Space Debris Laser Ranging with range-gate-free Superconducting Nanowire Single-Photon Detectors

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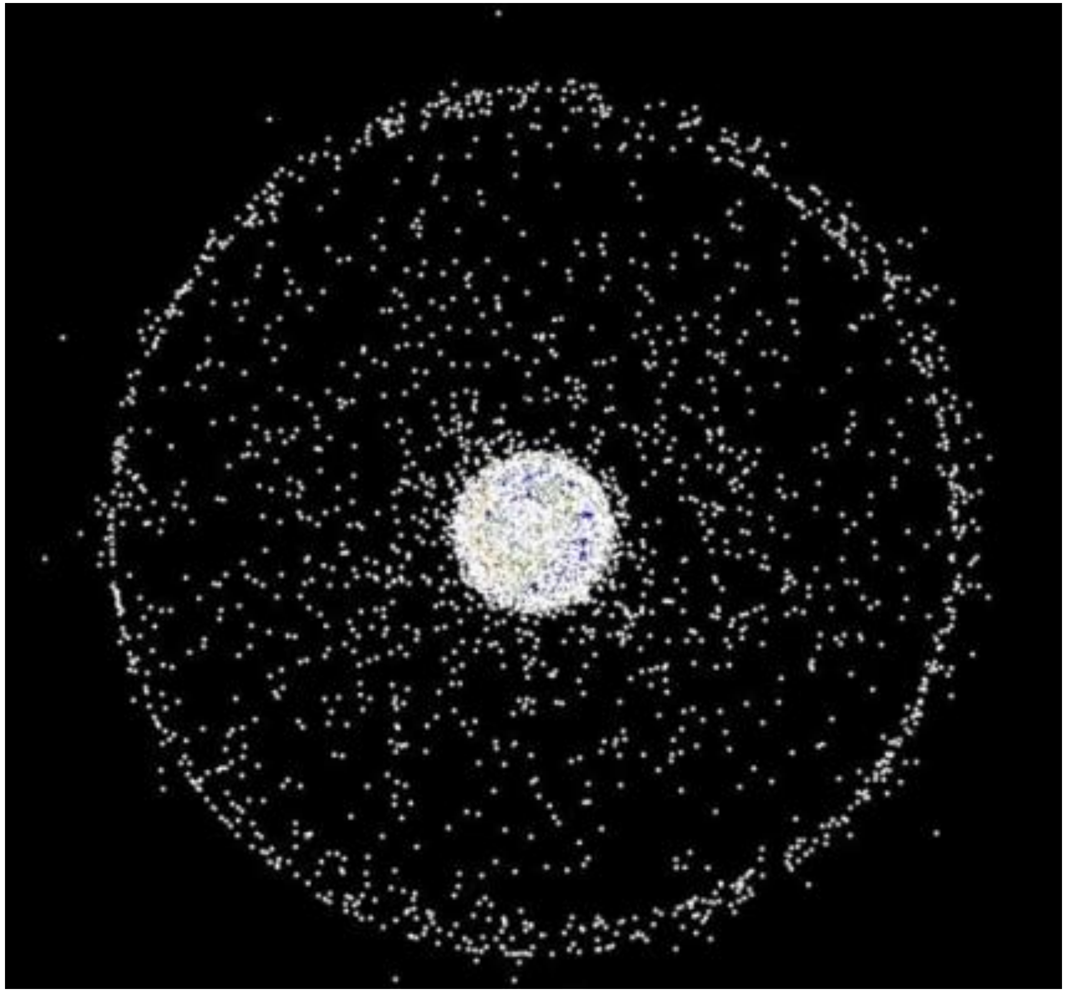
1 Introduction



DLR (Space Debris Laser Ranging)

- developed from SLR (Satellite Laser Ranging)
- non-cooperative targets (without retro-reflectors)

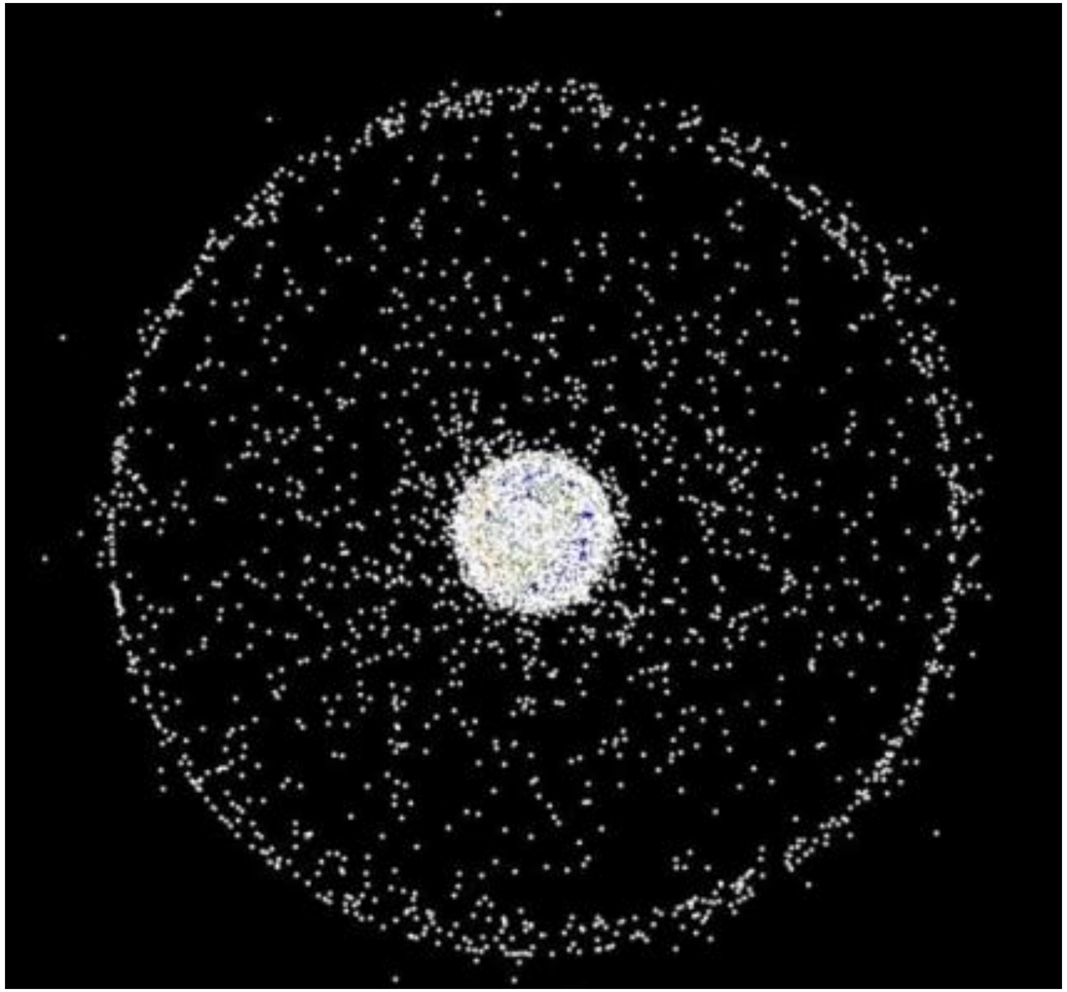
Difficulties

- the low reflectivity
- the inaccurate orbital prediction

Solutions

- improving the echo detection capability
- improving the accuracy of orbital prediction

2 DLR with range-gate-free SNSPD



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→ reducing the effect of the inaccurate orbital prediction

2.1 The role of high accurate orbital prediction

SLR

The **accurate** orbital prediction is required :

- to calculate the pointing of telescope (to aim at the target)
- **to calculate the opening time of the range gate (to find the signal)**

The detection probability (the probability of detecting an echo photon at the time of its arrival) :

$$p_s = \left(1-e^{-(n_s+n_n\tau)}\right)\left(\frac{n_s}{n_s+n_n\tau}\right)$$

n_s - the number of echo photons reaching the detector.

n_n - the noise-photon rate reaching the detector.

