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

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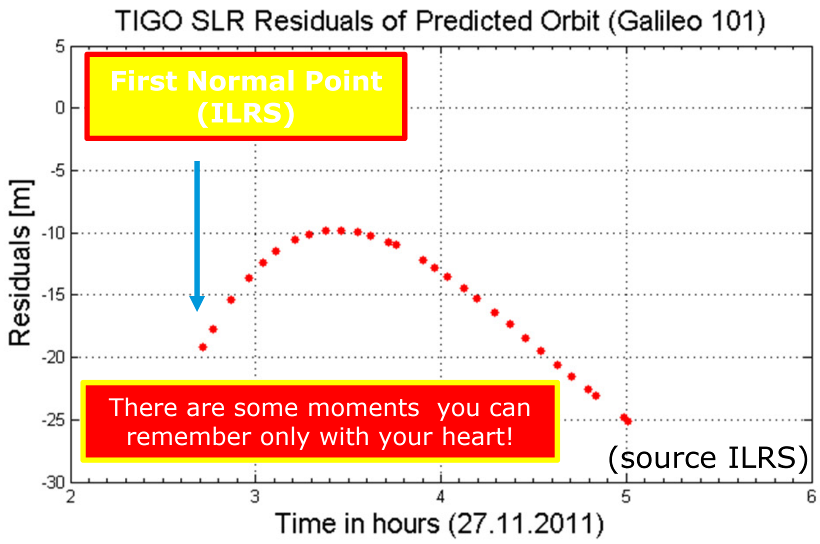
- SLR calibration with GNSS Clock: How GNSS Clock can be used to compare all SLR stations?

# First Galileo SLR Tracking

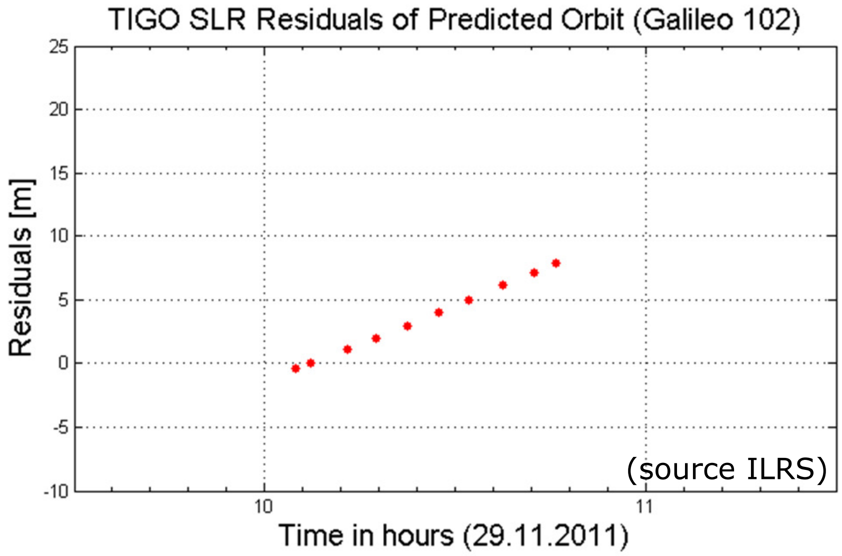
ESA Press Release Dec/2011



**First Normal Point (ILRS)**

There are some moments you can remember only with your heart!

(source ILRS)



(source ILRS)

**News**

**First laser measurements of Europe's Galileo satellites made from Chile**

15 December 2011

The first laser ranging of Europe's new Galileo navigation satellites has been achieved from Concepción in Chile. Laser contact with the satellites at an altitude of 23 230 km has provided distance measurements with subcentimetre accuracy.

Laser ranging

The Transportable Integrated Geodetic Observatory, TIGO, in Concepción, performed the world's first laser ranging to the first Galileo satellite on 27 November at 02:45 GMT, and to the second satellite two days later at 10:05 GMT, using a near-infrared laser beam.

ervations: in 2006 its radio oon mission, SMART-1, during unar surface.

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to the ground is measured with of light is fixed, so the distance to the satellite can be measured with an accuracy of better than a centimetre.

**International Laser Ranging Service**

TIGO is owned by the German Bundesamt und Geodäs been operat Universidad (UdeC) and Instituto G (IGM) since established various typ geodetic m

TIGO station

TIGO was the 40-stro Laser Ranging Service network to range the G with Herstmonceux in the UK and Matera in It Satellite Laser Ranging stations to succeed.

As well as being widely used for precise orbit determination of satellites, laser ranging is also employed for calibrating satellite instruments, contributing to the International Terrestrial Reference Frame (Earth's standardised geodetic coordinate system) and measuring slight ground

