# SLR Measurements of the Forthcoming ESA Earth Observation and Fundamental Physics Missions and Their Applications in the Reference Frames Realization

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**Summary:** We give a short overview of the forthcoming ESA Earth Observation (EO) and Fundamental Physics missions that implement highly accurate SLR tracking; discuss the ''SLR network effect'' and its impact on the geocenter in the case of ocean altimetry with the two antipodal Sentinel-3 satellites; present laser retro-reflectors of the Sentinel-3 and the three Swarm satellites, and potential SLR tracking restrictions for Sentinel-3 mission. We discuss applications of laser retro-reflectors (LRR) with zero-signature such as BLITS, in order to capture sub-mm LEO orbit perturbations for gravity field and POD, and show improvements in the GOCE orbit validation by introducing "SLR ANTEX" file. In sequel, we discuss the possibility of using the highly elliptical orbit of the STE-QUEST mission for the reference frame realization, combining GNSS, SLR and VLBI (radio source) in HEO. In the second part, we introduce double-difference approach of space geodesy for SLR/LLR/VLBI/GNSS and with simulated SLR measurement show how common biases are removed by forming SLR double-differences, i.e. station range biases, common signature effects and (GNSS) orbit errors for baselines up to 5000 km. Simulated data show how remaining noise in the SLR measurements nicely averages out, leading to orbit-free and bias-free estimation of station coordinates, local ties between different space geodesy techniques and precise comparison of optical/microwave tropospheric effects. SLR scale is preserved by differencing.

**Prospects in SLR Tracking of ESA Earth Observation and Fundamental Physics Missions:** There are several ESA missions that will be launched in the near future and will require highly accurate SLR measurements. Swarm is an ESA's geomagnetic field mission, a constellation of three LEO satellites planned for launch in April 2013, whereas Sentinel-3 is the ocean/land altimetry mission (scheduled for 2014/2015) with two antipodal satellites in the same orbital plane (with SLR LRR, GPS and DORIS receiver). Considering the "SLR network effect'' (unequal global distribution of SLR stations, especially between northern and southern hemisphere) and associated geocenter effects (z-bias), it is recommended to observe both Sentinel-3 satellites in the same station tracking session. This will also preserve the common SLR range bias between the two satellites. There is a potential SLR tracking restriction for Sentinel-3 satellites due to the onboard Ocean and Land Colour Instrument and this issue will need to be discussed with ILRS before the launch. STE-QUEST is a fundamental physics mission pre-selected for the M3 slot of the ESA Cosmic Vision Programme. If finally approved in 2013, it will be interesting to use the highly elliptical orbit of this satellite for the reference frame realization and combination of space geodesy techniques by means of SLR, GNSS and an optional onboard VLBI radio source. ESA is extremely pleased with the ILRS Tracking of GOCE mission, currently approaching the target orbit altitude of only 235 km. In addition, the first SLR tracking of Galileo satellites has been reported in [Svehla et al., 2011]. Calibration of CHAMP and GOCE LLRs reveals significant reflector signature in the order of 9 mm peak to peak, whereas for GOCE, this effect is in the order of 15 mm. Converting this calibration table into a SLR ANTEX file (in analogy to GPS), bias in the SLR residuals of the GOCE Precise Science Orbit is reduced from 5.2 mm to 0.1 mm, whereas standard deviations of the residuals is slightly improved from 14.5 mm to 14.4 mm. For both, the Swarm and Sentinel-3 satellites, the GFZ-design for laser retro-reflector is foreseen with the recommendation to possibly embark superior BLITS design with zero signature. Sentinel-3 mission is the first altimetry mission with antipodal satellites. Although equipped with GPS receiver, it will not be possible to form GPS baseline between the two satellites and get relative orbit information, since there is no common GPS satellite in view. In the case of GRACE mission, it was demonstrated for the first time in [Svehla and Rothacher 2004] that GPS baseline (or vector between two satellites) can be determined with the very high accuracy of only 2.8 mm RMS when validated against the GRACE KBR measurements. With refined models, this RMS has been reduced to 0.7 mm. Thus, for Sentinel-3 satellites it will be very interesting to improve orbit quality by forming a "LEO network in space" (Sentinel-3, Swarm, Jason-2, etc.) in order to provide relative orbit information between the two antipodal satellites with utmost accuracy.

**Double-Difference Approach of Space Geodesy - SLR/LLR/GNSS/VLBI:** Double-differences (DD) have been widely used in the processing of global GPS measurements, forming so-called GPS baselines, or vectors between IGS stations. When ETALON and LAGEOS satellites are observed by SLR, any orbit error propagates directly into station coordinates. However, by forming differences between two satellites and two ground stations this orbit error can be eliminated or to a great extent reduced. Both satellites need to be observed quasi-simultaneously in the same tracking sessions in order that station range bias and common reflector signature effect are removed by differencing. By forming single-difference of SLR measurements between two stations and a common satellite, range biases are not eliminated, thus single-difference to another satellite in a common view is needed, see Fig. 1. In this way we obtain double-difference SLR measurements of utmost precision and accuracy. By applying so-called "Bauersima rule of thumb" (1) and considering that GNSS orbit can be estimated with an accuracy of about 1 cm RMS, one can see that for baselines of 5000 km the impact of orbit error on station coordinates is on the order of only 2.2 mm (STD of SLR normal points from GPS36), whereas for a baseline of 1000 km the effect is only 0.4 mm. Eq. (1) relates the station vector component error $\delta\rho_{xyz}$ with an orbit error $\delta r$ scaled by the baseline length $l$ and normalized by the orbit altitude $R$. Table 1. shows ZIML station coordinates estimated from WETL based on simulated SLR double-differences with normal points every 5, 10 and 15 min. Before differencing, SLR measurements were simulated with RMS of 2.2 mm (STD of normal points for GPS36).