τ - the response time of the detector.

The false alarm probability (the probability of the detector being triggered by noise photons during the period when the detector is waiting for the echo photons after the range gate is opened) [1, 2] :

$$p_n = 1-e^{-n_n t_{rg}}$$

accurate

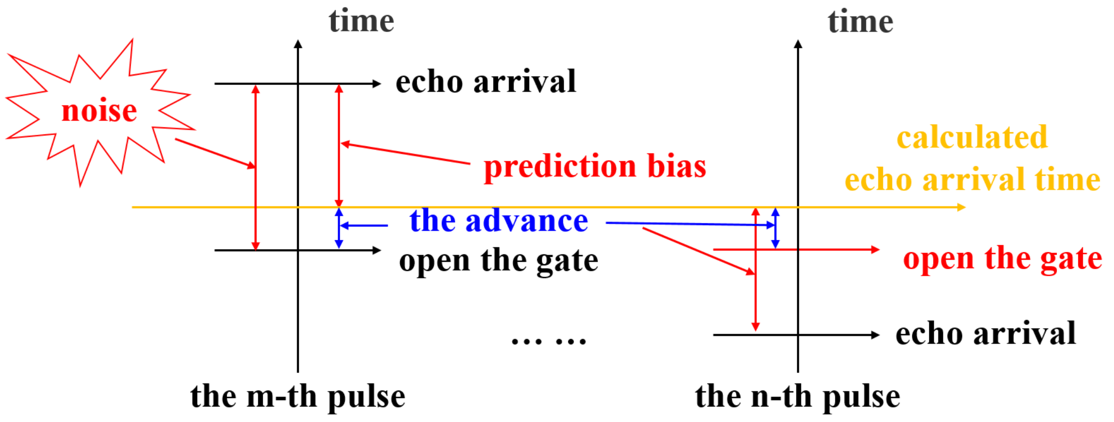
$t_{pb} \approx 0$

t_{rg} - the advance of the opening time of the range gate.

The success probability of laser ranging :

$$p = (1\text{-}p_n)\,p_s$$

DLR



- respond once for each laser pulse.
- the m-th pulse : it is possible to detect an echo photon only if the detector is not triggered by noise photons during the period (from the opening time of the range gate to the echo arrival time).
- the n-th pulse : the range gate opens after the arrival of the echo due to the orbit-prediction bias.

The false alarm probability :

$$p_n = 1-e^{-n_n(t_{pb}+t_{rg})}$$

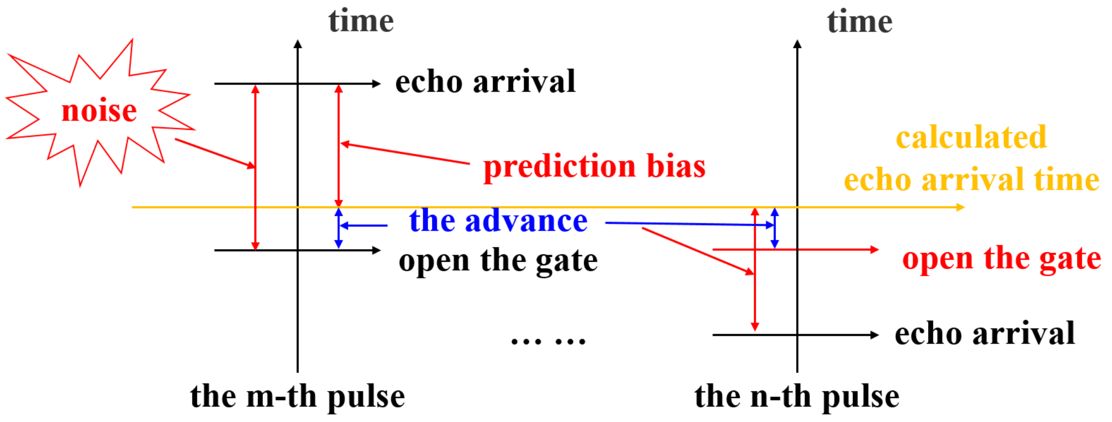
t_{pb} - the orbit-prediction bias.

inaccurate

t_{rg} - the advance of the opening time of the range gate.

2.2 DLR in Normal mode and Range-gate-free mode

Normal mode



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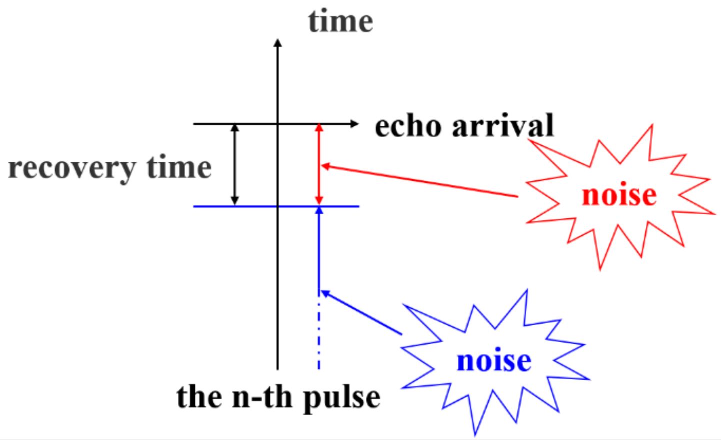
The false alarm probability (**normal**) :

$$p_n = 1 - e^{-n_n(\boxed{t_{pb}} + t_{rg})}$$

t_{pb} - the orbit-prediction bias.

t_{rg} - the advance of the opening time of the range gate.

Range-gate-free mode



SNSPD (Superconducting Nanowire Single-Photon Detector) :

- The SNSPD can **automatically recover its working state** in range-gate-free mode.
- For each laser pulse, the SNSPD can respond multiple times.

As long as the detector is not triggered by noise photons during recovery time, it is possible for the SNSPD to detect an echo photon

The false alarm probability (**range-gate-free**) :

$$p_n = 1 - e^{-n_n \boxed{t_{rt}}}$$

t_{rt} - the recovery time.