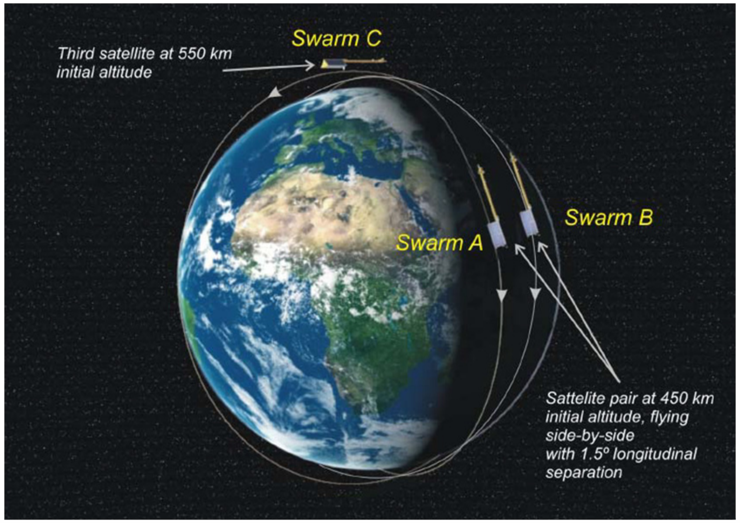
Laser ranging team

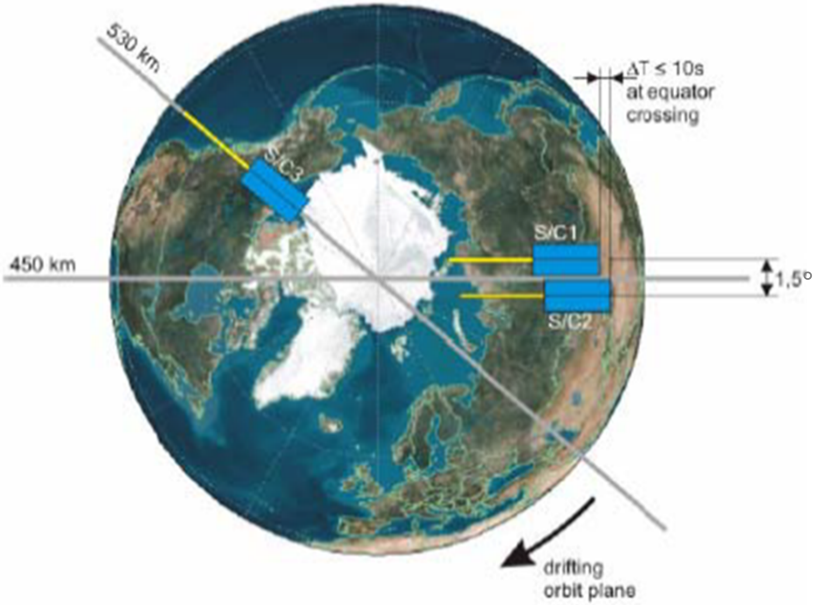
**ESA Homepage**

http://www.esa.int/SPECIALS/Galileo_IOV/SEM6HT7XZVG_1.html#subhead4

# Swarm

ESA's Earth Explorer Mission





## Science Objective:

- The best survey ever of the geomagnetic field and its temporal evolution

## Instruments:

- Vector Field Magnetometer
- Absolute Scalar Magnetometer (Laser)
- Electric Field Instrument
  (Thermal Ion Imager & Langmuir Probe)
- Accelerometer
- GPS Receiver (dual-frequency)
- Laser Retro-Reflector

**Contribution to Reference Frames? "LEO Network"**

- Launch Date: **April/2013**

# Sentinel-3 (A/B)

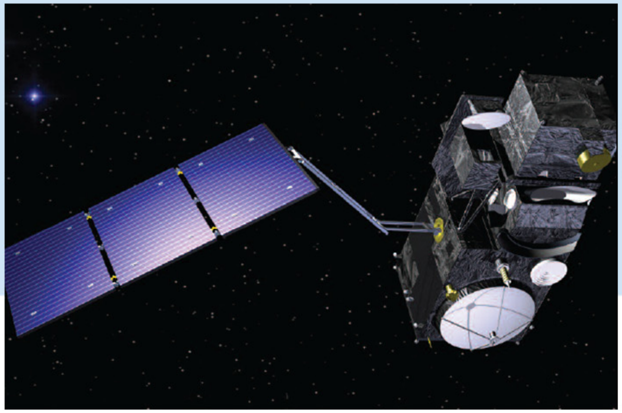
ESA/GMES Medium Resolution Land and Ocean Mission - Altimetry

## MISSION OBJECTIVES

European global land and ocean monitoring mission. It provides 2 day global coverage Earth observation data (with 2 satellites) for sea and land applications with real-time products delivery in less than 3 hours.

These services include applications such as:

- sea and land colour data, in continuation of MERIS (Envisat)
- sea and land surface temperature, in continuation of AATSR (Envisat)
- sea-surface and land-ice topography, in continuation of Envisat altimetry
- along-track SAR for coastal zones, in-land water and sea ice topography
- vegetation products through synergy between optical instruments



- Launch Dates: 2014, 2015

## SATELLITE PAYLOAD

**OLCI** (Ocean and Land Colour Instrument)

- Swath width: 1270 km, with 5 tilted cameras
- Spatial sampling: 300 m @ SSP
- Spectrum: 21 bands [0.4-1.02] µm
- Radiometric accuracy: 2% abs, 0.1% rel

**SLSTR** (Sea and Land Surface Temperature Radiometer)

- Swath width: dual view scan, 1420 km (nadir) / 750 km (backwards)
- Spatial sampling: 500 m (VIS, SWIR), 1 km (MWIR, TIR)
- Spectrum: 9 bands [0.55-12] µm
- Noise equivalent dT: 50 mK (TIR) at 270K

**SRAL** (Sentinel-3 Ku/C Radar Altimeter)

- Radar measurement modes: LRM and SAR
- Tracking modes: closed and open-loop
- Pulse repetition frequency: 1.9 KHz(LRM), 17.8 KHz (SAR)
- Total range error: 3 cm

**MWR** (MicroWave Radiometer)

- dual 23.8/36.5 GHz
- Radiometric accuracy 3K absolute (0.6 K relative)

