The Progress of Space Debris Laser Ranging at Shanghai SLR station (focus of ps-laser measurements)

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Outline

1. Introduction

2. ps-Laser DLR with green and infrared wavelength

3. Hundreds kHz rate ps-laser ranging to space targets

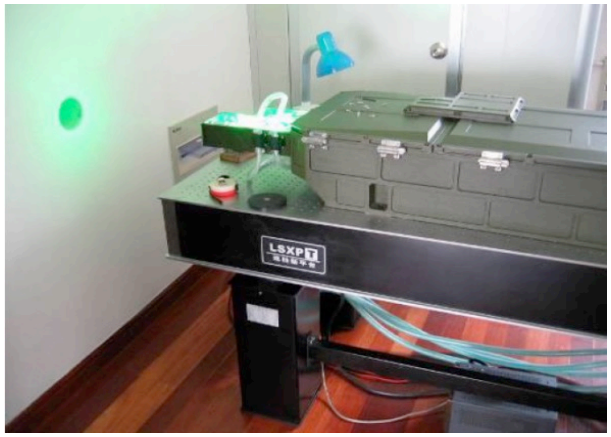
4. Future plans

1. Introduction

Start of DLR at Shanghai SLR station

- **Since 2006, Shanghai Astronomical Observatory firstly in China have begun to develop the technology of laser ranging to space debris through updating the 60cm routine SLR system.**
- **In July 2008, the preliminary DLR system was established and laser data from debris target (Rocket body) were obtained by using the nano-second pulse width and lamp-pumped laser system.**

- **Repetition: 20Hz**
- **Pulse energy: 2J**
- **Wavelength: 532nm**
- **Power: 40W**
- **Pulse-width: 12ns**



1. Introduction

Developments of DLR technology at Shanghai SLR station

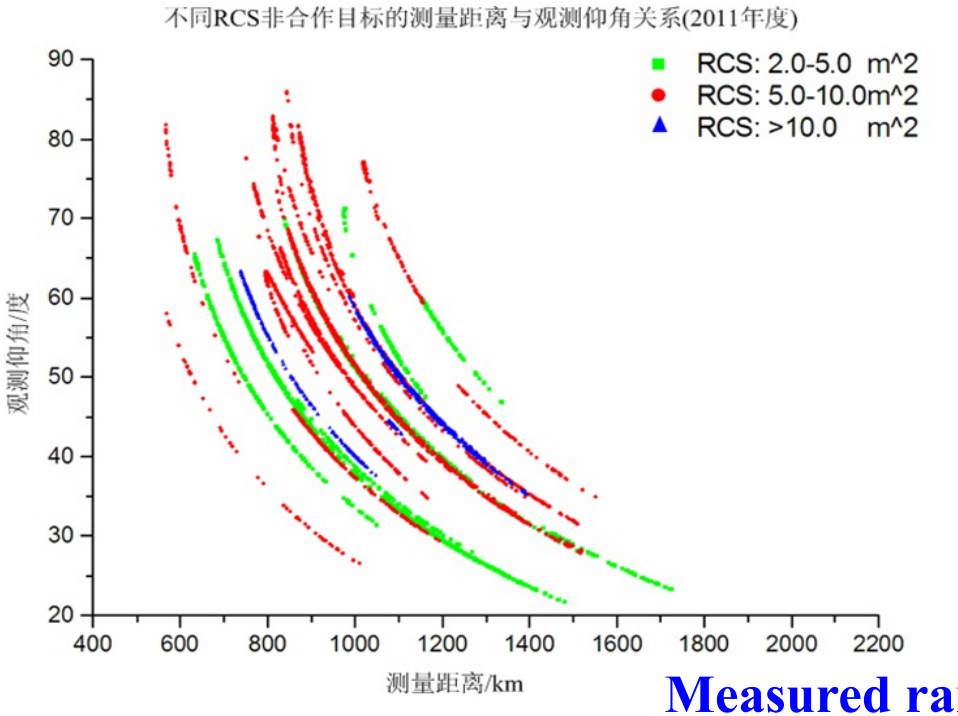
ns-high repetition rate laser system:

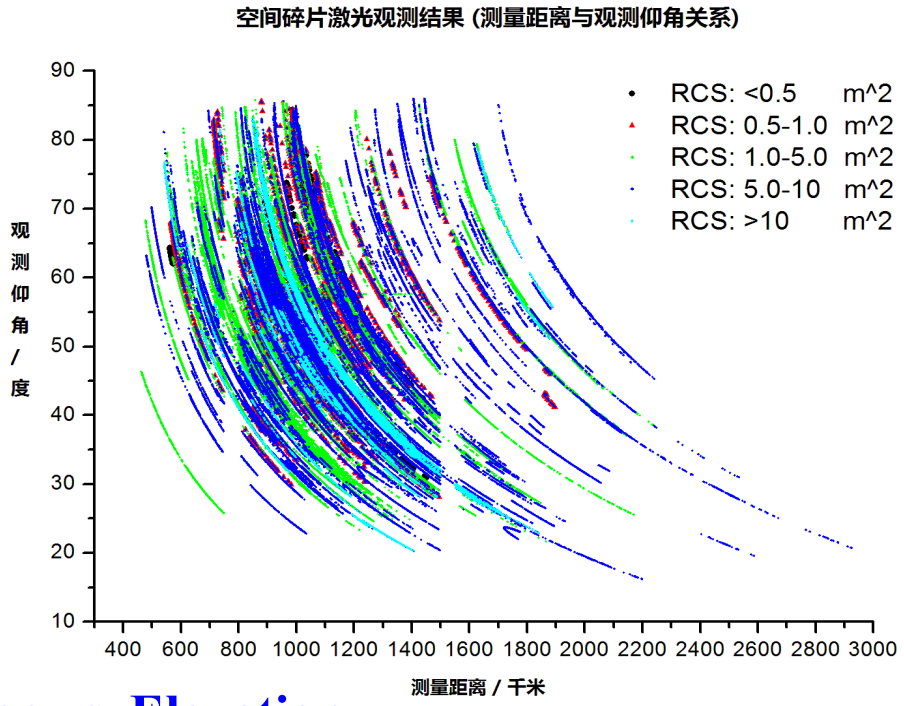
- The diode-pumped laser with high repetition rate became a good choose for space debris laser measurement, especially at the stability, beam quality while increasing power.
- Since 2013, Shanghai SLR station used laser unit with the power of > 50W@532nm wavelength at the frequency of 200Hz (~8ns pulse width) to perform laser ranging to debris target.
- Also working with high efficiency, low noise APD detector (HQE) and narrow bandwidth spectrum filter (bandwidth: 2nm).
- More than 200 objects (Rocket body, Iridium, Radar Cal. Objects, Debris) with 600 passes of laser data were obtained.

1. Introduction

DLR system with ns-high power laser unit (200Hz)

Low repetition rate → High repetition rate





Measured range vs. Elevation

- Size of target: 2m^2 → 0.3m^2;
- Max. range: 1700km → 2900km;
- Observation rate: <30% → >80%

Outline

1. Introduction

2. ps-Laser DLR with green and infrared wavelength

3. Hundreds kHz rate ps-laser ranging to space targets

4. Summary

2. ps-Laser DLR with green and infrared wavelength

- **According to the nonlinear effect theory of ps-laser pulse atmospheric transmission, there exists advantages (div. angel along path) for DLR measurements compared to ns-laser in the certain case.**

  - Refractive index: $n = n_0 + n_2 I(r)$
  - Diffraction limitation: $r = M^2 \frac{2\lambda L}{\pi D}$
  - Div. angle along path: $\theta = \frac{r - D}{L}$

- **So, the idea of using ps-laser unit for DLR measurements was proposed in 2018.**

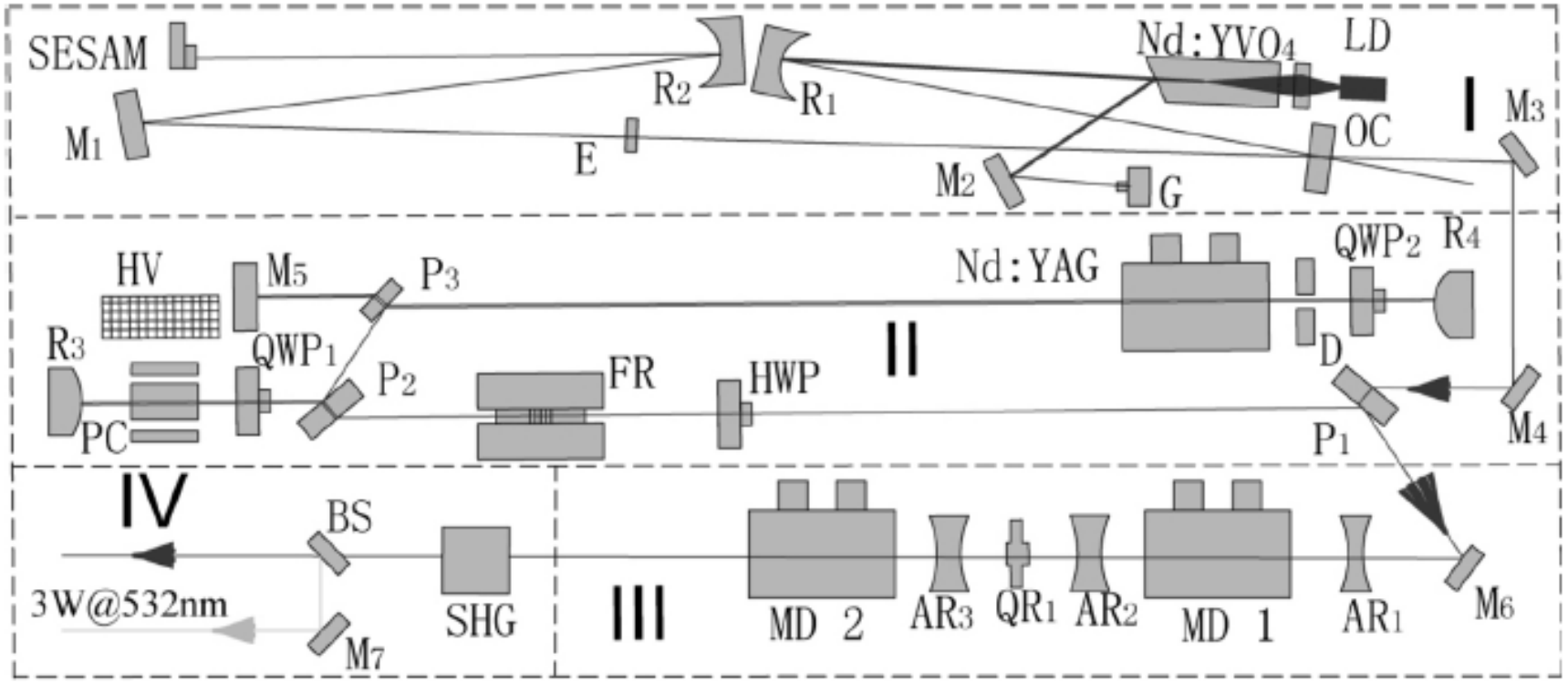
- **However, the output power of ps-laser unit for routine SLR is only 1-2W, not enough for DLR.**

- **In order to increase the output power of ps-laser unit, an average power of 4.2W green ps-laser unit with double-pulses at a pulse repetition frequency of 1 kHz was developed by Shanghai station.**

2. ps-Laser DLR with green and infrared wavelength

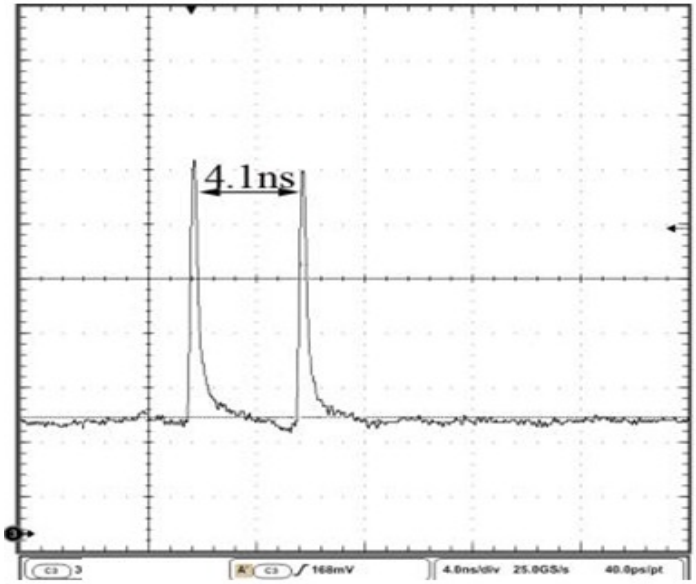
(1) ps-laser unit with :

- Dual-length of regenerative cavity for Nd:YAG picosecond laser was designed:
  - I, Nd:YVO4 mode-locked laser;
  - II, dual-length of the RA;
  - III single-pass two Nd:YAG modules amplifier;
  - IV, LBO frequency doubling.

