Lares-2
The "Next generation" Lageos
By
David Arnold

Lares-2 is intended to be the first geodetic satellite that can provide one millimeter accuracy. One of the important features is that it eliminates the polarization bias that causes systematic errors in both Lageos and Lares-1.

The design is based on a thermal-optical model that I developed 50 years ago. The tool used to design the Lares-2 retroreflector array is program TRANSFR described in SAO Special Report 382. http://davidarnoldresearch.org/1979SAO382.pdf .

To the best of my knowledge no one else has ever developed a similar program in the 50 years since I wrote it. The TRANSFR program is unique in that it models diffraction. It computes the far field cross section, centroid, and RMS matrices of the reflection from a retroreflector array.

This program was developed to design the first Lageos satellite. The reason is that the diffraction pattern of a retroreflector is not constant over the annulus in the diffraction pattern defined by the velocity aberration.

Another measure of the signal from a retroreflector is the active reflecting area. This is a single number that gives the total energy. But does not tell you how much of that energy is in the annulus defined by the velocity aberration or how it is distributed.

To demonstrate the importance of diffraction, I have computed the histogram of Lageos using the two different measures of the signal from each active retroreflector. The results are shown in Figure 1 below.

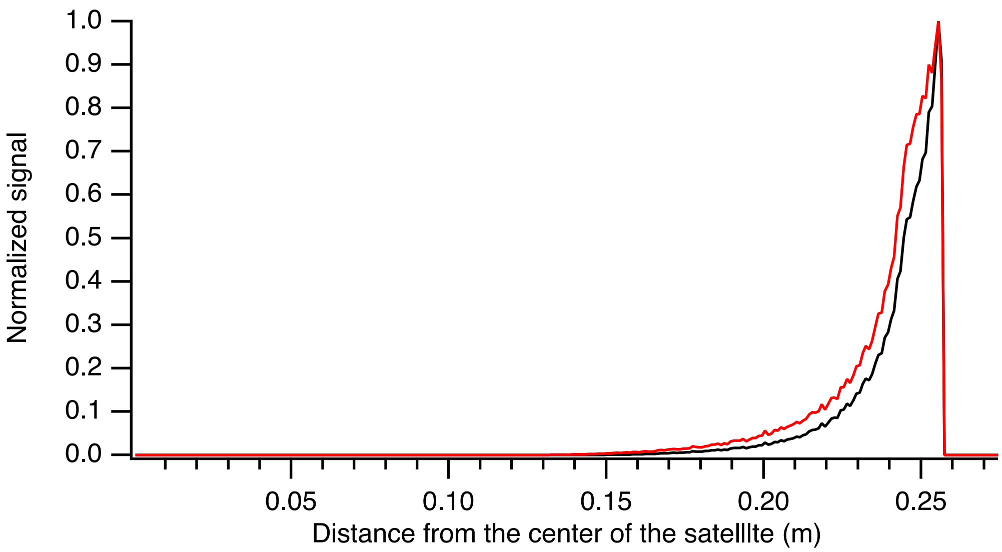


Figure 1. Normalized histogram of Lageos (bin size one millimeter)
Red = using active reflecting area
Black= using the average cross section in the velocity aberration annulus 32 – 40 microradians.

The shape and slope of the curves are different. The change in slope where total internal reflection is lost is different in the two curves. The centroid of the red curve is 0.239404 m. The centroid of the black curve is 0.242515 m. The difference is 3.1 mm. The active reflecting area is not an adequate measure of the signal from each retroreflector.

The transfer function has been averaged over 1080 incidence angles in a spiral pattern around the sphere. A bin size of one mm has been used to plot the histogram. This shows noise due to the number of points in each bin. The larger the bin size, the smoother the curve. The smaller the bin size, the noisier the curve. The bin size does not seem to affect the average value of the histogram.

Figure 2 below shows a similar plot for Lares-1. Lares-1 is at a lower altitude than Lageos with different velocity aberration.

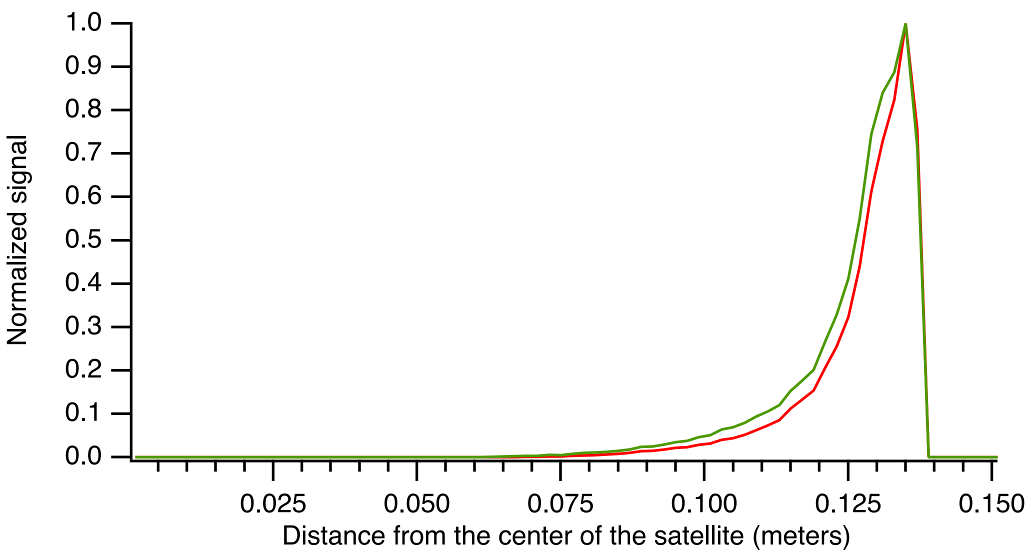


Figure 2. Normalized histogram for Lares-1.
Green = using active reflecting area
Red = using the average cross section in the velocity aberration annulus 30 – 45 microradians.

