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BKG
Wir geben Orientierung.

hHz monostatic Lunar Laser Ranging at the WLRS

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Introduction
- LLR @ WLRS -

SCOPE

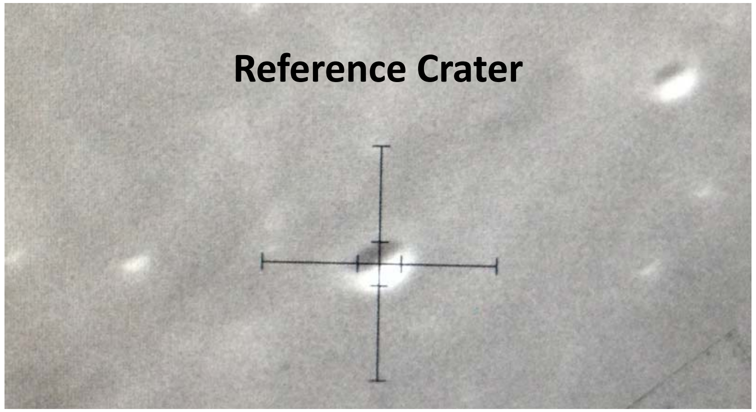
- Good connection to reference frames
- T&F system, good representation of SI second (3 Masers, CS clocks)
- Well defined SLR reference point
  - Station coordinates & velocity (ITRF)
  - Local tie network (system calibration, range bias)
- 10 ps Laser pulse, intrinsic precision < 4 mm RMS
- Good intrinsic system stability, Calibration mean
- Daytime LLR possible

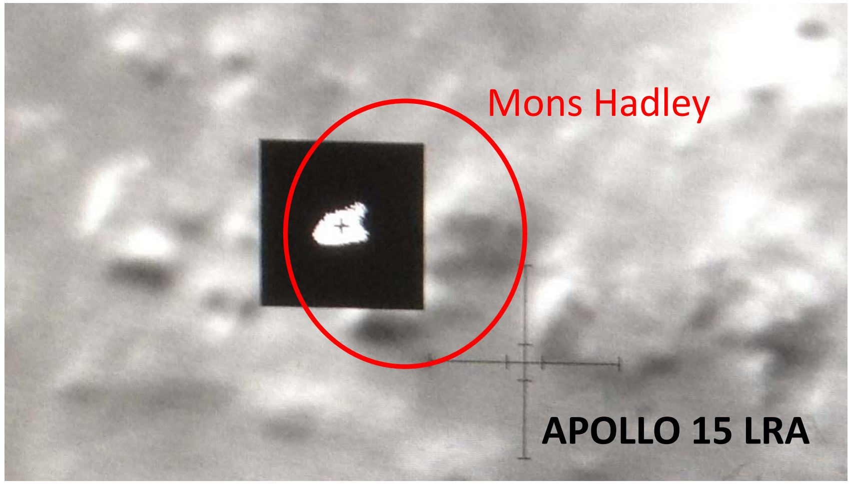
LIMITATION

- 75 cm Telescope & 100 mJ Pulse Energy (2 pulses!)
- Return Rate ~0.2% @ 20 Hz
  → ~2.4 Echoes per Minute!!!
  - Elevation > ~55 deg
  - No blind tracking (also full moon difficult)
  - No reflector switching possible
  - LLR only in very good atmospheric conditions

Introduction
- LLR tracking procedure -

1. Crater referencing (many Thanks to OCA team!!!)
2. Reflector tracking & definition of a reference
3. Automatic telescope guiding wrt defined reference

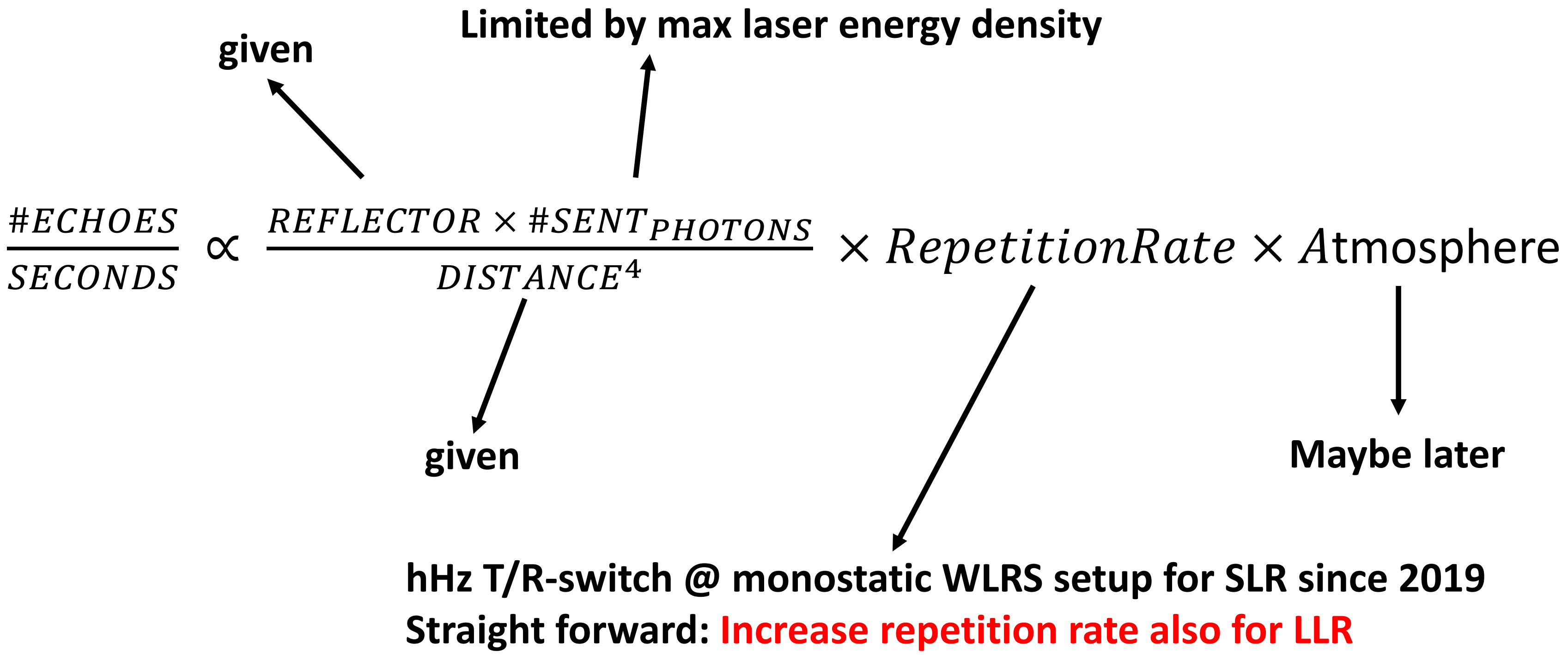




-> first lunar echoes since many years in 2018 -> start of timeline

Introduction
- link budget -

- GOAL: achieve „real-time“ feedback (~1 echoe in 2 sec)
  AND: support of weaker future targets (MoonLIGHT, etc.)



given

Limited by max laser energy density

$$\frac{\#ECHOES}{SECONDS} \propto \frac{REFLECTOR \times \#SENT_{PHOTONS}}{DISTANCE^4} \times RepetitionRate \times \mathrm{Atmosphere}$$

