Sub-Millimeter Lunar Laser Ranging: Novel Approach to Moon Reference Frame

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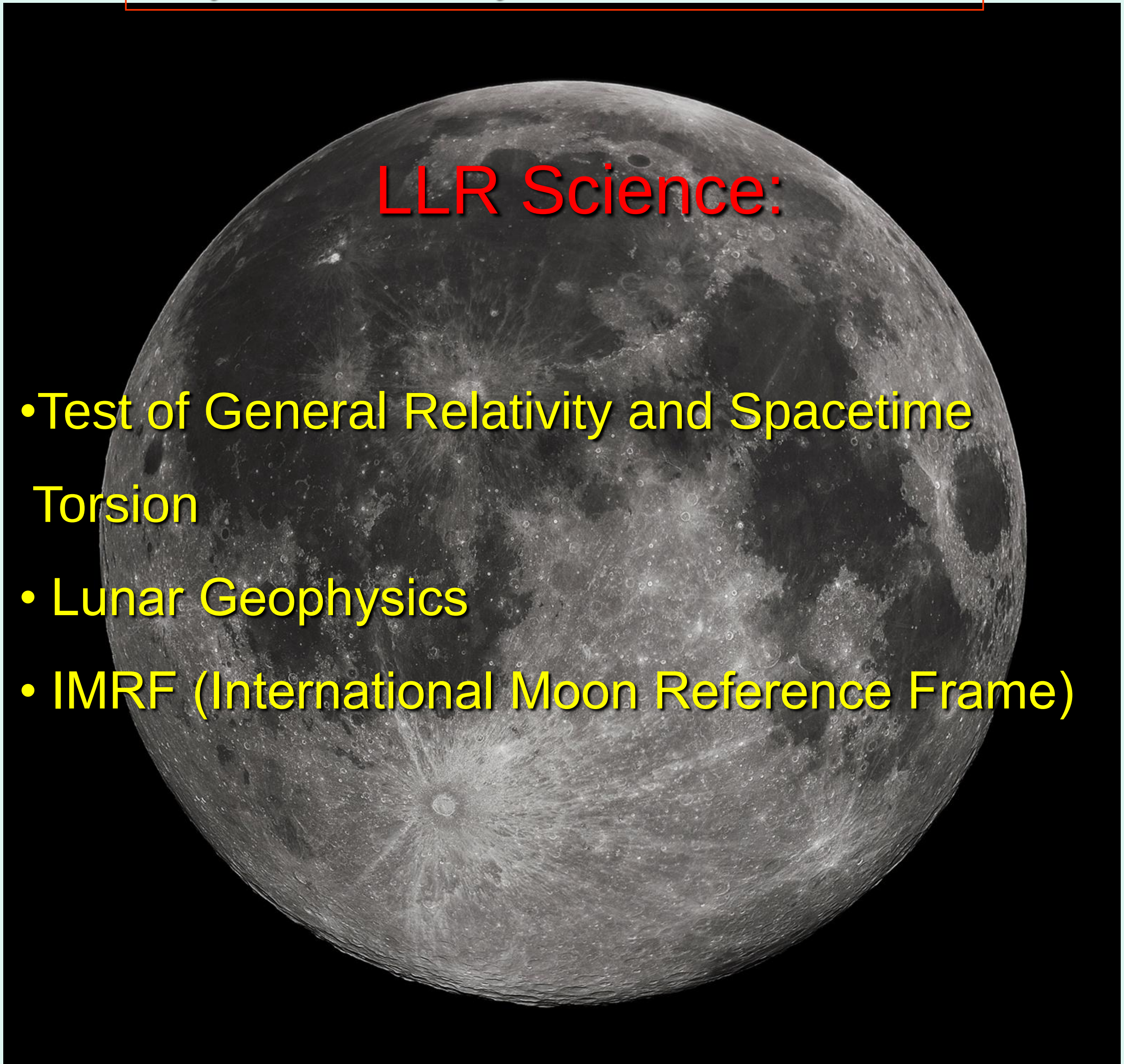
Outline

1. Lunar Laser Ranging Science
- 1.1. Precision Tests of General Relativity
- 1.2. Lunar geophysics (selenophysics)
- 1.3. ITRF and IMRF

2. Super Lunar Laser Ranging (SLLR)
- 2.1. Schematic diagram of Super LLR
- 2.2. New Caucasus Observatory of Moscow University
- 2.3 Time and frequency synchronization system
- 2.4. Laser
- 5.8. Super LLR Configuration

3. Conclusion

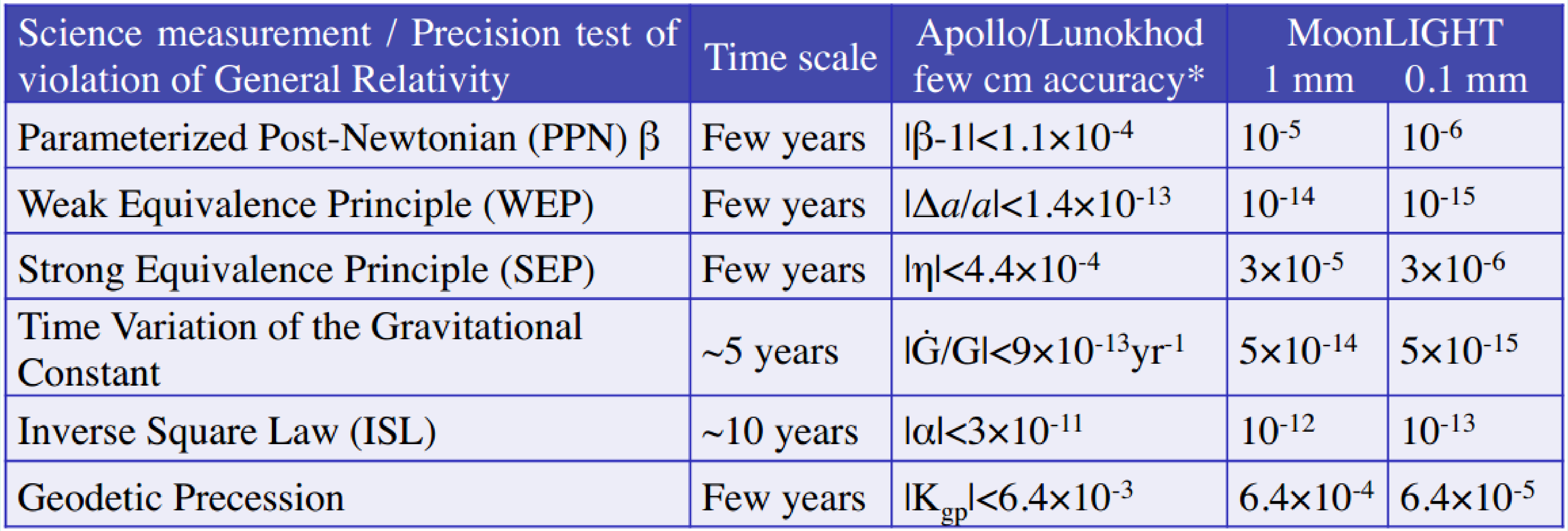
Why it is necessary to do



LLR Science:

- Test of General Relativity and Spacetime Torsion
- Lunar Geophysics
- IMRF (International Moon Reference Frame)

Targets of new advanced experiments in LLR



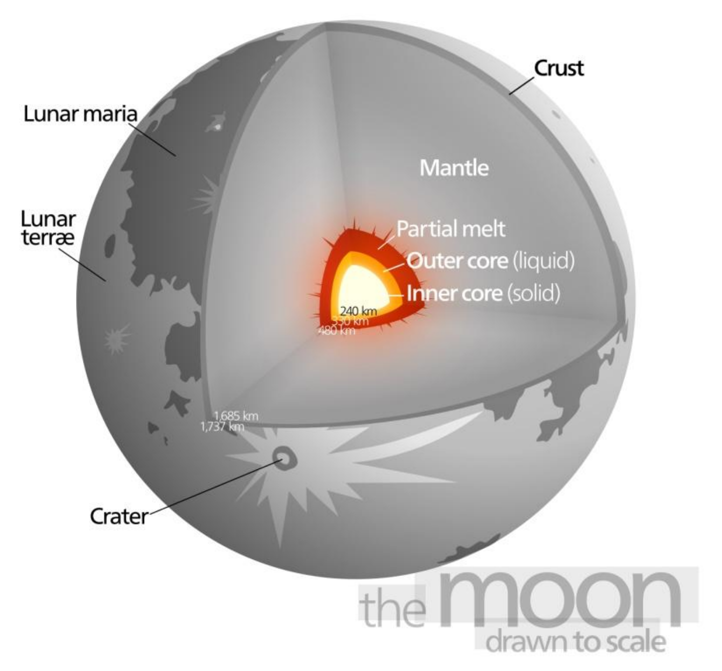
Science measurement / Precision test of violation of General Relativity	Time scale	Apollo/Lunokhod few cm accuracy*	MoonLIGHT	
			1 mm	0.1 mm
Parameterized Post-Newtonian (PPN) β	Few years	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	Few years	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	Few years	$\lvert\eta\rvert<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	~5 years	$\lvert\dot{G}/G\rvert<9\times10^{-13}\text{yr}^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}
Geodetic Precession	Few years	$\lvert K_{gp}\rvert<6.4\times10^{-3}$	6.4×10^{-4}	6.4×10^{-5}

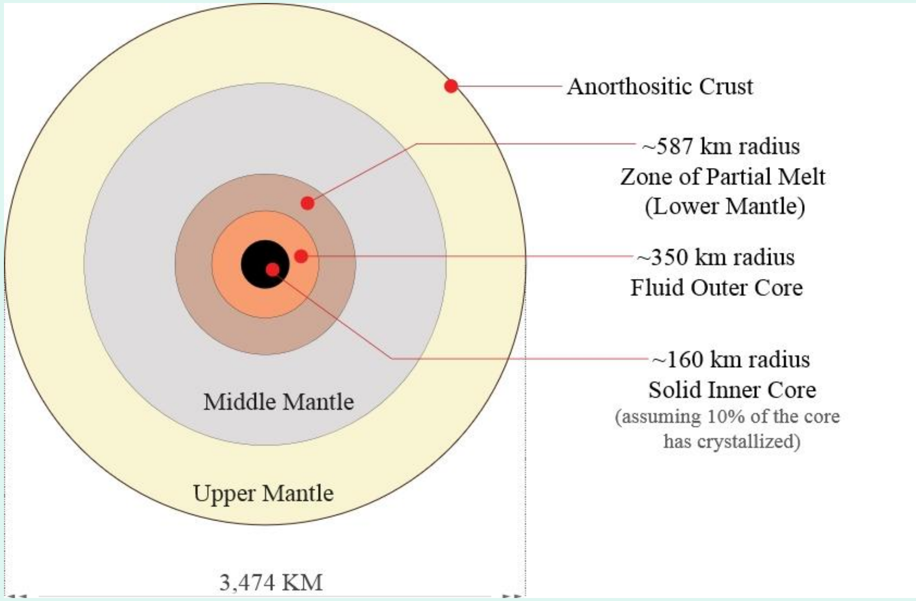
Towards sub-millimeter accuracy!

Williams, Turyshev, Boggs (2004)

LLR: Lunar geophysics (selenophysics)

- Libritions, Interior parameters
- Love numbers
- Presence of a liquid core in the Moon, having a radius of ~ 350 km.





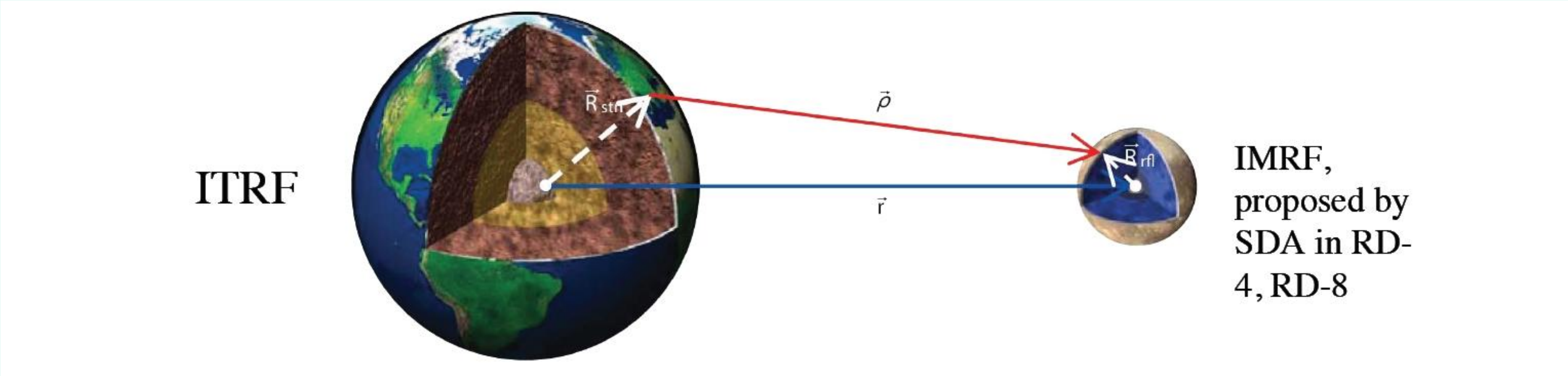
LLR: ITRF and IMRF (International Moon Reference Frame)

