Optical time transfer and the GENESIS-1 mission

GENESIS-1 Online Workshop
Co-location of Geodetic Techniques in Space

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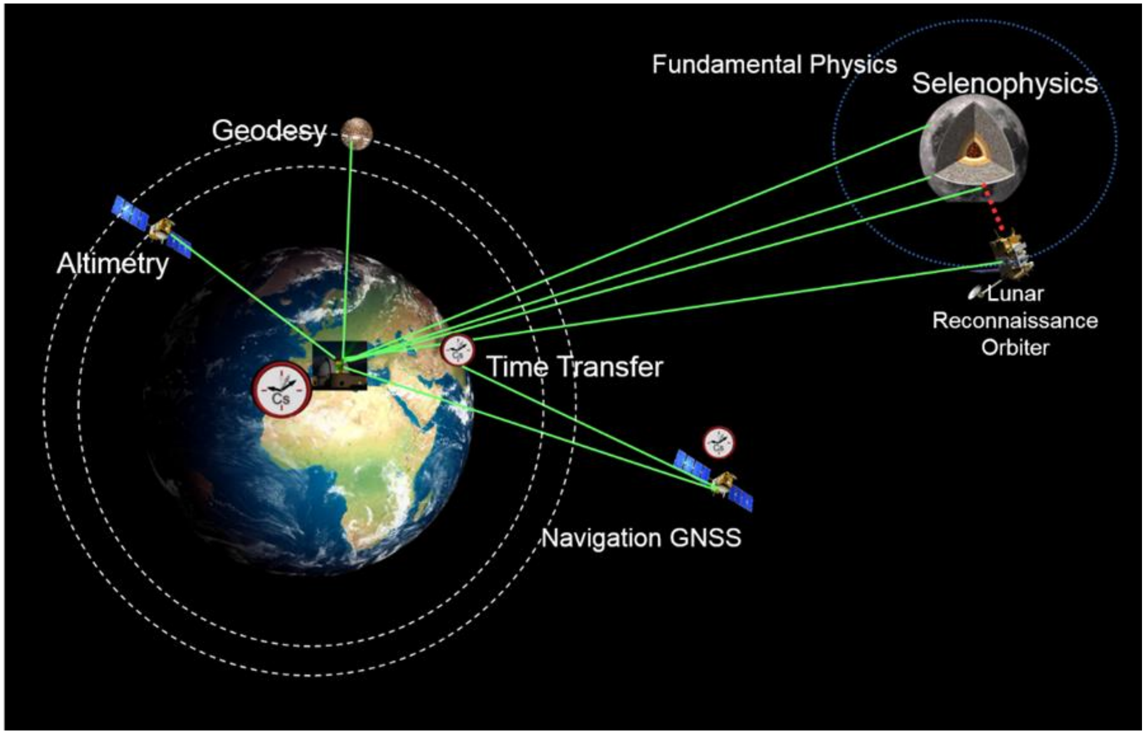
Context

Ground-Space Laser links for probing the close universe

Precise metrological links between space bodies (<cm et ps):

- Relativistic ephemeris versus Observations
- Information on forces acting on the bodies (external and internal)
- Reference frame for space (geodesy) and Time
- This a traditional task for astronomers (ITRF, UTC, BIPM...)
- Fundamental physics testing (Gravitational red-shift, Lense–Thirring, …)



SLR Principle vs Time transfer

Measurement of the time of flight of laser pulses

On ground

In space

Passive Retro-Reflector

Event timer

$\Delta T = \text{date}_{return} - \text{date}_{start}$

$$D = \frac{c.\Delta T}{2}$$

⇨ High stability clock is required

Required accuracy on the date: 100 ns / UTC
Required accuracy on the clock frequency: better than ~10^{-11}

Measured distance:
[400km – 400 000 km]
Accuracy < 10 mm
Precision ~ mm

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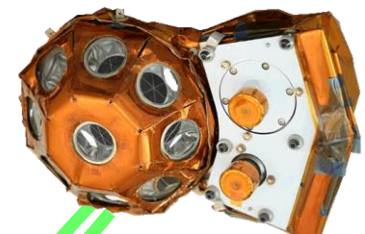
Measured distance:
[400km – 400 000 km]
Accuracy < 10 mm
Precision ~ mm

On ground

In space

Active Retro-Reflector



Event timer

$\Delta T = date_{return} - date_{start}$

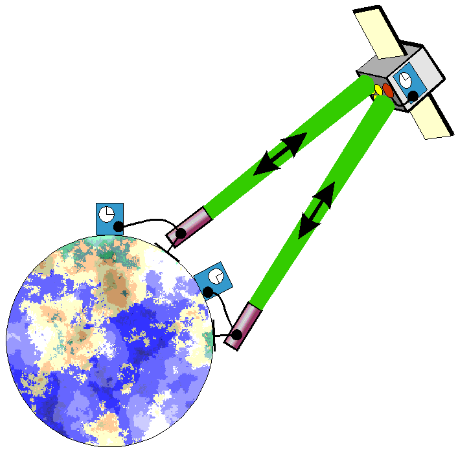
Event timer

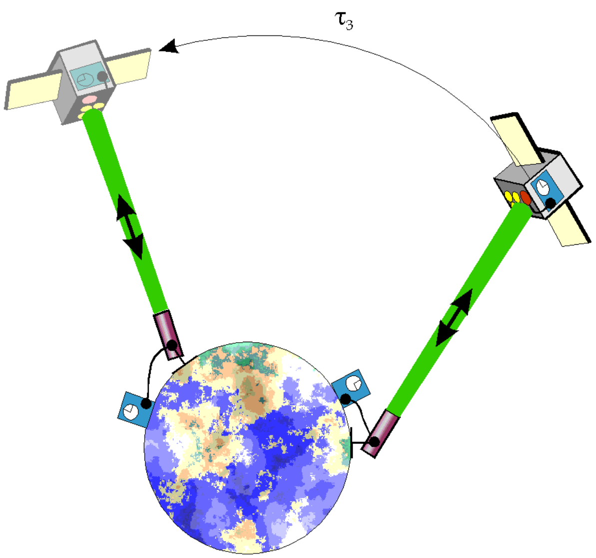
$date_{board}$

the relative time lag between on-board and ground time :

$$\chi = \frac{date_{start} + dater_{eturn}}{2} - dateb_{oard} + corr$$

Common view and non common view Ground to ground time transfer





Common View

No noise added from the onboard oscillator

Non common View

Noise added from the onboard oscillator when the satellite is not visible by any station