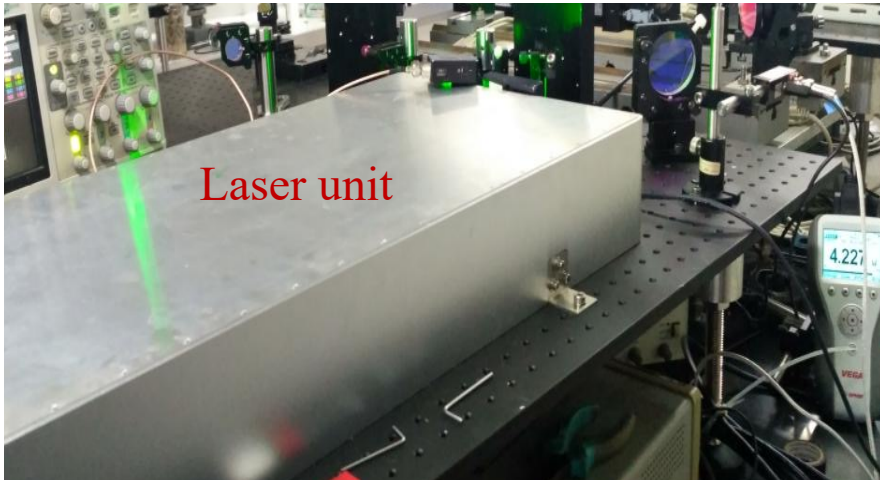


2. ps-Laser DLR with green and infrared wavelength

- The double-pulses in a burst is output by changing the buildup time of the regenerative amplifier and quarter-wavelength plate (QWP).
- The space between two pulses was 4.1 ns. And if the pulses cannot be separated, it was equivalent to ns-laser.



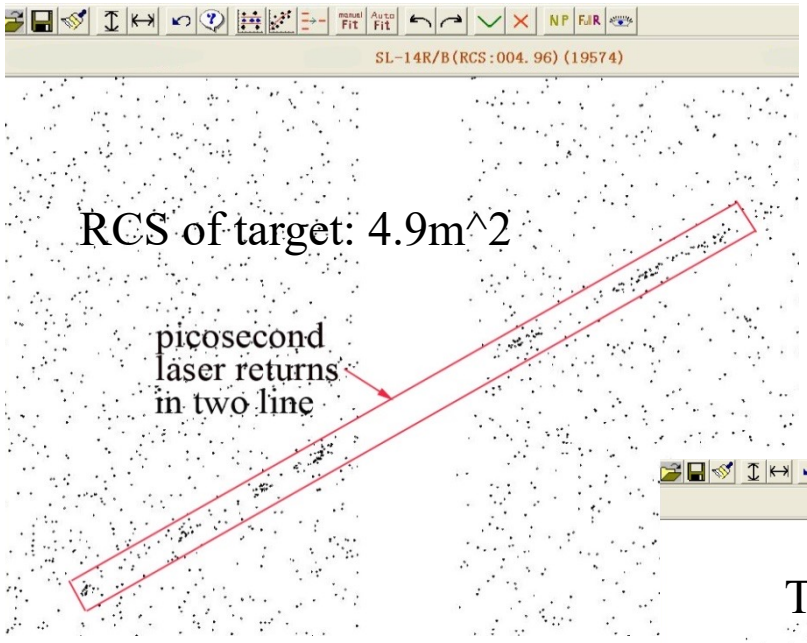
- An average power of 4.2 W at 532 nm was achieved with double-pulse:
  - M^2 :1.2,
  - stability of power RMS: <2 %,
  - pulse width of 60 ps,
  - divergence of 0.6 mrad.

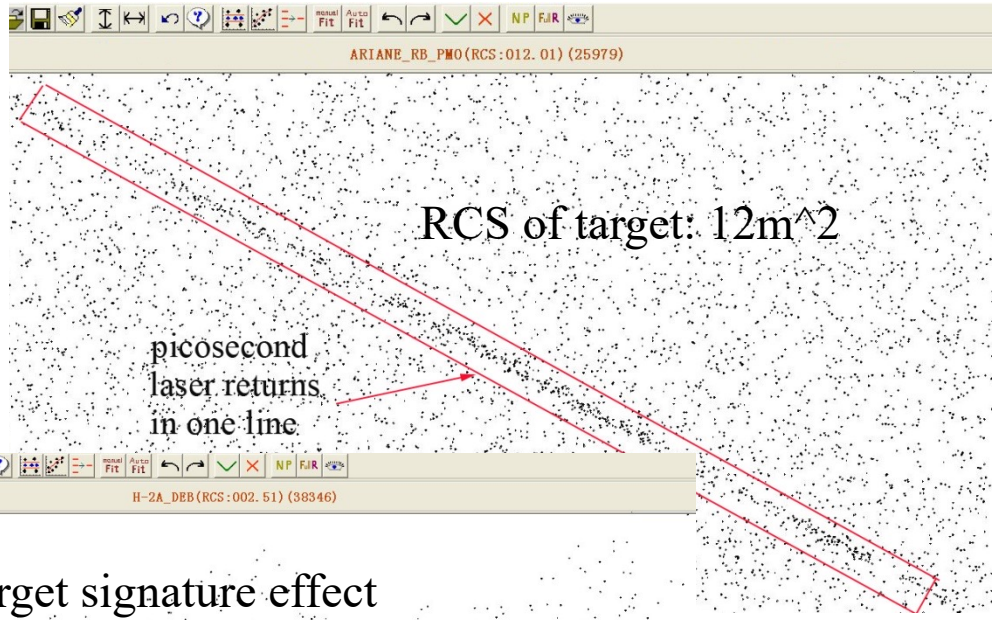


2. ps-Laser DLR with green and infrared wavelength

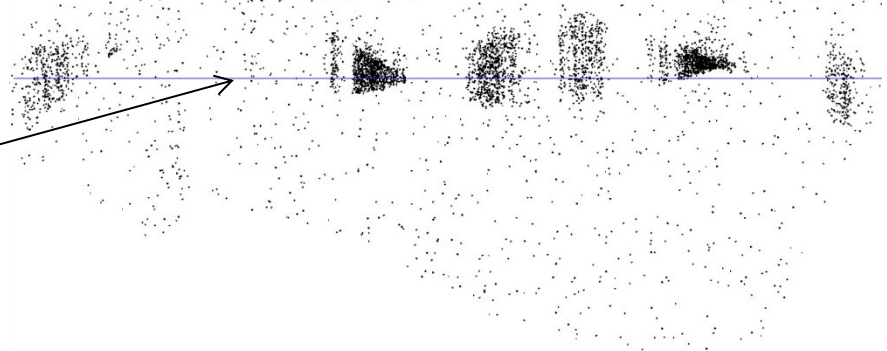
- **Observation results by using double-pulse ps-laser unit at Shanghai station.**

Laser returns from space debris of ID.19574 and 25979





Target signature effect



Due to the better ranging precision, the shape information of debris target was also be shown.

2. ps-Laser DLR with green and infrared wavelength

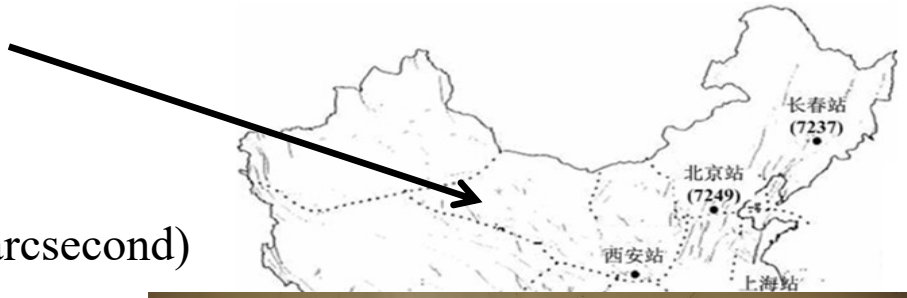
The results of ps-laser ranging to space debris (4.2W ps laser unit), some ones of RMS: 5-6cm.

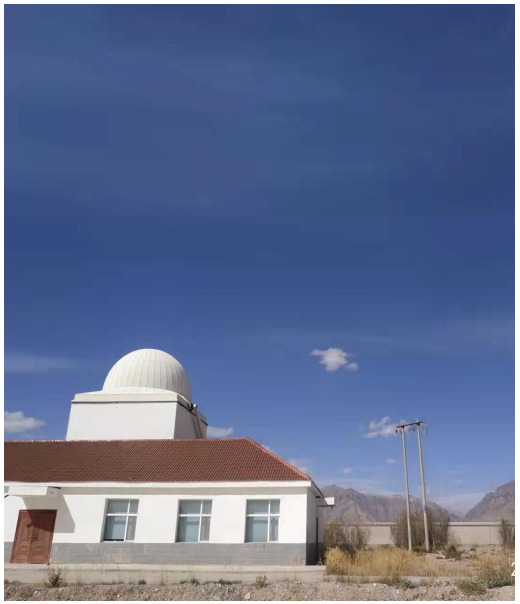
No.	Date	ID	Type of space debris	Measured Distance(km)	RMS (mm)	RCS (m^2)
1	2018-8-18	21423	Cosmos 2151 Rocket	879~1132.7	56.4	4.61
2	2018-8-18	25979	Helios 1B Rocket	948.7~1020.8	594.3	12.01
3	2018-8-18	19275	Okean 1 Rocket	863.4~1433.7	315.4	4.69
4	2018-8-18	19574	Cosmos 1975 Rocket	683.2~962.0	46.9	4.96
5	2018-8-18	19650	Cosmos 1980 Rocket	885.7~1156.5	2165	12.11
6	2018-8-18	27665	GPS 51 Dl Rocket	853.7~870	486.3	5.55
7	2018-8-24	14700	Cosmos 1536 Rocket	709~739.7	217.1	4.06
8	2018-8-27	22220	Cosmos 2219 Rocket	860.8~874.2	1592.4	5.72
9	2018-9-9	38345	GCOM W1 ShrdF	888.7~1005.7	58.3	4.43
10	2018-9-9	38347	GCOMW1 Adptr Debris	750.9~979.6	164.6	10.71
11	2018-9-9	20362	GPS 2-05 r1	649.1~853.9	61.4	9.99
12	2018-9-9	38346	GCOM W1 ShrdG	810.8~1010.7	317.5	2.51
13	2018-9-28	20303	GPS 2-04 r1	656.5~896.8	400.5	2
14	2018-9-28	20453	GPS 2-06 r1	684.1~766	1002.8	9.86