2.3 DLR in Normal mode and Range-gate-free mode

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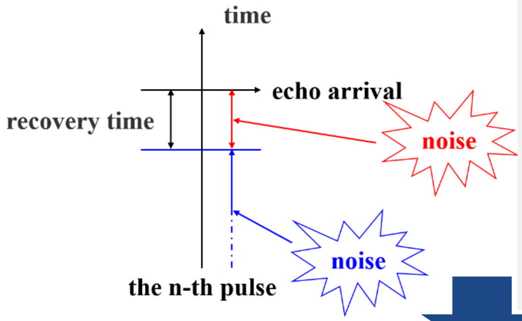

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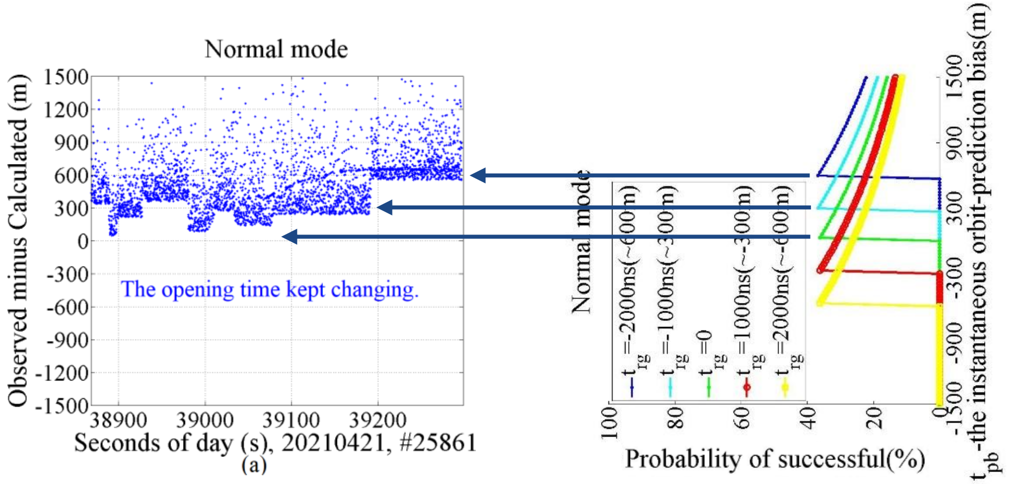
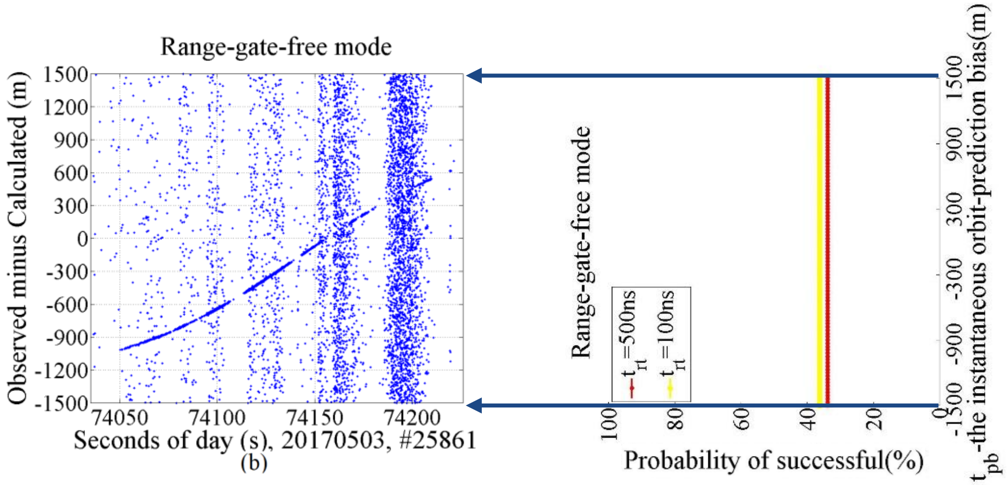
The false alarm probability (**normal**) : $p_n = 1 - e^{-n_n(\boxed{t_{pb}} + t_{rg})}$

The false alarm probability (**range-gate-free**) : $p_n = 1 - e^{-n_n \boxed{t_{rt}}}$





1.Keep searching for target position.

2.Keep searching for the opening time of range gate

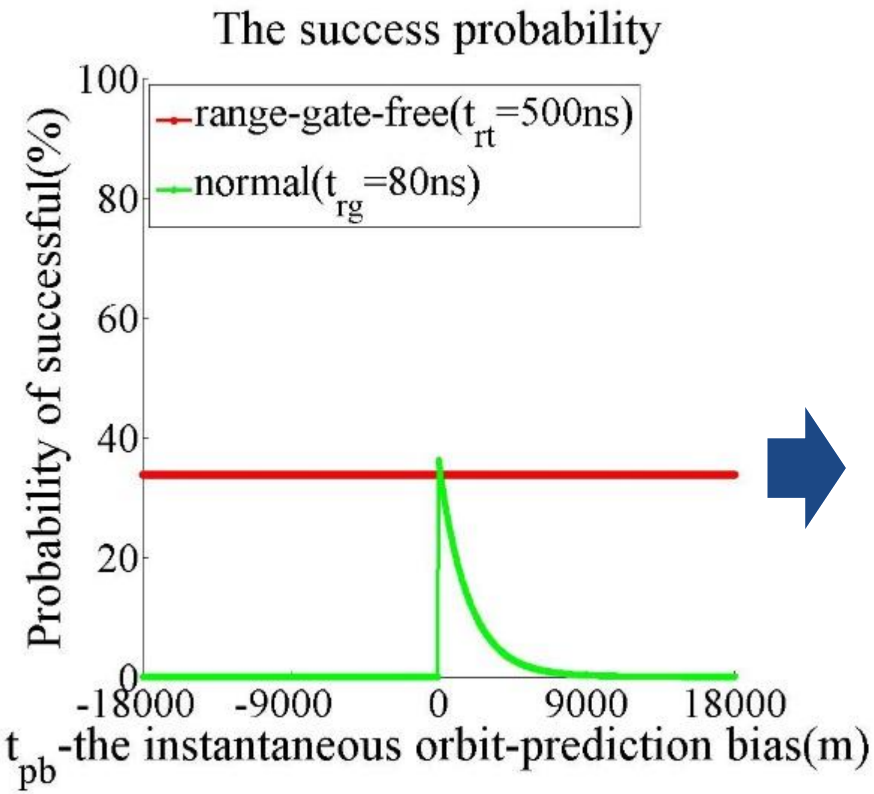
t_{rg}↘↗ : $(t_{pb} + t_{rg}) > 0$ & $(t_{pb} + t_{rg}) \to 0$

1. Just search for target position.

2. No need to do anything. (**reduce the effect of the prediction**)

t_{rt} : constant

2.4 DLR with range-gate-free SNSPD



- the success probability is not affected by the accuracy of the orbital prediction : the echo photons are within the threshold of Observed-minus-Calculated (O-C).
- the maximum threshold of O-C can be set to ±60 000ns (**≈±18km,** related to data processing capability).
- **greatly reduce the effect (the RB in the radial direction, max.~±18km) of the inaccurate orbital prediction.**

