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LEO-to-GNSS Laser Interferometer for Space Geodesy with Laser DORIS and Laser SAR

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Summary:

In order to increase the accuracy of precise orbit determination for a single satellite or satellites in LEO formation, we propose using a LEO-to-GNSS laser interferometer, what we call a "laser GNSS receiver", to measure the Doppler shift with a continuous-wave (CW) laser between LEO and GNSS satellites equipped with SLR arrays (Galileo, GPS, GLONASS, Beidou). LEO orbit is above atmosphere (no atmospheric attenuation and turbulence in laser signal) and this makes the "laser GNSS receiver" very attractive for future LEO missions. At the EGU and AGU conferences, over the last several years, we have presented the link budget, design and feasibility of such a new instrument in space geodesy and discussed applications in: reference frame missions; gravity field missions; laser atmospheric sounding (above the clouds) and combination with microwave GNSS-RO; time/frequency transfer for ground optical clocks at 10^{-18} frequency uncertainty (TAI, UTC); and Earth-to-Moon laser interferometry using an ILRS telescope. Here we extend this new instrument in space geodesy to laser DORIS and laser SAR.

Laser altimetry is an established technique that uses a pulsed laser to measure a range from LEO orbit to the ground in the nadir direction. In a similar way, interferometric laser tracking could be established on the continuous-wave laser signal transmitted from the LEO orbit in the nadir direction and reflected from the ground. This could be done, e.g., by modulating a microwave-like signal on a CW laser, providing a microwave phase on a laser carrier. The main advantage of the laser altimetry or laser SAR/inSAR is that microwave modulation on a laser carrier is not going to be affected very much by the wet delay of the atmosphere and in this way does not require radiometers in LEO to correct atmospheric propagation effects, and instead, they can be corrected a priori using models like those used for the SLR measurements.

Therefore, compared to the microwave SAR/inSAR, laser SAR/inSAR opens up the possibility of using the SAR/inSAR technique along with space geodesy techniques if permanent geodetic stations are equipped with the well-defined laser retro-reflectors on the ground. Compared to the pulsed lasers used by ILRS, a continuous-wave laser is more appropriate for higher laser powers since the lower laser peak power avoids damage to the transmitting optics and allows simplified optics with non-mechanical laser beam steering. We present link budget of such a laser DORIS technique to observe Doppler shift from LEO orbit to the ground laser retro-reflectors and laser SAR/inSAR based on laser signal reflected from the ground surface. The IceSAT-2 mission from NASA indirectly confirmed the link budget with the onboard pulsed laser used for laser altimetry, opening up the possibility of a laser SAR/inSAR technique from LEO.

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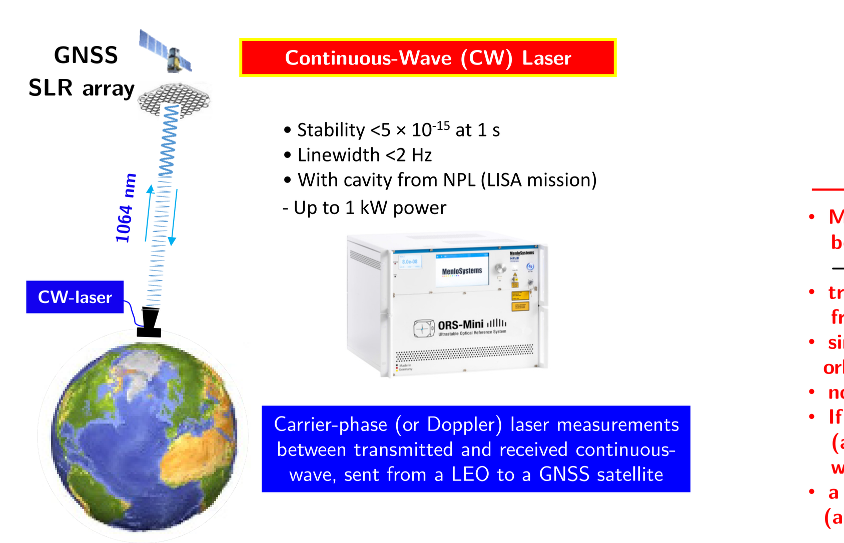
LEO-to-GNSS Interferometer



SCIENCE:

1. LEO-to-GNSS laser interferometer for LEO precise orbit determination
2. Future gravity field missions (such as GRACE-I/MCM, MAGIC)
3. Reference frame mission (such as GRASP/eGRASP)
4. Laser-occultation GNSS-LO for atmospheric sounding (above the clouds) complementing GNSS-RO
5. Time/frequency transfer for optical clocks at 10^{-18} frequency uncertainty (BIPM)
6. Earth-to-Moon laser interferometer using an ILRS telescope
7. Laser SAR/inSAR
8. Laser altimetry with a CW-laser (see Svehla, 2017, 2018, 2020-2023)

Figure 1 We propose using a LEO-to-GNSS laser interferometer, to measure the Doppler shift with a continuous-wave (CW) laser between LEO and GNSS satellites equipped with SLR arrays (Galileo, GPS, GLONASS, Beidou). Accurate orbit determination is of utmost importance for all gravity, reference frame, and altimetry satellite missions for sea level monitoring. We have already demonstrated that such a LEO-to-GNSS interferometer in LEO, could deliver huge improvements in determining the terrestrial reference frame of the Earth with GNSS satellites (ITRF), see e.g. Svehla (2018). A LEO satellite is above the clouds and there is no atmospheric attenuation and atmospheric turbulence in the LEO-to-GNSS laser interferometric link, it opens the door to securing a very accurate laser metrology system in LEO, combining LEO and GNSS satellites, that could be used for many new applications in gravity and altimetry mapping and Earth Observation missions for atmosphere sounding.