The centroid of the red curve is 0.127799 meters and the centroid of the green curve is 0.126257 meters. The difference is 1.54 millimeters. The bin size is 2 millimeters to reduce the noise level.

The Lares-1 curves have a different shape from Lageos. But there is the same problem of the change in slope coming in a different place for loss of total internal reflection.

Computing CoM corrections.

In the calculations of the CoM done by ILRS the signal from a retroreflector is given by the equation

$$I \propto a^n e \qquad (1)$$

The signal *I* is proportional to a power *n* of the active reflecting area *a* times the reflection coefficient *e*. The exponent *n* is determined experimentally. This is wrong in principle. The CoM corrections should be computed from the physical parameters, not from the data.

Raising the area to a power is not going to change the shape of the histogram to match the shape of the curves computed by diffraction.

The computation of the histogram using diffraction should give very accurate results for Lares-2 since the thermal perturbations are minimal.

It takes about 15 minutes of computer time to compute the average transfer function over 1080 orientations of the satellite using program TRANSFR. The program writes a file giving the position, active reflecting area, and average cross section in the annulus for each active reflector at each orientation of the satellite. This data can be binned to create the histogram.

Other issues

1. It would be useful to compute a transfer function report for Lares-2 as has been done for Lageos and Lares-1. This will document the changes in Lares-2 relative to Lageos and Lares-1. A recent short report for Lageos is available at http://davidarnoldresearch.org/Lageos-2.pdf . This report is written in with modern graphics that are easier to read than the original Lageos transfer function report. http://davidarnoldresearch.org/Lageos1978.pdf .

2. It would be good to compare the results of pre-launch tests on Lares-2 with theoretical calculations to see if the predicted behavior matches the lab tests. The JASR report on the thermal-optical design gives various diffraction patterns. https://www.sciencedirect.com/science/article/abs/pii/S0273117720300491?via%3Dihub .

3. The calculated cross section for both Lares-1 and Lares-2 is 4 million sq meters. This is almost a factor of 4 smaller than the calculated cross section of 15 million sq m for Lageos.

There is no sharp cutoff for the required signal from a retroreflector. The signal to noise drops as the signal decreases. There are still large variations in signal due to coherent interference. If the noise ratio approaches 50% the least squares method breaks down.

One can use a screening process that identifies the good points by looking for residuals that form a straight line. This can be done visually or by computer. That process breaks down at about 90% noise ratio. If the passes are long enough and the orbit stable enough one can take a lot of data and then use the screening process to identify the good data before going back to a least squares solution.

4. Program TRANSFR was used to design many satellites and compute the transfer function for many other satellites. It was used to rescue TOPEX when the range errors were too large to meet the program requirements. No one else has ever run the program. It is a very valuable program that will be lost when I am gone.

5. I have designed other retroreflectors that can provide one millimeter accuracy. I have been keeping them secret because of the problems protecting intellectual property.

6. I wrote and presented a paper on the Correlation Method at the Riga workshop in 2017. http://davidarnoldresearch.org/Correlation%20function.pdf .
Data clipping during screening changes the centroid of the reflected pulse by cutting off the tail but leaving the leading edge intact. The ILRS website gives tables of CoM corrections for 2σ and 3σ screening. The correlation method gives more accurate CoM corrections because it matches the shape of the pulse and is insensitive to data clipping. Figure 3 below shows an example from the report.

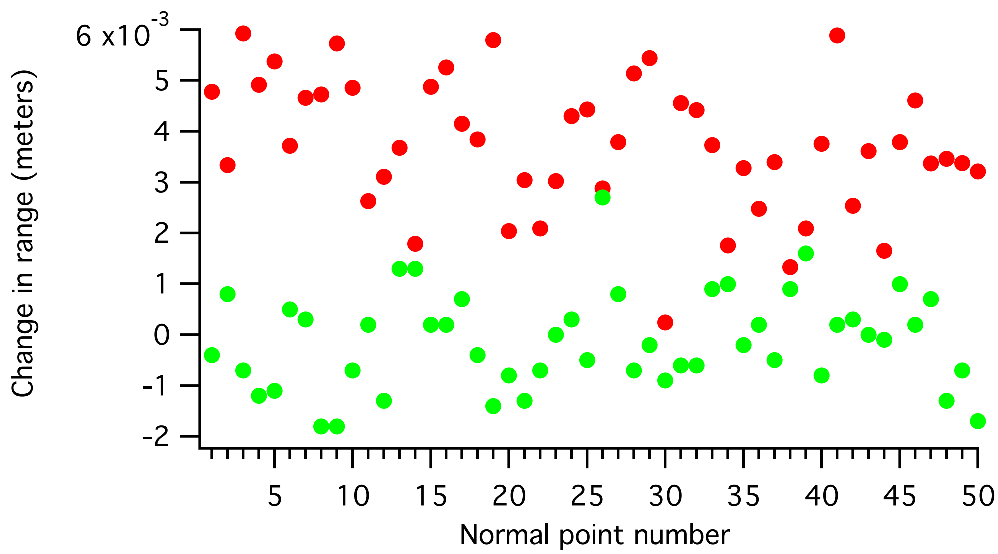


Figure 3. Correlation method.
Red = centroid
Green = correlation method

The miniSLR® - A low-budget, high-performance satellite laser ranging system

Daniel Hampf

DLR

Heritage & Vision

- UFO laser ranging station (2015 – 2020)
  - Inexpensive hardware
  - Fibre-coupled transmitter
  - 100 kHz repetition rate
- Successful first try, but many limitations

