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Day- and Night-time SLR at MHz Repetition Rate in Graz

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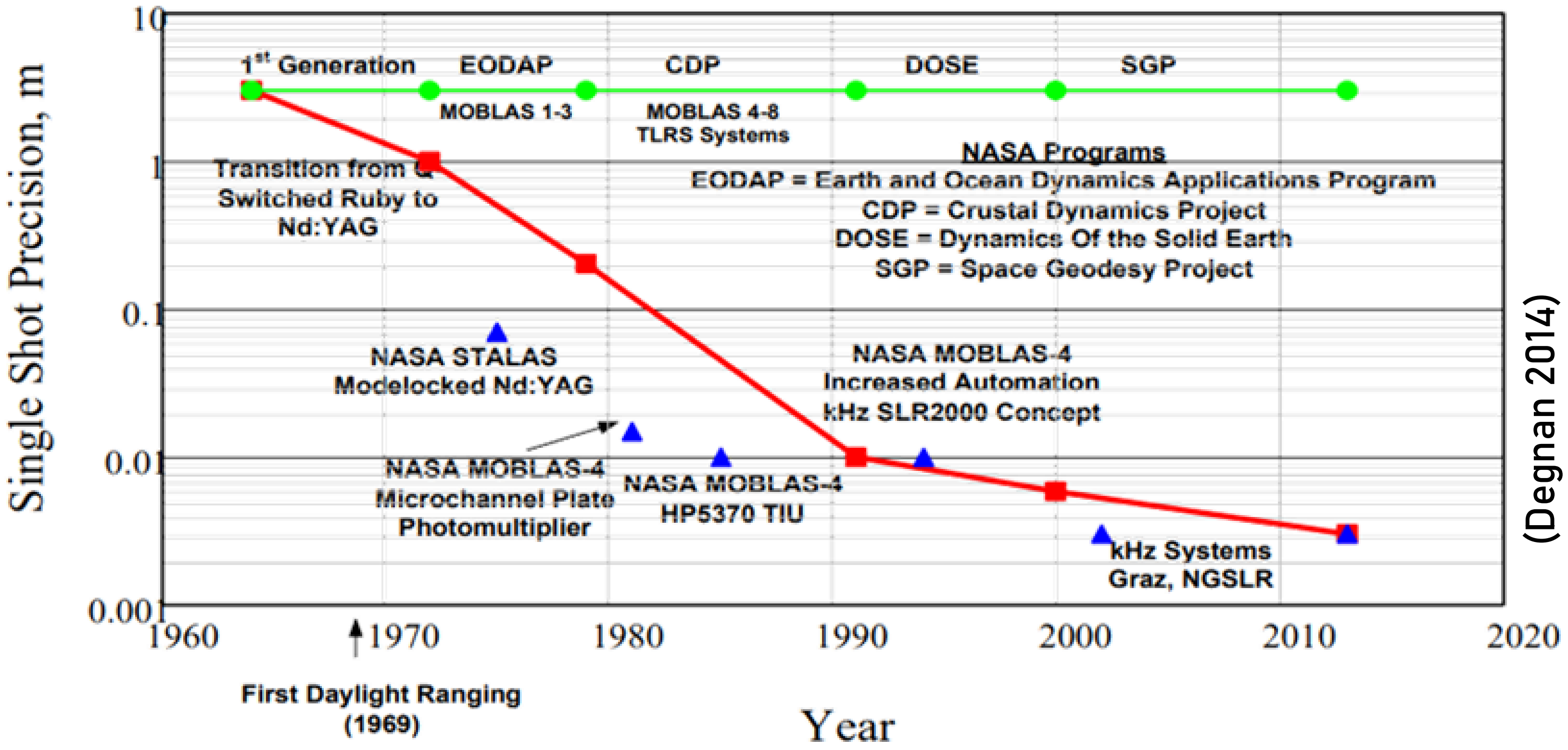
History -- focus on repetition

- The first laser ranging was conducted October 31, 1964 at GSFC NASA, 1 Hz repetition rate

  SLR (accuracy < ~3 meters) had 25 times better than microwave radars (accuracy < ~75 meters);

- kHz SLR concept was introduced by John Degnan (SLR2000) in 1990s
- Graz SLR , very early station to achieve kHz technique (Kirchner 2004)



(Degnan 2014)

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Requirements for MHz

- Laser

Wavelength	1064nm (org.)	Pulse duration	< 10 ps
Max. power	> 40 Watt @ 1MHz, 1064nm	Repetition rate	100 k…10 M (int.) / Single… 1M (ext.)
Max. pulse energy	25 µJ @ 1 MHz, 532 nm	Beam quality	1.13; 1.14 M^2 (x;y)

neoMOS picosecond MOPA (Nd:YVO4)

- Single photon sensitive detector

Sensitive area	100 µm	Q.E. (typ.)	48%@ 550nm
Time accuracy	35 ps (NIM, typ. FWHM)	Dark count	<250 counts/sec
Dead time	77 ns	Work mode	Free/Output gating

MPD (PDM serial)

- Event timer

	A033/USB	TimeTagger Ultra
Input / trigger level	2 channels; NIM	18 channels; -2.5..+2.5 trigger range
Single shot RMS resolution	3..4 ps typ.; 5 ps max.	8 ps typ.;
Dead time	50-70 ns	2.1 ns
Meas. rate	1 M events/s avg.;	70 M events/s cont.