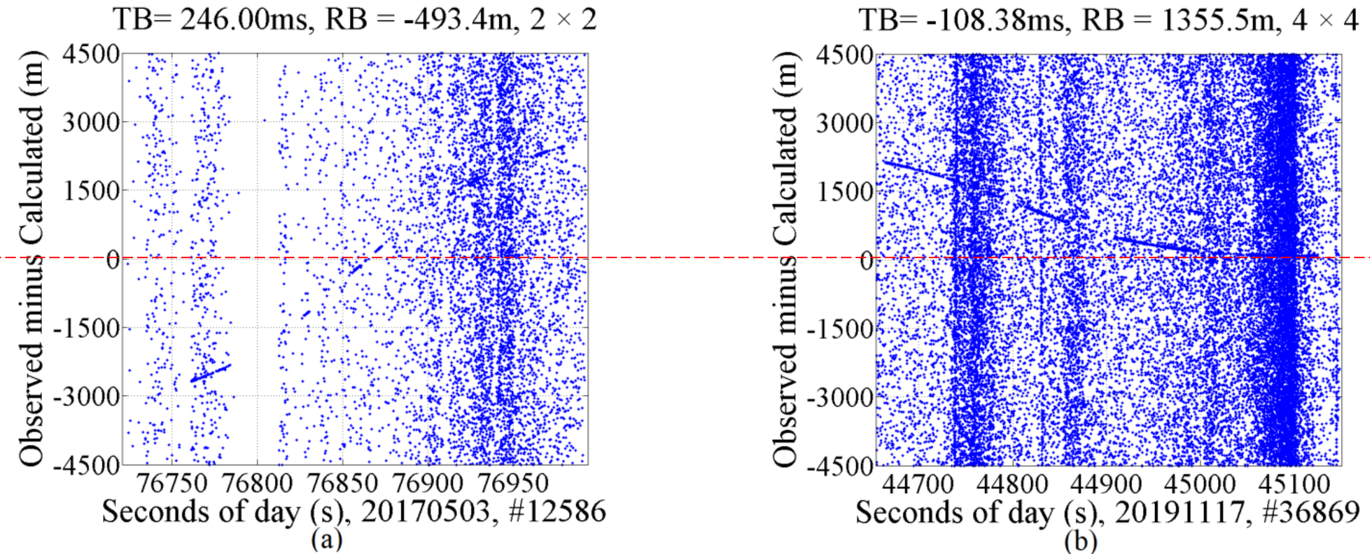
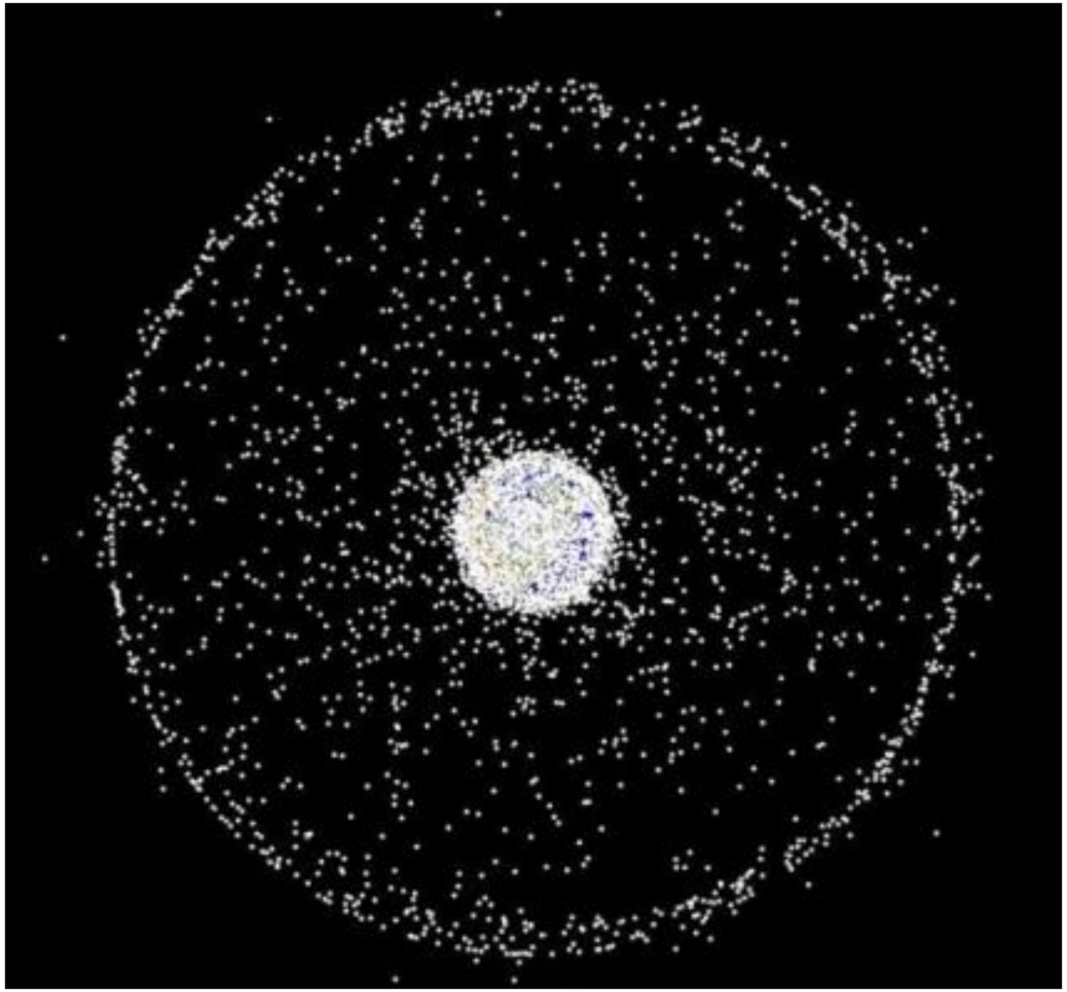


Fig (a) : TB (Time Bias) = 246.00ms, RB (Range Bias) = -493.4m
Fig (b) : TB = -108.38ms, RB = 1355.5m

