Advances in daytime Debris laser ranging(DLR) technology on the Changchun Station

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Changchun Observatory, NAOC, CAS

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Outline

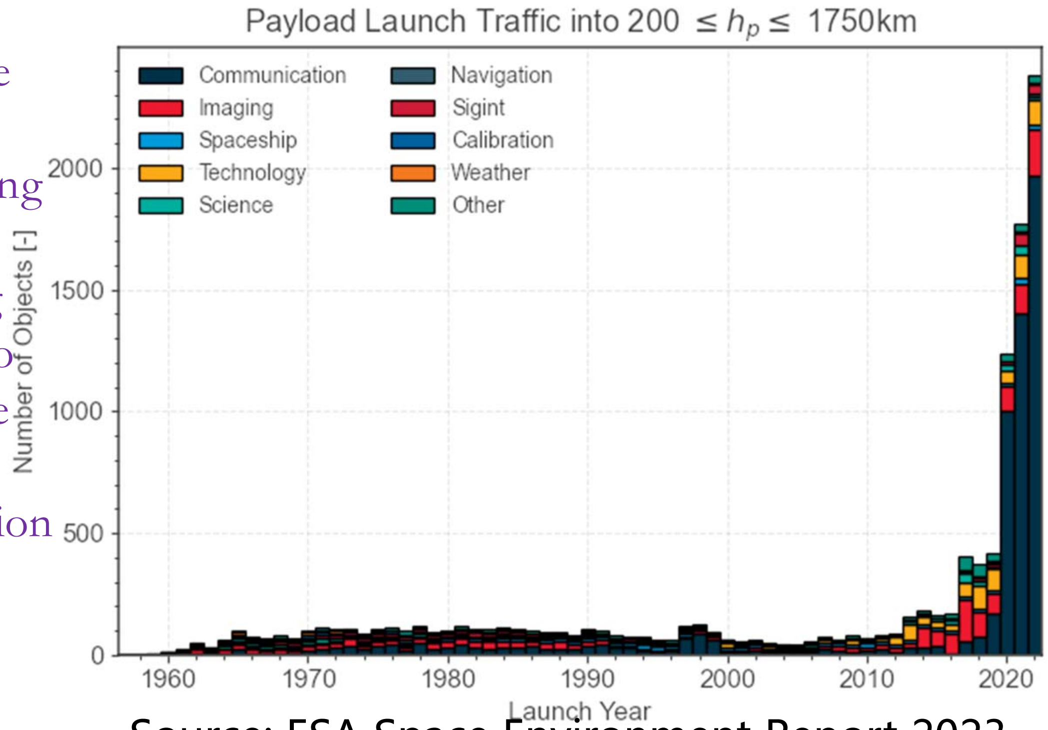
1. Status of DLR technology
2. Key technologies for DLR
3. Changchun 532nm DLR Platforms
4. 1064nm DLR platform
5. Development of single-photon detectors
6. Summary and future

1. Status of DLR technology → Trends in the space environment

With the rapid growth in the amount of space debris in recent years, the space situation for resources in near-Earth orbit is becoming more critical.

According to the ESA Space Environment Report 2023, the number of new satellites to be launched in 2022 is higher than any previous year.

- In the economically valuable LEO orbit, the number and size of commercial satellite constellations are increasing rapidly, crowding out orbital resources.
- Active satellites must perform an increasing number of collision avoidance maneuvers to evade the threat of other satellites and space debris.
- The limited capacity of space debris mitigation measures places greater demands on the capacity and accuracy of high-precision measurements of space debris.



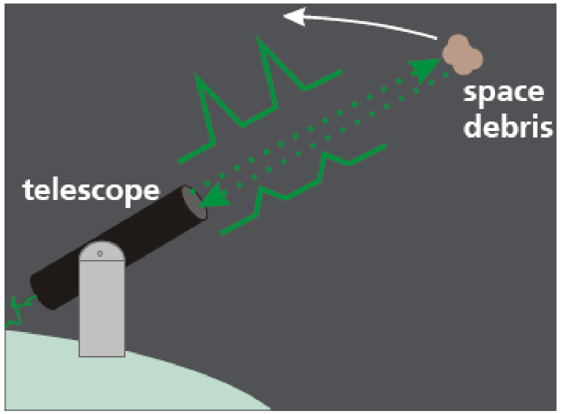
Source: ESA Space Environment Report 2023

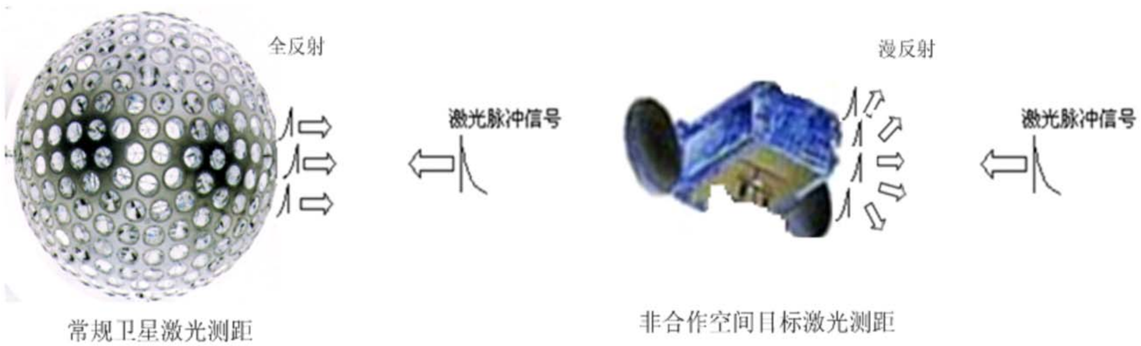
1. Status of DLR technology → DLR technology

Space debris laser ranging (DLR) is based on essentially the same principle as target laser ranging (SLR) with laser reflectors, in which the round-trip time of a laser signal from a ground station to a space target is measured and the distance to the space target is thus obtained. Space debris reflects diffusely off the surface of an incident laser pulse, therefore a very small number of laser return photons are returned to the ground observatory.

Technical characteristics of DLR, compared to other debris detection technology

- High observation accuracy (decimeter level)
- Fast measurement speed (real-time distance acquisition)
- Low cost of equipment compared to radar systems
- Weather-dependent, unable to work on rainy or cloudy days





1. Status of DLR technology → DLR Development

Since the development of space debris laser ranging (SLR) technology at the end of the last century, the detection capability has been significantly improved, however, compared with SLR technology, both in terms of the detection success rate, the output rate of effective DLR data, and the utilization rate of the data, there is still a great deal of room for improvement in terms of technological maturity.