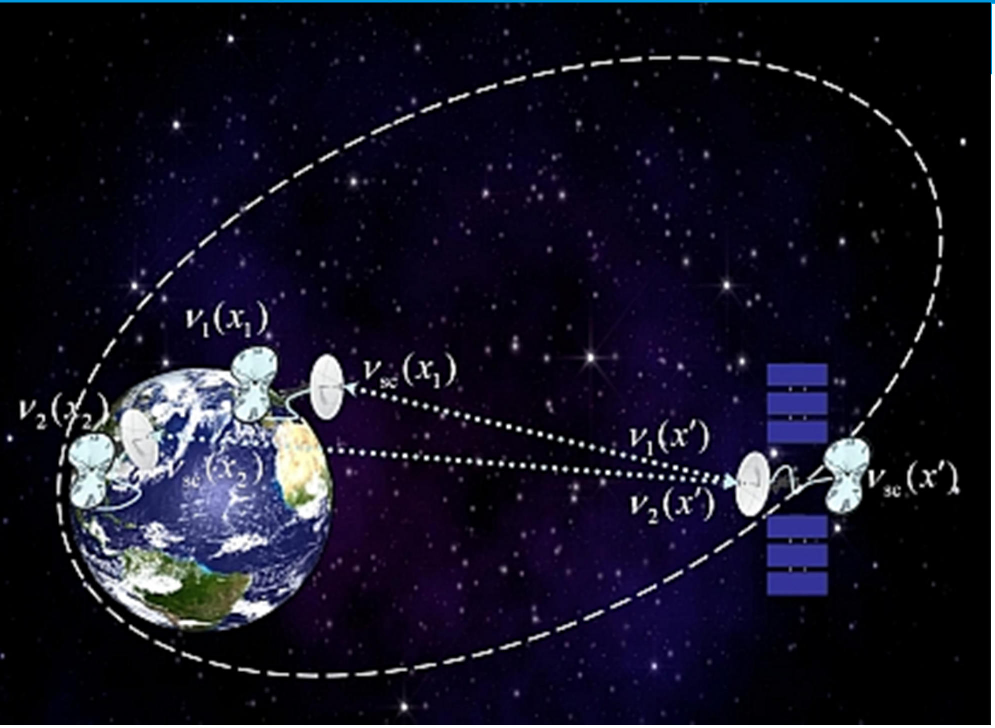
**POD** (Precise Orbit Determination)

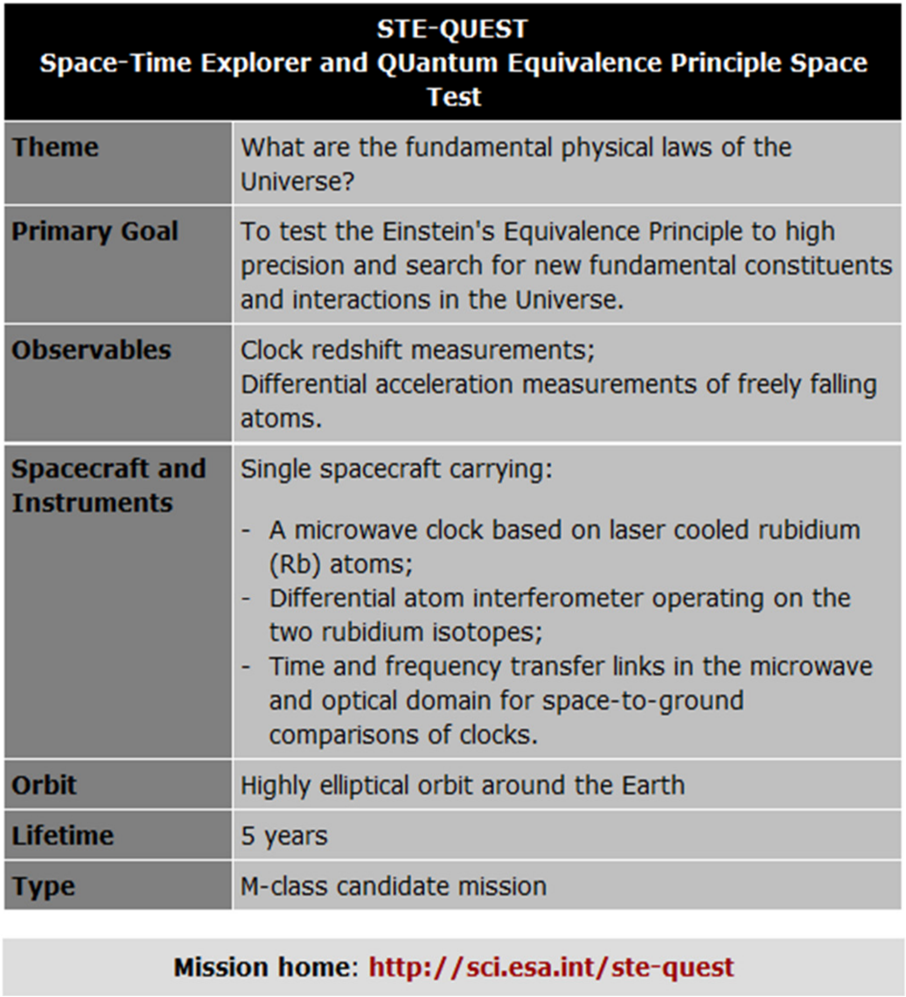
- GPS, LRR and DORIS

**Reference Frame Mission**

# STE-QUEST - ESA Cosmic Vision Programme

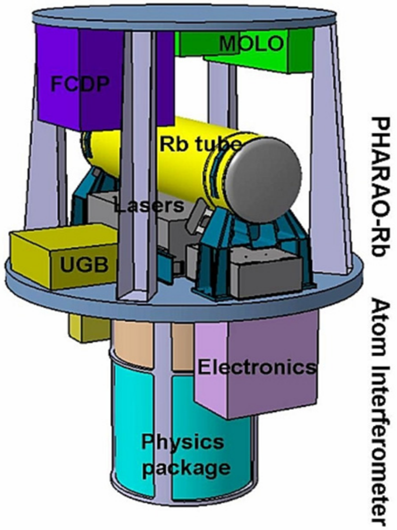
Final Selection in 2013





| STE-QUEST<br>Space-Time Explorer and QUantum Equivalence Principle Space Test | |
|---|---|
| **Theme** | What are the fundamental physical laws of the Universe? |
| **Primary Goal** | To test the Einstein's Equivalence Principle to high precision and search for new fundamental constituents and interactions in the Universe. |
| **Observables** | Clock redshift measurements;<br>Differential acceleration measurements of freely falling atoms. |
| **Spacecraft and Instruments** | Single spacecraft carrying:<br>- A microwave clock based on laser cooled rubidium (Rb) atoms;<br>- Differential atom interferometer operating on the two rubidium isotopes;<br>- Time and frequency transfer links in the microwave and optical domain for space-to-ground comparisons of clocks. |
| **Orbit** | Highly elliptical orbit around the Earth |
| **Lifetime** | 5 years |
| **Type** | M-class candidate mission |