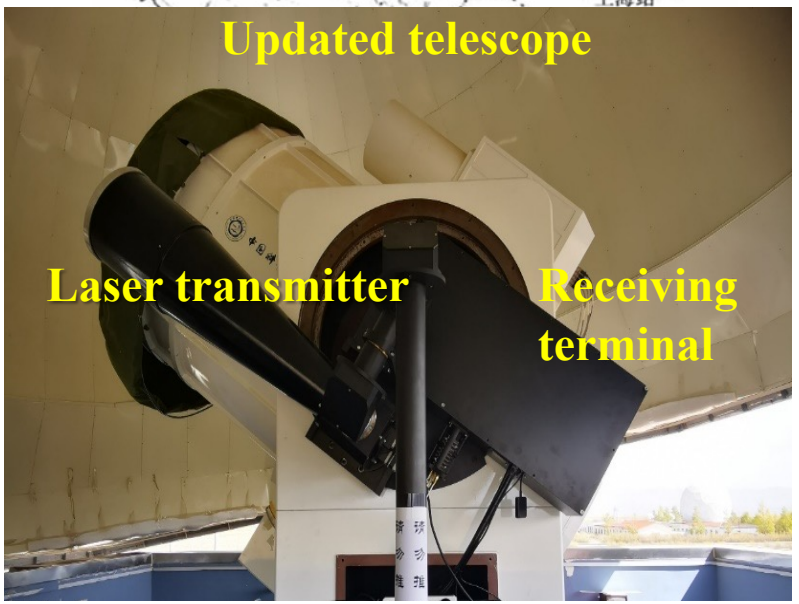
2. ps-Laser DLR with green and infrared wavelength

(2) Laser tracking to debris by using 1.2m aperture of telescope and 1.2W ps-laser unit with 1kHz, 532nm.

- In collaboration with PMO observatory in China, Shanghai station updated one set of the telescope system used for quantum communication between satellite and ground in Qinghai province.
  - Aperture of telescope: 1.2m
  - Tracking precision: <1 arcsecond
  - Site attitude: 3200m (seeing:<1.5 arcsecond)



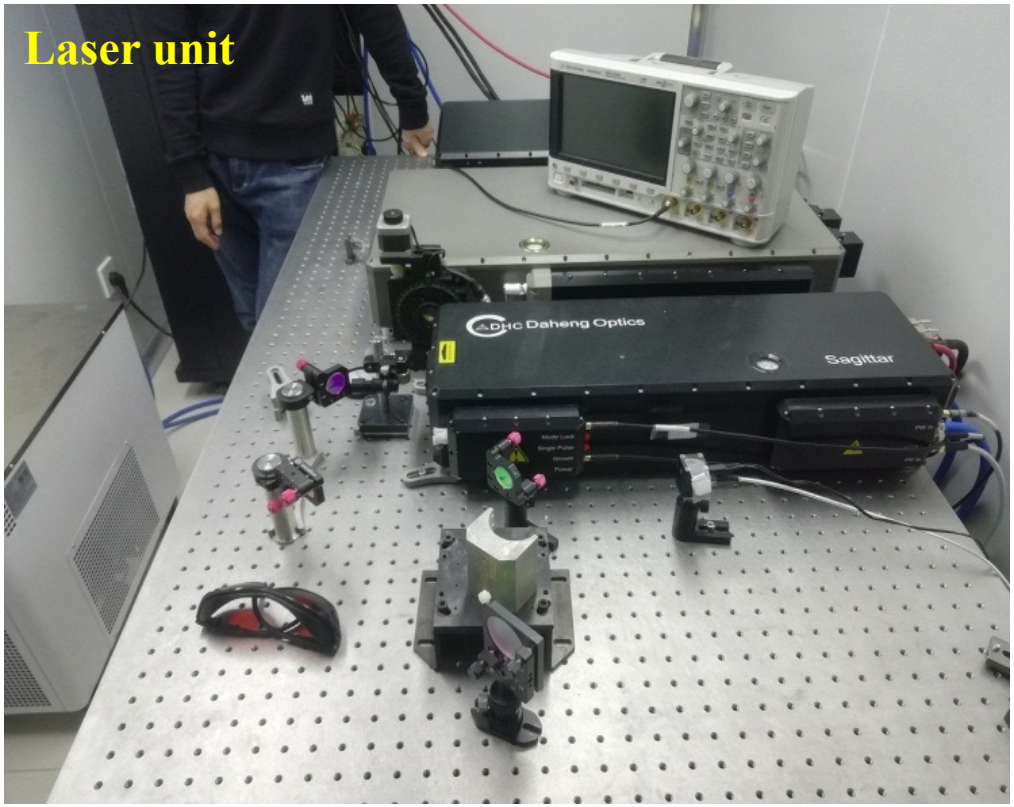


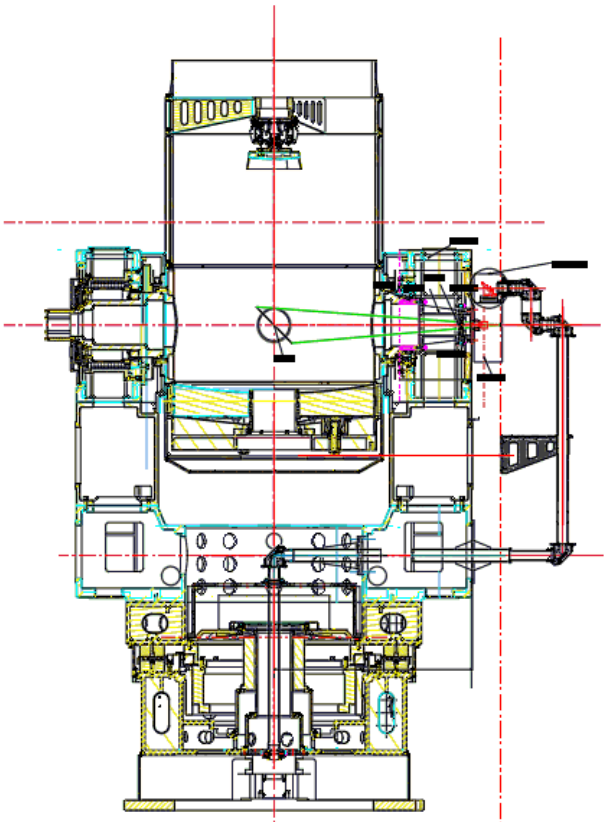


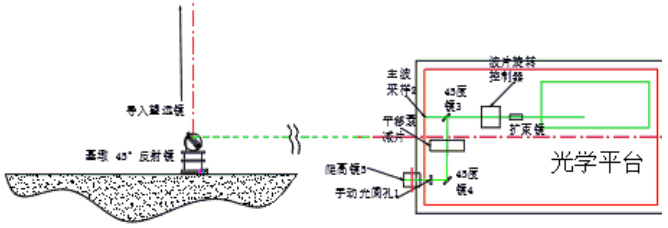
2. ps-Laser DLR with green and infrared wavelength

- **Laser unit**

  - Beijing Daheng laser company:
    1.2W@1kHz, 35ps, 532nm, dev. 0.6mard.



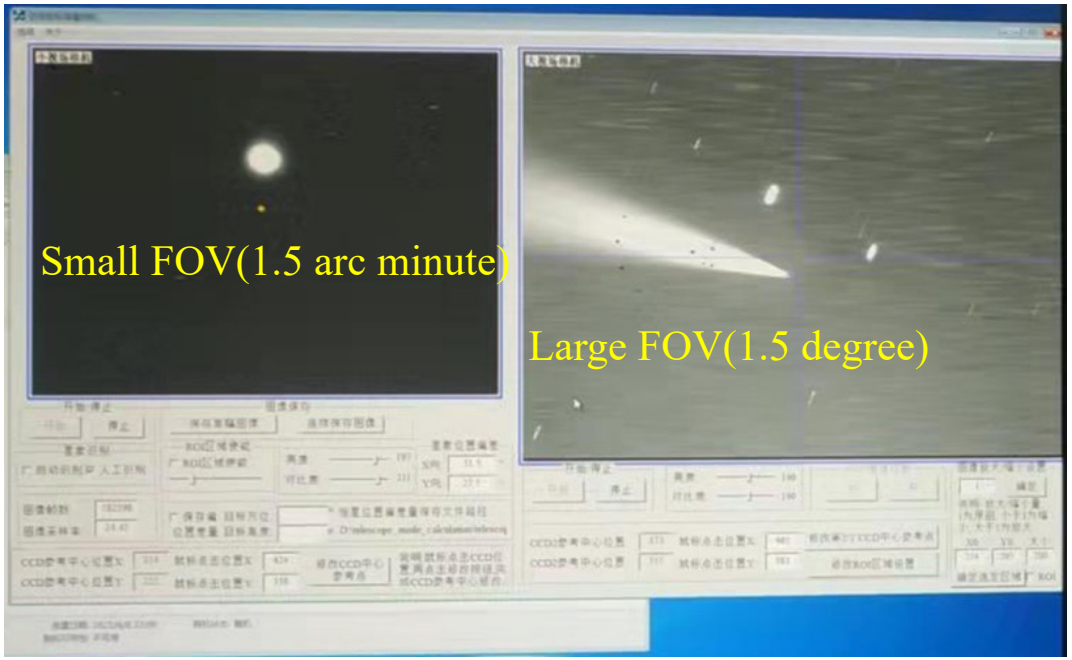




2. ps-Laser DLR with green and infrared wavelength

Target guiding unit

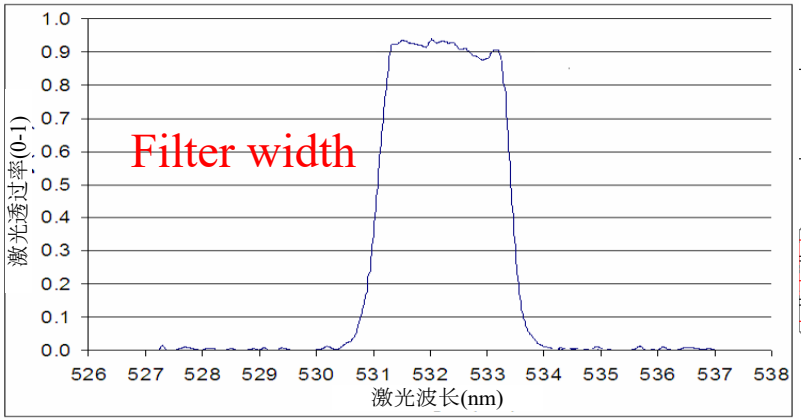
- Two different cameras were used for target guiding while DLR measurements;
- One's FOV: 1.5 arc minute for tracking target and laser pointing, another one's FOV: 1.5 degree for searching targets.