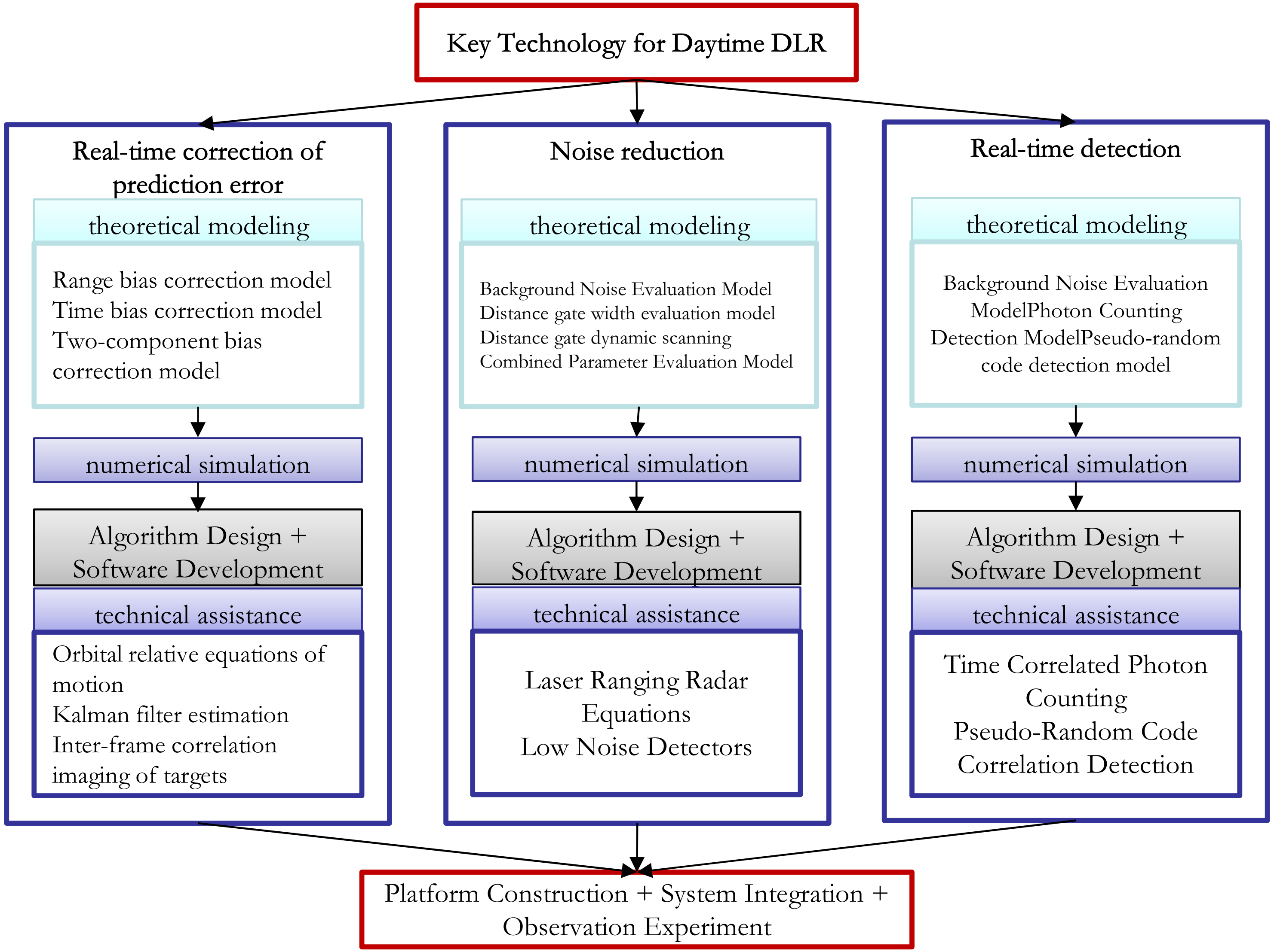
DLR capacity enhancement challenges

- Low signal-to-noise ratio for diffuse echoes
- Large deviations in initial orbit forecasts (kilometers)
- High transit speeds and low capture rates
- Daytime background noise effects
- Single station, single arc data only
- Low effective energy density of far-field lasers

Directions for further enhancement of DLR capabilities

- Detecting smaller target sizes
- Ranging accuracy (decimeters to centimeters)
- Rapid transit detection success rate
- morning and twilight → daytime → whole day
- Multi-station data fusion and synergistic utilization of the same target
- near-Earth target → higher orbit

2. Changchun Station Daytime DLR Key Technology

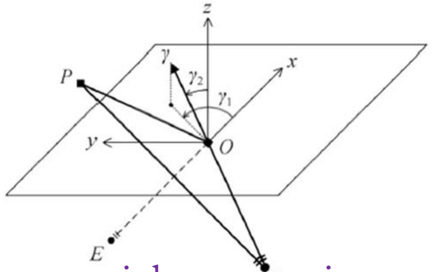


2. Changchun Station Daytime DLR Key Technology→ Real-time correction of distance forecast deviations

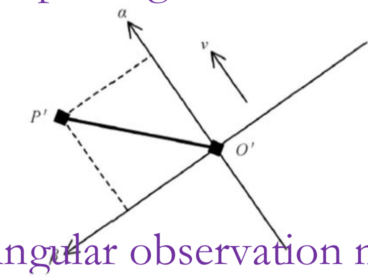
In daytime DLR ranging, in addition to the effect of background noise, in order to maintain a low false alarm rate, the conventional C-SPAD detector has a limited range gate width to cover the range error, so having the ability to improve the range prediction deviation in real time is the key to the success of daytime DLR.

- Based on the theory of relative motion of space target orbits.
- Correction of distance deviation by apparent position deviation.
- The concept and mathematical model were proposed in 2013.
- Patent for invention was authorized in 2016.
- Algorithm design and software engineering have been completed.
- Numerical simulation validation has been completed.
- Has been integrated and applied in DLR system.