OCA-CNES T2L2 space mission

T2L2 metrological results

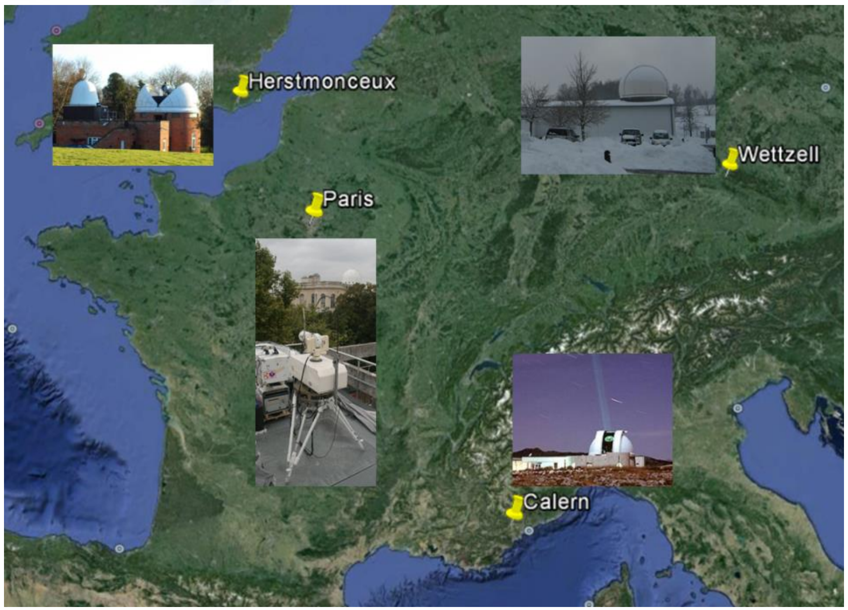
10 ps stability @ 1000 s for Ground-Space & Ground-Ground time transfer

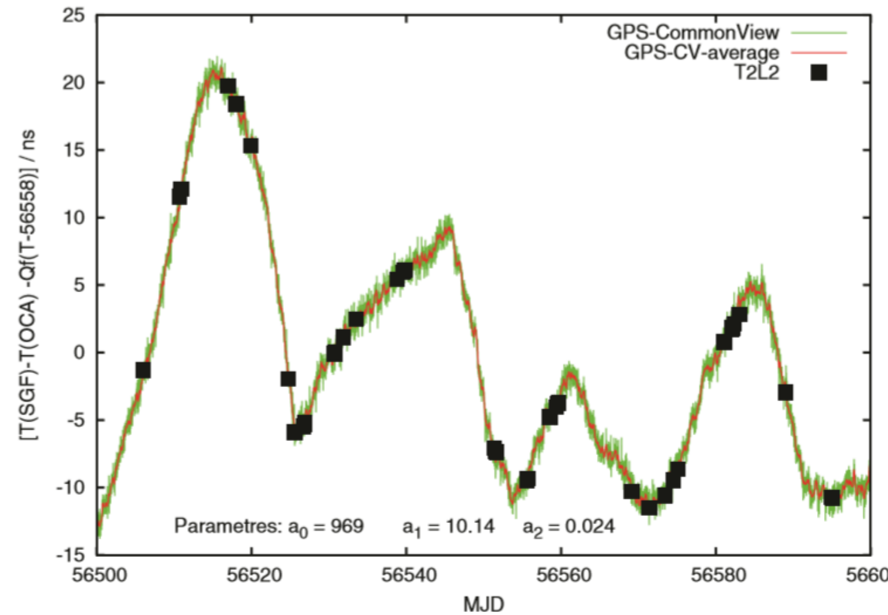
Uncertainty at 150 ps   E. Samain et al., 2015, Metrologia

Ground to ground time transfer in common view
European campaign

Direct comparison between GPS CV & T2L2

P. Exertier et al. 2016, Metrologia





For the two time transfer techniques GPS CV and T2L2, two independent relative calibration campaigns were undertaken with the same travel calibration equipment

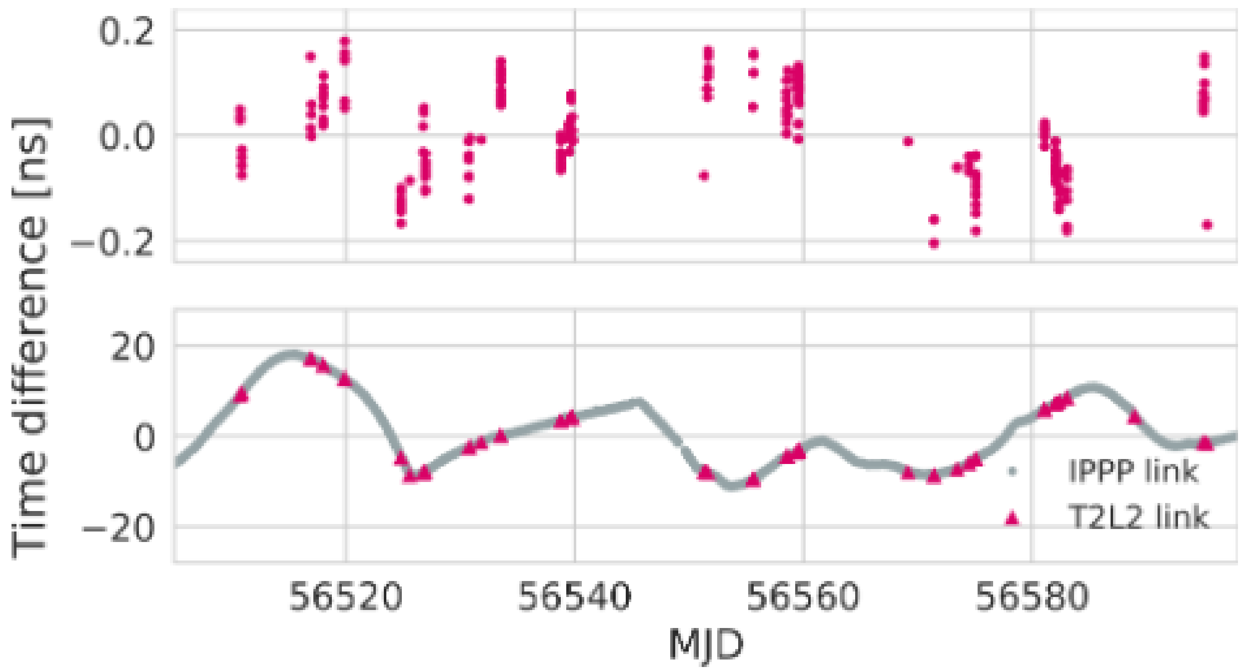
Figure 3. Time differences between time scale reference points in OCA and in SGF with a quadratic fit removed: green continuous noisy line is for GPS CV, red smoothed continuous line is for GPS CV filtered by a moving average over 13 samples, and blue squares are for T2L2.