LEO-to-GNSS Interferometer for GRACE

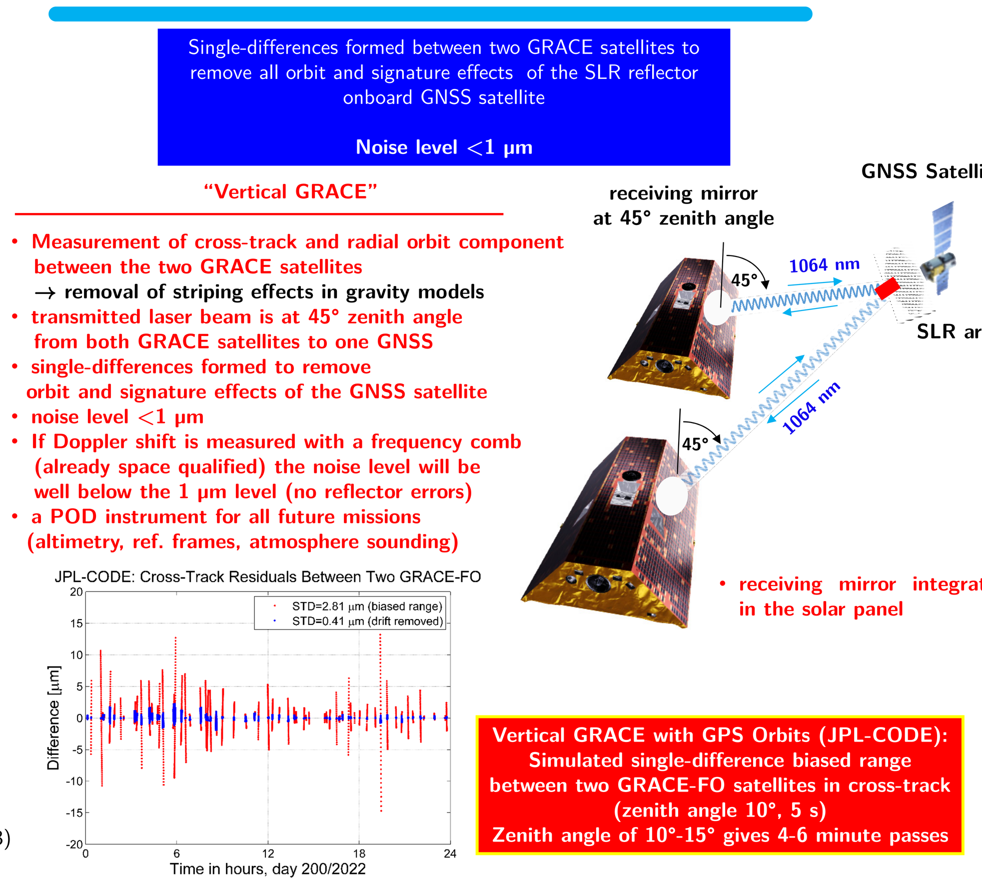


Figure 2 By forming single-differences of two LEO-to-GNSS interferometer measurements between the two GRACE satellites it is possible to remove all GNSS orbit and laser retro-reflector related errors (signature effect) and secure the relative orbit information between two GRACE satellites, with an accuracy similar to a LEO-LEO laser link. For gravity mapping missions, such as GRACE-FO and MAGIC, a LEO-to-GNSS interferometer can provide gravity measurements in the cross-track and radial orbit direction between the two LEO satellites (free of GNSS obit errors) — "vertical GRACE" complement the along-track LEO-LEO laser tracking. This will significantly reduce striping effects in the GRACE gravity models. We simulated single-difference biased range between the two GRACE-FO satellites and a GPS satellite projected in the cross-track (based on orbit differences between JPL and CODE for GPS satellites) and have **STD=2.8 µm (for zenith angle 15°, STD=4.6 µm) reduced to STD=0.41 µm by removing a linear drift and one can get STD=12 nm by removing a quadratic fit (STD=45 nm for zenith angle of 15°).**

Simulations

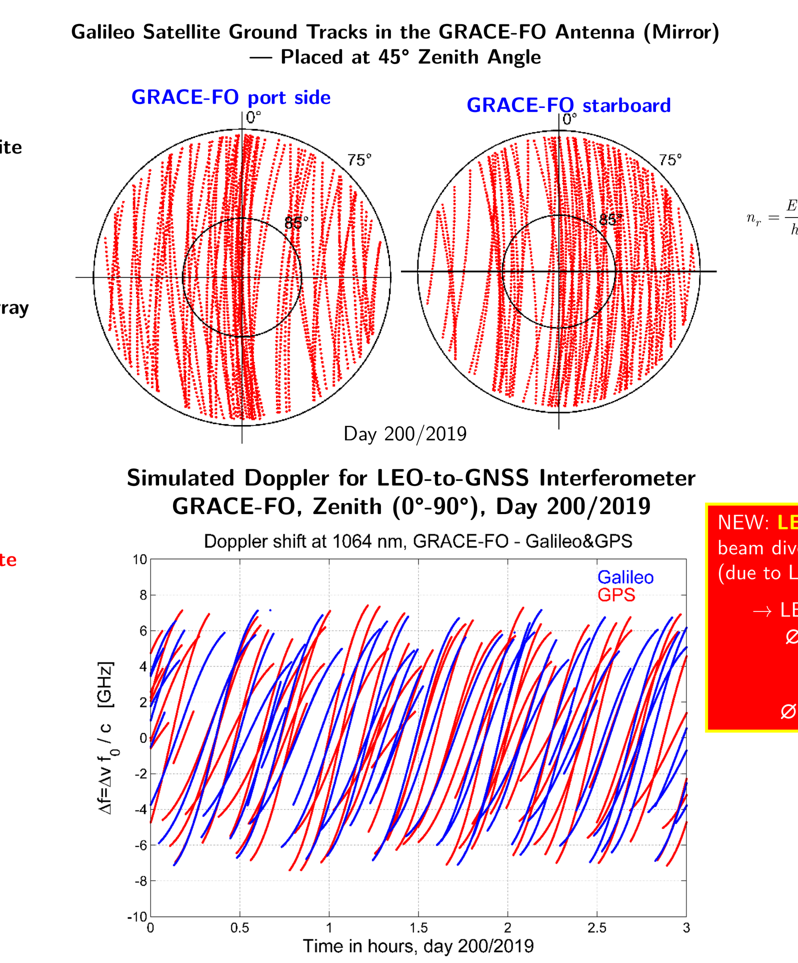
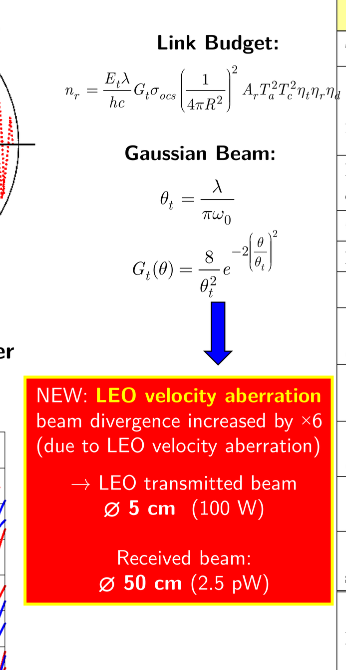


Figure 3 Top: Simulation of the ground tracks of Galileo satellites in the receiving mirror of the GRACE-FO satellite placed at starboard and port side of the satellite, day 200/2019. Bottom: Simulation of the measured Doppler shift for observed Galileo and GPS satellites with a zenith pointing antenna/mirror (0°-90°), day 200.2019.

