Development of hollow corner cube retroreflector for the future lunar and deep space satellite laser ranging

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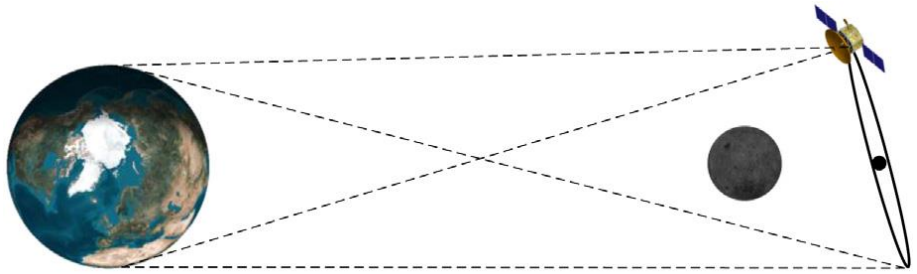
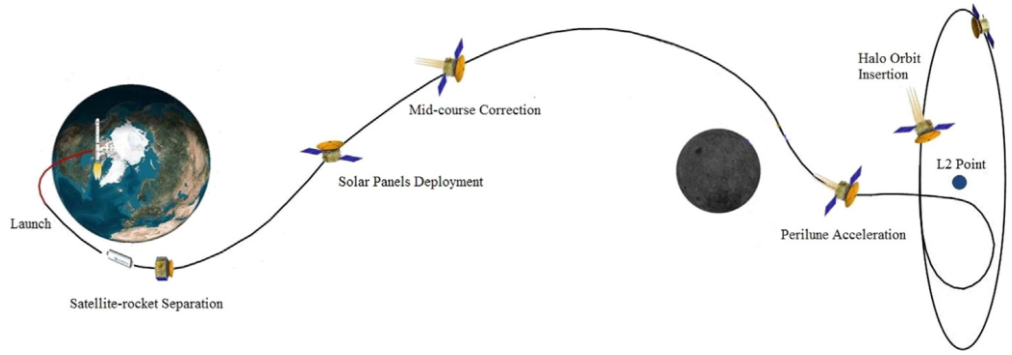
Outline

1. Background
2. Mission design
3. Hollow Corner cube retro-reflector
4. Laser ranging station
5. Summery

1.Background – Queqiao

- **Queqiao：** A lunar relay satellite
- **Main task：** Communication station for the Chang'e-4 lunar lander on the far side of the Moon (launched at the end of 2018)
- **Launch Time：** May 21st, 2018
- **Orbit：** Halo orbit rounds L2 point with radius of 15,000km
- **Distance from the Earth：** ～450,000km
- **Distance from the landing point:** ≤80,000km



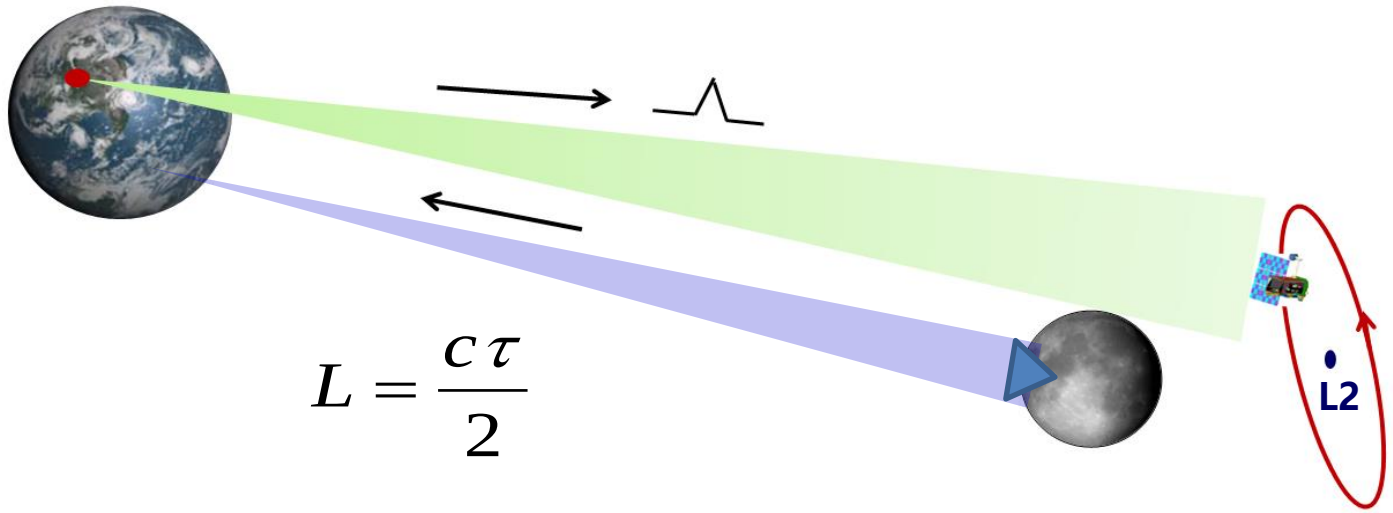


[Wang and Liu, Acta. Astronaut., 2016]