3 Array detection



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array detection

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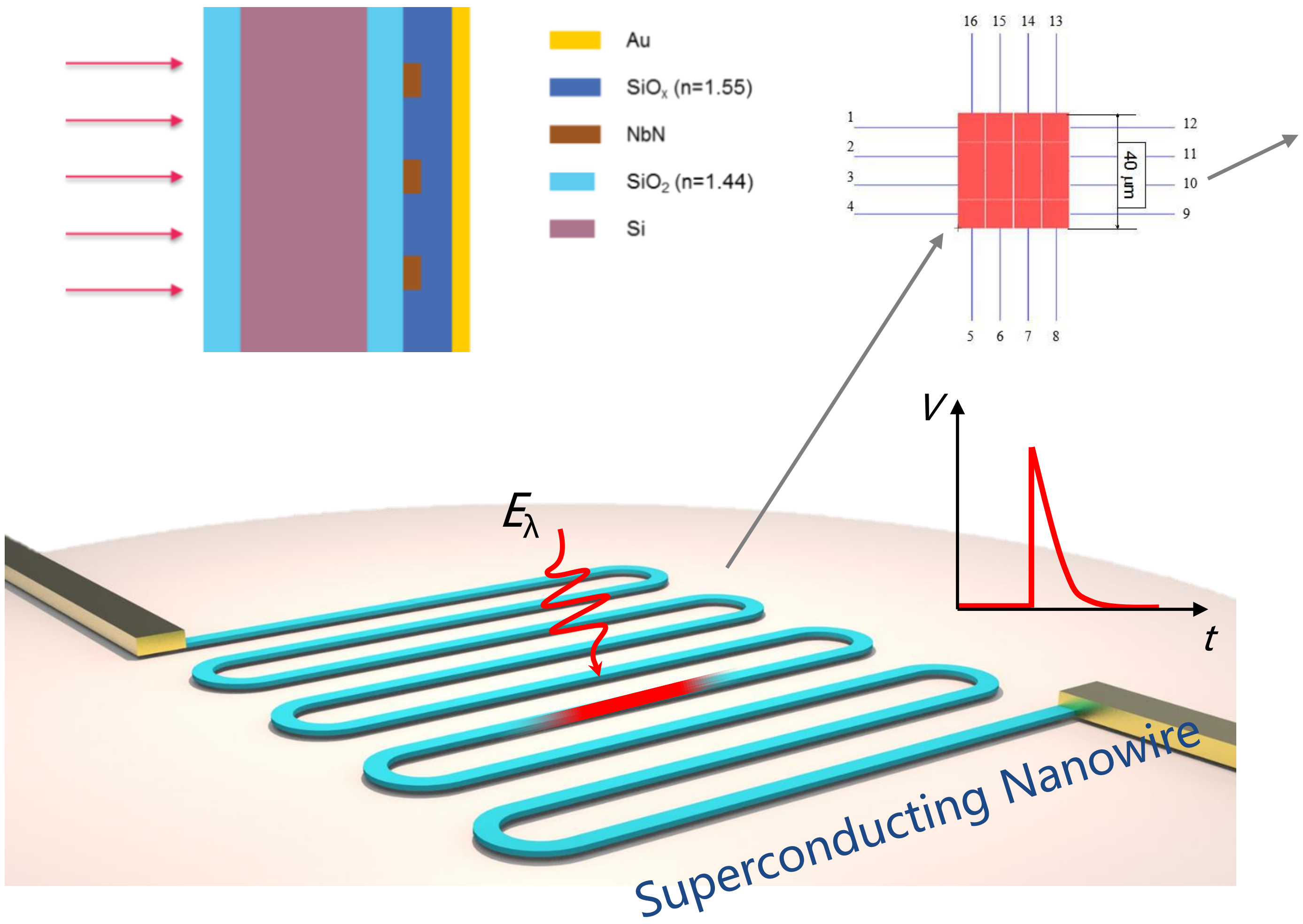
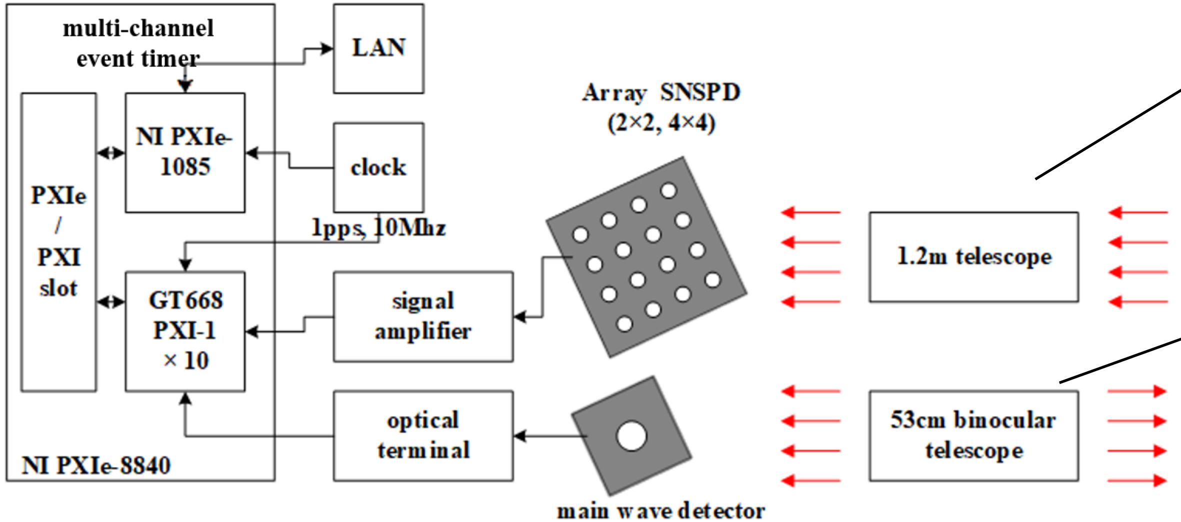
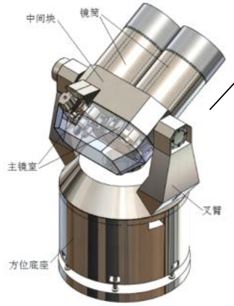


Assuming that the number of pixels of the SNSPD array is w, the detection efficiency of each pixel is equal ($\eta_1 = \eta_2 = \ = \eta_w = \eta_{pixel}$), and each pixel is independent of each other, the success probability of laser ranging for each pixel is p_{pixel}, the success probability of laser ranging with a range-gate-free SNSPD array is expressed as equation

$$\begin{aligned} p_{\text{array}} &= 1-\left(1-p_{\text{pixel}}\right)^w \\ &= 1-\left(1-e^{-n_{\text{n}}t_{\text{rt}}}\left(1-e^{-(n_{\text{s}}+n_{\text{n}}\tau)}\right)\left(\frac{n_{\text{s}}}{n_{\text{s}}+n_{\text{n}}\tau}\right)\right)^w. \end{aligned}$$

4 Experiment and Results





LLR (7820)，DLR

Space Debris
(DLR)

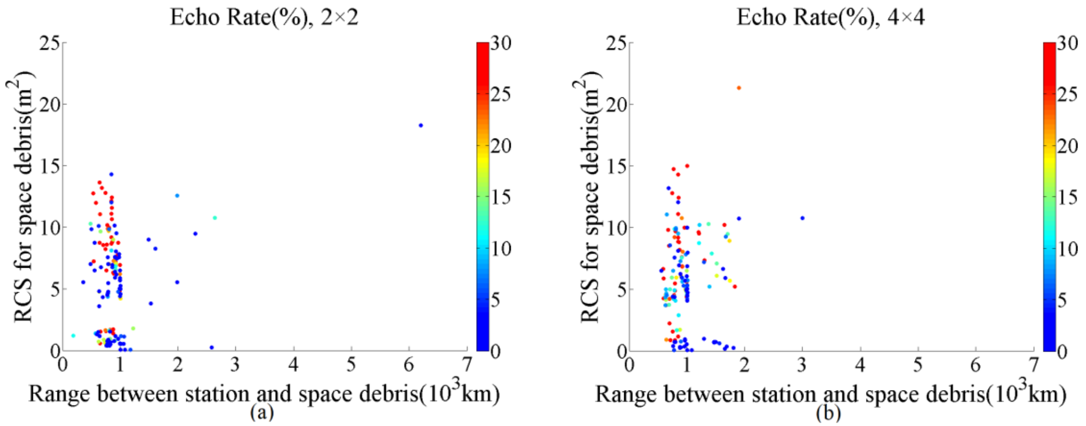
SLR (7819)，DLR

In order to further improve the success probability of DLR :

- a **range-gate-free SNSPD array**.
- a multi-channel event timer.
- laser wavelength is **1064nm**, laser power is 40 W-300 W (generally using 40W), laser repetition rate is 100Hz.

