Laser GNSS Receiver for LEO POD, Laser Occultation and Time&Frequency Transfer of Optical Clocks in the Timing Labs

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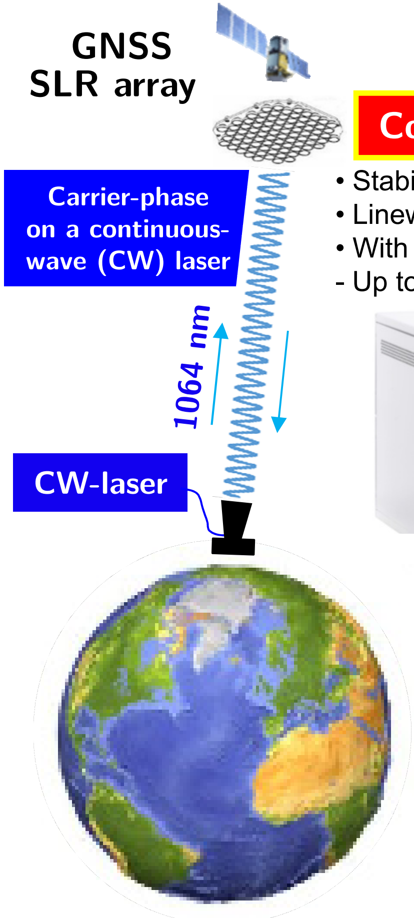
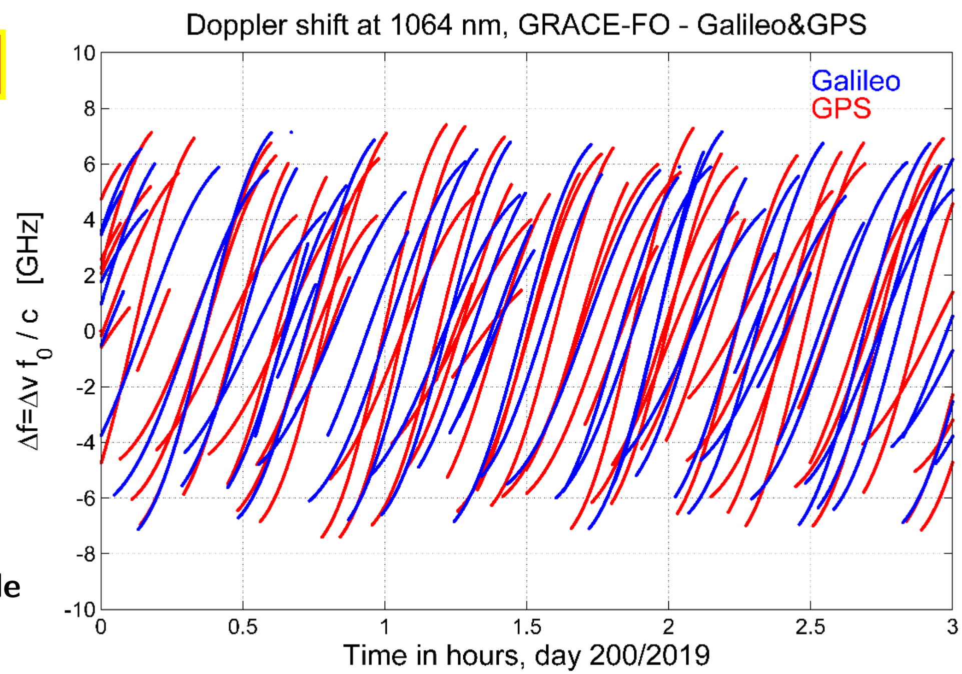
Laser GNSS Receiver in LEO



Continuous-Wave (CW) Laser

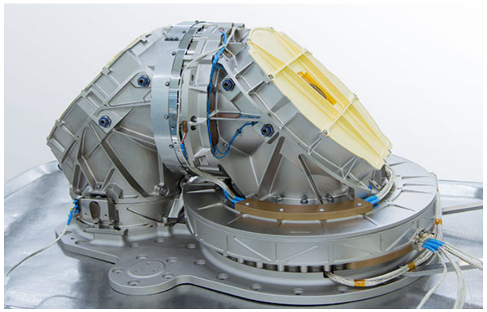
- Stability $<5 \times 10^{-15}$ at 1 s
- Linewidth <2 Hz
- With cavity from NPL (LISA mission)
- Up to 1 kW power

No atmosphere in LEO
One could improve LEO attitude (quadrant photodiode)

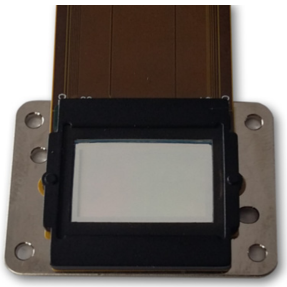


Laser beam steering in LEO

"Sinopta" laser steering terminal for LEO steering over 360°/90°



Spatial Light Modulator steering over 24°



Link Budget for CW Laser: LEO, Ground, Moon

Link Budget:

$$n_r = \frac{E_t \lambda}{hc} G_t \sigma_{ocs} \left(\frac{1}{4\pi R^2} \right)^2 A_r T_a^2 T_c^2 \eta_t \eta_r \eta_d$$