1.Background – laser ranging to Queqiao

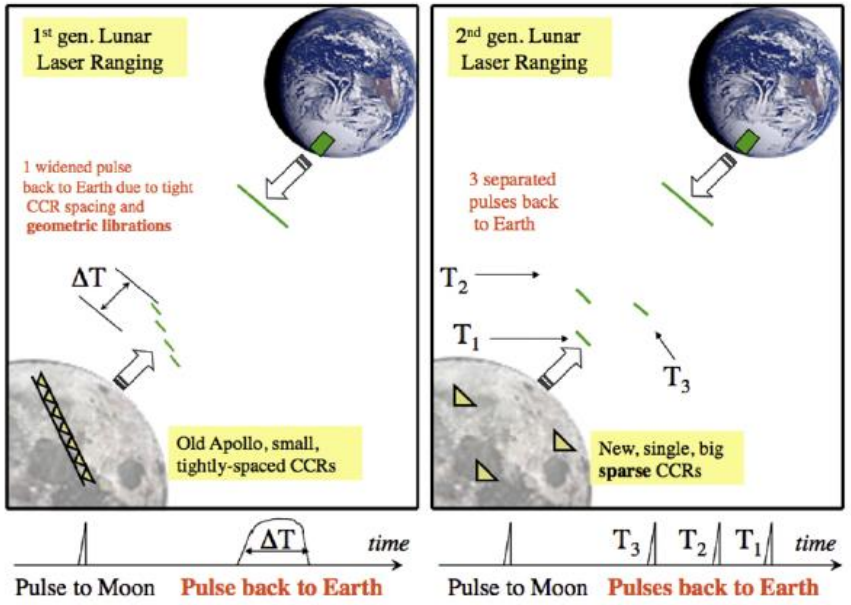
Our objectives

- Realize laser ranging to the hollow corner cube retro-reflector (CCR) carried on Queqiao with meter-level precision
- Verify the long-distance laser ranging technology and prepare the manufacture technology of CCR used for the new generation of lunar laser ranging (LLR)



$$L = \frac{c\tau}{2}$$

1.Background-lunar CCR



Error budget of APOLLO

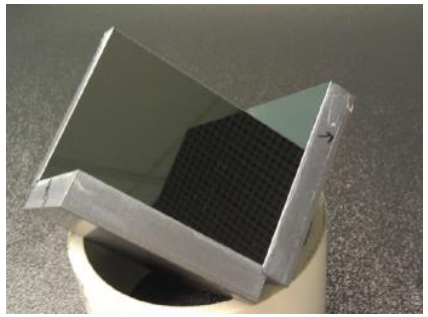
APOLLO RANDOM ERROR BUDGET PER PHOTON.

Error Source	rms Error (ps)	rms Error (mm)
APD illumination	60	9
APD intrinsic	<50	<7.5
Laser pulse	45	7
Timing electronics	20	3
GPS clock	7	1
Total APOLLO	93	14
Retroreflector array	100–300	15–45
Total random uncertainty	136–314	20–47

Largest error

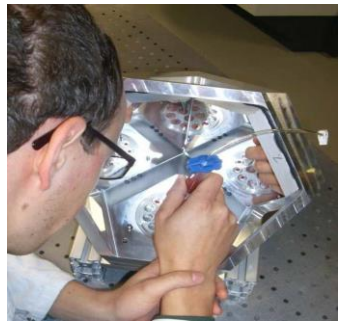
Current CCR arrays limit the ranging precision to several centimeter

INFN-ASI-UMD



NASA

NAOJ



GFZ

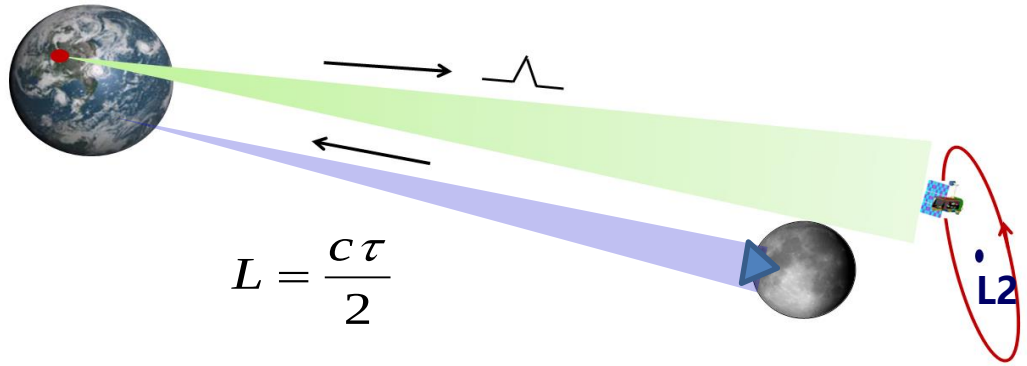
New lunar CCR

- INFN-ASI-UMD： 100-mm solid
- NASA： 40-mm hollow
- Germany GFZ: 200-mm hollow
- National Astronomical Observatory of Japan 200-mm hollow

2.Mission design

Task of mission

- Lunar laser ranging to lunar CCR arrays (384,000km)
- Satellite laser ranging to Queqiao probe (450,000km)



What we do?