**Mission home: http://sci.esa.int/ste-quest**



- ESA Fundamental Physics
- Two-way optical/microwave metrology link – development

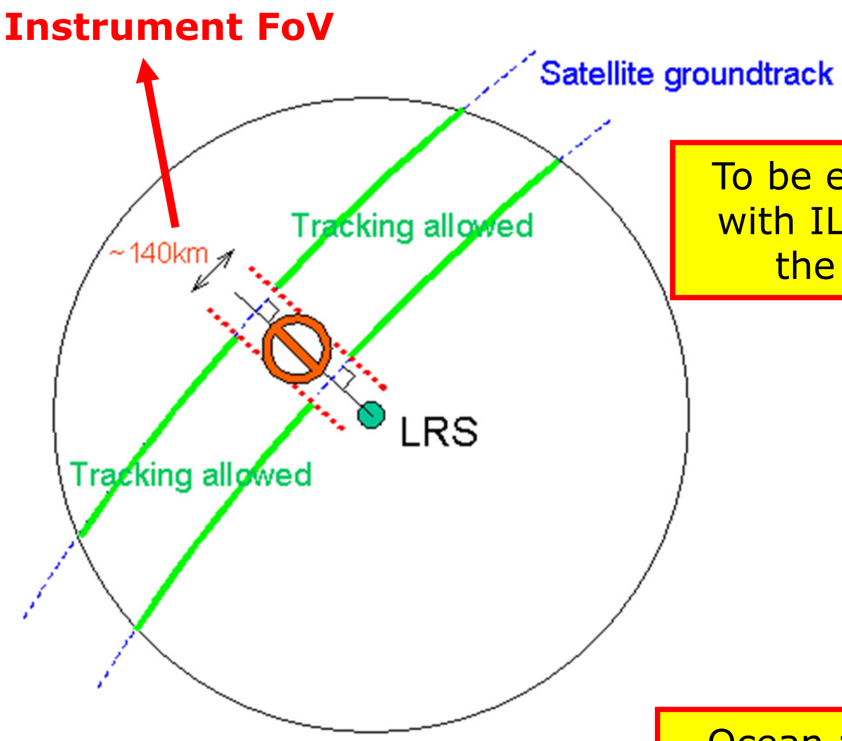
- GNSS Receiver + SLR
- Ground tracking VLBI possibility
  - “quasar signal” is optional

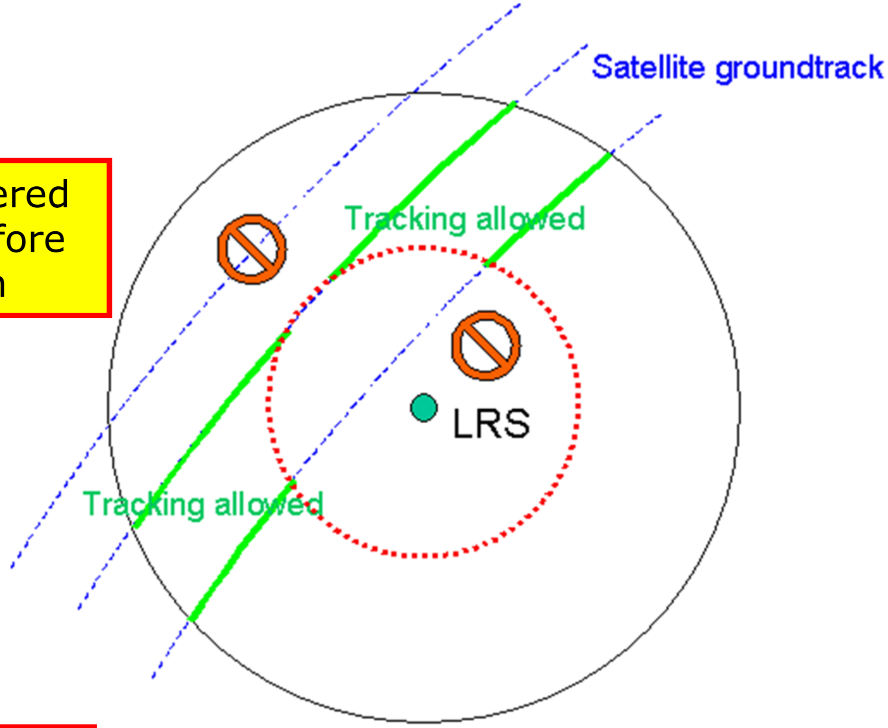
**Reference Frame Mission?**
**Highly Elliptic Orbit!**

# Sentinel-3: Potential Tracking Restrictions

**Pass segmentation restriction?**

**or Elevation restriction?**





To be engineered with ILRS before the launch

Ocean and Land Colour Instrument (OLCI)

# Laser Retro-Reflectors

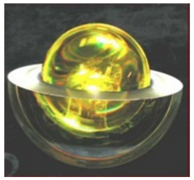
ESA is extremely pleased with the ILRS tracking of GOCE!

GOCE

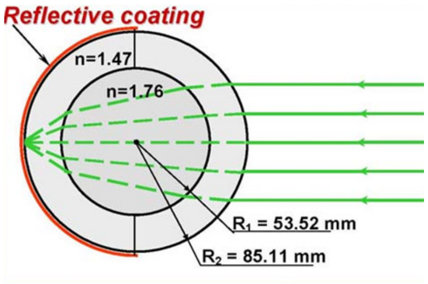
Swarm A/B/C
Sentinel-3 A/B

- Heritage from
  CHAMP, GRACE, TerraSAR-X , TerraDEM-X, Kompsat-5, PAZ, …

With BLITS retro-reflector (zero signature)
“SLR noise” is only 0.2 mm!!