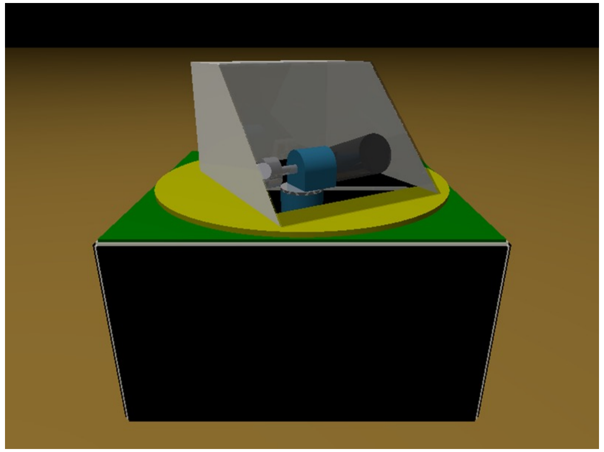
- Could we make it even smaller, even cheaper, and at the same time more powerful?

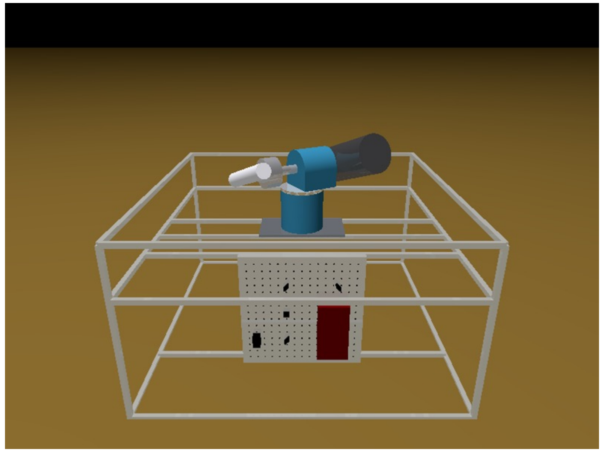
- Comment by Toshi: “Interesting approach towards ‘minimal SLR’ ”…

UFO laser ranging station in 2017

Design goals

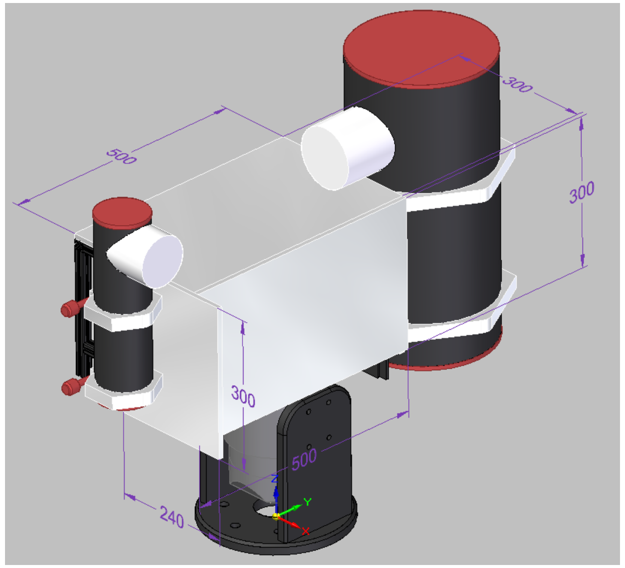
- High-performance:
  - Sub-cm precision for Normal Points
  - Range from LEO up to GNSS targets
  - Long-term stability
  - Highly automated
- Low budget:
  - Small footprint
  - Transportable (can be integrated at factory)
  - Simple design
  - Fully encapsulated (no dome)
  - Based on amateur mount and small telescope