Gaussian Beam:

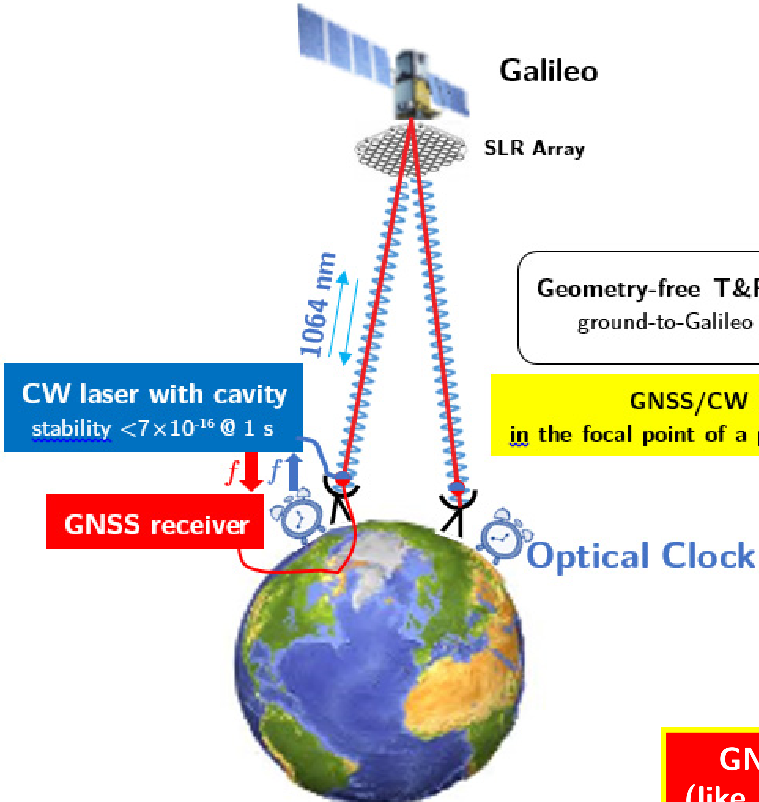
$$\theta_t = \frac{\lambda}{\pi \omega_0}$$

$$G_t(\theta) = \frac{8}{\theta_t^2} e^{-2\left(\frac{\theta}{\theta_t}\right)^2}$$

Link budget parameter	GRACE-FO – Galileo	Ground – Galileo	Ground – Moon
Transmitted power of a CW laser	200 W	1 kW	1 kW
σ_{ocs} optical cross section for GNSS (Pearlman, 2008) and Moon (Arnold, NASA TN)	$45-80\times10^6\ \mathrm{m}^2$	$45-80\times10^6\ \mathrm{m}^2$	$1400\times10^6\ \mathrm{m}^2$ 300 corner-cubes
Radius for the aperture area of the receiving optics A_r	0.15 m	0.30 m	0.50 m
Gaussian beam divergence half-angle, θ_t	0.47"	0.23"	0.14"
Fine pointing error (steering in steps of 0.01"), θ	0.20"	0.20"	0.10"
G_t transmitter gain	1.1×10^{12}	1.4×10^{12}	6.3×10^{12}
T_a^2 Two-way atmospheric transmission (Degnan, 1993), (Matthews 2020)	1.0	0.5	0.5
T_c^2 Two-way cirrus transmission (Degnan, 1993)	1.0	0.5	0.8
η_t efficiency of the transmitting optics (Degnan, 1993)	0.9	0.9	0.9
η_r efficiency of the receiving optics (Degnan, 1993)	0.9	0.9	0.9
η_d is the detector efficiency (photodiode sensitivity, Hamamatsu) see also (Jennrich & Heinzel, 2013),	$0.7\ \frac{\mathrm{A}}{\mathrm{W}}$	$0.7\ \frac{\mathrm{A}}{\mathrm{W}}$	$0.7\ \frac{\mathrm{A}}{\mathrm{W}}$
Received laser power from a CW laser	16.5 pW	100.1 pW	507.2 fW (1.5 pW)