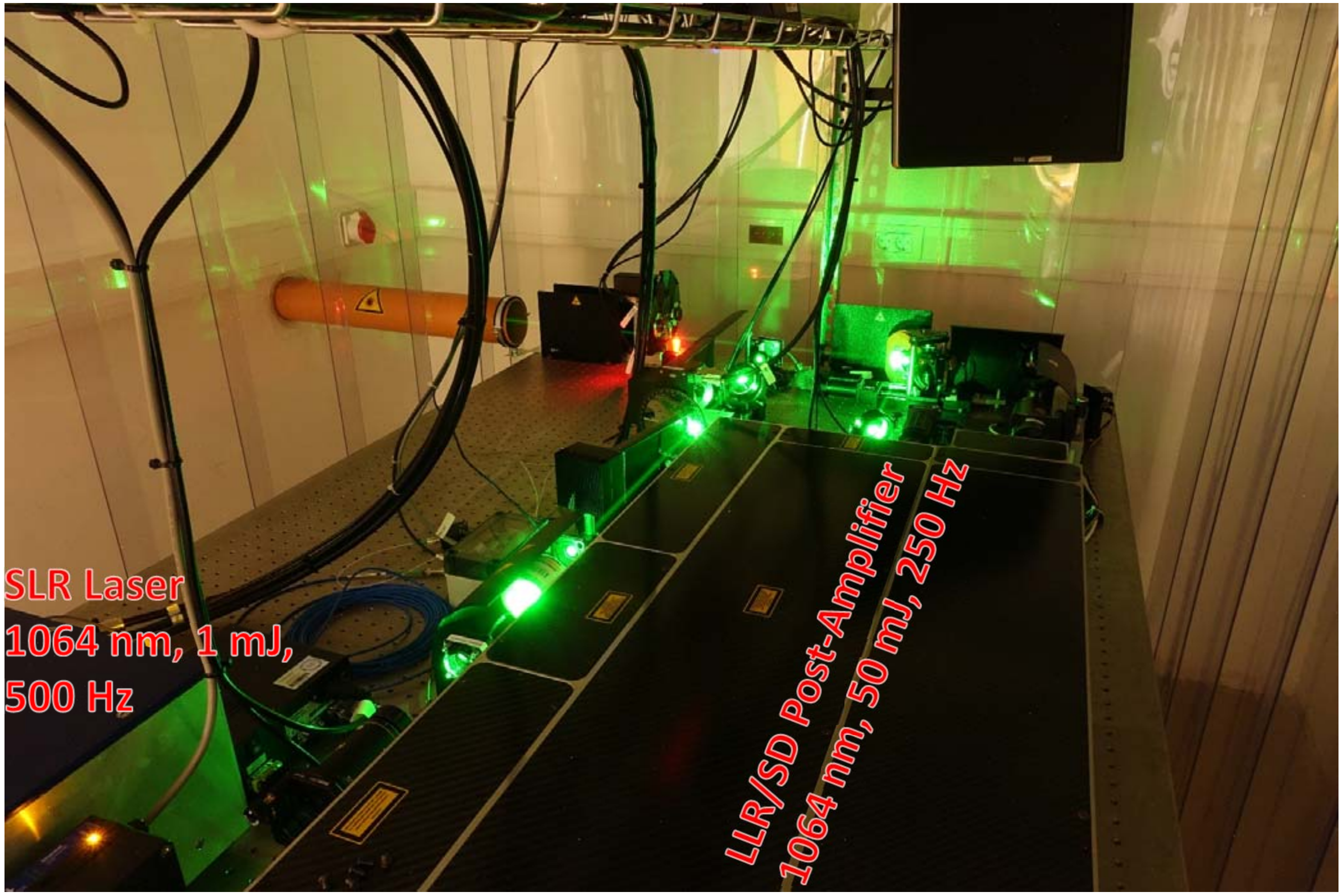
given

Maybe later

hHz T/R-switch @ monostatic WLRS setup for SLR since 2019
Straight forward: Increase repetition rate also for LLR

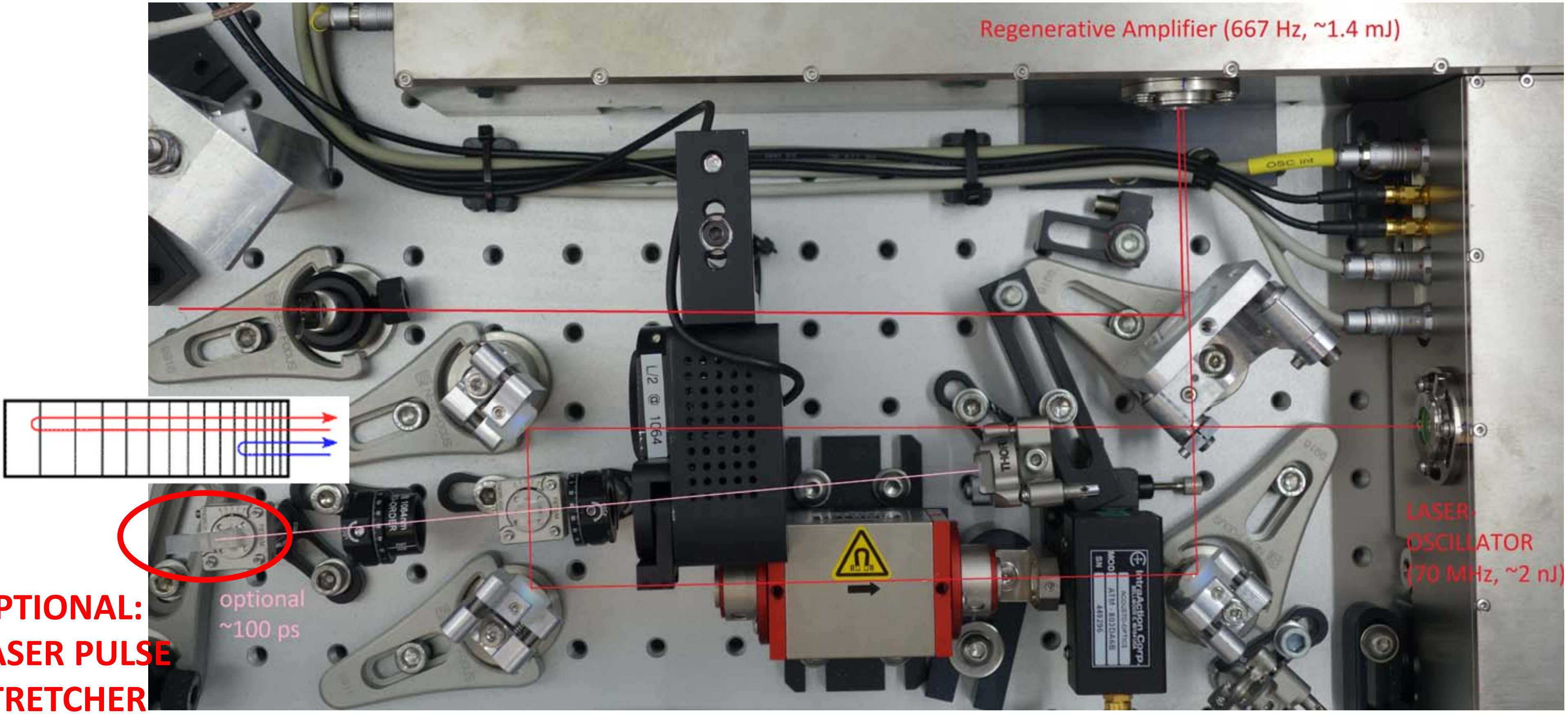
PART 1: Laser Upgrade
- phase 1 (diode pumped post amplifier) -

- Laser post amplifier upgrade to 250 Hz (InnoLas GmbH)
- Initial average power ~ 6 W (25 mJ)
- But:
  - **Reduced single pulse energy (goal: factor 2, initial 8)**
  - **Use of polarisation dependent T/R switch neccessary**



PART 1: Laser Upgrade
- phase 2 (stretcher/compressor) -

REGENERATIVE AMPLIFIER

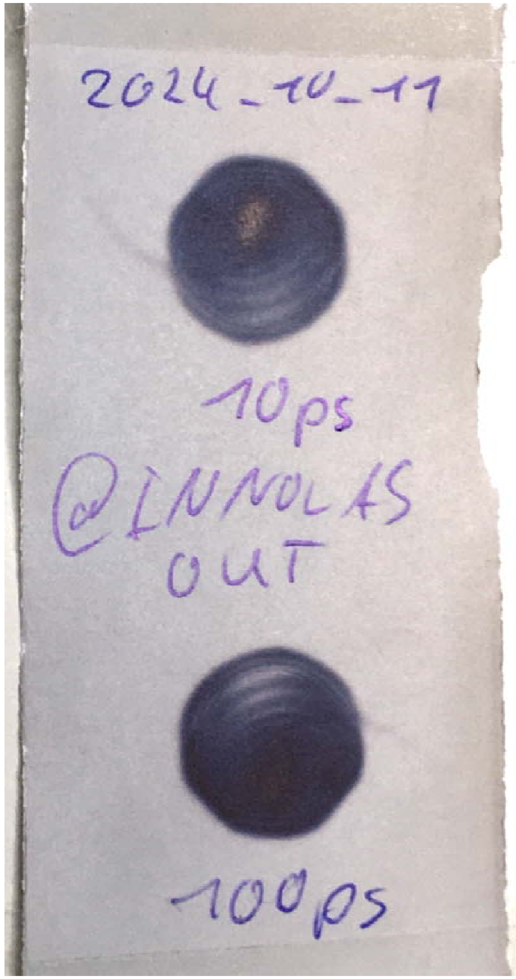


SEED LASER

OPTIONAL:
LASER PULSE STRETCHER
Chriped volume bragg grating (OptiGrate Corp. ~300 ps/nm)

