CELESTE

First European LEO-PNT In Orbit Demonstrator

INNOVATING SOLUTIONS

¿What is CELESTE IOD?

CELESTE IOD

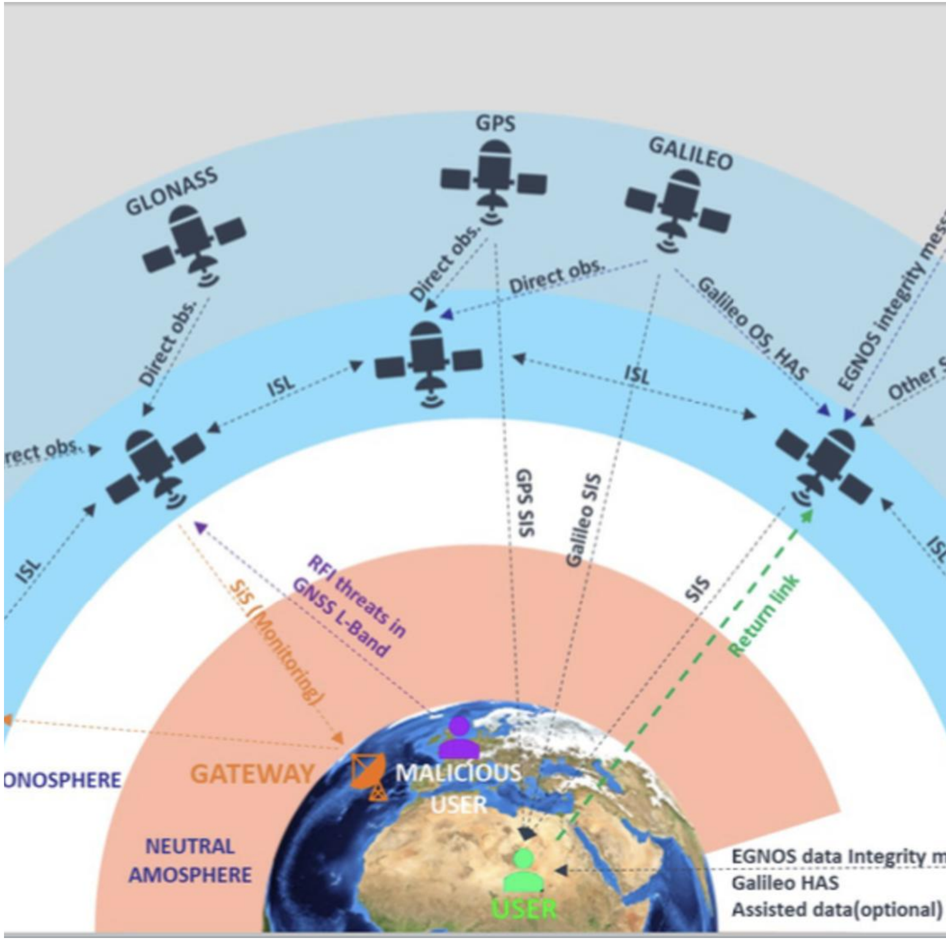
Low Earth
Orbit (LEO) Positioning, Navigation and Timing (PNT) constellation.

Complement Galileo through a multi-layer architecture

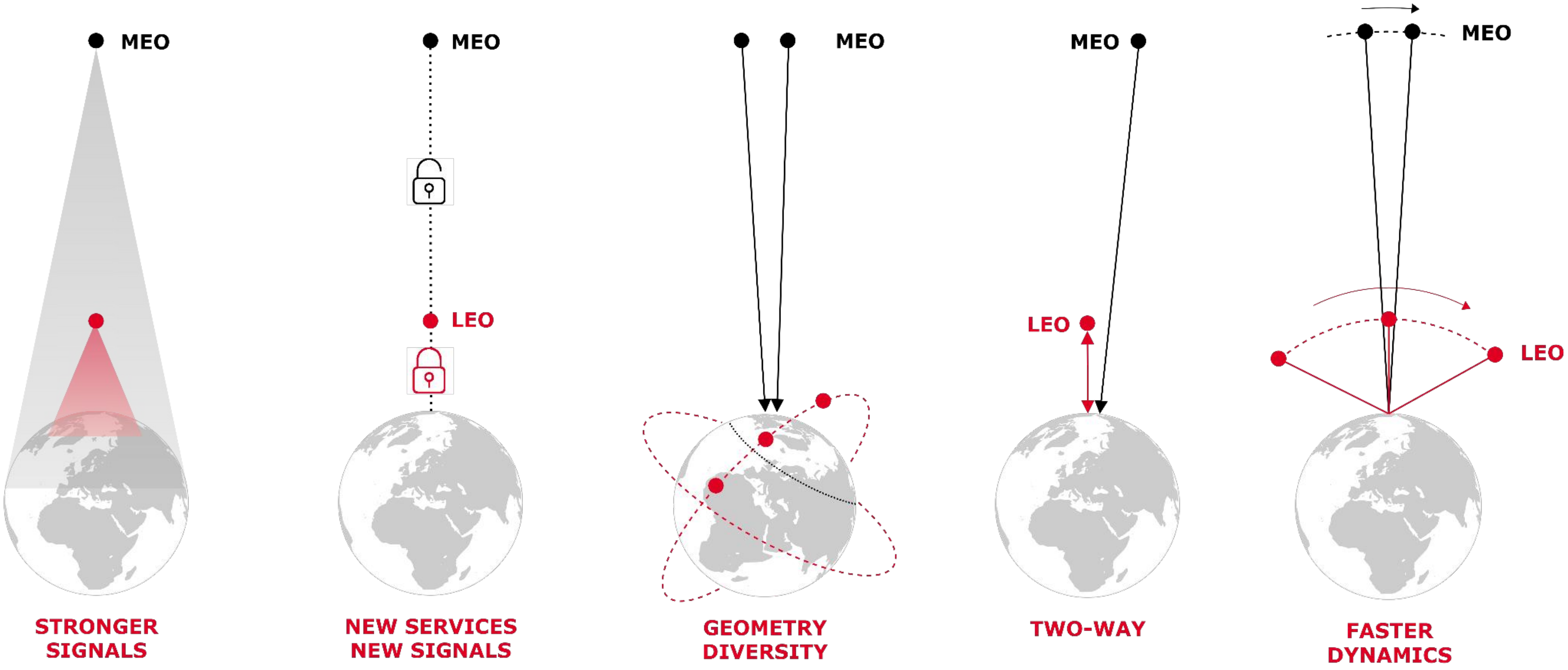
2 Parallel Contracts

Complete System Demonstrator

- Space Segment
- Ground Segment “as a service”
- User Receivers Prototypes
- Launcher
- Operations



¿Why LEOPNT?


MEO
LEO
STRONGER SIGNALS
MEO
LEO
NEW SERVICES NEW SIGNALS
MEO
GEOMETRY DIVERSITY
MEO
LEO
TWO-WAY
MEO
LEO
FASTER DYNAMICS

CELESTE In-Orbit-Demonstration

https://www.esa.int/Applications/Satellite_navigation”/Celeste

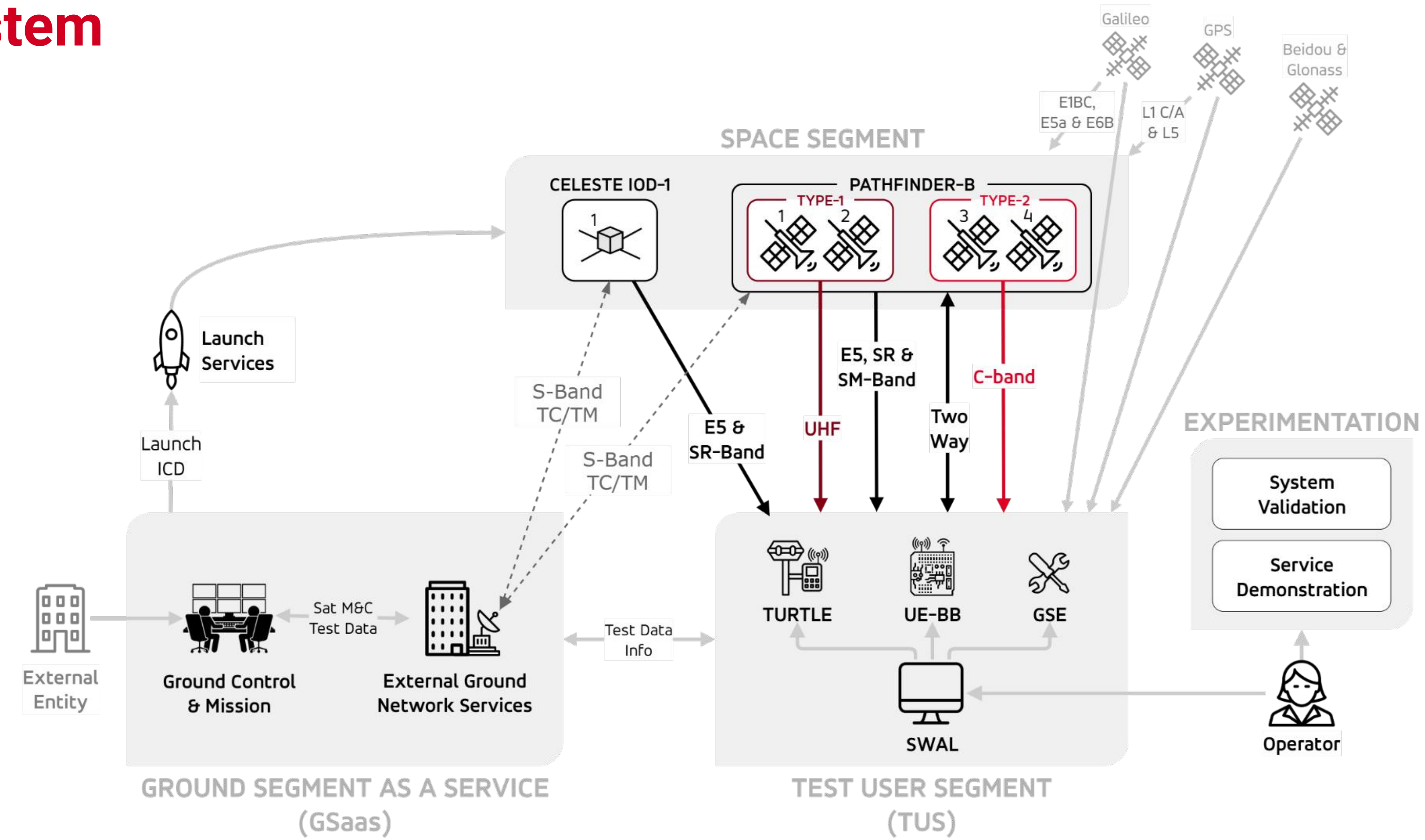
The **European Space Agency (ESA)** has launched a program to develop space infrastructure with Low Earth Orbit (LEO) satellites, with 2 contracts in parallel

The first step is the **Celeste In-Orbit Demonstrator** for **Positioning, Navigation, and Timing (PNT) services**

GMV is prime contractor of one of the contracts and leads **Celeste IOD-1**, **Ground Segment** and **Operations**, Test **User Segment**, and coordinates **Launch** activities.

OHB is a core partner of GMV, main role as **Pathfinder B space segment prime**.

System


Galileo
GPS
Beidou & Glonass
E1BC, E5a & E6B
L1 C/A & L5
SPACE SEGMENT
CELESTE IOD-1
1
PATHFINDER-B
TYPE-1
1
2
TYPE-2
3
4
Launch Services
Launch ICD
S-Band TC/TM
S-Band TC/TM
E5 & SR-Band
UHF
E5, SR & SM-Band
Two Way
C-band
EXPERIMENTATION
System Validation
Service Demonstration
External Entity
Sat M&C Test Data
Ground Control & Mission
External Ground Network Services
Test Data Info
TURTLE
UE-BB
GSE
SWAL
Operator
GROUND SEGMENT AS A SERVICE (GSaas)
TEST USER SEGMENT (TUS)

Space Segment

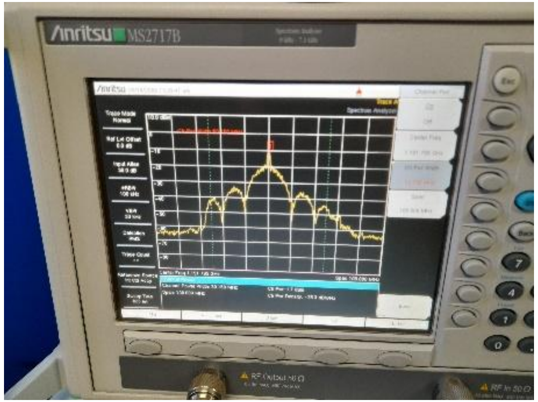
6 satellites under GMV consortia

Celeste IOD-1
One 12U Cubesat precursor satellite (Alén Space/GMV).

Celeste IOD-3/5/7/9
Four Microsats (OHB) will follow with in 2027 with additional capabilities.

Celeste IOD-11 (former IOD-1 Ground Spare) Enhanced to test additional technologies (CSAC and GNSS Rx).

CELESTE IOD-1 VALIDATION



IOD-1 In Orbit

Celeste IOD-1 launched with Electron (RockeLab) From New Zealand 28/03/26

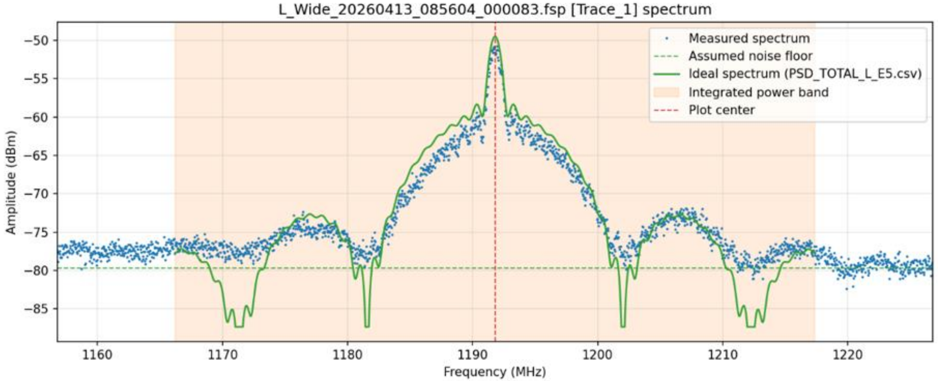
Final Orbit: 510km sun-synchronous orbit (97.41º, LTAN 10:30h, around 15 orbits a day)

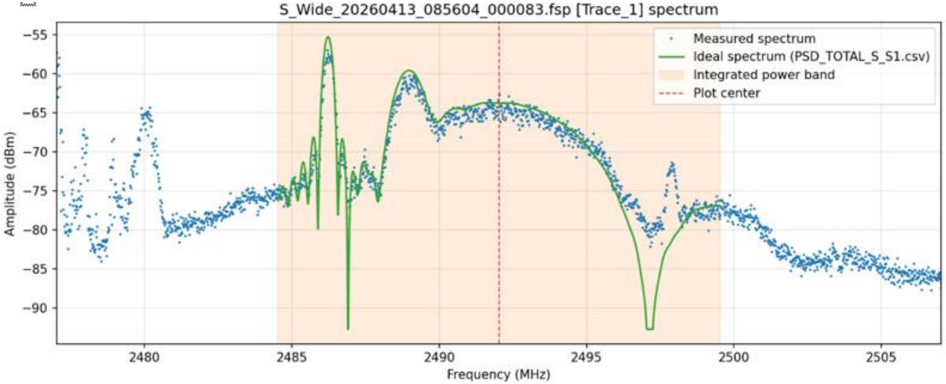
https://www.esa.int/Applications/Satellite_navigation/Celeste/Celeste_s_first_satellites_launched_to_explore_LEO-based_satellite_navigation

First Tx LEO-PNT in Europe

The first test IOT test confirmed the correct power emission and central frequencies (continuous-wave signal). This was the first transmission from IOD-1 and received by the HGA at ESTEC.

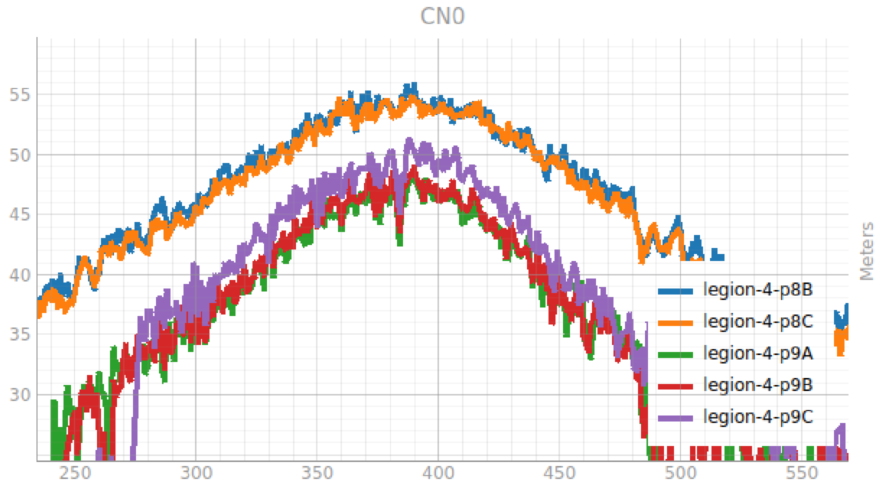
Next, a modulated signal was transmitted for the 1st time in E5 and SR bands.

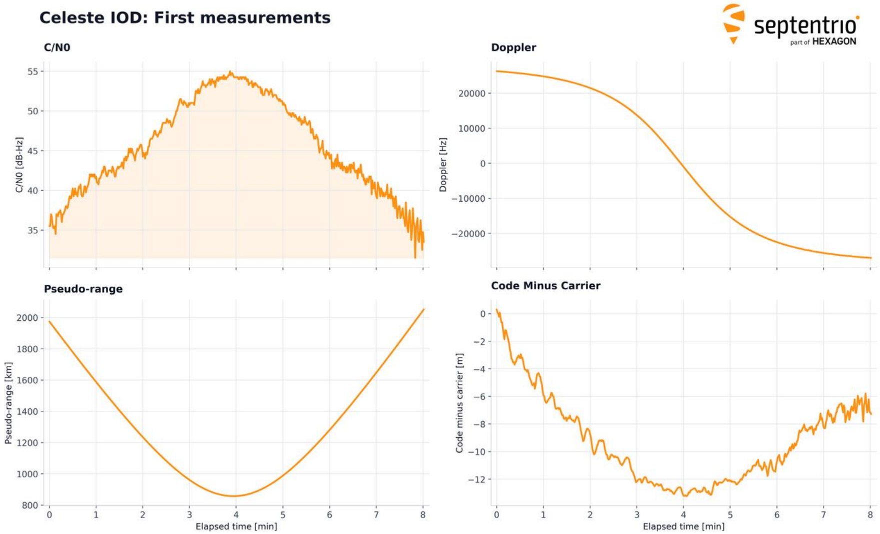




First tracking performances

Test User Rx and Septentrio Rx





Ground Segment

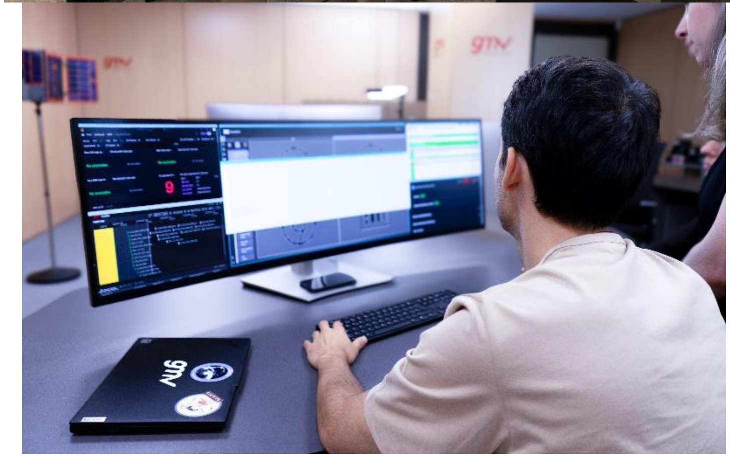
GSaaS

Celeste Ground Segment is provided as a Service (GSaaS) by GMV, based on state-of-the-art technologies and services included in GMV portfolio such as ***Hifly***® **,** ***Archiva, GMV Flexplan***®, **FocusSuite**®, etc. (adapted to cover CELESTE satellites)

It is physically located at GMV premises in Tres Cantos

KSAT provides the TTC stations

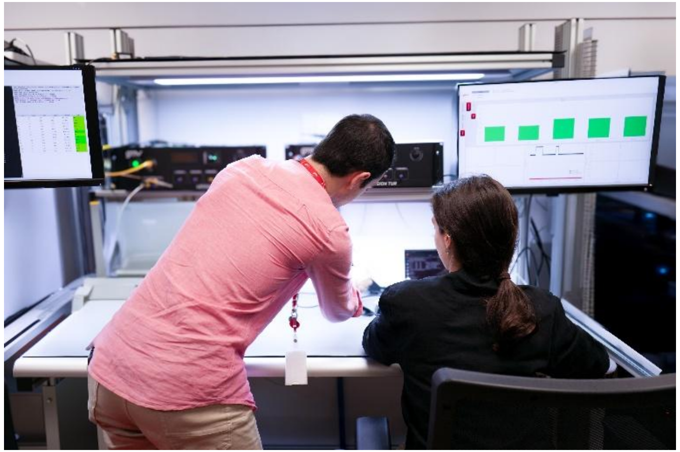
Operations are also provided by GMV.



User Segment

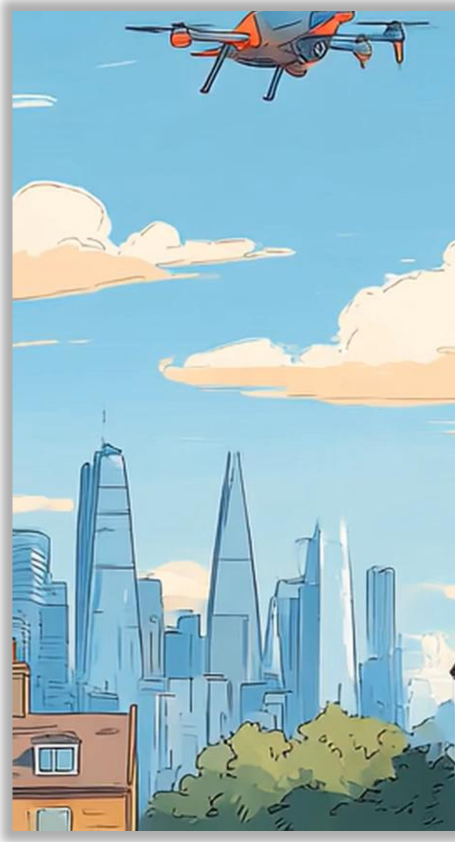
TUS

- GMV develops the **Test User Receiver** supporting all IoD signals while maintaining compatibility with the Galileo Open Service signals.
- Implementation is derived from GMV's GNSS receiver technology, extended to support the specific signal structures and processing requirements associated with the LEO-PNT In-Orbit Demonstration (IoD).
- The subsystem is capable of processing multiple channels concurrently, enabling simultaneous tracking of both Celeste and GNSS signals.



IOD-Experimentation

- On Board ODTS performance
- Clock stability
- Navigation message generation and Transmission (L and S bands)
- Signal acquisition and Tracking (L and S bands)
- Ranging accuracy (L and S bands)

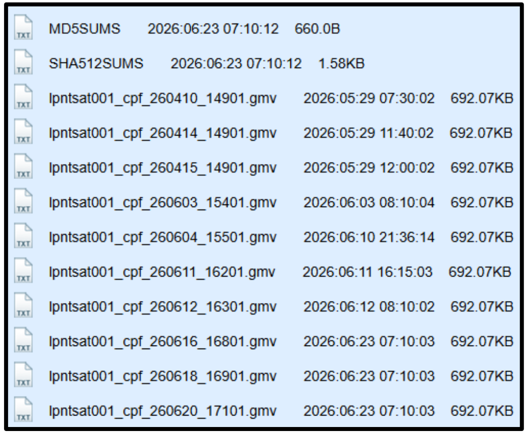


Precise Orbit Determination

ILRS collaboration

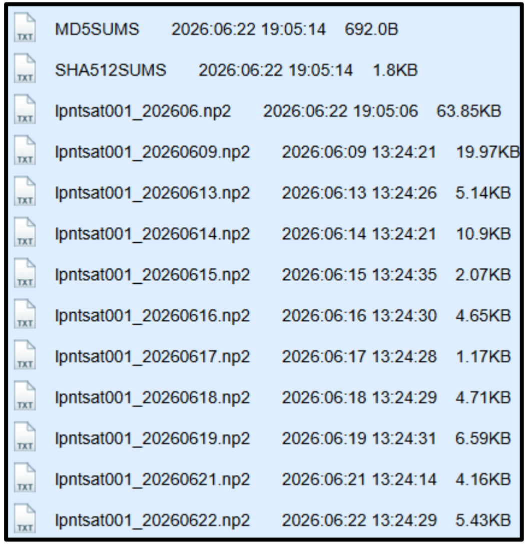
- GMV generates the reference orbits for the CELESTE satellites using GNSS signals.
- External means are needed to validate the generated orbits.
- CELESTE satellites are equipped with an LRR instrument; therefore, SLR observations can be obtained and used as an external source.
- Right plots show the list of generated CPF (from GMV) and NPT (from ILRS stations) files.
- The current validation of SLR residuals shows differences of ~10 cm. Further investigation is ongoing.