Eventech A033/USB

SwabianInstrument TimeTagger Ultra

- Home developments
  -- PC program & algorithm
  -- Timing control (laser trigger & range gate)

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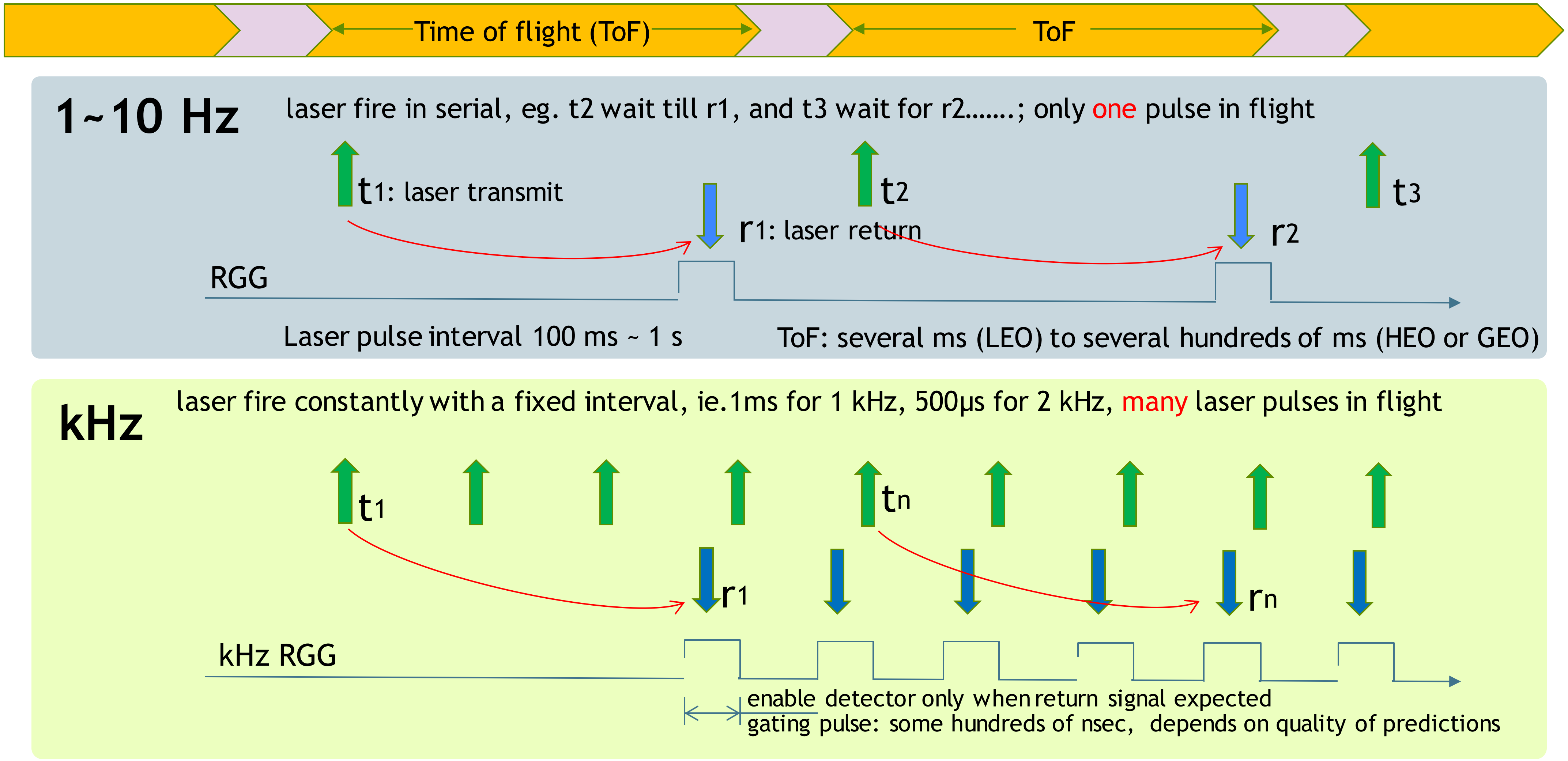
Timing – 10 Hz vs. kHz

Range Gate Generator (RGG): temporal filtering



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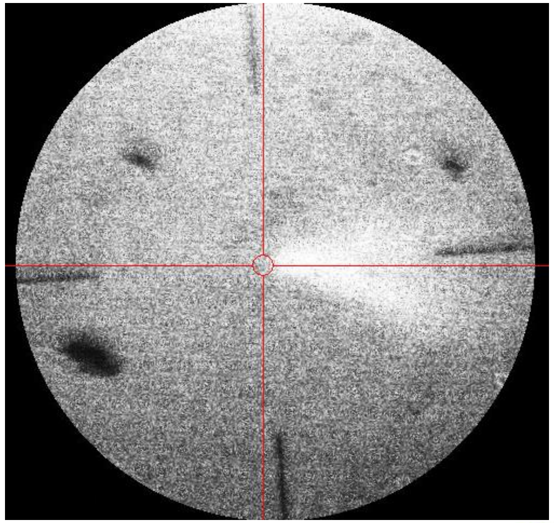
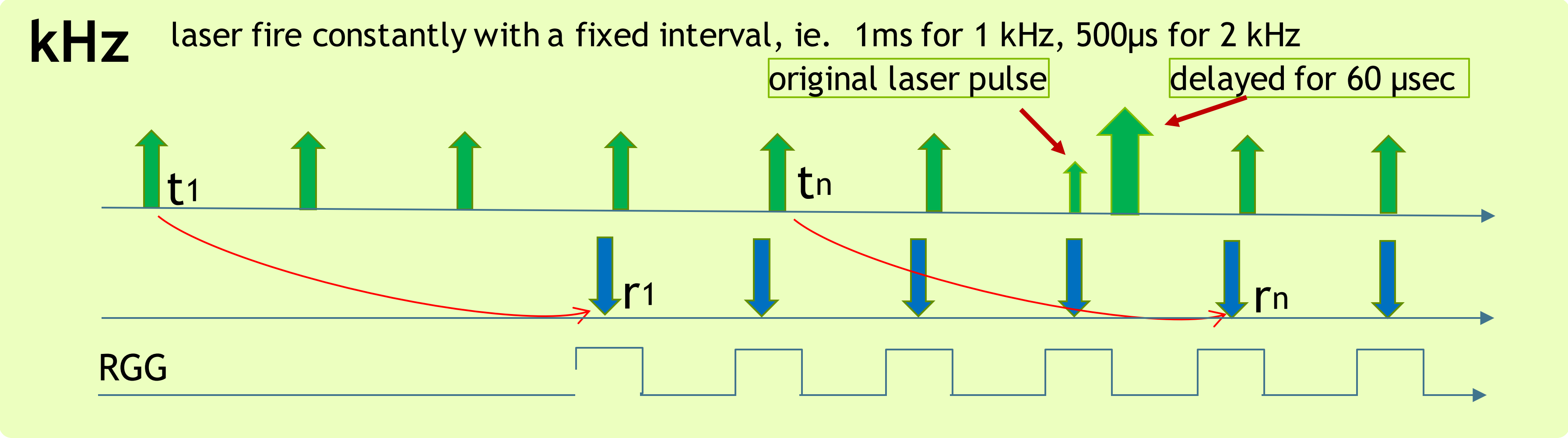
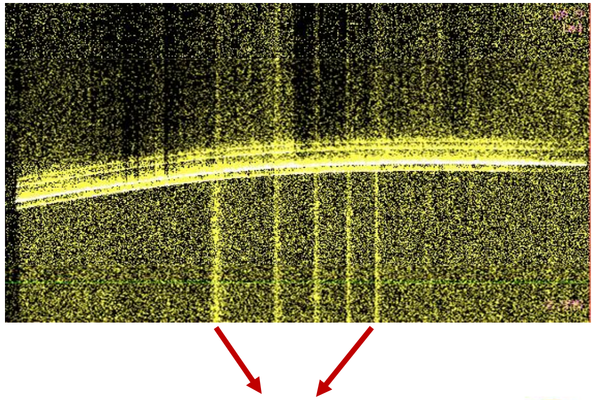
Backscatter collision avoidance @ kHz