(source ILRS)

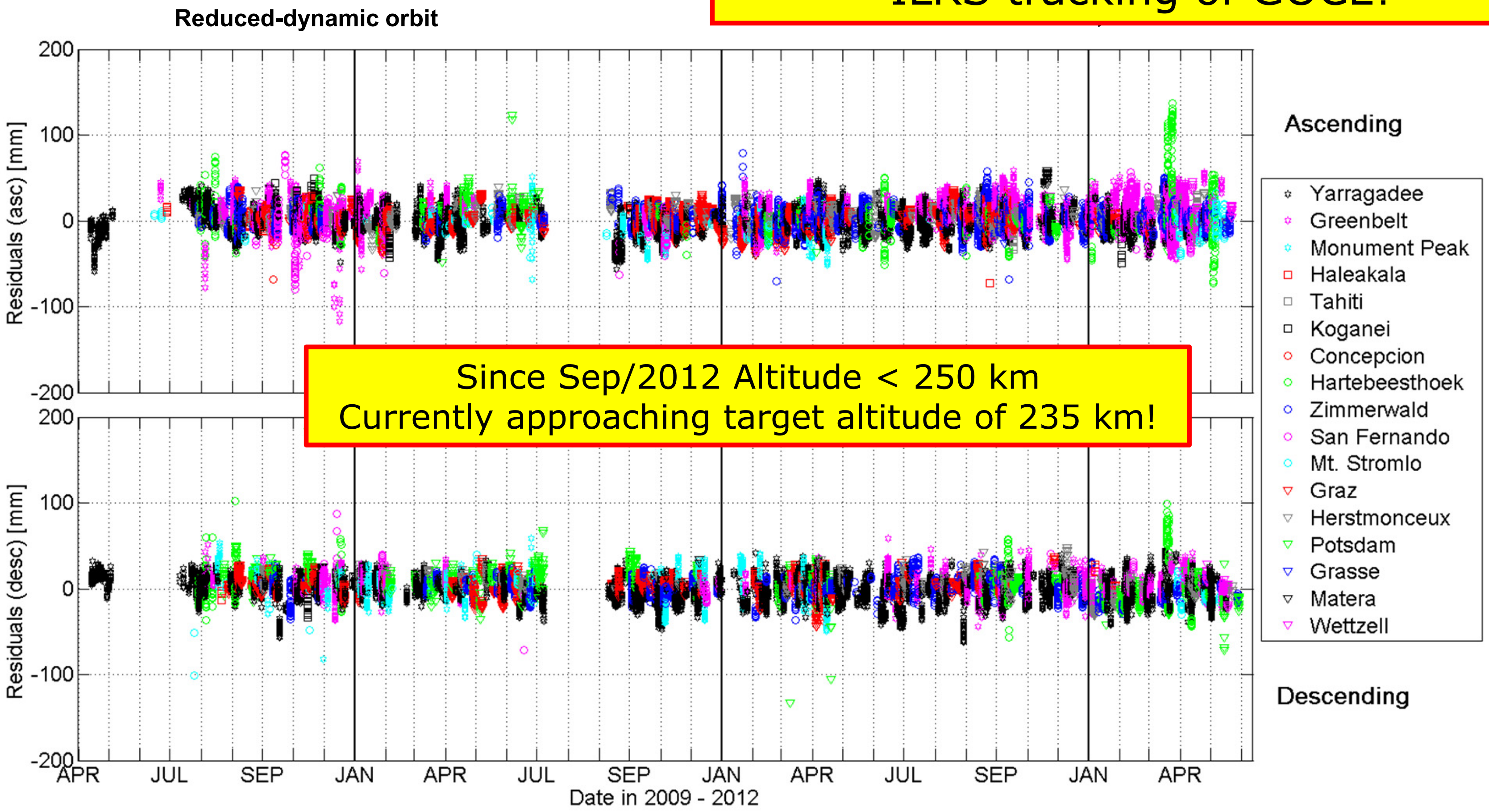


**Do we have the standard LRR for LEO satellites?**

ESA could develop “standard LEO LRR” for altimetry/reference frame missions

# GOCE Orbit Validation - SLR

ESA is extremely pleased with the ILRS tracking of GOCE!



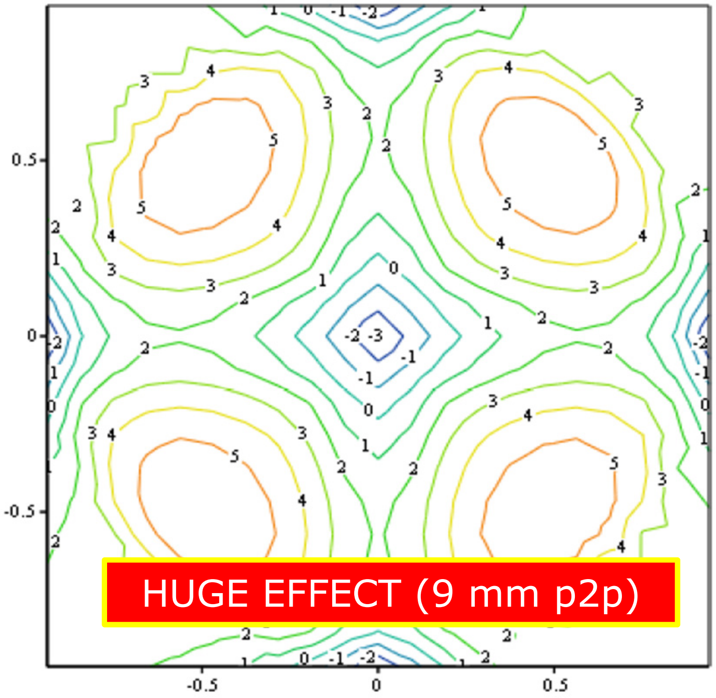
Since Sep/2012 Altitude < 250 km
Currently approaching target altitude of 235 km!