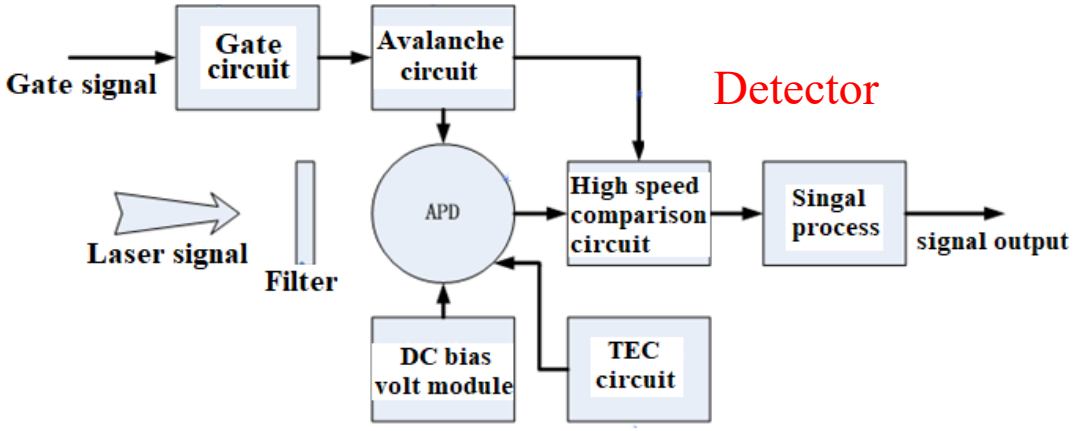


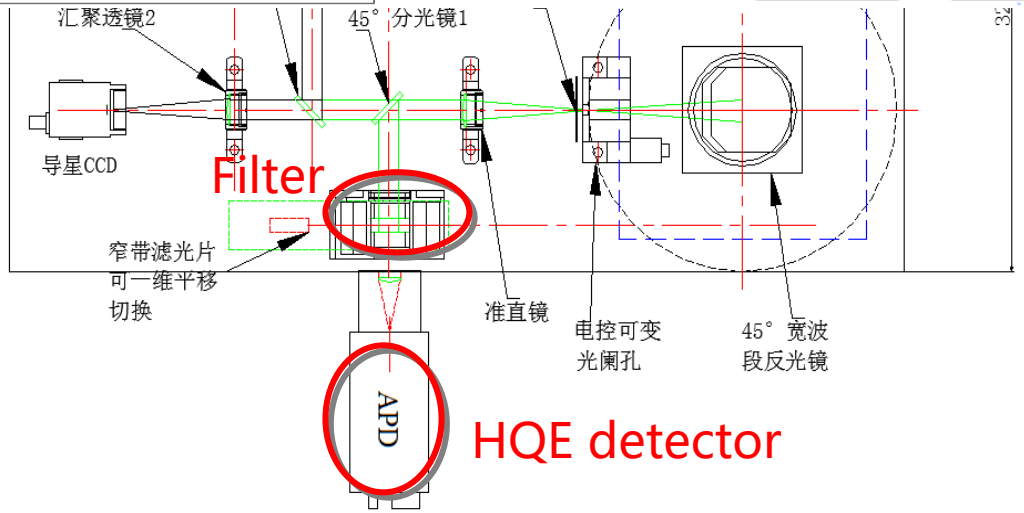
2. ps-Laser DLR with green and infrared wavelength

Laser signal detection unit

- HQE detector: 500um chip, detection efficiency 40%, dark noise: ＜10kHz.
- Spectrum filter: 532nm±2nm.

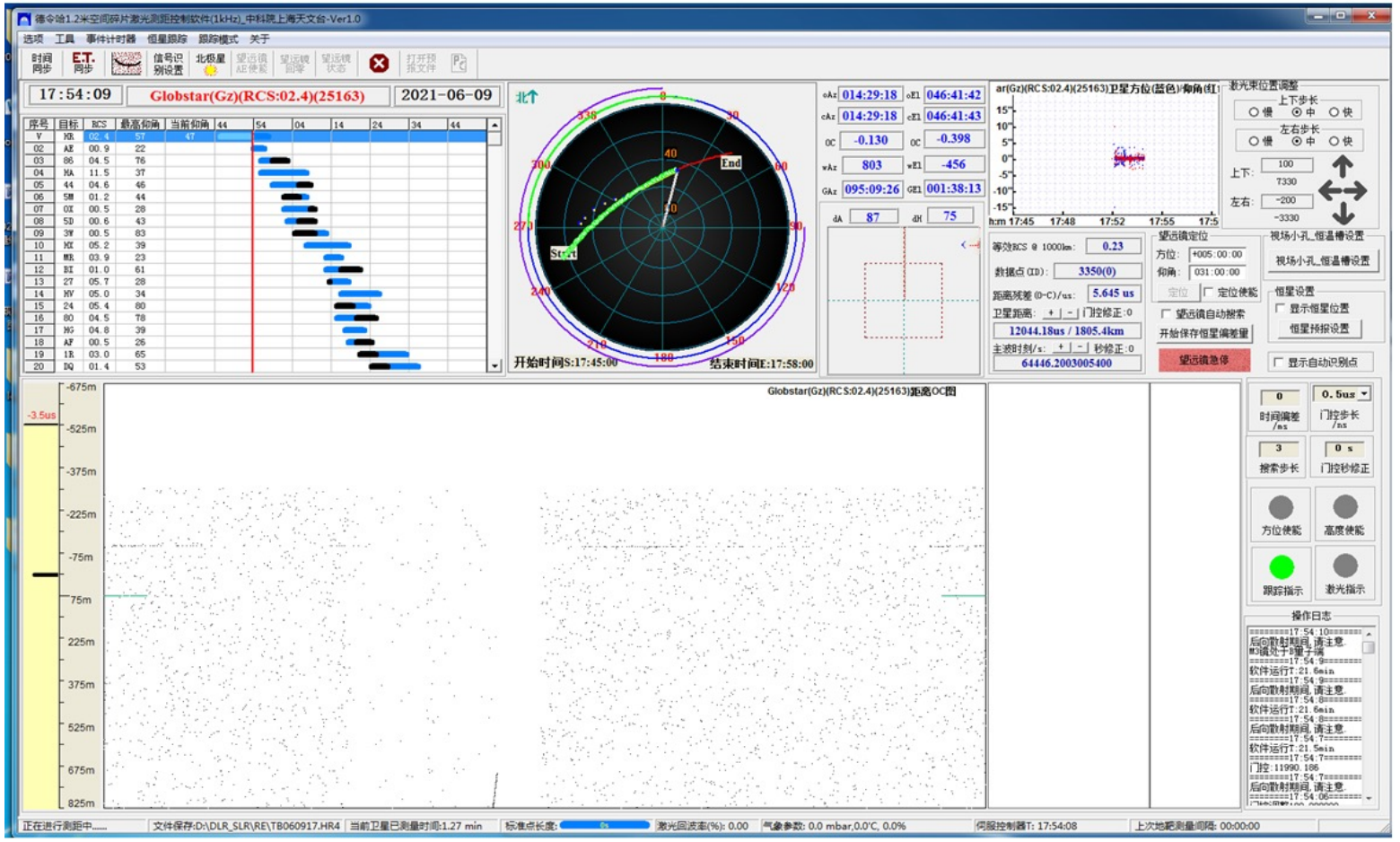






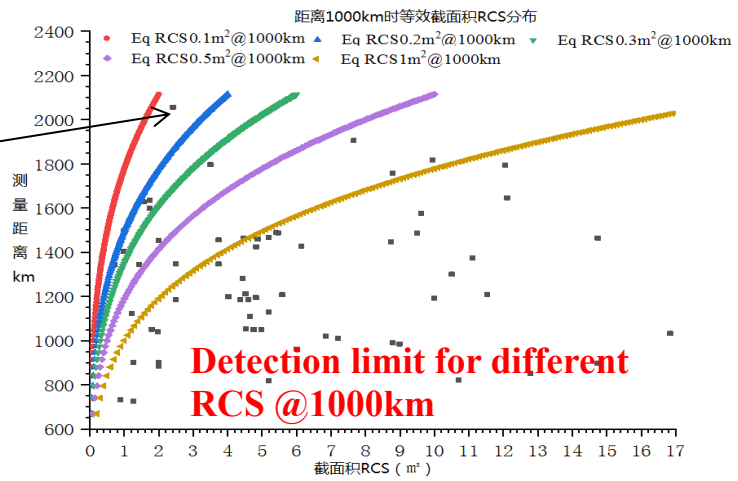
2. ps-Laser DLR with green and infrared wavelength

- **Observation results of space debris**
  - During one week period of observations in June 2021, there were more than sixty passes of debris targets.



2. ps-Laser DLR with green and infrared wavelength

- **Observation results of space debris**
  - Max. distance: 2056km, RCS:2.41m^2
  - RCS@1000km: 0.13m^2.
  - The precision (RMS) of laser data was better than 10cm because of 35ps pulse width.



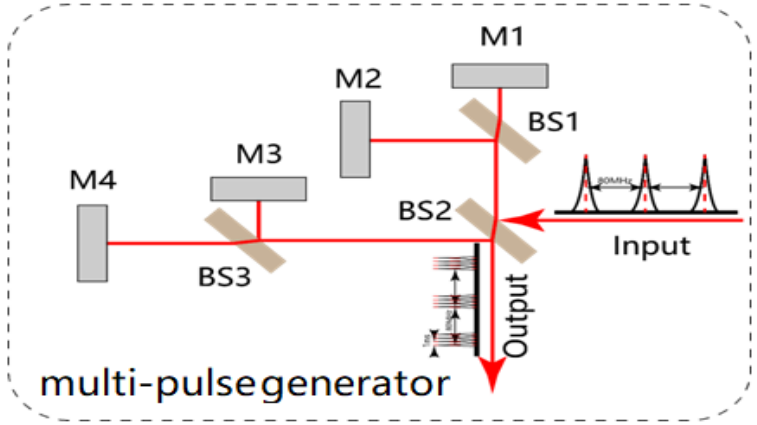
Parts of passes of laser data from debris targets

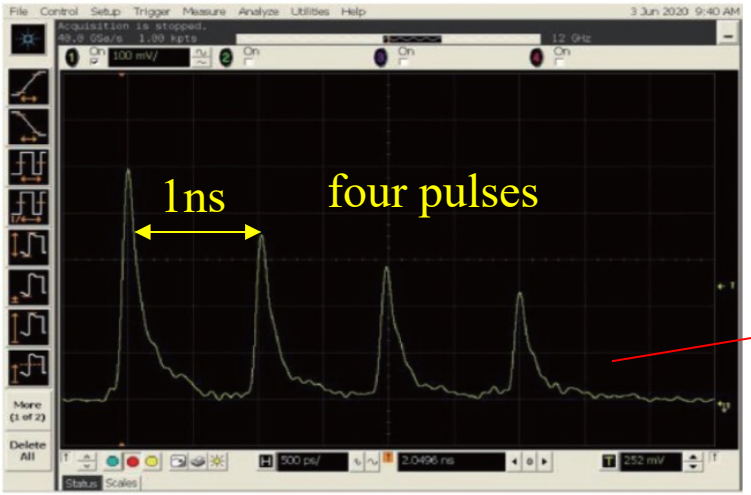
- This work gives the validation of feasibility of one laser unit for routine SLR and DLR measurements for the certain site (extreme good weather, good seeing, signal receiving ability).
- Worth of consideration of the effect of ps-laser signal atmospheric transmission.