CPF files



MD5SUMS	2026:06:23 07:10:12	660.0B
SHA512SUMS	2026:06:23 07:10:12	1.58KB
lpntsat001_cpf_260410_14901.gmv	2026:05:29 07:30:02	692.07KB
lpntsat001_cpf_260414_14901.gmv	2026:05:29 11:40:02	692.07KB
lpntsat001_cpf_260415_14901.gmv	2026:05:29 12:00:02	692.07KB
lpntsat001_cpf_260603_15401.gmv	2026:06:03 08:10:04	692.07KB
lpntsat001_cpf_260604_15501.gmv	2026:06:10 21:36:14	692.07KB
lpntsat001_cpf_260611_16201.gmv	2026:06:11 16:15:03	692.07KB
lpntsat001_cpf_260612_16301.gmv	2026:06:12 08:10:02	692.07KB
lpntsat001_cpf_260616_16801.gmv	2026:06:23 07:10:03	692.07KB
lpntsat001_cpf_260618_16901.gmv	2026:06:23 07:10:03	692.07KB
lpntsat001_cpf_260620_17101.gmv	2026:06:23 07:10:03	692.07KB

NPT files



MD5SUMS	2026:06:22 19:05:14	692.0B
SHA512SUMS	2026:06:22 19:05:14	1.8KB
lpntsat001_202606.np2	2026:06:22 19:05:06	63.85KB
lpntsat001_20260609.np2	2026:06:09 13:24:21	19.97KB
lpntsat001_20260613.np2	2026:06:13 13:24:26	5.14KB
lpntsat001_20260614.np2	2026:06:14 13:24:21	10.9KB
lpntsat001_20260615.np2	2026:06:15 13:24:35	2.07KB
lpntsat001_20260616.np2	2026:06:16 13:24:30	4.65KB
lpntsat001_20260617.np2	2026:06:17 13:24:28	1.17KB
lpntsat001_20260618.np2	2026:06:18 13:24:29	4.71KB
lpntsat001_20260619.np2	2026:06:19 13:24:31	6.59KB
lpntsat001_20260621.np2	2026:06:21 13:24:14	4.16KB
lpntsat001_20260622.np2	2026:06:22 13:24:29	5.43KB

Thanks

中国科学院大学
University of Chinese Academy of Sciences

NAOC

中科院国家天文台长春人造卫星观测站
Changchun Observatory, NAO, Chinese Academy of Sciences

Single point positioning of cis-lunar spacecraft with tri-static common view laser ranging

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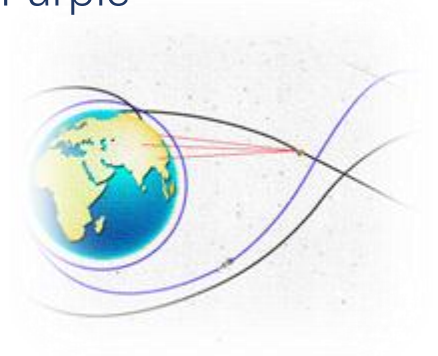
ILRS NESC, 25 June 2026, online

Based on journal article https://doi.org/10.3724/ati2025084



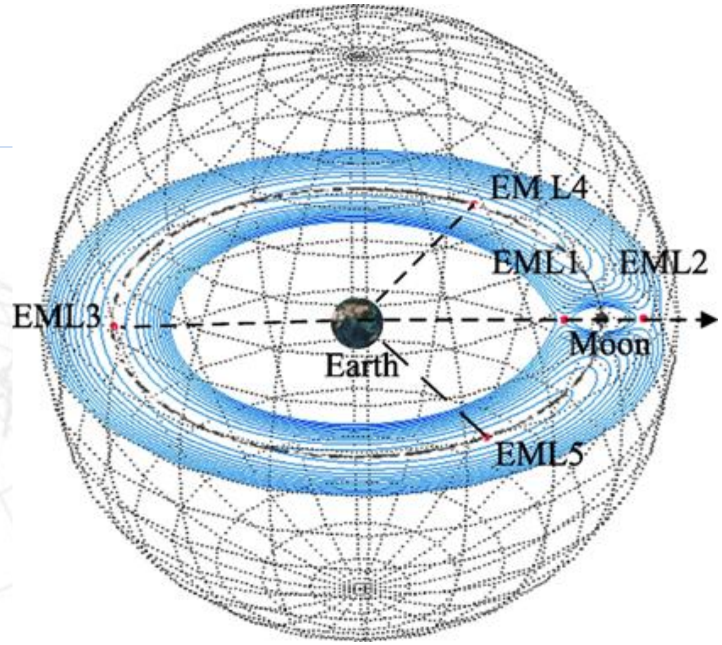
CONTENTS

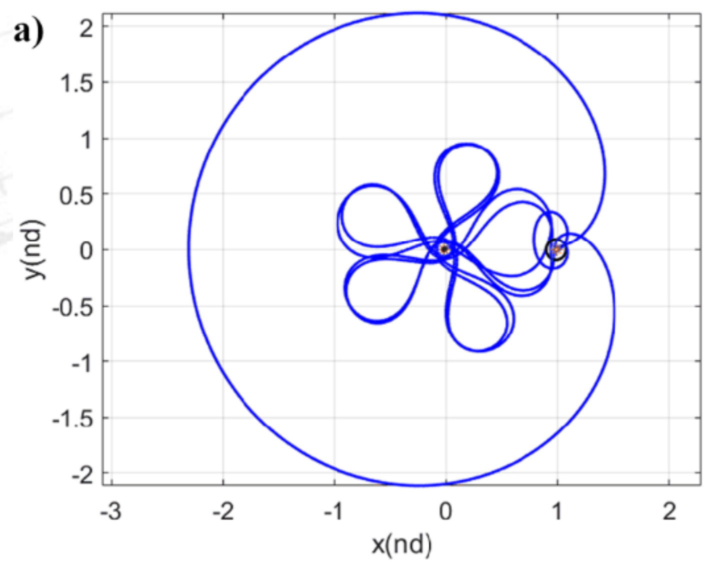
1 Research Background

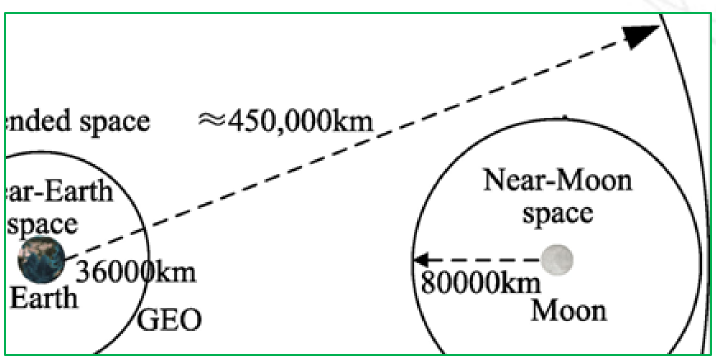
1.1 The Cis-lunar Space

The cis-lunar space reaches as far as the second Earth-Moon Lagrange point (EML2) at about 450,000 km from the Earth.

The challenges of positioning a cis-lunar spacecraft arise from the complex gravitational environment, combined with limited deep space telemetry / tracking / command (TT&C) resources.

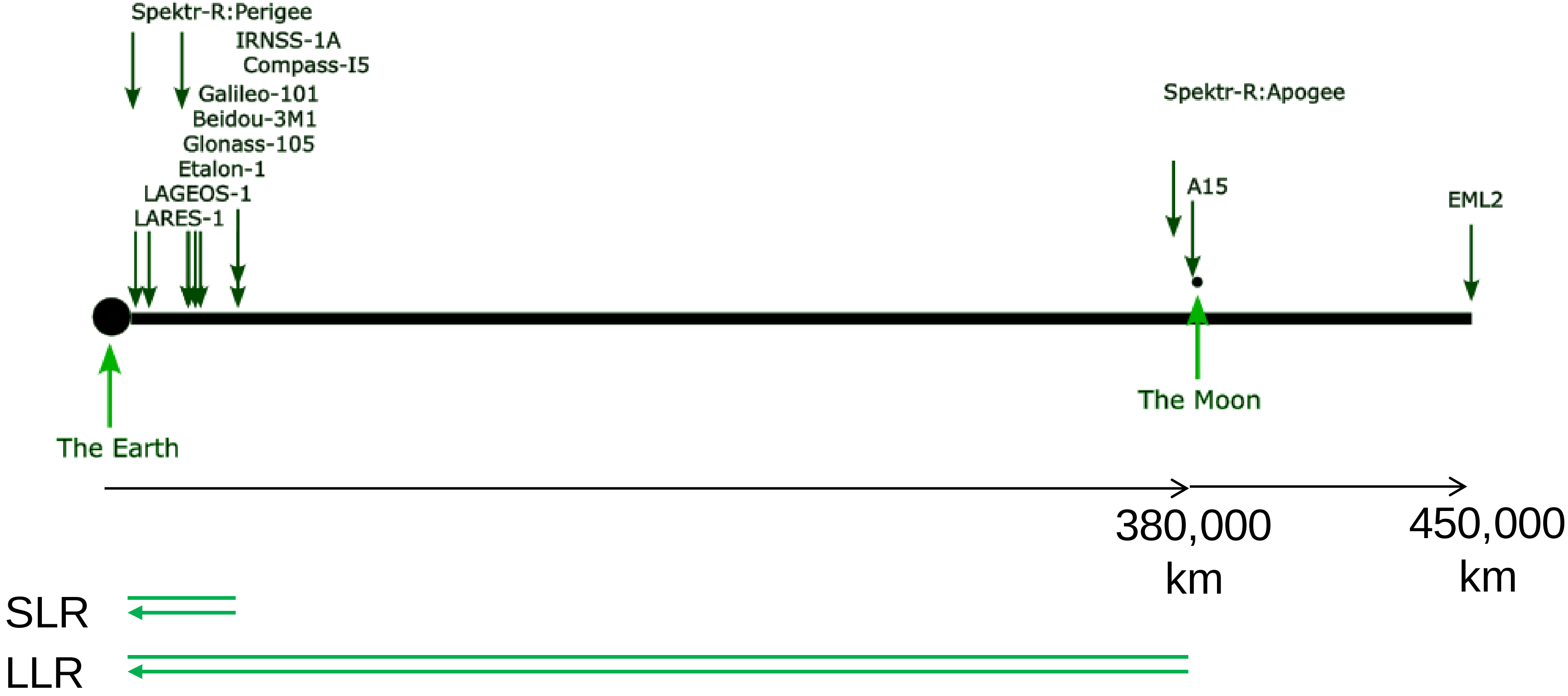






Cis-lunar Space Orbit Heights (To Scale)

The moon is so far and the Earth is so small.



1.2 Positioning Technologies

(1) Technologies for Cis-lunar Positioning

Technology	Representatives	Position Accuracy
Deep Space Network	USB / VLBI	10 m in selenocentric orbit (Park et al. 2025)
Auto-Navigation	Star sensor / Pulsar Sensor	N/A
Lunar constellation	LunaNet	100 m in early stage
GNSS Receiver	Lunar GNSS Receiver Experiment / NaviMoon	50 m in selenocentric orbit (MAISTRO, 2023)
Laser ranging	Tiandu-1、DRO-A	Sub-meter level range precision
Tri-static laser ranging (this work)	**proposed**	**10 meter level real-time position**

- PARK et al., 2025. Radio Science, 60(7): 1-20. DOI: 10.1029/2025RS008296.
- MAISTRO, 2023. University of Padua. https://thesis.unipd.it/handle/20.500.12608/52957.

1.2 Positioning Technologies

(2) Positioning by Multi-Static Ranging

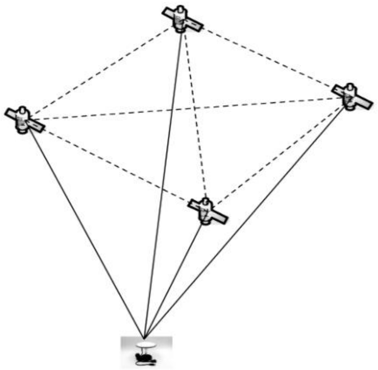
Period	Representatives	Technology	Precision / Accuracy
1960s	Sequential Collation of Range (SECOR)	Radio: ranging by four coordinated stations	4 m positioning accuracy
2000s	Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)	Radio: satellite-borne Doppler measurements	radial accuracy<10cm for Jason-2 orbit
1980	Leick A.	Laser: LLR common-view (proposed)	30 cm (≈10mas) for Earth pole motion
2009	Müller J. et al.	Laser: transponder on the moon (proposed)	N/A
2013	Kirchner G. et al.	Laser: Multi-static ranging to space debris targets	centimetric
2023	Battat et al.	Laser: LLR with APOLLO	millimetric
2025	Yunnan Astronomical Observatory, CAS	Laser: Tiandu-1 ranging in daylight	centimetric

2 Theoretical Basis

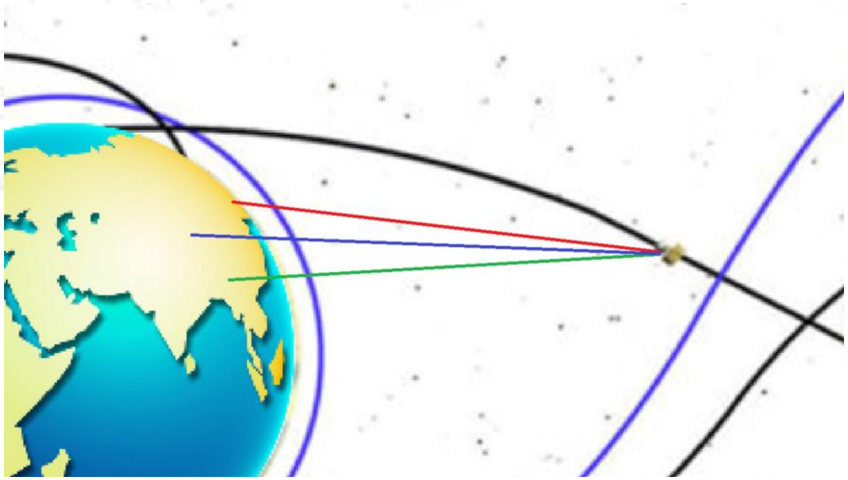
2.1 Single Point Positioning (SPP)

Refer to Zogg(2007)

- GNSS positions you by simultaneous range measurements.
- **Position Dilution of Precision (PDOP)**
  - Small PDOP : Good precision
  - Large PDOP : Bad precision



$$\hat{\delta}_{\rm pos}({\rm PDOP}) = \delta_{\rm obs} \times {\rm PDOP},$$



Position error is PDOP times range error.

2.2 Synchronization of Range Measurements

The SPP needs Euclidean distance from station to target. There are three major biases between the range (ToF) measurement and the distance.

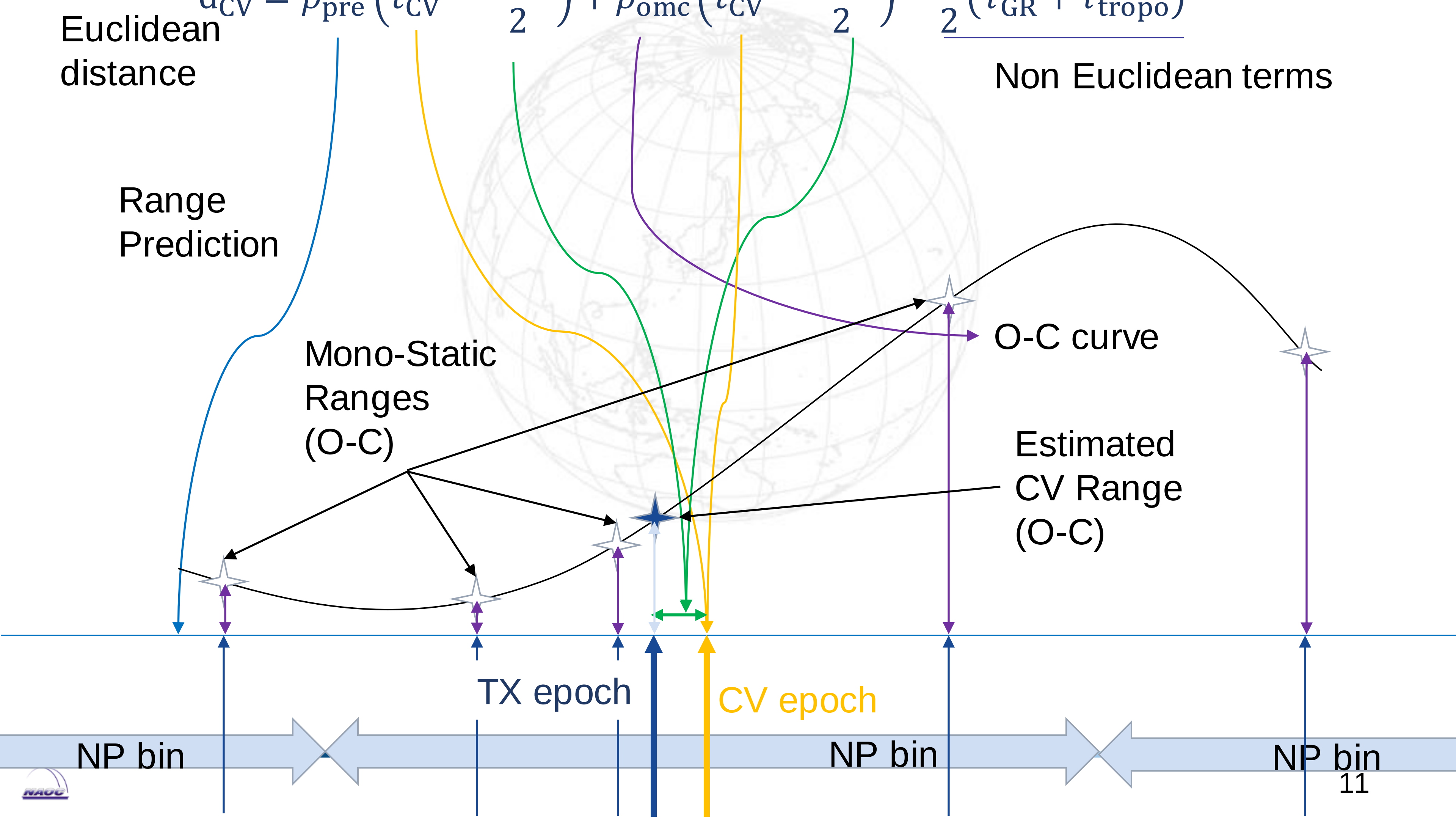
1. Propagation medium delay: the tropospheric and gravitational delays.
2. Uplink time: (hit epoch) – (transmit epoch)
3. Alignment of time: (common-view epoch) - (hit epoch)

After correcting these biases, the resulting distance is a good estimation of the Euclidean distance between station and target at the given common-view epoch.

$$\hat{\mathrm{d}}_{\mathrm{CV}} = \rho_{\mathrm{pre}}\left(t_{\mathrm{CV}} - \frac{\tau_{\mathrm{TOF}}}{2}\right) + \rho_{\mathrm{omc}}\left(t_{\mathrm{CV}} - \frac{\tau_{\mathrm{TOF}}}{2}\right) - \frac{c}{2}\left(\tau_{\mathrm{GR}} + \tau_{\mathrm{tropo}}\right)$$

2.2 Synchronization of Range Measurements

$$\hat{d}_{CV} = \rho_{pre}\left(t_{CV} - \frac{\tau_{TOF}}{2}\right) + \rho_{omc}\left(t_{CV} - \frac{\tau_{TOF}}{2}\right) - \frac{c}{2}\left(\tau_{GR} + \tau_{tropo}\right)$$



3 Validation

3.1 Matching LAGEOS NPs in 2020

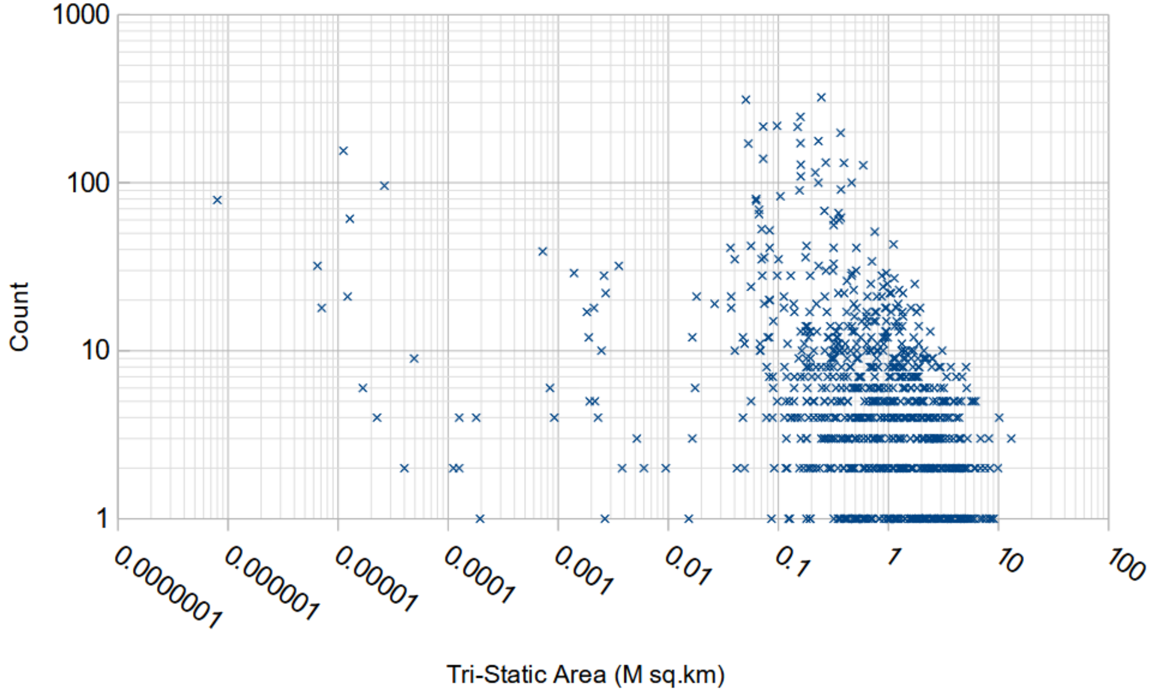
- Based on LAGEOS NPs in year 2020, we did the following:
  - Match NPs to find tri-static events.
  - Synchronization
  - SPP calculation
  - Comparison

- Matching
  - Traverse all LAGEOS NP bins in 2020,
  - For each NP bin, find all NPs of all stations.
  - Form 3-tuples from different stations.

- Synchronization
  - Mid-point of NP bin as common-view epoch.
  - Need initial TLE orbit to fit O-C curve
- SPP calculation
  - Initial position from TLE.
  - Iterate and converge.
  - Get ITRF vector of LAGEOS.
- Comparison
  - SP3C orbit as reference

• 3) Validation

3.2 LAGEOS Matching Results



- ~10,000 tri-static events
- In 800+ tri-static combinations
- Most triangles under 3 M sq.km
- Number drops over 1 M sq.km

- Largest triangle
  SHA2(7821)+ YARL(7090)+ STL3(7825)
  over 10 M sq.km
- Most matched combination
  ZIML(7810)+ POT3(7841)+ HERL(7840)
  over 300 events

3.3 SPP Results

For LAGEOS, we compare SPP results with SP3C orbit.

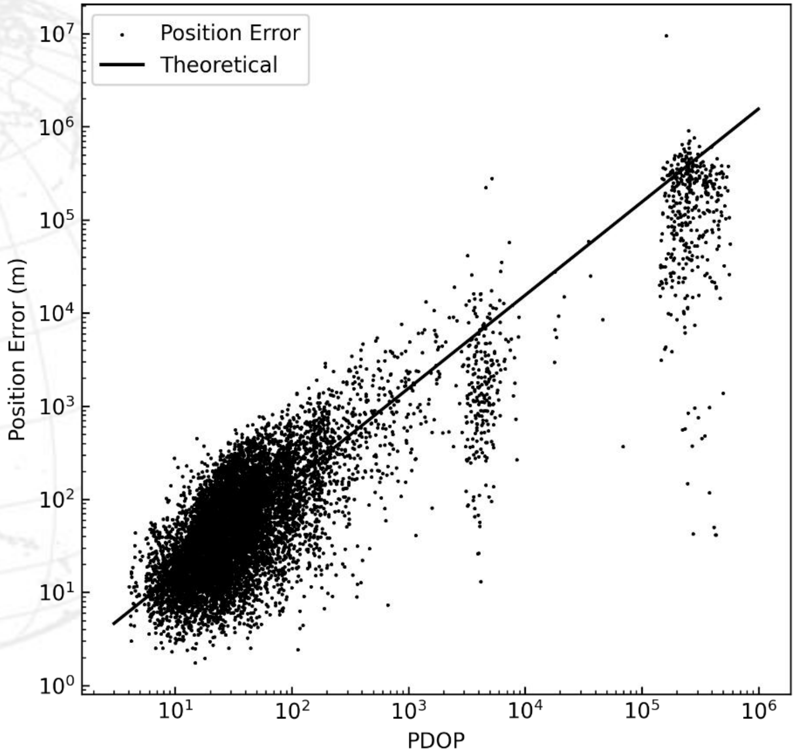
- Total ~10,000 events in 2020
- < 10 s calculation time for each event
- Position error

$$\delta_{\mathrm{Err}} = \left\| \hat{\mathbf{r}} - \mathbf{r}_{\mathrm{sp3}} \right\|$$

- Remember the law from GNSS

$$\hat{\delta}_{\mathrm{pos}}(\mathrm{PDOP}) = \delta_{\mathrm{obs}} \times \mathrm{PDOP}$$

- Plot δ_{Err} and $\hat{\delta}_{\mathrm{pos}}$ versus PDOP →
- The law holds with PDOP from 1 to 10^6



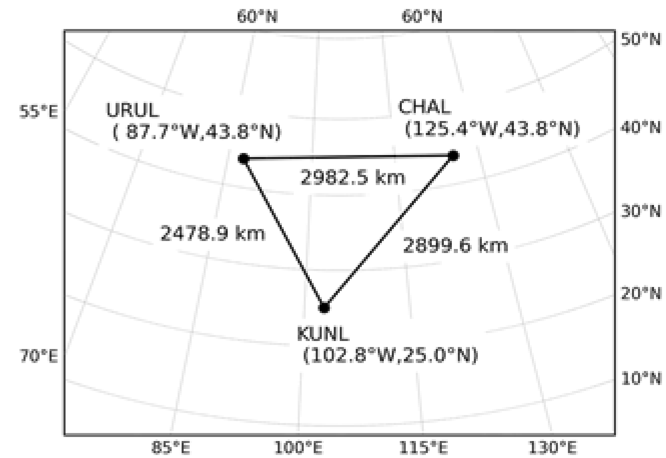
4 Simulation

• 4) Simulation

4.1 Settings

We simulated PDOP values on multiple orbit types in cis-lunar space, using:

- Three stations in China
  - CHAL(7237), KUNL(7819), URUL(7355)
  - Data from ITRF2020
  - Baselines from 2478 km to 2982 km
  - Triangle area ~3.3 M sq.km。
- 10 targets in cis-lunar space
  - LEO, MEO, IGSO, EHEO, Moon
  - Data from TLE (satellites) and DE430 (moon)
  - Height from 1,450 km ~ 356,400 km



Target	Orbit Type	Height (km)	NP bin (s)
LARES-1	LEO	1,450	30
LAGEOS-1	LEO	6,000	120
Etalon-1	MEO	19,105	300
Glonass-105	MEO	19,140	300
Beidou-3M1	MEO	21,500	300
Galileo-101	MEO	23,220	300
Compass-I5	IGSO	35,786	300
IRNSS-1A	IGSO	35,794	300
RadioAstron	EHEO	500-350,000 *	300
Apollo-15	Moon	356,400	900

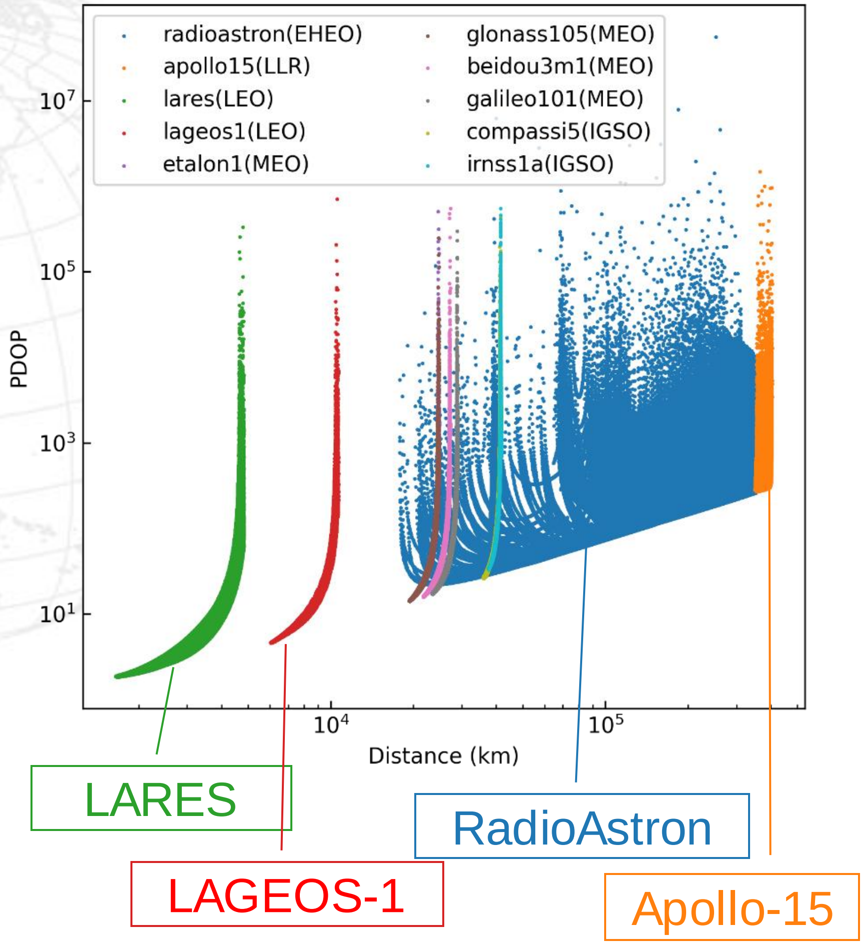
* Nominal

• 4) Simulation

4.2 Result and Analysis

(1) Plotted by target →

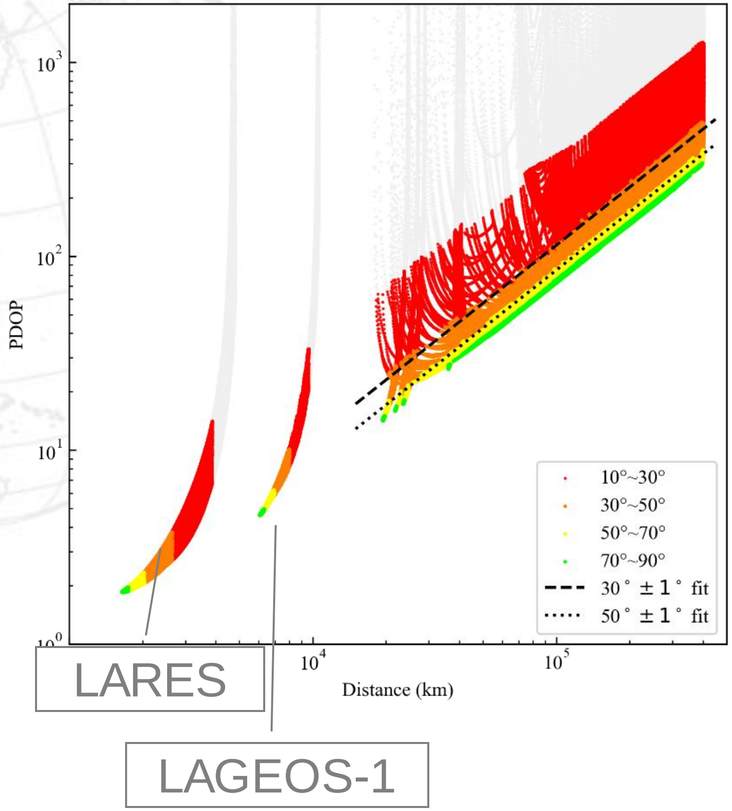
- PDOP vs distance
  - Distance to tri-static centroid
- Both axes log scale
- The farther distance, the larger PDOP
- RadioAstron (Spectr-R) contributes largest span of distance, from 2×10^4km to 3.5×10^5km
- LEO orbits reaches high PDOP by low elevation angles.