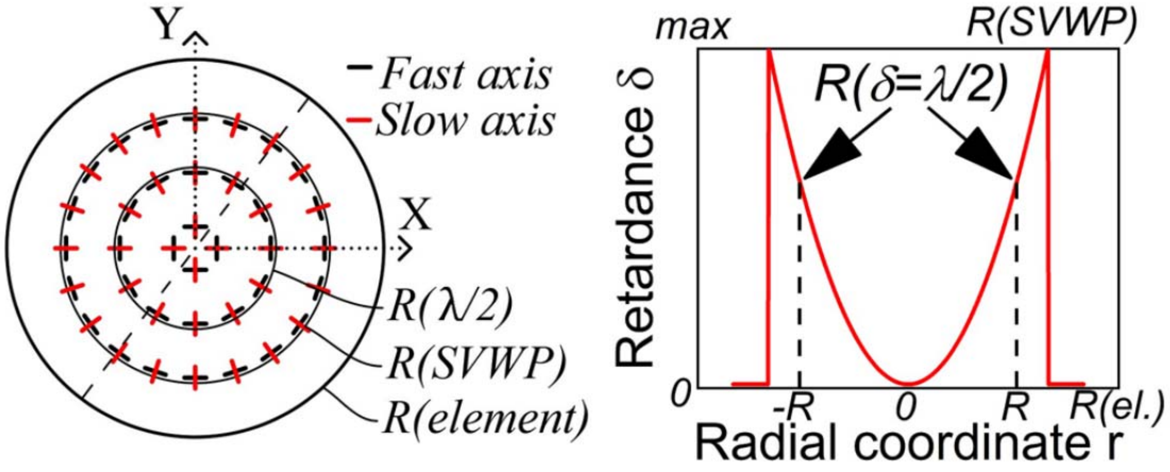
PART 1: Laser Upgrade
- current status -

- Beam profile 100 ps smoother than 10 ps
- Due to implementations → realignment necessary
- Output Power: > 12 Watt

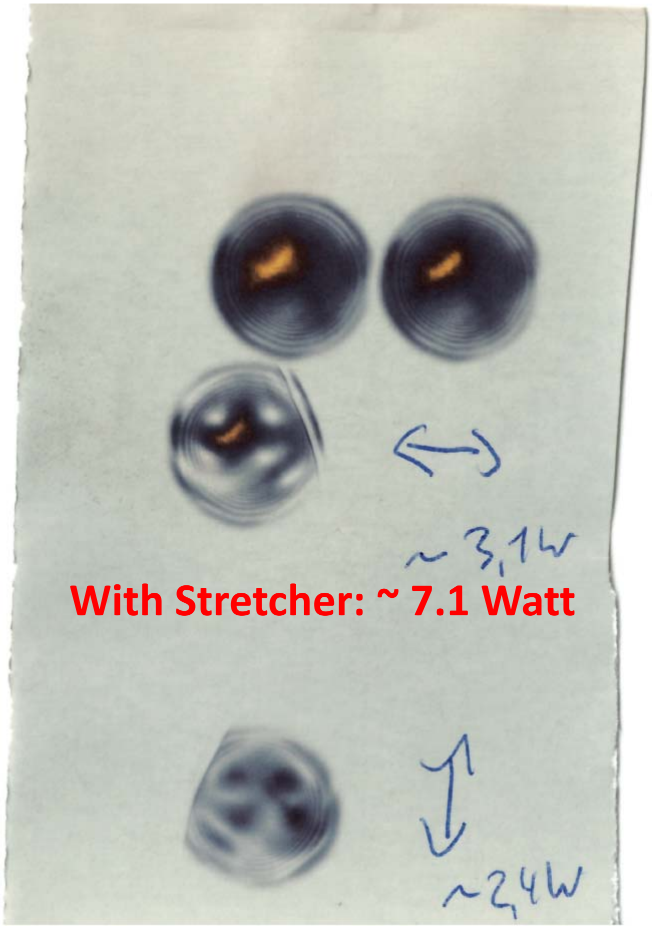


PART 1: Laser Upgrade
- depolarisation -

- Laser light depolarisation due to thermally induced birefringence in laser crystal



Laurynas V., et al.: “Depolarization compensation with a spatially variable wave plate in a 116 W, 441 fs, 1 MHz Yb:YAG double-pass laser amplifier”, (2021)



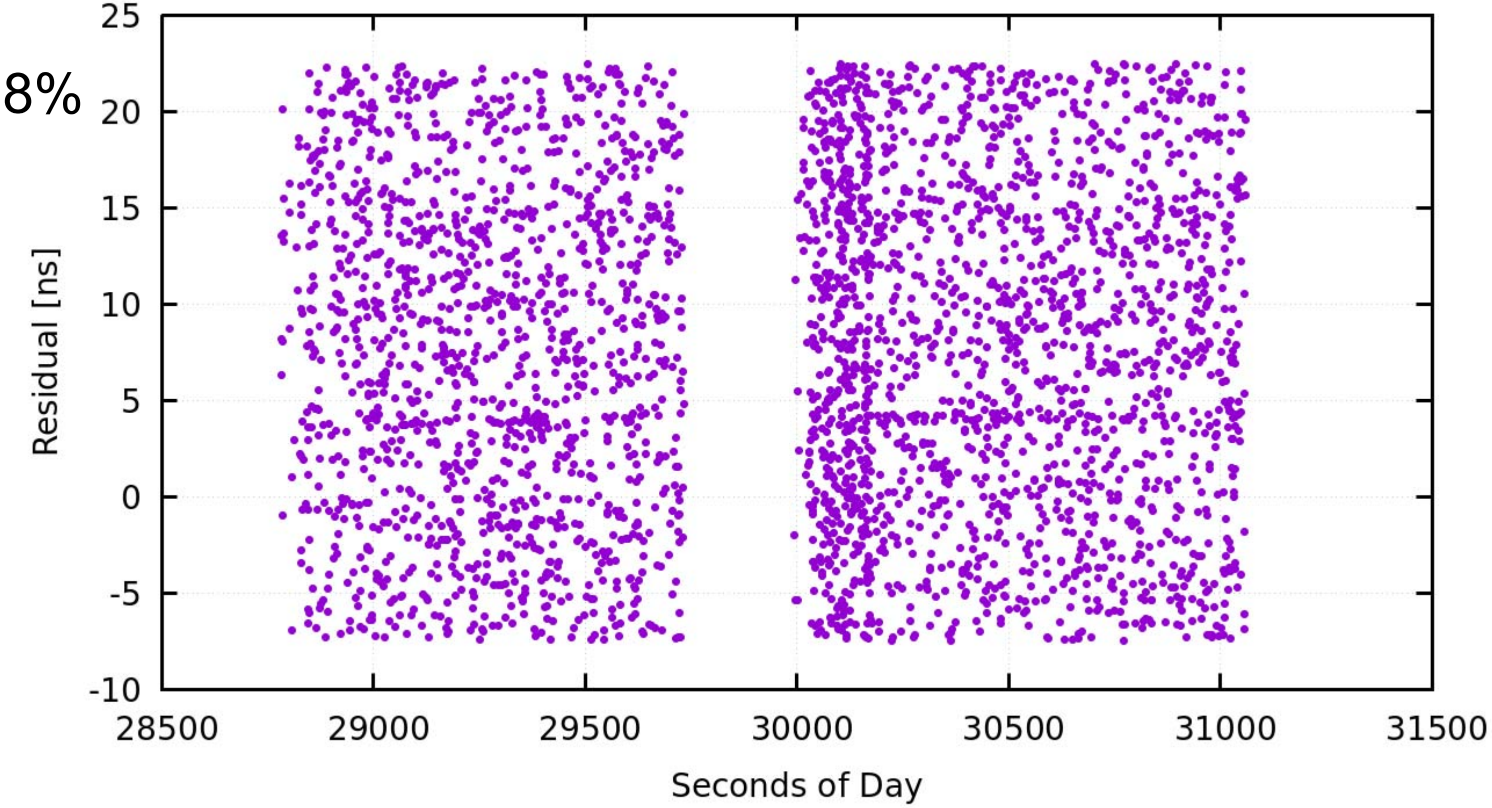
With Stretcher: ~ 7.1 Watt

PART 1: Laser Upgrade
- first light after upgrade -

- Poor conditions during August 2024 → high humidity
- LUNA 17 ranging:

max. Echoe Rate ~0.08% (1 echoe / 5 sec)