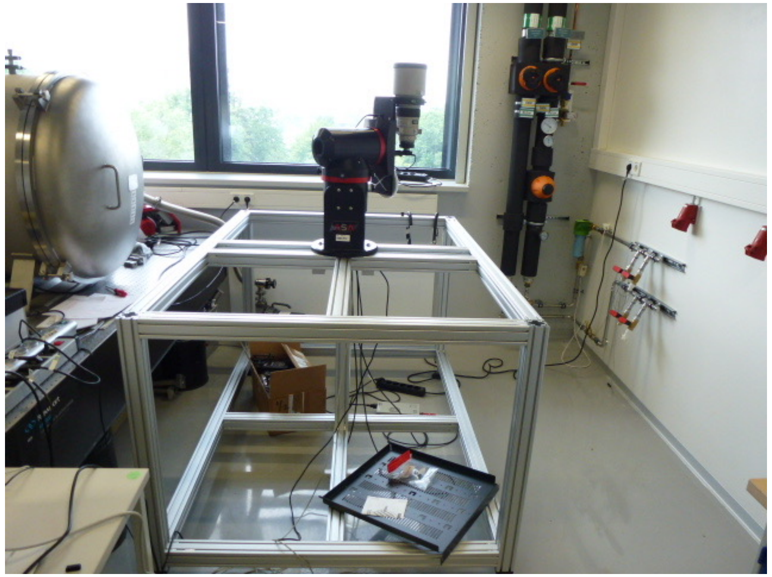


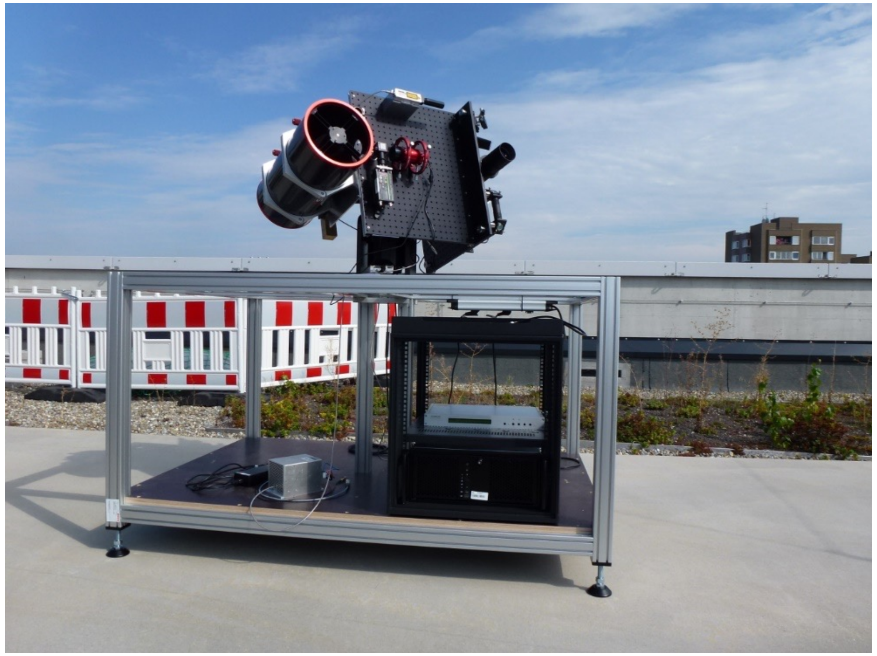


First concept drawings (Jan 2018)

From concept to first experiments

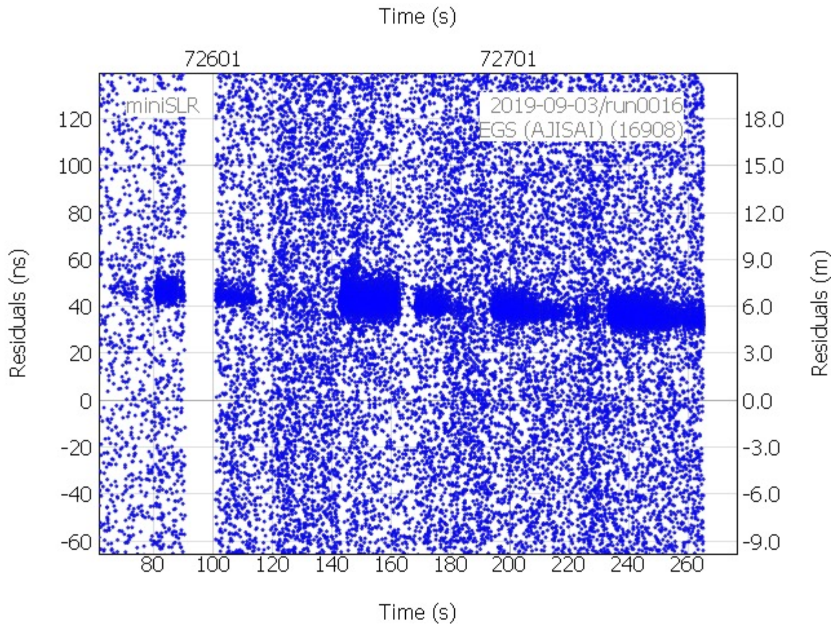






First laser ranging

- First prototype
    - Largely from available hardware
    - Based on ASA DDM85 mount
- 2019-09-03: First returns with the new miniSLR



First returns received with miniSLR

miniSLR version 1.0 at ILRS workshop 2019

Refining the development and funding

- What do we need for a high-performance miniSLR:
  - A better mount
  - A sub-ns laser with sufficient energy
  - Environmental protection
  - Refined optics and electronics
  - Software upgrades

- Received funding to develop a “commercial prototype” within 3 years (2020-2022).

miniSLR version 3.0 with new mount and housing (summer 2021)

The curious case of finding a suitable laser

- Small receive aperture ➔ laser has to be reasonably powerful (~ a few Watts)
- Sub-nanosecond pulses
- To be installed on moving platform (lightweight, robust, small)

- Findings after market research:
  - Stationary seed laser / amplifier on moving platform
  - Q-switched lasers (mode locked too heavy / big)
  - Use 1064 nm (more power at same size)

- Use high repetition rate for averaging

$$\sigma_{\text{single}} = \sqrt{\sigma_{\text{L}}^2 + \sigma_{\text{D1}}^2 + \sigma_{\text{D2}}^2 + \sigma_{\text{ET}}^2 + \sigma_{\text{S}}^2}$$

Component	Sigma error	Comment
Laser	170 ps	(~ 400 ps FWHM)
Start detector	40 ps	Worst case
Receive SPAD	200 ps	IR-SPAD
Event Timer	20 ps	
Total	**270 ps**	(Add squares)

Target	GNSS	Other satellites
NP precision goal	15 ps	5 ps
Required returns	300	3000

Lasers, lasers…

- Ordered custom system from French company Alphanov in Jan 2021
  - 400 ps
  - ~100 kHz / ~ 100 µJ (10 W)
  - Still not delivered
- Ordered another system from Lithuanian company Standa in Mar 2022
  - 600 ps
  - 50 kHz / ~ 100 µJ (5 W)
  - Still not delivered
- So far we use old nanosecond system
  - 5 ns
  - 10 kHz / 200 µJ (2 W)
  - Works perfectly ☺