- Backscatter: laser pulse diffusely reflected by atmosphere (Mie, Rayleigh…)
- Happens up to a few tens of km from ground
- Advantage: used to align direction of laser beam
- Disadvantage: trig false avalanches for detector if RG applied at same time; strong noise on detector, the detection probability reduced
- Solution: predict and apply a delay to laser firing, e.g. 60 µsec (~20 km in distance)



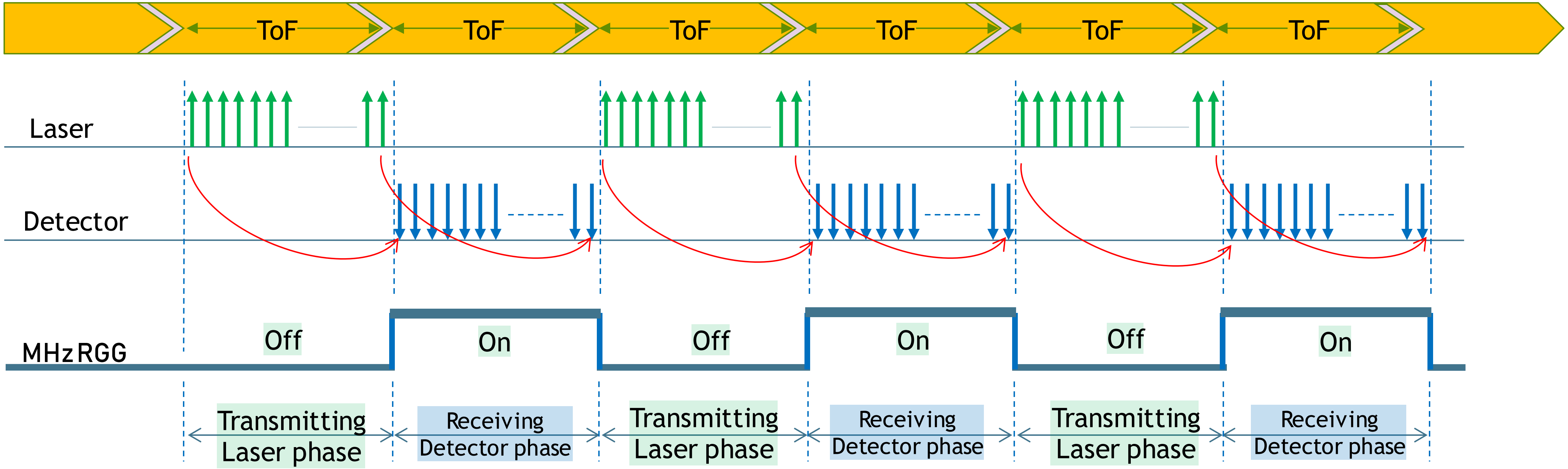
Camera image: laser backscatter used for direction correction



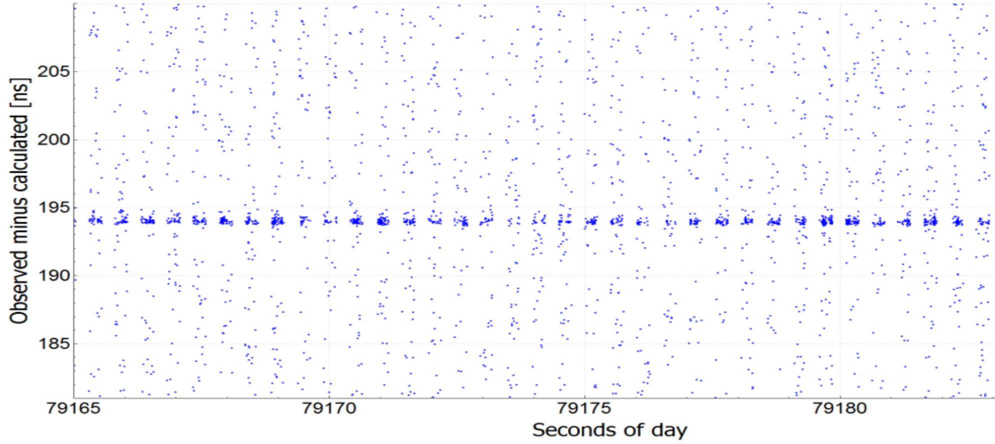


Repeatable laser backscatter collision/overlap cause significantly high noise on detector (Kirchner 2014)