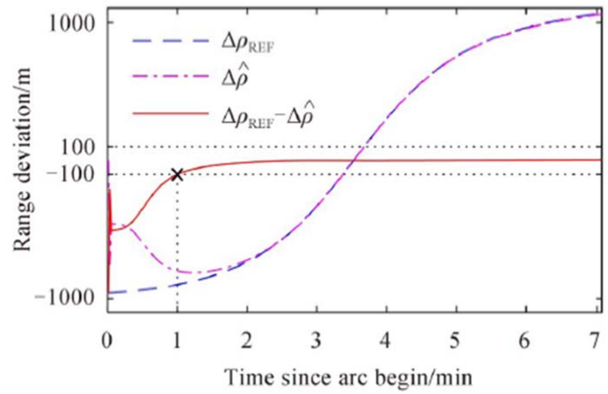

发明专利证书



spatial geometric model



Angular observation model



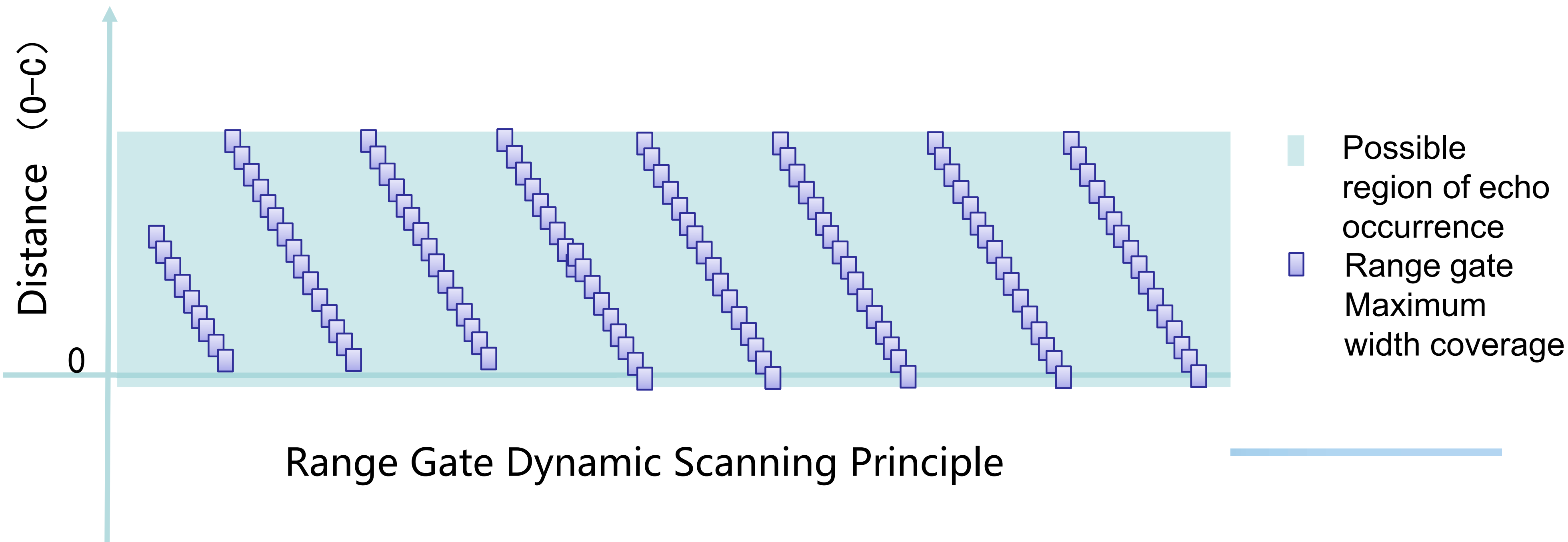
Distance deviation correction process

Gao jian,Liang zhipeng,Han xingwei et.al. Range Prediction Deviation Real-time Correction Algorithm for Space Debris Laser Ranging[J]. Acta Photonica Sinica,2022,51(09):342-350.

2. Changchun Station Daytime DLR Key Technology → Range gate dynamic scanning

Adopts range gate dynamic scanning technology, specific time threshold, narrow pulse width range gate, high speed searching

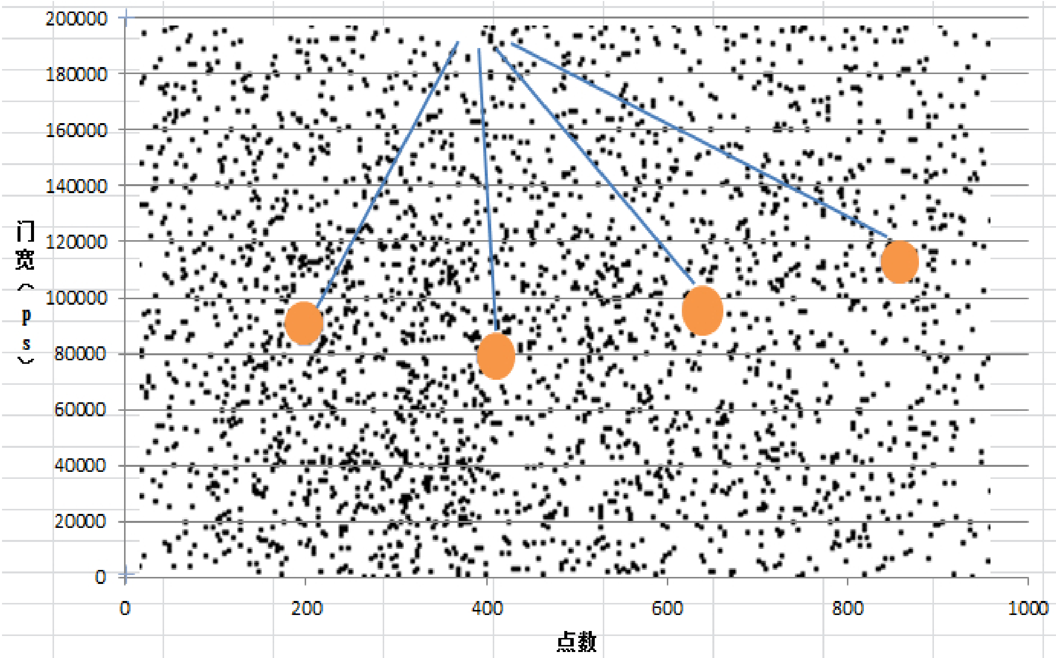
- Automation of range gate adjustment
- Dynamic scanning
- Time for space (equivalent reclocking reduction for larger range gate width coverage)



Range Gate Dynamic Scanning Principle

2. Changchun Station Daytime DLR Key Technology → Low signal-to-noise data recognition

The data recognition method of multiple iterative filtering is added to the DLR to identify and detect the effective data, thus reducing the probability of signal misjudgment and improving the detection success rate. In the process of laser ranging measurement, the effective data is normally distributed, and the noise is a discrete point, according to the orbit pre-precision of the observed target, the variation range of O-C value can be deduced as the basis for the multiple iterative filtering algorithm.