- S/N on the edge

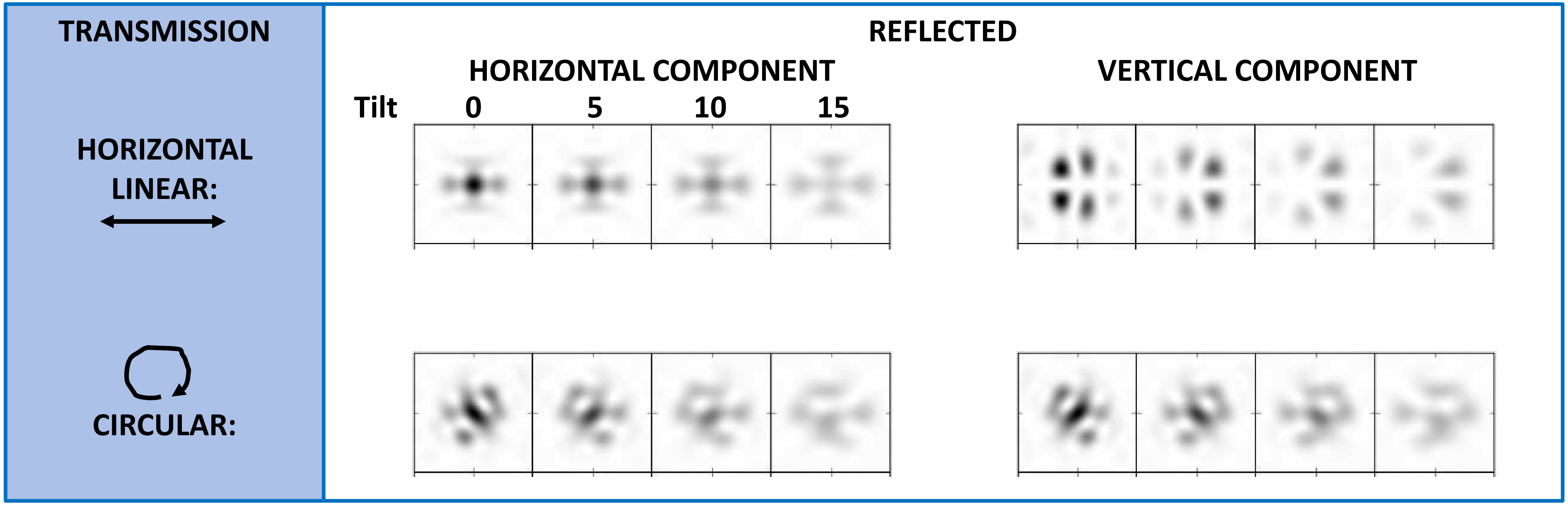


Next Steps:

- Depolarisation compensation
- Beam profile optimisation

PART 2: T/R Upgrade
- FFDP of uncoated CCRs -

- Transmission of linear or circular polarised light possible..



TRANSMISSION

REFLECTED

HORIZONTAL COMPONENT

VERTICAL COMPONENT

HORIZONTAL LINEAR:

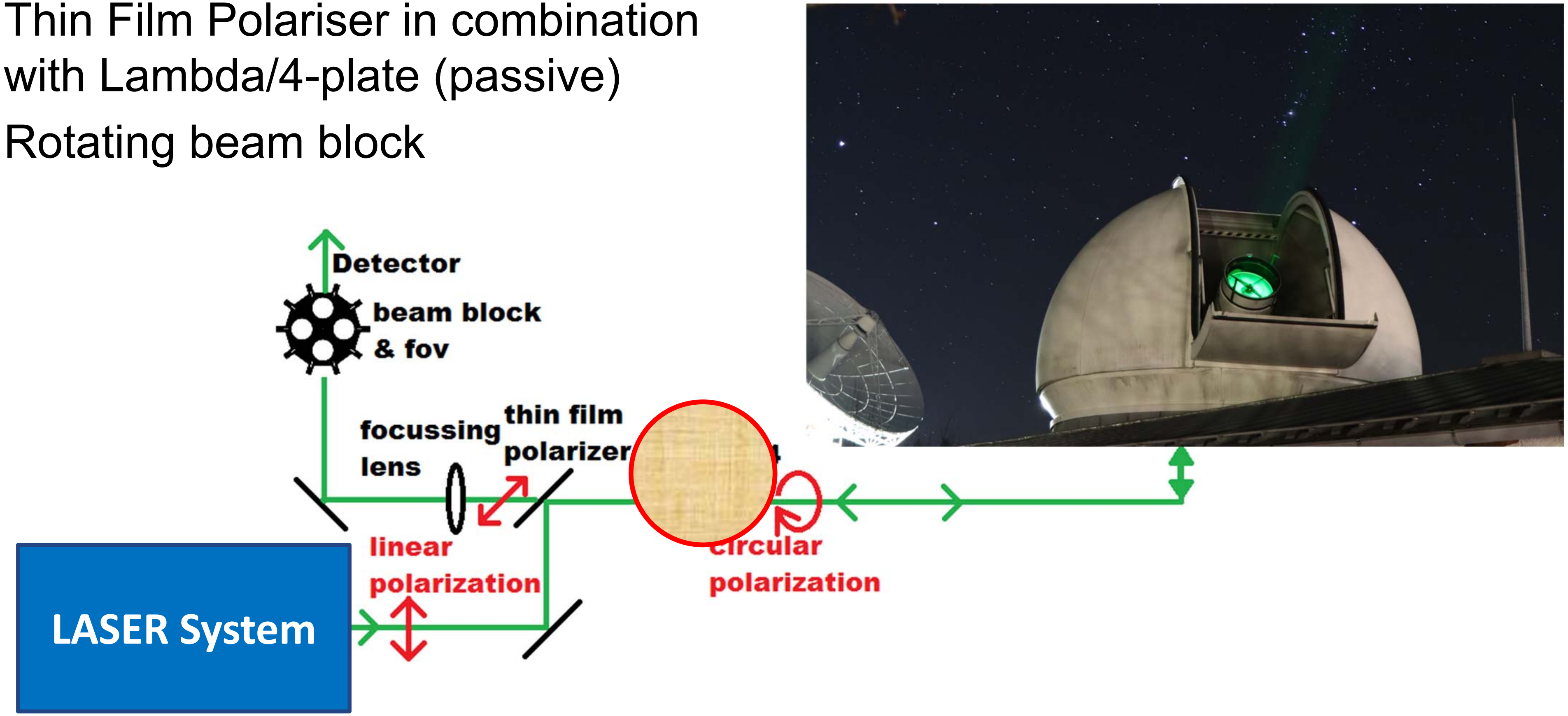
CIRCULAR:

T. W. Murphy and S. D. Goodrow: “Polarization and far-field diffraction patterns of total internal reflection corner cubes”, (2013)

- Detection of horizontal or vertical component possible (not both!)
- CIRCULAR: Energy of main lobe is split in both components (50% loss) → USE LINEAR!

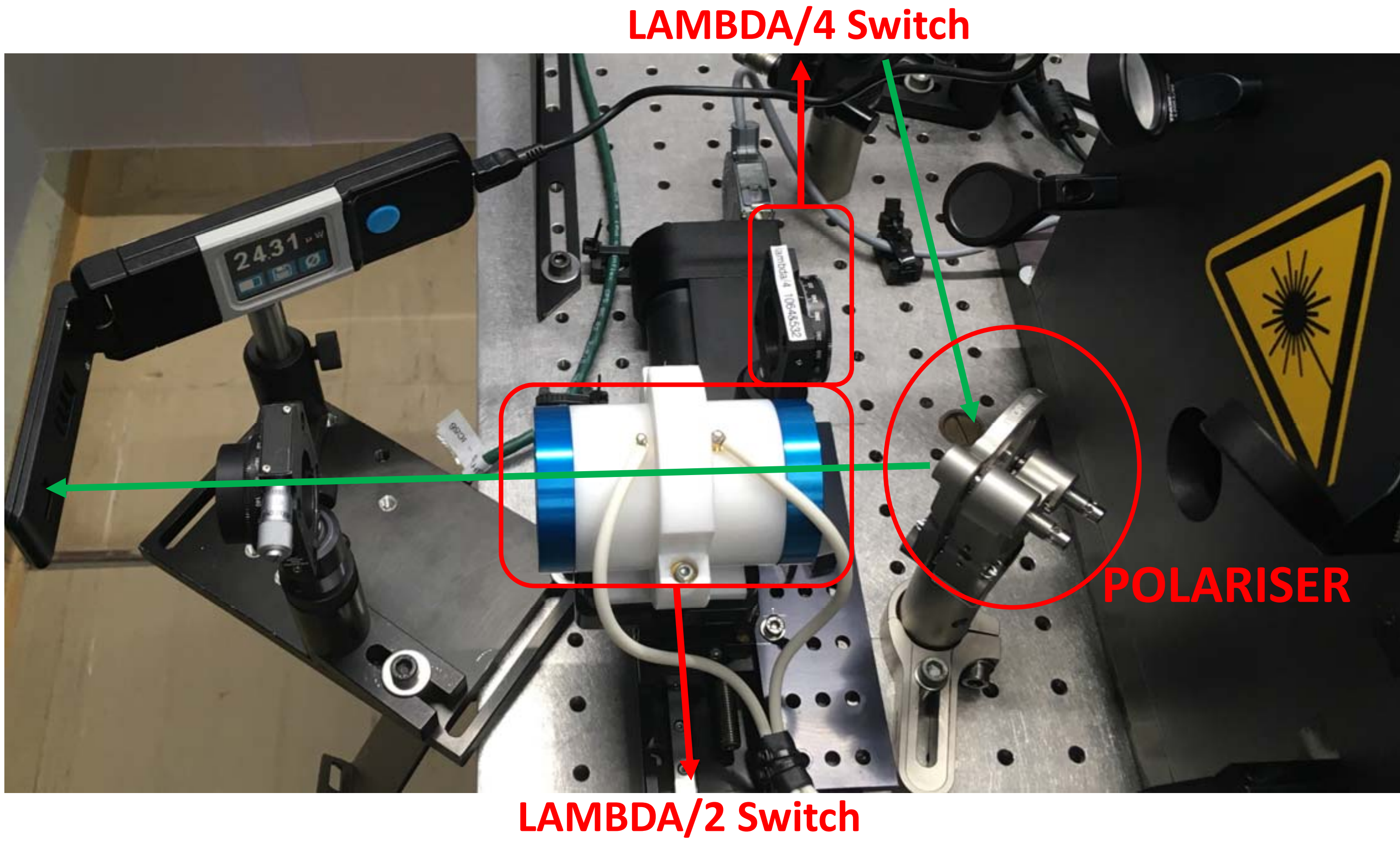
PART 2: T/R Upgrade
- Lambda/4 principle -