Burst mode – Timing for MHz

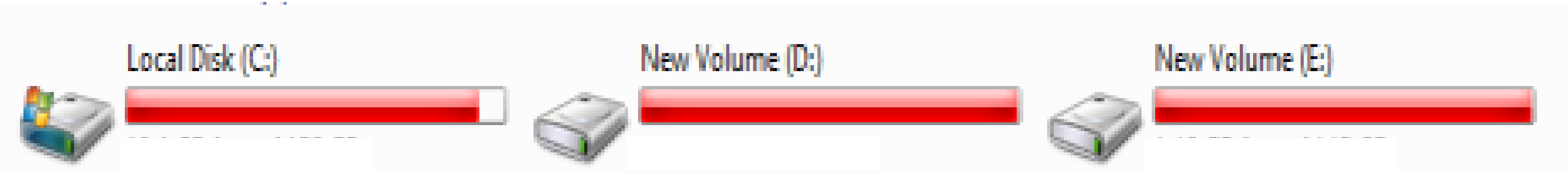


- <10 Hz system "backscatter collision" not happen
- kHz system "backscatter collision" avoid by shifting laser shots (60 µs)
- MHz laser shifting impossible, instead burst mode applied; transmitting phase only firing laser, detector gate off; receiving phase only collect returns, detector free running (night time only)
- Detector/ET/PC saturated (gate keep on for ToF) in receiving phase



MHz Obs.-Cal. data, burst mode
(Wang, 2021)

First Result



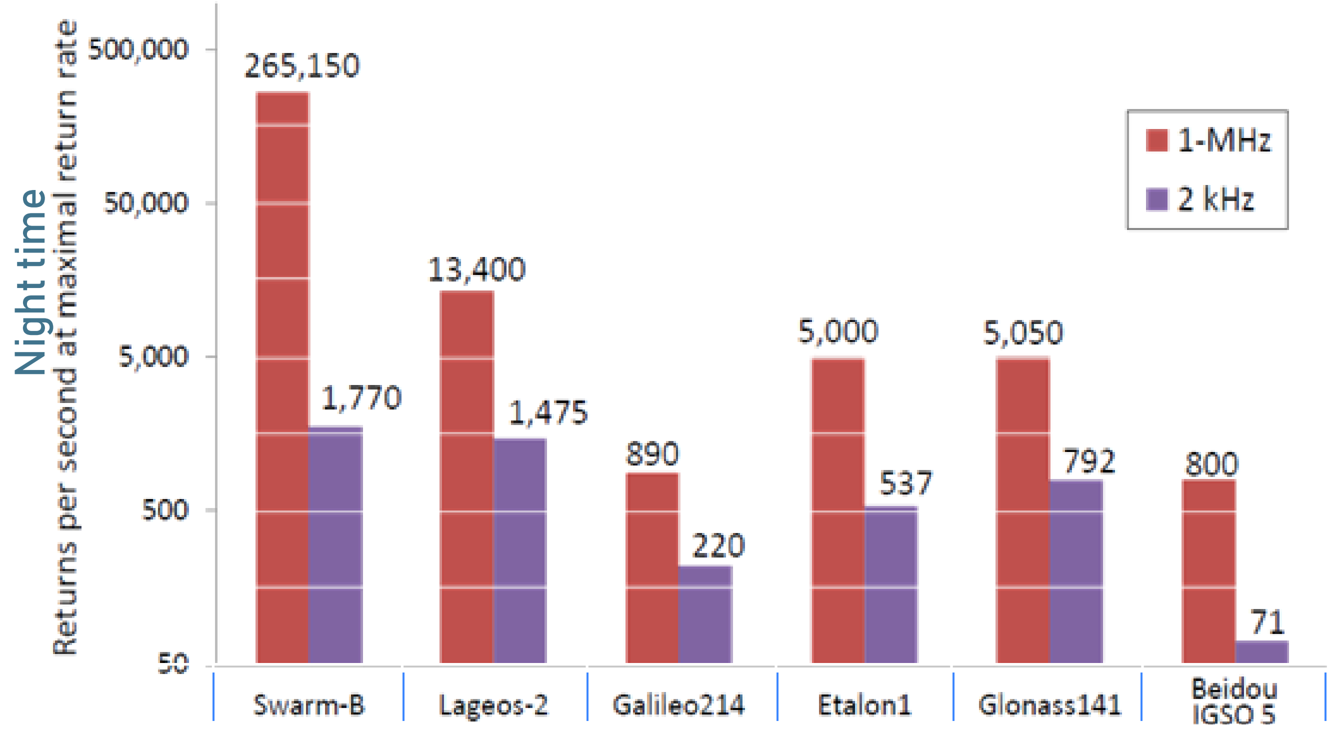
HARD DISK FULL

High data quantity

Night time

Satellites	MHz		Graz 2kHz system	
	Max. Return rate [%]	Returns per second *	Max. Return rate [%]	Returns per second
Swarm-B	53.0	265,150	88.5	1,770
Lageos-2	2.68	13,400	73.75	1,475
Galileo214	0.18	890	11.00	220
Etalon1	1.00	5,000	26.85	537
Glonass141	1.01	5,050	39.60	792
Beidou IGSO 5	0.16	800	3.55	71

* Burst mode, only 500 k shots/sec sent at MHz; max. return rate calculation based on that.



	Swarm-B	Lageos-2	Galileo214	Etalon1	Glonass141	Beidou IGSO 5
Bin size [s]	5	120	300	300	300	300
Points/NP	1.325 M	160 K	267 K	1.5 M	1.52 M	240 K

- MHz SLR leads to significantly higher returns per second, for LEO (factor of ~200), MEO, IGSO; or
- Fast switch between passes

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Daytime: Difficulties & Solution for MHz RG

- Night time: detector in free-running mode, RG keep HIGH during whole RECEIVING phase
- Day time: Range Gate Generator (RGG) required, must gate for single return individually

    -- PC is fast, but never real time; instead, Field Programmable Gate Array (FPGA) device used

    -- Speed limit: 10-20 µs calculate time for one ToF/RG

    -- Memory limit: FIFO capacity of FPGA for each RG (> 200 k epochs for GEO)

