SNAP 1 v2 for East-West arm. Image: Chunfeng Zhang

5.3 Hardware: Sample Boards

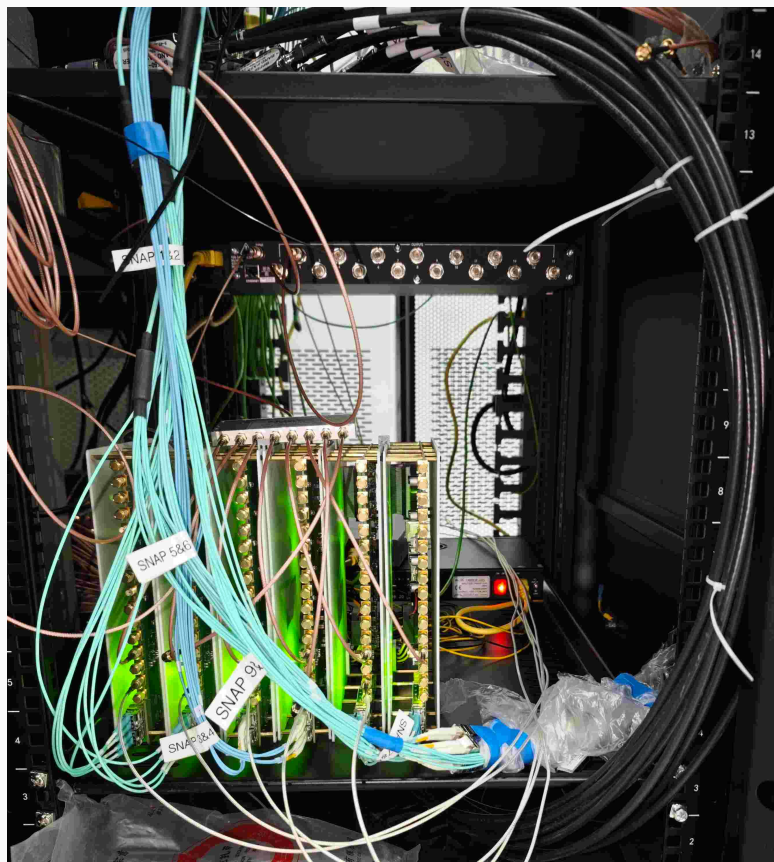


Figure 20: 6 个 SNAP 1 v2, 用于南北阵列; 另有 4 个暂时在仓库作为备件

5.4 Firmware: clock tree of RFSoc

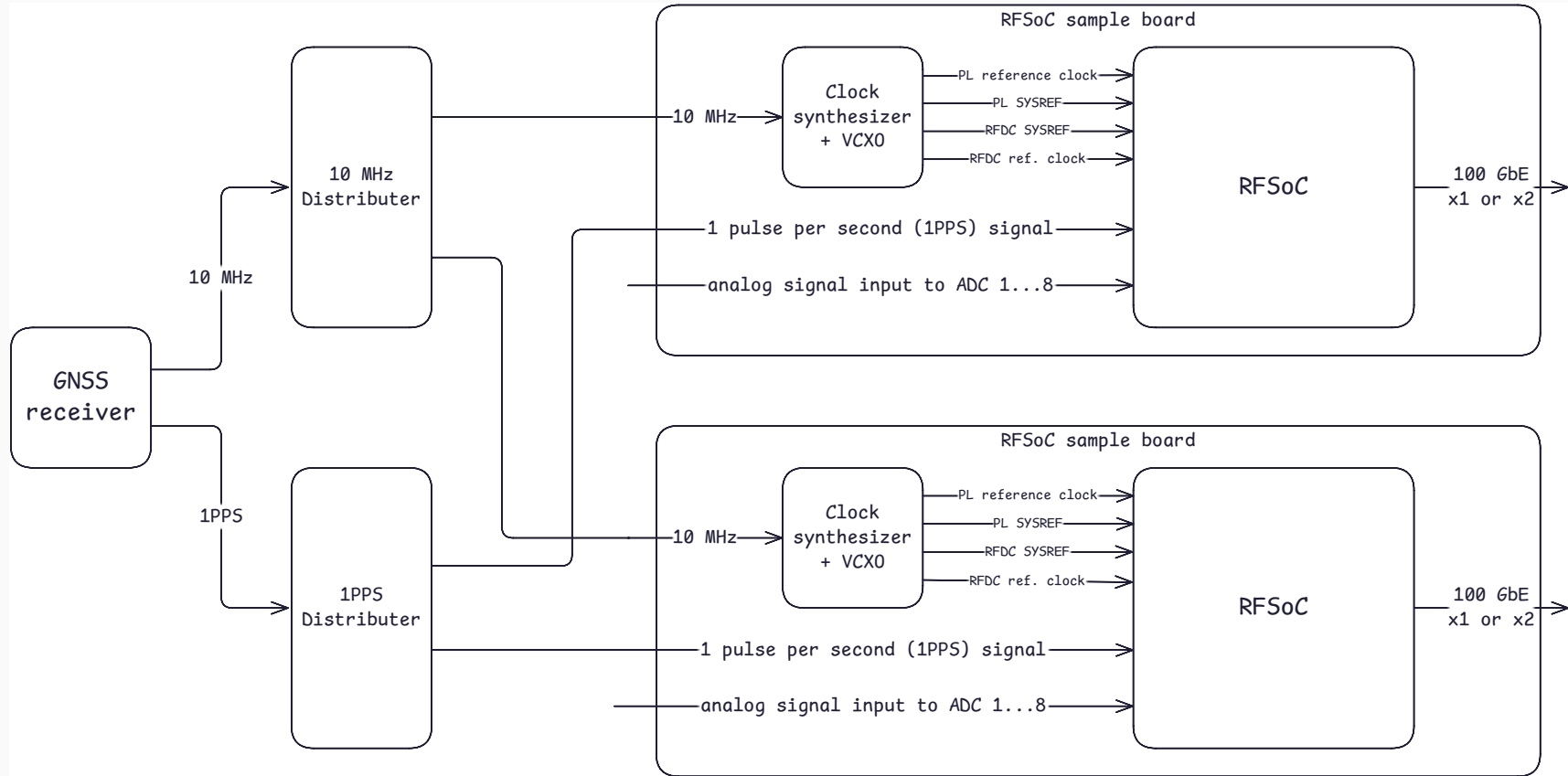


Figure 21: Clock tree of 21CMA RFSoc-based data acquisition system.

5.5 Initial Results: Delay Calibration

- cable delay calibrated using Cas A and Cyg A, residual mostly less than $\frac{1}{4}\lambda$

Baseline	S07 – S03	S07 – S04	S07 – S06	S07 – S08
Delay (m)	265.837 ± 0.017	-336.575 ± 0.023	-96.632 ± 0.011	210.881 ± 0.028
Baseline	S07 – S11	S07 – S12	S07 – S13	
Delay (m)	355.045 ± 0.022	405.509 ± 0.028	451.507 ± 0.022	

Table 2: Station cable delay solutions from observations shown in Figure 8.

- Note: here only statistical uncertainties, no systematic uncertainties accounted

6. Reference

6. Reference

- Alpay A, Heuveline V (2023) One Pass to Bind Them: The First Single-Pass SYCL Compiler with Unified Code Representation Across Backends. In: Proceedings of the 2023 International Workshop on OpenCL. Association for Computing Machinery, Cambridge, United Kingdom
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<https://doi.org/10.1017/pasa.2019.17>
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- Zheng C, Wu X-P, Johnston-Hollitt M (2015) The NCP Region Observed with the 21 CentiMeter Array (21CMA). <https://leo.phys.unm.edu/~lwa/abq2015/talks/Zheng.pdf>

6. Reference

Zheng Q, Wu X-P, Johnston-Hollitt M, et al (2016) Radio Sources in the NCP Region Observed with the 21 Centimeter Array. The Astrophysical Journal 832:. <https://doi.org/10.3847/0004-637X/832/2/190>