Link Budget: LEO, GNSS, Moon



velocity aberration corrected

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)	$45-80 \times 10^6\ m^2$	$45-80 \times 10^6\ m^2$	$1400 \times 10^6\ m^2$ 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, 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)	$0.7\ \frac{A}{W}$	$0.7\ \frac{A}{W}$	$0.7\ \frac{A}{W}$
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

Figure 4 Link budget for the laser interferometer: LEO satellite to GNSS, ground-to-GNSS and ground-to-Moon laser interferometer. Hamamatsu (Japan) confirmed that their InGaAs photodiodes can continuously observe all three cases of a laser link. In order to account for the LEO velocity aberration, we reduce diameter of the transmitted beam from ∅30 cm to ∅5 cm, that is equivalent to increasing the Gaussian beam divergence by a factor of 6.

LEO-to-GNSS Interferometer for GRACE

Transmitted beam:

- ∅5 cm transmitted laser beam (for velocity aberration)
- 50-100 W transmitted power (amplified GRACE laser beam)
  - small laser amplifier (COTS) and to be space qualified by Menlo
- transmitted power could be reduced to 50 W with a ∅50 cm mirror
- if needed an average transmitted power could be reduced to e.g., 50 W, if measurements are not continuous between GNSS
- non-mechanical laser beam steering with SLM (24°) or piezo fast steering mirrors
- piezo fast steering mirrors offer 0.0004" precision (space qualified)

Received beam:

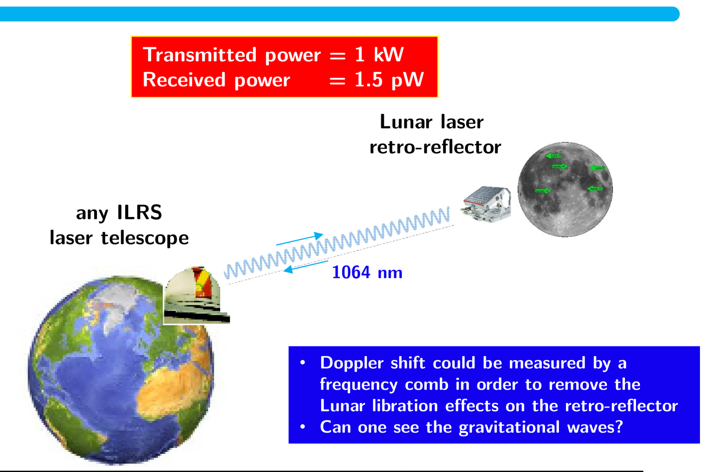
- ∅30-50 cm of the primary receiving mirror
- 0.3 - 2.5 pW received power
- photodiode receiving power confirmed by Hamamatsu Japan
- 1st order Doppler is to be corrected a priori before phasemeter
- to measure Doppler frequency comb is already space qualified

LISA development at Goddard (zerodur)
- secondary mirror is now too far from the primary mirror
  - to be shortened to e.g. 0-30 cm from the primary mirror
- Same LISA telescope (∅30 cm) inside GRACE-I/MCM?

- Coarse + fine fast steering piezo mirror for max. deflection angle and fine steering precision of 0.0004"
- ×4-5 increase in max. steering angle with this design

Figure 5 Design of the LEO-to-GNSS interferometer: transmitting beam of ∅5 cm and a receiving beam of ∅30-50 cm. Since LISA telescope has been developed (right) - elegant breadboard in 2021/engineering model - one could consider installing an existing LISA telescope ø30 cm inside the future gravity satellites such as GRACE-I/MCM and MAGIC. Link budgets for the ø30 cm and ø50 cm are very similar (0.3 pW and 2.5 pW). Secondary mirror placed at a distance of 72.5 cm could be shortened to e.g., 30-50 cm, or one could even considered exactly the same telescope. Star-trackers are also placed inside the GRACE satellites.