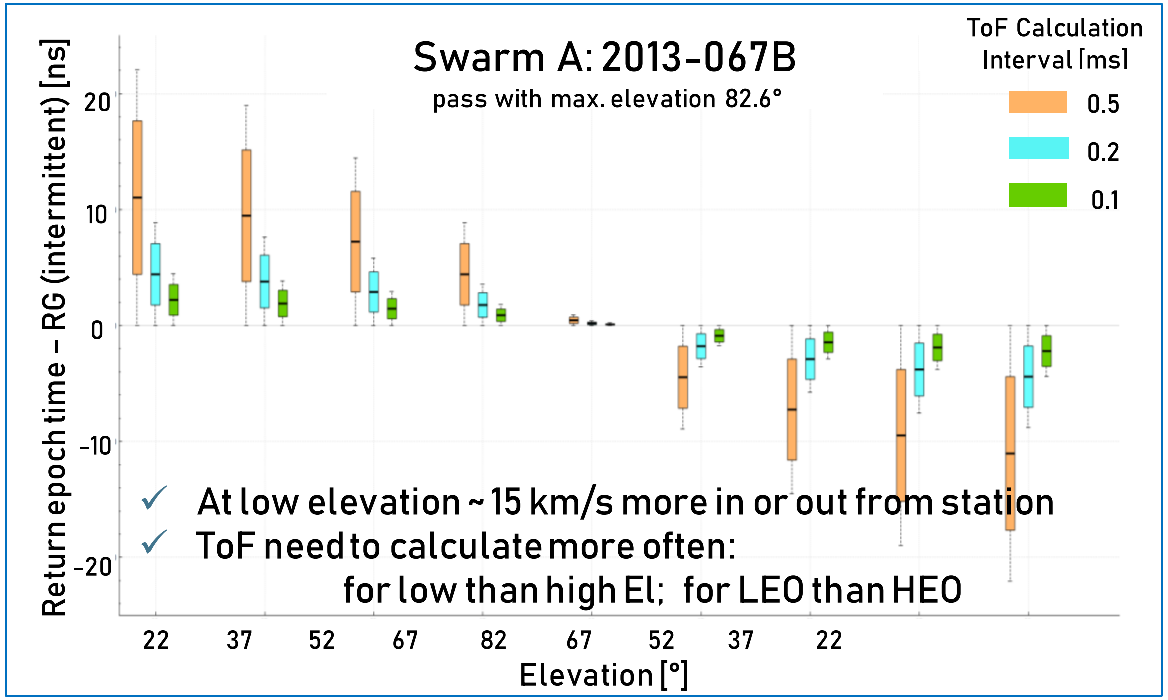
Does RG need to be calculated for every shot??

(1) Laser pulses fire with very “stable” intervals; one start epoch can be taken for several ToF calculation

(2) Once per 100 µsec to calculate ToF enough to reach 5 nsec RG accuracy even for LEO

Jitter measurement of laser start pulse interval (10^6 samples meas. with interval counter)

Rep. rate	Max. [ps]	Min. [ps]	Peak-Peak [ps]
100 kHz	10,474,943	10,474,536	407
1 MHz	1,053,307	1,052,143	1,164



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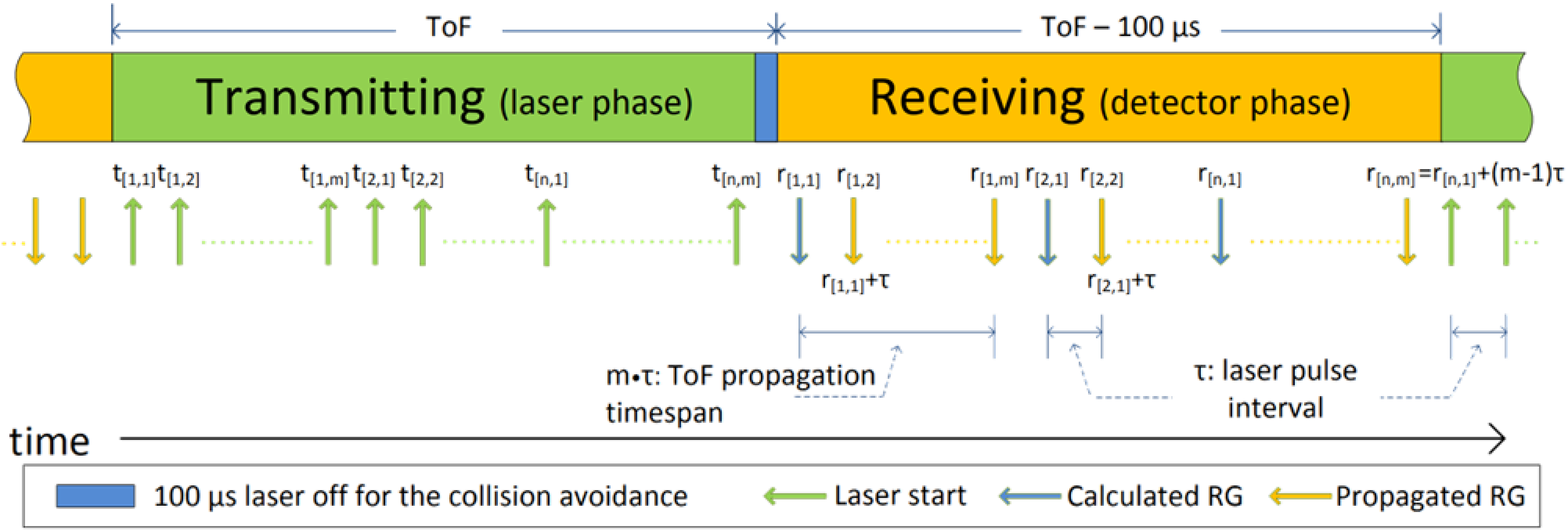
„Propagated“ RG for MHz daylight

- Intermittent (true RG):

  -- Only calculate time of flight (ToF), and set RG epoch time to FIFO of FPGA

  -- Enable/gate detector when RG condition fits (blue r[n,1])

- “Propagated” RG: add several “propagated” RG (yellow, r[n, 2…m]), which have fixed delays (the laser pulse interval)



Results (daytime)

Satellite	Rep. rate	Max. Return rate [%]*	Sun Altitude [deg]
Ajisai	100 k	3.8	≥ 51
	100 k	1.96	≥ 27
Starlette	100 k	4.7	> 25
	1 MHz	2.15	≥ 27
	1 MHz	2.64	≥ 12

* Burst mode, only 500 k shots/sec sent at MHz; max. return rate calculation based on that.