| | Two Double-Differences (Three GNSS Satellites, day 293/2012) | | | Full GNSS Constellation |
|---|---|---|---|---|
| **ZIML coordinates** | NPT every **5 min** [mm] | NPT every **10 min** [mm] | NPT every **15 min** [mm] | NPT every **10 min** [mm] |
| **Up** | **-1.4**/-3.7 | **5.4**/14.6 | **-5.7**/-15.6 | **-0.1**/-0.3 |
| **North** | **0.3**/0.7 | **-0.7**/-2.0 | **0.1**/0.3 | **0.0**/0.0 |
| **East** | **0.2**/0.5 | **0.1**/0.2 | **0.0**/-0.1 | **0.0**/0.0 |

$$\delta\rho_{xyz} = \frac{l}{R}\delta r \qquad (1)$$

Table1. 1. SLR double-difference simulation: ZIML station coordinates estimated from WETL based on only one SLR tracking pass with three GNSS satellites (left columns) and the full GNS S constellation (last column).

An error in the order of 4-6 cm RMS was introduced to GNSS orbits, however the effect on station coordinates in negligible over such a short SLR baseline. Simulation shows that just with one DD pass one can estimate station coordinates at mm-level. When in parallel, both GNSS satellites are observed with microwave measurements, one can estimate very accurate local ties by comparing (or subtracting) GNSS and SLR DD measurements (2). In Eq. (2), $\rho$ denotes geometry term and $\delta\rho(\cdot)$ stands for troposphere effect. Eq. (2) can be used for very precise comparisons of troposphere models and mapping functions between optical and microwave domain. Fig. 3 show different ways to form double-differences based on satellites in different orbit, such as Lunar orbit, Moon, MEO and LEO. In this case one could combine orbits of GNSS satellites with ETALON and LAGEOS satellites used for realization of terrestrial reference frame, as well as Lunar Laser Ranging. One could also form DDs between two retro-reflectors on the Moon, considering that baseline/altitude ratio in (1) approaches zero in that case. It is expected that in the future GNSS satellites will be observed by ground VLBI antennae, thus (2) is proper set up to for double-difference space geodesy approach to consistently combine all three space geodesy techniques (GNSS, SLR and VLBI). An alternative is to observe quasars at approximate locations of GNSS satellites and to process VLBI data in DD mode in order to remove clock related parameters (freq. offset).

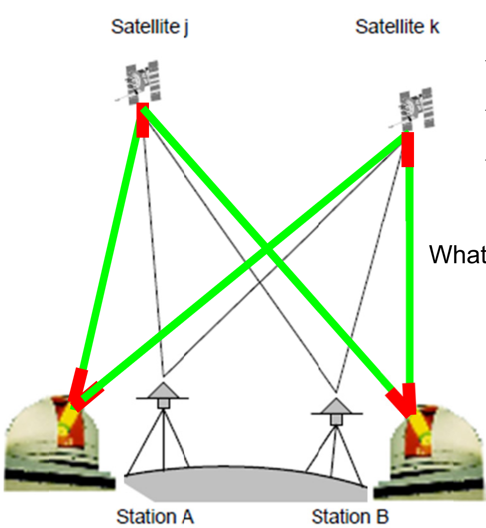


Fig. 2. SLR double-differences (green) with satellite biases and station range biases (red).

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\begin{aligned}
DD_{A\,B}^{jk}(GNSS) &= \rho_{A\,B}^{jk} + \delta\rho_{A\,B}^{jk}(TRP_{\mu wave}) \\
DD_{A\,B}^{jk}(SLR) &= \rho_{A\,B}^{jk} + \delta\rho_{A\,B}^{jk}(TRP_{optial}) + local\ tie \qquad (2) \\
DD_{A\,B}^{jk}(VLBI) &= \rho_{A\,B}^{jk} + \delta\rho_{A\,B}^{jk}(TRP_{\mu wave}) + local\ tie
\end{aligned}
$$

What is removed with SLR double-differences?

- Station SLR range bias
- Satellite LRR signature
- GNSS orbit error ($l$<5000 km)
- *SLR scale is preserved!*

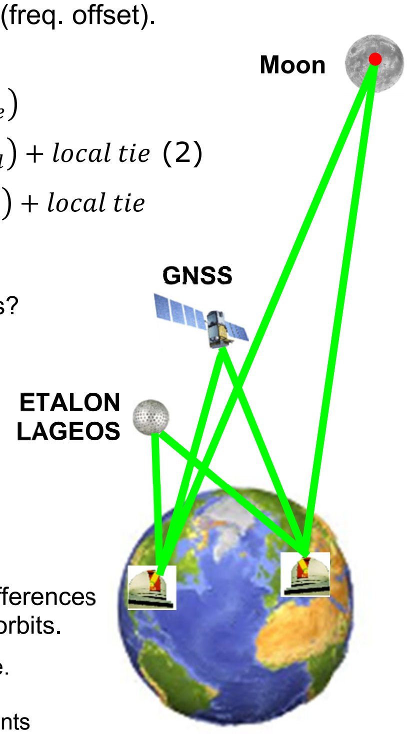


Fig. 3. SLR double-differences between different orbits.

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**References:**


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