Multiple Filtering Principle

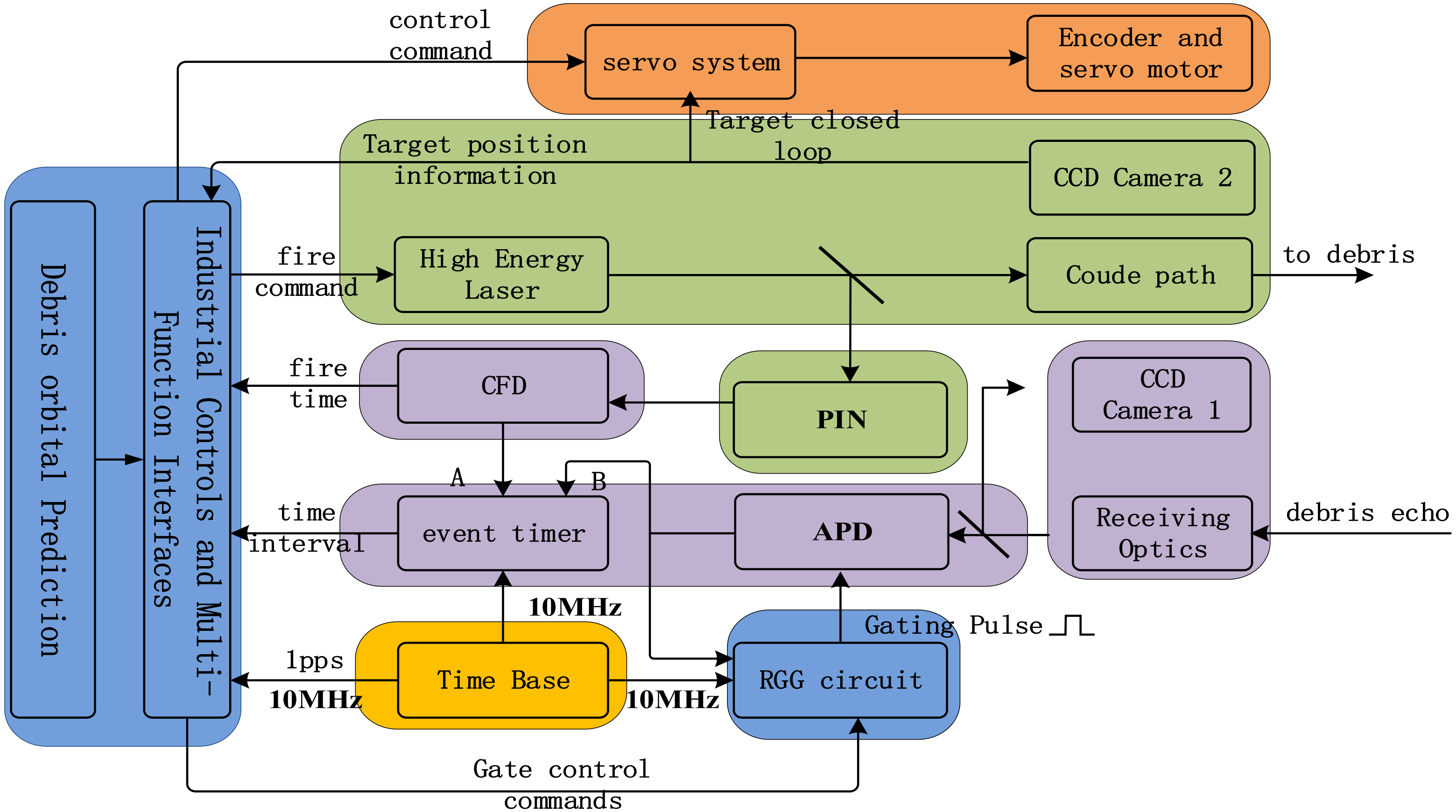
Multi-filter technology

$$\left|\Delta R - \Delta R_J\right| < \delta$$

where ΔR, ΔR_J are the spatial target distance O-C values, ΔR is the current O-C value, and ΔR_J is the assumed true value. δ is the comparison threshold, which is determined by the ranging error and forecast accuracy. The spatial debris threshold is set to 100 cm. applied in real-time observations to increase the identification of low signal-to-noise data.

3. Changchun 532nm DLR Platforms → System Components

System Architecture Diagram



Time subsystem, laser transmitter subsystem, echo receiver subsystem, control subsystem, target tracking subsystem

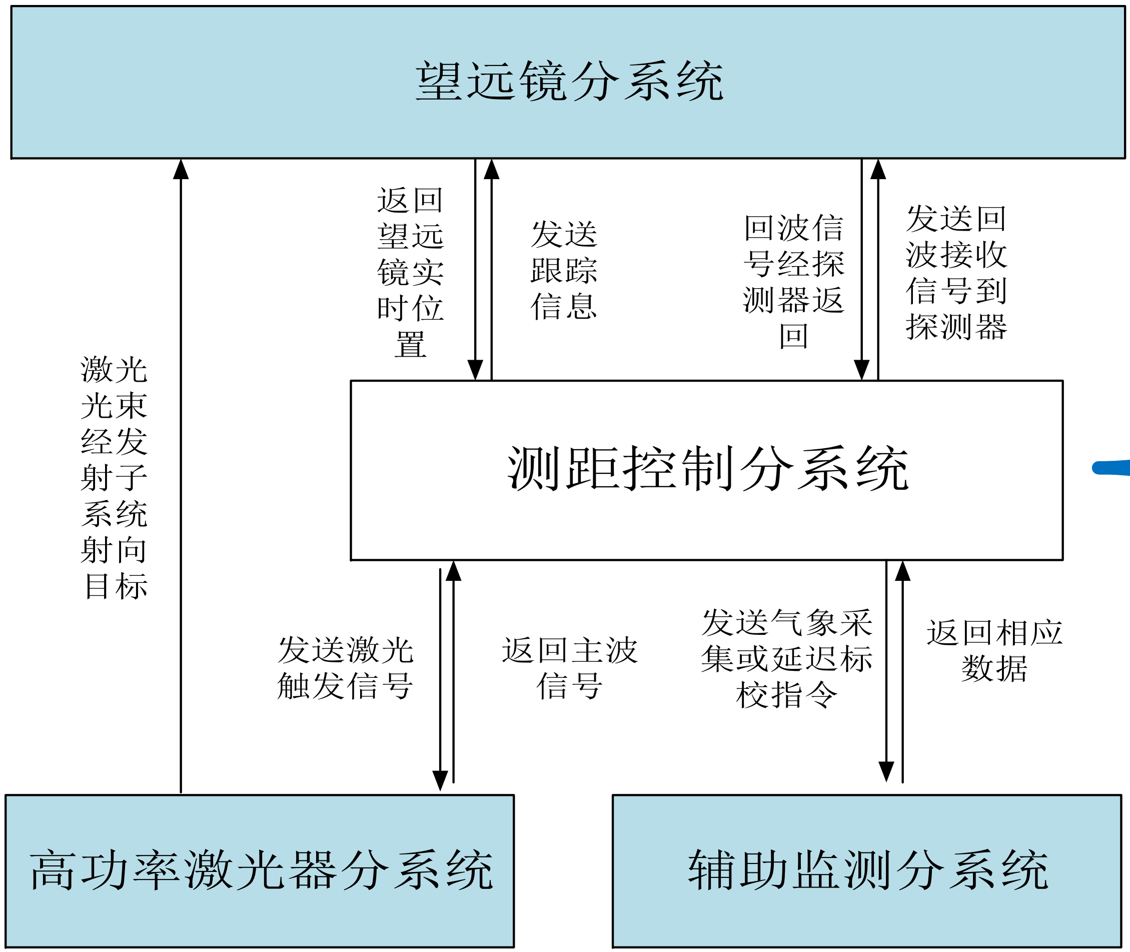
3. Changchun 532nm DLR Platforms → Key Equipment

High beam quality, high repetition frequency, high power lasers

- LD Pump
- Repetition rate： 500Hz
- Pulse energy： 60mJ@532nm
- Beam quality： $M^2 \leqslant 1.5$
- Divergence angle： 0.4 mrad
- Pulse width： 9-10 ns

60cm telescope/532nm-DLR system laser

4. Changchun 1064nm DLR Platforms → System Components



- Time acquisition timing subsystem
- Laser Emission Subsystem
- Echo Detection Subsystem
- Ranging control subsystem
- Distance Measuring Auxiliary Subsystem

1.2m/1064nm DLR system components

4. Changchun 1064nm DLR Platforms → system parameter

1.2m@1064nm-DLR system parameter table

items	parameter	
telescopes	Receiving telescope aperture	1.2m
	Emitting mirror caliber	40cm
	near infrared stargazer	40cm （@800nm-1100nm）
laser	output power	100W@1064nm
	repetition rate	400Hz
	divergence angle	⩽ 0.2mrad
	pulse width	⩽ 8ns
1064nmSPAD	quantum efficiency	⩾20%@1064nm
	photosensitive surface	Φ80um
RGG	time resolution	10ns
	Maximum operating frequency	10kHz
	framework	FPGA+DSP heterogeneous hardware architecture
Event timer	Time measurement accuracy	<10ps
Clock	UTC synchronization accuracy	<50ns(1PPS)
	frequency stability	⩽4E-13@1s