- With "propagated" RG enormous sky noises can be handled during daytime; seldom saturation of ET and detector;
- *Ultra narrow filter (< 0.3 nm FWHM) need to be implemented as next step*

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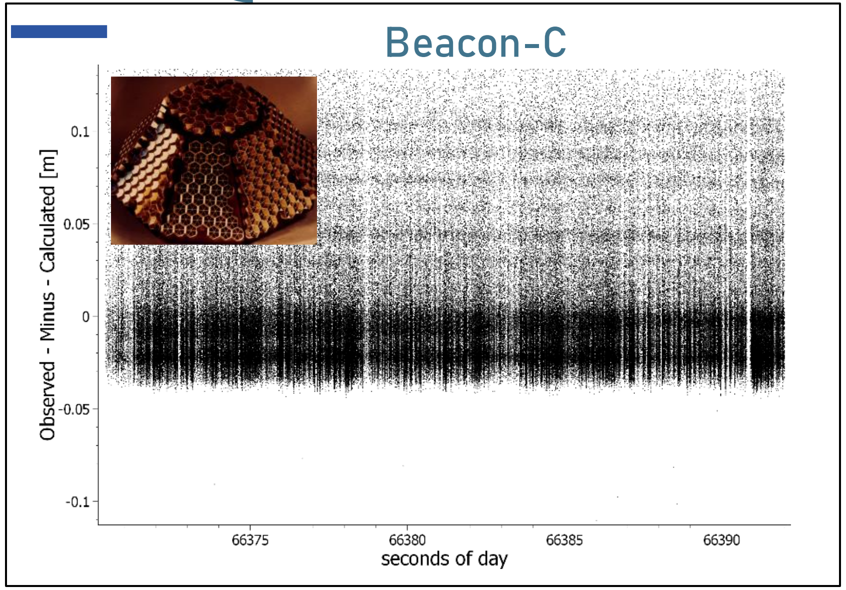
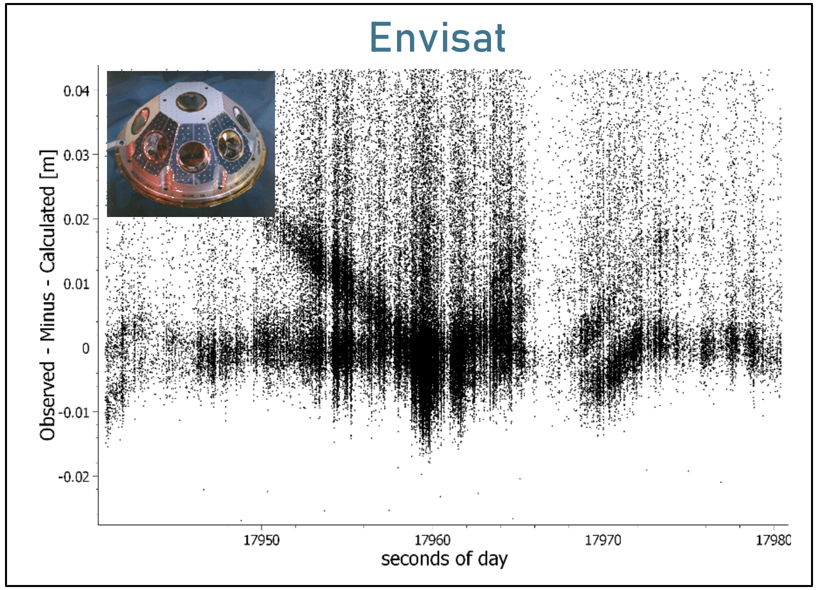
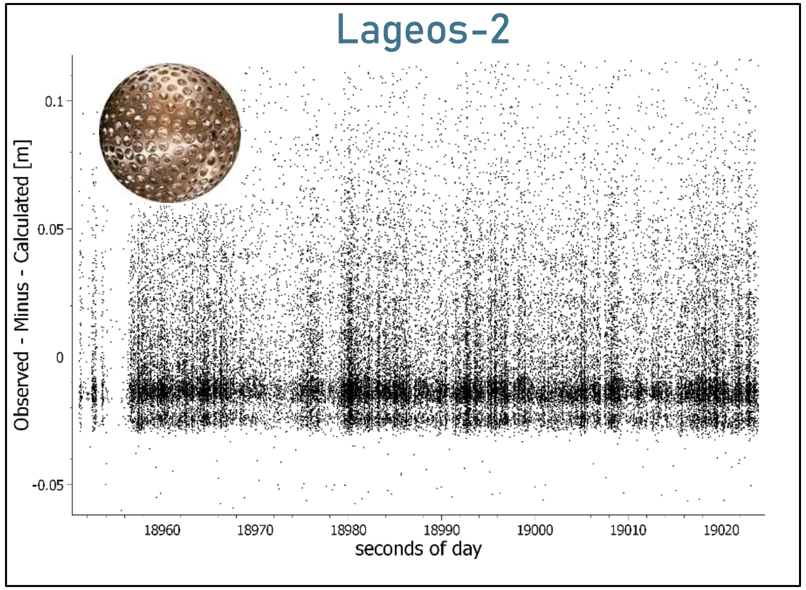
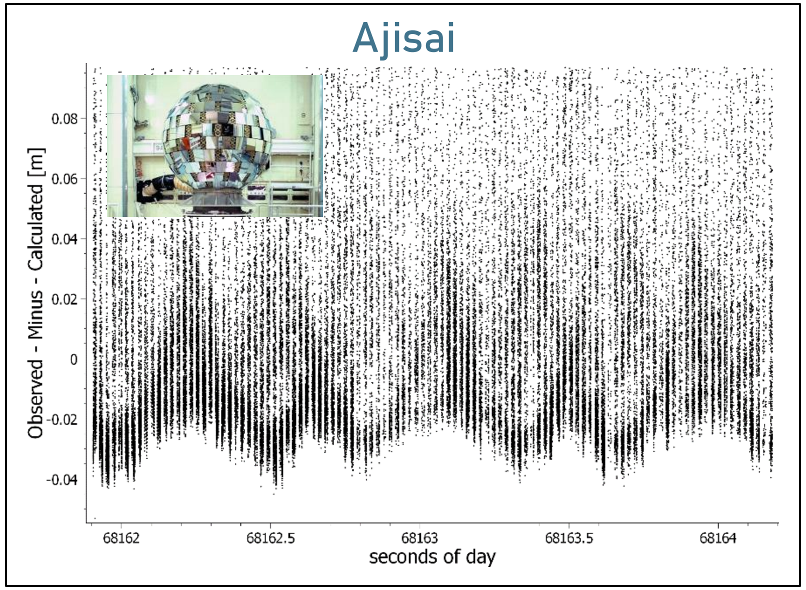
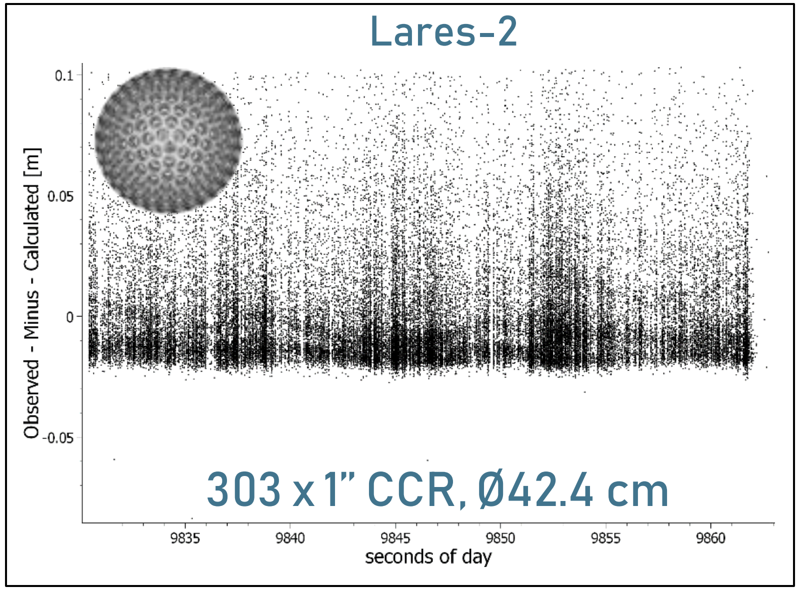
Satellite Signatures