- Manufacture 170-mm hollow CCR with the similar intensity of return signal as Apollo 11 on the Moon ;
- Upgrade the ranging system based on 1.2-m telescope at Kunming (Yunnan Observatory). Ranging precision: <1m (width of laser pulse: 10ns) ;
- Construct a new ranging system based on 1.2-m telescope at Zhuhai (SYSU). Ranging precision: <2cm (width of laser pulse: ~80ps) ;

2.Mission design-Schedule

Schedule of ranging experiment

- **Lunar laser ranging**

  2017-10 to 2018-04

- **First phase of laser ranging to Queqiao**

  20 nights; 2019-03 to 2019-04

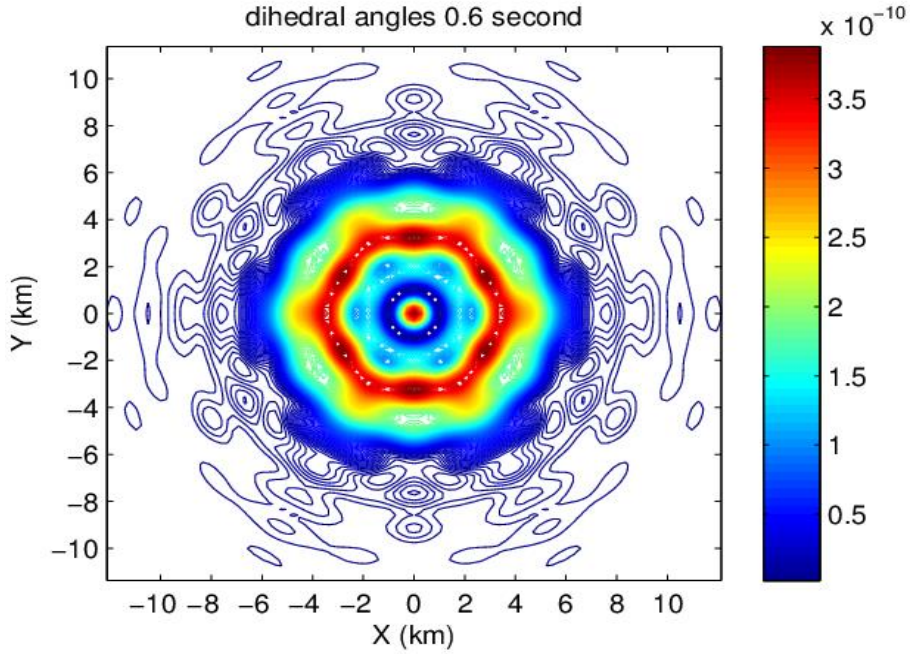
- **Second phase of laser ranging to Queqiao (possible)**

  20 nights; 2019-11 to 2020-04

2.Mission design-CCR angle error

Angle error (arc-sec)	Return signal (%)
0.1	28.7
0.2	62.2
0.3	**87.0**
0.4	85.8
0.5	62.0
0.6	**33.1**
0.7	13.1
0.8	4.9
Apollo 11 or 14	100
Apollo 15	300

FFDP with three angle errors of 0.6”



- Return signal: Averaged intensity within the velocity aberration area (3.5-7urad)
- Normalized to ideal Apollo 11 CCR array
- Three angle errors 0.6 arcsec determine a divergence angle of 2 arcsec