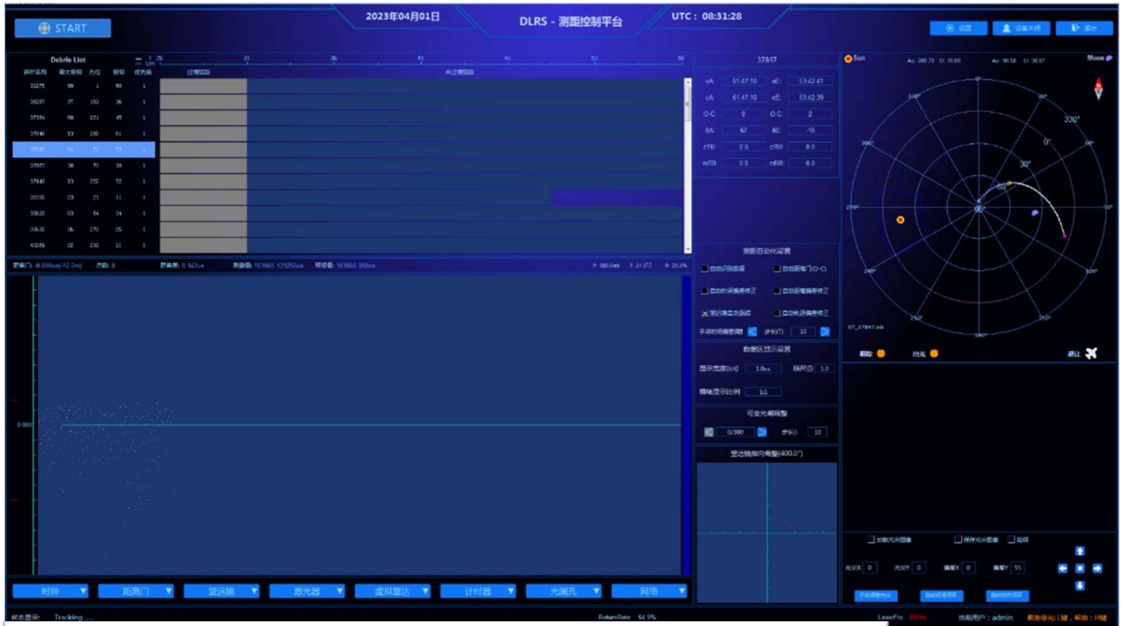
4. Changchun 1064nm DLR Platforms → Major equipment

1.2m laser ranging telescope + 0.4 transmitting telescope + 0.4 star guide mirror

DLR range control equipment

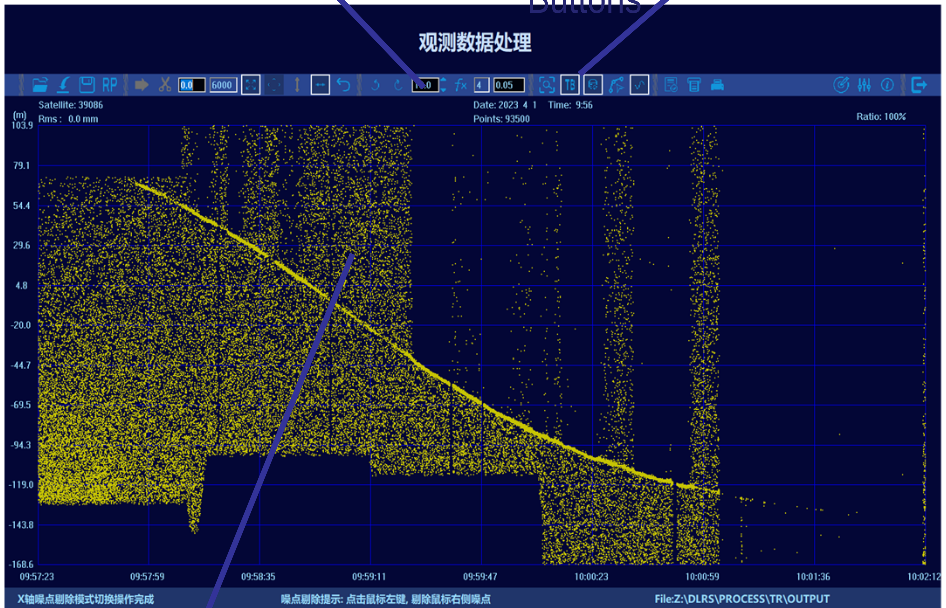
High Power Lasers

4. Changchun 1064nm DLR Platforms → Observation Interface

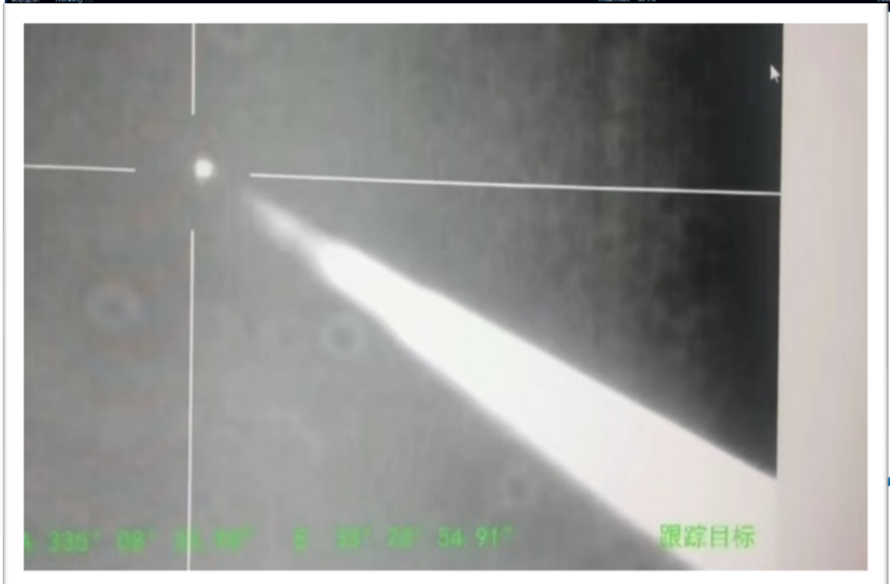


fitting function

Data Processing Series Function Buttons



Ranging O-C data



For the 1064nm dark weak signal-to-noise ratio, the backscattered image is processed to realize the optical tip position solving and real-time correction of the outgoing light direction.

4. Changchun 1064nm DLR Platforms → Night test results

1064nm DLR Interim Test Results (March 28, April 1, Morning + Night)

NORAD编号	RCS (㎡)	最大距离(km)	最小回波率(%)	最小距离(km)	最大回波率(%)	平均测量误差(mm)	数据识别
12792	5.09	1071.7	0.004	982.7	0.024	526	后处理识别
16612	4.47	1187					
18959	4.18	1449.9					
21820	5.39	1255.8					
22285	8.79	1072.6					
23405	8.91	1108.2					
24797	10.05	1014.2					
25281	1.35	969.9					
33505	4.09	1047					
39069	3.17	952.4					
39203	8.23	1428.6					
39211	7.96	1360.9					
39359	9.62	757.1	0.002	734.8	0.032	469	后处理识别