Earth-to-Moon Laser Interferometer



Link budget parameter	Ground – Moon	Ground – Moon	Ground – Moon
Transmitted power: Ground–to–Moon	2 kW $\lambda = 534$ nm	1.5 kW $\lambda = 1064$ nm	1 kW $\lambda = 1064$ nm
σ_{ocs} optical cross section of Lunar laser retro–reflectors (Degnan, 2019)	$2200 \times 10^6\ m^2$	$2200 \times 10^6\ m^2$	$2200 \times 10^6\ m^2$
Radius of the aperture area of the receiving optics A_r	0.25 m	0.35 m	0.50 m
Gaussian beam divergence half-angle, θ_t	0.14"	0.2"	0.14"
Fine pointing error, θ	0.1"	0.1"	0.1"
G_t transmitter gain	6.3×10^{12}	5.2×10^{12}	6.3×10^{12}
T_a^2 Two-way atmospheric transmission (Degnan, 1993), (Matthews 2020)	0.5	0.5	0.5
T_c^2 Two-way cirrus transmission	0.8	0.8	0.8
η_t efficiency of the transmitting optics	0.9	0.9	0.9
η_r efficiency of the receiving optics	0.9	0.9	0.9
η_d detector efficiency (photodiode sensitivity, Hamamatsu)	$0.7\ \frac{A}{W}$	$0.7\ \frac{A}{W}$	$0.7\ \frac{A}{W}$
Received laser power from the Moon	0.4 pW (1.2 pW)	0.5 pW (1.5 pW)	0.8 pW (2.4 pW)

Figure 6 The link budget (together with Figure 4) shows that a 0.5-1-m laser telescope of the ILRS with a 1 kW continuous-wave (CW) laser could be used to demonstrate for the first time the Earth-to-Moon laser interferometer making use of the Apollo retro-reflectors on the Moon. Compared to the pulsed lasers used by ILRS, a continuous-wave laser is more appropriate for higher laser powers since the lower peak power avoids damage to the transmitting optics. Very small compact fiber laser amplifiers are commercially available for the amplification of laser power and do not affect the laser carrier-phase. Doppler shift could be measured (instead of phase) by a frequency comb in order to remove the Lunar libration effects on the retro-reflector. Can one see the gravitational waves?