ITRF (International Terrestrial Reference Frame):

- Coordinate-and- time support

IMRF (International Moon Reference Frame):

- Referenced to ITRF with laser and/or radio; realized by network of geodetic points.
- For lunar surface exploration and colonization
- Link of Principal Axes and Mean Earth - systems

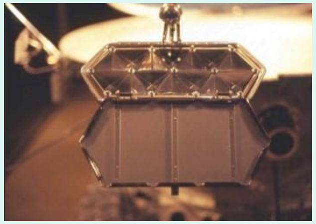


Advanced lunar laser ranging stations (achieved accuracy 1-3 mm)

APOLLO – 3,5 m (Apache Point, USA)

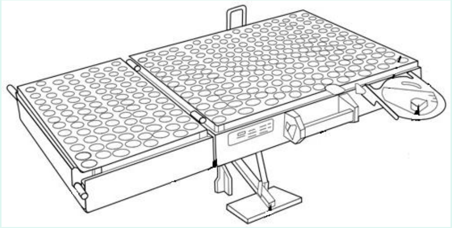
MeO – 1,54 m (Grasse, France)

Accuracy 1-3 mm is the physical limitation with multi-CCR arrays



Луноход-1, Луноход-2
14 шт.
Ø65

Apollo-11, Apollo-14
100 шт.
Ø38



Apollo-15
300 шт.
Ø38

Improvement in LLR efficiency and precision can only come from single large retroreflectors.

Laser parameters and “frozen turbulence”

Laser repetition rate

Number of measurement to obtain the normal point with 0.1 mm precision

$$N_m > \frac{RMS_L^2}{(0.1)^2} = \frac{(2.6)^2 \div (4.3)^2}{0.01} \approx 680 \div 1850$$

Let’s return photons: 0.1/pulse, to obtain 0.1 mm precision one needs

$$N_{pulse} = \frac{N_m}{0.1/\,pulse} \approx 6800 \div 18500$$

During the time of “frozen turbulence” $t_{fr} \approx 100$ ms
must be radiated ~ $10^4 \div 2 \times 10^4$ pulses,

→ Laser repetition rate:

$$LRR \approx \frac{10^4 \div 2\times 10^4}{10^{-1} s} \approx (10^5 \div 2\times 10^5) Hz$$

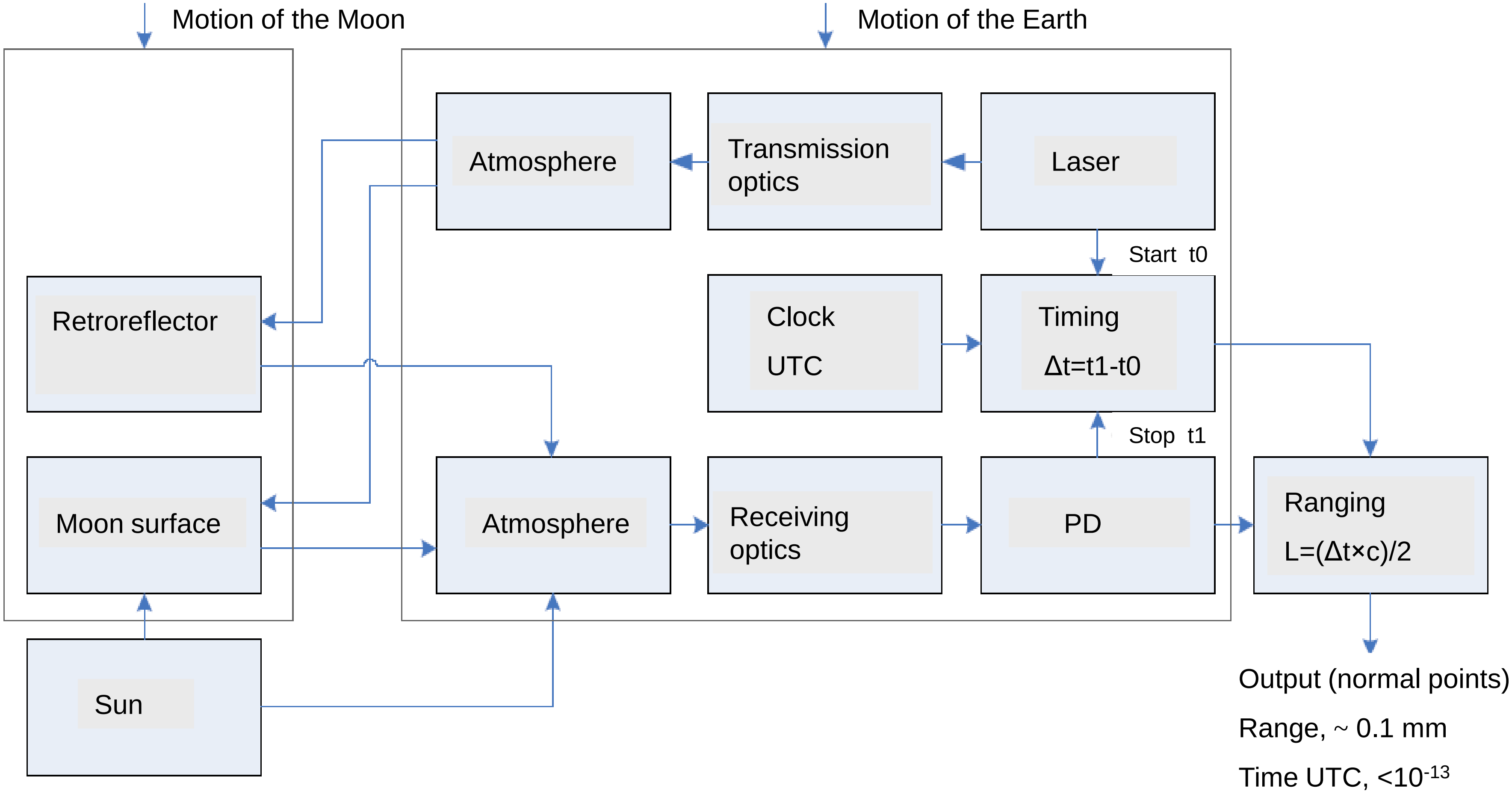
LRR~100 kHz.