List of non-cooperative target data for March 28

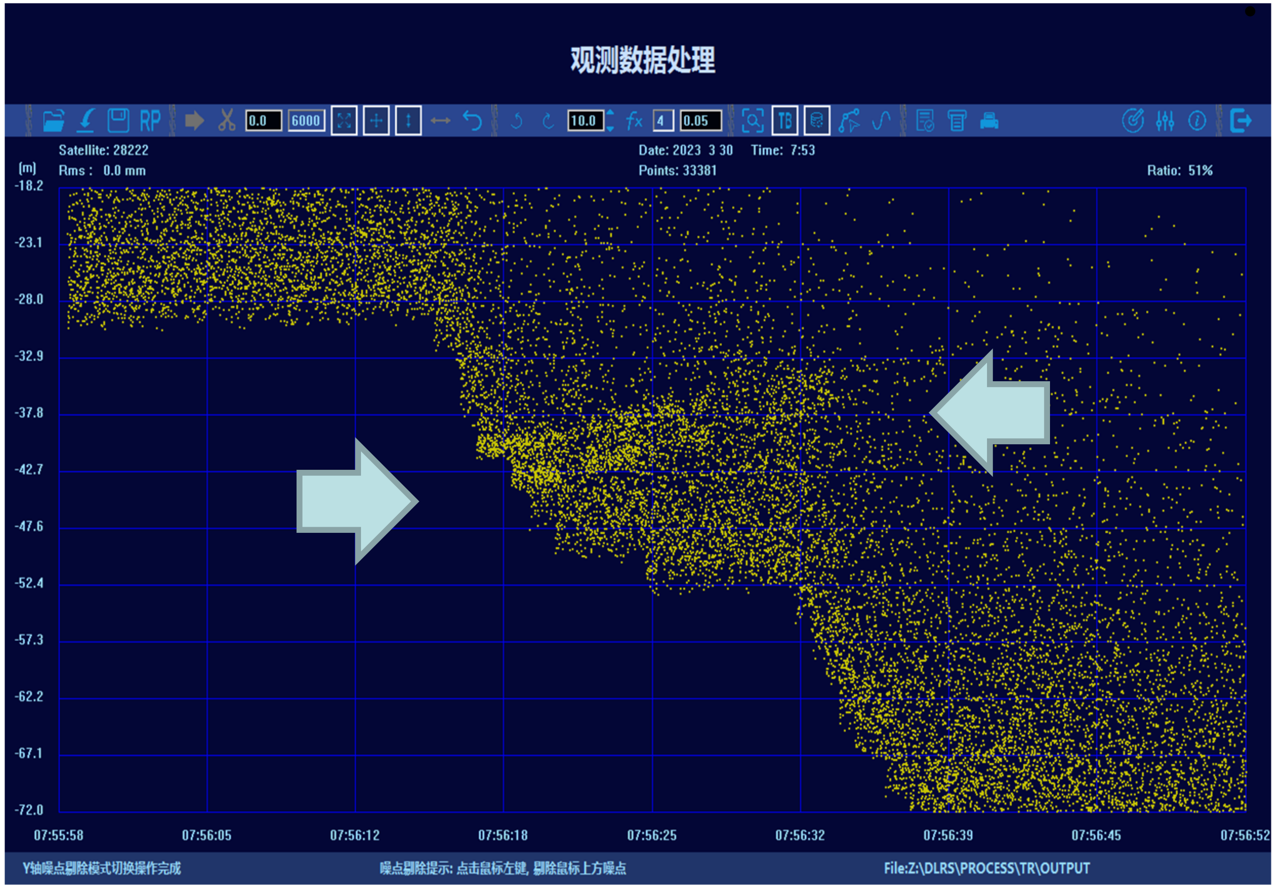
NORAD编号	RCS (㎡)	最大距离(km)	最小回波率(%)	最小距离(km)	最大回波率(%)	平均测量误差(mm)	数据识别
10521	4.51	1180	0.2	884	1.4	890	后处理识别
				41	0.6	760	后处理识别
				17	1.4	367	后处理识别
				92	0.5	802	后处理识别
				091	1.5	710	后处理识别
				78	4.1	474	后处理识别
				21	0.9	756	后处理识别
				87	0.7	621	后处理识别
				002	0.7	711	后处理识别
39261	8.03	1056	0.2	811	1	629	后处理识别

List of non-cooperative target data for April 1

The measurement accuracy is related to the target attitude, spin characteristics, laser beam stability and other factors, and varies greatly, and the single ranging precision is generally less than 1 m (RMS).

- Maximum Slope distance： 1449km;
- Minimum Slope Distance： 757km;
- RCS range： 1.4~10.0 ㎡;
- Acquisition of arc segments： Total about 30min

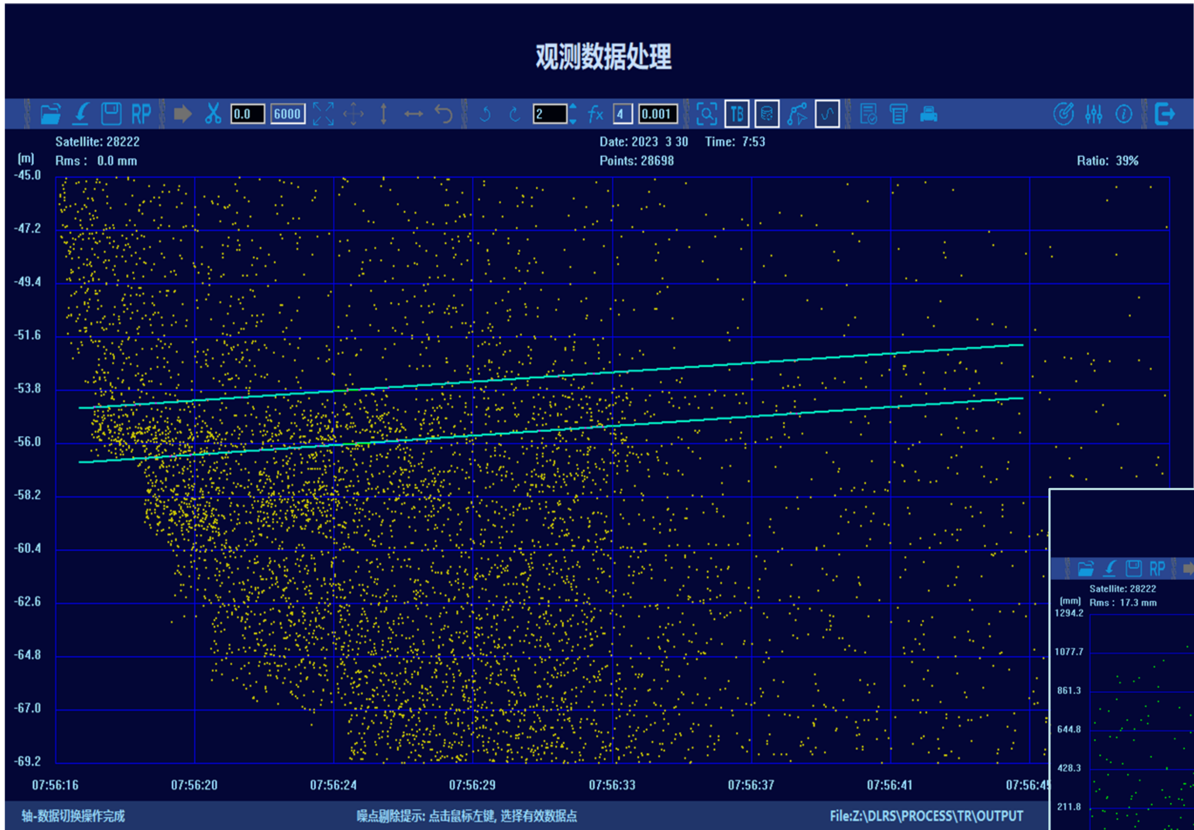
4. Changchun 1064nm DLR Platforms → Daytime test results table



On the afternoon of March 30, 2023, 1 pass of non-cooperative targets was observed during the daytime, with a solar altitude angle of 20 degrees, and the effective data of the observation could be clearly seen, successfully realizing the daytime ranging test of space debris at the wavelength of 1064 nm, and laying a platform and technological foundation for the follow-up further research.