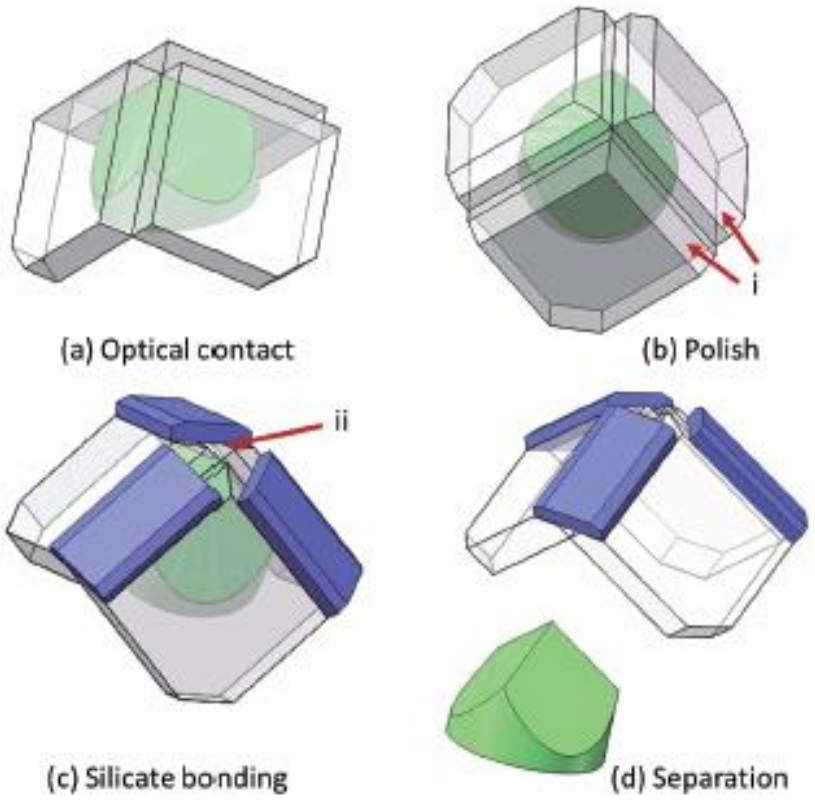
3.Corner cube retro-reflector

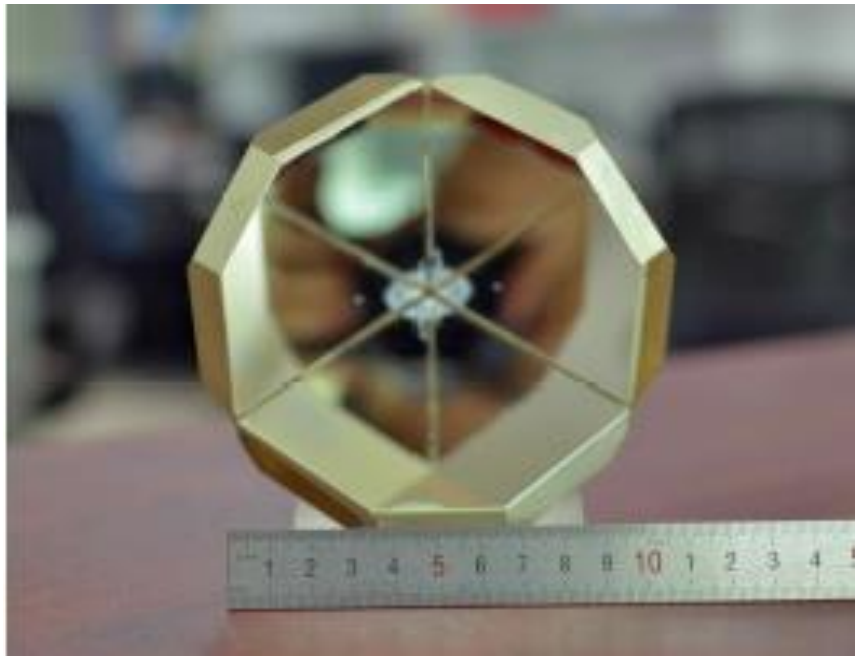
	Name	Actual Value
Hollow CCR	Aperture	170mm
	Mass	1.4kg
	Dihedral angle	0.1, 0.3, 0.4 arcsec
	Divergence angle	<1.3 arcsec
	Material	Corning ULE 7972
	coating	Protected silver
Total payload	Mass	3.0kg
	Total size	Φ239mm×170mm
	Life time	5 years

3.Corner cube retro-reflector

- The first generation of our hollow CCR

  [He et al., Res. Astron. Astrophys., 2018]





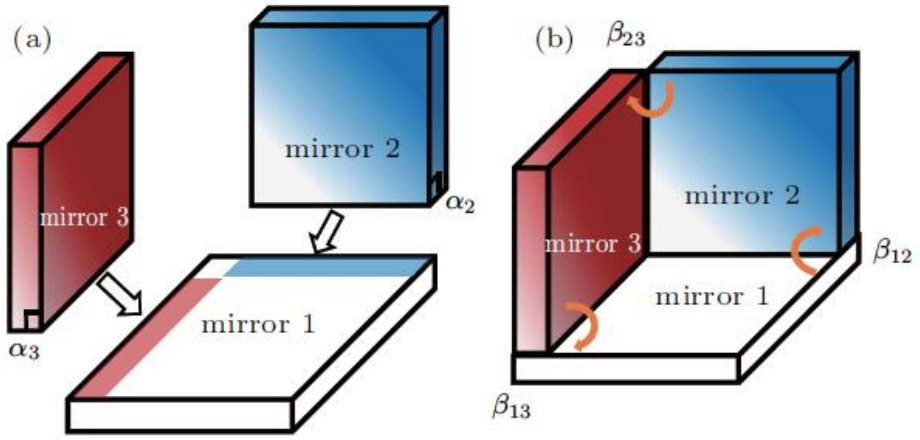
		Angle 1	Angle 2	Angle 3
Master CCR		0.27	0.31	0.39
Hollow CCR (before)		0.5	0.8	1.9
Hollow CCR (after)	Six Measurements	0.38	(1.17)	1.98
		0.42	(1.30)	1.99
		(0.14)	0.92	2.22
		(0.26)	1.11	2.04
		0.43	0.90	(2.59)
		0.32	1.09	(2.16)
	Average	0.39	1.00	2.06

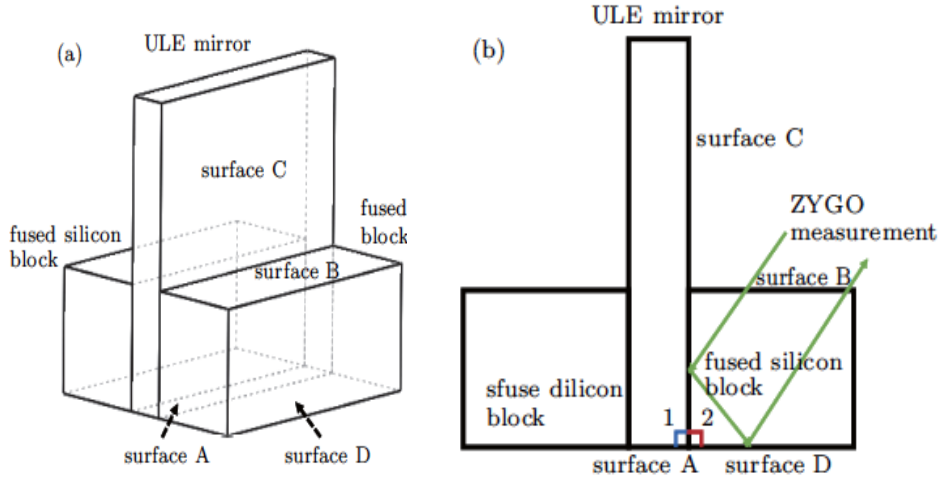
- **Preliminary thermal test: –40℃～+75 ℃**