Super Lunar Laser Ranging (SLLR)

- New Retroreflector
- Telescope with aperture 1,5 – 3 m
- High Laser Repetition Rate and “Frozen” Atmosphere
- H-maser
- Photodetector ?
- Super LLR Configuration

Super Lunar Laser Ranging (SLLR)

Schematic diagram of Super LLR



Motion of the Moon

Motion of the Earth

Atmosphere

Transmission optics

Laser

Start t0

Retroreflector

Clock

UTC

Timing

Δt=t1-t0

Stop t1

Moon surface

Atmosphere

Receiving optics

PD

Ranging

L=(Δt×c)/2

Sun

Output (normal points)

Range, ~ 0.1 mm

Time UTC, <10^{-13}

Super Lunar Laser Ranging (SLLR) / Telescope

New Caucasus Observatory of Moscow University

Observatory location: N43^{o}44', E42^{o}40', mt. Shatdzhatmaz, 2112m a.s.l., alpine coverage. No higher mountains in 20km around.

•Yearly average temperature is +2^{o}C, range of clear night temperatures is +18 to -17^{o}C. Day/night contrast is <5^{o}C.

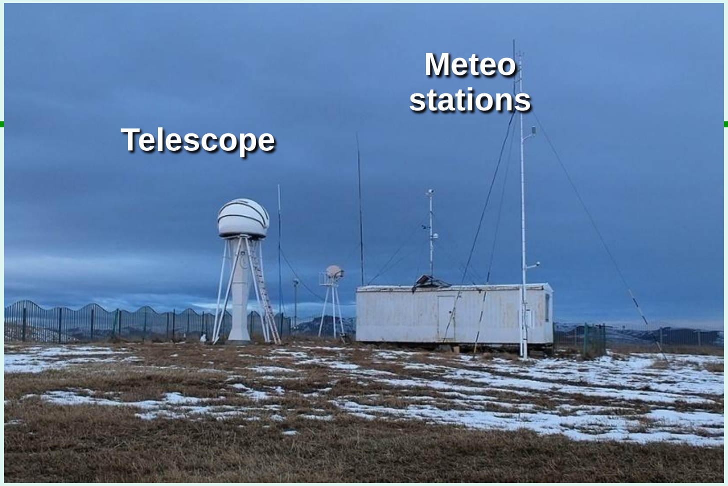
• Wind in clear sky nights: 2.3m/s (median; dir is SE and W).

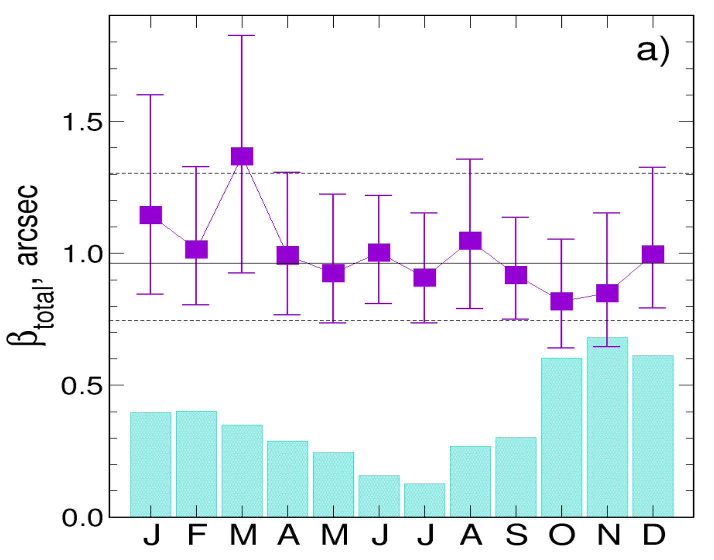
•Average RH (relative humidity): summer ~80%, winter ~65%.

•“Clear astronomical nights” 1330 h/year (~200 nights/year)

Super Lunar Laser Ranging (SLLR) / Telescope

Site astroclimate monitoring (SAM)

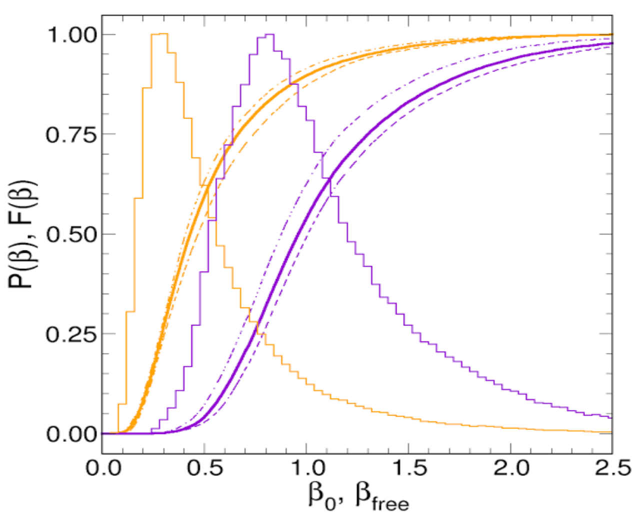




- Image quality behavior by months (2007-2013; medians and quartiles of distribution). Histograms below: input in the total data volume.

- Median seeing is 0.96''; mode (most probable) value 0.81''.

- March outlier is related to high wind shear in lower atmosphere (2-4km).



Integral and differential seeing distributions(– - free atmosphere (h>1km), – - full image quality β_0): in 10% of cases $\beta_0 < 0.6''$ (in Oct-Nov mostly).

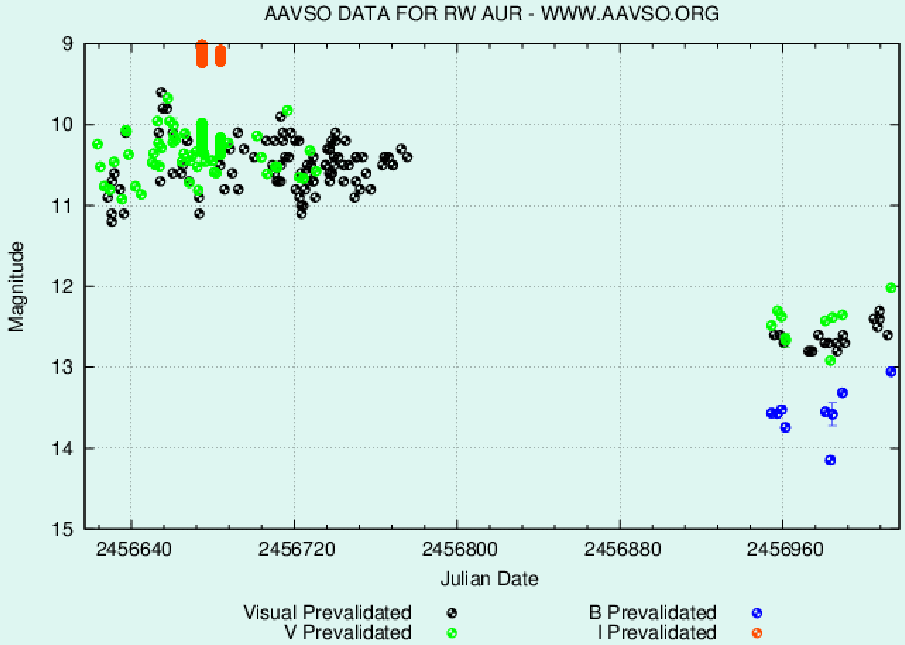
Super Lunar Laser Ranging (SLLR) / Telescope