4.2 Result and Analysis

(2) Plotted by elevation angle →

- Y axis enlarged
- Plotted <10° (gray), 10°~30°(red), 30°~50°(orange), 50°~70°(yellow), 70°~90°(green).
- LEO (<10^4 km) targets elevation correlates with distance.
- High targets divides parallel by elevation angles.
- Higher elevation , Lower PDOP



4.2 Result and Analysis

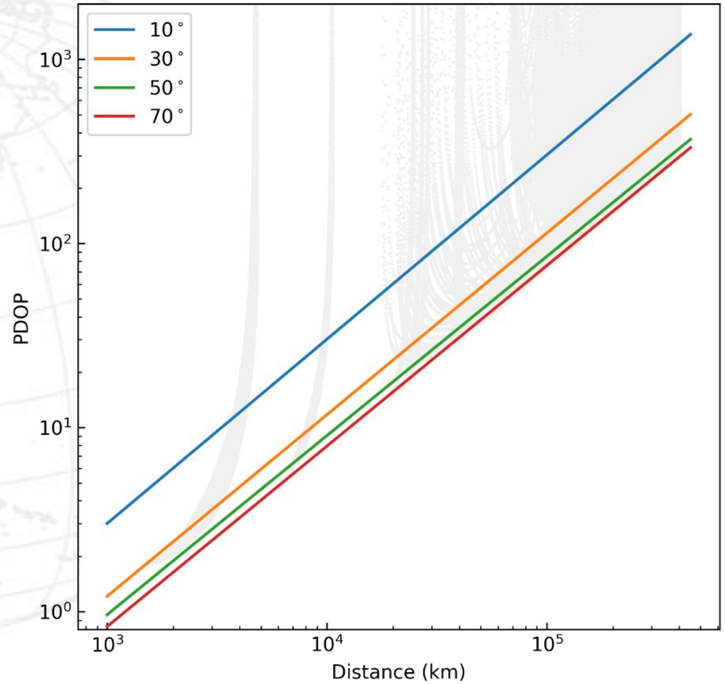
(3) PDOP upper and lower bounds

- By fitting elevations $30^\circ \pm 1^\circ$ and $50^\circ \pm 1^\circ$ in non LEO data, we get imperative formulae (distance D in km):

$$\mathrm{PDOP}(30) = 10^{-2.913} \times D^{0.9939},$$

$$\mathrm{PDOP}(50) = 10^{-3.042} \times D^{0.9939},$$

- We choose PDOP(30) as the upper bound for elevations limit 30°, and PDOP(50) to be the practical lower bound. For the selected stations, it is rare to have elevations above 50°.



4.3 Error Bounds

(1) Position error formulae $\hat{\delta}_{\mathrm{pos}}(\mathrm{PDOP}) = \delta_{\mathrm{obs}} \times \mathrm{PDOP}$

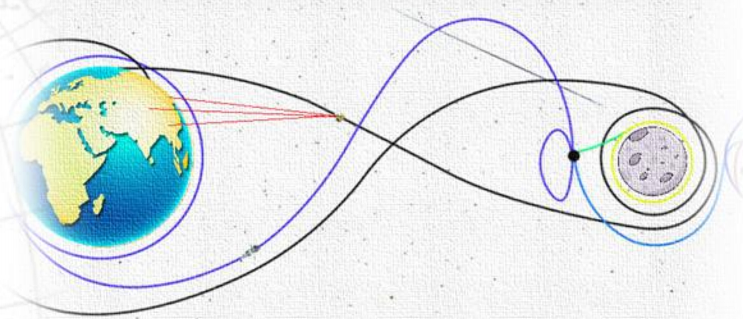
- Errors in m, D in km.

• δ_{obs} lower bound = 0.02 m – From LLR residual RMS in DE430 fitting. (Williams et al. 2013) • Lower bound of position error at distance D： lower×lower $\hat{\delta}_{\mathrm{pos,L}} = 0.02 \times \mathrm{PDOP}(50)$ $= 1.816 \times 10^{-5} \times D^{0.9939}$,	• δ_{obs} upper bound = 1.04 m – Length of Apollo-15 LRA, the biggest LRA in cis-lunar space. • Upper bound of position error at distance D： upper×upper $\hat{\delta}_{\mathrm{pos,U}} = 1.04 \times \mathrm{PDOP}(30)$ $= 1.271 \times 10^{-3} \times D^{0.9939}$,

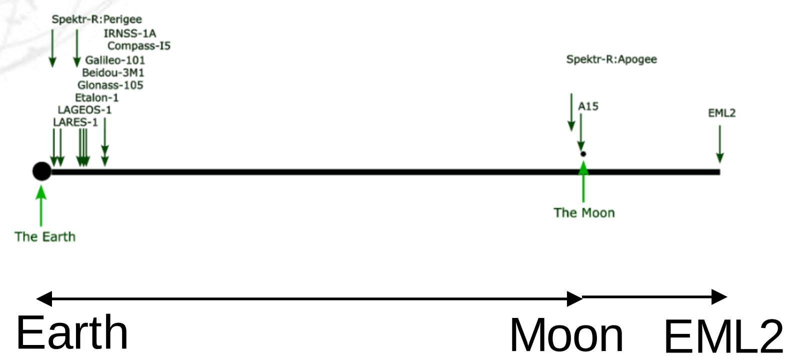
4.3 Error Bounds

(2) Results

- Position error < 500 m at lunar distance (EL>30°)
- Compared with DSN+VLBI (1d)
  - Similar precision, but faster (1 NP bin)
- Compared with VLBI
  - Same geometry, but better precision
  - Due to better range precision
- Feasible in cis-lunar space application.



Target	Distance (km)	Lower Bound (m)	Upper Bound (m)
Moon	380 000	**6.4**	**446.5**
EML2	450 000	**7.5**	**528.2**

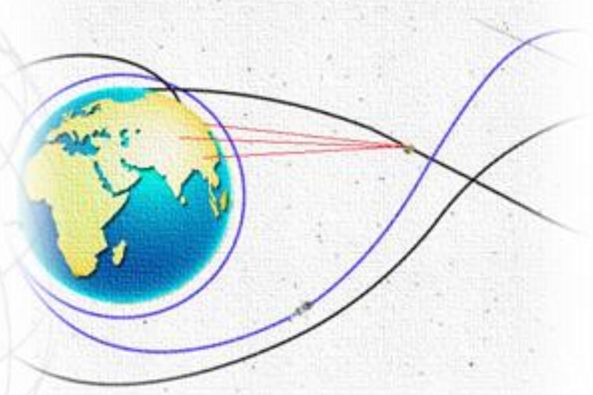


5

The Bigger Picture

5.1 Summary of the Tri-Static SPP method

- Relies on the coordinated operation of three stations.
- Minimal time requirement
  - Minutes of data
  - Seconds of computation.
- Meter-level precision at best.
- No long arcs or kinetic models required.
- Works in Euclidean geometry, like GNSS.
- Requires long baselines, like VLBI.
- Has all the good sides of laser ranging.

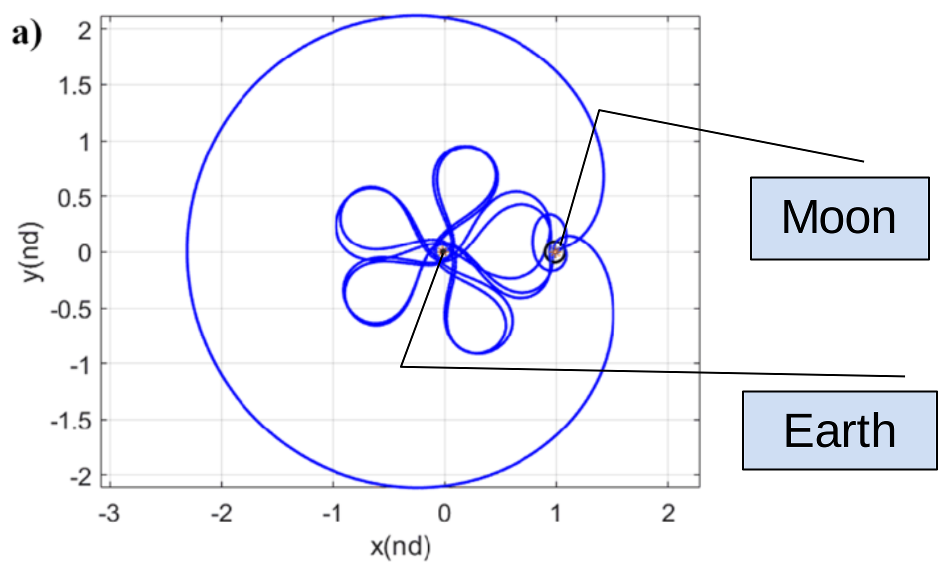


5.2 Laser Ranging Beyond Moon

A spacecraft may go beyond lunar orbit in a low-energy transfer. For example, the distance of 2 times lunar orbit requires 16 times two-way lunar laser ranging capability or 4 times one-way capability.

The transfers from lunar DROs to Earth orbits via optimization in the four body problem

Fig. 5 The selected low-energy transfer orbits from the **a**) DRO (1) and **b**) DRO (2) to the LEO in the synodic frame (left) and the Earth-centered inertial frame (right)

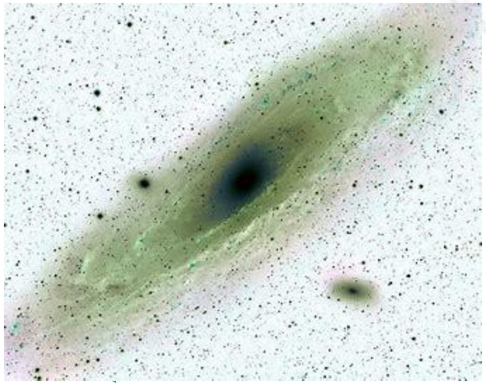


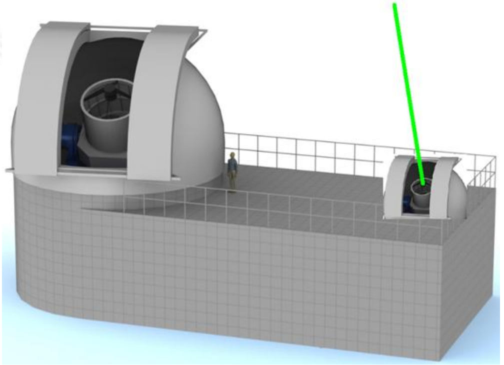
(ZHANG et al. 2021)

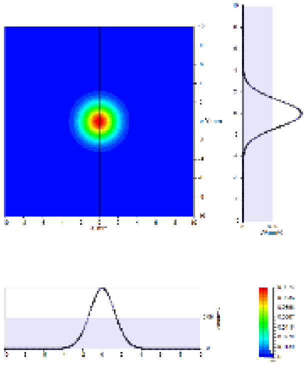
5.3 Separated Transmitter and Receiver

A new design of LLR system, refer to (Liang et al. 2023)

- Off-axis transmit optics. Smaller beam divergence.
- Supports arbitrarily high repetition rate.
- The bigger telescope can do astronomy tasks in moonless nights.
- The transmit telescope can do SLR on its own, to maintain site coordinates.





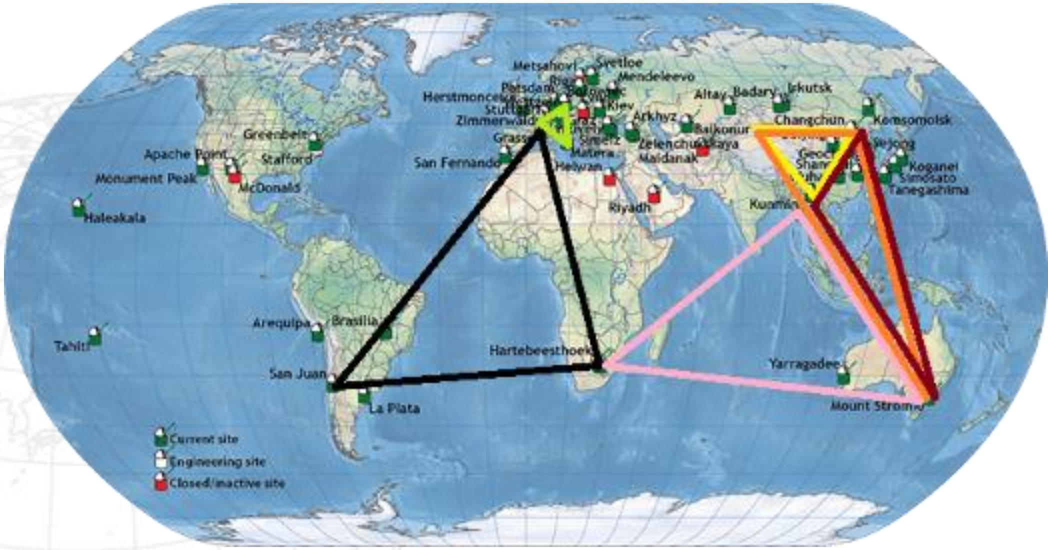


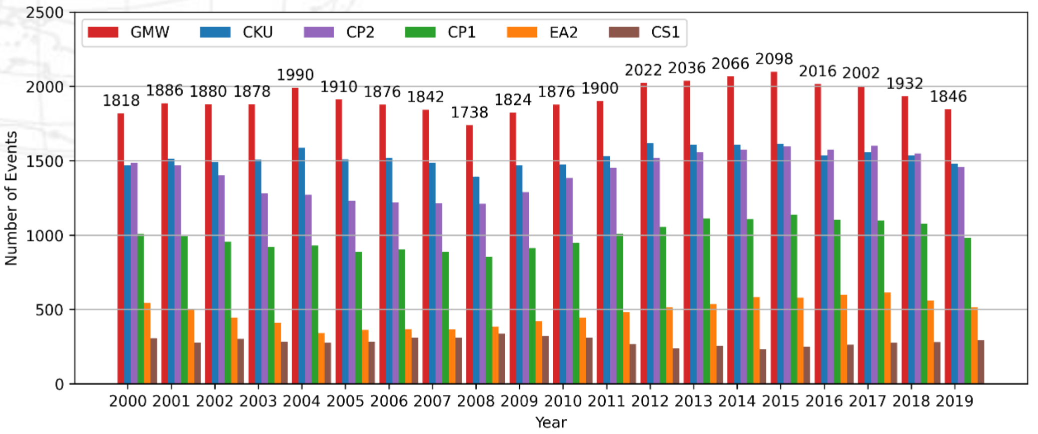
5.4 Global Tri-Static Network

A selection of global tri-static networks, refer to Liang et al. (2024)

Simulation shows that:

- Smaller networks have more common-view time.
- Larger longitude span reduces common-view time.
- Larger latitude span has little impact on common-view time.
- Larger triangle area provides better numerical stability.





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谢谢

Thank You!

Updates of Beijing SLR Station (7249)

Fu Yuanchen, MI Jinzhong, ZHAO Chunmei

June 25th, 2026

Chinese Academy of Surveying and Mapping, Beijing, China

Content

1

Introduction

- Beijing SLR station (7249) was built in 1980, which is located in Fangshan district, Beijing, China
- There are 28 employees and nearly 50 graduate students for geodetic observation and research of Beijing SLR Station currently

The Team

Prof. MI Jinzhong

Group Leader

Space geodesy and reference frame

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Scientist

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PHD student

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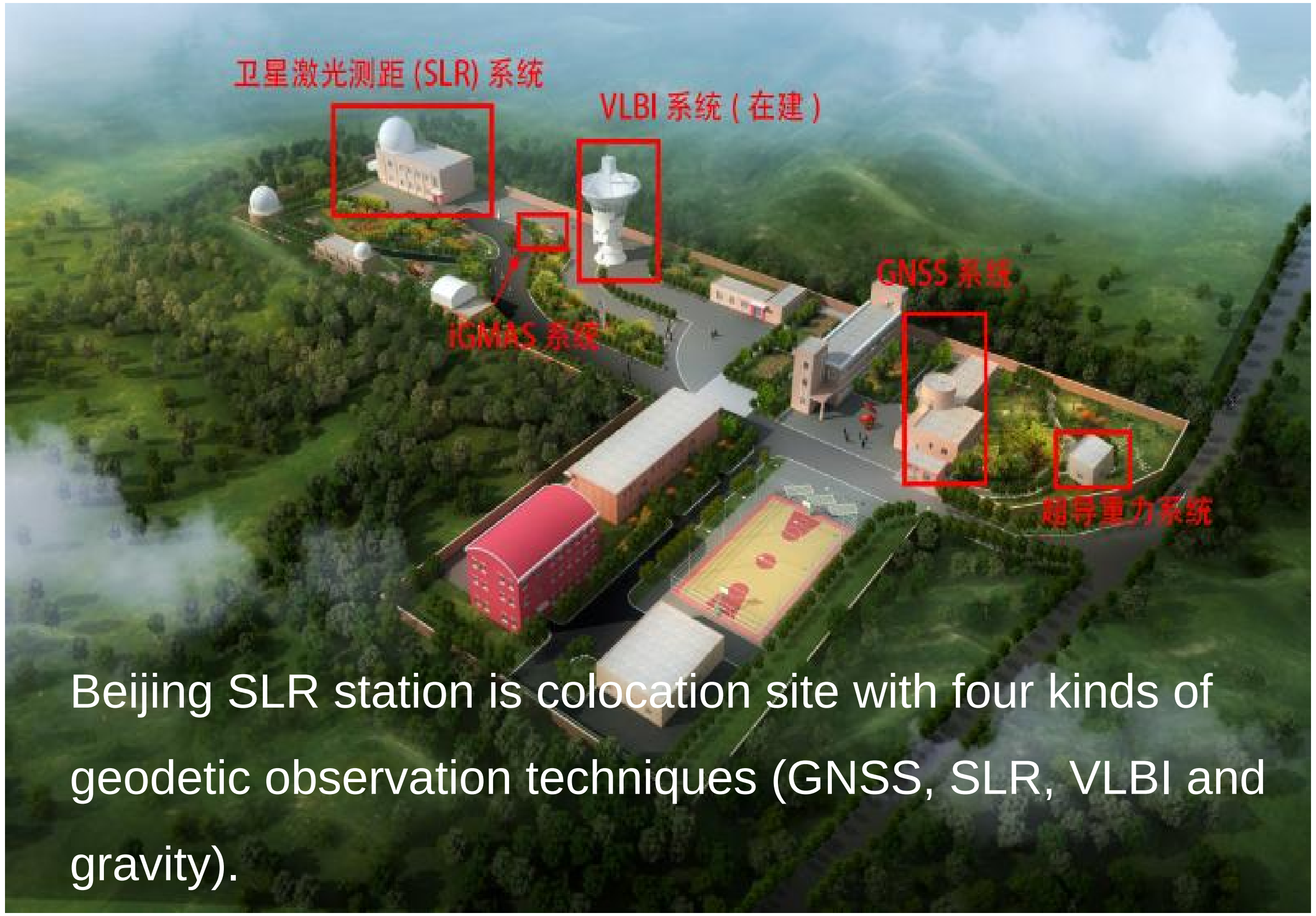
Introduction

- GGOS co-locate site
- IGS site
- ILRS site
- iGMAS site
- National Science Popularization and Education Base
- Co-located with four kinds of geodetic techniques

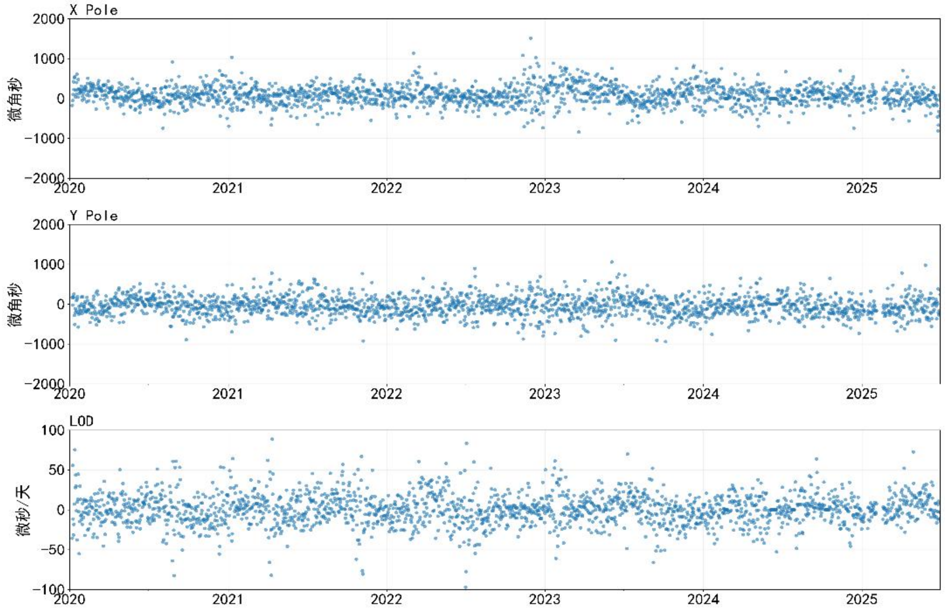


Beijing SLR station is colocation site with four kinds of geodetic observation techniques (GNSS, SLR, VLBI and gravity).