3.Corner cube retro-reflector

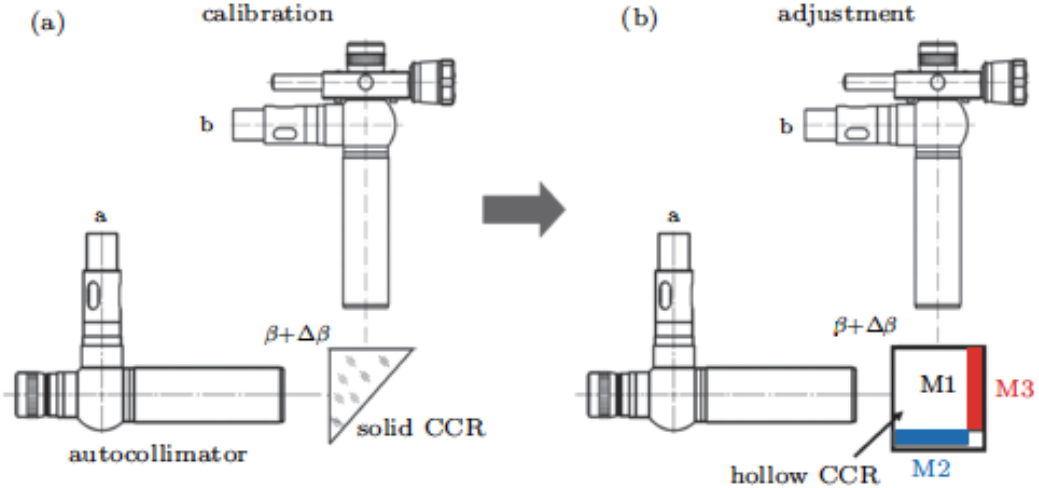
- The second generation of our hollow CCR

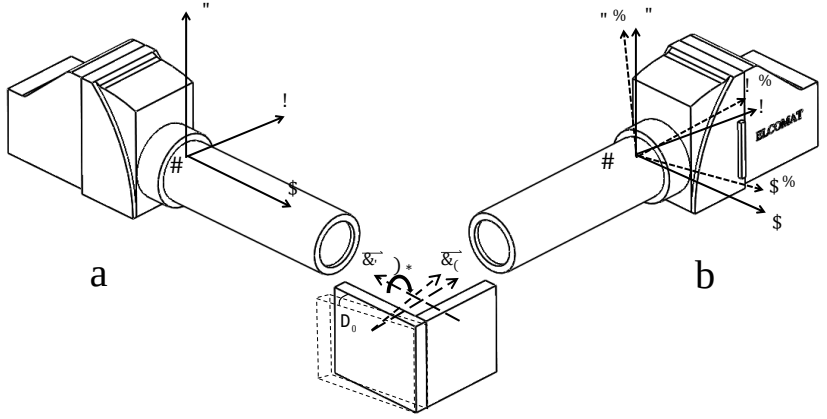
  [He et al., Chin. Phys. B, 2018]