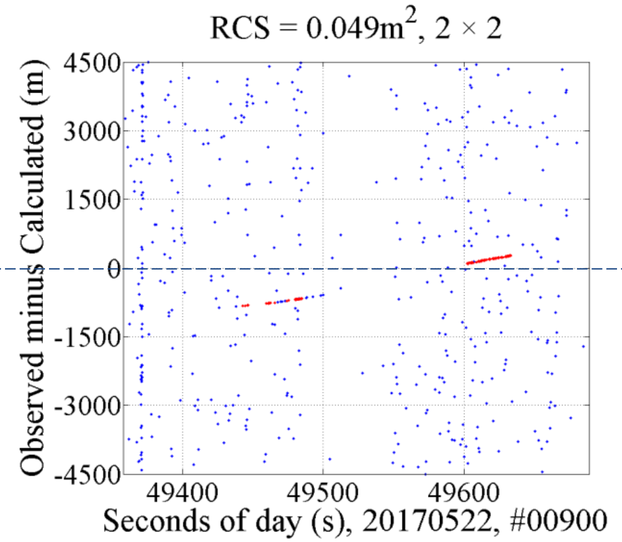
Results (2017-2020)

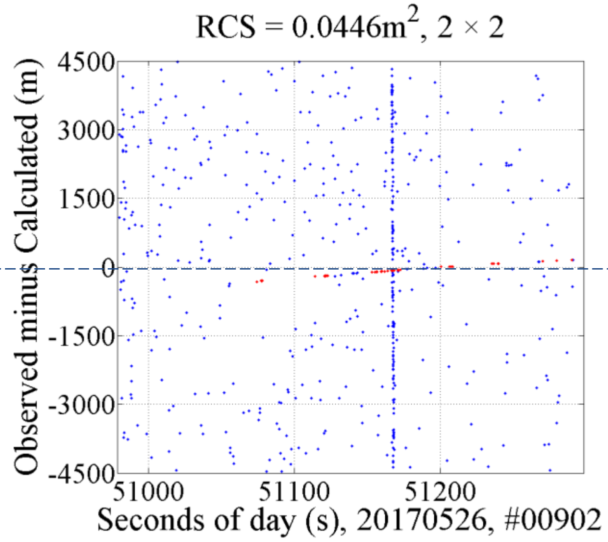
Number of days of observation	Number of targets	Number of passes
87	**249**	**532**

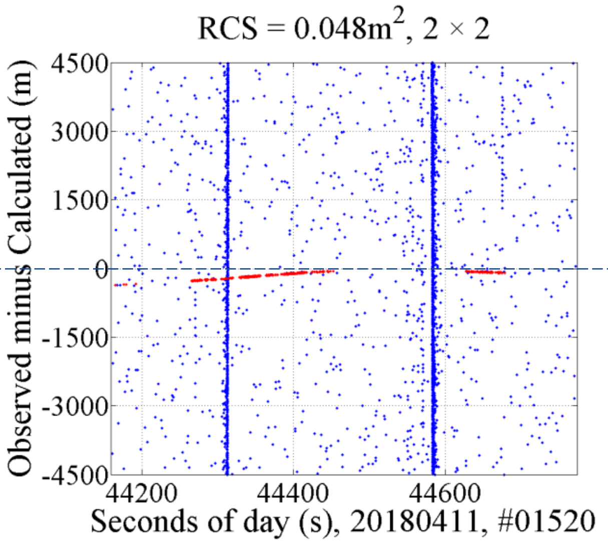


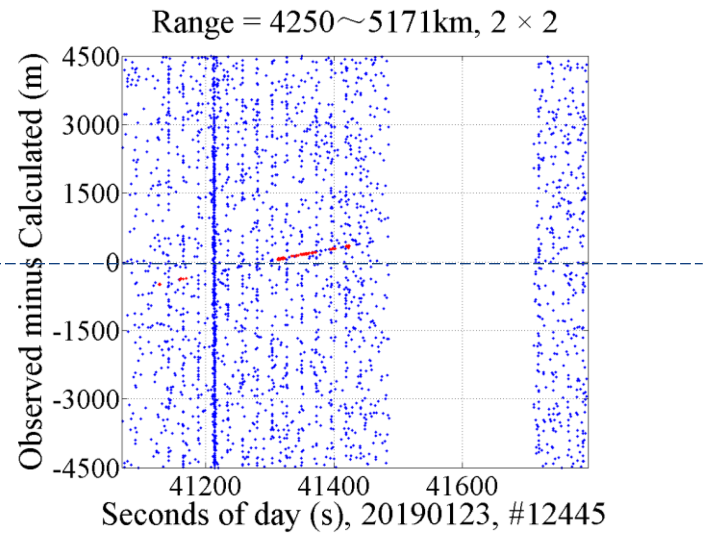
the echo rate statistics for different targets.
a) 2×2 SNSPD array. b) 4×4 SNSPD array.

4.1 Experiment and Results (the smallest & farthest)









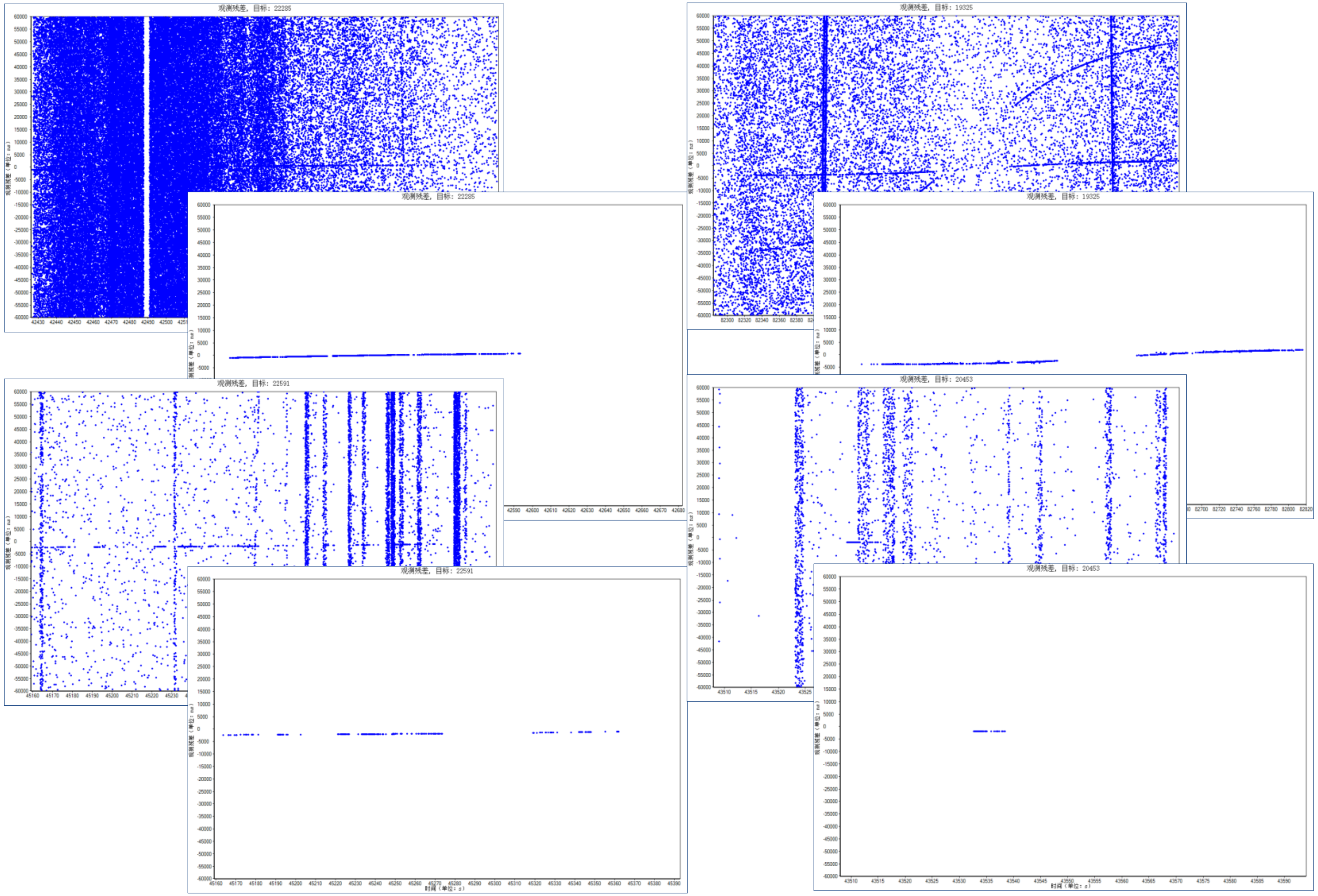
the smallest targets detected in the experiment