- TargetNo. 28222 for CZ-2C rocket upper stage
- orbital inclination： 97.8°
- Orbital Height ： about 510km
- radar scattering cross section area ： about 12 ㎡。

4. Changchun 1064nm DLR Platforms → Daytime test results table



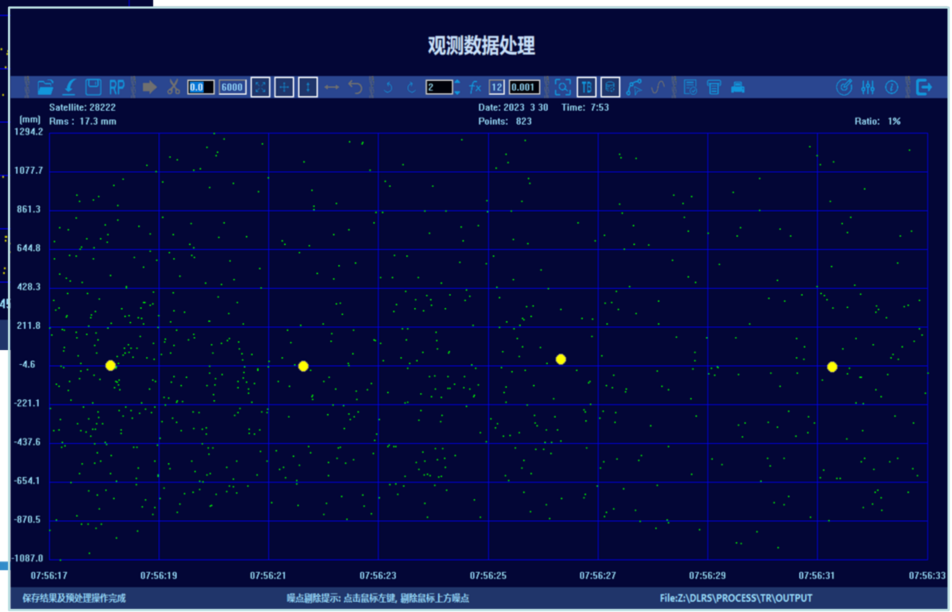
Observation arcs ： 30s

Effective point ： 823点

Ranging accuracy ： 537mm

Time bias ： 95.6ms

Range bias： -54.3m



Data processing interface for daytime non-cooperative target observations (top) Standard point generation screen (right)

5. Development of single-photon detectors

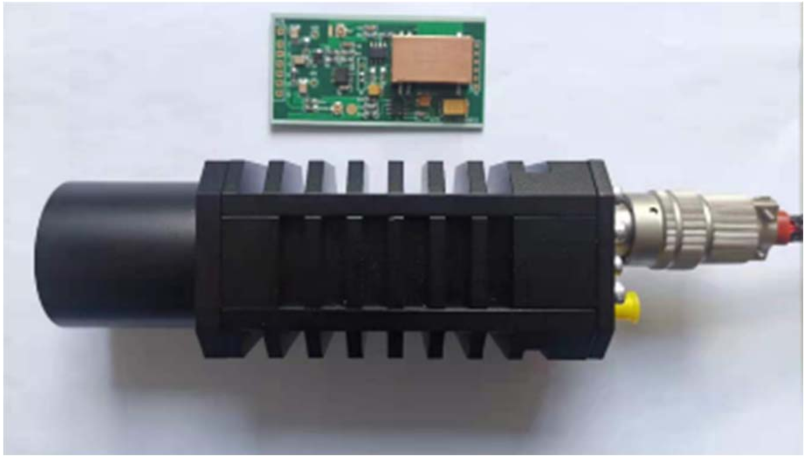
Application of 1064nm detector laser ranging station

- OCA
- GRAZ station
- Wettzell station
- Stuttgart station
- Izana station

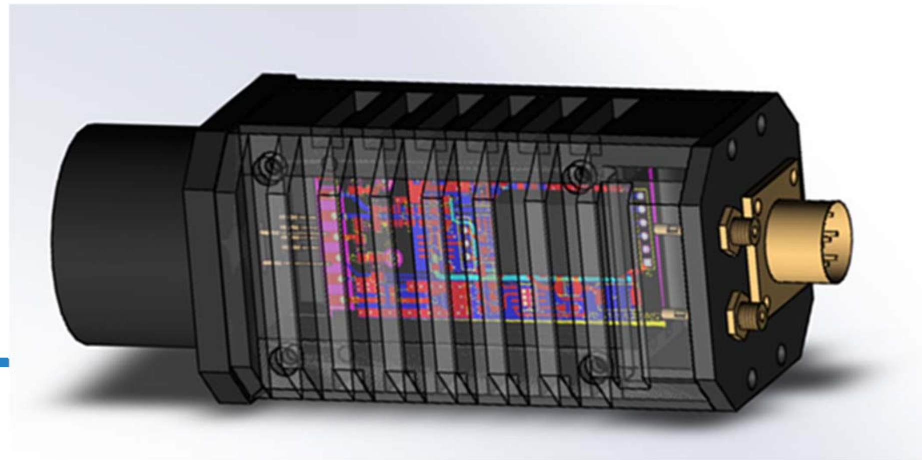
We developed our 1064nm detectors. While COTS 1064nm detectors did not meet our requirements or was not available.

5. Development of single-photon detectors

➢ Near-infrared single-photon detector @ 1064 nm: developed and applied



➢ Visible single photon detector @532nm: Optical coupling lens/si-APD selection/peripheral drive circuit design completed, integration and debugging in progress.



5. Development of single-photon detectors →

Near Infrared Single Photon Detector

Near Infrared Single Photon Detector Performance

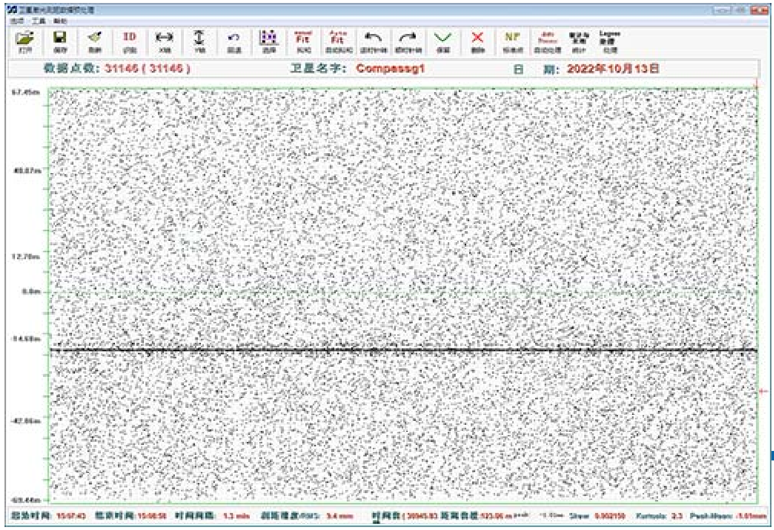
- chip material： InGaAs/InP
- operating wavelength ： 1064nm
- quantum efficiency ： ＞20%
- photosensitive surface ： Φ80um
- operating temperature ： @-50℃ （TEC Three-stage cooling ）
- avalanche voltage ： 79V_{b+} @-50℃
- Gate control signal ： 0.1-20us （TTL） @3.3-5V
- Effective aperture ： 19mm （ achromatic aberration ）
- DCR： <60KHz@10V_{br+}
- Jitter： ＜40ps