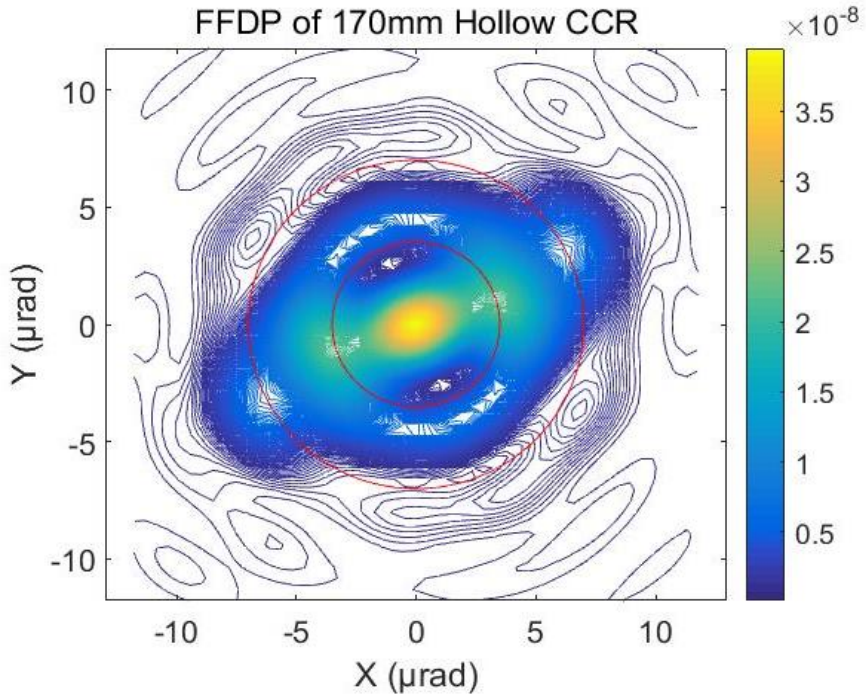
Polish of Mirror 2 and 3

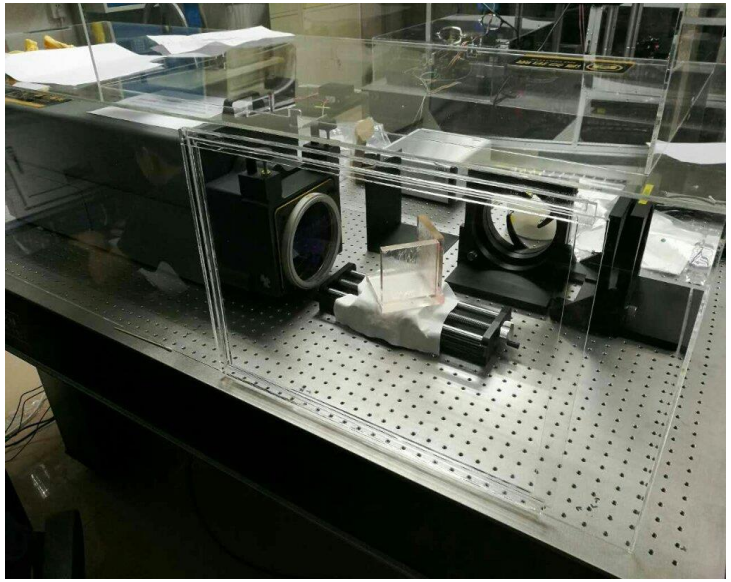


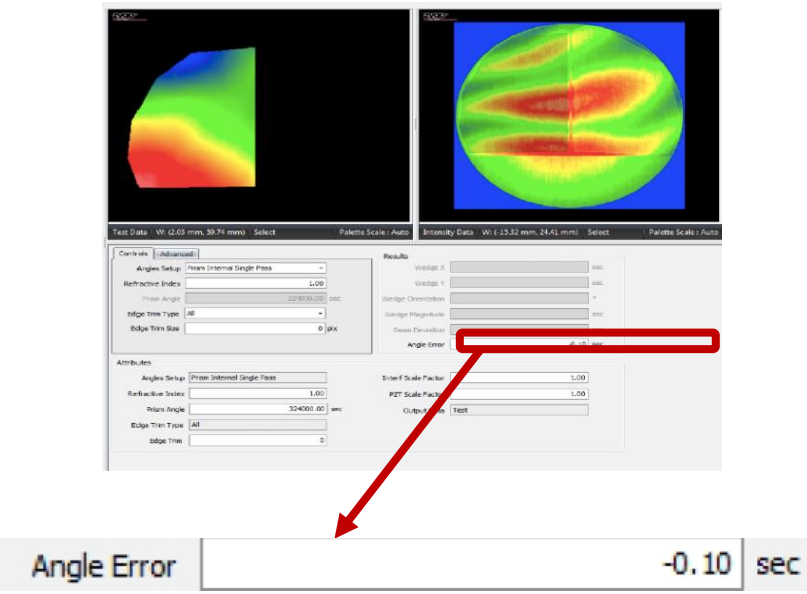


Error analysis

3.Corner cube retro-reflector-simulation

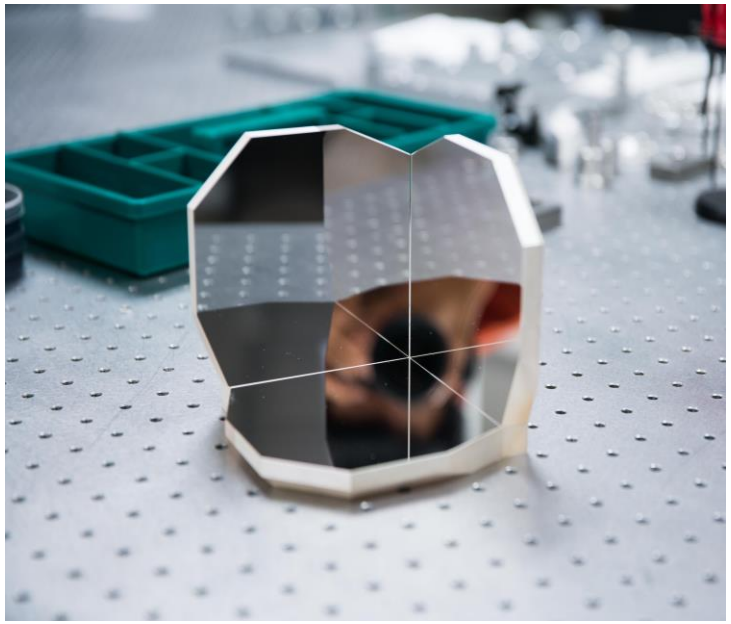


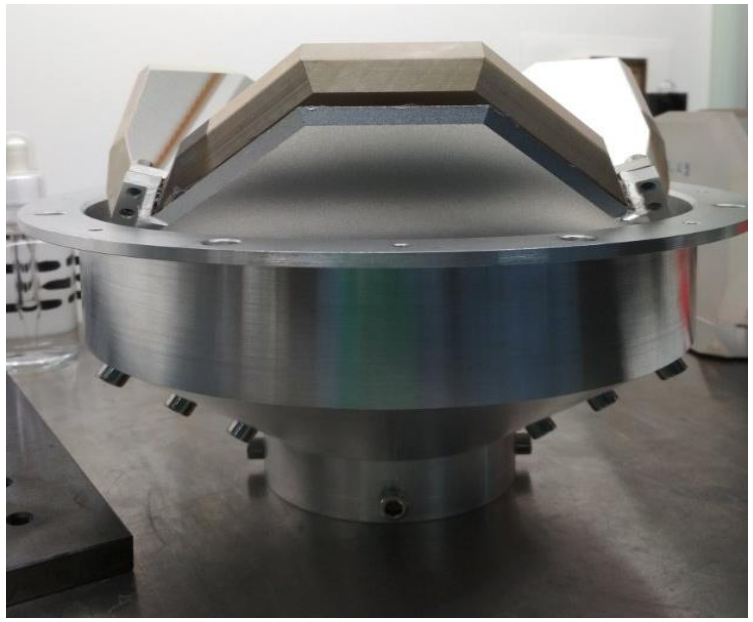




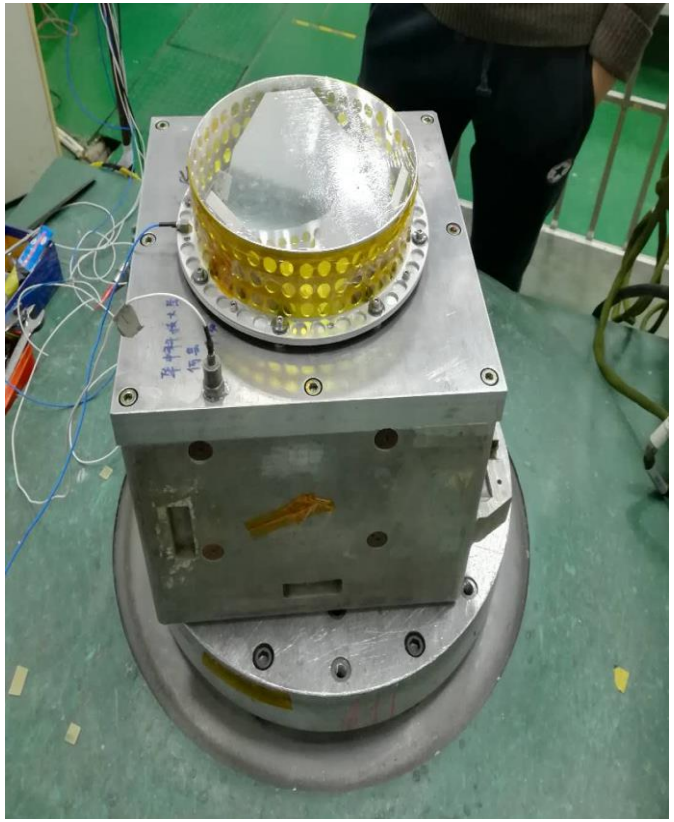