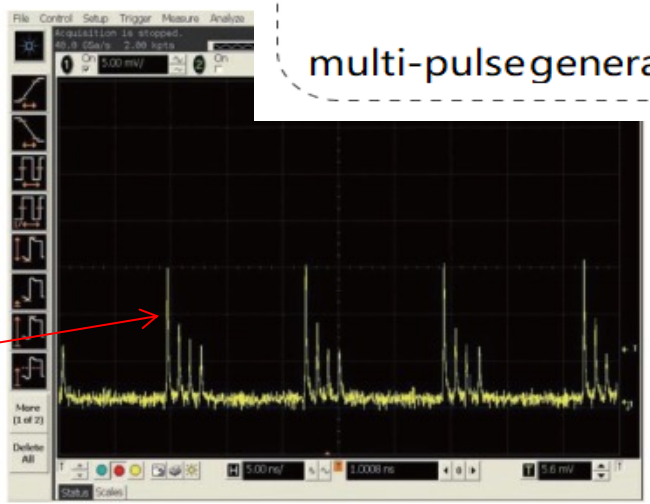
2. ps-Laser DLR with green and infrared wavelength

(3) Developing high power ps-laser unit with the burst pulse mode

- However, the output power at the level of several watts for ps-laser unit is still difficult to track debris for Shanghai station.
- So the method of the burst pulse mode of ps-laser unit was proposed in 2019 and realized in 2020. This mode was different from the traditional semi-train pulse.
- The single pulse will be divided into multiple adjacent pulses in the multi-pulse generator.
- Here, there are four pulses with the time space of 1ns.







2. ps-Laser DLR with green and infrared wavelength

(3) Developing high power ps-laser unit with the multi pulse mode

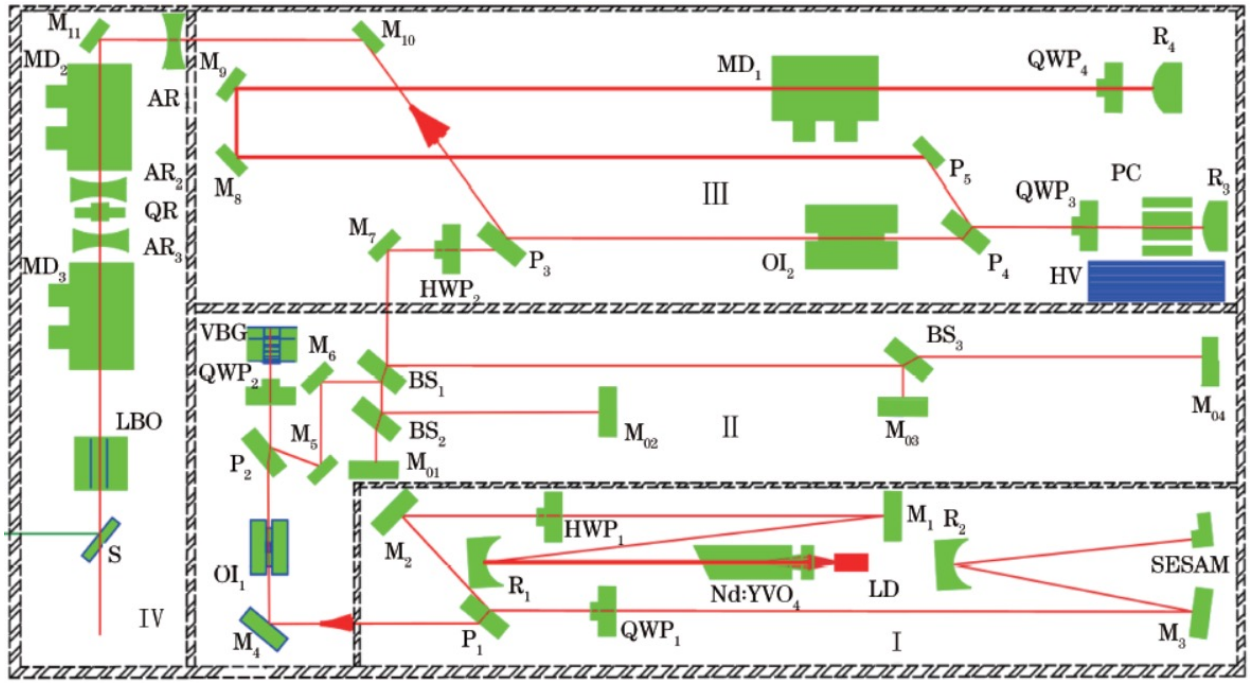
- **The inner optical principle of laser unit**

➢ I: Nd:YVO4 mode-locked laser, HWP1, QWP1, SESAM: power of 1064nm is 1.18W, 23ps pulse width. (Multi-pulse generator)

➢ II: VBG broadening pulse width and separating pulse transmitting path in order to produce multi pulses by setting the different mirrors.

➢ III: regeneration amplifier.

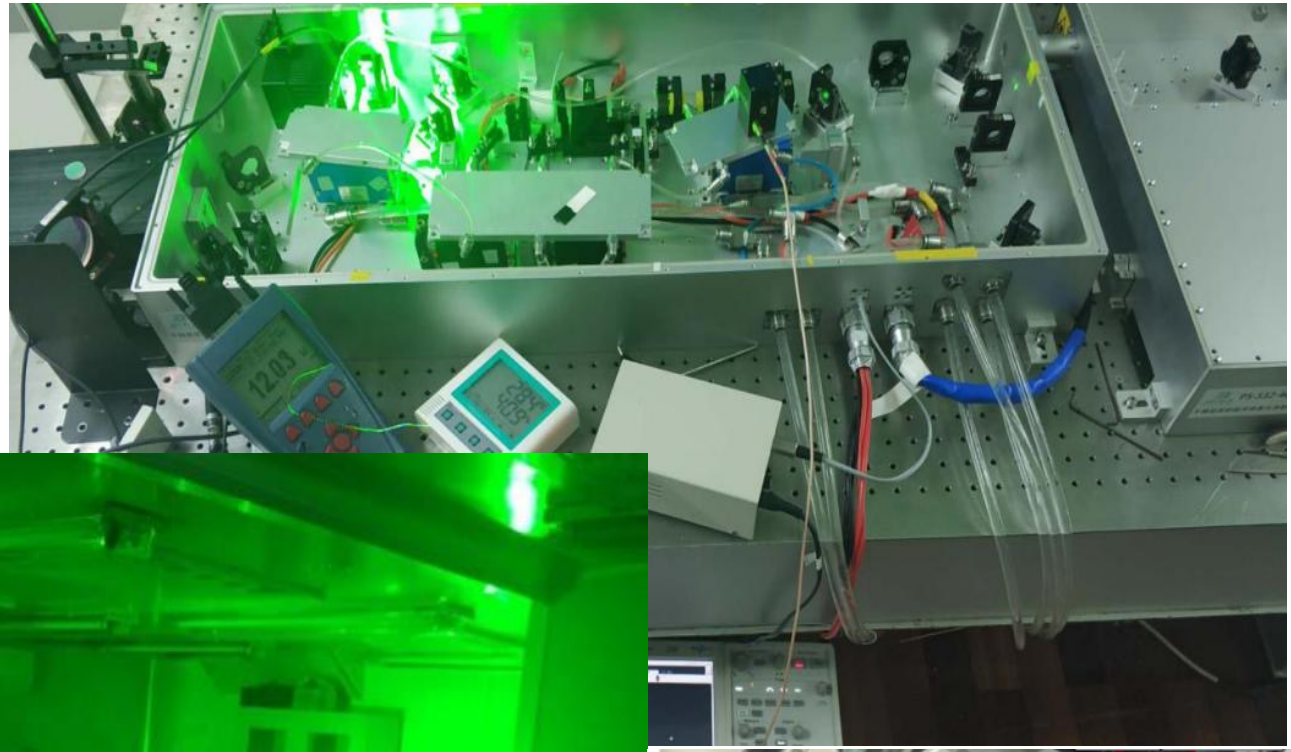
➢ IV: Two module single-pass travelling wave amplifier and LBO doubling frequency.

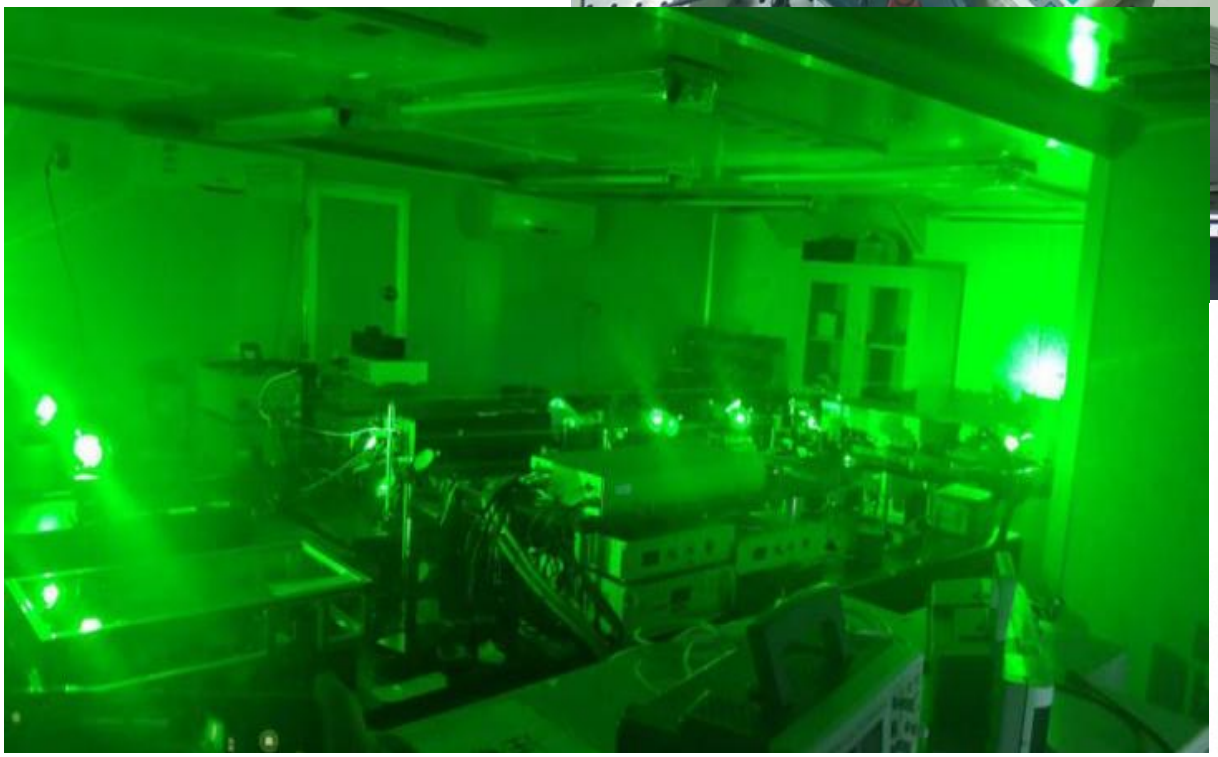


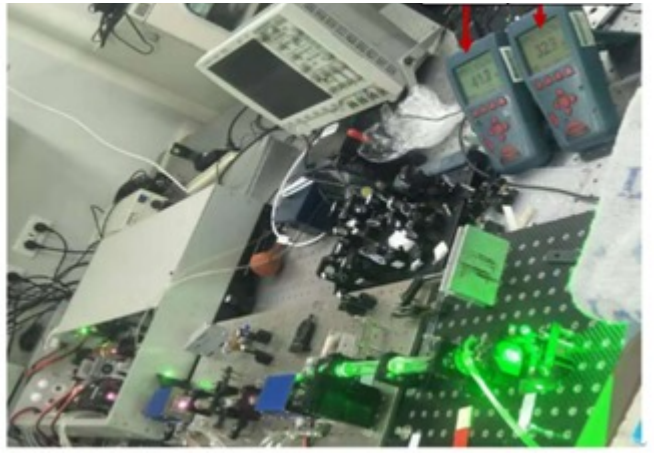
- Output: 1kHz, 4 pulses, Max. 40W@ 532nm and Max. 80W @1064nm,
- ~80ps pulse width, dev. 0.5mrad, M^2: ~2.5