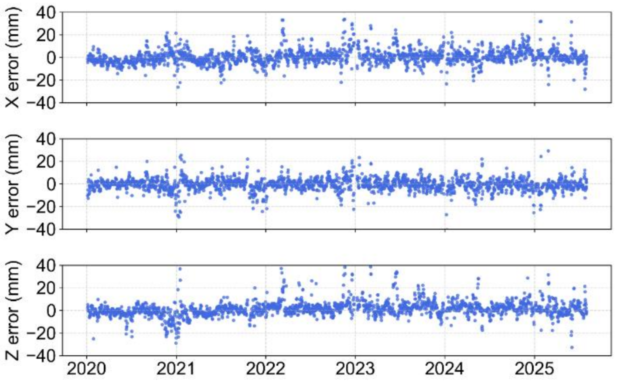
Introduction

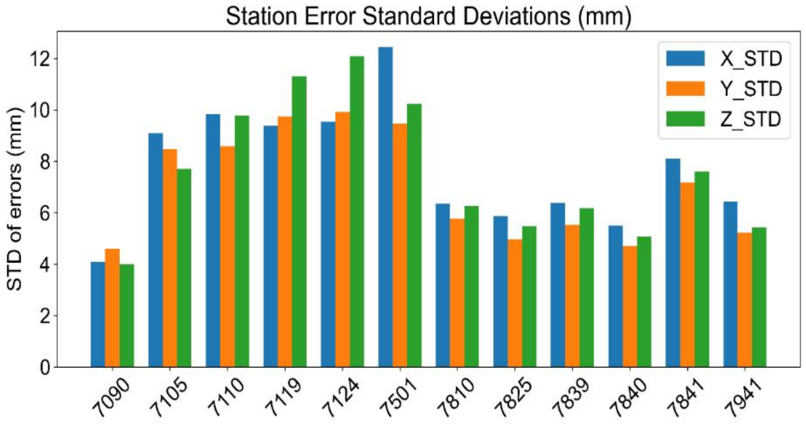
Introduction

- Conducted SLR data analysis using global SLR data
- Data analysis products comprising SLR station coordinates, Earth rotation parameters, and geocenter motion
- Demonstrated that the accuracy of the estimated parameters approaches that of ILRS analysis centers and related research



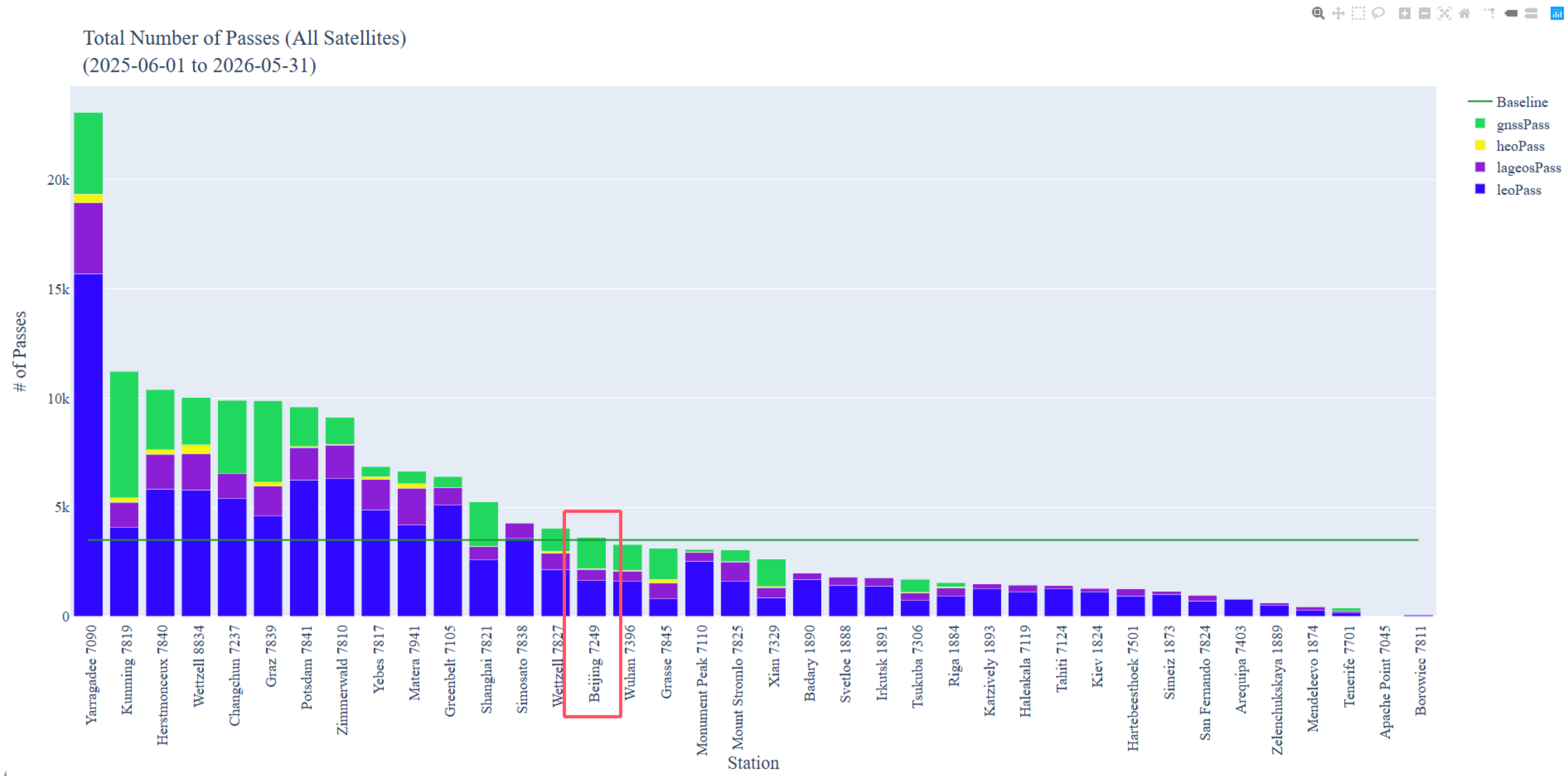
Year	Xpole (μas)		Ypole (μas)		LoD (μs/d)	
	Mean	STD	Mean	STD	Mean	STD
2020	102.6	209.1	-30.0	215.5	-0.9	20.7
2021	70.3	218.5	-18.6	241.7	2.6	22.1
2022	77.5	268.2	-47.8	260.2	-0.5	20.5
2023	142.8	274.5	-51.3	269.1	0.4	19.1
2024	80.3	217.5	-51.2	224.7	0.2	16.3
2025	5.6	232.9	-72.3	251.0	2.7	16.7
ALL	79.9	236.8	-45.2	243.7	0.7	19.2





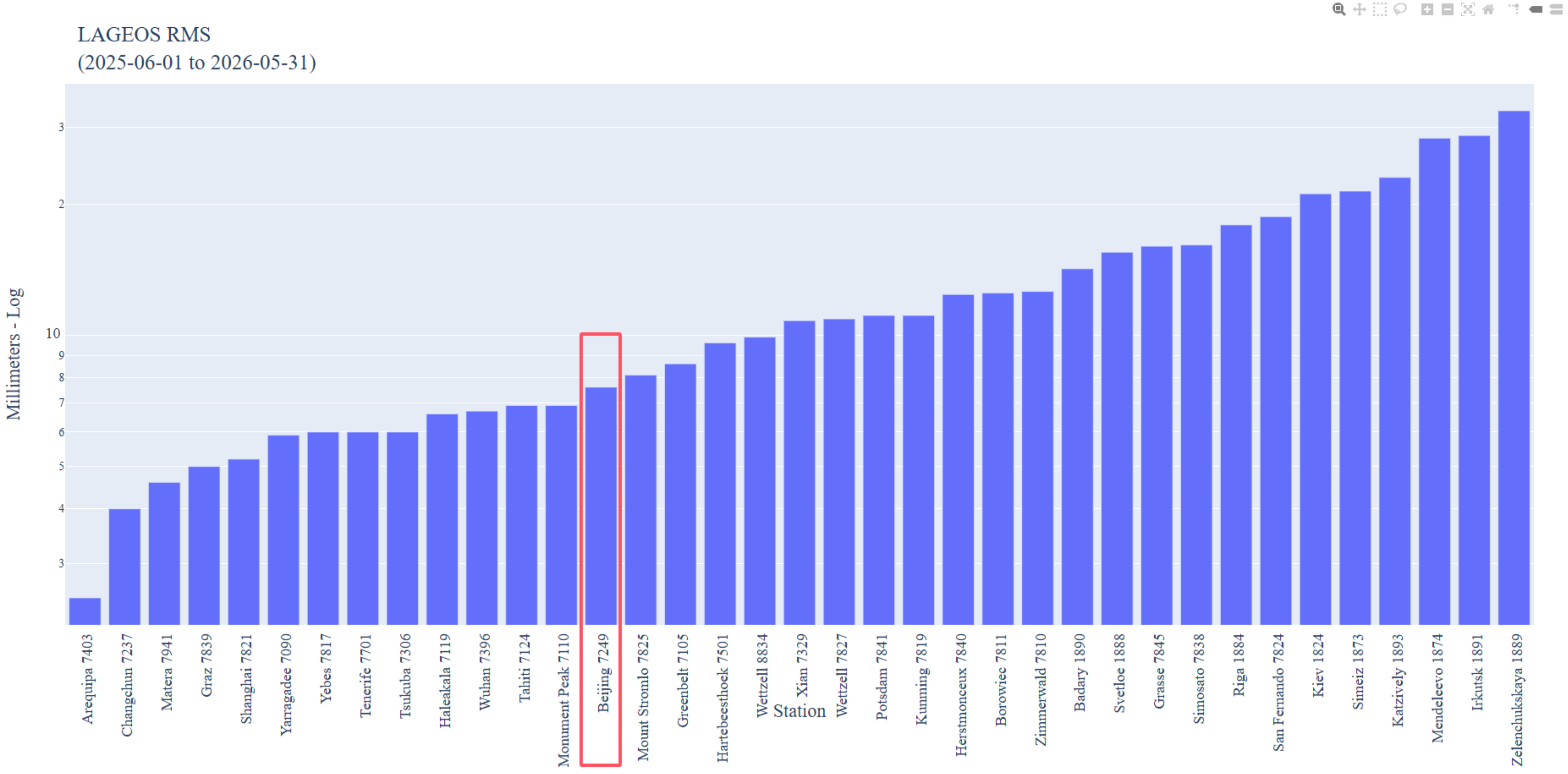
System performance

- During last year, Beijing SLR station have obtain 1636 LEO pass, 509 LAGEOS pass and 1458 high pass. The total pass is 3603, reaching the standard of 3500 total pass.



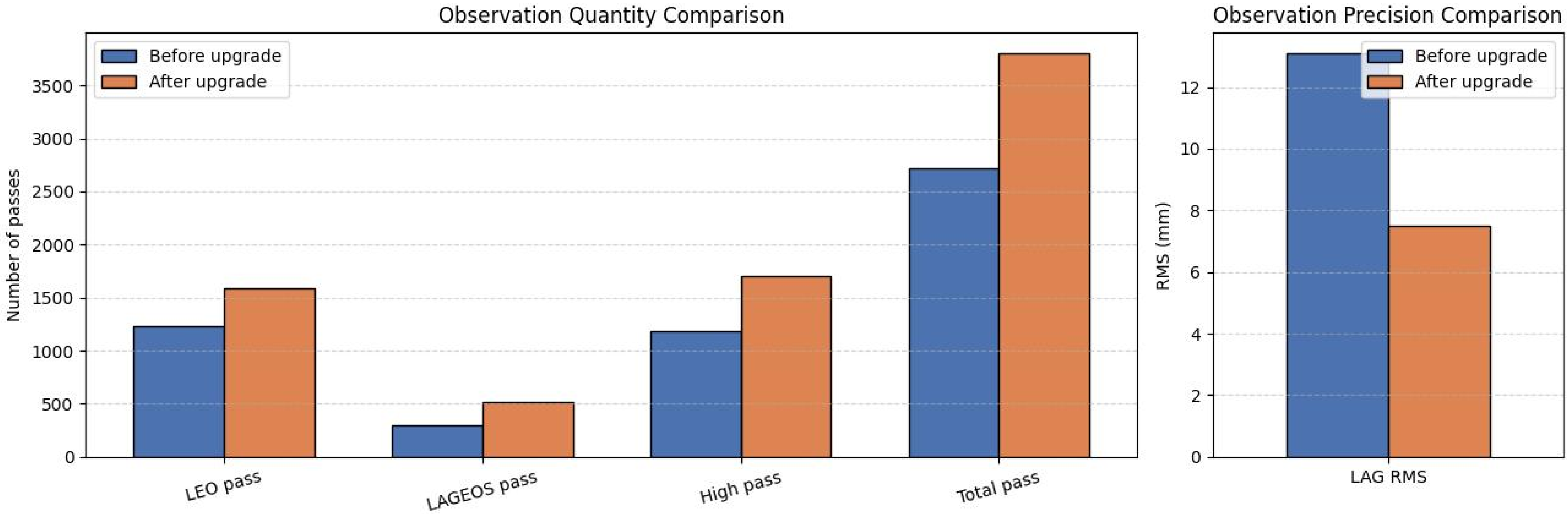
System performance

- Normal Point RMS values remained generally stable over the 2022-2026 period.
- Average NP RMS for LAGEOS is 7.6 mm in last year.



Updates of SLR system

- Beijing SLR station have been updated since 2022
- The update of SLR system have improved the productivity and observation precision of the SLR system



System performance comparison (2021 vs. 2025)

Updates of SLR system

- Telescope servo system and its control software
- Laser and emission path
- Receiving terminal box and receiving optical path
- Ranging control and data acquisition and processing software system

Telescope servo system and its control software

Develop new telescope control software

Replace Absolute encoder

Replace the servo controller

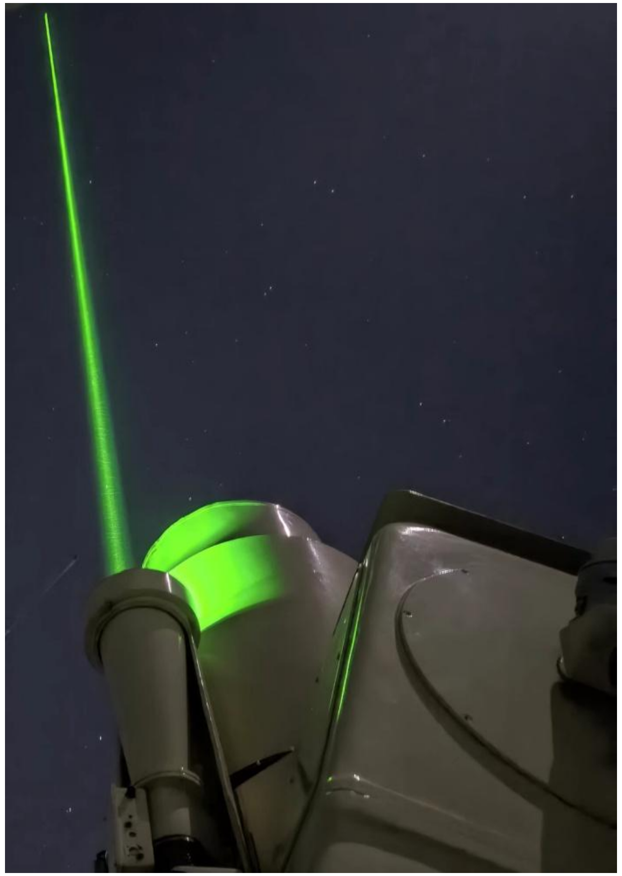
- **Laser and emission path**

Replace laser

2000Hz/2mj

Upgrade Kuder light path

Remodel transmitting mirror tube



- **Receiving terminal box and receiving optical path**

Redesign and develop the receiving terminal box

the devices in the terminal box include:

- 2 CMOS cameras
- 1 PCO camera
- 1 C-SPAD detector

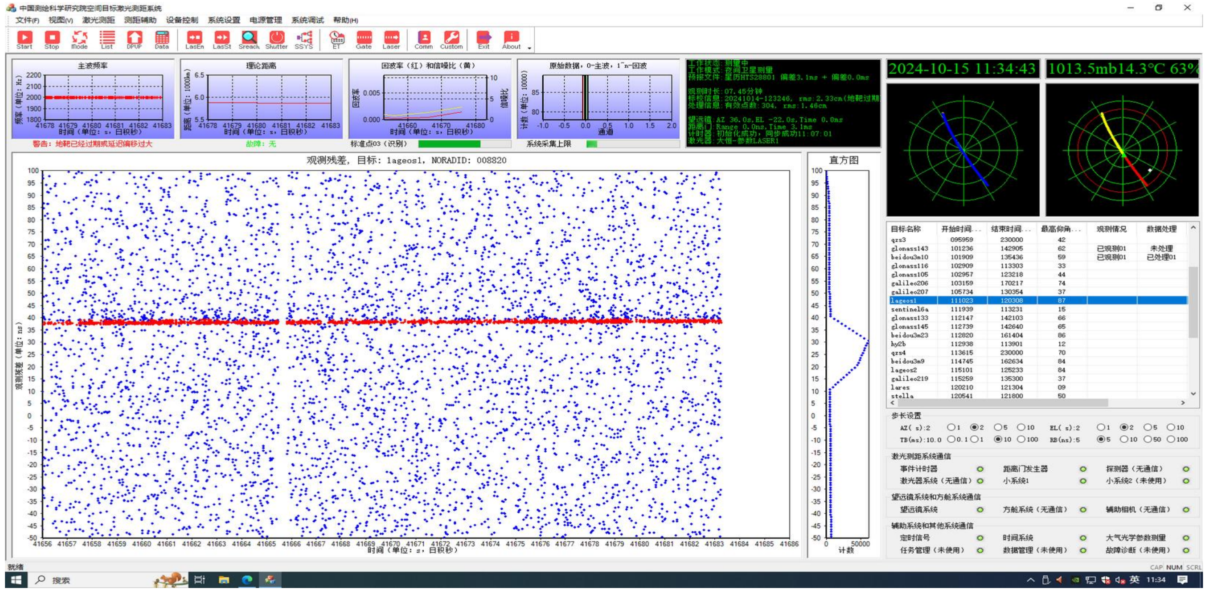
• Ranging control, data acquisition and processing software

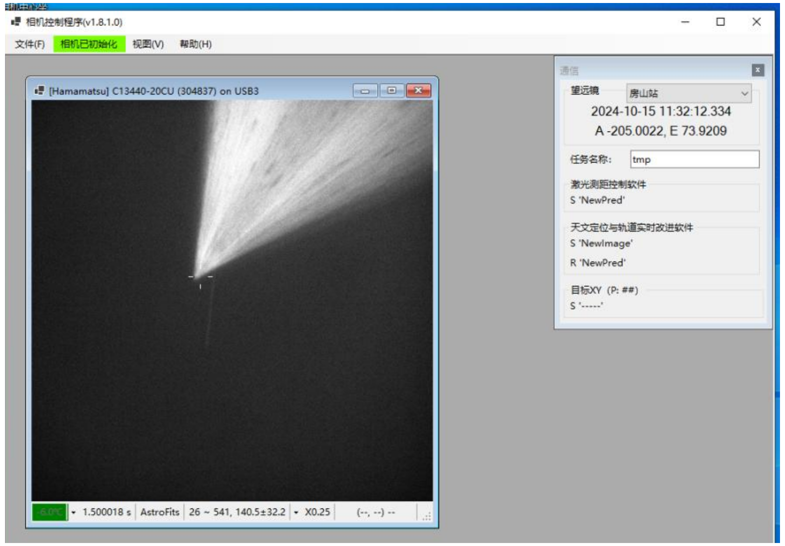
Replace the GPS Clock

Replace event timer

Replace the ranging control system

Update ranging control, data acquisition and real-time processing software





Update camera image capture and display software

System performance (after updated)

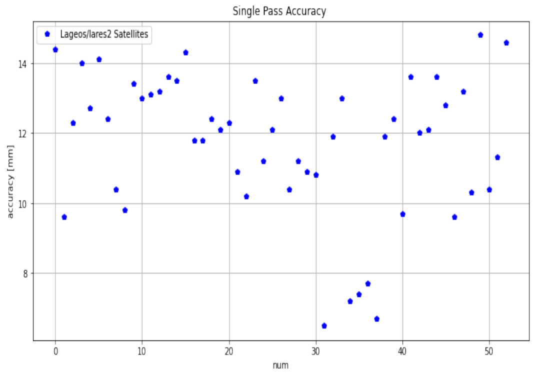
- Detection frequency : 2000Hz
- The longest detection distance: 36000km
- Daytime laser ranging
- Ground target ranging accuracy: <10mm
- Normal point accuracy and system stability

- Developing one mobile SLR system

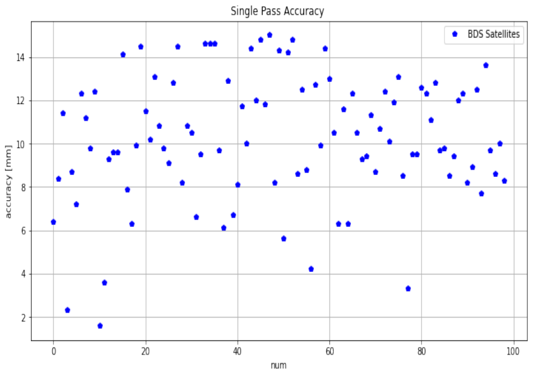
- Telescope (receiving) diameter: 1m
- Other technical index similar to the fixed system (7249)
- Laser ranging for satellite and space debris
- Size: 10.8*3*3m

The same ranging control software and hardware , laser, data acquisition software are used with the fixed station.

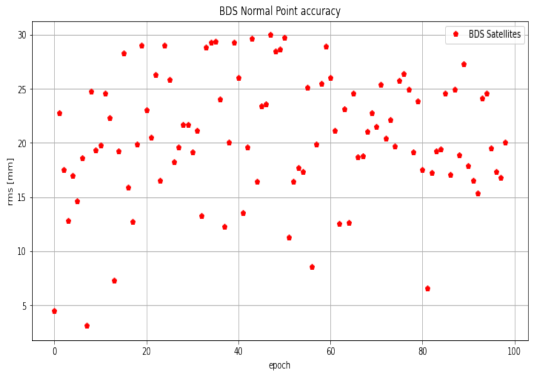
• Performance of mobile SLR system



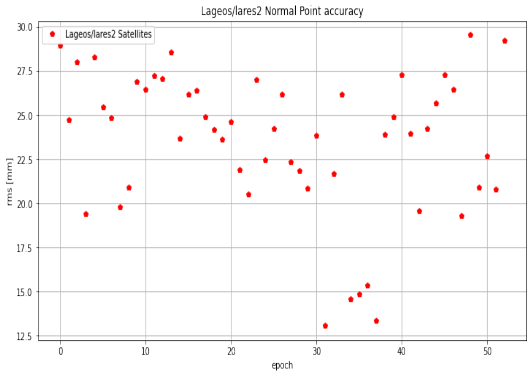
Single shot precision
of LAGEOS



Single shot precision
of BDS



Normal point precision
of BDS



Normal point precision
of LAGEOS

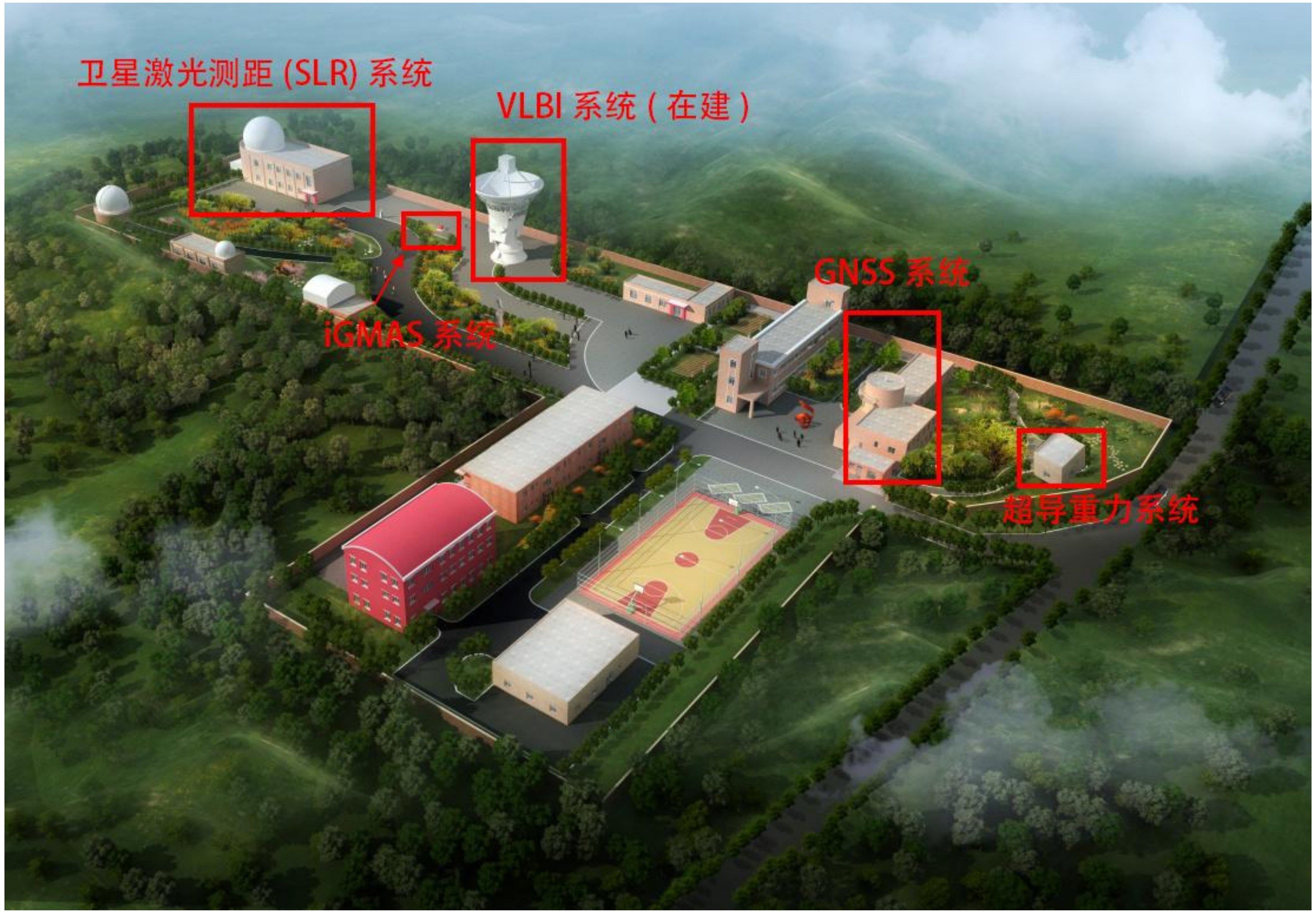
- ✓ The single-shot ranging precision reaches a maximum of 15.0 mm, a minimum of 1.6 mm, a mean of 10.3 mm, and a standard deviation of 2.6 mm.
- ✓ The normal point mean RMS from 18.7 to 23.5 mm, and the standard deviation ranges from 4.0 to 5.8 mm.

3

Local tie survey in Beijing station

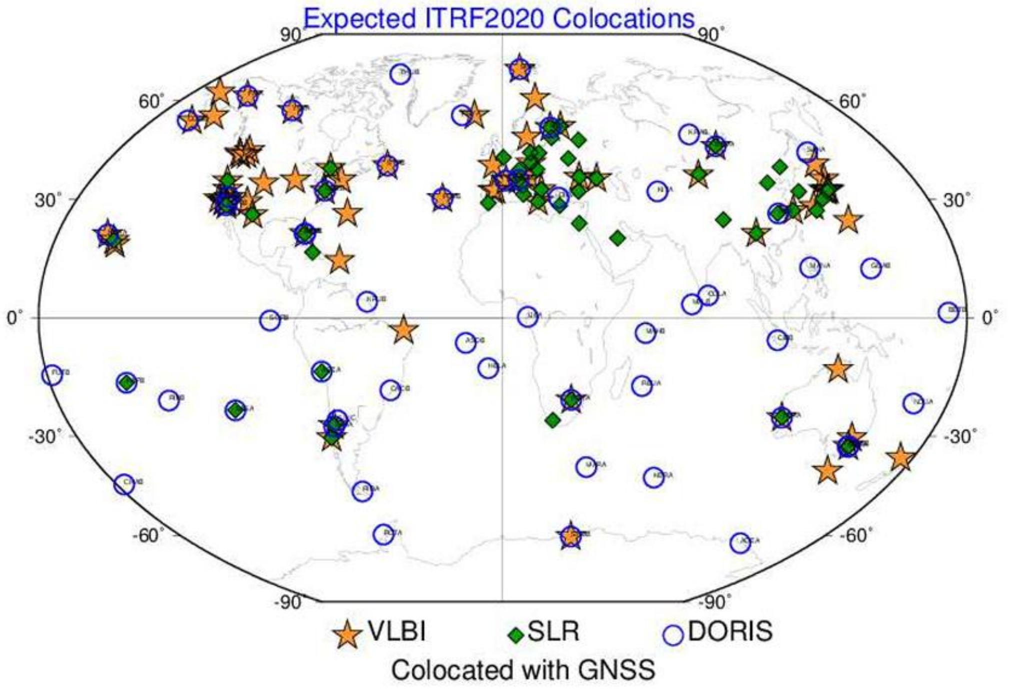
Local tie survey

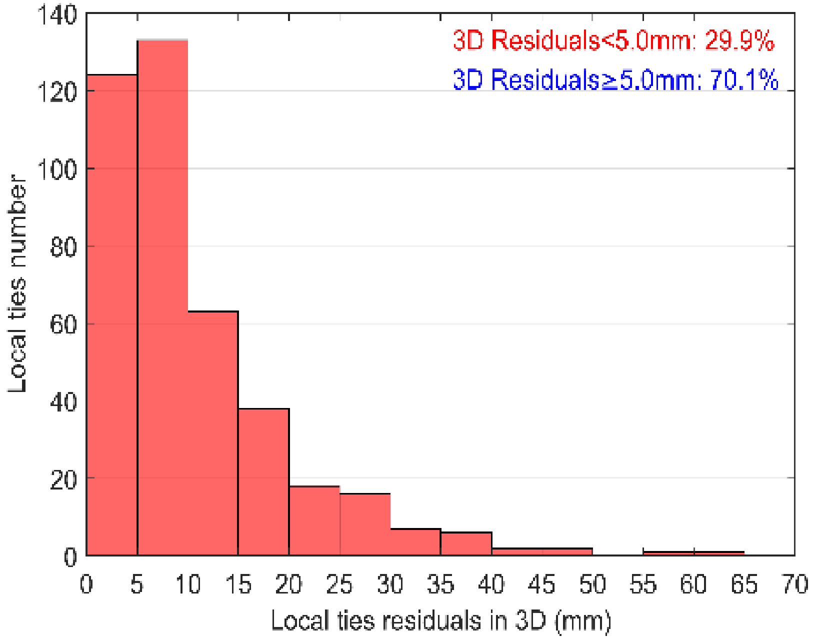
- Beijing station is a colocation site with an IGS station (BJFS), an ILRS station (7249), a newly built VGOS antenna, and a newly built Mobile SLR station.
- Local tie survey are made to ensure the combination of multiple geodetic technique.