Time differences between GPS CV and T2L2 are no greater than 240 ps, with a standard deviation below 500 ps, mostly due to GPS CV.

Ground to ground time transfer in common view In European campaign

Comparison between IPPP GPS & T2L2

J. Leute et al. 2018



(a) SGF / OCA

Difference between IPPP and T2L2 link

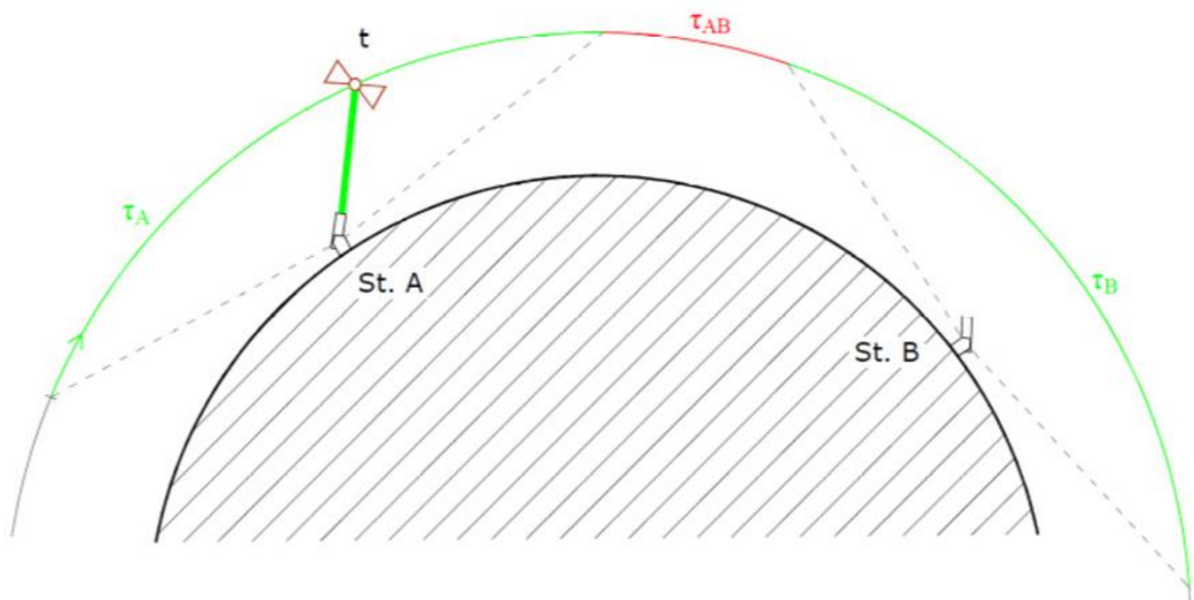
Time difference after an identical quadratic fit has been removed.

Agreement between two independent space-based time transfer techniques:

- IPPP based on GPS carrier-phase observations
- T2L2 based on laser ranging

=> standard deviation below 100 ps for baselines on which T2L2 can operate in CV.

Ground to ground time transfer over intercontinental distances: non common view between Europe and China



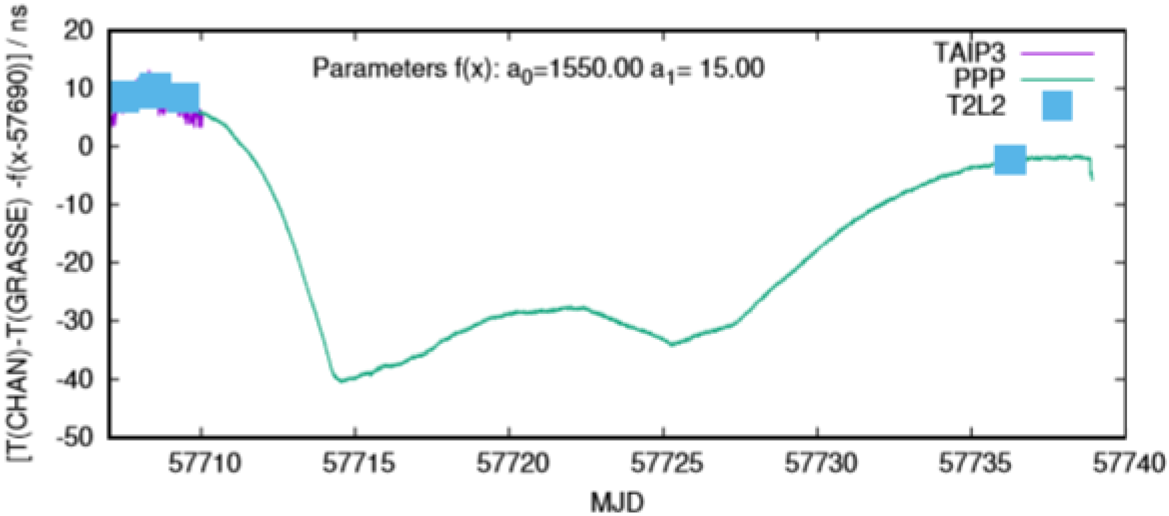
Can be improved from LEO to MEO/HEO satellites

- 419566 laser events detected on-board Jason2
- 180 passes from all stations
- 18 passes in non-common view (direct mode)
- 24 passes in common-view (Europe)
- 6 passes in common-view (Asia)