| | **2009:** | **2010:** | **2011:** | **2012:** |
|---|---|---|---|---|
| **RMS:** | 1.61 cm | 1.44 cm | 1.99 cm | 2.05 cm |
| **Mean:** | 0.46 cm | 0.13 cm | 0.25 cm | 0.13 cm |

# Effective Range Correction

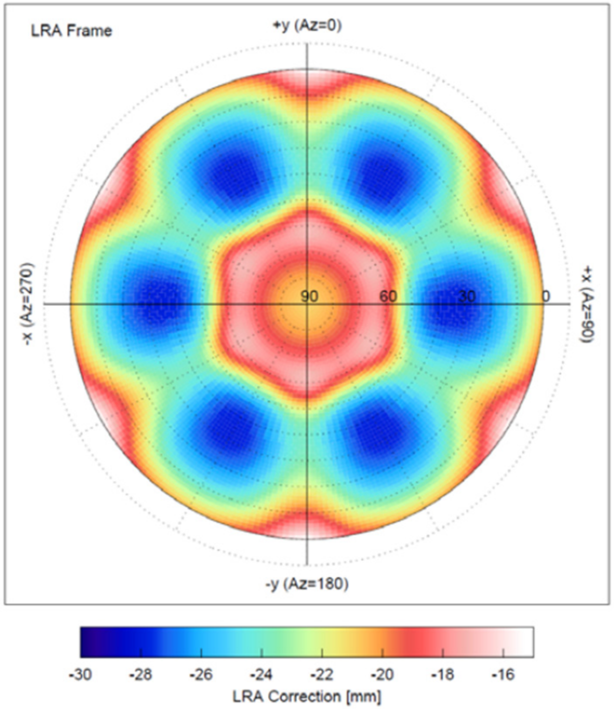
CHAMP

Contour Map of the Array Range Correction
λ=532nm (Neubert et al.)



HUGE EFFECT (9 mm p2p)

GOCE



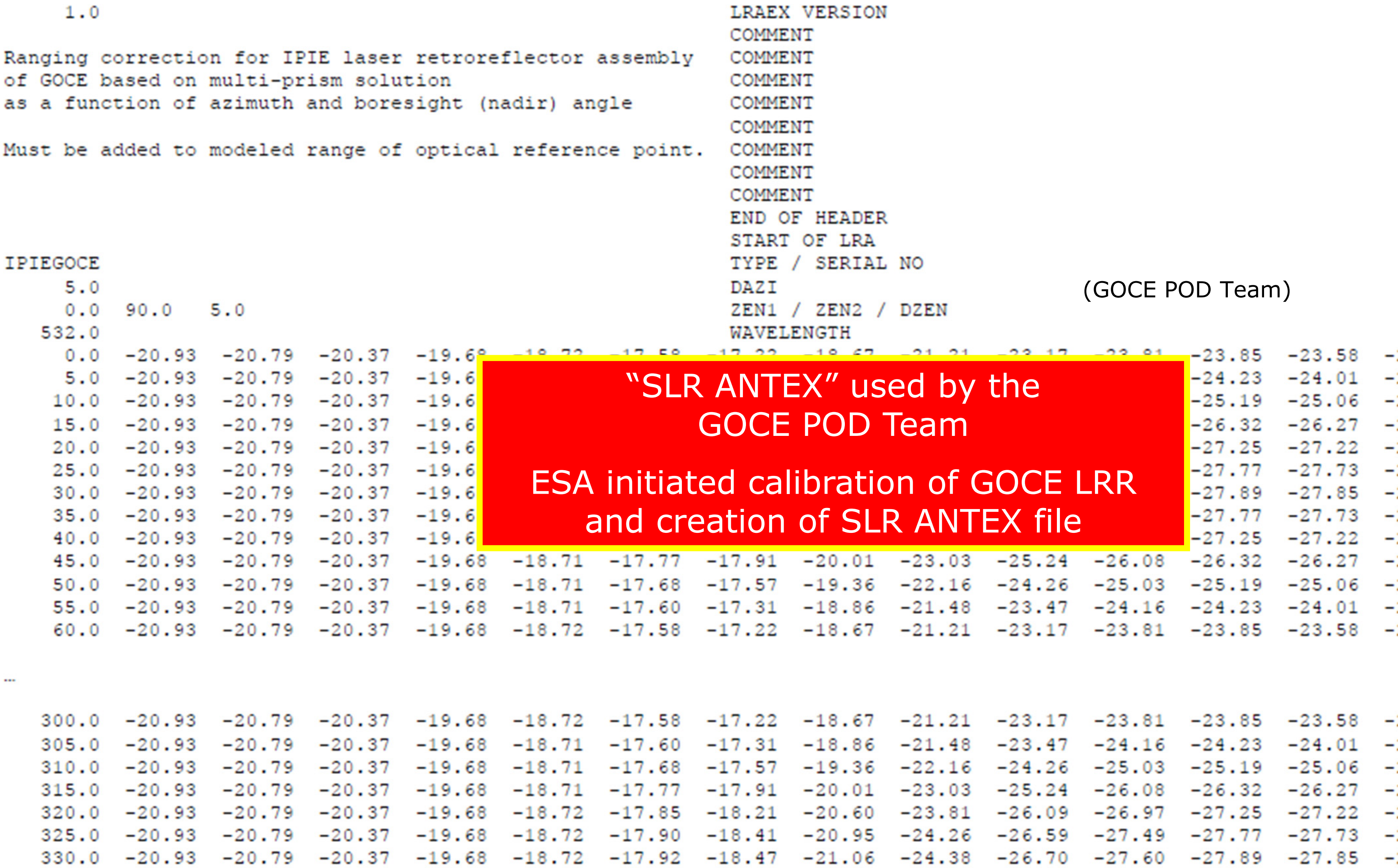
**GOCE reduced-dynamic PSO Orbit**
8 Sep 2010 - 14 Aug 2011 (GOCE POD Team)

before SLR ANTEX: Mean=5.2 mm, STD=14.5 mm
after SLR ANTEX: Mean=0.1 mm, STD=14.4 mm

Is the orbit validation limited by LRR?