- Thin Film Polariser in combination with Lambda/4-plate (passive)
- Rotating beam block



PART 2: T/R Upgrade
- implementation -

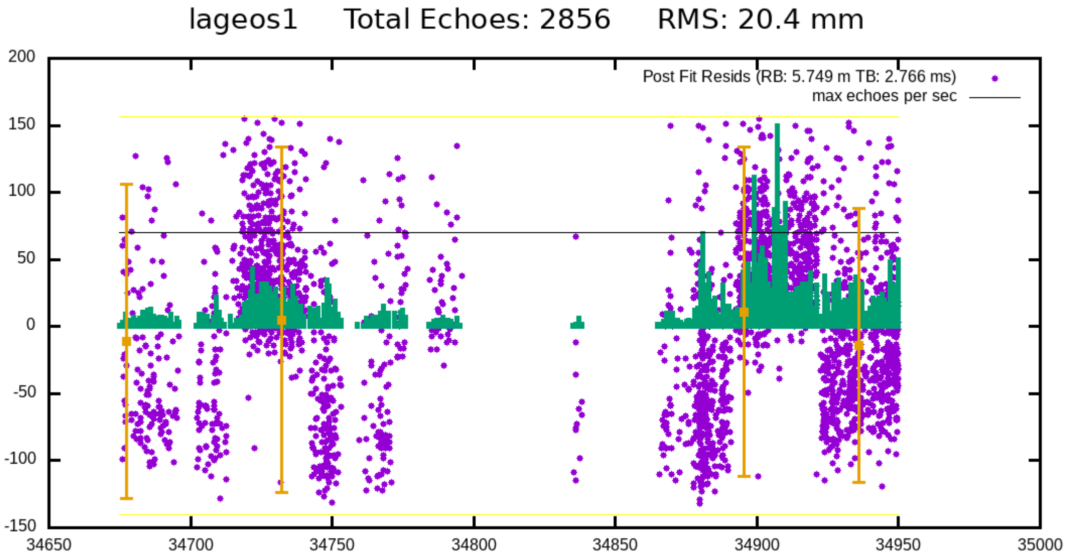
- 25 mm Aperture Pockels-Cell (G&H Photonics Centaur)
- Optional: L/4 or Pockels-Cell L/2 (circular or linear polarisation)



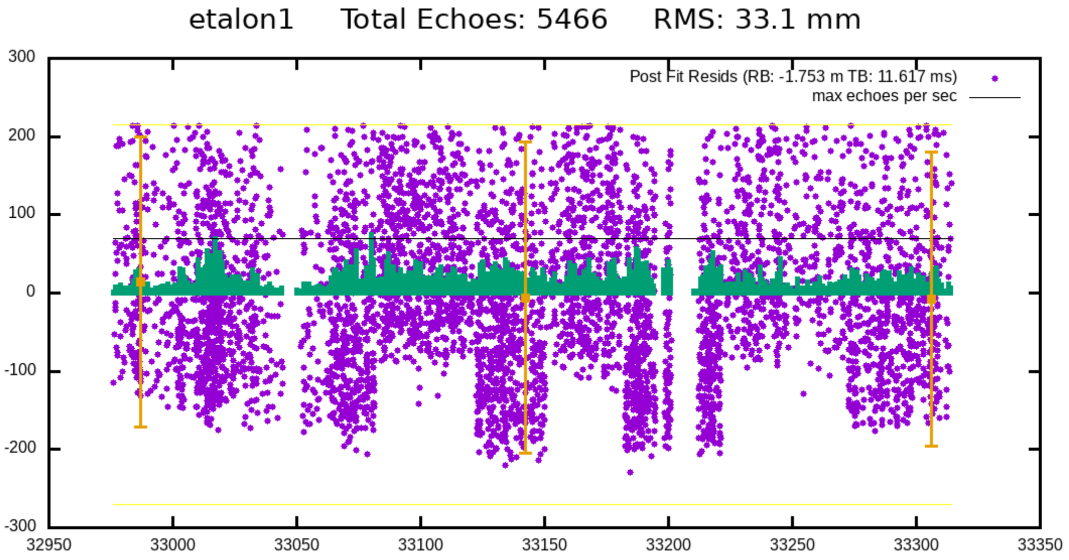
PART 2: T/R Upgrade
- preliminary results -

- Return Rate variation when switching between circular & linear polarisation

Uncoated CCR



Coated CCR



Conclusion

- PART 1:
  - Laser Upgrade Phase 2 finished: > 7 Watt usable laser power
  - In 08/2024 echoes from LUNA17 reflector (coated), after almost 1 year without data
  - Compensation of Depolarisation & Laser Beam profile optimisation pending
- PART 2:
  - T/R switch upgraded to use circular or linear polarised laser light for LLR & SLR
  - Functionality of PC half wave switch verified
  - LLR to uncoated Retroreflector arrays pending (APOLLO15, …)
- Question: should we try to use linear polarisation for SLR (investigate LAGEOS response for circular and linear polarisation)???

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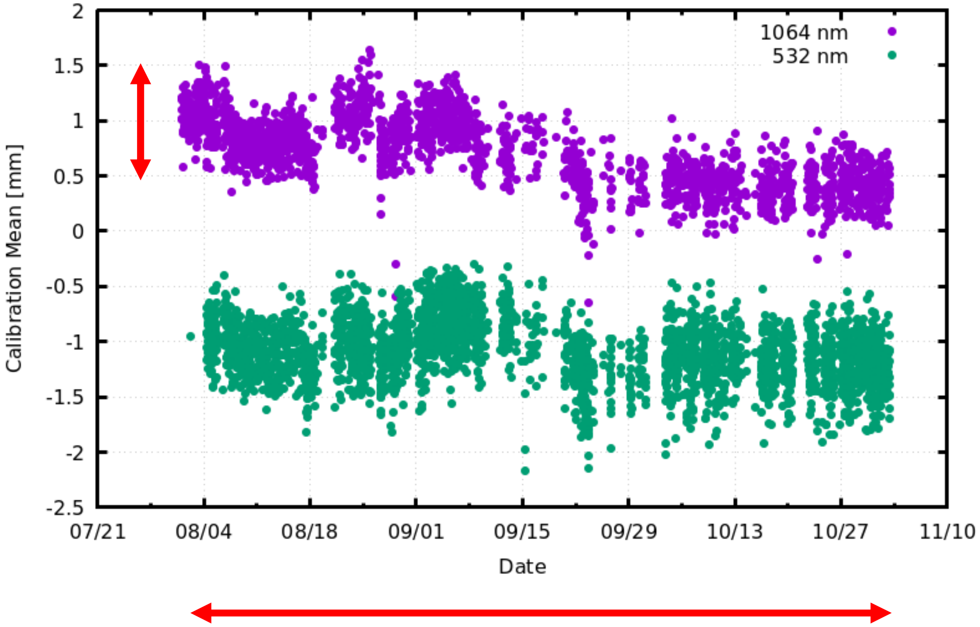
Thank you for your attention!