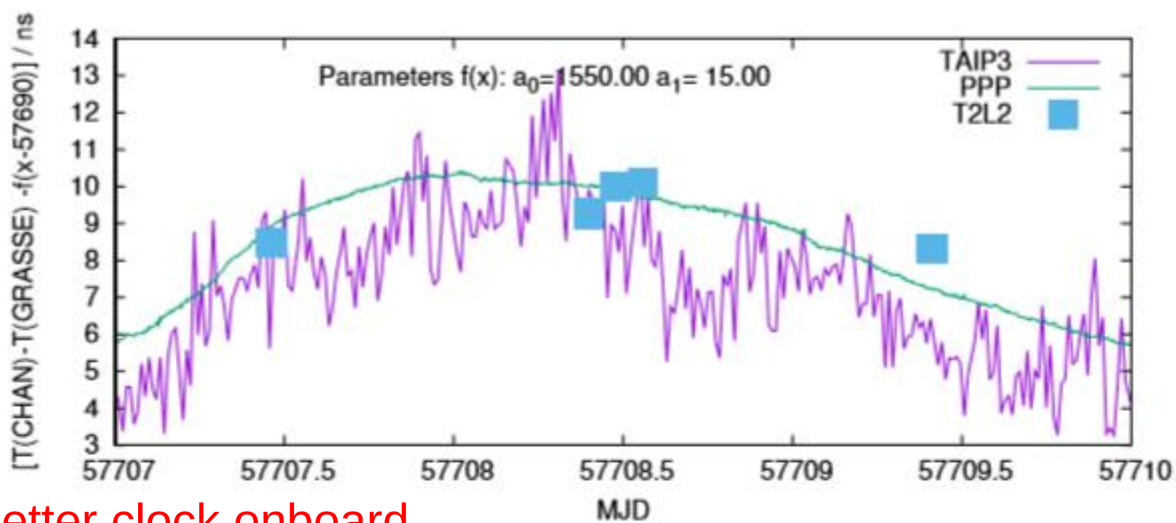
E. Samain et al., 2018, *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*

Ground to ground time transfer in non common view between Europe and China

A direct comparison of T2L2 results with GPS time transfer was achieved thanks to a GPS PPP link calibration technique.



Both techniques having been calibrated independently, the T2L2 - GPS differences obtained over the links between Europe and China are all clearly in line with the estimated combined uncertainties, which are close to the 1 ns level.



Can be improved with a better clock onboard

Space missions

T2L2 results

10 ps stability @ 1000 s for Ground-Space & Ground-Ground time transfer

Uncertainty at 150 ps E. Samain et al., 2015, Metrologia

Agreement between T2L2 and GPS-CV better than 240 ps
P. Exertier et al. 2016, Metrologia

Agreement between T2L2 and IPPP in common view with a standard deviation below 100 ps J. Leute et al. 2018

Impact of the SAA on the USO frequency behaviour
A. Belli et al., Advanced in spaces research, 2015

Agreement between T2L2 and GPS PPP in non common view at 1 ns level
E. Samain et al., 2018, *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*

Shutdown in 2014

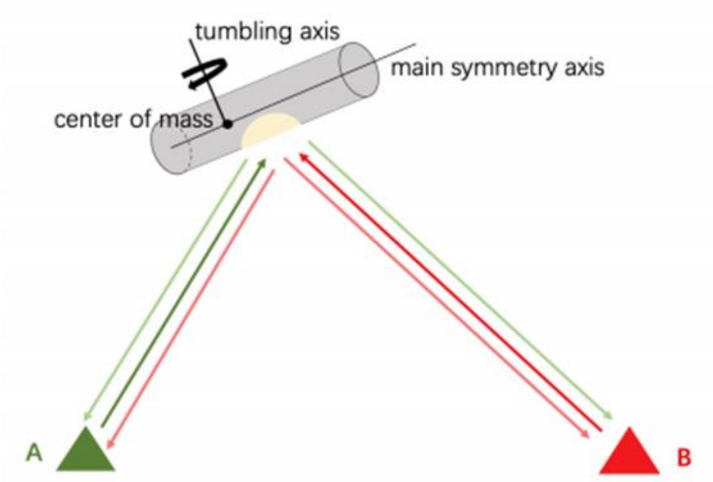
Perspectives : ACES with MWL & ELT : 2024 ?

Advantage : high quality clocks (Pharao)

Limitation : orbit

And in the meantime ?

Time transfer by laser links thanks to diffuse reflections



Liu, T., Eckl, J. J., Steindorfer, M., Wang, P., & Schreiber, K. U. (2021). Accurate ground to ground laser time transfer by diffuse reflections from tumbling space debris objects. *Metrologia*

Each station performs two-way ranging to the rocket body. In addition to that, each station performs one-way detection of the laser pulses from another stations.

The use of two distinct wavelengths allows to satisfy the single-photon level of the detection.