Alphanov laser

Standa laser

Commissioning V3.0

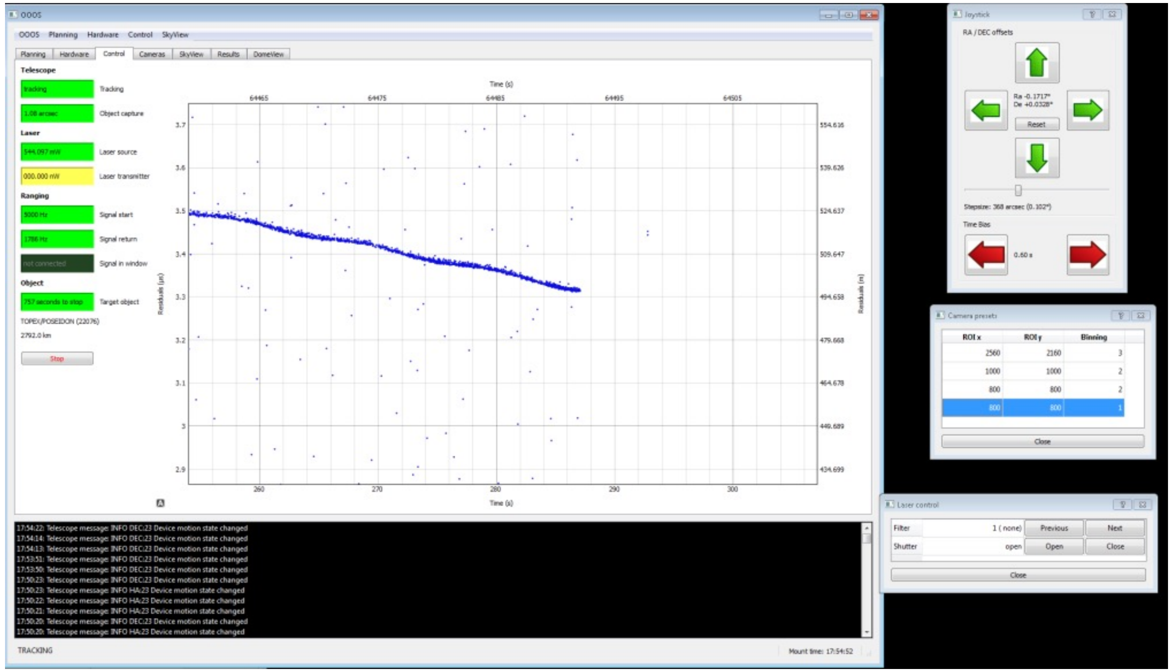
- Features:
  - Sealed, water-tight and air-conditioned
  - Air-craft detection system (ATC data, T-IR camera)
  - Blind-tracking accuracy ~ 10”
  - Closed-loop tracking better than 2”
  - Motorised beam-control
  - Integrated calibration target (1.45 m)
  - Remote-controlled (from lab or home-office)

- In operation since February 2022

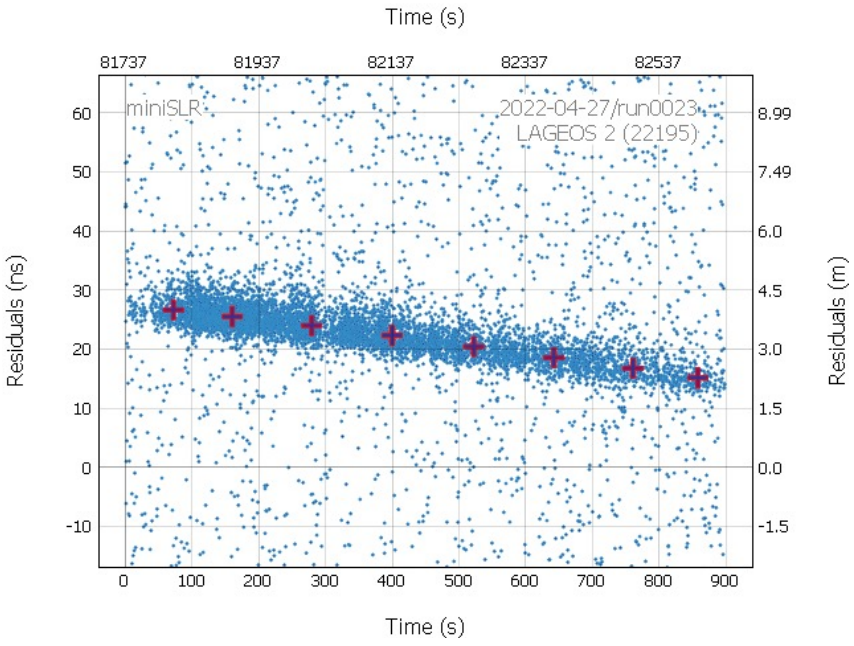
miniSLR version 3.0 on roof of institute (summer 2022)