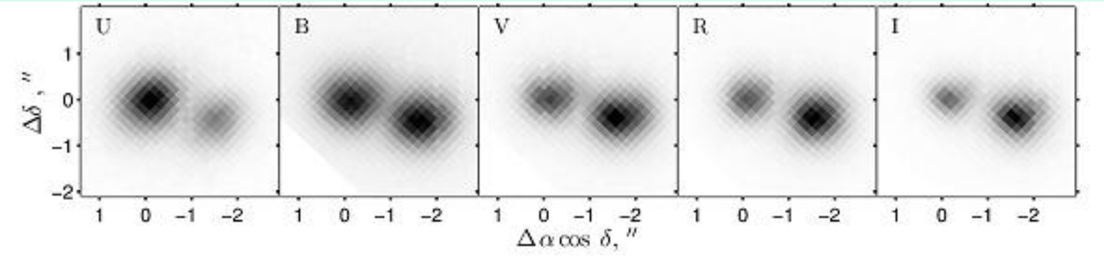
2.5m Telescope: basic parameters

- **Ritchey-Chretien design**; D=2500мм, F_{equiv}=20м;
- **M1**: Zerodur, th_{edge}=250мм, cell:27ax/3rad pts
- $D_{EE=80\%}$~0.4''. FOV=40' with WFC (λ ≈ 0.3-1μ) (test data)
- **Mount:** Alt-Az, direct drive, 3^o/sec, δ_{point}=5'', $\delta_{blind\ track}$(10min)=0.2''
- **Focal stations:** 1 Cassegrain (C1) + 4 Nasmyth (N1-N4); change <2min; mechanical derotation and Autoguiding in C1, N1; optical derotator and bench in N2
- **Dome**: slit 3m; thermal insulation + Air conditioning
- **Manufacturers**: optics+cells: SAGEM/REOSC (France); mount Nanjing Inst. of Astron. Optics & Technology (China) ; dome: Gambato SAS (Italy).

Super Lunar Laser Ranging (SLLR) / Telescope

First on-sky scientific tests (November 2014)