Time/frequency transfer for optical clocks at 10^{-18} frequency uncertainty

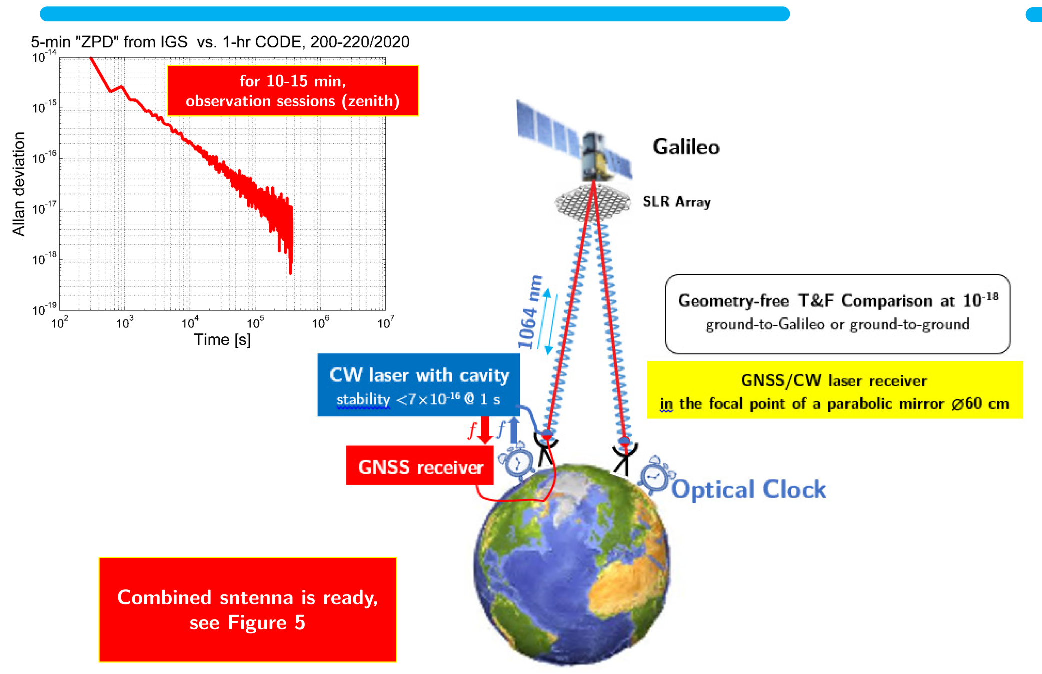


Figure 7 GNSS is not accurate enough to be used for optical clocks in the timing labs that operate at 10^{-18} fractional frequency uncertainty or for an official time in general (TAI, UTC). Frequency clock comparison using GNSS is mainly based on precise point positioning techniques and is limited to the level of about 10^{-16} fractional frequency uncertainty. This has not changed much since we demonstrated this level of stability of about 10^{-16} by introducing the phase clock method for GPS, Svehla and Rothacher (2003). In order to use GNSS for time and frequency transfer of optical clocks in timing labs and an official time in general, we propose to add a CW laser to the GNSS receiver and measure both carrier-phase in the microwave and optical band with the same parabolic mirror (∅40-60 cm) to the same GNSS satellite. Such an antenna is ready, see Figure 5. GNSS satellites are equipped with SLR arrays and can be used to measure the optical carrier-phase between the transmitted and received signal with a CW laser. If the same parabolic mirror (∅40-60 cm) is used as an antenna to observe laser and microwave GNSS measurements, all geometry effects can be removed (geometry-free), resulting in the GNSS satellite clock and GNSS receiver clock parameters being the only parameters of such a geometry-free, ground-to-space optical/microwave metrology link for GNSS. Considering that the optical frequency of a CW laser, stabilised by an internal cavity, can be provided with the frequency stability of $<7\times10^{-16}$, it can be transformed into a microwave band (via a frequency comb) with the same level of stability used as a reference frequency for the GNSS receiver. Therefore, the optical frequency of a CW laser can be used via the microwave GNSS signal to compare the frequency of GNSS satellite clocks or optical clocks in two separate timing labs. Atmospheric effects for the optical band (CW laser) can be applied a priori, whereas for the microwave GNSS troposphere zenith delays (TZDs) need to be estimated with an additional GNSS antenna/receiver close to the parabolic mirror. We know from the IGS network that troposphere zenith delays can be estimated with the noise level of about a millimeter in the zenith direction. However, here a Doppler shift is measured by a frequency comb and only the first derivative of estimated tropospheric zenith delay is needed. Therefore, by selecting one GNSS satellite close to zenith from two timing labs on the ground, all GNSS satellite-related errors will be removed, including the GNSS satellite clock parameter, and the time and frequency of optical clocks could be compared at the 10^{-17} - 10^{-18} frequency uncertainty level. This opens up the possibility of the timing labs using GNSS for the generation of the official time (TAI, UTC) making use of the optical clocks.

Laser Occultation for Atmosphere Sounding (GNSS-LO + GNSS-RO)

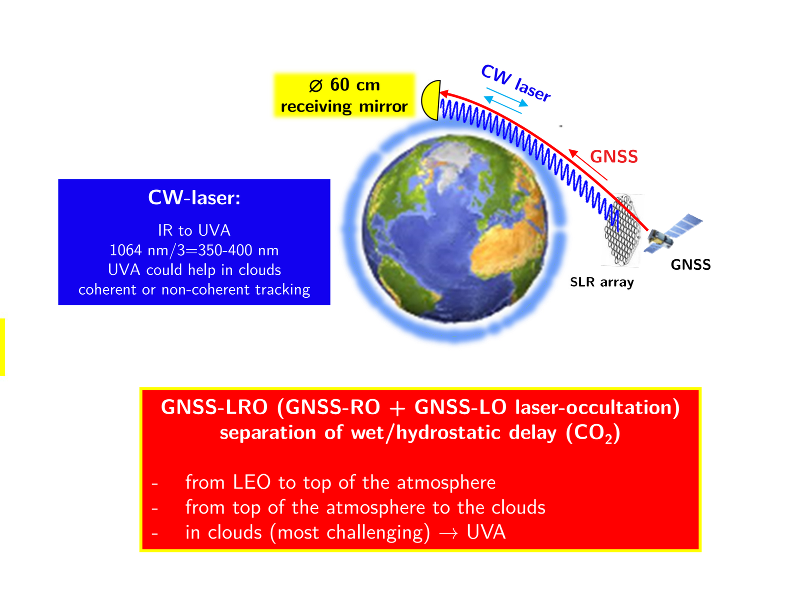
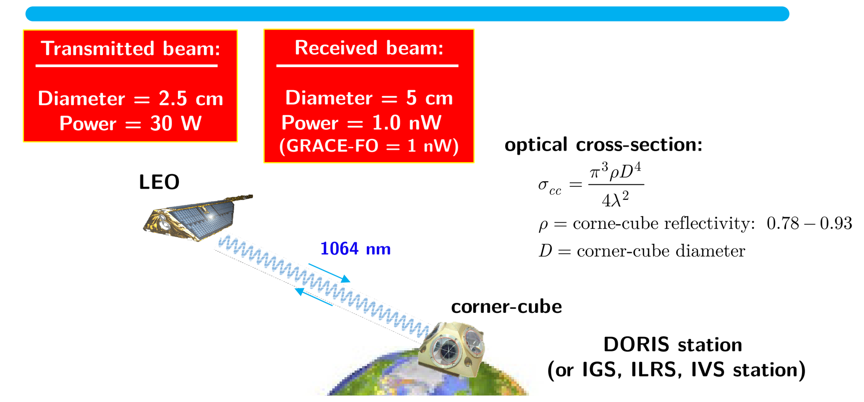