- 20 µJ/pulse, MHz SLR most time within single-photon regime
- With high data quantity and precision of single-shot, signature effects are clearly visible for spherical and pyramidal CCR arrangements
- Lares2 has 1” CCR, smaller than 1.5” of Lageos1/2; no clear signature effects with 2 kHz; but visible with MHz data
- Allow better center of mass (CoM) or attitude determination

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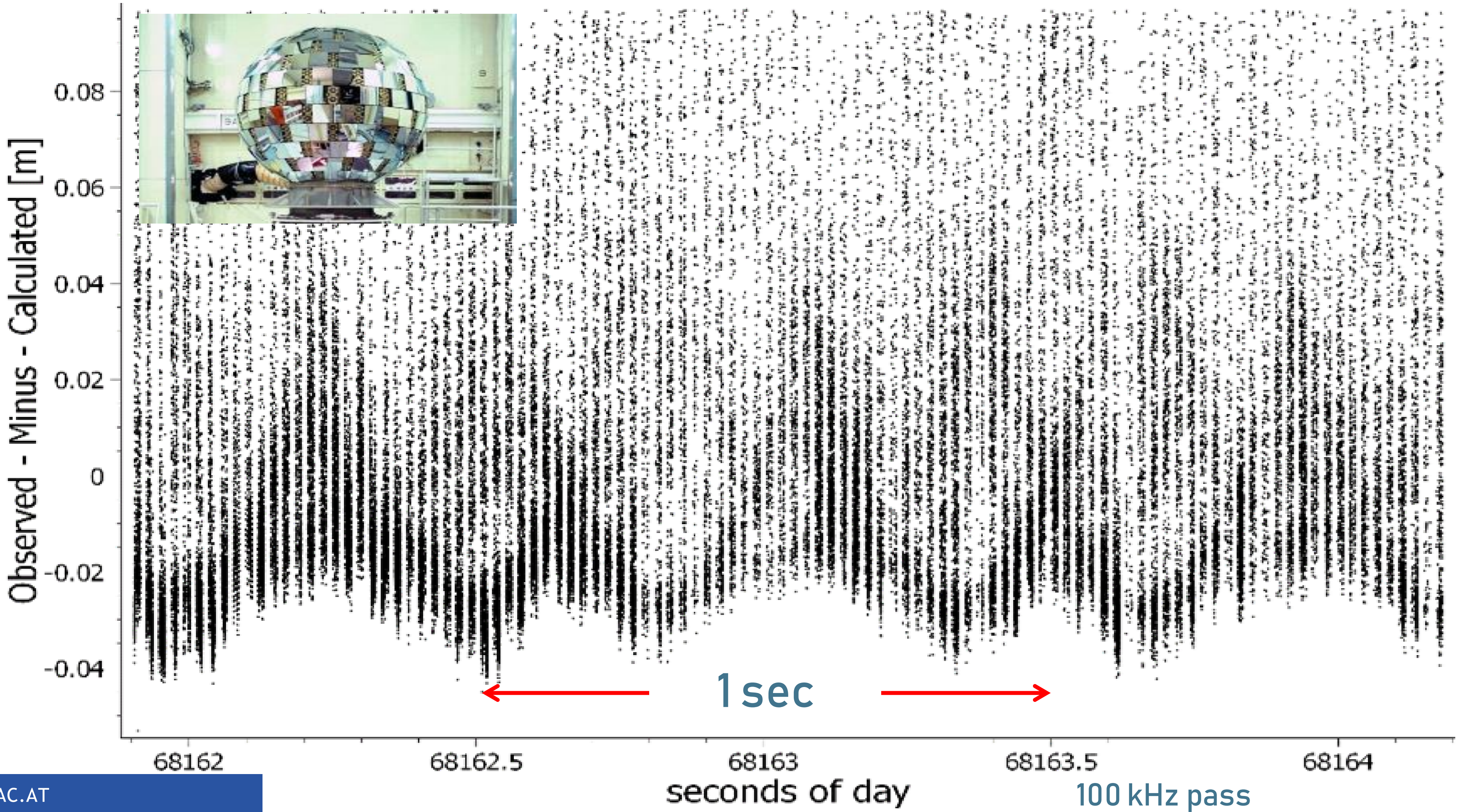
Satellite Signature(Ajisai)