Local tie survey

In ITRF2020, there are 101 co-location sites, most of which are distributed in the Northern Hemisphere. Local ties remain the primary means of ground-based co-location. However, fewer than 50% of the terrestrial tie measurements achieve an accuracy better than 5 mm.





Local tie survey

(1) Relative 3D coordinate error between local control network points ≤ 0.1 mm;

(2) 3D geocentric coordinate error of local control network points in ITRF ≤ 0.5 mm;

(3) Fitting residual of local-to-geocentric coordinate transformation ≤ 5 mm;

(4) 3D coordinate error of observation equipment reference point in local network ≤ 0.5 mm;

(5) 3D geocentric coordinate error of observation equipment reference point in ITRF ≤ 1.0 cm;

(6) Equipment axis offset measurement error ≤ 1.0 cm;

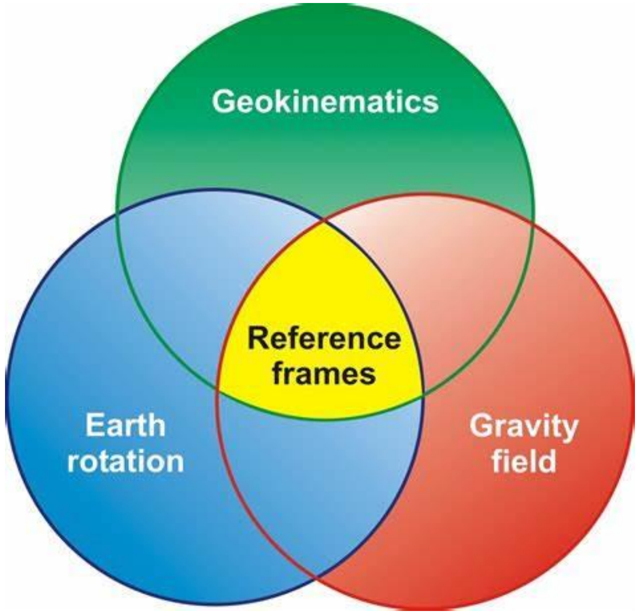
(7) Equipment axis tilt measurement error ≤ 100 as.

Local tie survey

The formal error of the local tie is 0.25 mm

Tropospheric error in SLR process

SLR can provide millimeter accuracy range measurement



SLR is an fundamental technique for reference frame

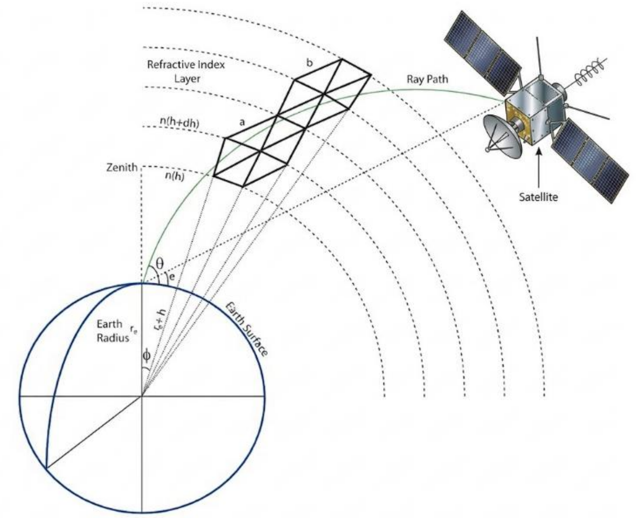
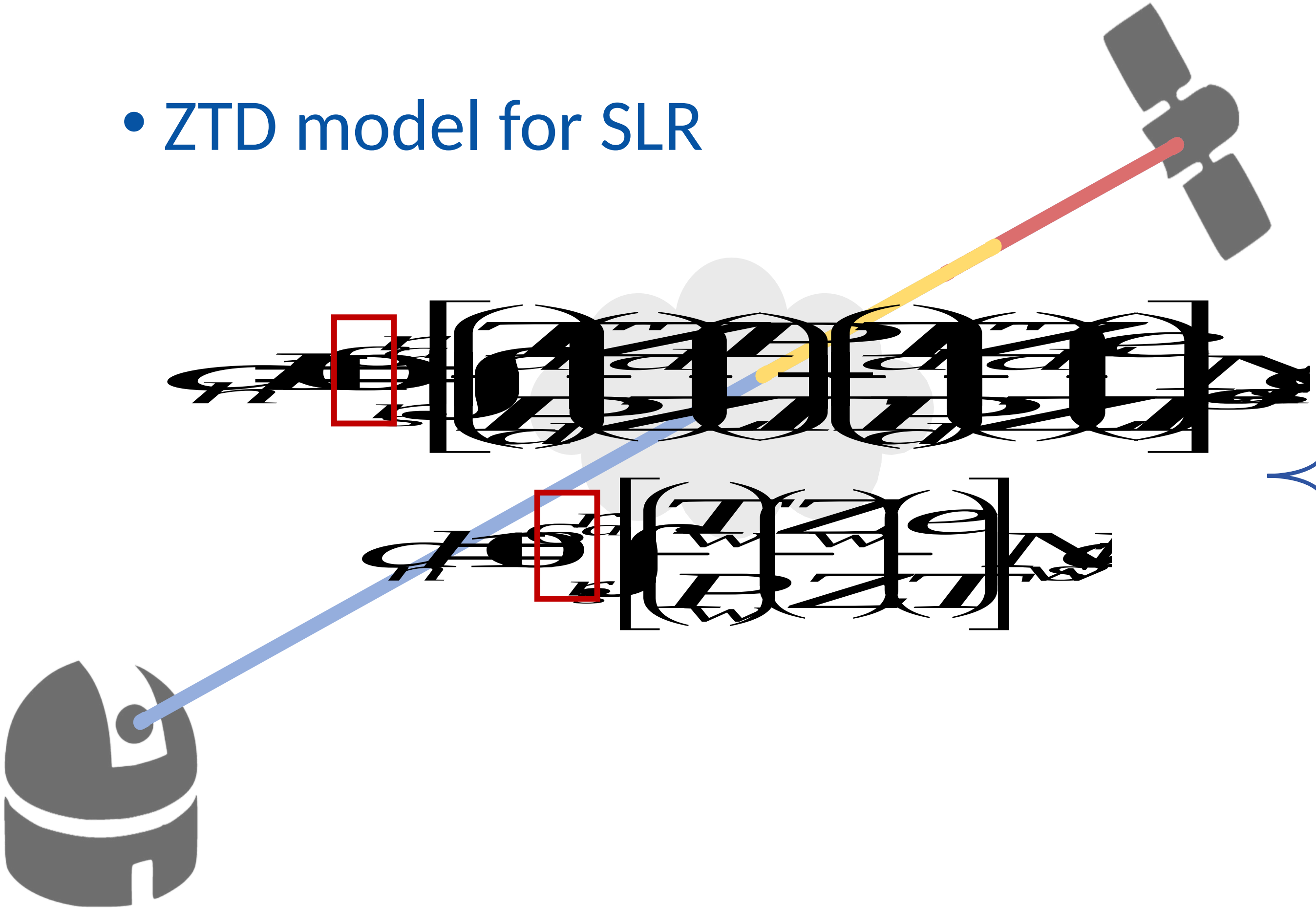


Figure 1. Schematic showing the geometry of the raypath between the tracking station and satellite. Where r_e is the radius of the Earth; $n(h)$ is the refractive index layer at height, h, and $n(h + dh)$ is the refractive index layer at height $h + dh$; θ is the elevation angle of the raypath; e is the elevation angle of the vacuum path; ϕ is the geocentric radius angle; a and b are examples of two data grid cells at height h and $h + dh$ that the ray passes through.

Tropospheric error is an important error source for SLR

- ZTD model for SLR



（1）Simplify the integration, using the meteorological data from the SLR station

$$d_h^z = 0.002416579 \frac{f_h(\lambda)}{f_s(\phi, H)} P_s$$

$$d_{nh}^z = 10^{-4}\left(5.316 f_{nh}(\lambda) - 3.759 f_h(\lambda)\right) \frac{e_s}{f_s(\phi, H)}$$

（2）Using the meteorological information in the integration path

Radiosonde

Numerical weather model (VMF3o)

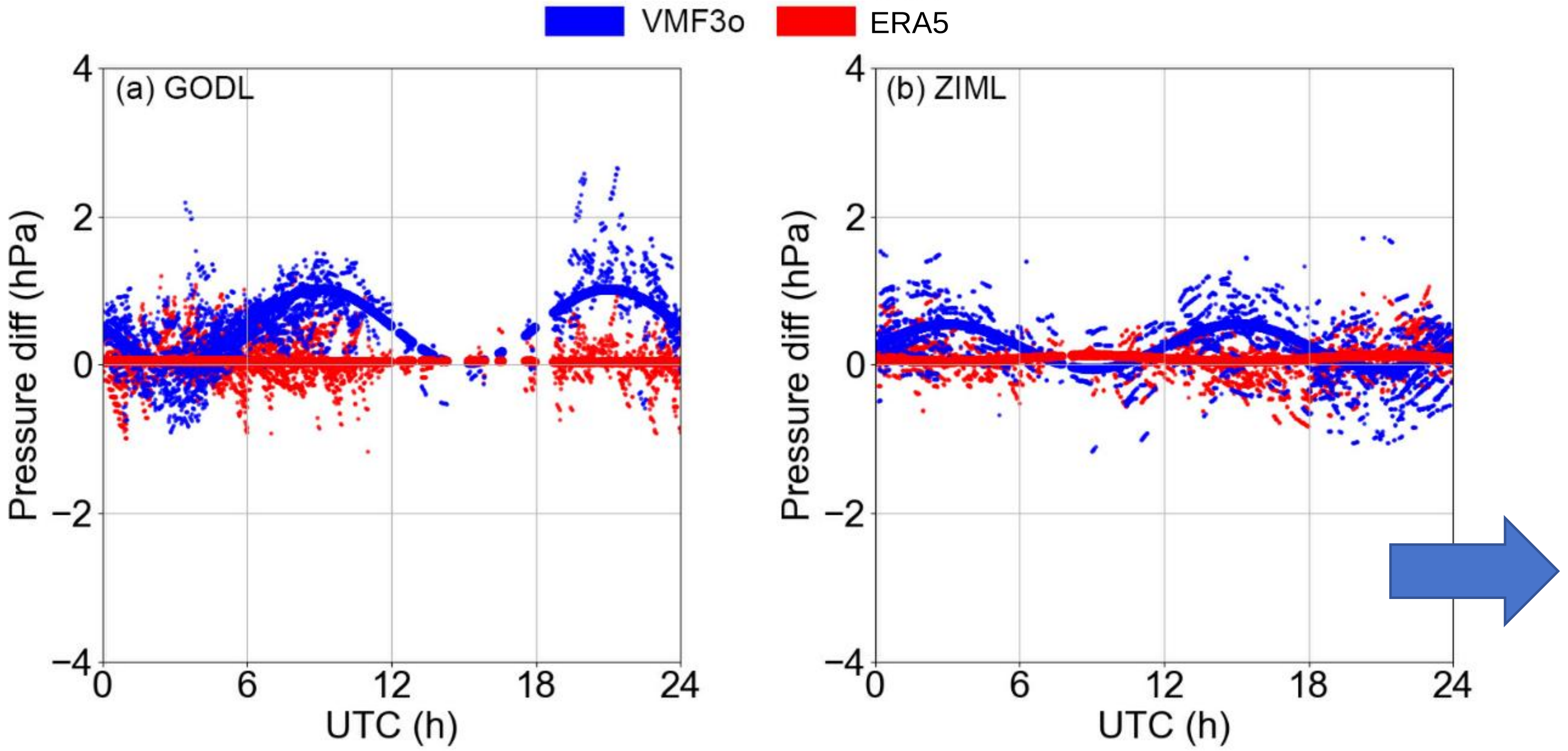
Simplification in the MP model:

- Hydrostatic approximation
- Average in the gravity
- Simplification in the numerical coefficient in non-hydrostatic delay calculation

ZTD error in SLR process ?

- Identify the ZTD error using ERA5

Using the vertical integration method through ERA5 reanalysis data to Identify the potential ZTD error in MP model



Semidiurnal ZTD error > 1mm

ERA5 is with higher temporal resolution of 1h, which can capture the semidiurnal variation of troposphere

• Strategy and data

To assess the tropospheric modeling error in the MP model and their impact on SLR-derived geodetic parameters, we perform a five-year validation (2019–2023) using SLR observations to the LAGEOS-1 and LAGEOS-2 satellites.

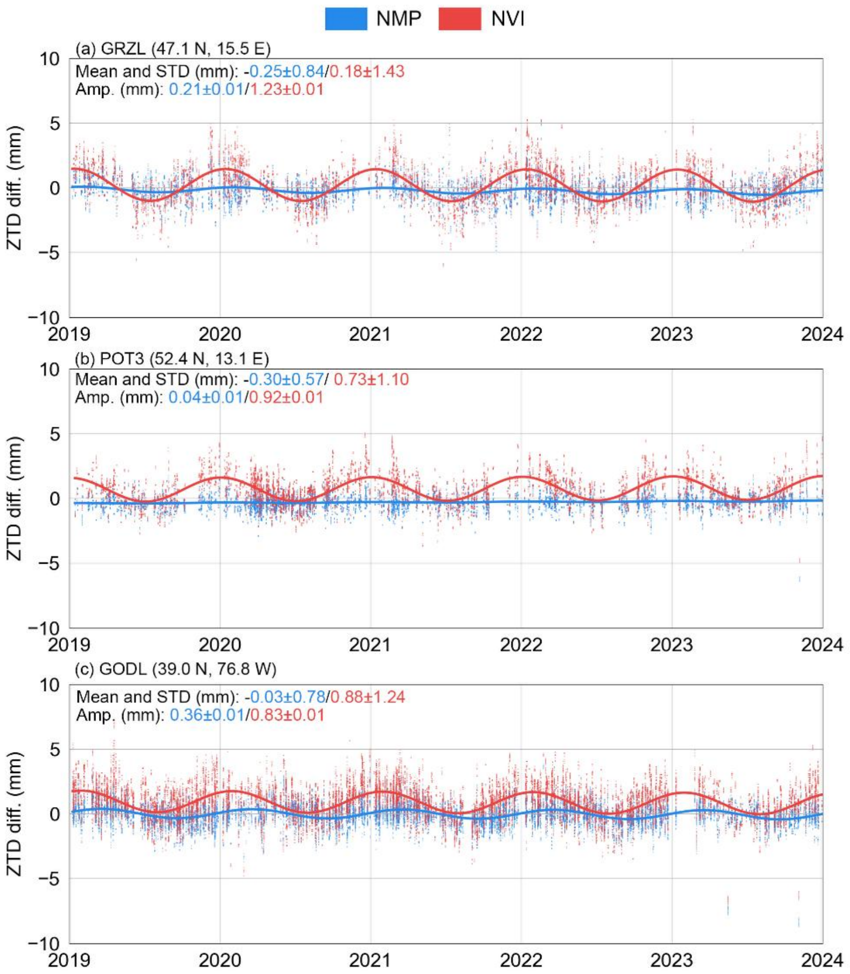
Solution	Data	ZTD model	Mapping function
IMP	In situ	MP	FCULa
NMP	NWM	MP	FCULa
NVI	NWM	Vertical Integration	FCULa

IMP-NMP: impact of NWM

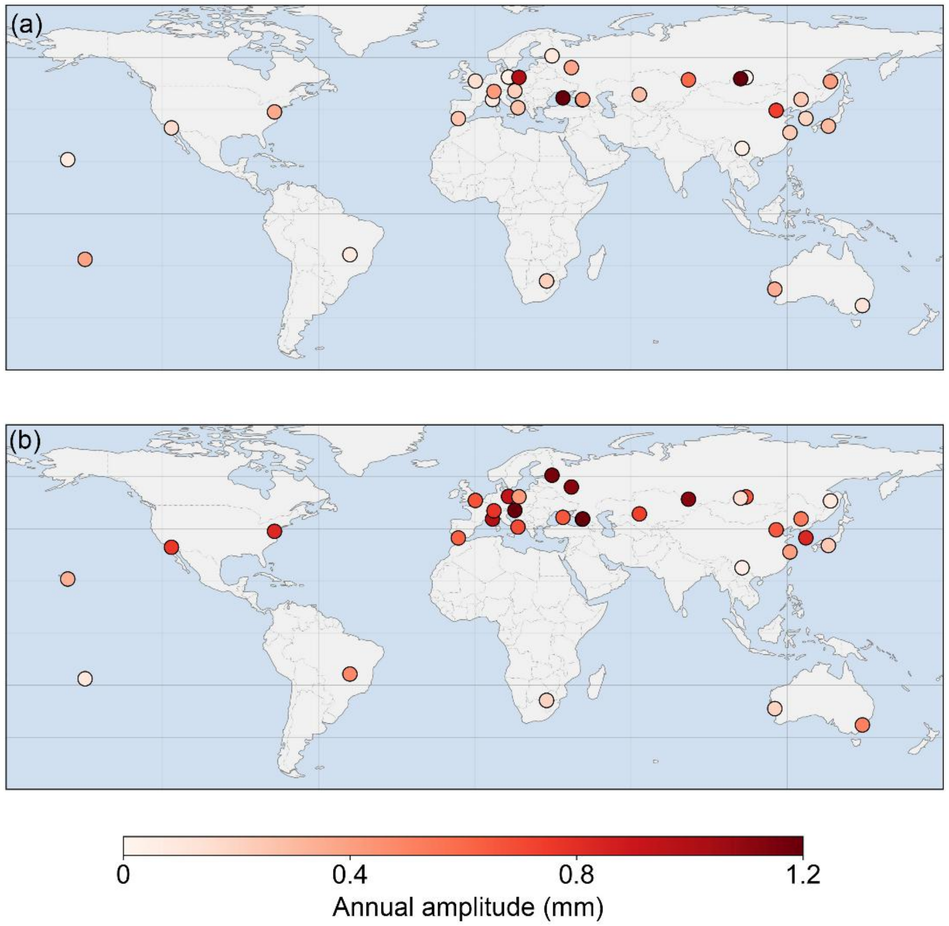
IMP-NVI: impact of ZTD error

• Characteristics of systematic error

- ZTD from vertical integration is systematic larger than those from MP model.
- Annual amplitude of ZTD difference exceeds 1 mm in some region.



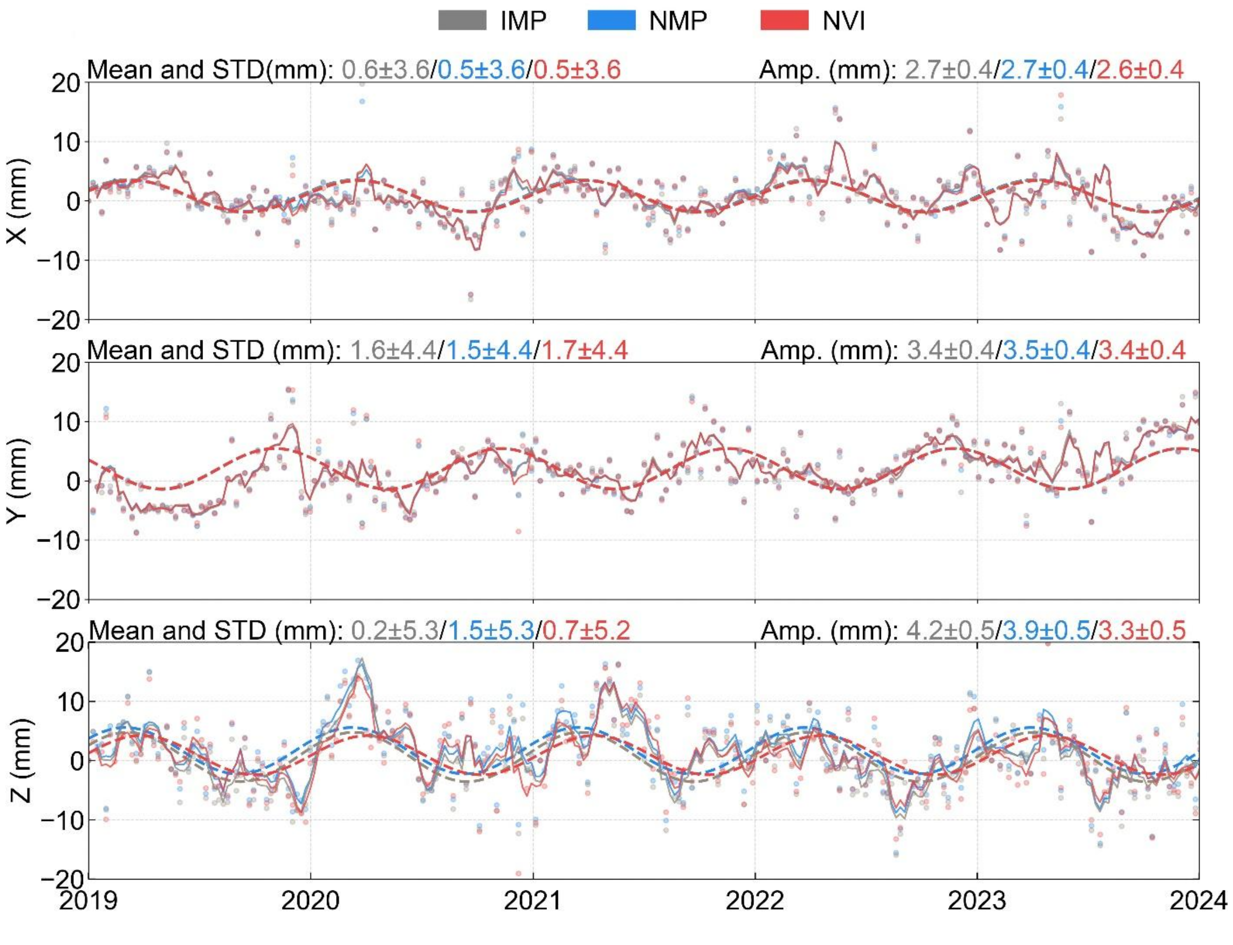
ZTD difference between IMP and NVI



Annual amplitude of ZTD difference

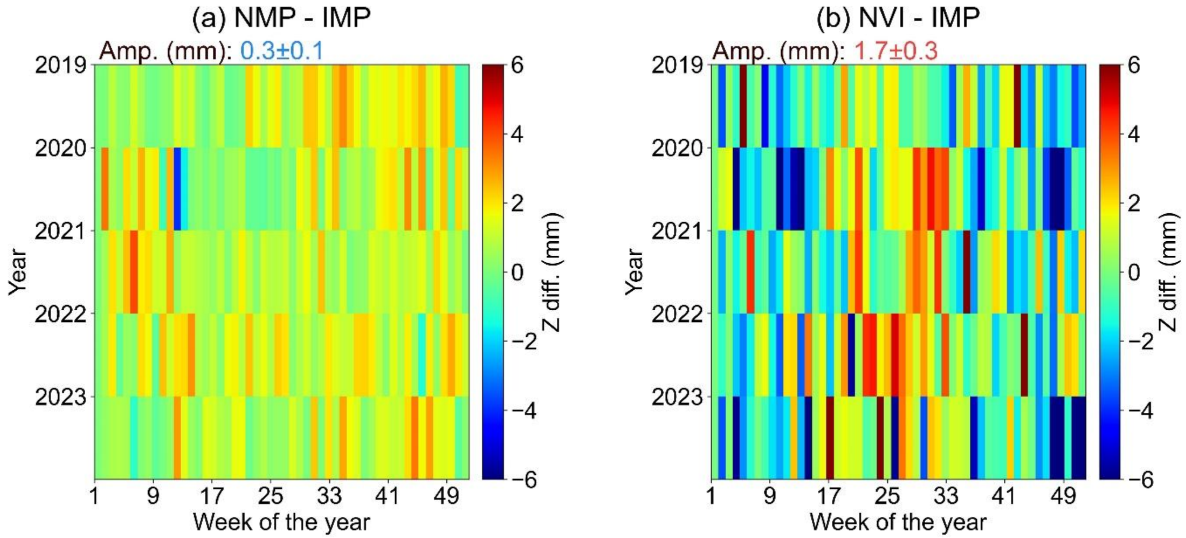
• Geocenter

Analysis the impact of ZTD model on the GCC determination.



GCC series with amplitude

- Highly consistent between IMP and NMP
- X and Y component of GCC is insensitive to the ZTD model
- The annual amplitude of GCC-Z decreased by 21.4% with the vertically integrated ZTD.