- Dihedral angle offset： 0.1, 0.3, 0.4 arcsec
- Relative return intensity： ～82.8% of initial Apollo 11

3.Corner cube retro-reflector

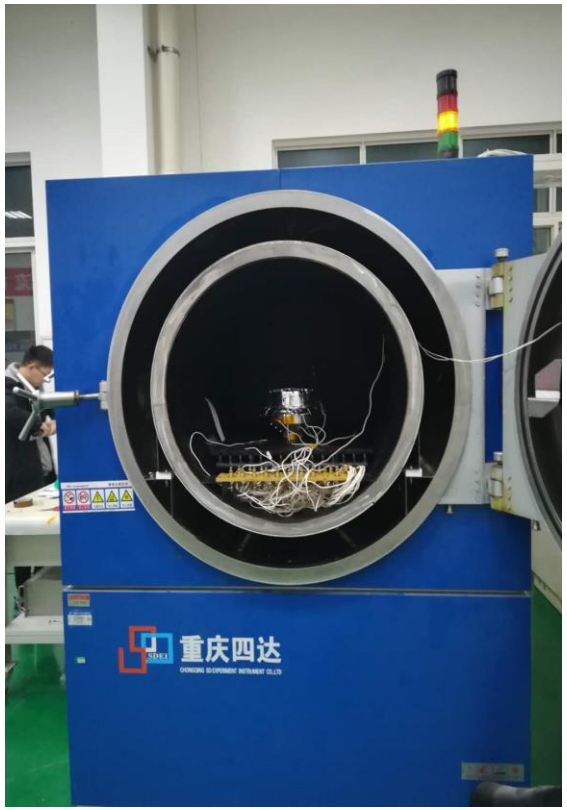




3.Corner cube retro-reflector - test

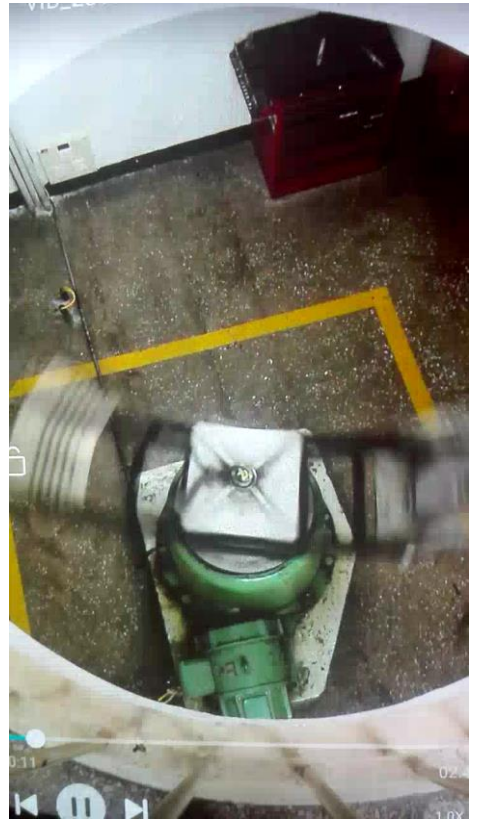


Vibration



Vacuum thermal
(-50 to +50°C)