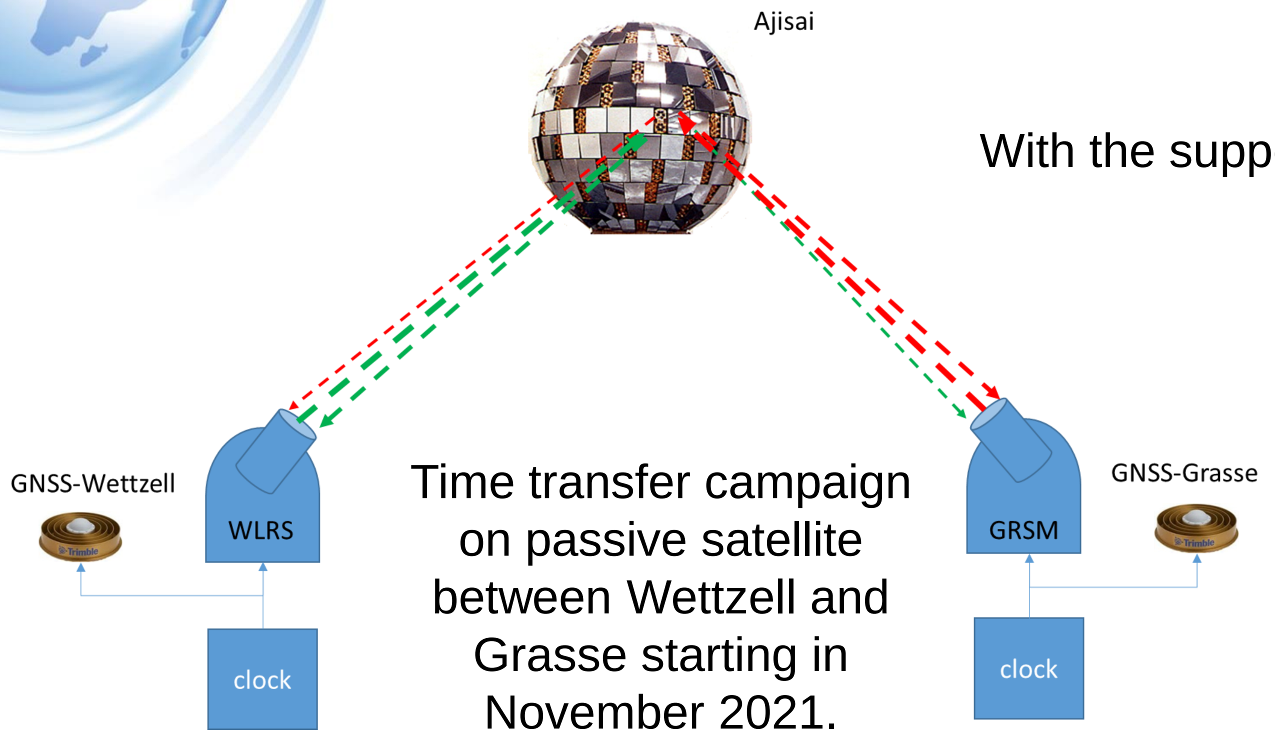
Time transfer demonstration on a rocket body between Wettzell and Graz with 1 σ statistical uncertainty of 3 ns.

Advantage : a long term and fully passive space segment

Limitations : works only for common view, needs of a better target model

Time transfer by laser links on passive satellite between Wettzell and Grasse

With the support of FIRST TF



Time transfer campaign on passive satellite between Wettzell and Grasse starting in November 2021.

Schedule :

- Calibration of the GNSS links & of the laser links with the support of OP-SYRTE May 2022
- Common view observations with Wettzell firing in infrared and Grasse hearing

⇒ **first success confirmed !!**

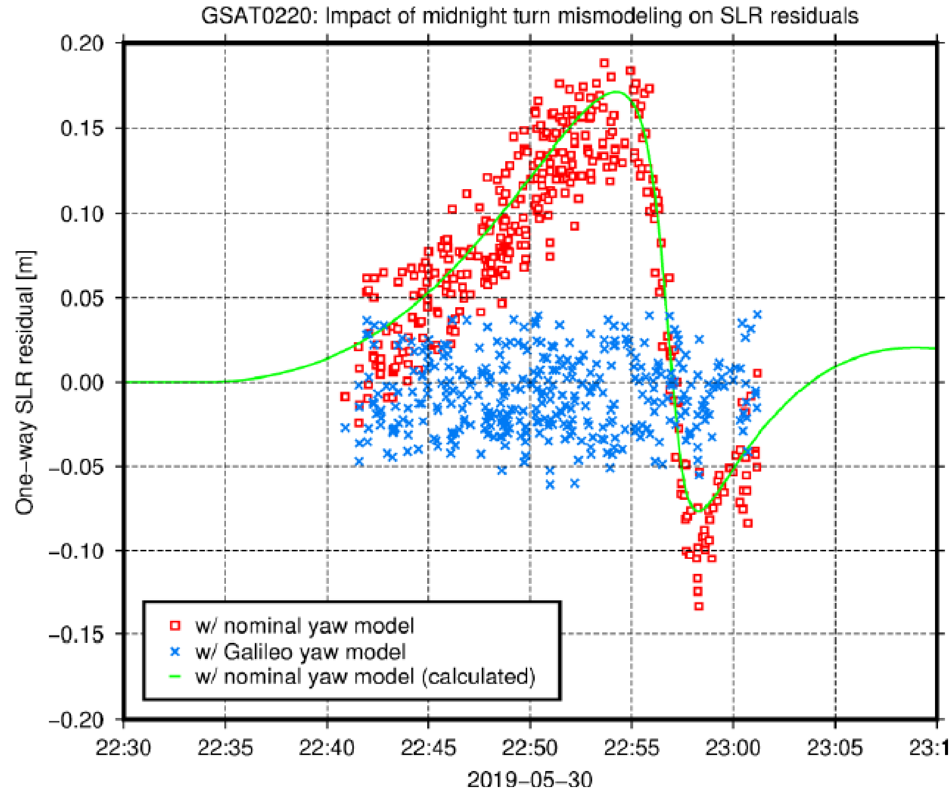
The following:

- Common view observations with Wettzell firing in infrared and Grasse in green with the LLR lasers
- Common view observations with Wettzell firing in infrared and Grasse in green with the high count rate lasers

Outcome from the ESA-SUCCESS SLR campaign on Galileo

1. **Orbit improvements: "**When compared to solutions without SLR data, the precision of the orbits was improved by more than 10 percent."

2. **Eclipse behaviour: "**Analysis of SLR range residuals confirmed the presence of remaining model errors in current operational Galileo orbit products. The approach may offer an interesting alternative to the reverse point positioning (RPP) approach, especially for retroreflector-array-equipped GNSS satellites where the attitude law is unknown and the phase centre offset of the transmit antenna is too small to provide the necessary lever arm needed for the RPP. precision. "



3. **Normal point accuracy: "**Analysis of SLR single-differences formed between multiple stations tracking GSAT0102 or GSAT0220 at the same time has revealed 1-2 cm range biases and 1-2 mm NP "

4. **SLR-derived orbits: "**Moreover, the good temporal and spatial data coverage allowed us to determine precise independent SLR-only orbit solutions. The excellent agreement with standard (radiometric) orbits of better than 0.1 m (3D-RMS) underlines the value of SLR tracking and also demonstrates that one may actually use it as a backup for Galileo POD in case the radio system fails (as happened for GSAT0104)."