2. ps-Laser DLR with green and infrared wavelength

Laser working scene at Shanghai station







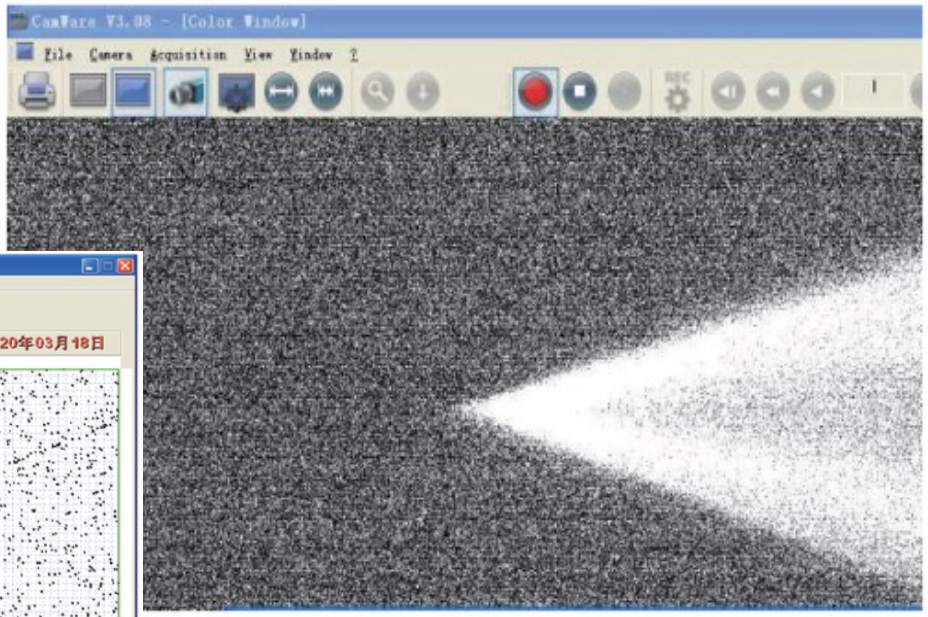
2. ps-Laser DLR with green and infrared wavelength

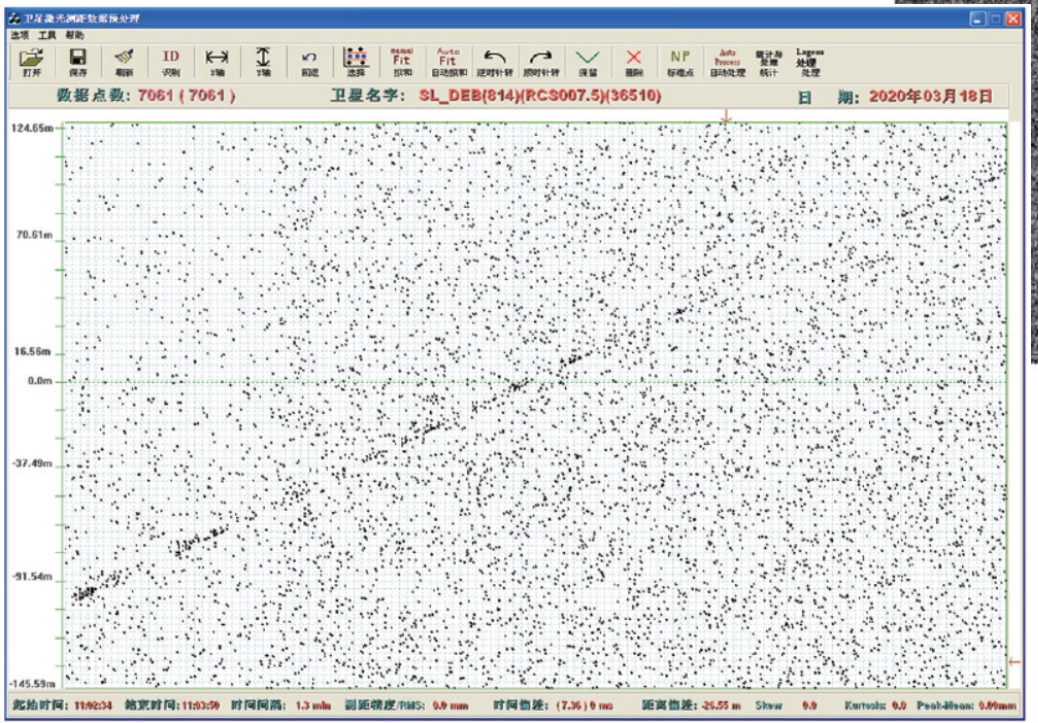
(3) Developing high power ps-laser unit with the multi pulse mode

- **Observation results:**

➢ Updated the ranging system to suit for 1kHz rate DLR measurements and 532nm HQE detector and 1064nm APD detector.

➢ Since March 2020, the ps-laser unit with 532nm and 1064nm were put into the DLR measurements.





2. ps-Laser DLR with green and infrared wavelength

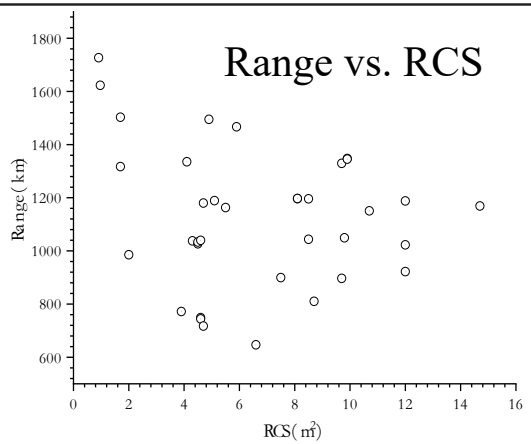
(3) Developing high power ps-laser unit with the multi pulse mode

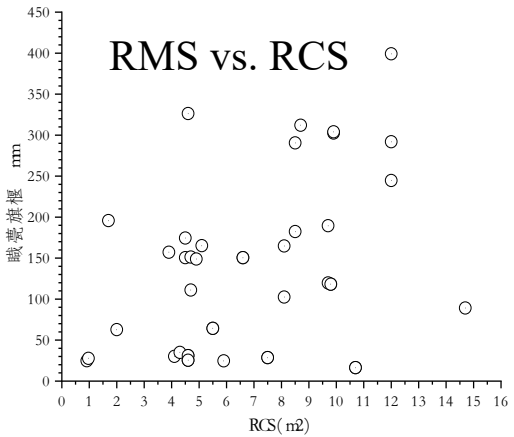
- **Observation results (532nm)**
  - For four pulses, the time space between pulses is 1ns and the pulse width of total envelope is about 3ns.
  - Due to the target size signature, the four pulses from targets will be mixed together (equivalent to ns-laser unit). So the ranging precision (RMS) was about decimeters level.

Parts of passes of laser data from debris targets

Number	Date	Name	RCS /m^2	Root mean square /cm	Measured distance /km
1	2020-03-15	SL-14R_B	4.6	31.06	727.5–749.0
2	2020-03-15	Cz-2c-r-b1_Gz	10.7	16.44	1083.4–1150.7
3	2020-03-18	Delta2R_B	9.8	118.17	1006.4–1049.3
4	2020-03-18	SL_DEB(814)	7.5	28.65	836.7–899.4
5	2020-03-18	DELTA2R_B_O	5.5	64.27	1100.3–1162.9
6	2020-03-18	SL-3R_B	6.6	150.51	643.8–646.5

Max. distance: 1700km





Min. RMS: 16cm

2. ps-Laser DLR with green and infrared wavelength

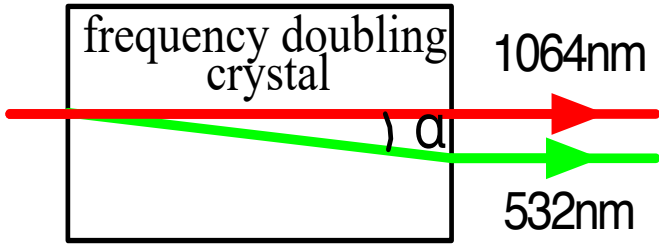
(3) Developing high power ps-laser unit with the multi pulse mode

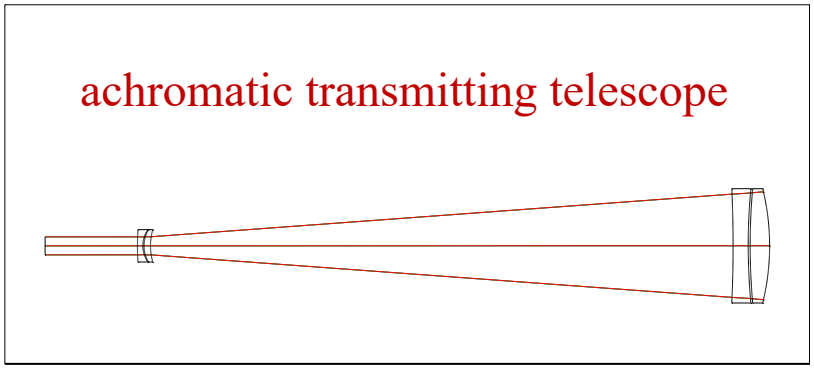
- **1064nm wavelength laser**

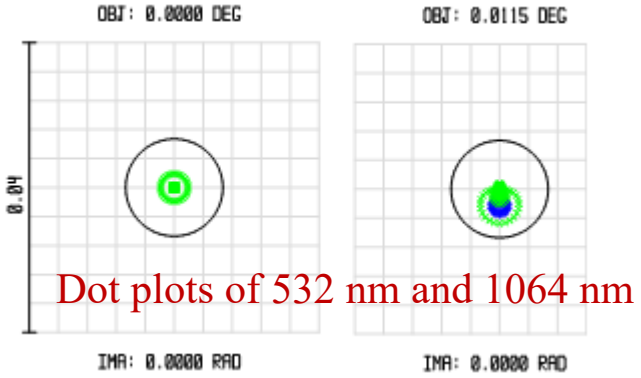
➢ For this type of ps-laser unit, the 1064nm wavelength signal can be also output by changing the temperature of LBO through the one channel.

➢ The 40W power with 1064nm wavelength was obtained for DLR measurements.

➢ For guiding the laser beam point, the remain 532nm wavelength light was used through the achromatic transmitting telescope.