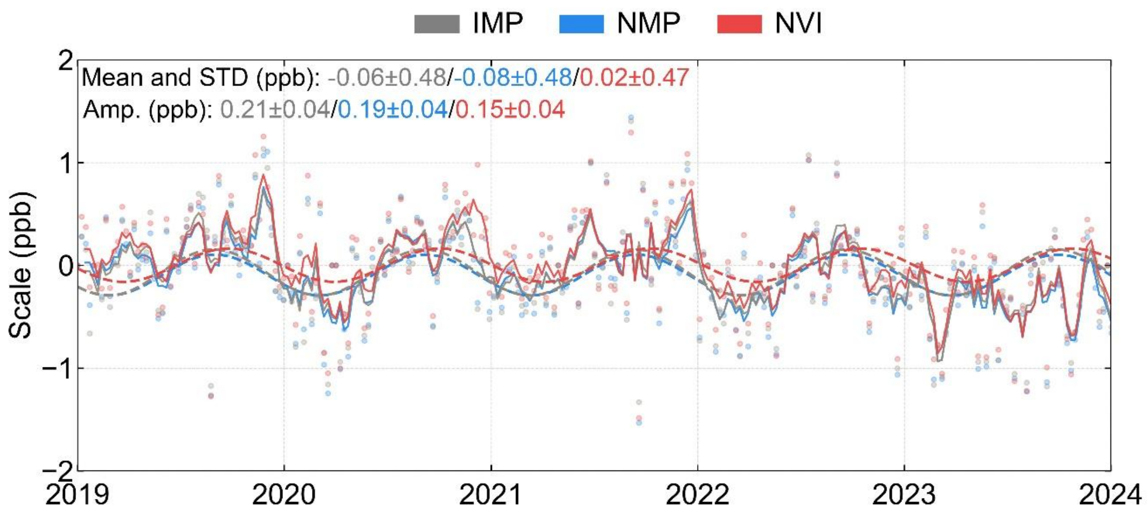


GCC difference

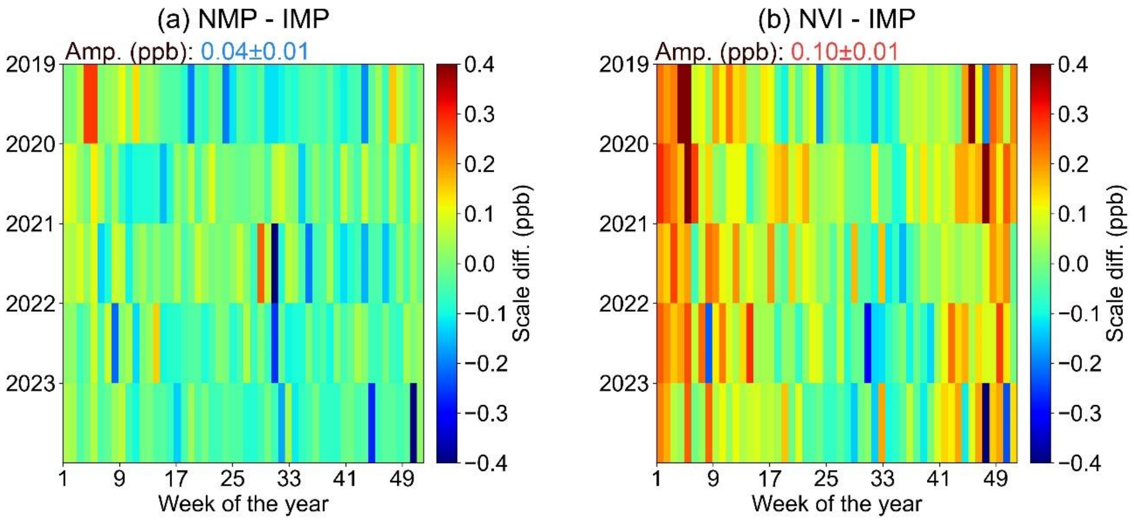
• Terrestrial scale

Analysis the impact of ZTD model on the scale determination.

- Highly consistent between IMP and NMP
- ZTD from vertical integration shift the scale by +0.08 ppb towards the VLBI scale.
- The annual amplitude of scale decreased by 28.5% with the vertically integrated ZTD.



Scale series with amplitude



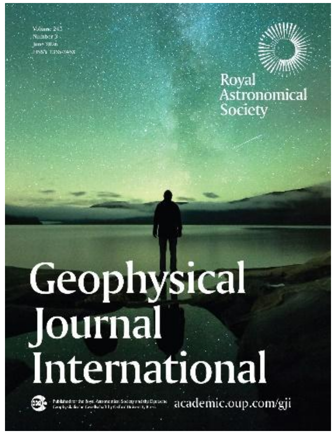
Scale difference

• Conclusion

Analysis the ZTD error in the MP model by the vertical integration method via ERA5.

- The ZTD difference between MP and vertical integration method has millimeter level of mean offset and annual amplitude.

- The Z component of GCC is sensitive to the ZTD model, and its annual amplitude decreased by 21.4% when using the vertically integrated ZTD.
- ZTD from vertical integration shifts the scale by +0.08 ppb towards the VLBI scale and decreases the annual amplitude of the scale by 28.5%.
- The ZTD error can be directly absorbed into the SLR-derived geodetic parameters.



For more information:

Yuanchen Fu, Keke Zhang, Xingxing Li, Chunmei Zhao, Yongqiang Yuan, Xuanzhen Zhang, Zenith Tropospheric Delay Modeling Errors in SLR-Derived Geodetic Parameters: Analysis Using ERA5 Hourly Data, *Geophysical Journal International*, 2026;, ggag218, https://doi.org/10.1093/gji/ggag218

Summary

- Updates of SLR instrument and improve the system performance
- Carry out Local tie survey of multiple geodetic techniques
- Strengthen SLR/GNSS/VLBI/gravity data application and related research

The New 1 kHz Laser System in Zimmerwald: Transmit and Receive in the Telescope Coudé

Pierre Lauber

Astronomical Institute, University of Bern, Switzerland

ILRS Networks & Engineering Standing Committee (NESC)

Virtual meeting

25th June 2026, Online

Outline

Introduction / History

1. Simple principles / Recap
2. The innovation: Transmit and Receive in Coudé
3. Some first results

Conclusion/Outlook/Acknowledgements

SLR History of the last 12 month

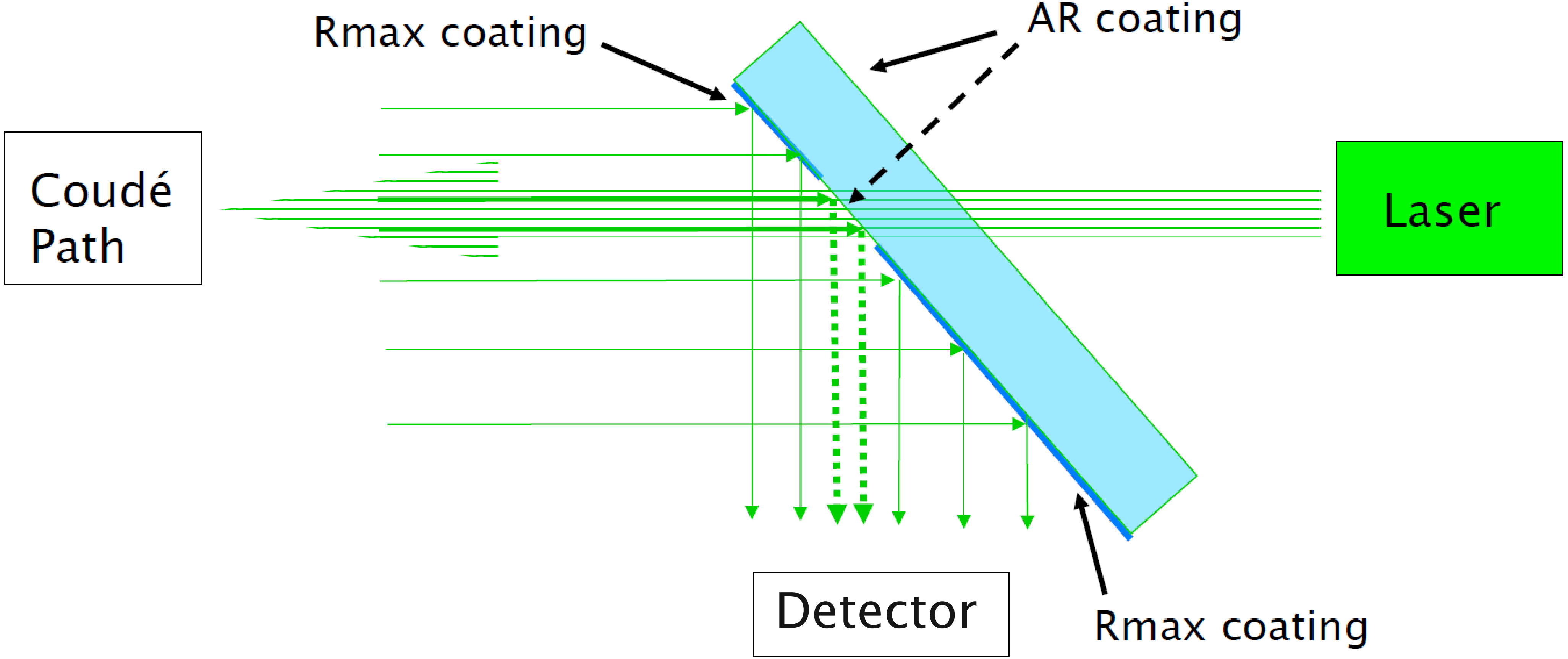
- **What happened to us?**
  - Beginning of January 2024, we still had less pulse energy due to less efficiency at the IR-green light conversion crystal; the laser manufacturer did and does still not understand why.
  - End of January, we got again a water leakage a laser head; a re-newal is ~100 kEuro, and they will reproduce just one piece because production is discontinued. The laser consists of two laser heads. From experience after some years, each laser head will fail again.
  - Thales laser has too many problems and new geodetic laser is not yet setup.
- **Necessity is the mother of invention**
  - Moved new geodetic Passat laser to Zimmerwald and installed it close to the Thales laser. Because this 1 kHz laser has a pulse energy of 10% of the Thales laser, and we have to operate it at 100 Hz (due to the rotating shutter), we did not expect too much.
- **First passages**
  - End of October: Got first LEO passage @100 Hz.
  - 5. February 2025: Got first LEO and Lageos passage @ 1 kHz.

1. Simple principles / Recap

Transmit/Receive Switch Mirror

Adapted from:
Werner Gurtner, Eugen Pop, Johannes Utzinger, The New 100-Hz Laser System in Zimmerwald: Concept, Installation, and First Experiences, 16th International Workshop on Laser Ranging,13-17 October 2008, Poznan

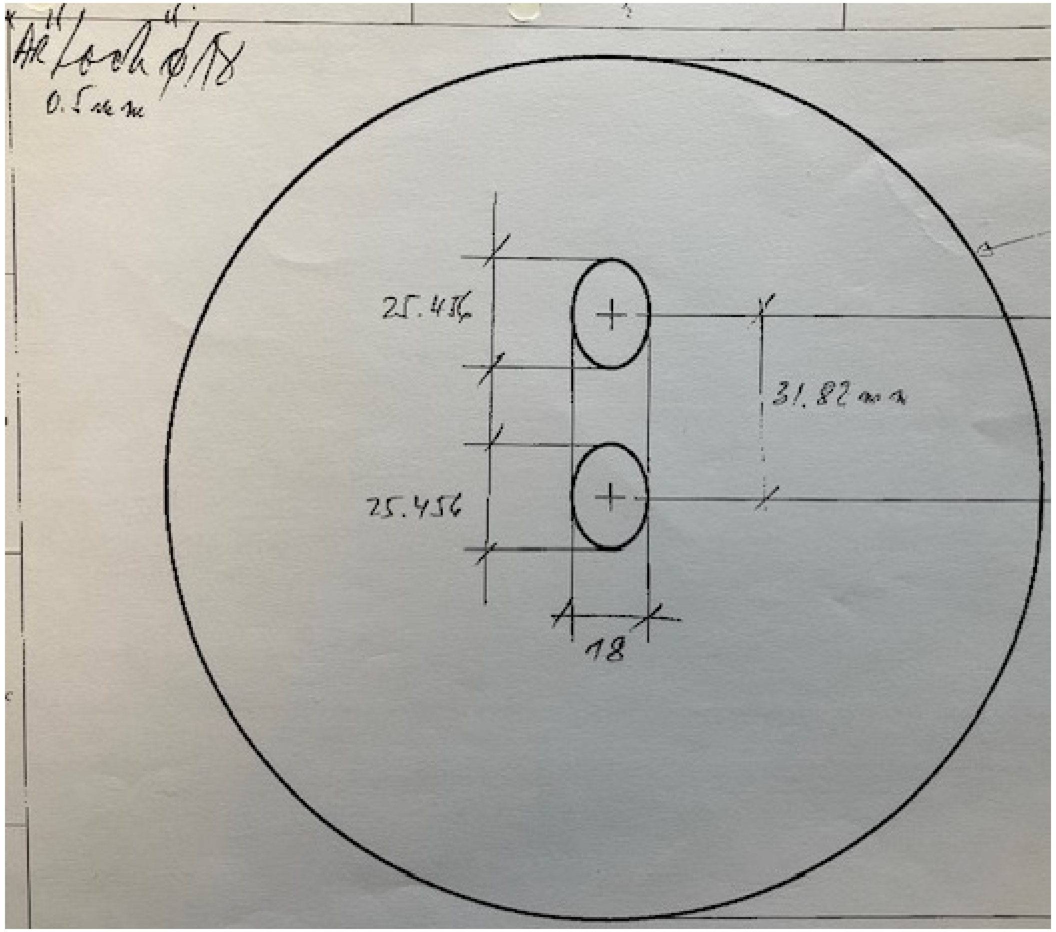
- Laser side: AR coating
- Telescope side: Rmax coating plus elliptic AR coating



Eugen Pop Transmit/Receive Switch Mirror - Explanations (1/2)

- **How it works on the satellite**
  - Laser beam goes through the hole at the backside of the mirror.
  - Laser beam travels to the target. **Due to divergence, the beam size is increasing.**
  - Reflection at the satellite. The divergence remains.
  - The reflected beam travels back again to the station. Due to divergence, the beam size is increasing again
  - Telescope takes from the downcoming beam a part and reflects it onto the entire mirror area, where it is reflected towards the detector. At the hole, most photons are lost.
- **For calibration, minor is different**
  - Because the reflexion target is not far away, the beam did not yet increase remarkably
  - (In case of a glass hole, the photons travel back to the laser and cannot be detected.)
  - In case of a coating hole, **some photons will reflect at the glass surface** towards the detector (dotted lines).

Eugen Pop Transmit/Receive Switch Mirror - Explanations (2/2)



From a facsimile of Eugen Pop to the manufacturer

- **Telescope adjustment**
  - Needed to be co-axial, for firing out of the tube offset to M2 needed, so, one excentric
  - In reality, finally **two coating holes** are needed. The co-axial can be used for internal cal.
  - A **stray light shield** at detector side is required to reduce backscatter.
- **Characteristics**
  - Passive component
  - Two 18 mm «holes» under 45 degree view
    - Mirror diameter 150 mm
    - Reflection loss for 2 holes ~4%
  - Arbitrary photon flow, e.g. repetition rate, entanglement, etc.
  - Wavelength depending on coating and glass

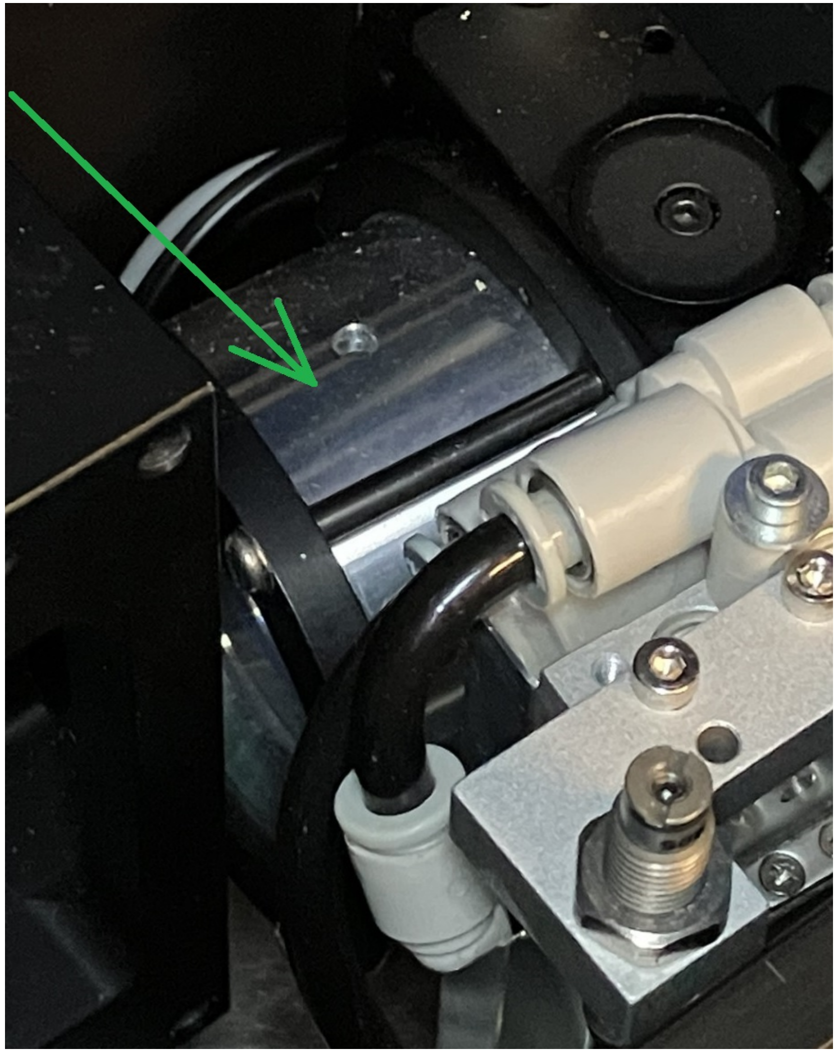
Eugen Pop Transmit/Receive Switch Mirror - Products

Version with glass holes, not working

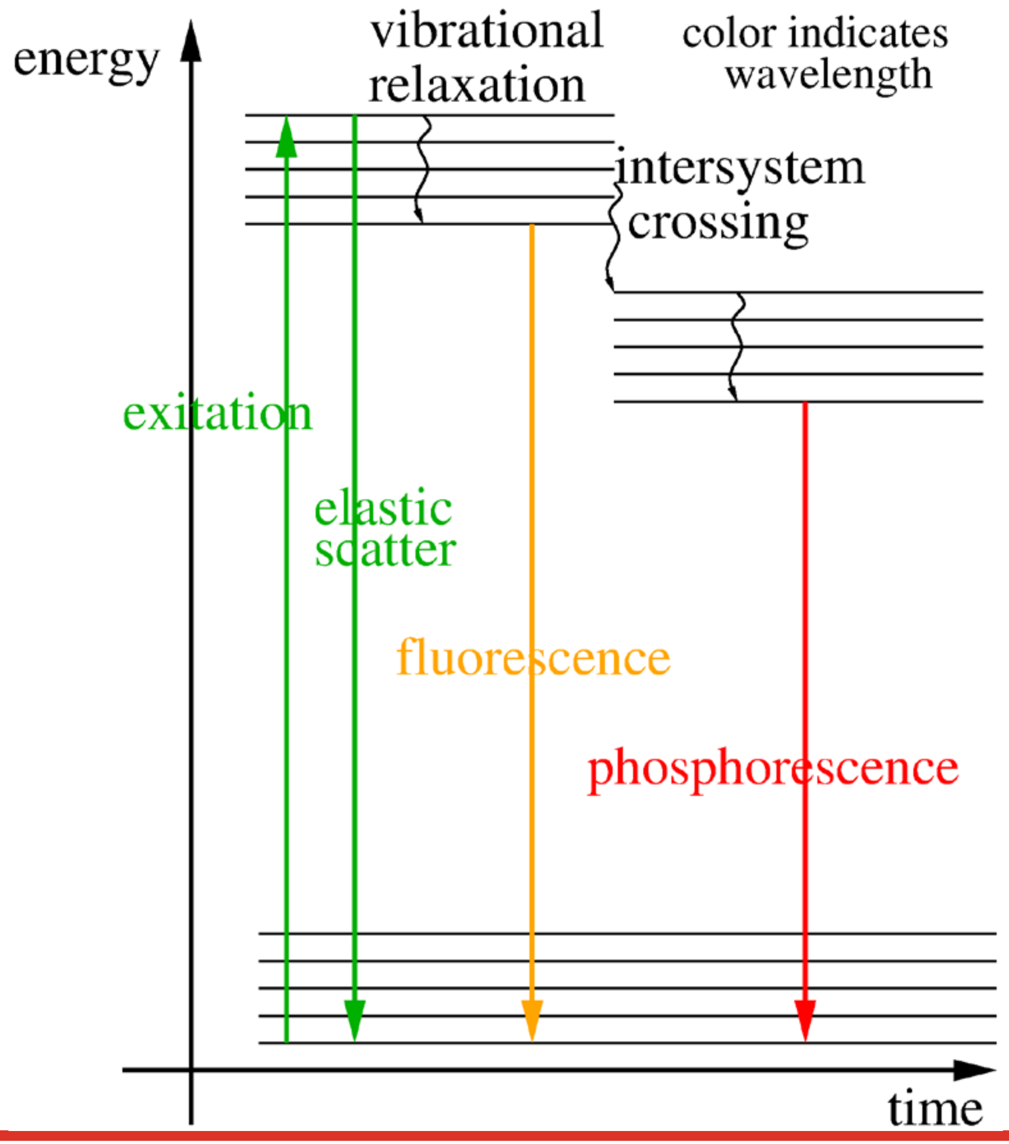
Version with coating «holes», used in system

Reception Filters

- **Interference filter / Fabry–Pérot**
  - Well adjusted to the laser emission wavelength
  - **Air-spaced etalon,** 0.1nm spectral width, >3nm FSR, finesse>=20
  - Parasitic period comb
- **Band pass filter**
  - In series to remove the periodic
  - Blocking about centre wavelength: ±50 nm better than OD5
- **Both filters suppress especially during daytime a lot of parasitic sun photons**



Energy states vs. Time (Standard Physics)



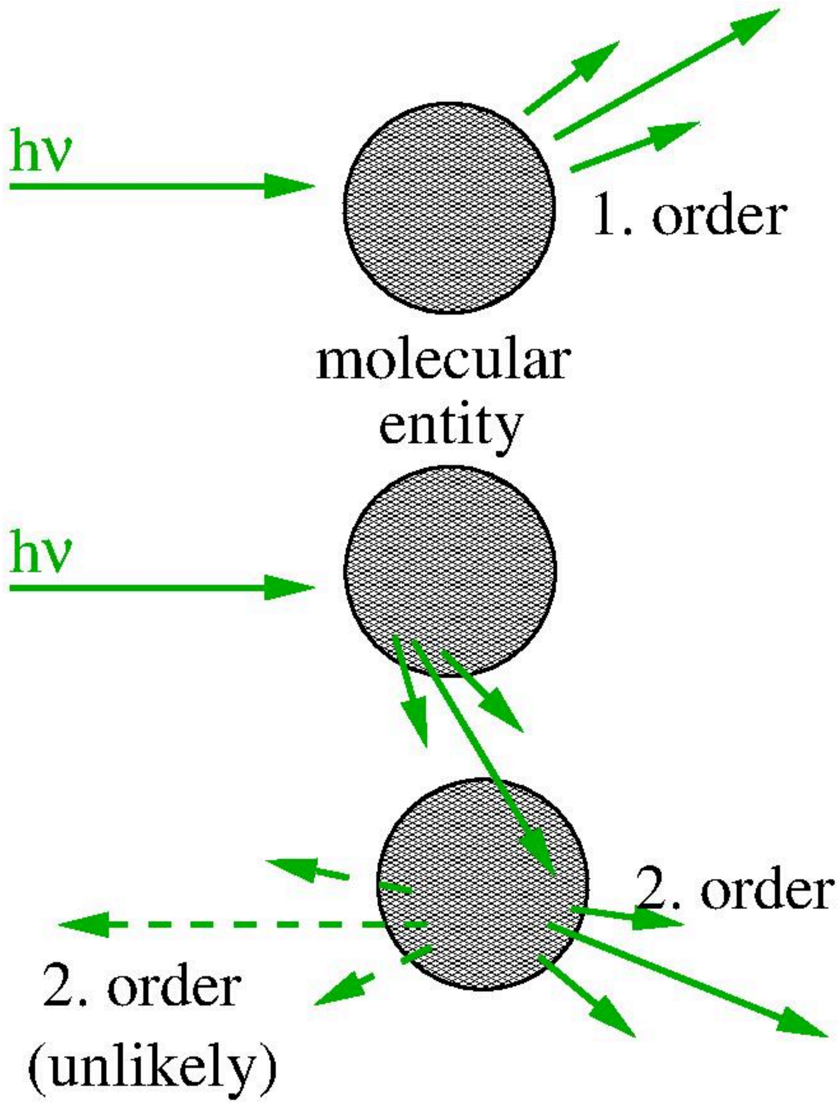
- **Standard Jablonski diagram**
- **Exitation (Absorption), Elastic scatter (Emission)**
  - vibrational relaxation
- **Fluorescence (Emission)**
  - Intersystem crossing + vibrational relaxation
- **Phosphorescence (Emission)**
- **Lessons learned**
  - **The later the emission the less the energy the higher the wavelength (Stokes shift etc.)**
  - **The «response» time depends highly on the matter**

What's Afterglow in this Context

- **Prerequisite here**
  - **Light changes wavelength**
  - Quantum mechanics interaction
    - **Inelastic scatter, so,**
      - Luminescence (without band change), phosphorescence (with intersystem crossing)
      - Raman scattering, Compton effect

- **Afterglow (Definition)**
  - **If a short pulse and local high intensity beam like a picosecond laser hits a surface, e.g. glass or coating of a mirror, the material might glow for some time after.**
  - Due to the latter, it is considered to be the problem when working with Transmit and Receive in the telescope Coudé.
  - Something in me refuses to write time numbers here. (Too much different things)

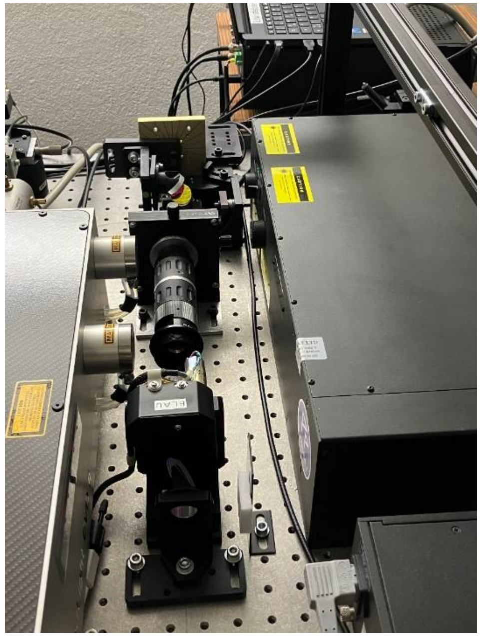
Light Scatter / Stray Light

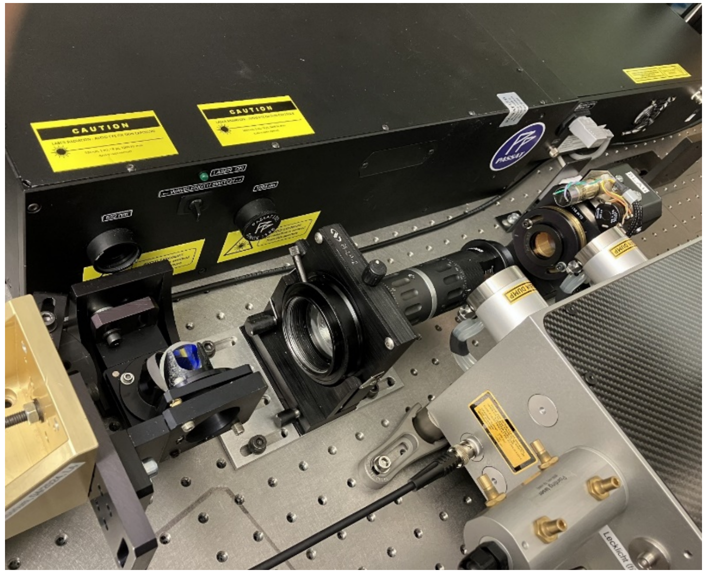


- **Prerequisite here**
  - Light keeps wavelength
  - Quantum mechanics interaction
    - **Just elastic scatter, so**
      Thomson or Rayleigh scattering
    - No diffraction
    - In this frame especially "**No afterglow**":
- **Cascading (Definition here)**
  - 1. order: one interaction
  - 2. order: two interactions
- **Backscatter = unintended reflexions**
  - at coating, glass, metal etc.
  - exact opposite direction is unlikely (solid angle)
    - Calculus depends highly on matter/molecular entity
    - Probabilities might decrease by powers of ten (IMHO)
    - E.g. reflections: lens distance 10 m, 1% glass reflectivity, from 1e15 photons down to <1 photon → <0.3 us.