Figure 8 We extend the concept of LEO-to-GNSS interferometer to laser occultation for atmosphe sounding between a LEO satellite and GNSS satellites equipped with SLR arrays. We are combining measurements from a CW laser in LEO to a GNSS satellite (IR, UV) and standard GNSS radio-occultation, what we call the GNSS-LRO. By comparing the LEO-to-GNSS laser measurements (IR, UV) with GNSS microwave measurements in the GNSS-LRO approach, it is possible to directly separate hydrostatic and wet delays in signal propagation (above the clouds only). Space geodesy measurements show that the wet delay in signal propagation is typically ×67 smaller for optical waves than for microwaves. To a lesser degree, hydrostatic delay in signal propagation also differs for optical and microwave measurements and is influenced by the atmospheric constituents, such as CO_2. The main issue of such a concept is the atmospheric attenuation of the laser signal and is limited to above the clouds. Therefore, laser and microwave GNSS-RO measurements could be compared from LEO down to the top of the atmosphere and from the top of the atmosphere down to the clouds. We again make use of the higher power of the CW laser that could be enlarged above 1 kW in the LEO orbit. From the development point of view, all components of such a LEO-to-GNSS interferometer for the laser atmosphere sounding are nearly space qualified and it will be ready from the gravity mapping missions. Considering that there is no velocity aberration in the laser link to GNSS satellites, one could make use of the full laser power without narrowing the laser beam, like for the zenith-type pointing applications, where one needs to use narrow laser beam to increase the Gaussian beam divergence in order to compensate the velocity aberration correction of a LEO satellite (diameter decreased by a factor of 6). Doppler shift between the transmitted and received laser signal to a GNSS satellite could directly be measured by a frequency comb (already space qualified). In this way, Doppler shift is measured in microwave (GNSS-RO) and optical band (GNSS-LO) from a LEO satellite to the same GNSS satellite. This combined atmosphere sounding approach GNSS-RO + GNSS-LO we call the GNSS-LRO.

Laser DORIS



Link budget parameter	GRACE-FO – Ground corner-cube	GRACE-FO – Ground corner-cube	GRACE-FO – Ground corner-cube
Transmitted power: LEO to a ground corner-cube	30 W	30 W	30W
σ_{ocs} optical cross section of a single ground corner-cube reflector of a diameter=38 mm, 2×38 mm, 3×38 mm	$D = 38$ mm $13 \times 10^6\ m^2$	$D = 2 \times 38$ mm $212 \times 10^6\ m^2$	$D = 3 \times 38$ mm $1075 \times 10^6\ m^2$
Diameter of the aperture area of the receiving optics A_r	0.05 m	0.05 m	0.05 m
Gaussian beam divergence half-angle, θ_t Transmitted beam diameter=0.025 m	2.8"	2.8"	2.8"
Fine pointing error θ	0.2"	0.2"	0.2"
G_t transmitter gain	4.3×10^{10}	4.3×10^{10}	4.3×10^{10}
T_a^2 Two-way atmospheric transmission	0.5	0.5	0.5
T_c^2 Two-way cirrus transmission	0.8	0.8	0.8
η_t efficiency of the transmitting optics	0.9	0.9	0.9
η_r efficiency of the receiving optics	0.9	0.9	0.9
η_d detector efficiency (Hamamatsu)	$0.7\ \frac{A}{W}$	$0.7\ \frac{A}{W}$	$0.7\ \frac{A}{W}$
Received laser power (from 1000 km)	12.2 pW	195.4 pW	1.0 nW