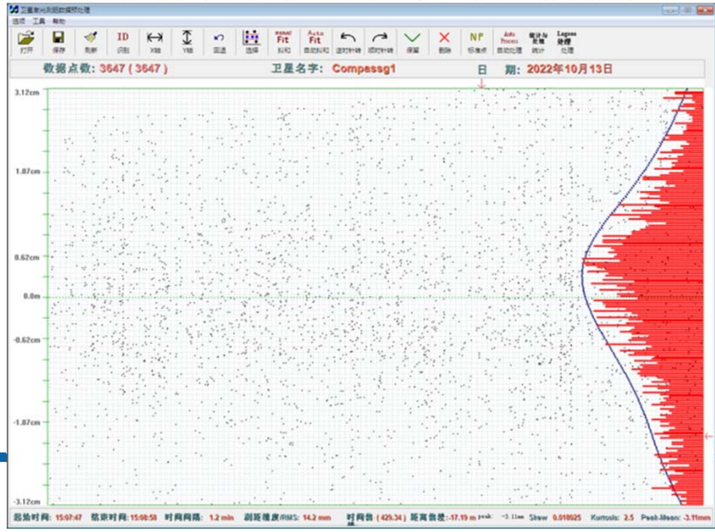
5. Development of single-photon detectors → Near-infrared single-photon detector (cooperative) test

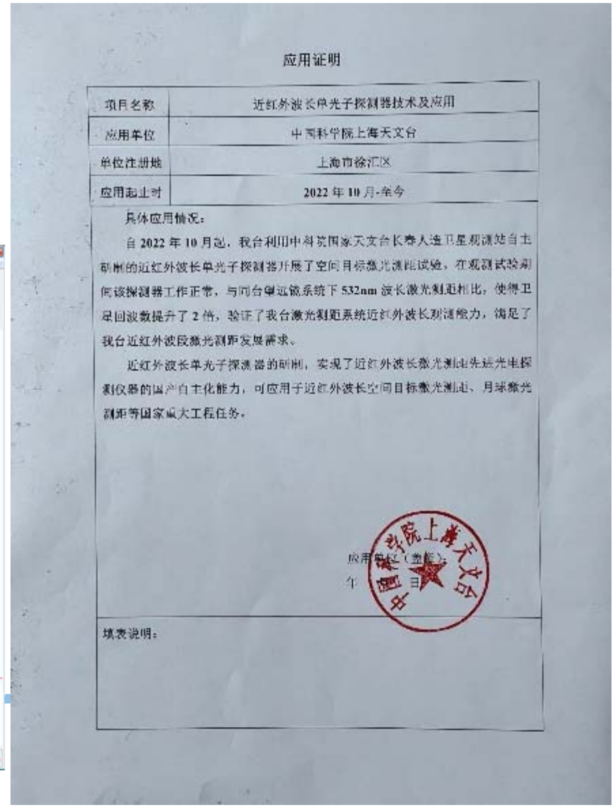
- Application in Shanghai station 60cm laser ranging system

Based on the 60cm laser ranging system of Shanghai Observatory, we have completed the validation of 1064nm cooperative target measurement and realized the effective ranging of GEO Beidou G1 satellite and other high-orbit targets, and the echo rate is significantly higher than that of the conventional 532nm detector.

序号	时间段（UTC）	时长（min）	星名简称	星名全称	点数	精度cm	备注
1	14点26分至27分	1	07	Glonass107	26408	2.55	夜晚
2	14点32分至33分	2	B9	Beidou3m9	29178	1.27	夜晚
3	14点27分至29分	2	I5	compassi5	4516	1.36	夜晚
4	15点6分至8分	2	G1	compassg1	5749	1.65	夜晚
5	8点39分至41分	3	07	Glonass107	4064	2.43	白天







应用证明

项目名称	近红外波长单光子探测器技术及应用
应用单位	中国科学院上海天文台
单位注册地	上海市徐汇区
应用起止时	2022年10月-至今

具体应用情况：

自2022年10月起，我台利用中科院国家天文台长春人造卫星观测站自主研制的近红外波长单光子探测器开展了空间目标激光测距试验，在观测试验期间该探测器工作正常，与同台望远镜系统下532nm波长激光测距相比，使得卫星回波数提升了2倍，验证了我台激光测距系统近红外波长观测能力，满足了我台近红外波段激光测距发展需求。

近红外波长单光子探测器的研制，实现了近红外波长激光测距先进光电探测仪器的国产自主化能力，可应用于近红外波长空间目标激光测距、月球激光测距等国家重大工程任务。

应用单位（盖章）

年 月 日

填表说明：

5. Development of single-photon detectors → Near-infrared single-photon detector (non-cooperative) test

- Applied in the temporary 1.2m space DLR system of Changchun Institute of Optical Mechanics and Physics (CIOMP).

- During the test period from 27.Mar.2023 to 1.Apr.2023, DLR system acquired 36 observations, of which 10 were of cooperative targets, 26 were of non-cooperative targets and 1 was of non-cooperative targets during the day.

- The total number of space debris arcs obtained amounted to 105 minutes, with a maximum space debris observation arc of 3 minutes and a minimum space debris observation arc of 1 minute;

- The space debris RCS has a minimum of 1.4 square meters and a maximum of 12.3 square meters;

- The maximum effective range value is 1449km and the minimum is 608km.

5. Development of single-photon detectors → Near-infrared single-photon detector (non-cooperative) test

- Applied in the temporary 1.2m space DLR system of Changchun Institute of Optical Mechanics.

1.2m laser ranging telescope test platform to carry out 1064nm near-infrared band high repetition rate space debris daytime ranging test, the application of 40cm infrared guide star to realize the daytime target tracking, the use of narrow-band interferometric filters spectral filtering, the use of the TLE for the initial forecast orbit, the Solar altitude angle of 20°, the target and the sun angle of 88°, the successful realization of diffuse reflectance on the body of the rocket The effective observation arc segment is 30s, the effective echo point number is 823, and the single measurement accuracy (RMS) after data preprocessing is 537mm, time deviation is 95.6ms, and distance deviation is -54.3m.

Date	code	Time of observation (Beijing)	Solar altitude angle	Observation arc length	Number of observation points	RCS	Orbital Information	Single measurement accuracy (RMS)	note
2023-3-30	28222	3:56 p.m.	20° (Target angle to the sun about 88°)	30s	823	$12m^2$	Altitude 510km, Period 95min, Inclination 97.8°	537mm	TB=95.6ms RB=-54.3m

Summary and future

- Changchun Station has carried out Space Debris Laser Ranging (DLR) experiments on 532nm and 1064nm platforms, and utilized and verified a number of key technologies.
- Self-developed key devices the low-noise, low-jitter 1064nm APD single-photon detector package;
- Daytime ranging of space debris at visible and near-infrared wavelengths has been realized. However, the maturity of daytime DLR technology and the level of system automation need to be further improved;
- A number of new DLR techniques (real-time estimation of daytime background noise, distance gate width adaption, etc.) are currently under experiment, and in the future, space debris ranging capability and ranging accuracy will be further improved to prepare for the application of small-size, all-day DLR technology.

Thank you!