2. The innovation: Transmit and Receive in Coudé at 1 kHz

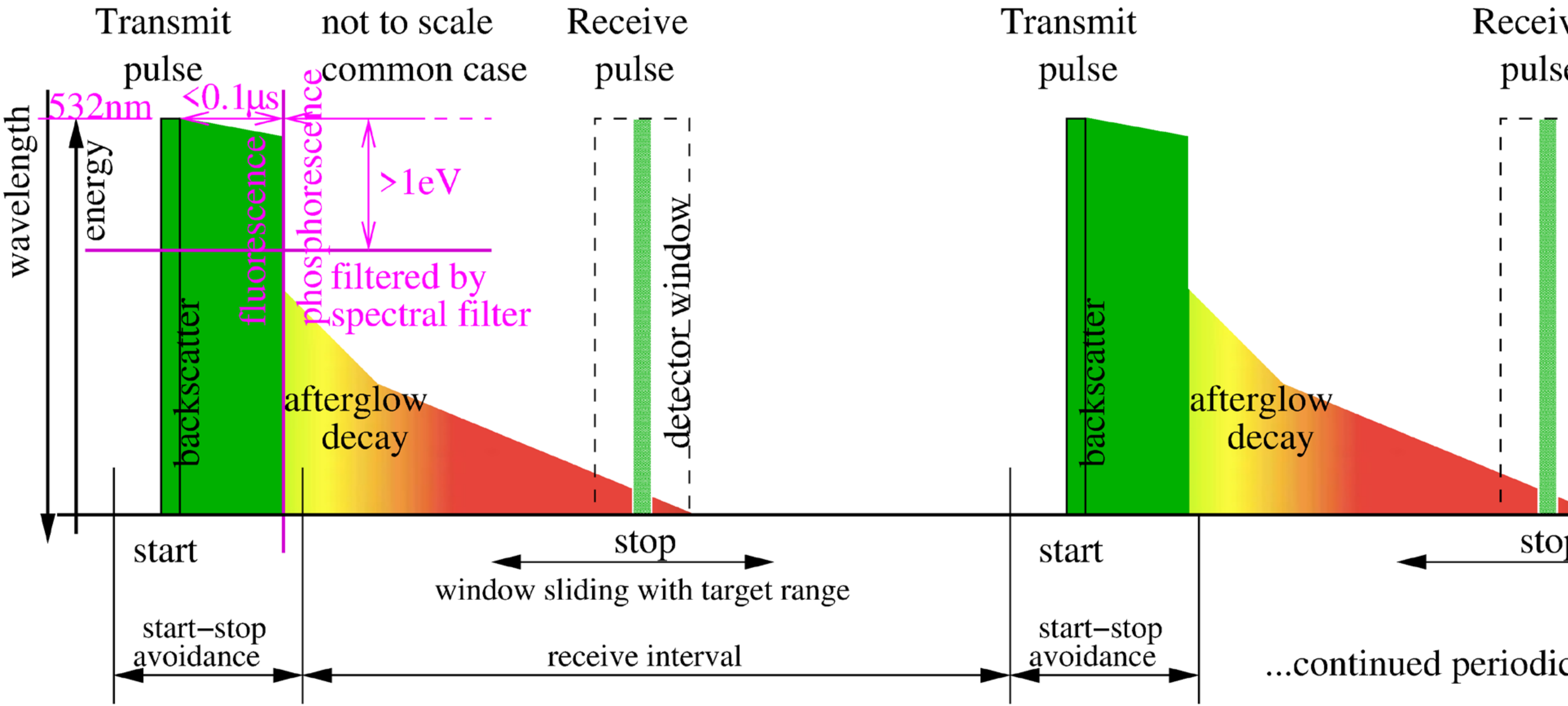
New Nd:YAG laser





- Attached complete new laser due to multiple failures of the old
- Passat laser stock version
  - Has different specifications than the previous Thales laser
  - **only slightly modified:** access to a reflex of the internal beam for start
  - Diode pumped solid state laser as well but **without water cooling**
  - Model "Compiler Upgrade 1000", **1 kHz repetition rate,** 532/1064 nm
  - Pulse energy/width: **0.9mJ@532nm**, 1.8 mJ@1064 nm, **8 ps**
  - About same power than Thales laser but
    - More measurement samples AND
    - Less signal-to-noise ratio !
- Mounting
  - Original idea was: On top of the telescope tube within a thermal isolation box
  - Changed due to several things: try it in the telescope Coudé

Transmit-Receive Timing



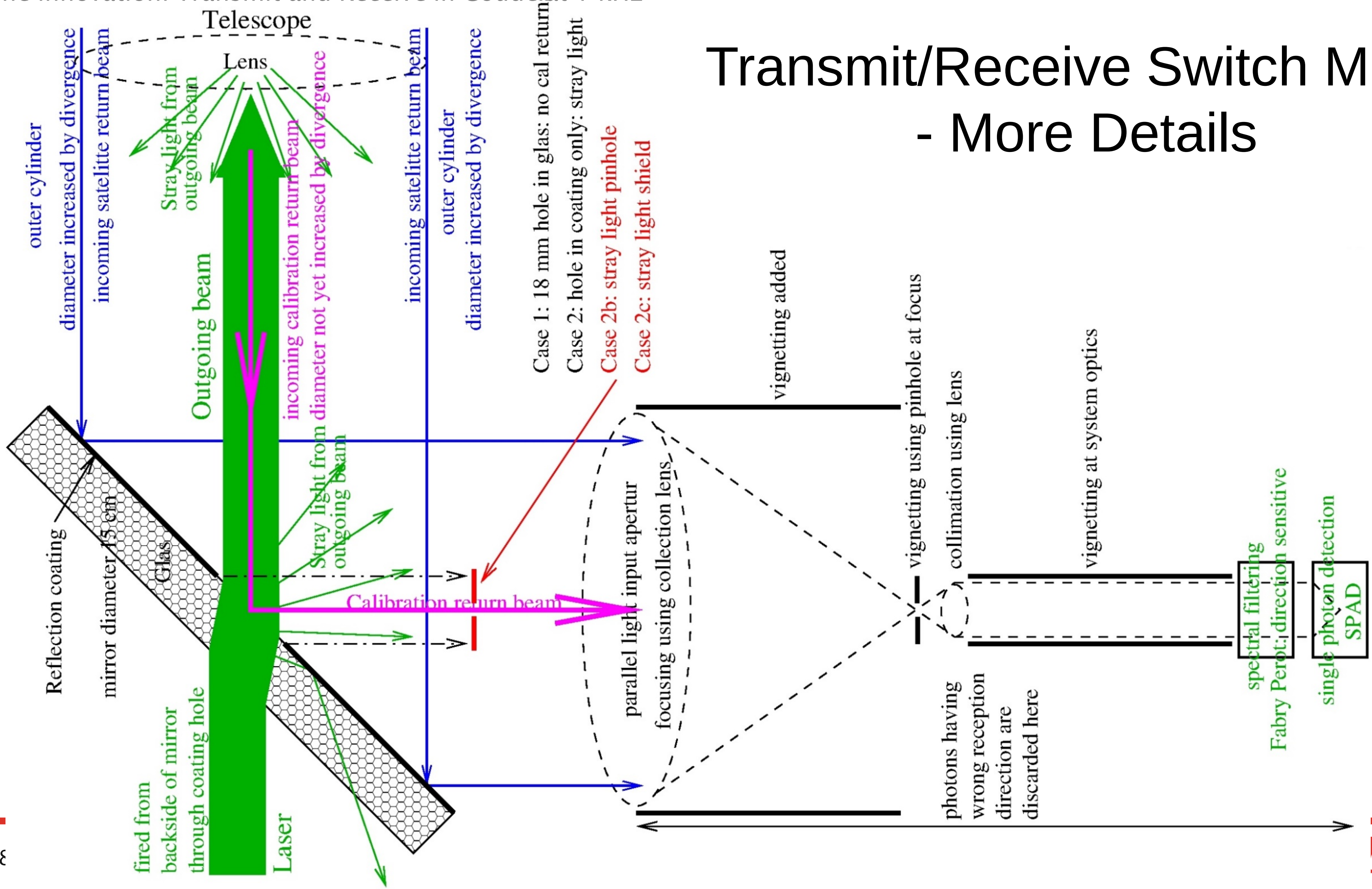
New 1kHz Laser System

- **The opinion of the last years**
  - The rotating shutter limits the laser rep.-rate to 100 Hz and an increase for the mechanical devices seems to be not realistic. It is needed for suppression of parasitic light (afterglow) generated during transmitting the outgoing laser pulse.
  - Due to the latter, a 1 kHz laser cannot be operated in the Coudé path and, therefore, if operated must be mounted on top of the telescope tube.
- **The opinion is changing**
  - For ZIMLAT, we are using the Eugen Pop Transmit-Receive-Switch-Mirror design. It separates geometrically the transmit and receive photons and prevents photons to travel directly from the laser to the detector.
  - **Afterglow effects are very close in time to the outgoing pulse and change their wavelength. Light with other wavelengths are suppressed by our interference filter.** The detector time gate is setup anyway to avoid start-stop conflicts.
  - **Why not removing the rotating shutter at all?, and increasing the rep.-rate.?**

Photon Conditions

- **For Detection**
  1. +On time
  2. +At wavelength
  3. +In direction
  4. +Within reception path
- **Else no detection**
  - Vignetted
  - Reflected
  - Finally all absorbed

Transmit/Receive Switch Mirror - More Details



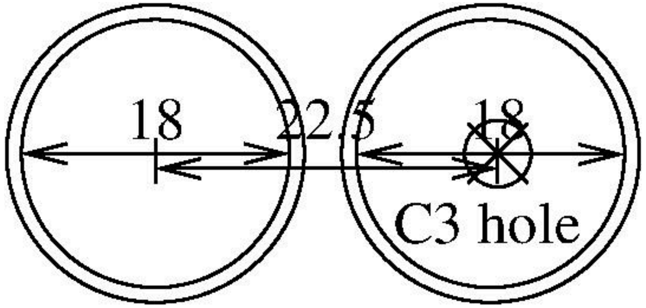
Analysis

- Analysis of the matter (Passive and Active Components)
  - **Lenses**: high quality glass, parasitic reflectivity ~1-2%
  - **Mirrors**: Coatings Rmax, AR, parasitic transmittivity ~1-2%
  - Manufacturers try to use matter without parasitic atoms
    There should be less backscatter due to these matter
  - **Laser**: Parasitic light from the light source/the laser itself: There should not be anything.
- Analysis of the environment (Do not trust anything)
  - **Parasitic light:** of sensor LEDs and glow lamps (CW operation and spectrum non-discrete) of pneumatic relays: put a thick tape on it
  - **Reflexes, Stray light/Direct Backscatter**: of Coudé glass window (not totally clear yet): removed it
  - **Shielding/Absorber**: Inserted several card boards to ensure optical path separation
- Analysis of the beam path
  - At and around the **Eugen Pop Transmit-Receive Switch Mirror**
  - Ensure that no direct outgoing laser beam can pass directly to the detector starting at low laser energy and finally increasing it

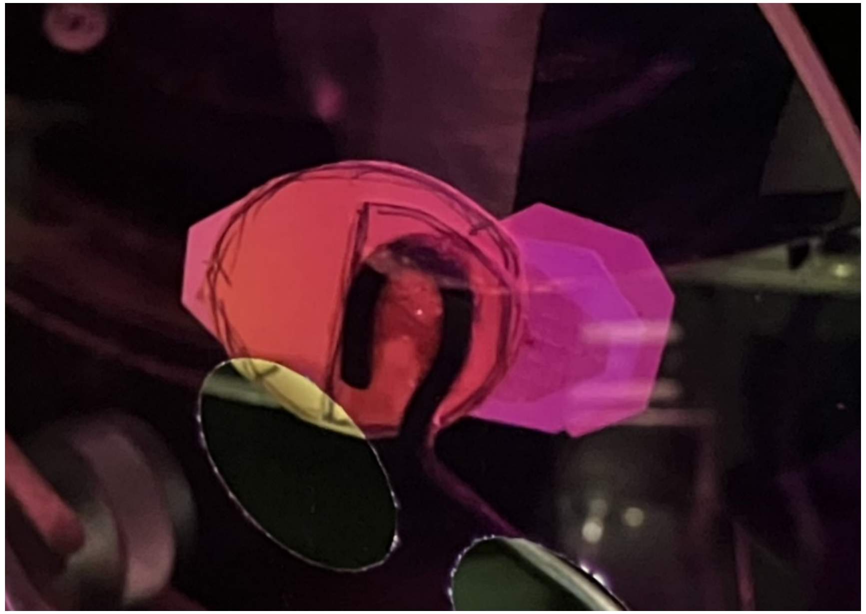
Rotating Shutter – Totally Removed

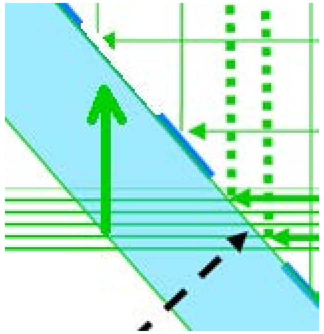
1. **Mechanically: Moved it out of the optical path**
   - **Start-Stop-Conflict Avoidance**: still active
   - Testing
2. **Software**
   - Removed controlling: Disabled functions calls to the FPGA driving the shutter
   - **Laser Trigger**: Re-added adjustment software to still avoid Start-Stop-Conflict
     - Transmit pulse: there are **e.g. 1E15 photons** under way
     - Always place the receive window in between the starts with some safety distance
     - Currently using three working points: 1 kHz -0%, -2.5%, -5% (might even be smaller)
3. **Tests**
   - Because during day time of course a lot of noise (sun), use
   - Best case during night time: If system intrinsic parasitic noise would exist one must see it, but **there is nothing**
4. **Why was this part required at all?**
   - From where derived the parasitic light? (at Graz, at Zimmerwald)
   - Graz: From site log, uses a "Spectral filter". Comparable TR-switch mirror?

Stray Light Shield



- **Adjustment conditions: At detector port, no light should be seen using a camera during laser transmission.**
- **2 shields**: For co-axial and for excentric coating hole
  - **TRS excentric hole** is used for main calibration (C3): Made by using the tip of a compass. Also good to prevent multipath and decrease flux. Reset C3 hole in case condition above cannot be hold due to parasitic atoms in the glass.
  - **TRS co-axial hole** is also used for internal calibration (C1) (injection of the attenuated transmit beam, in the figure at the left side); currently not used. When the laser beam enters the glass at the TRS mirror backside for transmission through the TRS excentric hole (in the figures on the right side), it generates stray light directed through the co-axial (left) hole.
- **At the margin of the coating holes** (due to manufacturing), there can be some special stray light. Extended the shield accordingly.





Other Intermediate Milestones

- **Attached the Laser**
  - For software remote control
  - Optically into the system: needed beam steering and beam expander (see other slides)
- **Rep.-rate**
  - 400 Hz Reverted to last test of the data acquisition software some years ago
  - 500 Hz Thought to have limit of Riga event timer “SLR mode” (=option 2)
    But, our event timer interface uses ”continuous mode” (=option 1)
  - 800 Hz Limit of real-time loop in the data acquisition software
  - **1 kHz** Limit of real-time loop workaround is working and no problems seen so far
- **Others**
  - **Replaced damaged**: some fans, power supply
  - **Upgraded:**
    - Sun ephemerides for telescope protection up to year 2200
    - PowerFlarm Aircraft warning for laser firing disable up to year 2099

Current Limitations

- The main idea relies on
  - **The telescope system does not contain active components**: So, energy loss during light «relaxation» → wavelength increase: with interference filter cannot pass to the detector
  - The active component/the light source/the **laser must not emit parasitic light** !
- Calibration type
  - **Pre- and Post calibration:** Works (standard in Zimmerwald the last decades)
    If problems around the hole in the stray light shield would arise
    the hole can be closed mechanically during satellite tracking
  - **Real time calibration:** not yet completely evaluated
    Similar to above in the stray light shield for the co-axial coating hole,
    a second hole might re-enable C1 (Zimmerwald internal calibration).
    If the latter is not working switching a (delay calibrated) Pockels cell might solve
- Repetition rate > 1 kHz not tested
  - More might be possible
  - Real limit unknown

Still Open Questions Wrap-up

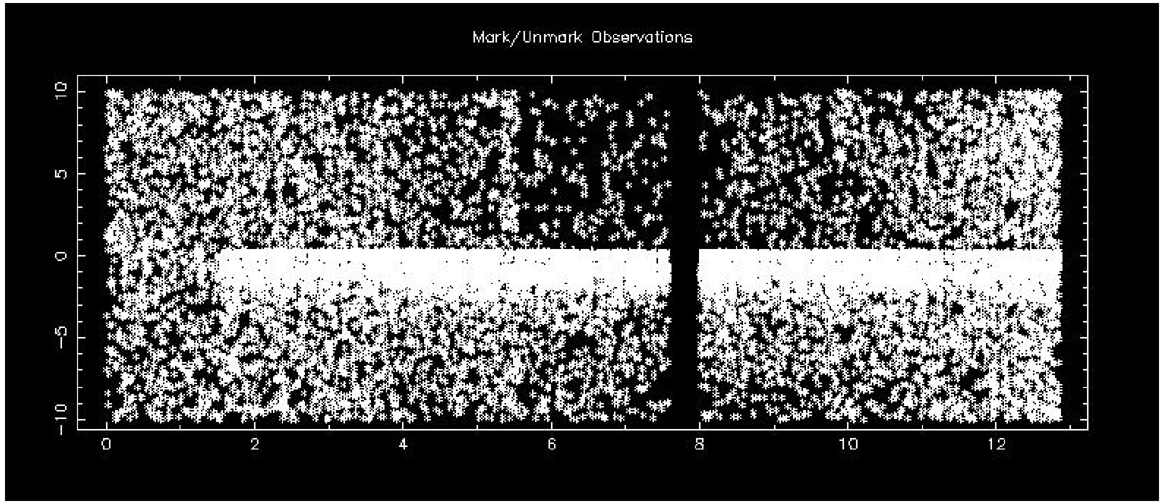
- Still not understood completely
  - **Rotating shutter**: Why was it required at all?
  - **Parasitic light**: Did the old flash lamp laser emit some? If yes, the rotating shutter cannot be the solution. Can the diode pumped solid state (DPSS) laser generate some? After 20 years, it is hard to setup same test conditions.
- Relaxation times
  - External knowledge
    - **Widely spread.** Still refused to write numbers here.
    - Physics extreme: I have read a photon can be emitted from a triplet state after 1000 years but at a very **low probability.**
  - Internal knowledge
    - Directly experimentally: not yet determined.
    - The SLR detector is used for our measurements. It is direct laser light protected by the TR-switch mirror design. If there is any residual light=noise we will discover it.
    - Without using the rotating shutter, noise was reported. But, we do not see any noise.

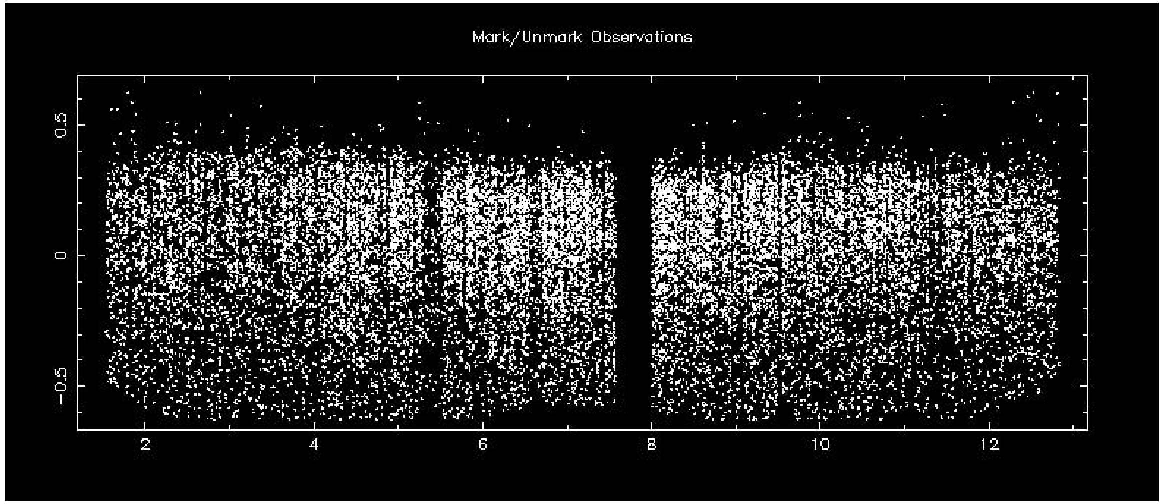
3. Some first results

Very first Results

- **400 Hz:** 8. Nov.2024: Increased rep.-rate
  - In-between e.g. Ajisai (see right side)
    - 20’000 good returns
    - Hit detection and post-processing seem to work
  - **Short visible satellites** like Grace-FO1/2 **work better then ever** !!
  - HIT-U time biases seem to be ok
- **1 kHz: 5. Feb. 2025: Increased rep.-rate**
  - Lageos 1 and Lares1/2 work
  - Lageos2 work sometimes, not yet always due to low inclination, too less normal points

Raw data

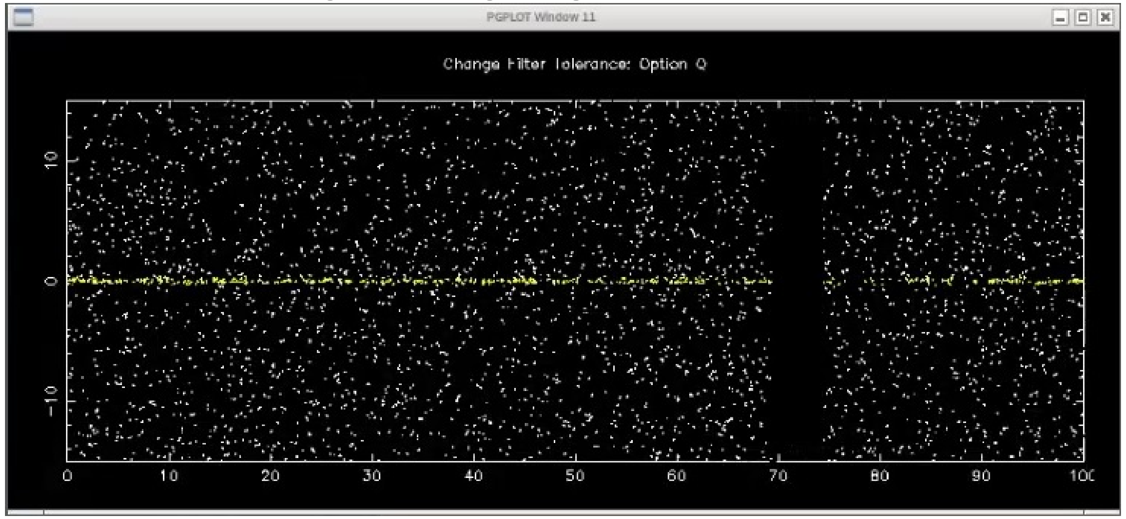


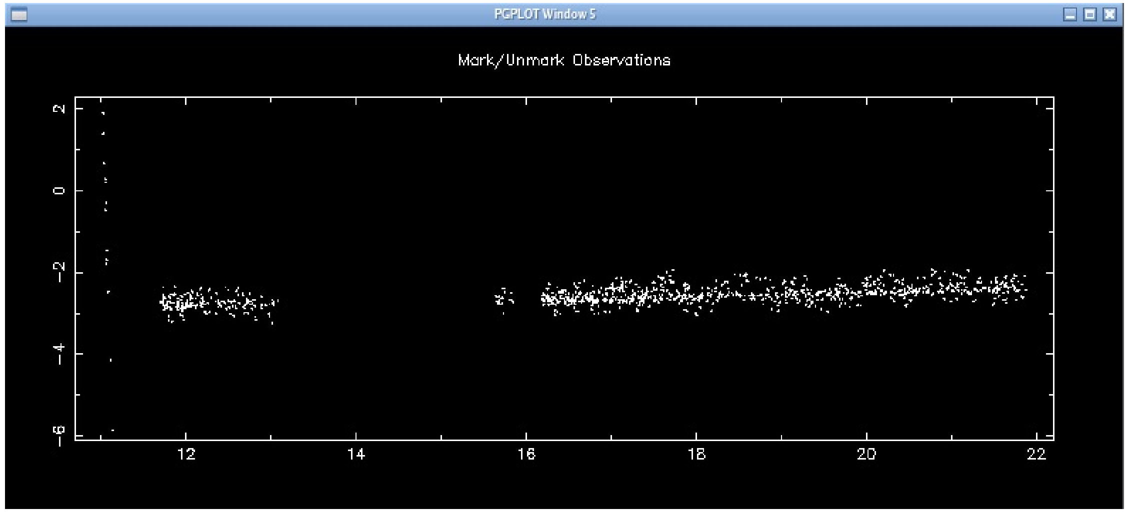


Screened data

Hit Detection Problem

Real-time / during tracking, Lageos1 (L126NO24H) at 500 Hz



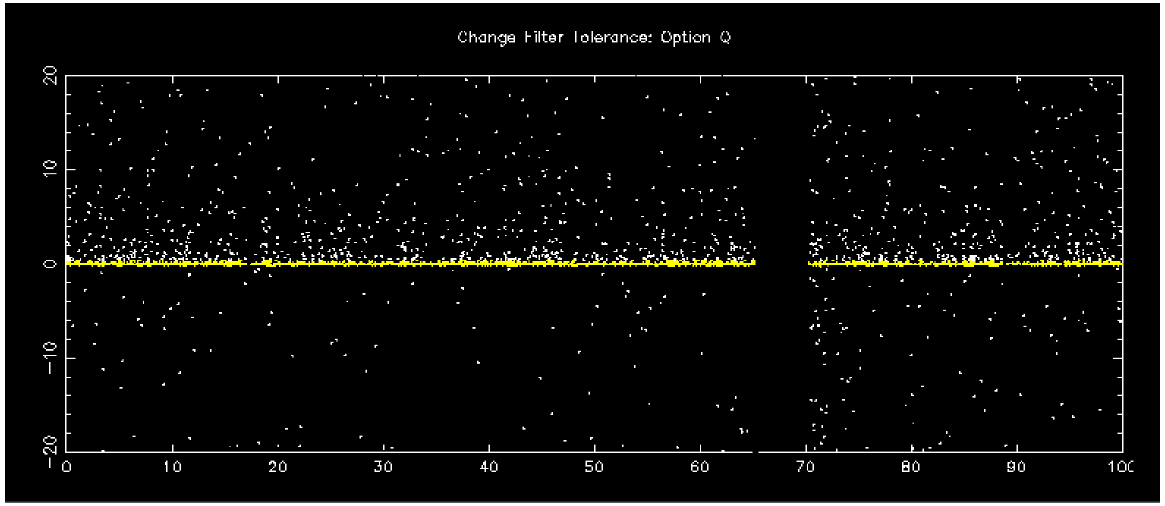


Post-processing / screening, Lageos1 (L108NO24O) at 400 Hz

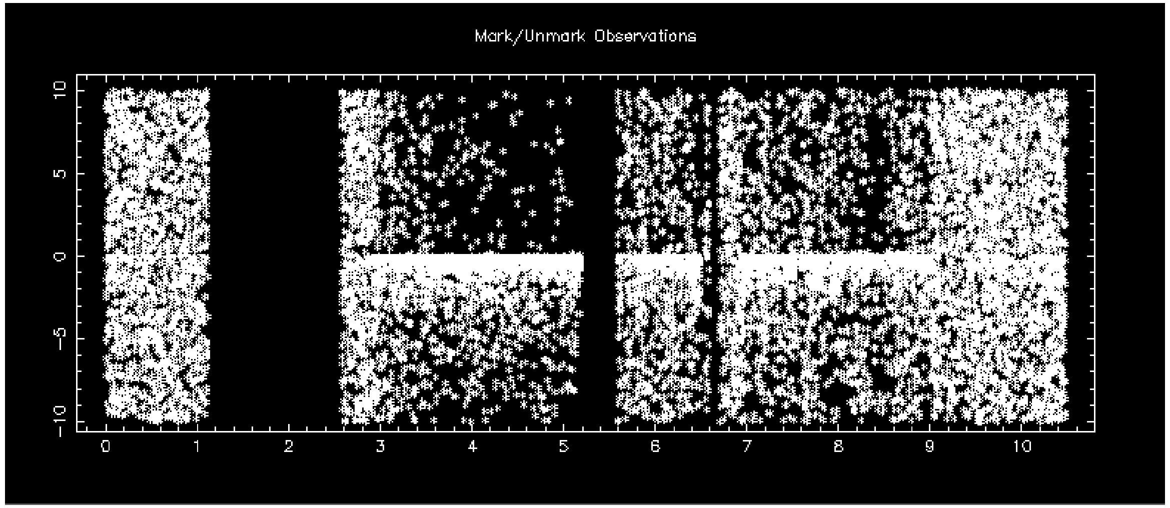
- **Higher rep.-rate but lower pulse energy (new laser has about same power)**
  - We want to separate noise from real returns
  - Taking everything within a tolerance around the predictions is a bad method
- **Trace with a lot of noise around it**
  - Where are the satellite returns?
  - How can we distinguish them?
  - Real-time filter has to decide on time, post processing filter for finalisation
- **Both filters have to be**
  - Reconfigured (for sure)
  - Redesigned (possibly)