	Apogee / km	RCS / m²	Size / m	RMS / m	Laser power / W
900	1006	0.0490	spherical 0.36	<1.5	~70—150W
902	1075	0.0446	spherical 0.36	<1.5	~70—150W
1520	1175	0.0480	spherical 0.36	<1.5	~70—150W

the farthest target (12445, RCS~18.2505m²) detected in the experiment

date	Range / km	RMS / m	Laser power / W
Jan. 23, 2019	~4250—5171	2.32	~200
Jan. 27, 2019	~6261	2.12	~200

4.2 Data preprocessing automation

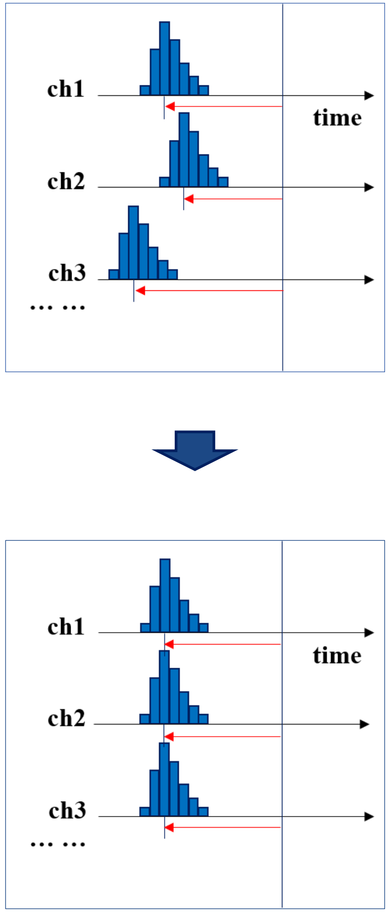


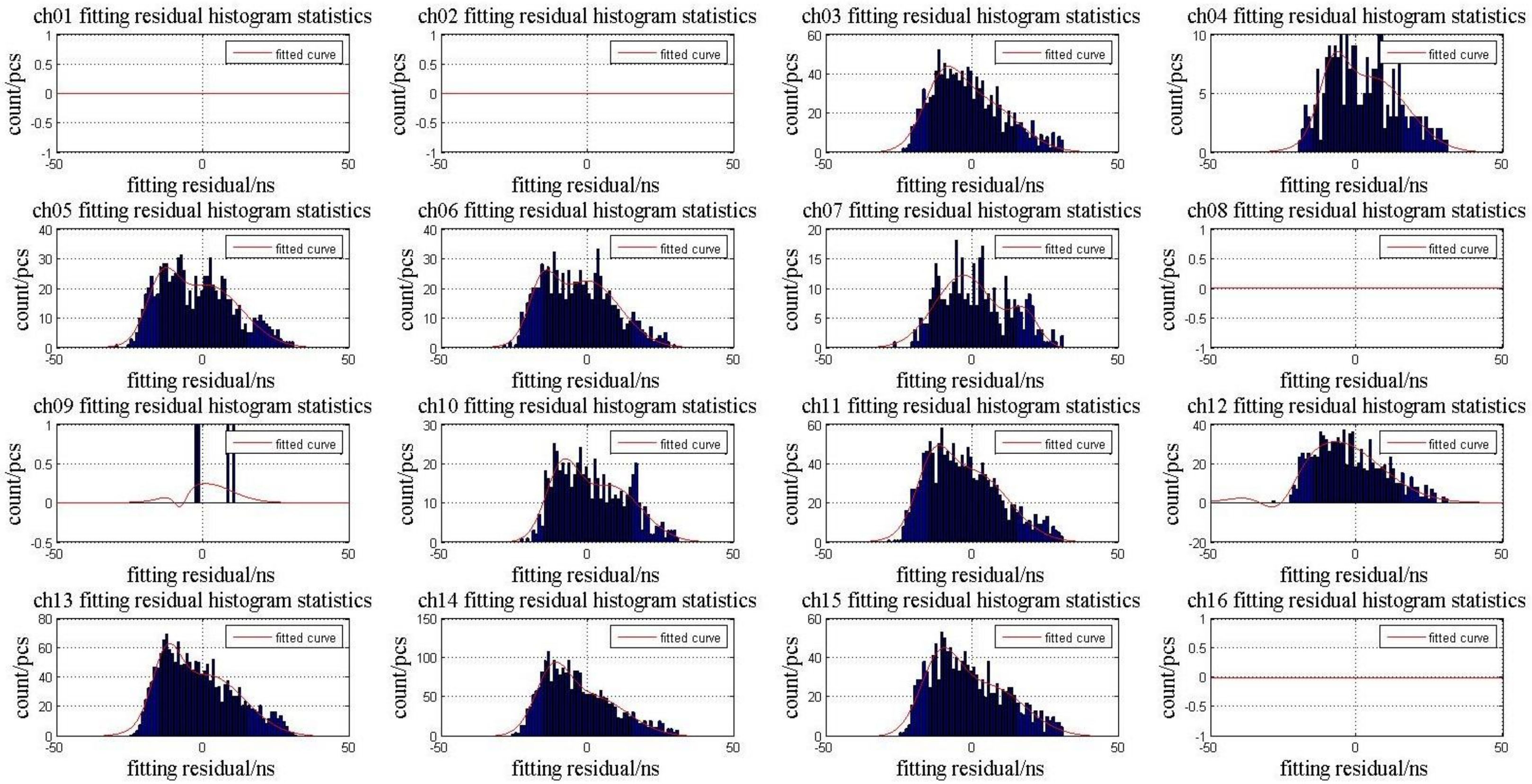
Data preprocessing automation

The noise of SLR is usually considered to be consistent with the Poisson distribution, and with gate-free SNSPD, the noise distribution of SLR is more consistent with the Poisson distribution.