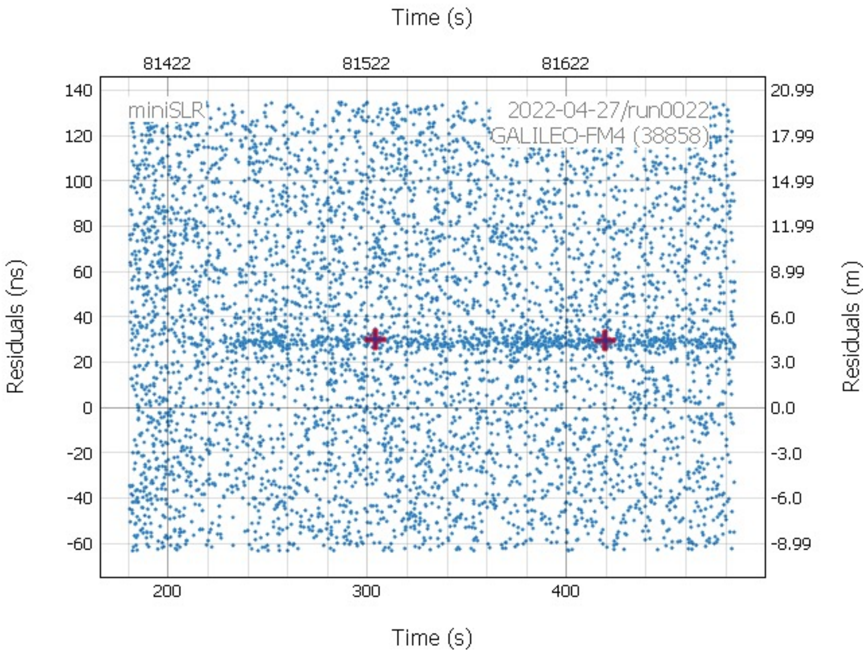
Orbital Objects Observation Software (OOOS)

- miniSLR runs on the newest version of our own control software OOOS (see talk at ILRS WS 2017)
- Contains a lot of lessons-learned from UFO
- De-coupled hardware layer
- Pure python
- Cross-platform
- Open-source (GPL v3)



Some early highlights





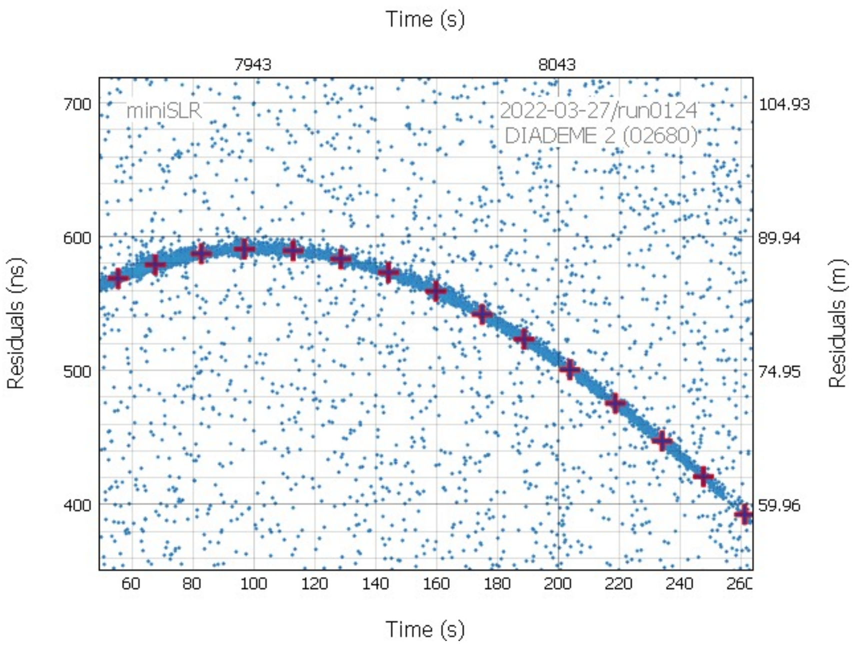
LAGEOS 2

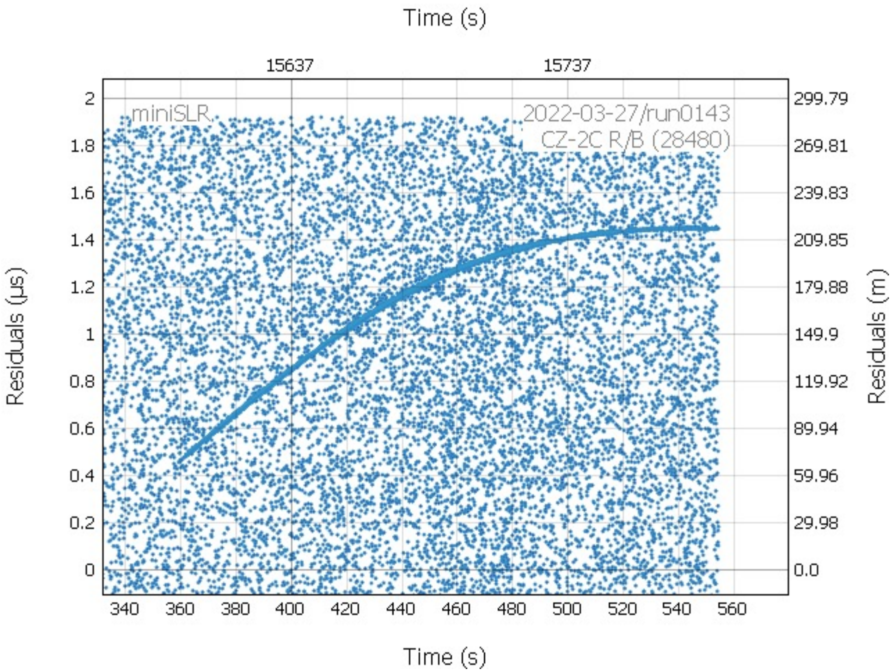
- 2000 to 7000 returns per Normal Point
- (Goal: 3000 data points)
- Return Quote: 0,1 bis 0,3 %

Galileo-FM4

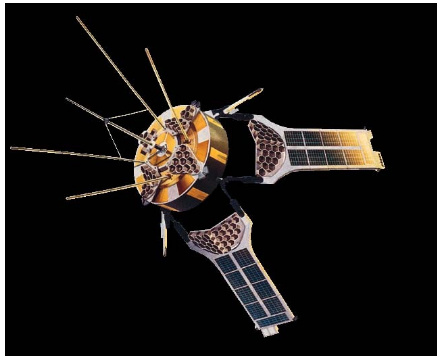
- 350 returns per NP
- (Goal: 300 data points)
- At the edge of capabilities of current set-up

Ranging space debris (with retros)





DIADEME-2
- Launched Feb 1967
- Second oldest LR target (?)