# ANTEX Format for SLR?

## Used for GOCE Mission



```
     1.0                                                    LRAEX VERSION
                                                            COMMENT
 Ranging correction for IPIE laser retroreflector assembly  COMMENT
 of GOCE based on multi-prism solution                      COMMENT
 as a function of azimuth and boresight (nadir) angle       COMMENT
                                                            COMMENT
 Must be added to modeled range of optical reference point. COMMENT
                                                            COMMENT
                                                            COMMENT
                                                            END OF HEADER
                                                            START OF LRA
 IPIEGOCE                                                   TYPE / SERIAL NO
     5.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
   532.0                                                    WAVELENGTH
     0.0  -20.93  -20.79  -20.37  -19.68  -18.72  -17.58  -17.22  -18.67  -21.21  -23.17  -23.81  -23.85  -23.58
     5.0  -20.93  -20.79  -20.37  -19.6                                                           -24.23  -24.01
    10.0  -20.93  -20.79  -20.37  -19.6                                                           -25.19  -25.06
    15.0  -20.93  -20.79  -20.37  -19.6                                                           -26.32  -26.27
    20.0  -20.93  -20.79  -20.37  -19.6                                                           -27.25  -27.22
    25.0  -20.93  -20.79  -20.37  -19.6                                                           -27.77  -27.73
    30.0  -20.93  -20.79  -20.37  -19.6                                                           -27.89  -27.85
    35.0  -20.93  -20.79  -20.37  -19.6                                                           -27.77  -27.73
    40.0  -20.93  -20.79  -20.37  -19.6                                                           -27.25  -27.22
    45.0  -20.93  -20.79  -20.37  -19.68  -18.71  -17.77  -17.91  -20.01  -23.03  -25.24  -26.08  -26.32  -26.27
    50.0  -20.93  -20.79  -20.37  -19.68  -18.71  -17.68  -17.57  -19.36  -22.16  -24.26  -25.03  -25.19  -25.06
    55.0  -20.93  -20.79  -20.37  -19.68  -18.71  -17.60  -17.31  -18.86  -21.48  -23.47  -24.16  -24.23  -24.01
    60.0  -20.93  -20.79  -20.37  -19.68  -18.72  -17.58  -17.22  -18.67  -21.21  -23.17  -23.81  -23.85  -23.58

…

   300.0  -20.93  -20.79  -20.37  -19.68  -18.72  -17.58  -17.22  -18.67  -21.21  -23.17  -23.81  -23.85  -23.58
   305.0  -20.93  -20.79  -20.37  -19.68  -18.71  -17.60  -17.31  -18.86  -21.48  -23.47  -24.16  -24.23  -24.01
   310.0  -20.93  -20.79  -20.37  -19.68  -18.71  -17.68  -17.57  -19.36  -22.16  -24.26  -25.03  -25.19  -25.06
   315.0  -20.93  -20.79  -20.37  -19.68  -18.71  -17.77  -17.91  -20.01  -23.03  -25.24  -26.08  -26.32  -26.27
   320.0  -20.93  -20.79  -20.37  -19.68  -18.72  -17.85  -18.21  -20.60  -23.81  -26.09  -26.97  -27.25  -27.22
   325.0  -20.93  -20.79  -20.37  -19.68  -18.72  -17.90  -18.41  -20.95  -24.26  -26.59  -27.49  -27.77  -27.73
   330.0  -20.93  -20.79  -20.37  -19.68  -18.72  -17.92  -18.47  -21.06  -24.38  -26.70  -27.60  -27.89  -27.85
```

"SLR ANTEX" used by the GOCE POD Team

ESA initiated calibration of GOCE LRR and creation of SLR ANTEX file

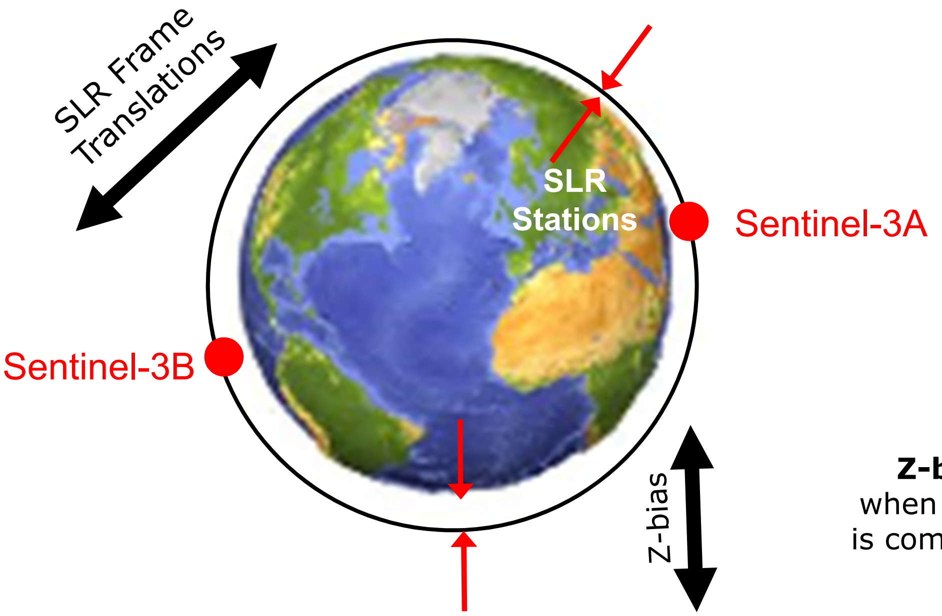
(GOCE POD Team)