WLRS
- system calibration -

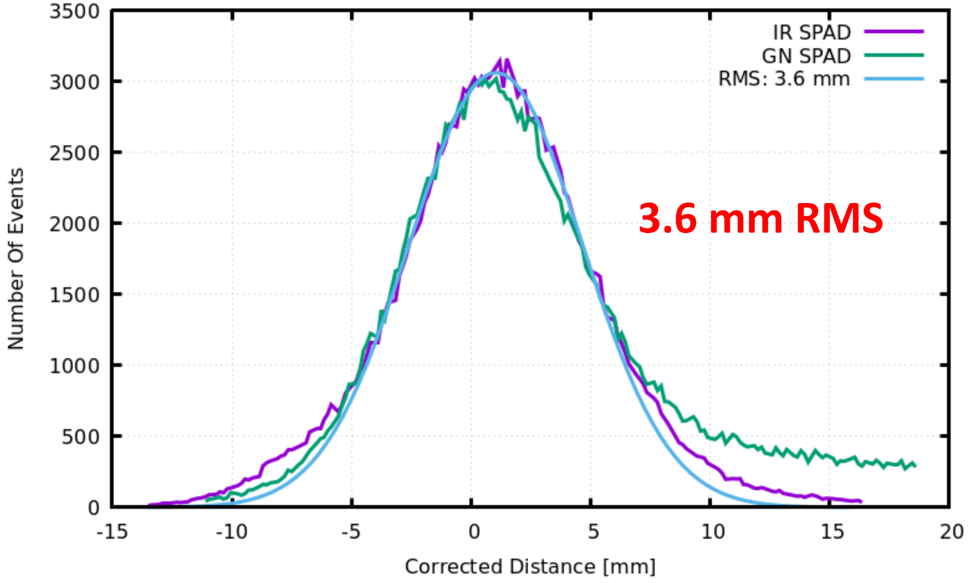
- Measurement to target with known distance to eliminate delay variations in electronics, cables, … & determine system constant (absolute measurement)

1 mm (1-W)

6.7 ps (2-W)



3 months



3.6 mm RMS

Lunar Laser Ranging
- link budget -

$$\textit{Received Number of Photoelectrons}$$
$$\propto \textit{Telescope Aperture} * \textit{Pulse Energy} * \textbf{Detection Efficiency} * \textbf{Wavelength}$$
$$* \textbf{Transmit Gain} * \textbf{Reflector Cross Section}$$

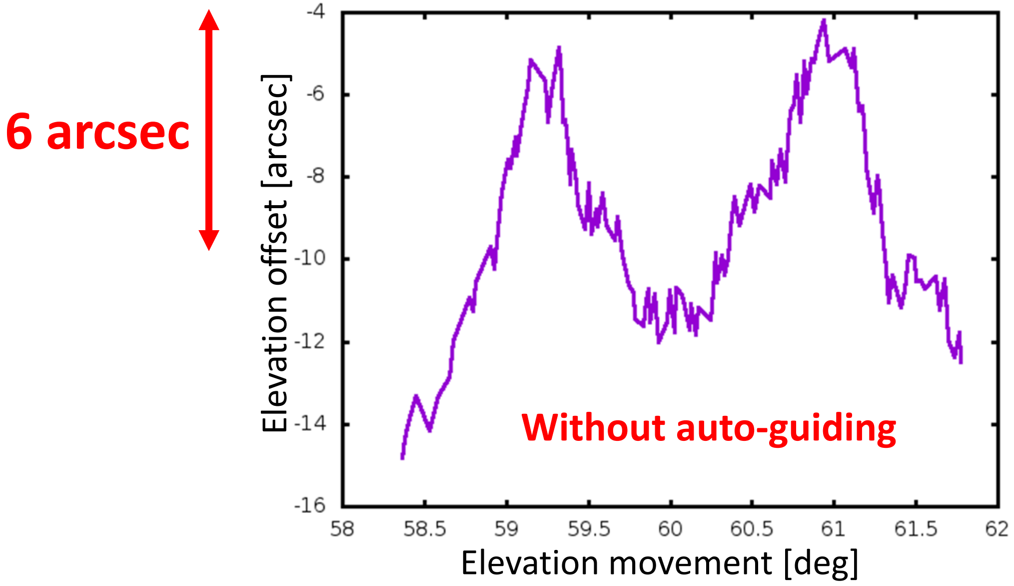
Transmit Gain is function of pointing precision & atmospheric condition

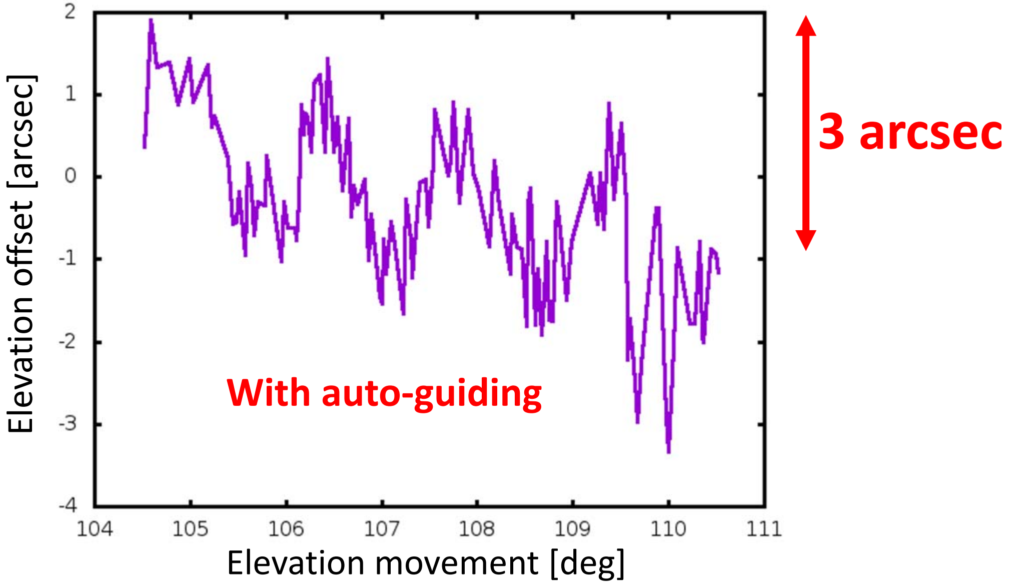
	APOLLO	Grasse MeO	Matera MLRO	WLRS
Telescope Aperture [m]	3.5	1.54	1.5	0.75
Laser Pulse Energy [J]	0.115	0.3 (0.2)	0.1	0.07 & 0.04
Detection Efficiency [%]	30	20 (20)	15	30
Wavelength [nm]	0.532	1.064 (0.532)	0.532	1.064
Elevation [m]	2788	1323	540	665

- WLRS link budget more than one order of magnitude below best performing LLR systems.
- Considering just number of photons, Ranging @ 1064 nm provides ~ factor 4 gain in signal strength.

WLRS
- telescope tracking issue -

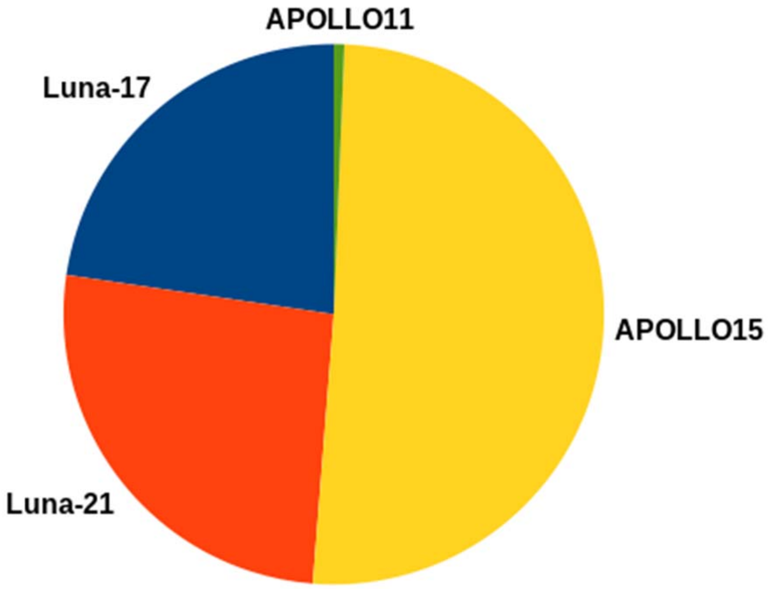
- Tracking error discovered (caused by worm gear)
- Workaround needed
- Camera assisted automatic guiding
- Tracking performance verified by star tracking → Residual RMS error < 1 arcsec