Shocking

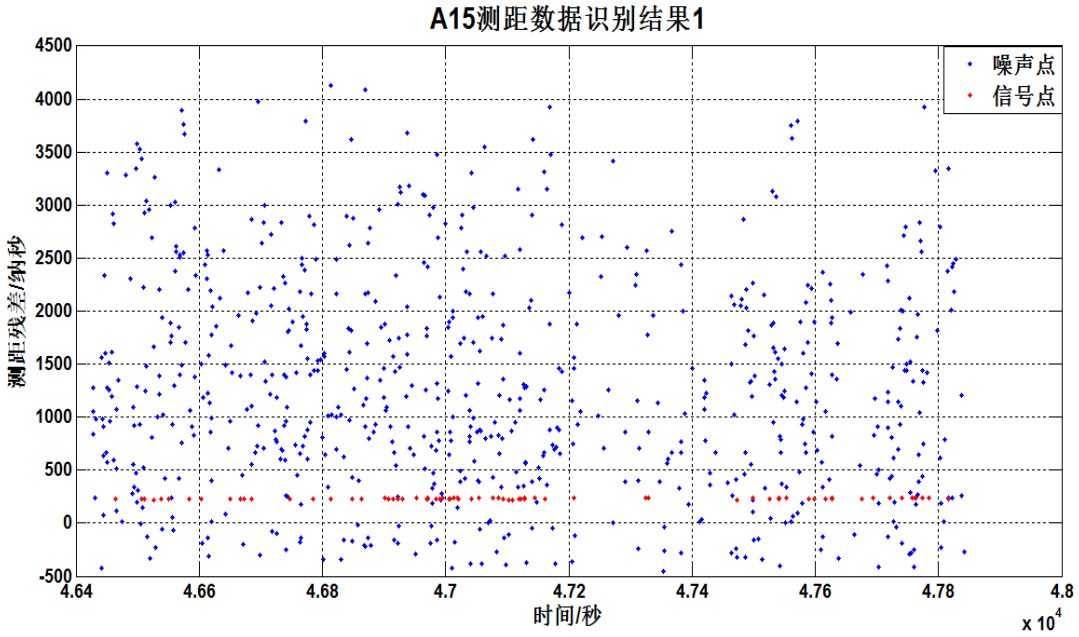


Acceleration

4.Laser ranging station- LLR results

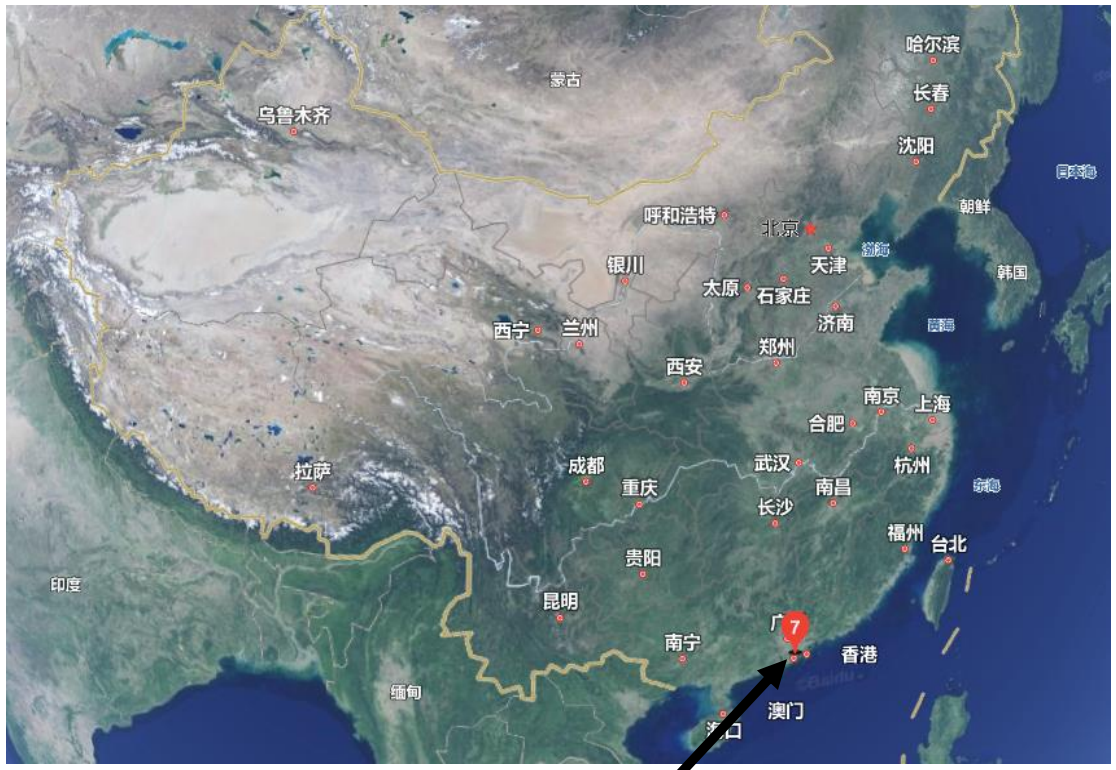
Lunar laser ranging experiment at Kunming station

- Laser pulse: 10ns and 3J; telescope aperture: 1.2m
- The first return was captured from Apollo 15 on Jan 22, 2018
- The following experiments received the return signal from three Apollo CCRs during Jan 23 - Feb 25, 2018.



4.Laser ranging station- Zhuhai

Laser ranging system at Zhuhai (SYSU)



Sun Yat-sen University Zhuhai campus

- **Telescope**

aperture：1.2m；

- **Laser Pulse**

Energy：800mJ@1064nm；
Width：~80ps；
Frequency：100Hz

- **Detector**

2×2 array APD;
Quantum Efficiency：~30%@1064nm；

5.Summery

- A hollow CCR with the similar reflecting performance of Apollo 11 array has been developed and is currently in orbit around the L2 point of earth-moon system.
- Kunming station successfully received the return signal from lunar CCR and are ready for the open of ranging schedule of “Queqiao” satellite.
- The construction of Zhuhai station as well as the ranging system are still in progress. It is expected to be operated at the beginning of 2019.

Thank you for your attention