From ESA Technical note, SUCCESS data analysis **DOPS-SYS-TN-0505-OPS-GN**

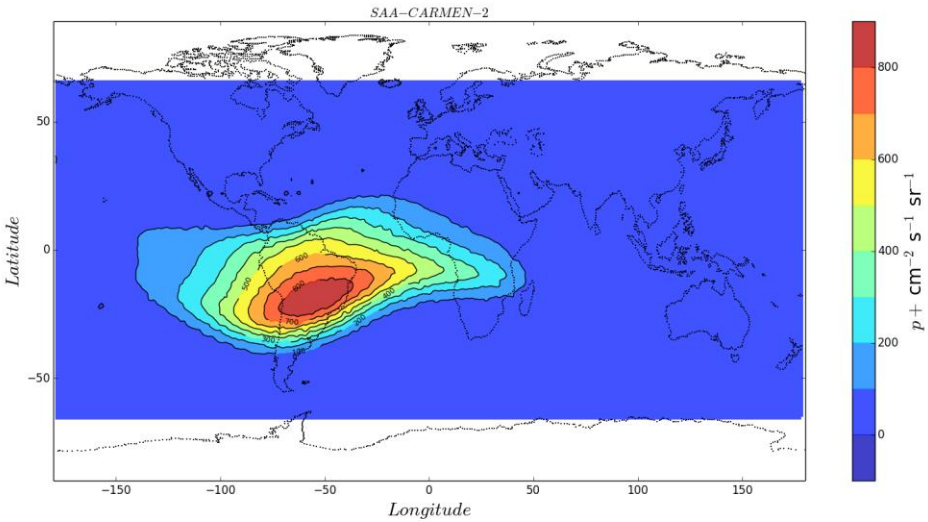
Outcome from the ESA-SUCCESS SLR campaign on Galileo

And for the time:
"Comparison of the SLR residuals against the satellite clock estimates after removal of first order fit *shows mediocre correlation*, indicating *that the remaining systematics* in the satellite clock estimates are not necessarily caused by radial orbit errors only but also ***reflect the actually behaviour of the satellite and the selected reference clock.*** ***"***

Example during the T2L2 mission:
On the satellite : *Jason-2 space environment (radiations) => impact on the USO frequency*

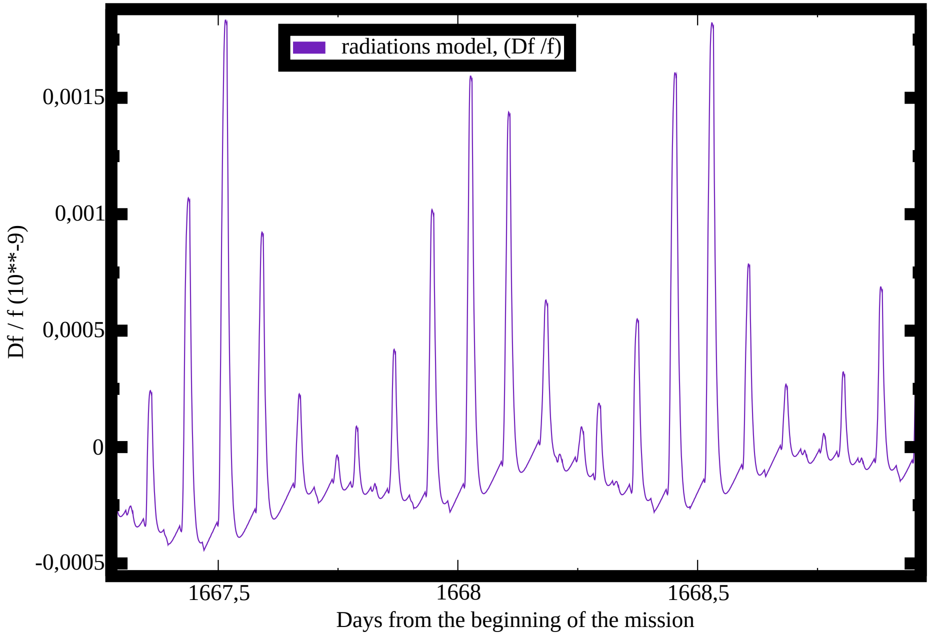
DORIS Ultra Stable Oscillator (USO) & SAA

Jason-2 space environment (radiations) => impact on the USO frequency



Proton flux, Carmen – 2 Calibration

[J.M. Lemoine & H. Capdeville 2006]



A. Belli et al., Advanced in spaces research, 2015

- The USO is driven by the attitude law (very specific) of the platform
- A common huge 60-days pseudo-periodic frequency variation of $1-2\ \cdot 10^{-10}$due to radiation combined with the anisotropy of the platform and its attitude law
- A complete model has been developed which explains more than 99.99% of the frequency bias.

Outcome from the ESA-SUCCESS SLR campaign on Galileo

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"Comparison of the SLR residuals against the satellite clock estimates after removal of first order fit *shows mediocre correlation*, indicating *that the remaining systematics* in the satellite clock estimates are not necessarily caused by radial orbit errors only but also ***reflect the actually behaviour of the satellite and the selected reference clock.*** "

Example during the T2L2 mission:
On the satellite : *Jason-2 space environment (radiations) => impact on the USO frequency*

$\Rightarrow$ **Good clocks directly sense the gravity potential & the space environment (chronometric geodesy)**

Examples:
GREAT project (P. Delva et al.) => best measurement of the gravitational time shift in clocks thanks eccentric Galileo satellites
GASTON project (P. Delva et al. Collaboration OP-ORB-OCA) => Dark Matter research with Galileo

Dedicated instrumentation needed for time & frequency comparison between ground and board.

Opportunity for ground to space optical time transfer

T2L2

1st demonstrator

But limitations due to the onboard clock

Not developped for combination with other geodetic technics onboard

Finished

ACES

Good clocks => promising scientific results

But the choice to put the instrument onboard ISS is not the best (constraint, orbit, etc)

Shifting schedule ….