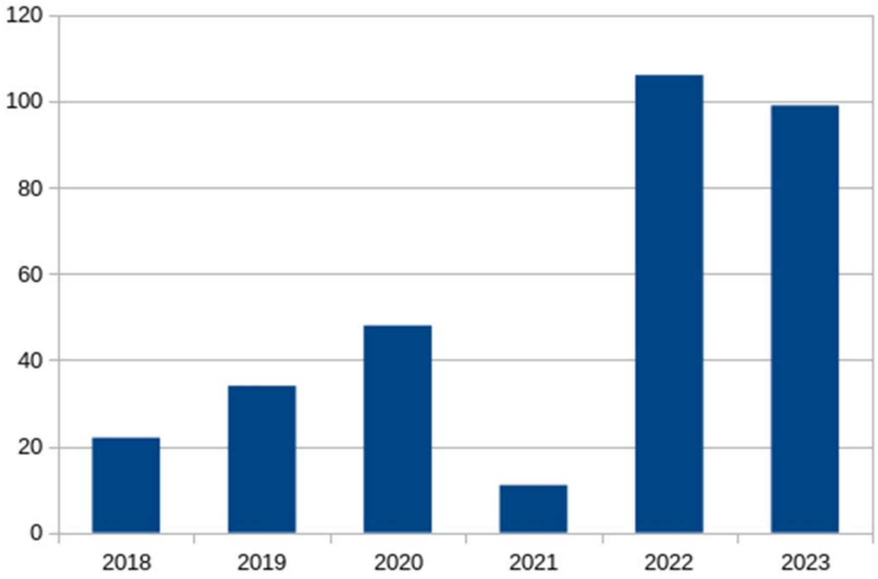




Lunar Laser Ranging
- measurements so far … -

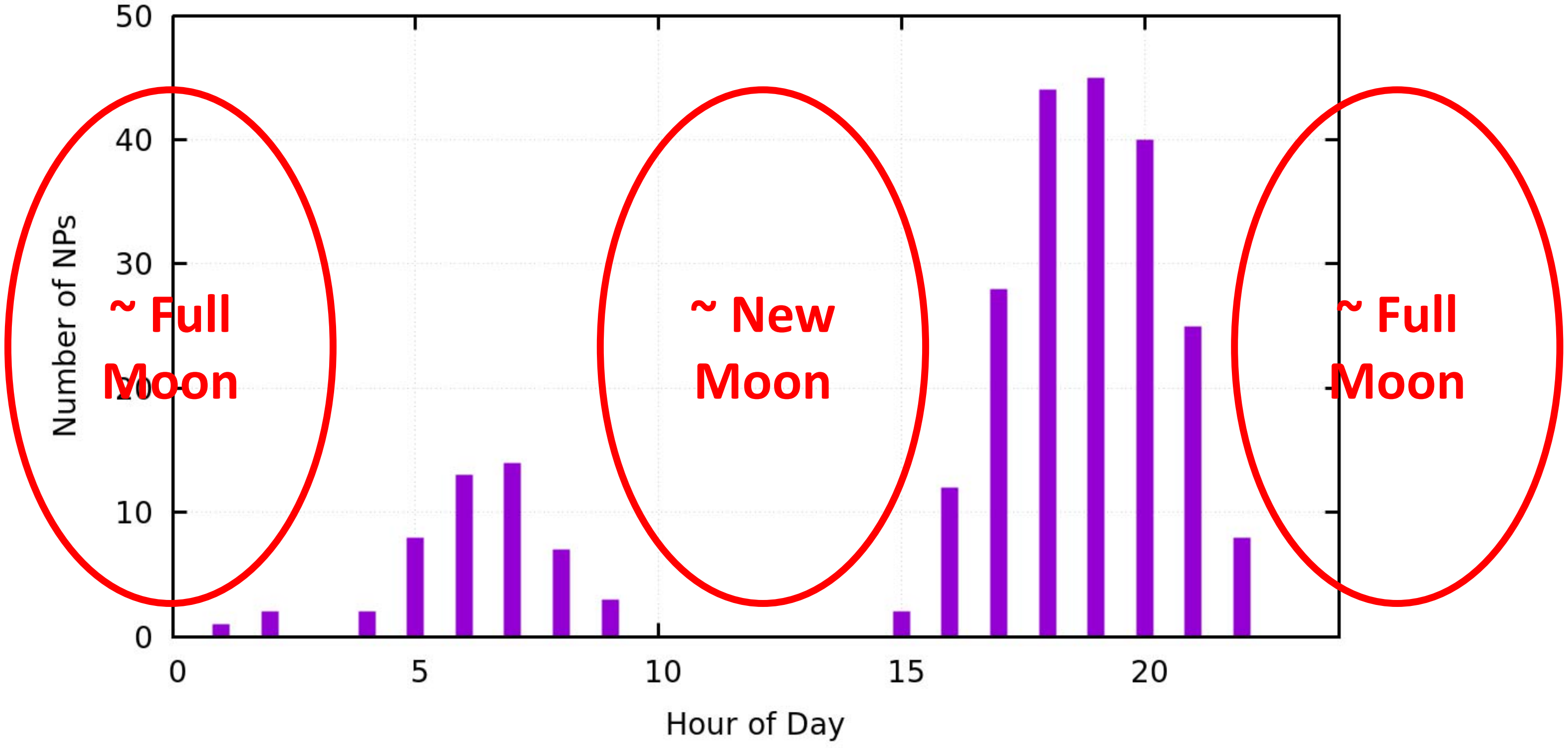
- Target distribution depending mostly on visibility of tracking reference point
- Steady rise of number of „Normal-Points“ since start in 2018





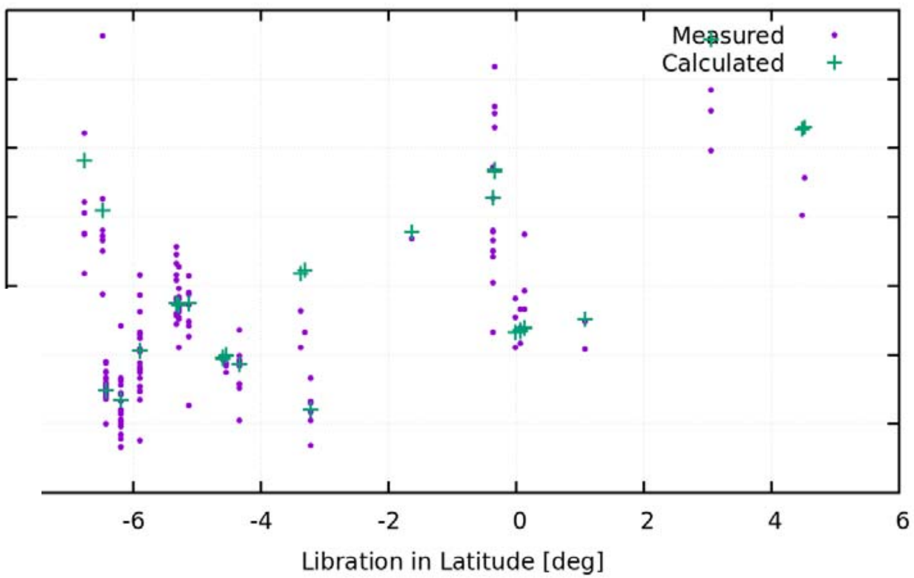
Lunar Laser Ranging
- hour of day -

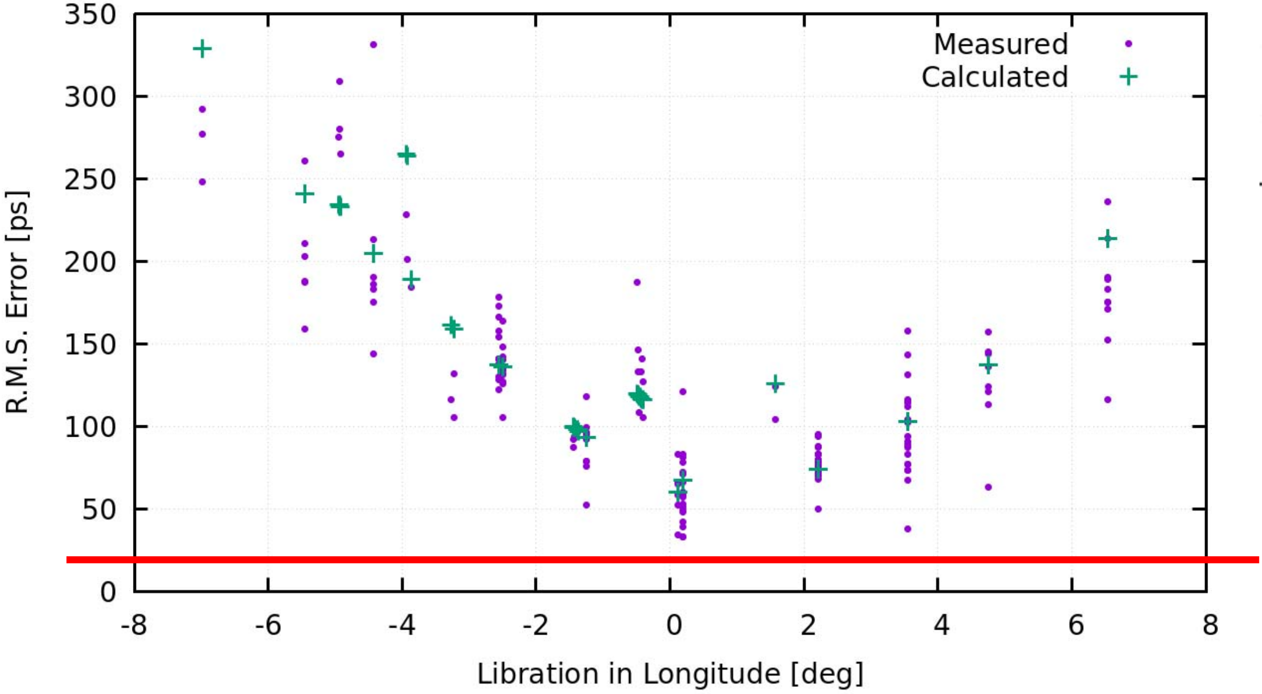
- Daytime ranging uncritical
- Due to Elevation > 55 deg → hour of day represents ~ lunar phase