Long-March Rocket Body
- Launched in Nov 2004
- Reason for retro unknown

First estimation of accuracy

- First data analysis kindly provided by Toshi (April 2022)

- Bias of 12 cm (probably understood)
- Pass to pass jitter: 10 cm
- Precision: 2 cm

These two should improve with sub-ns laser (5 ns → 500 ps)

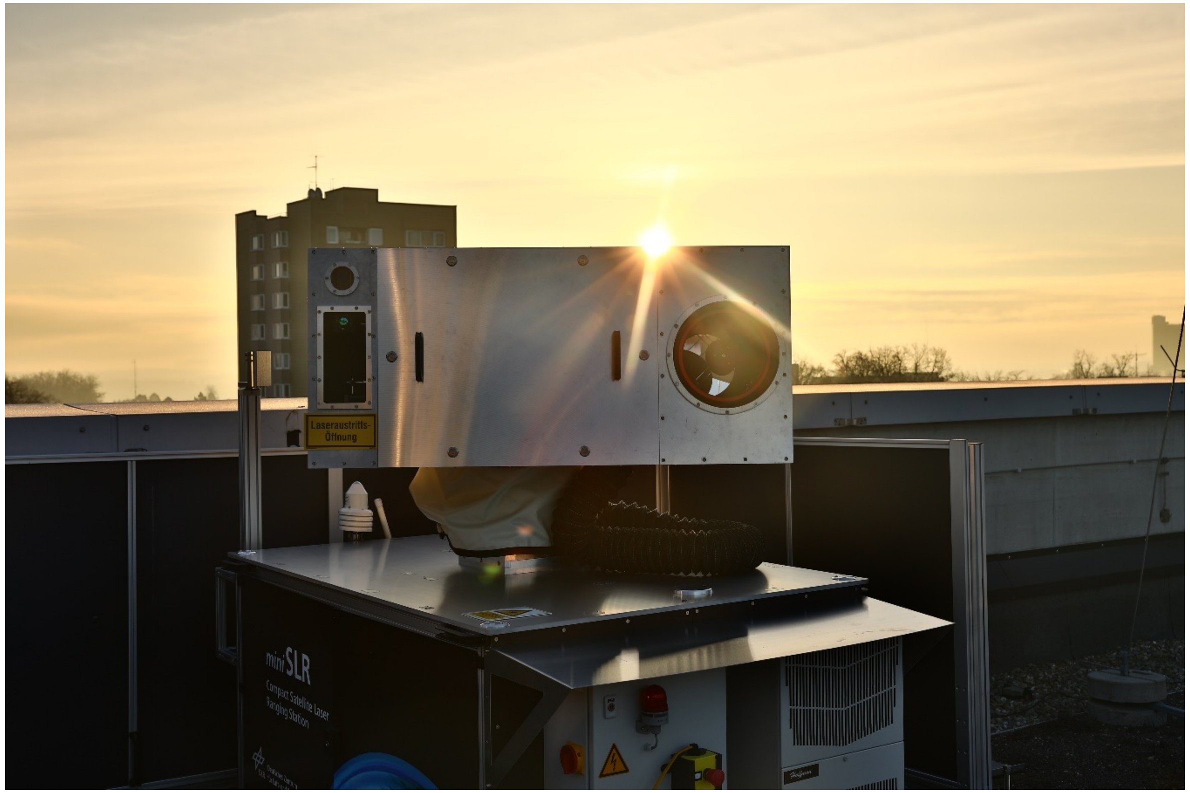
sat	date	time	dur	rb mm	error	tb us	error	prec	bad	total	rms
AJI1	2022/04/27	19:45	10	10	(7)	-8.2	(2.2)	9	0 /	21	316
LARS	2022/04/27	20:18	2	-60	(28)	--------.-	(----.-)	9	0 /	5	315
AJI1	2022/04/27	21:47	8	9	(8)	1.8	(2.5)	12	0 /	14	329
LAG2	2022/04/27	22:17	39	-42	(15)	1.0	(8.0)	5	0 /	11	334
AJI1	2022/04/27	23:46	12	-1	(7)	-2.3	(1.7)	9	0 /	22	330
LAG1	2022/04/28	00:29	25	37	(13)	-21.6	(6.8)	4	0 /	11	344
AJI1	2022/04/28	22:56	8	31	(9)	1.1	(2.7)	21	0 /	16	328
LAG1	2022/04/28	23:14	0	------	(-----)	--------.-	(----.-)	-----	0 /	1	289