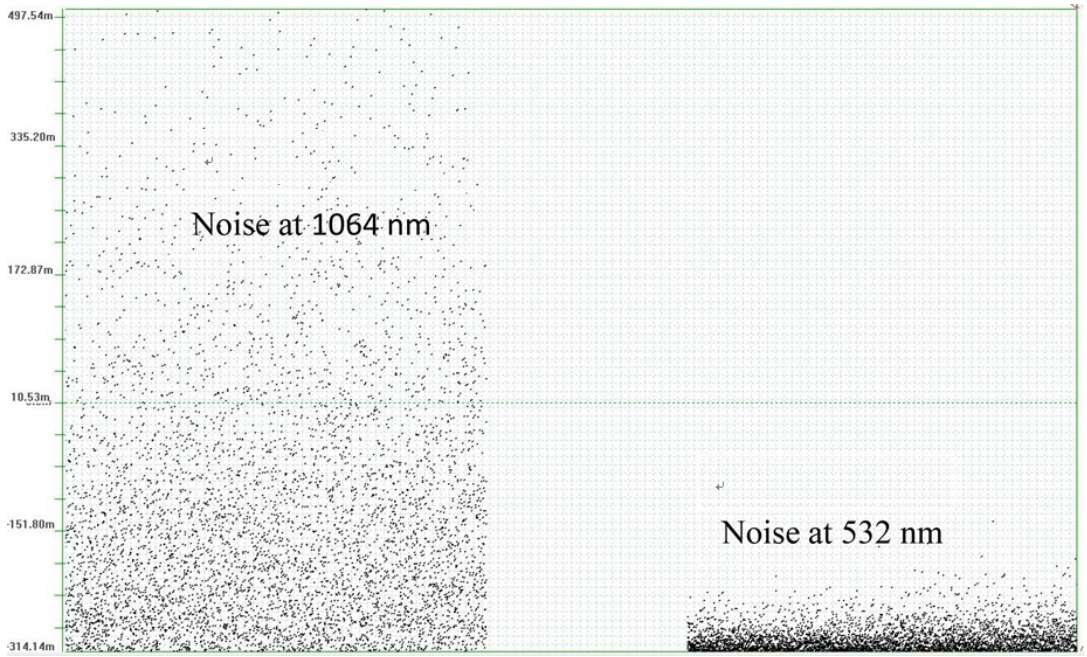
2. ps-Laser DLR with green and infrared wavelength

(3) Developing high power ps-laser unit with the multi pulse mode

- **1064nm signal detector**

- The APD detector with InGaAs was developed in 1064 nm wavelength: chip 80um; detection efficiency 20%.

- System noise measured for the SPAD and InGaAs APD detector with the filter bandwidth of 0.15 nm and bandwidth of 2nm filter respectively.



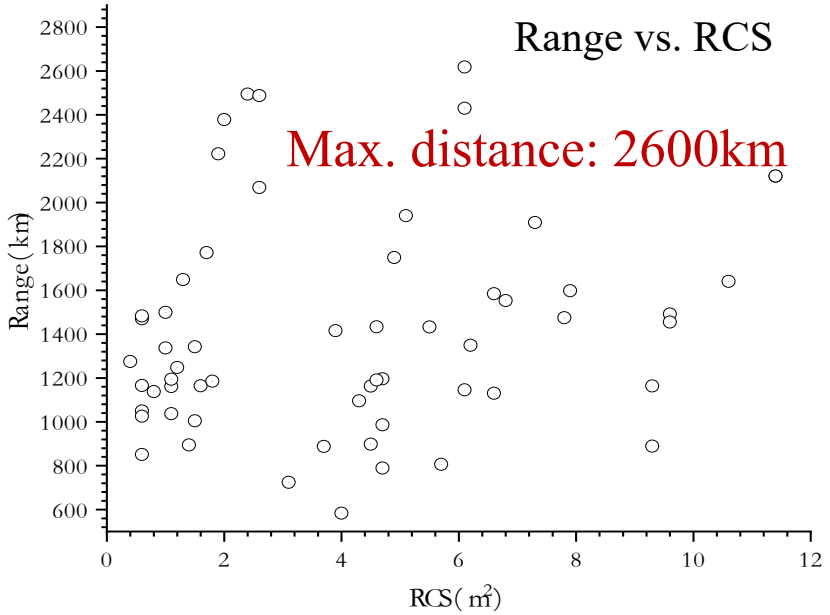
- The noise from InGaAs APD is well better than that of SPAD.

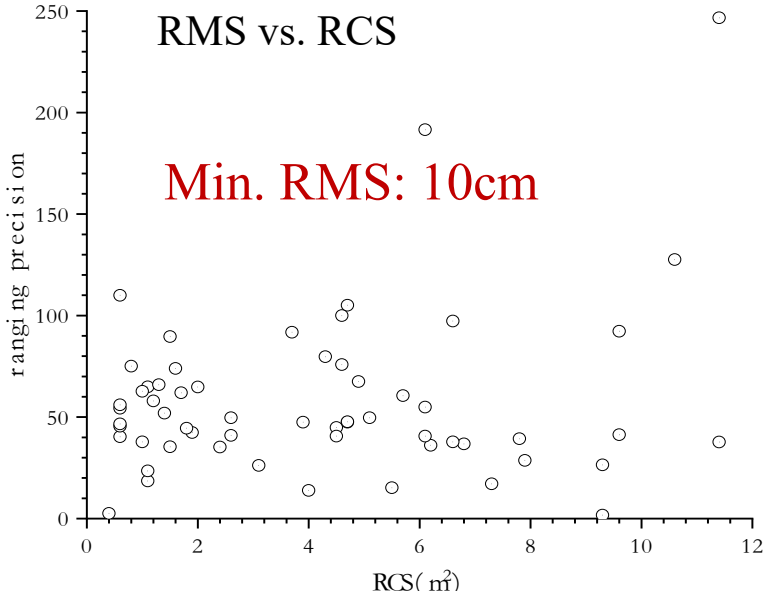
2. ps-Laser DLR with green and infrared wavelength

(3) Developing high power ps-laser unit with the multi pulse mode

- **Observation results at the wavelength of 1064nm (infrared)**

➢ During two weeks period of observations at Shanghai station, over 50 passes of laser were obtained.





➢ Measured min. RCS of target is 0.4m^2 corresponding to RCS @1000km:0.06 m^2.

➢ Compared to 532nm, the power of 1064nm wavelength is stronger.

➢ The infrared laser will become an significantly way for DLR measurements.

Outline

1. Introduction

2. ps-Laser DLR with green and infrared wavelength

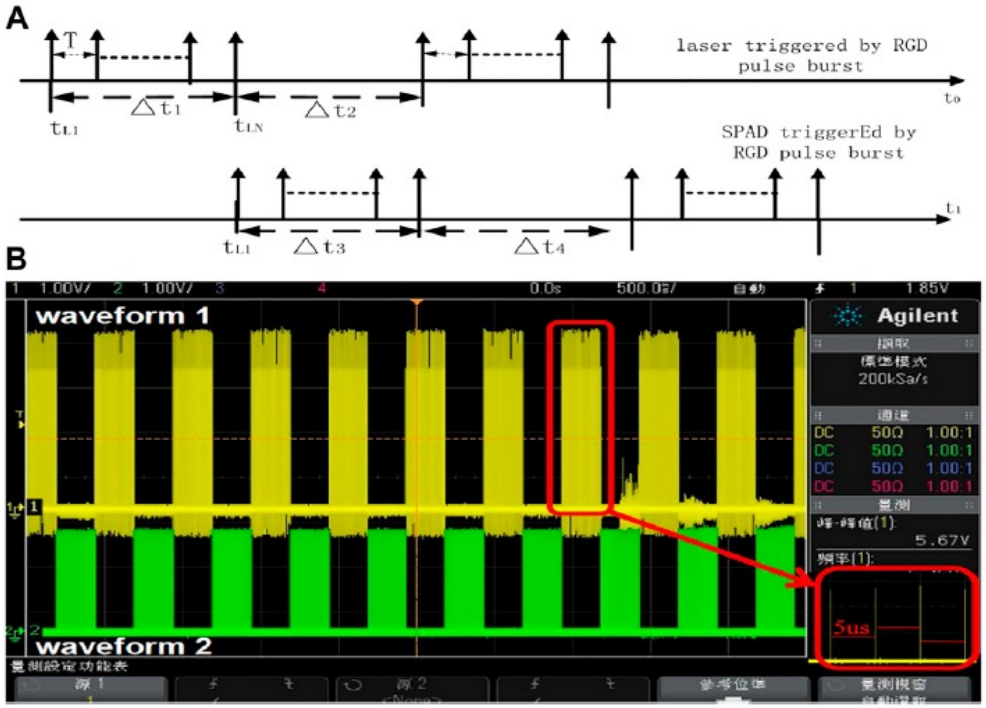
3. Hundreds kHz rate ps-laser ranging to space targets

4. Summary

3. Hundreds kHz rate laser ranging to space targets

(1) UH-SLR key technique

- The Ultra-High repetition rate (above 100 kHz) SLR (UH-SLR) is a trend of development to make the SLR system more better performance
- For UH-SLR, the laser backscattered under laser transmission in the atmosphere very easily interferes with the laser echoes, which increases the difficulty of laser echo identification.
- Pulse bursts in the alternating mode are proposed to solve the the backscatter problem
- And also, APD detector with low noise worked in the Geiger mode was used.

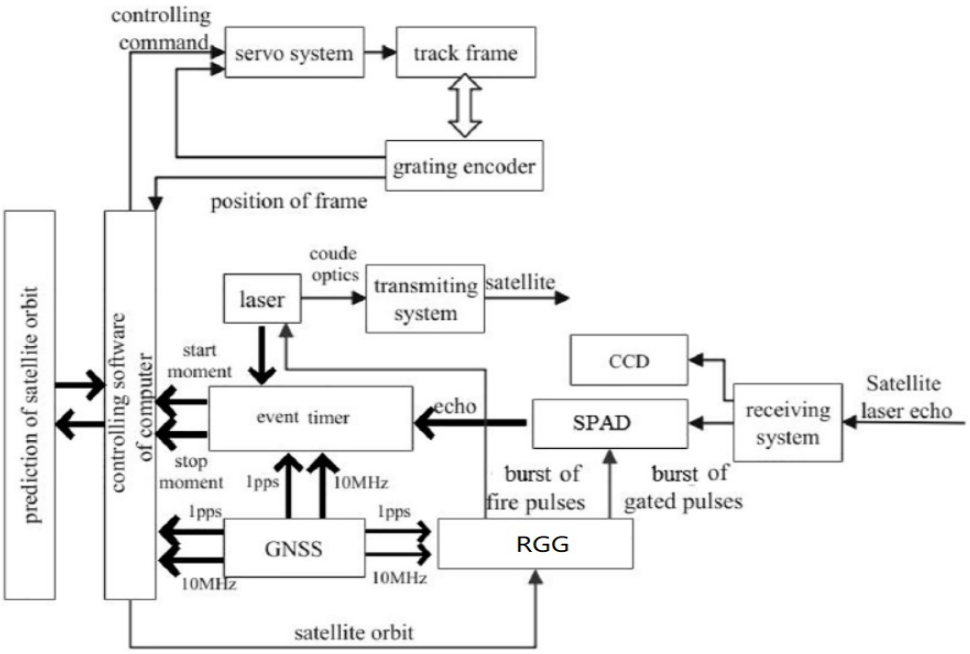


Sequence of the alternated working mode for laser emission and the triggered gate signal

3. Hundreds kHz rate laser ranging to space targets

(2) Test UH-SLR system at Shanghai station

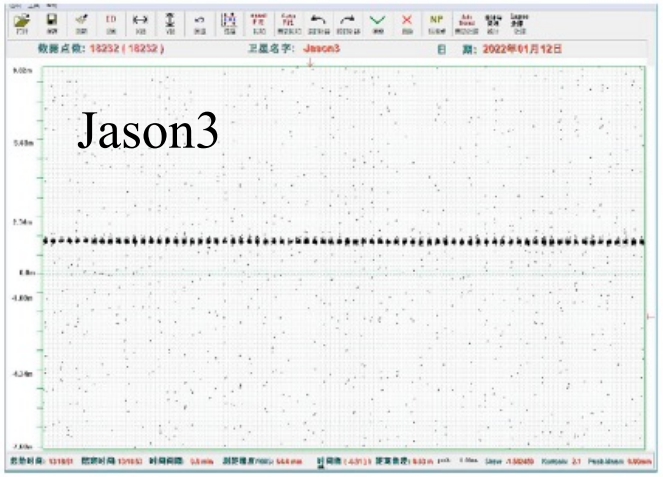
- Laser unit: working frequency of 200kHz (5us time interval between pulse), 80μJ per pulse, the total output power of 8W@532nm, 50ps pulse width.
- Detector: no gated APD detector, but its working is started by a high level signal (2V) and zero level signal will stop its working.
- Event Timer: A033-ET with usb data interface to meet the requirements of high speed recording signal.
- Control mdoe: The laser outputs pulse bursts, and it stops from a ranging gate device. And vice versa.