GENESIS-1

Great opportunity to have both good clock, good orbit, combination of geodetic technics

Work program at Geoazur-MéO
In the Genesis-1 mission context

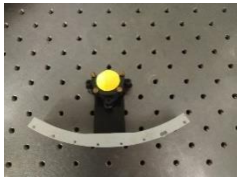
The expected results are:

- A simplification of the opto-electronic architecture compared to T2L2
- A decrease in volume/weight/consumption
- A time transfer accuracy of less than 100 ps thanks to a better integration of the passive and active segments.
- Greater common view due to higher satellite altitude
- Improved on-board satellite clock.
- Better uncertainty between optical and RF technics

Works in progress at Geoazur-MéO
High count rate SLR

New laser in 2020 : 100W 10ps FWHM @400kHz

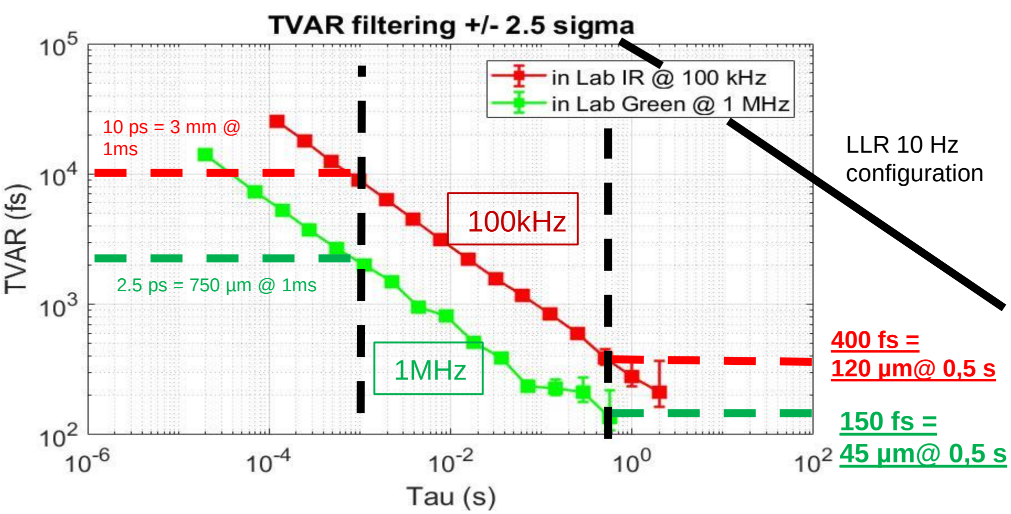
New SPAD in 2015 for 532nm (@1MHz) & 1064nm (@100kHz)



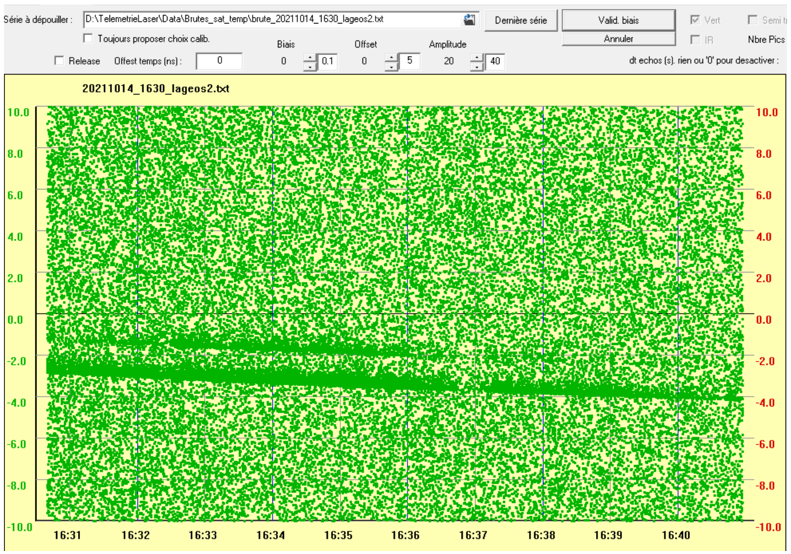
Aperture sharing in 2021

High count rate event timer (SigmaWorks)

Performances on ground (400kHz – 1MHz)