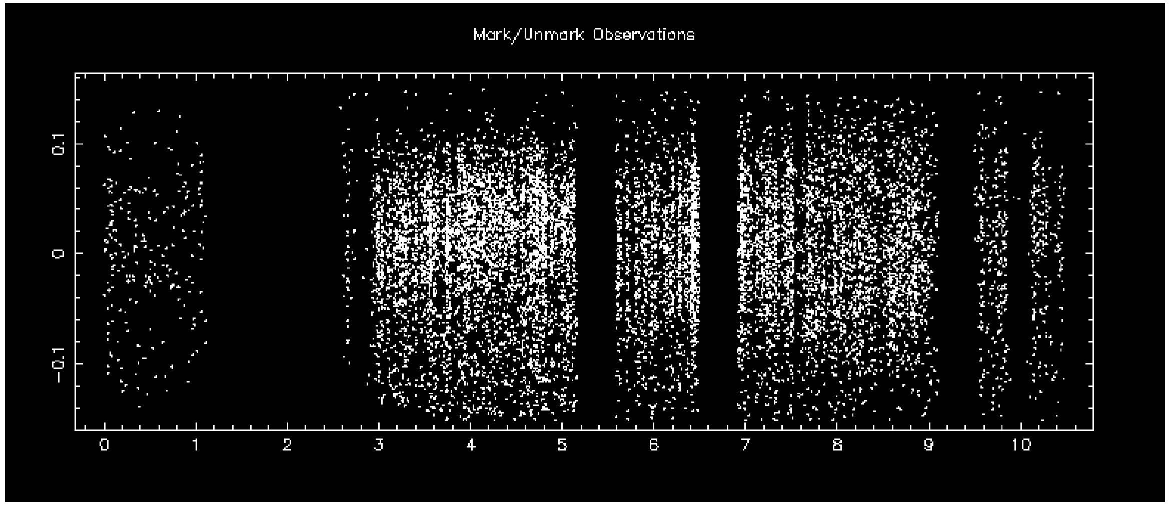
Some Filter Output – A Good One

SR21FE25K@1kHz-real-time-filter



SR21FE25K@1kHz-screening-start





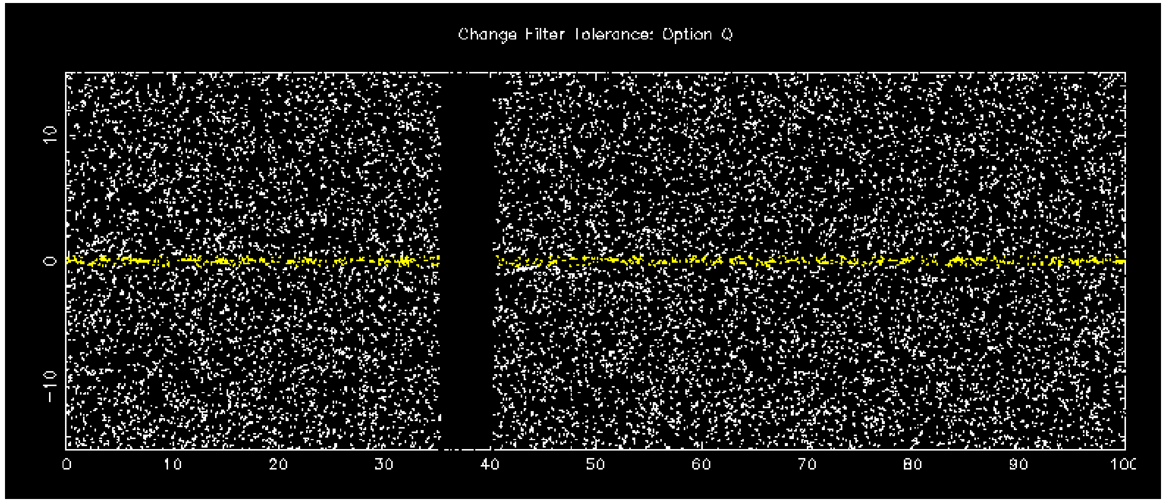
SR21FE25K@1kHz-screening-end

LEO: clear traces

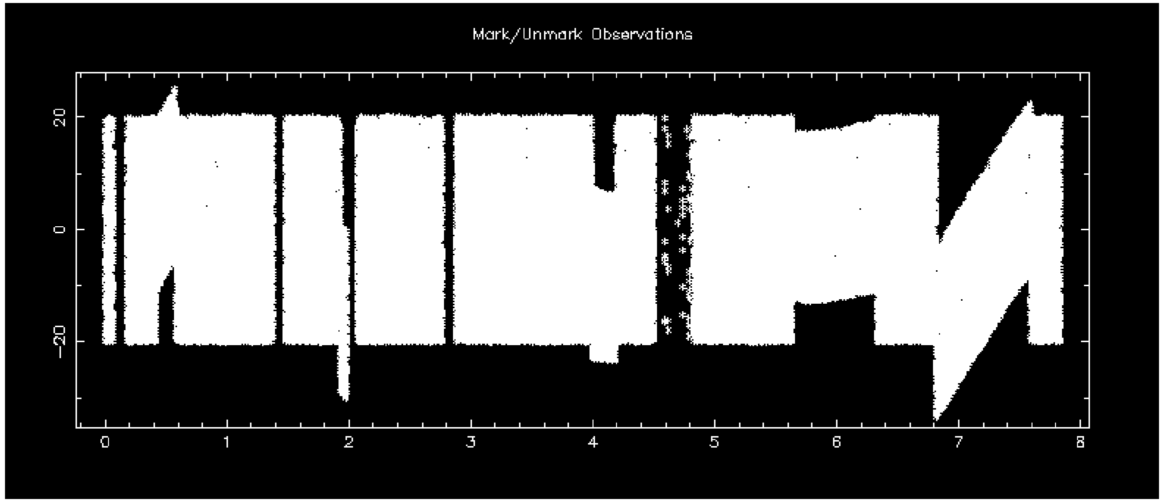
- In real-time filter
- In screening filter
- Almost everything is ok

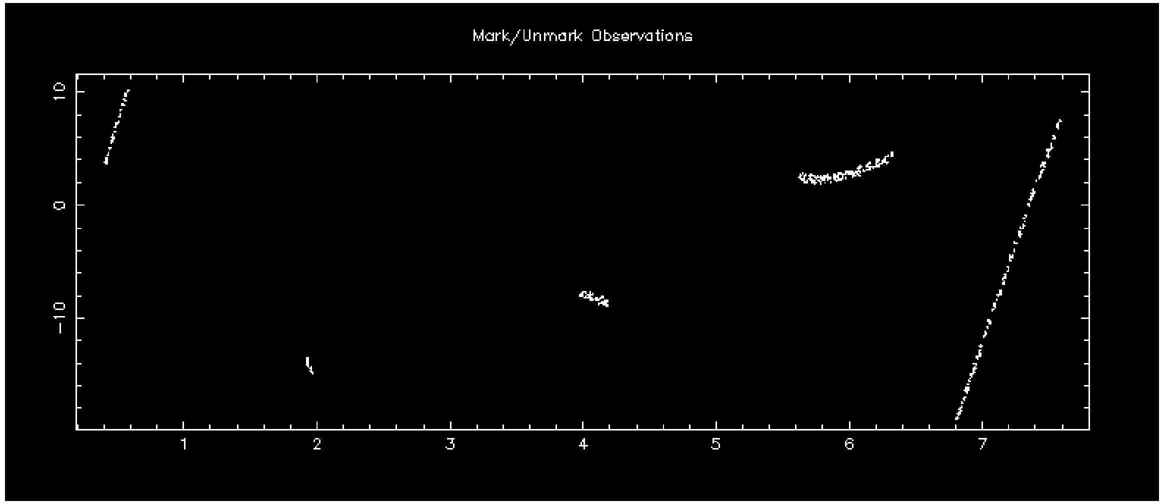
Some Filter Output – A Bad One

LB21FE25J@1kHz–real–time–filter



LB21FE25J@1kHz–screening–filter–start





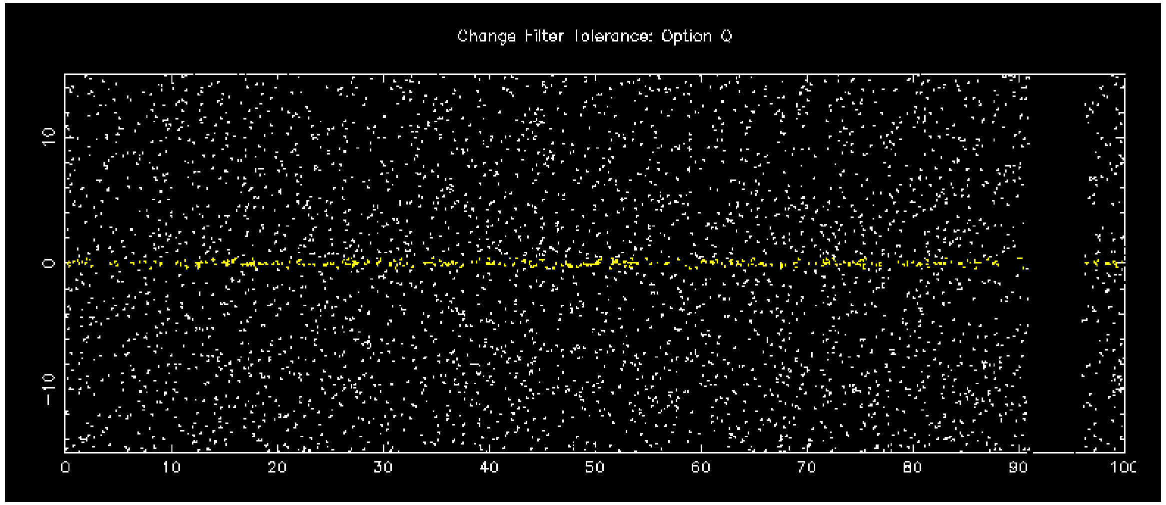
LB21FE25J@1kHz–screening–filter–end

Lageos altitude: noisy traces

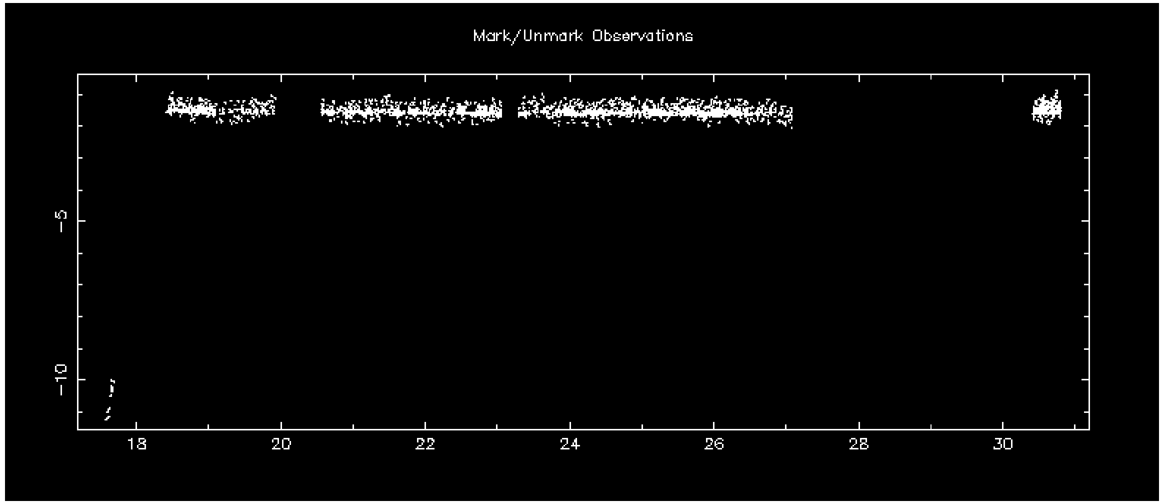
- In real–time filter
- In screening filter: post processing fails often, especially during daytime
- Bug: 1ns noise trace of real–time filter
- After filter parameter change, some is working even worse
- **Usually, Lares–2 is tracked good** and it is easier to track than Lageos–2

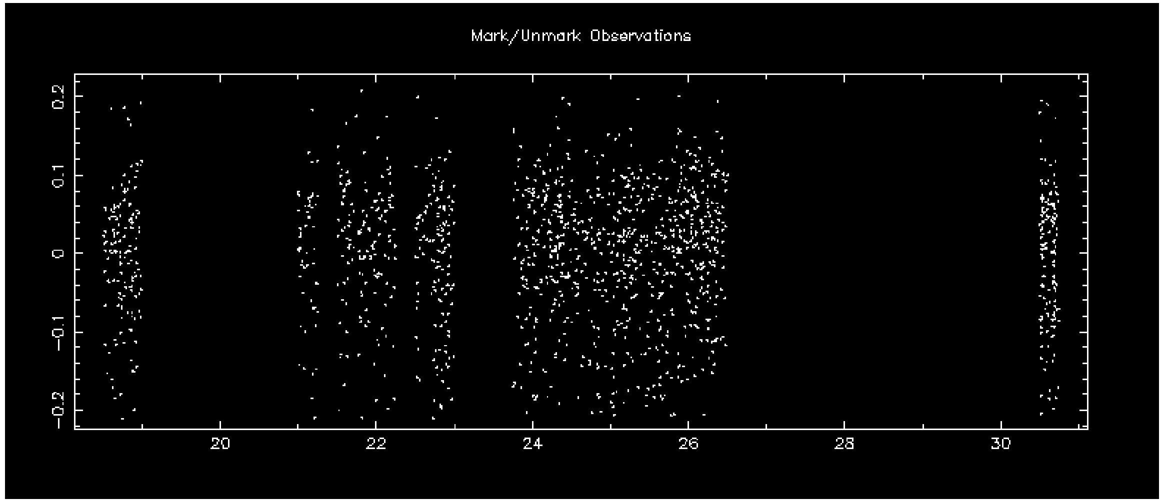
Some Filter Output – A Medium Good One

L228FE25K@1kHz-real-time-filter



L228FE25K@1kHz-screening-filter-start





L228FE25K@1kHz-screening-filter-end

Lageos-2: during daytime

- In real-time filter: Thales laser at 10mJ generated clear trace
- In screening filter: noise manually to be removed
- Full automatic processing does not yet work
- A least it is working during daytime but only at high elevation

Conclusion of Results

- **Very low LEOs (Grace-FO1/2, Swarm-A/B/C, Terrasar-/Tandem-X) work better than ever:**
  - If satellites come time parallel schedules pass interleaving, so, 60 s per Sat. for finding
  - If start-stop-conflict happens for e.g. 30 s
    - **With rotating shutter**: Needs resynchronization time of about 20 s: 10 s remain for finding
    - **Without rotating shutter**: No further time loss. 30 s remain for finding and hitting
- **ILRS Quarantine: Require for each Lageos1/2 and Lares1 20 passages**
  - Lageos1 and Lares1: no real problem
  - **Lageos2**: due to low inclination, low elevation, harder to track (Same problem with previous Thales laser). ~~Needs good weather and maybe night time tracking.~~
- **HEOs/GNSS: ~~do not work yet, except by good luck~~**
  - With Thales laser running at nominal pulse energy of 10mJ, we had them all
  - **Requirement**: We want them back again
- **Distinction problem: rep.-rate or laser transmit location**
  - Current problems derive from the lower signal-to-noise ratio and higher sampling rate
  - During night time up to now, no parasitic noise discovered, so, no TX in Coudé problem

Conclusion

- **We also had good luck!**
  - **Afterglow/Backscatter**: No impact between starts
  - **Event timers**: Continuous Mode (=Option 1) is still working fine for 1 kHz
  - **Entire zimlas software**: now running at 1 kHz (after some minor modifications)
- **Hit detection**
  - **Real-time** / Kalman filter and
  - **Post-processing** /screening filter has to be adapted to the new situation
  - **HEOs** can work with the lower pulse energy at daytime
- **Milestones achieved**
  - ILRS quarantine left in 04/2025
  - Fixed much more bugs
  - **HEOs observation** elevation minimum increased from 20 to 40 degrees improves
    - More satellites and data now
    - If the weather is ok: on ILRS passage statistics back again on the second position worldwide

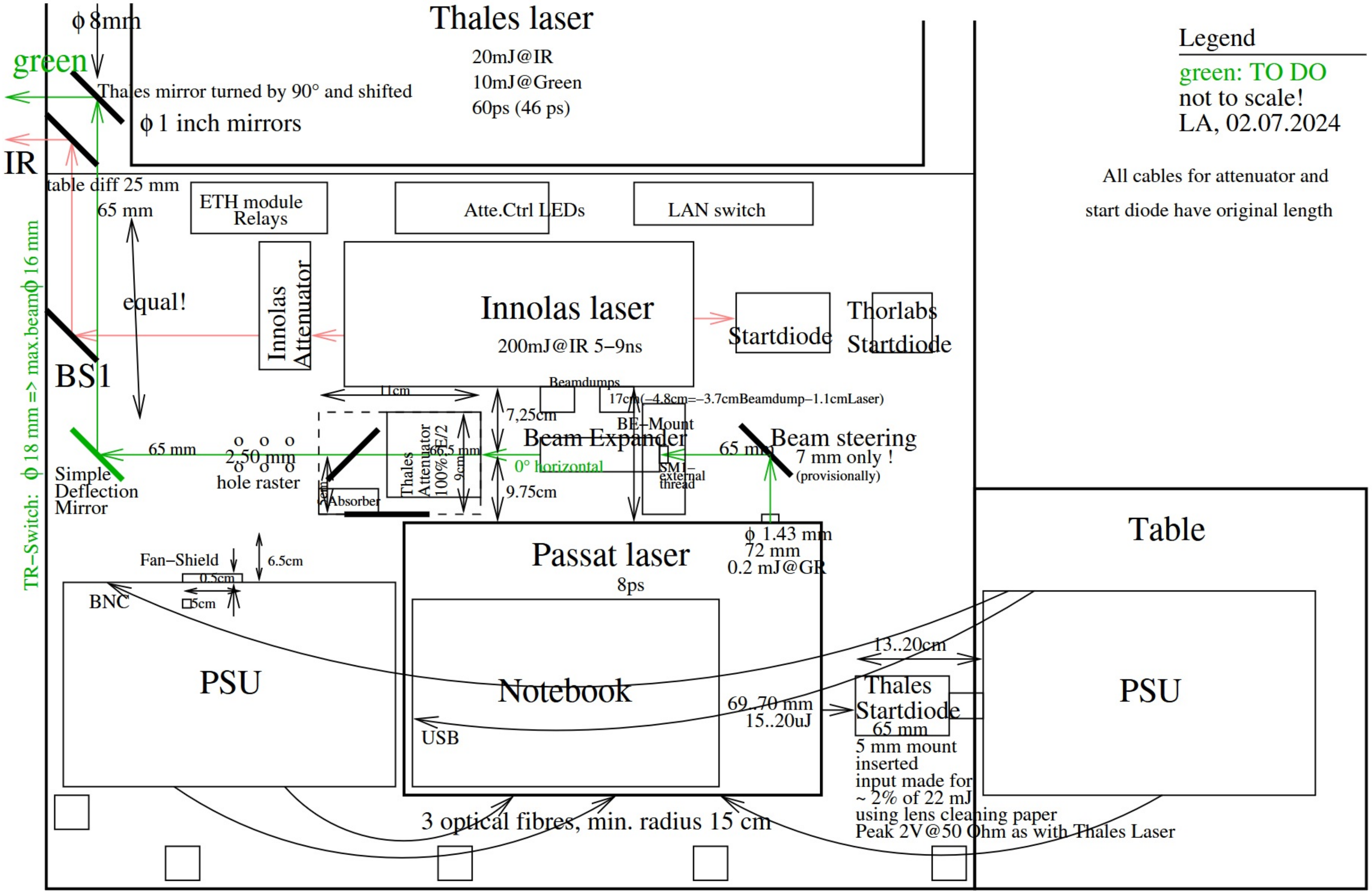
Outlook/Acknowledgements

- Other things we struggle with
  - Some new devices failed (bad manufacturing due to Corona?)
  - **Administrative**
    - **In-sky laser firing permission** with the swiss local «Federal Office of Civil Aviation» (BAZL) is still pending – at least we are allowed to proceed firing
    - **SLR budgets were cut**
      - **For employees**: man power minimum
      - **Travel expenses**: I am not allowed to go to a workshop although I have success

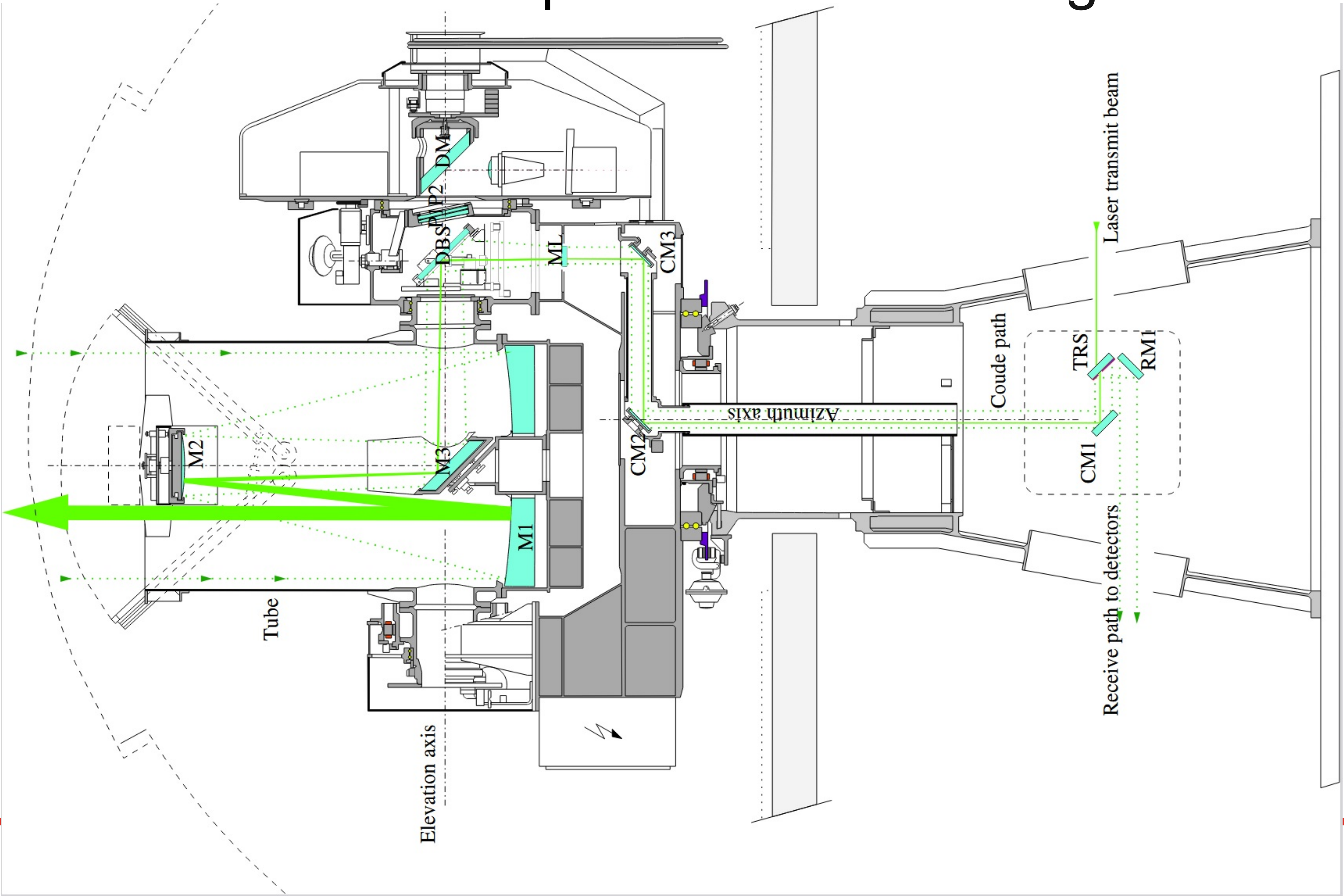
So, we cross the fingers that everything will work at Zimmerwald especially techniques and clear sky in the future 😉

- Acknowledgements to
  - **Linda Geisser** for finding big real-time filter bugs
  - **Thomas Schildknecht** for buying the new 1 kHz laser and for fruitful discussions
  - **Lucia Kleint** for allowing the implementation of my ideas

Optical Setup



Telescope sectional Drawing



Transmit and Receive Table