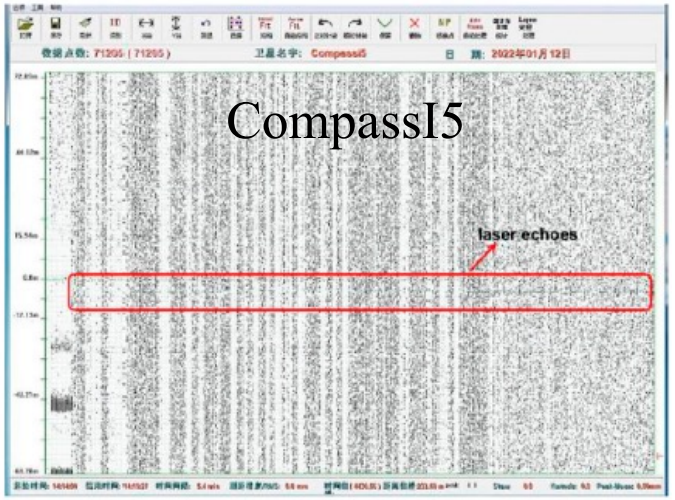


3. Hundreds kHz rate laser ranging to space targets

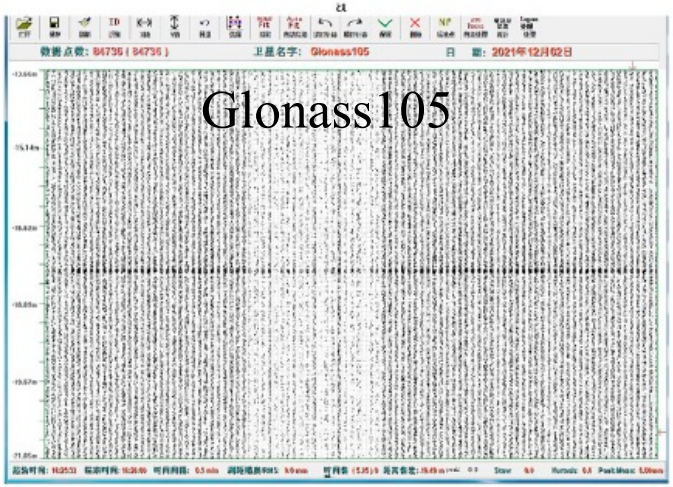
(3) Measuring results of UH-SLR

- Measuring satellites from low orbit to high orbit.





a



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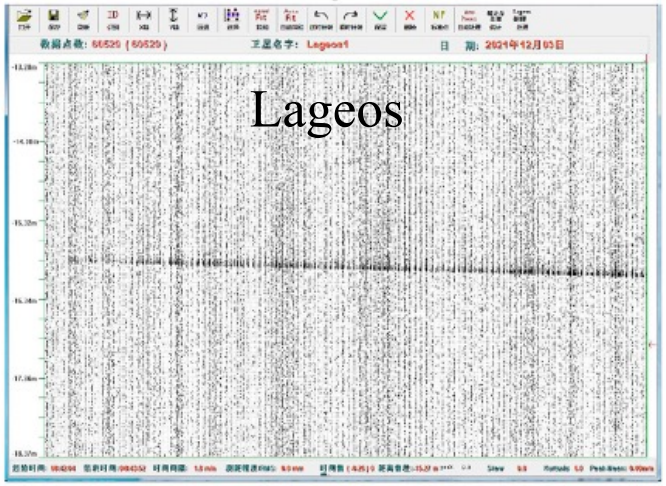
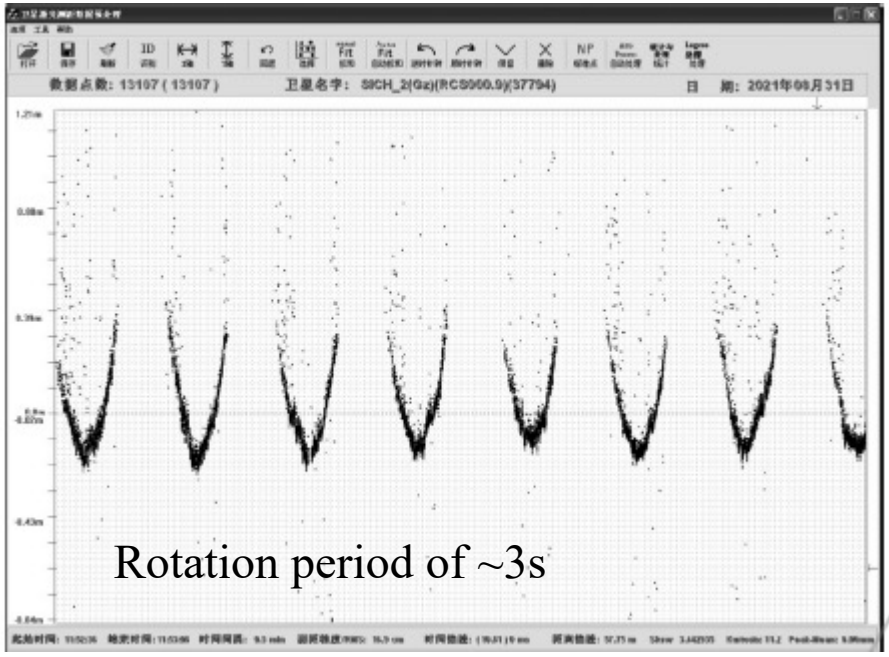


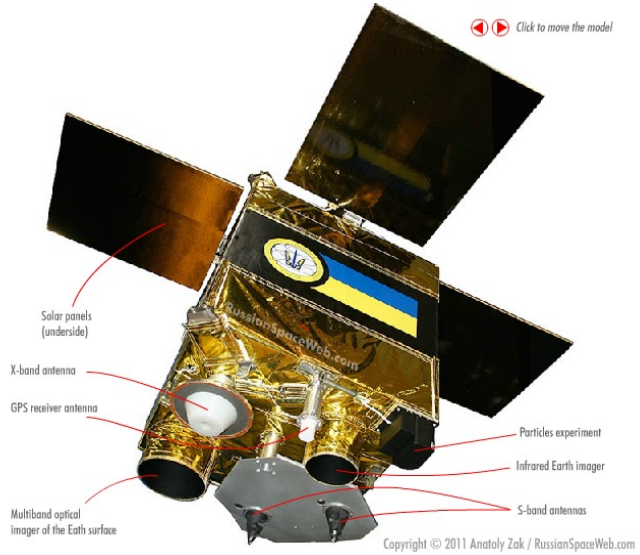
3. Hundreds kHz rate laser ranging to space targets

(4) Preliminary results from debris targets

- By using the UH-SLR system, special debris targets were successfully measured.

No.	Date	Laser echoes	RMS/mm	Max. range/km	Min. range/km
1	2021-06-08	2617	8.92	1496.4	1413
2	2021-06-11	8233	10.54	1404.2	1076.2
3	2021-08-29	2990	6.63	856.2	717.3
4	2021-08-31	4493	5.74	942.5	812.5



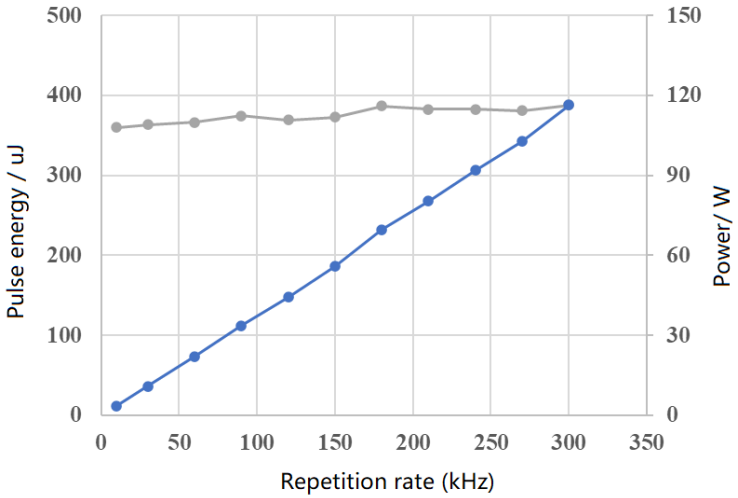


SiCH-2 Earth remote sensing satellite

3. Hundreds kHz rate laser ranging to space targets

(5) New UH ps-laser unit for tracking debris targets

- ps-Laser unit: output power of 116 watts @ 300kHz, 532nm, 15ps pulse width made by the way of industrial product line.
- The 1064nm wavelength can be also output.
- Detector: development of the no gated APD detector @532nm and 1064nm detector.
- Control unit: improving control software and data processing software for 150Hz to meet the requirements of DLR measurements.



- This ps-laser unit will be installed at Shanghai station in this month and next step it will be used to investigate the DLR technology.
- If the way is ok, we hope develop the more power ps-laser for tracking HEO debris.

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4. Summary

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(1) ps-Laser has been used for tracking to debris targets at Shanghai station with the advantages of better precision and it helps to investigate the posture of targets in space.

(2) For some certain sites, it is feasible to track debris by using ps-laser unit (power of W level) in the routine SLR system. From this beat-all works, there maybe an unclear knowledge for ps-laser signal atmosphere transmission.

(3) By adopting the burst pulse mode (multi-pulse generator), the high power ps-laser unit has been realized at the wavelength of 532nm and 1064nm.

(4) Ultra-repetition rate ps-laser unit will be used for tracking debris. Hope more power ps-laser unit used to DLR for HEO targets.

4. Summary

(5) Developments of daylight DLR measurements

- Guiding targets in daytime: an aperture of 20cm commercial telescope (Celestron company) is installed which can monitor targets with the brightness of 5 magnitude.
- ps-Laser unit with the power of ~40W @ 1064nm wavelength, ~80ps pulse width, 1kHz repetition rate, burst pulse mode.
- Detector: APD detector with InGaAs; spectrum filter of 0.6nm band width.
- Correction of orbit prediction error: time bias and range bias corrected by the pointing offset.
- In collaboration with domestic institutes and observatories, the debris target tracking campaigns will be performed through the combine of optical-angle measurements and DLR in order to provide the good orbit prediction.

Thanks for your attentions