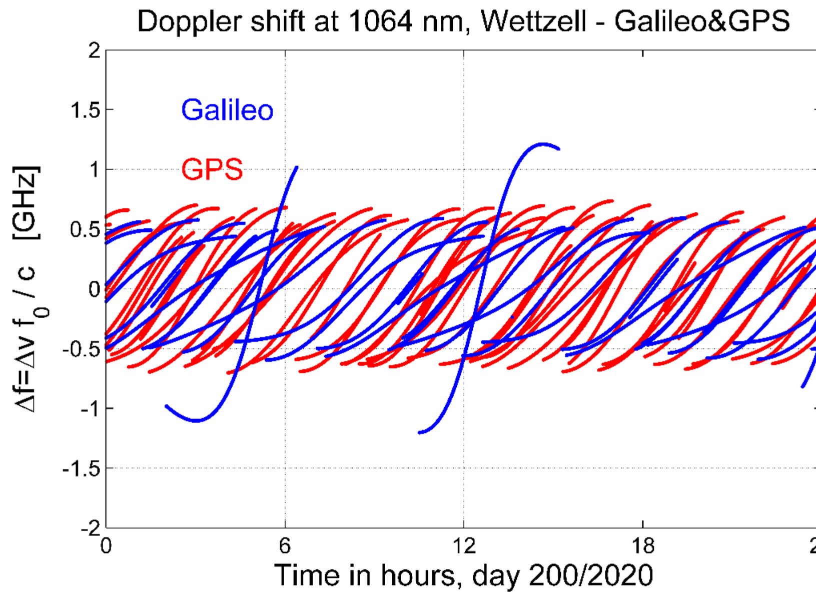
Hamamatsu (Japan) confirmed InGaAs photodiode for all three cases

CW-Laser for T&F Transfer at 10^{-18} for Optical Clocks



Geometry-free T&F Comparison at 10^{-18}
ground-to-Galileo or ground-to-ground

GNSS/CW laser receiver
in the focal point of a parabolic mirror ⌀60 cm



Laser Cavity (NPL&PTB) can provide microwave GNSS frequency more stable than H-maser on GNSS (via frequency comb)

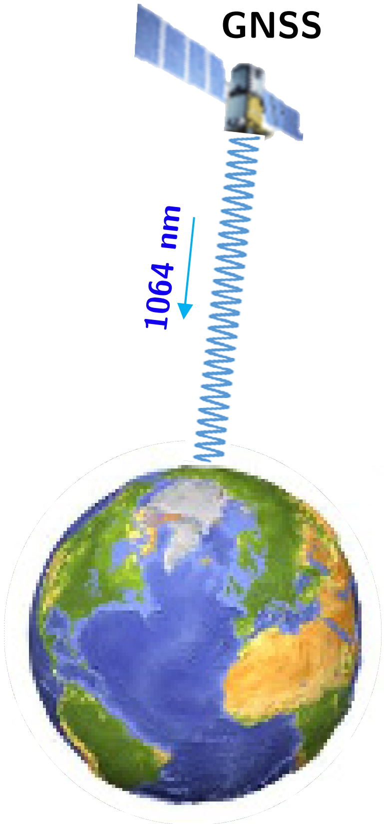
GNSS antenna rotated in space (like antenna calibration on a robot)

2D Antenna Rotation about Pivot point

With 'phase clock' approach for GPS we introduced in 2004 for LEOs, we managed to get T&F transfer down to 10^{-16} level

CW-Laser Onboard GNSS Satellites

Carrier-phase on a continuous-wave (CW) laser



"two-way"

CW-laser in LEO, signal reflected from GNSS

$$n_r = \left(E_t \frac{\lambda}{hc}\right) G_t \sigma_{ocs} \left(\frac{1}{4\pi R^2}\right)^2 A_r T_a^2 T_c^2 \eta_t \eta_r \eta_d$$

$$\sim \frac{1}{R^4}$$

"one-way"

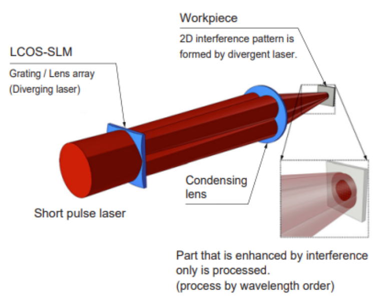
CW-laser onboard GNSS satellites

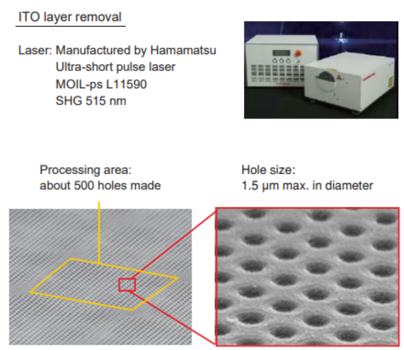
$$n_r = \left(E_t \frac{\lambda}{hc}\right) G_t \left(\frac{1}{4\pi R}\right)^2 A_r T_a^2 T_c^2 \eta_t \eta_r \eta_d$$

$$\sim \frac{1}{R^2}$$

Link budget	GRACE-FO – Galileo	Ground – Galileo	Ground – Moon
Two-way: Transmitted power of a CW laser	200 W	1 kW	1 kW
One-way: Transmitted power of a CW laser (**1 nW received**)	20 mW	15 mW	20 mW

We need 1-20 mW laser power transmitted from a GNSS to guarantee the received power of 1 nW (GRACE-FO) or 200 pW (LISA) with down to 10 cm collecting optics





With SLM, one can split laser beam into thousands of separate laser beams and steer them independently