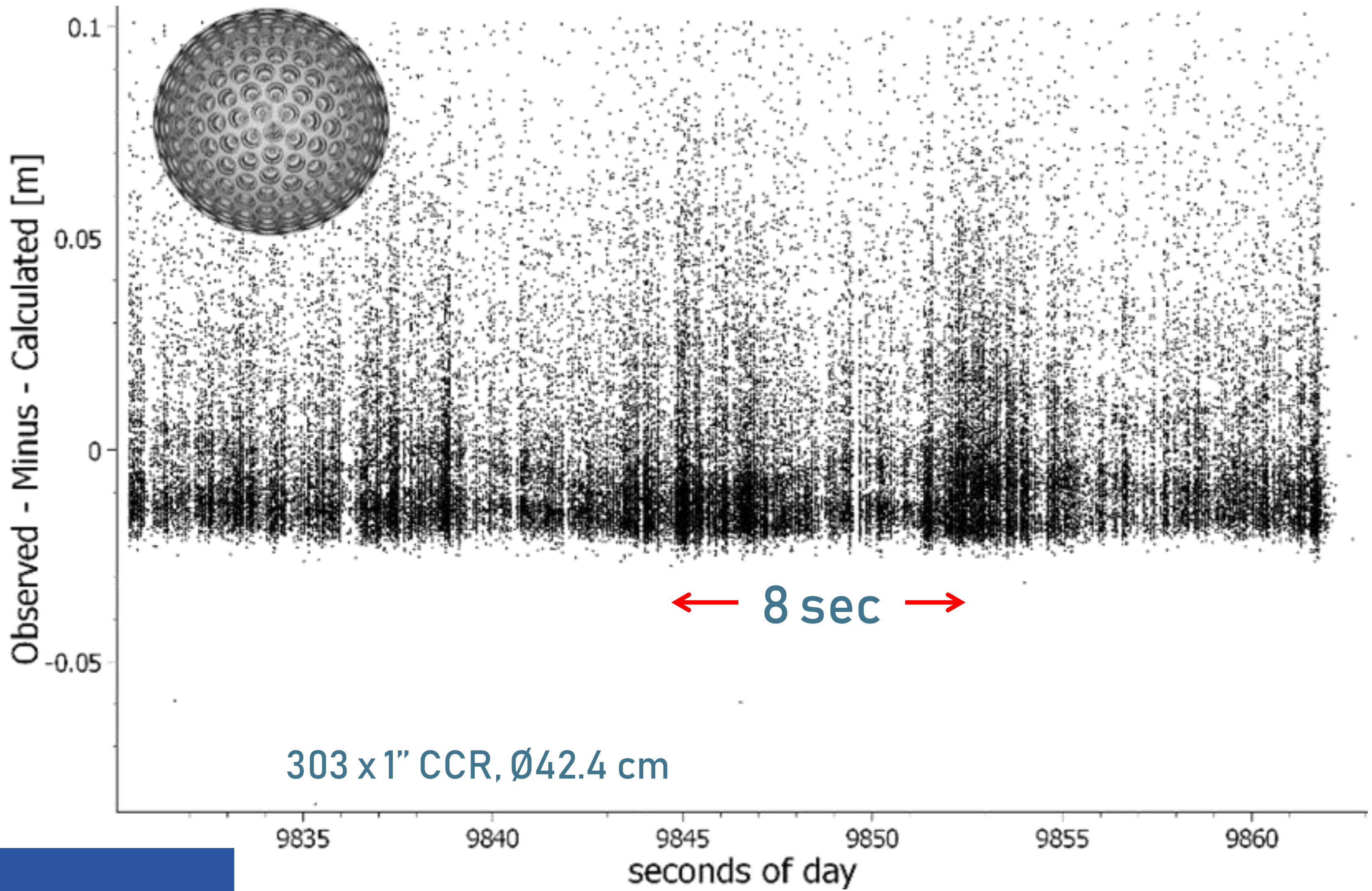
- Ajisai spins at the rate of 2-3 sec/revolution
- CCR fast switching clearly visible



100 kHz pass

Satellite Signature(LARES2)

- Lares2 has 1" CCR, smaller than 1.5" of Lageos1/2;
- Signature visible within MHz data; not within Graz 2 kHz system



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Conclusions

- Successful demonstration on MHz repetition rate SLR in Graz at day and night
- Returns per NP increased by a fact of ~200 for some LEOs; ~ 10 for HEO/GEO
- "Propagated" range gate in FPGA make detector and ET working during day time
- 25 µJ/pulse, MHz SLR within single-photon regime *MOST* time
- Satellite signature are more significant than kHz SLR (Lares2 visible only at MHz)

single photon sensitivity + data quantity – time walk == ???

Questions

?? Technology:

- ?? Efficiency of Real-time & post-processing software improvement
- ?? New key components (i.e. 1064 nm detector, event timer….)
- ?? Data storage locally, data center

?? Science & application:

- ?? NP formulating strategy: how many returns required for one NP?
- ?? Any improvement to accuracy/precision of NP and orbit determination
- ?? Any other usage of such massive data:

  signature identification; attitude/motion determination….

-- please add more…

Thanks for your kind attention