Lunar Laser Ranging
- APOLLO 15 LRA Target Signature -

- Simple rectangular reflector model, tilted with libration
- Found reflector offset pointing of -1.1 lon & 4.3 lat deg wrt WLRS position, when adjusting the data



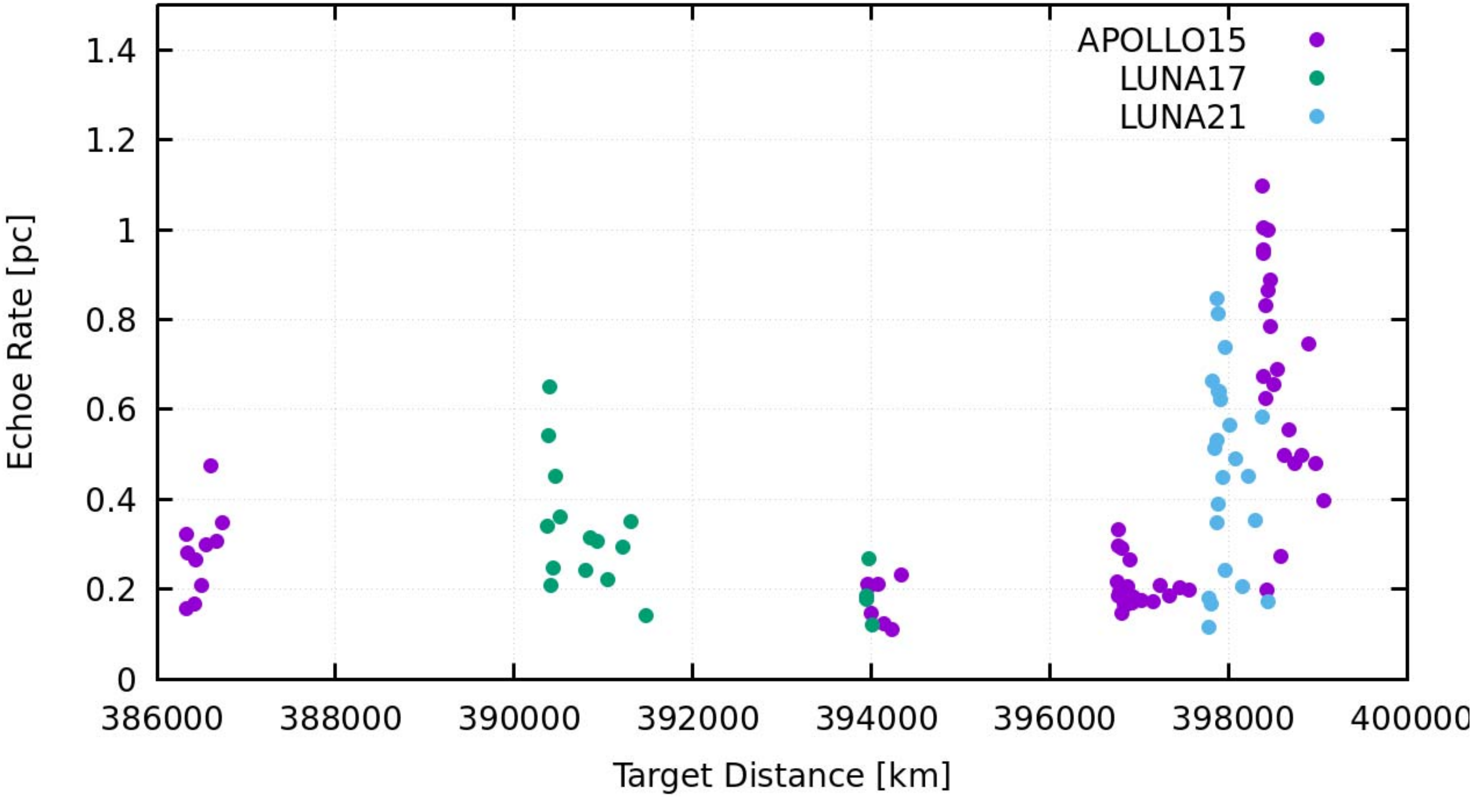


- Method for quality control (good indicator for systematic error)

→ Time correlated single photon counting

WLRS intrinsic timing precision

Lunar Laser Ranging
- echoe rates in 2023 -



- Rates from 1 echoe in 5 … 50 seconds!

→ NO signal strength optimisation possible!!!

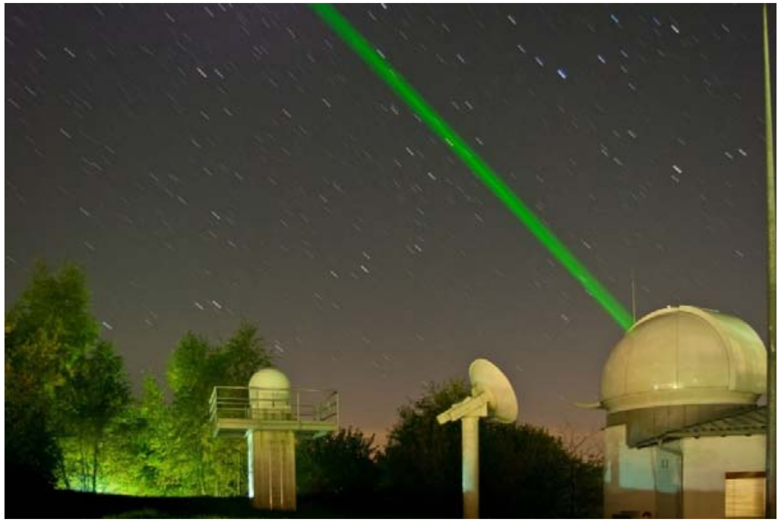
Further Outlook & Conclusion

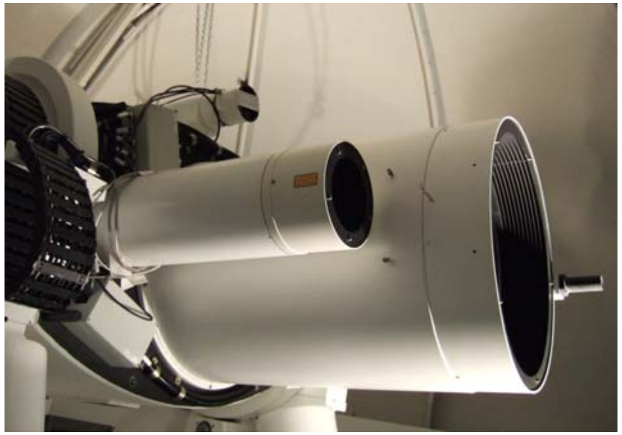
- Fortunately had some money during the last years:
  - Guide star laser
  - Deformable mirror
- GOALS: blind tracking capability & reduce minimum possible elevation

Conclusion:

- LLR timeline started in 2018
- Can not compete with LLR partner stations in terms of amount of data
- Focus on best possible precision and accuracy in combination with connection to reference frames & clocks (SI second)
- With ongoing/upcoming upgrades: Support new Missions with improved CCR!

Laser Ranging Systems





Wettzell Laser Ranging System (WLRS, 1990)

- 75 cm monostatic telescope
  - Identical beam path for transmit/receive
  - Pointing accuracy of optical axes 0,5 “
- Nd:YAG pulse laser
  - 532 nm (green) or 1064 nm (NIR)
  - Pulse width 10 ps (3 mm)
  - 667 pulses per second (20 for LLR)
- Observations
  - Satellites (all heights)
  - **Lunar Laser Ranging**, Space Debris Ranging
  - Scientific projects, e. g. Time Transfer

Satellite Observing System Wettzell (SOS-W, 2014)

- 16 cm / 50 cm bistatic telescope
- Ti:SAP pulse laser
  - 425 nm (blue) or 850 nm (NIR)
  - 1000 pulses per second (1 kHz)
- Observations
  - Satellites (all heights)

Next Steps

- Depolarisation
- Re-Alignment & improved air conditioning
- Optimisation beam profile

Introduction
- in the past -

- ???: Long accumulation times necessary to identify lunar echoes
- RR ~0.2% @ 20 Hz -> ~2.4 Echoes per Minute!!!
- Pointing optimisation during ranging NOT possible
- Instead: Optimise pointing wrt crater position & auto-guiding