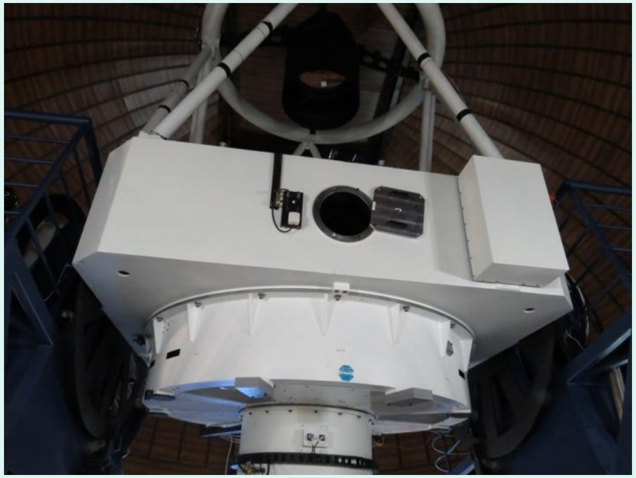


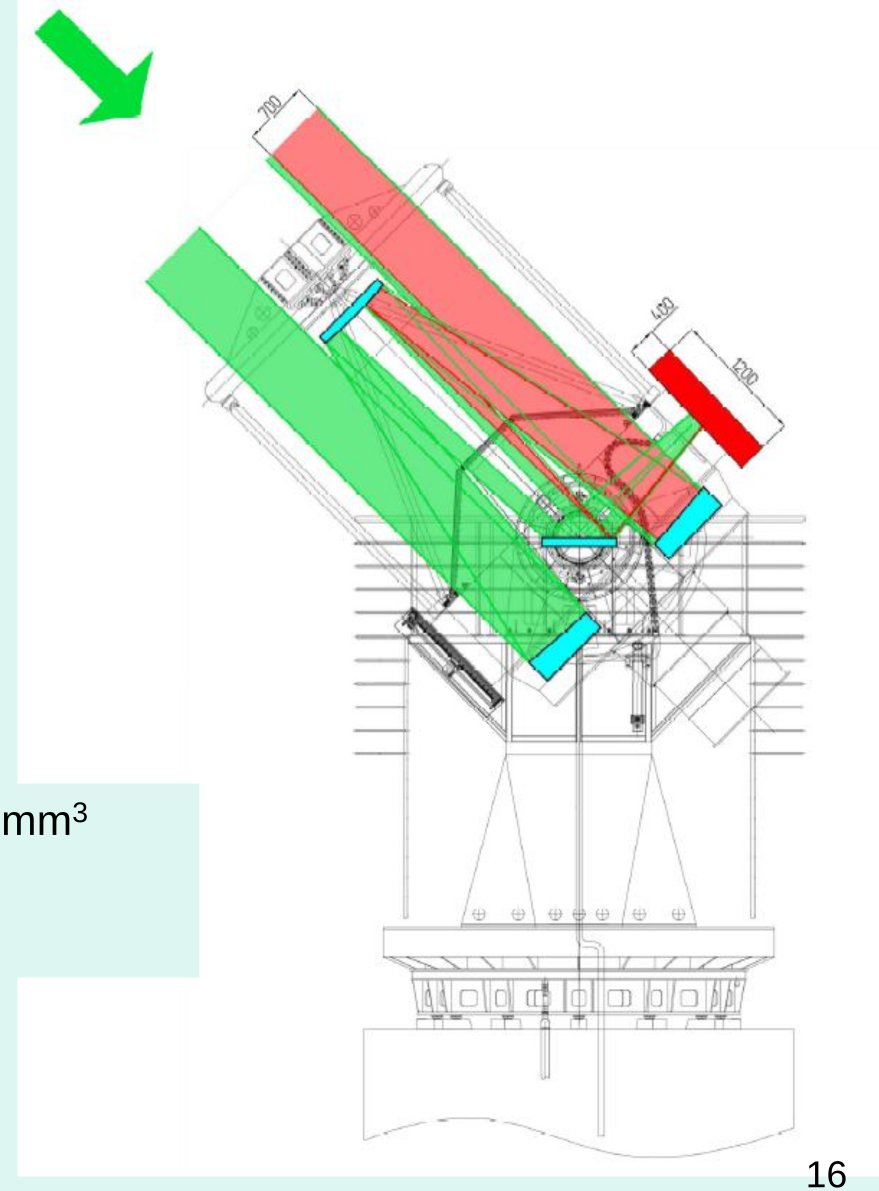


Left: a group of galaxies (Stephan's Quintet) . Right: a double young star RW Aur (ρ=1”.45) photometry in UBVRI (**FWHM 0”.5-0”.8**) *(Antipin et al, IBVS 6126, 2015).*

Design of SLLR in Nasmyth-3 focus set

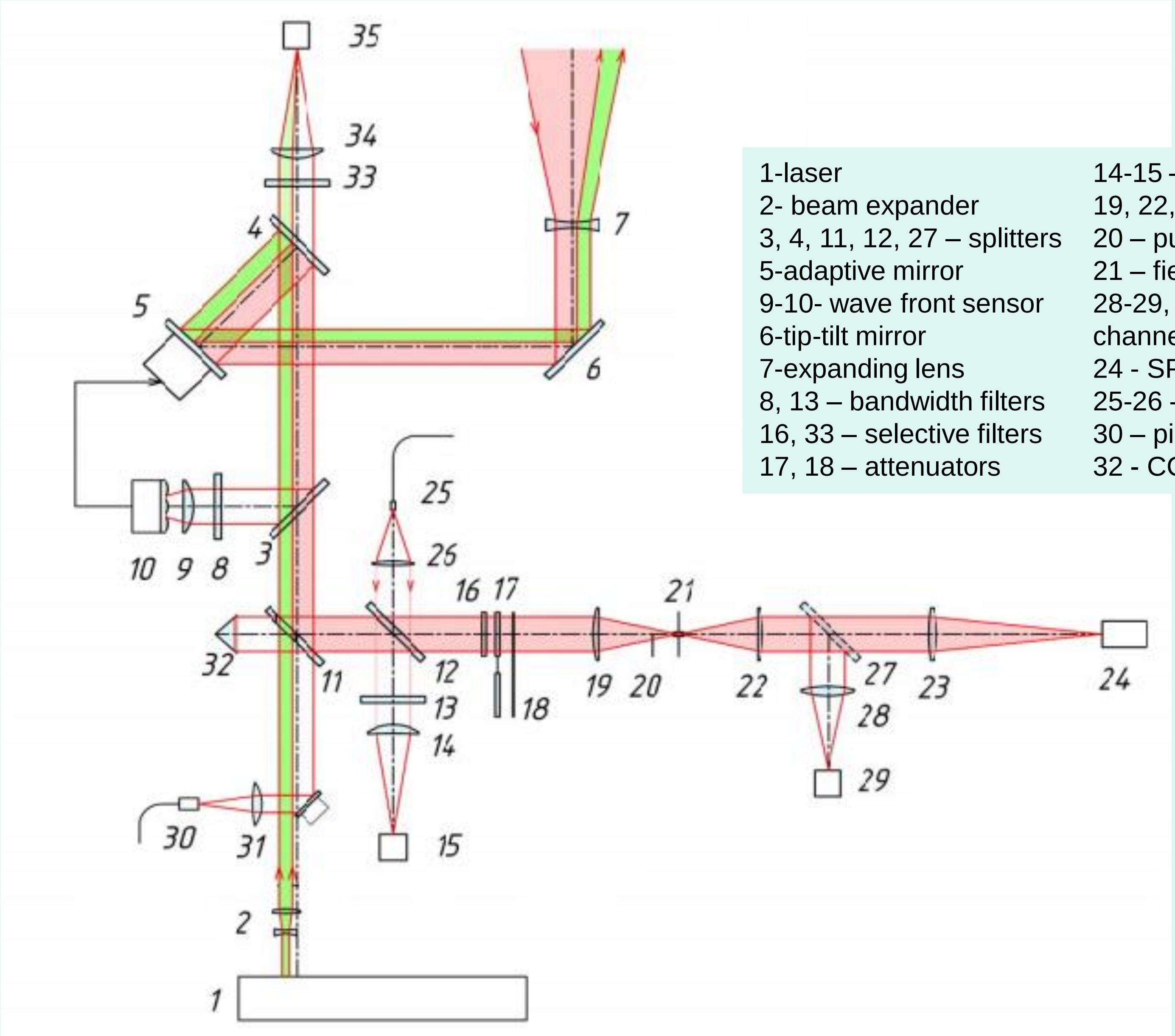
Placement of SLLR in Nasmyth-3 focus set (variant-2)





External dimensions - 1200×500×300 mm^3
Weight - 120 kg
Power – 1,5 kW max

OPTICAL LAYOUT



1-laser
2- beam expander
3, 4, 11, 12, 27 – splitters
5-adaptive mirror
9-10- wave front sensor
6-tip-tilt mirror
7-expanding lens
8, 13 – bandwidth filters
16, 33 – selective filters
17, 18 – attenuators