Figure 9 Link budget for the "laser DORIS" concept using a single ground corner-cube reflector with a diameter of 38 mm, 2×38 mm and 3×38 mm. For the transmitted laser power of 30 W (only 2.5 cm diameter), received power of 1.0 nW (5 cm diameter) is the same as the received laser power onboard the GRACE-FO mission (1 nW). Doppler shift between the transmitted and received laser signal in the LEO orbit could be measured by a frequency comb (already space qualified).

Laser SAR/inSAR

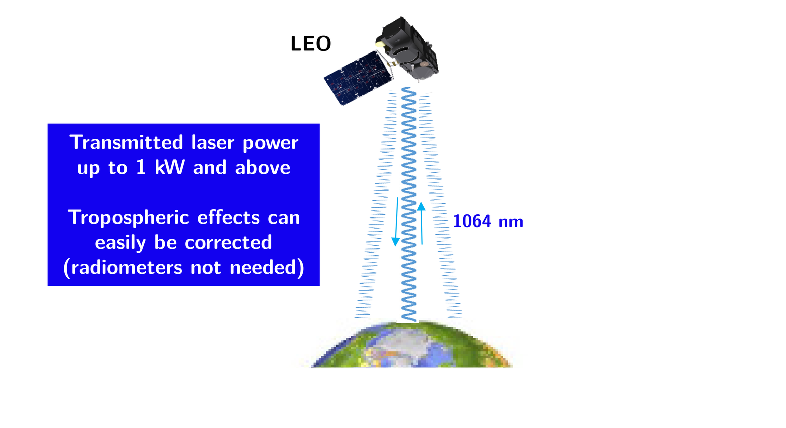


Figure 10 We propose to extend the SAR/inSAR technique from the microwave to the optical band. Laser altimetry is a technique established by the IceSAT-2 mission of NASA that uses a pulsed laser to measure a range from LEO orbit to the ground in the nadir direction. In a similar way, interferometric laser tracking could be established on the continuous-wave (CW) laser signal transmitted from the LEO orbit in the nadir direction and reflected from the ground. This could be established by some kind of modulated microwave-like signal on a CW laser, providing a microwave "phase" information on a laser carrier. This would be similar to the Doppler shift being measured on a pulsed laser at a very high repetition rate. Considering that such a CW laser signal in LEO could be transmitted to the ground in a grid swath or in a swath generated by fast beam steering, such a technique would be similar to microwave SAR/inSAR in the microwave band. As mentioned before, compared with pulsed lasers, a continuous-wave (CW) laser is more appropriate for higher laser powers since the lower laser peak power avoids damage to the transmitting optics. The main advantage of the laser SAR/inSAR is that microwave modulation on a laser carrier is not going to be affected very much by the wet delay of the signal propagation in the atmosphere and in this way does not require radiometers in LEO to correct atmospheric propagation effects, and instead, they can be corrected a priori using models like those used for the SLR measurements. Space geodesy measurements show that the wet delay in signal propagation is typically ×67 smaller for optical waves than for microwaves. Accuracy provided by the radiometers is still a limiting factor when using radiometers to correct for the atmospheric propagation effects of space geodesy measurements at fundamental geodetic stations (GNSS, VLBI, SLR, DORIS). Therefore a proposed laser SAR/inSAR opens up the possibility of using laser SAR/inSAR along with space geodesy techniques making use of the laser retro-reflectors on the ground (like the SLR arrays on board GNSS satellites).

Laser Altimetry with a Continuous-Wave Laser

Figure 11 With the onboard pulsed laser used for laser altimetry, the IceSAT-2 mission from NASA indirectly confirmed the link budget of a laser altimetry with a continuous-wave laser and the associated laser SAR/inSAR technique from LEO. Advantage over the pulsed laser altimetry is in the significantly higher laser power that could be transmitted on the continuous laser wave and one could directly correct tropospheric effects a priori. Considering that the IceSAT-2 mission demonstrated laser returns from the sea floor at 40 m depth in the ocean, this is a promising advantage of this fundamentally new altimetry technique.

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