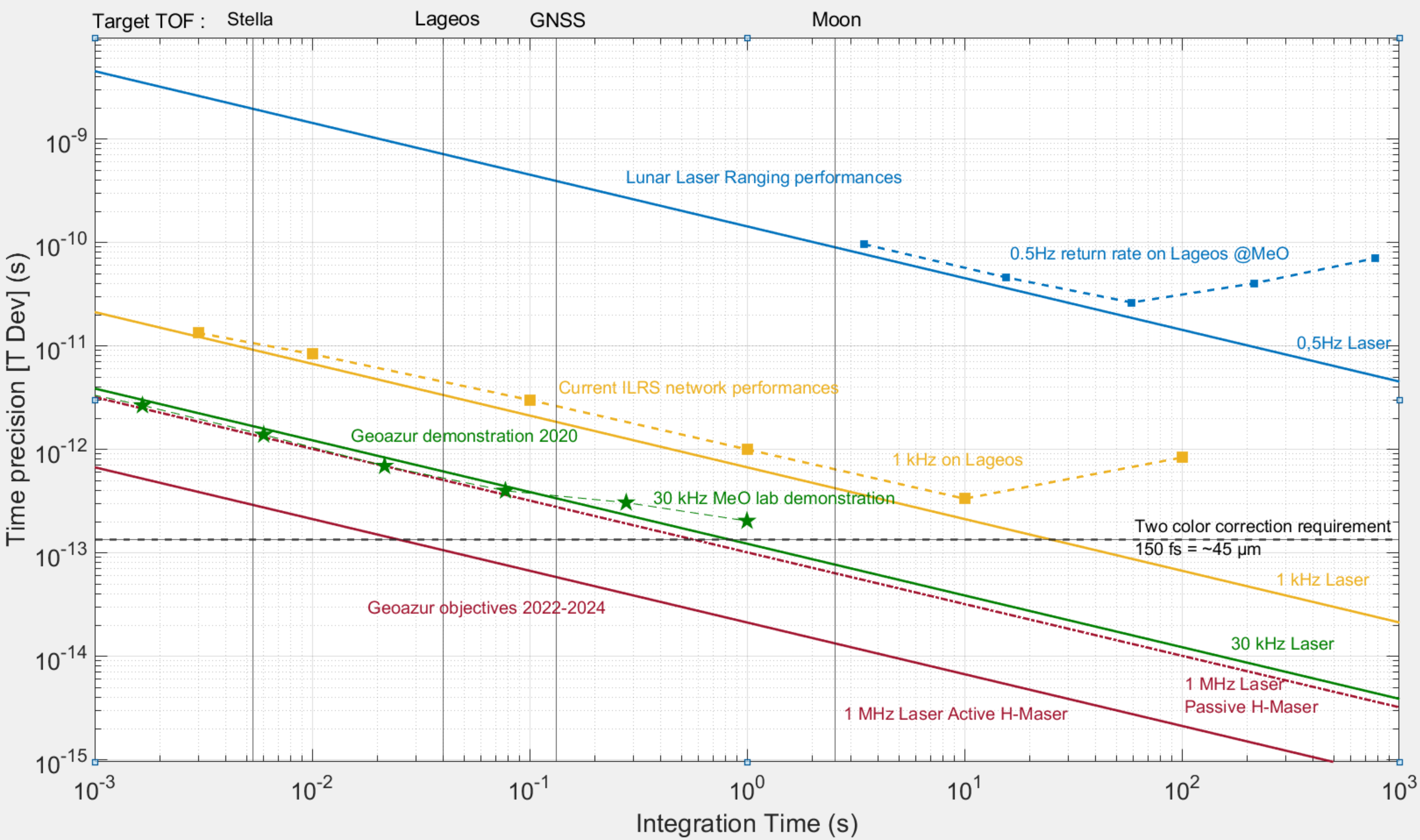


First results on satellite (lageos2 @4 kHz)



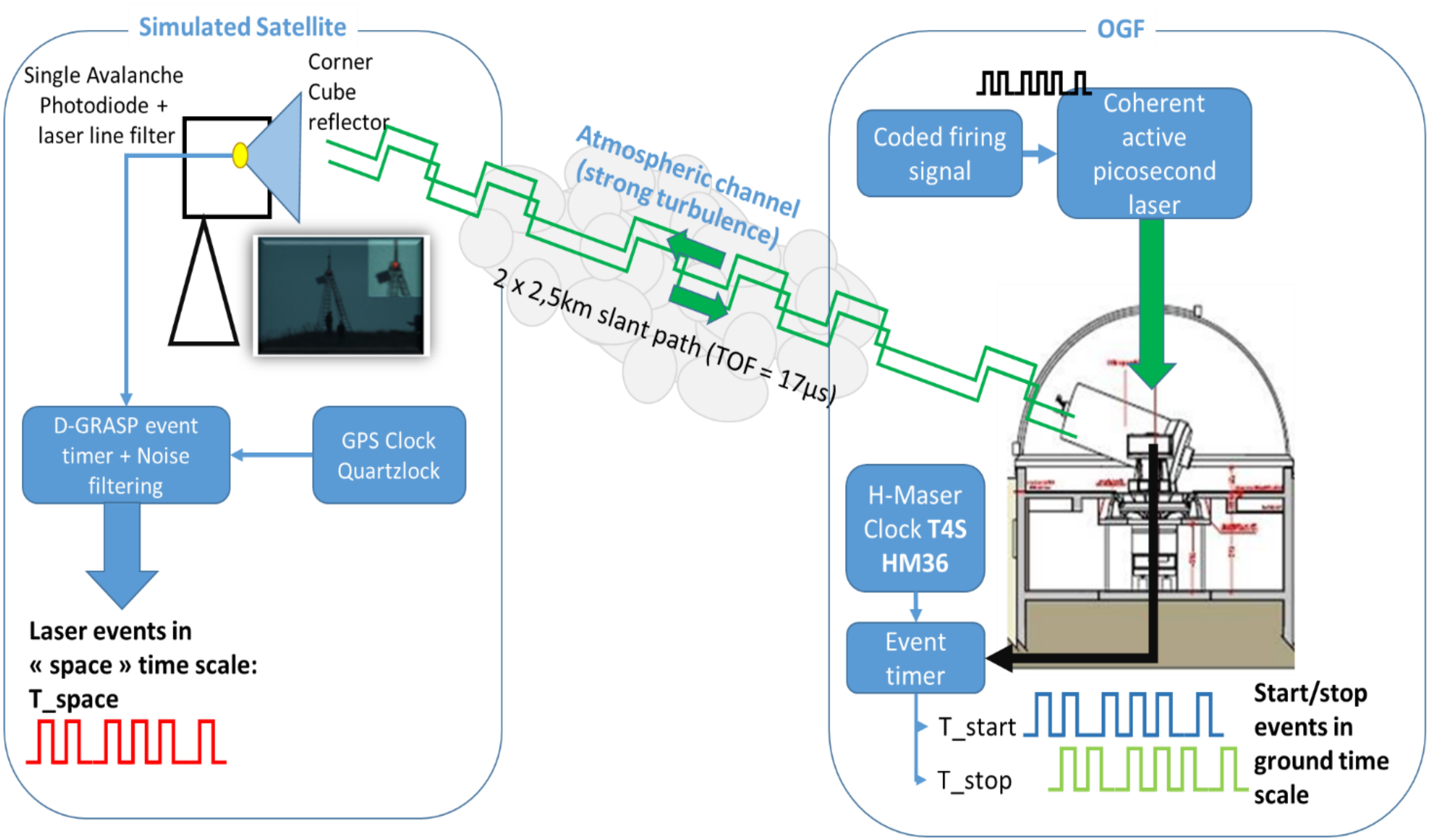
With the support of

Works in progress at Geoazur-MéO



Works in progress at Geoazur-MéO

Ground demonstration with potential combination of single-photon/optical telecom technologies



Works in progress at Geoazur-MéO

EURAMET JRP GeoMetre

Objectives :
The overall objective of this project is to improve the complex traceability chain in geodetic length metrology.

Our participation:
(WP2)
To develop technologies, methods and uncertainty assessment for the Earth-bound SI-traceable verification of space-geodetic measurement technologies like GNSS or SLR over distances of at least 5 km with uncertainties of 1 mm or better and their implementation in a European reference standard.

Collaboration OCA / LNE-CNAM / IGN
September 2022

The Genesis-1 mission

Conclusion

1) Passive SLR retroreflector is essential for:
   a. SLR only or combine solutions
   b. orbit improvement
   c. mismodelling in orbit products relative to the satellite attitude
   d. Backup when radio system fails

2) Active laser retroreflector is essential for:
   a. Time & frequency comparisons between ground & board and between geodetic techniques
   b. New insigth on phenomenons acting on clock behavior for fundamental physics, space environment, chronometric geodesy

Thanks for your attention