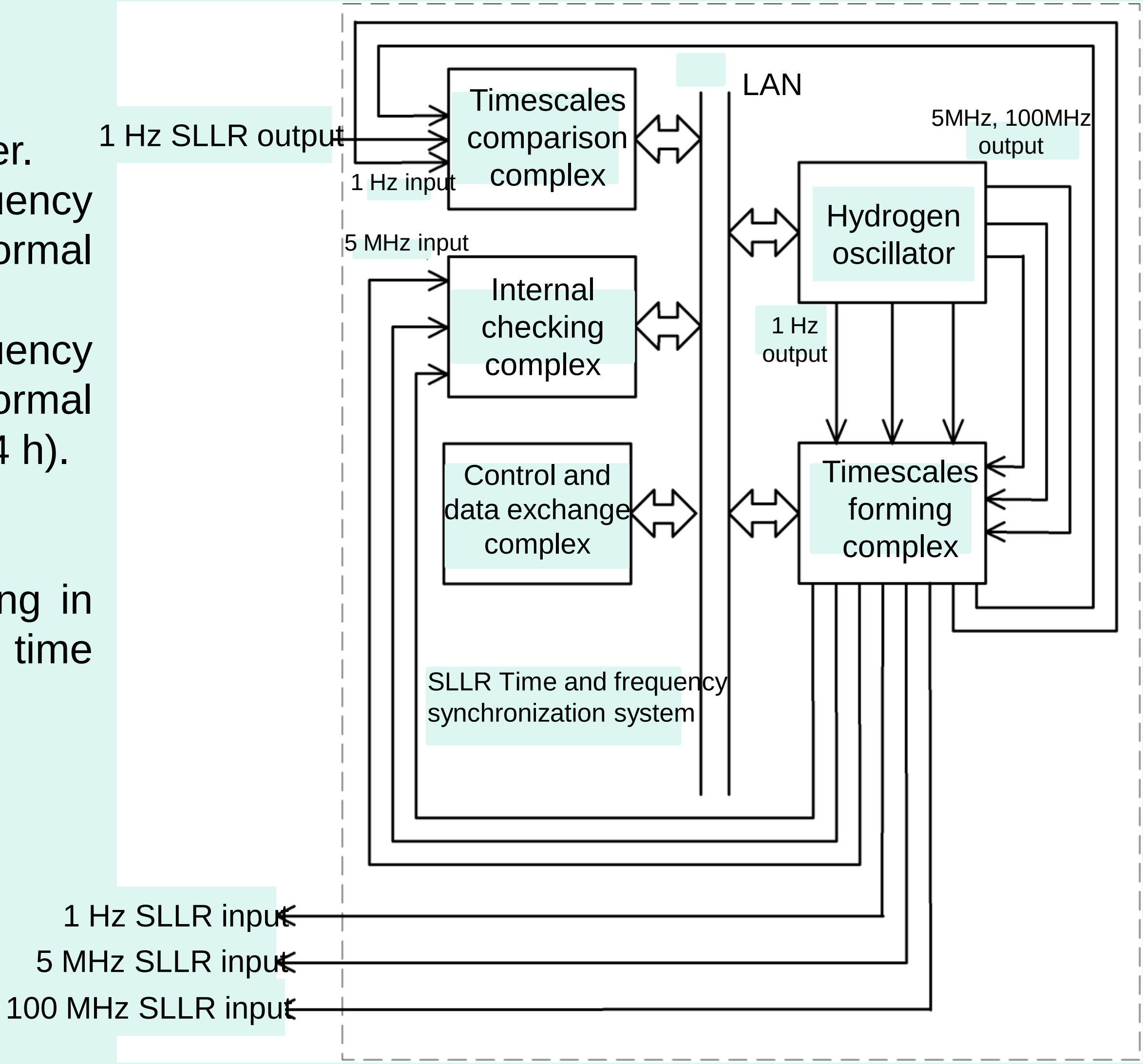
14-15 – TV-tracking channel
19, 22, 23, 31– lenses
20 – pupil diaphragm
21 – field diaphragm (pin-hole)
28-29, 34-35 – adjusting TV-channels
24 - SPAD
25-26 - adjusting star
30 – pilot laser
32 - CCR

Time and frequency synchronization system

Metrological characteristics:

- Type of oscillator – hydrogen maser.
- Short term stability of frequency standard ± (1...2)x10^{-13} (via normal conditions).
- Long term stability (RMS) of frequency standard ± (1...2)x10^{-15} (via normal conditions on measuring span – 24 h).
- Epoch accuracy (UTC) ±100 ns.
- Time reference – UTC.
- Limits of error 1 Hz signal shaping in SLLR timescale ±1,0 ns in real time (via normal conditions).

Functional scheme



1 Hz SLLR output

1 Hz input

Timescales comparison complex

LAN

5MHz, 100MHz output

Hydrogen oscillator

5 MHz input

Internal checking complex

1 Hz output

Control and data exchange complex

Timescales forming complex

SLLR Time and frequency synchronization system

1 Hz SLLR input

5 MHz SLLR input

100 MHz SLLR input

Time and frequency synchronization system parts

Hydrogen time-and-frequency standard CH1-1003M (“Vremya-CH”)

High resolution offset generator HROG-5 (“Spectradynamics”)

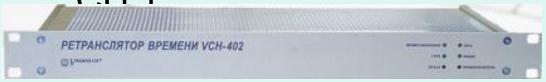
Frequency Distribution Amplifier TimeTech 10274

Data Acquisition /
Data Logger Switch Unit
34970 A (“Agilent”)

Universal Frequency Counter/Timer 53230A (“Agilent ”)

Frequency Distribution Amplifier TimeTech 10535

Time and frequency transfer GNSS receiver GTR51



Retransmitter VCH– 402 (“Vremya-CH”)

Multichannel Raydist VCH–315 (“Vremya-CH”)

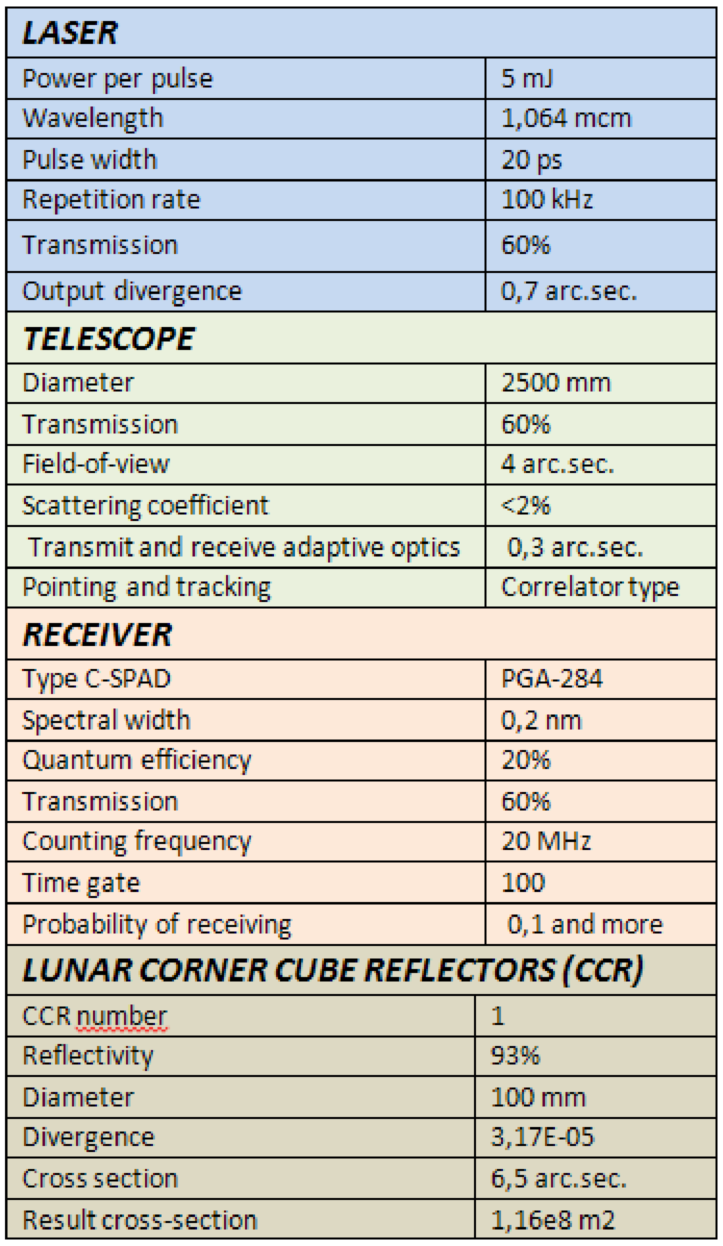
Antenna
GPS–703–GGG
(“NoVatel”)