Potential applications

- Supplement to busy SLR systems
- New SLR sites around the world

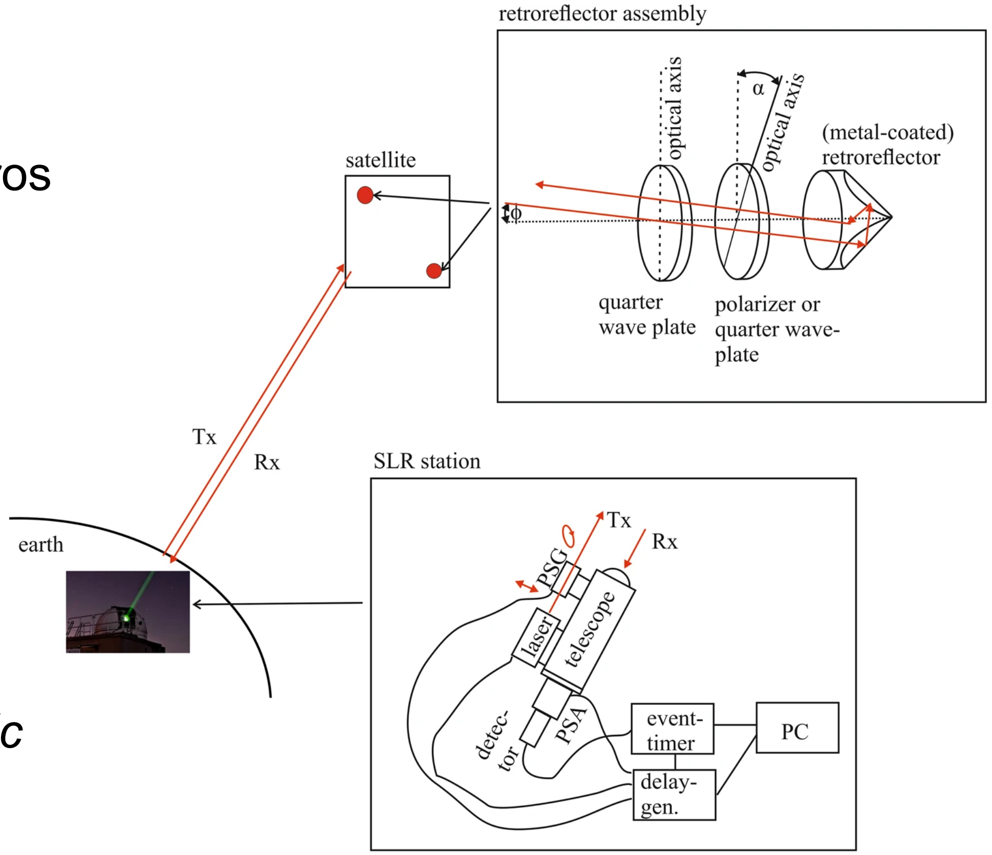
- Full range of traditional SLR applications:
  - Geodesy
  - Mission support

- New applications:
  - Support for commercial missions
  - Space traffic monitoring
  - Collision avoidance planning support



Polarimetric SLR

- Goal: Identify satellites by their retro-signature
- Under development: Retros with polarising optics
- The miniSLR will be used as a test platform for those retros
- Timeline:
    - On-going: Lab experiments
    - ~2024: Outdoor long distance tests
    - ~2026: Tests on real satellite in orbit



Details in Nature Communications paper (open-access):

Nils Bartels et al: *Space object identification via polarimetric satellite laser ranging*

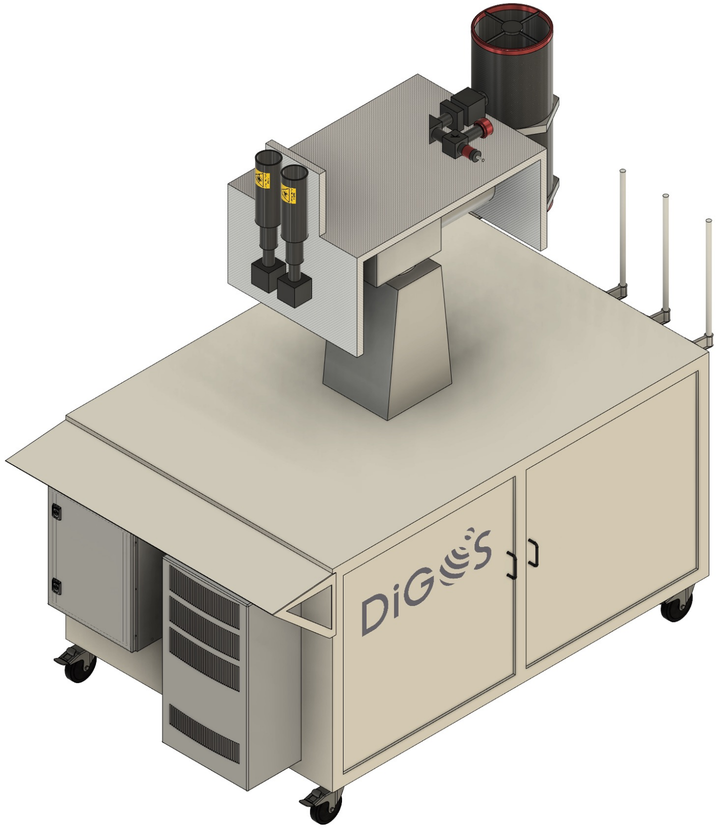
https://www.nature.com/articles/s44172-022-00003-w

Outlook

- Have been accepted into the ILRS as engineering station
    - Will start to deliver data after a few more quality checks
    - Feedback from ILRS analysis very valuable for validation of performance

- Short-pulse laser / high-precision operation
    - Waiting for laser to arrive

- Commercialisation with DiGOS Potsdam GmbH
    - Small company based in Potsdam (near Berlin)
    - One of world leading suppliers for SLR ground stations
    - The miniSLR® will soon be available to European and international customers



Conclusion

- The miniSLR® offers a cost-effective alternative to traditional SLR systems
- First tests show good performance
- Data will be delivered to ILRS for public validation
- System will be available commercially in the near future

The presented results have been made possible by great team work with:
Felicitas Niebler, Luis Gentner, Tristan Meyer, Robin Neumann, Wolfgang Riede, Paul Wagner (now at DLR Institute of Communication and Navigation), Ewan Schafer (now at Lumi Space, UK), DLR IT department, mechanical and electronics workshop, and many others

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