Using the Poisson filtering method (proposed by McDonald Observatory), more than 90% of the data is automatically processed within few minutes of the end of measurement

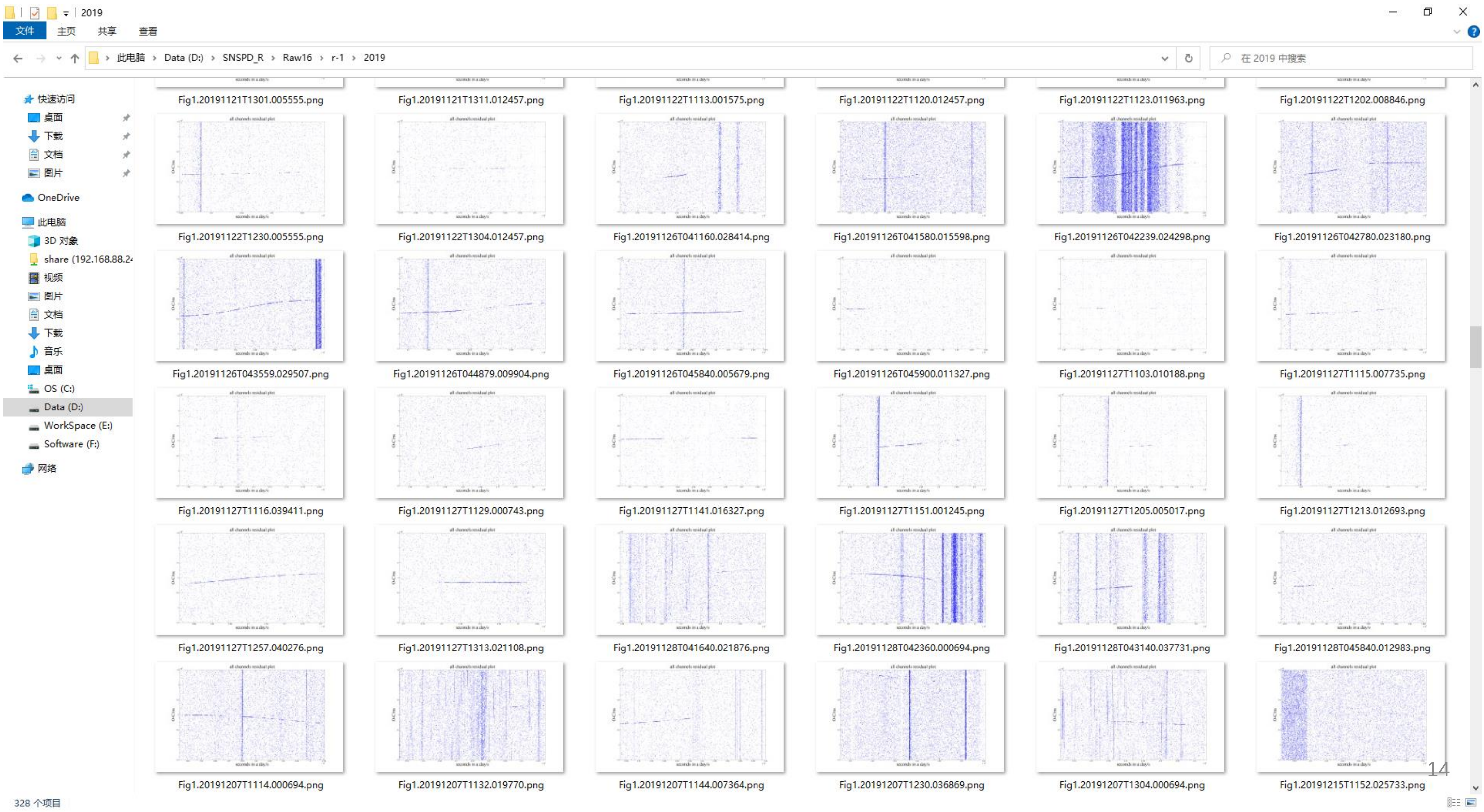
4.3 Data correction for array detection



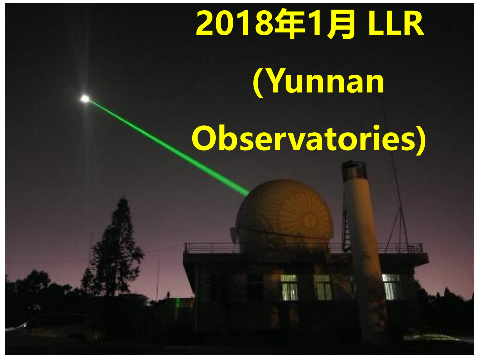


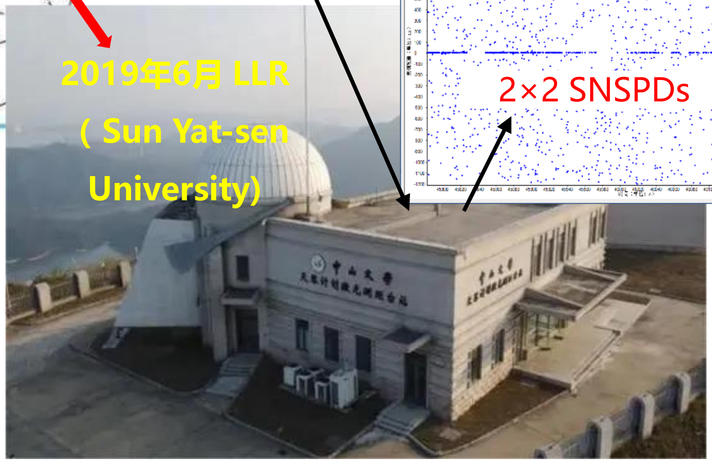
Data correction for array detection

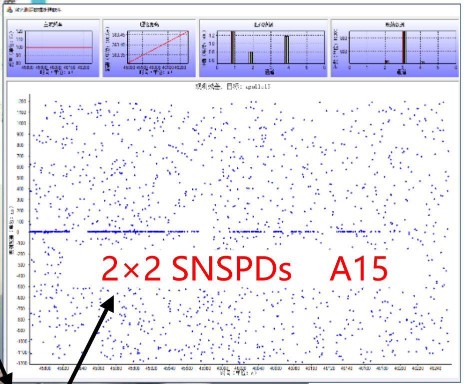
4.4 Experiment and Results (residual plots of some data)



5 Improvement and Application







LLR Station (Sun Yat-sen University)

LLR (Lunar Laser Ranging)

- developed from SLR
- the retroreflector array on the moon

Improvement

- range-gate-free → extra-large-range-gate
- Improvement of software and algorithms

Application

- The New LLR System of Yunnan Observatories，LLR data will be released when system commissioning is complete (7820)
- Yunnan Observatories led the construction of Sun Yat-sen University LLR Station，2019

6 Conclusion

Conclusion

- the SNSPD array running in automatic-recoverable range-gate-free mode : **greatly reduce the effect (the RB in the radial direction) of the inaccurate orbital prediction.**
- increasing the success probability of space debris laser ranging : increases the probability of detection (array) & **reduces the false alarm probability** (range-gate-free).
- After improvement, the method has been successfully applied to LLR.

Outlook

We will devote to applying the method to :

- **daylight** space debris laser ranging.
- lunar laser ranging with **extra-large-range-gate SNSPDs.**

Thanks for your attentions.

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