Super Lunar Laser Ranging (SLLR) / Laser

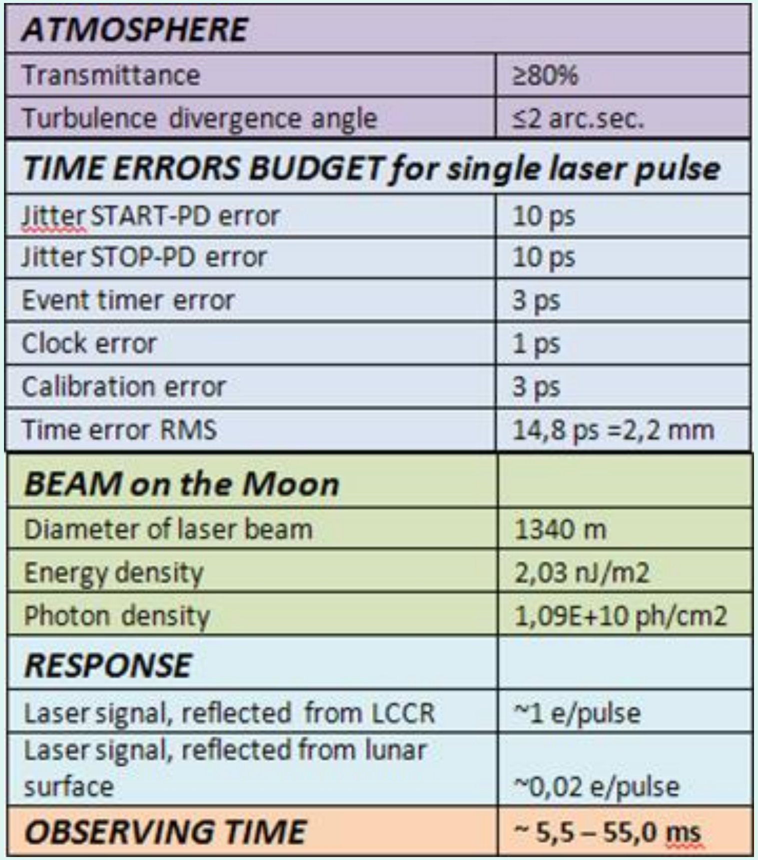
Laser overview

Company	Trumpf			PowerLase		Attodyne	CSIR	IRE “Polus”
Country	Germany			Switzeland		Canada	South Africa	Russia
Laser	SDL H2-200	TruMicro-5070	TruMicro-5270	Polaris-i200	Pico-Blade	APLQ-1000	LLR (HartRAO)	YLPS-150
Type	Yt:YLF	Yt:YLF	Yt:YLF	Nd:YAG Z-slab	Nd:YAG	Nd:YAG	Yt:YLF	Fiber Ytterbium
Wavelength, nm	1030	1030	515	1064 532	1064 532	1064	500-540	1010-1060
Pulse width (FWHM), ps	1-2	10	10	10	10	<30	<50	<70
Pulse power (FWHM), mJ	Max 2	Max 0,5	Max 0,25	Max 0,2…2,0	Max 0,2 0,1	1	200…400	Max 1
Frequency, kHz	100…800	200…800	200…800	100…1000	200…8000	1	1	150…700
Power, W	200 Max	100 Max	60	200 Max	<50	1	200…400	150-200

PRINCIPAL PARAMETERS of SLLR



LASER	
Power per pulse	5 mJ
Wavelength	1,064 mcm
Pulse width	20 ps
Repetition rate	100 kHz
Transmission	60%
Output divergence	0,7 arc.sec.
TELESCOPE	
Diameter	2500 mm
Transmission	60%
Field-of-view	4 arc.sec.
Scattering coefficient	<2%
Transmit and receive adaptive optics	0,3 arc.sec.
Pointing and tracking	Correlator type
RECEIVER	
Type C-SPAD	PGA-284
Spectral width	0,2 nm
Quantum efficiency	20%
Transmission	60%
Counting frequency	20 MHz
Time gate	100
Probability of receiving	0,1 and more
LUNAR CORNER CUBE REFLECTORS (CCR)	
CCR number	1
Reflectivity	93%
Diameter	100 mm
Divergence	3,17E-05
Cross section	6,5 arc.sec.
Result cross-section	1,16e8 m2



ATMOSPHERE	
Transmittance	≥80%
Turbulence divergence angle	≤2 arc.sec.
TIME ERRORS BUDGET for single laser pulse	
Jitter START-PD error	10 ps
Jitter STOP-PD error	10 ps
Event timer error	3 ps
Clock error	1 ps
Calibration error	3 ps
Time error RMS	14,8 ps =2,2 mm
BEAM on the Moon	
Diameter of laser beam	1340 m
Energy density	2,03 nJ/m2
Photon density	1,09E+10 ph/cm2
RESPONSE	
Laser signal, reflected from LCCR	~1 e/pulse
Laser signal, reflected from lunar surface	~0,02 e/pulse
OBSERVING TIME	**~ 5,5 – 55,0 ms**

Conclusion

- •The large single retroreflector (D ≈ 170 mm) must be deployed on the Moon during few years;
- •The new 2.5 m telescope with high resolution is already operated in the Northern Caucasus;
- •The Fiber Ytt laser with power ≈ 150W and frequency 150 kHZ can be fabricated;
- •Other equipment for Super LLR is the state of art of modern technology;
- •Lunar laser ranging with sub millimeter precision is the new challenge for testing gravitational science and exploration of the Moon;
- •The Super LLR in the Northern Caucasus will be useful for fundamental research.

Thanks for your attention!