# Altimetry with Antipodal Satellites

## SLR+GPS Frame Combination

**"SLR Network Effect"?**

**(most of ILRS stations are in the northern hemisphere)**



**Z-bias (6 mm) - Geocenter**
when Jason-2 (GPS+SLR+DORIS)
is combined with GPS Constellation

**Recommendation:**

Both satellites should be observed
quasi-simultaneously
by the same ILRS station
(after ca. 50 min)

# Jason-2 + GPS Constellation

## Weekly Solutions: Station Coordinates (Aug/2008)

**JASON-2 + GPS Constellation**

**GPS+SLR+DORIS**

### Week 1

dx = -0.83 mm
dy = -0.94 mm
dz = -5.90 mm

rx = 0.021 mas
ry = 0.052 mas
rz = -0.051 mas

scale = 0.13 ppb

### Week 2

dx = -1.78 mm
dy = -1.67 mm
dz = -5.75 mm

rx = 0.067 mas
ry = 0.055 mas
rz = -0.077 mas

scale = 0.14 ppb

### Week 3

dx = -1.72 mm
dy = -1.22 mm
dz = -5.60 mm

rx = 0.059 mas
ry = -0.011 mas
rz = -0.051 mas

scale = 0.16 ppb

6-mm bias in z-geocenter

**SLR Network Effect?**

**(most of stations in the northern hemisphere)**

(Svehla et al. 2012)

The 6-mm effect is well above the
GGOS Requirement of 1 mm and the sea level rise of 3 mm/y

# Altimetry
# with Antipodal Satellites

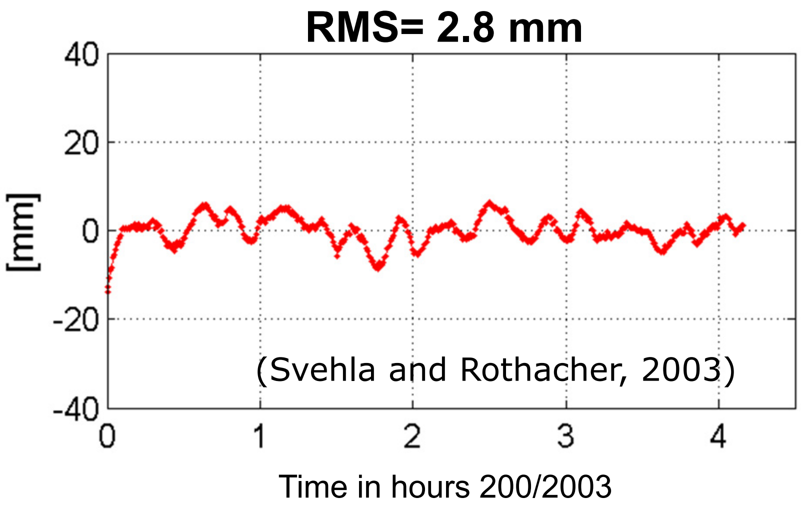
The ”mm-GPS Baseline” cannot be formed between the two Sentinels!

BUT

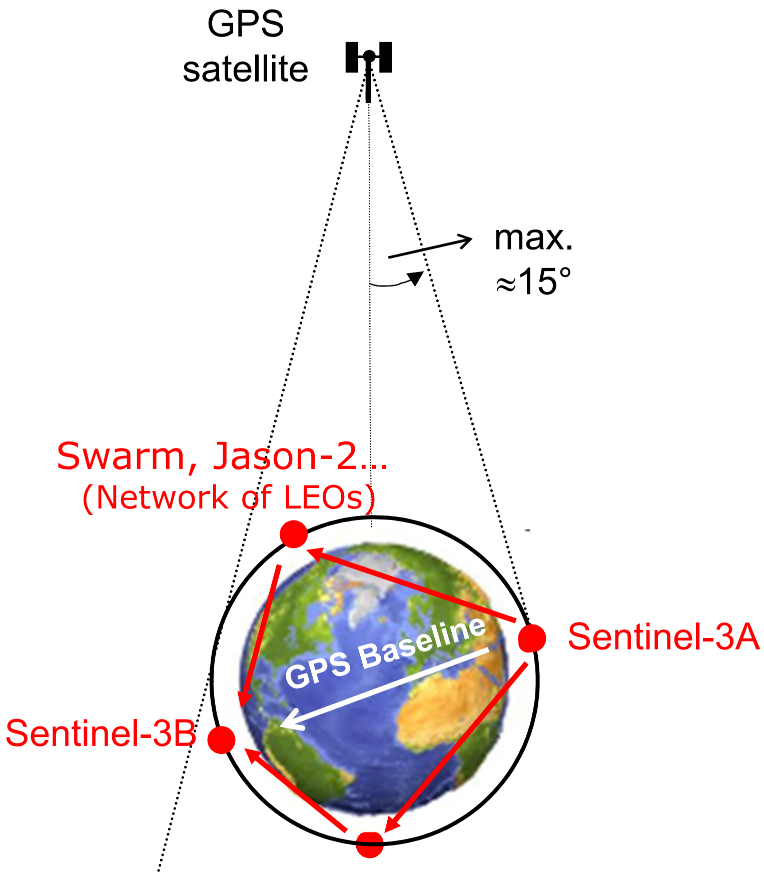
**It works with LEO Network!**

The First GPS Baseline in Space

**GRACE A-B GPS Baseline vs. KBR**
(RMS of 0.7 mm demonstrated)



(Svehla and Rothacher, 2003)



**Recommendation:**

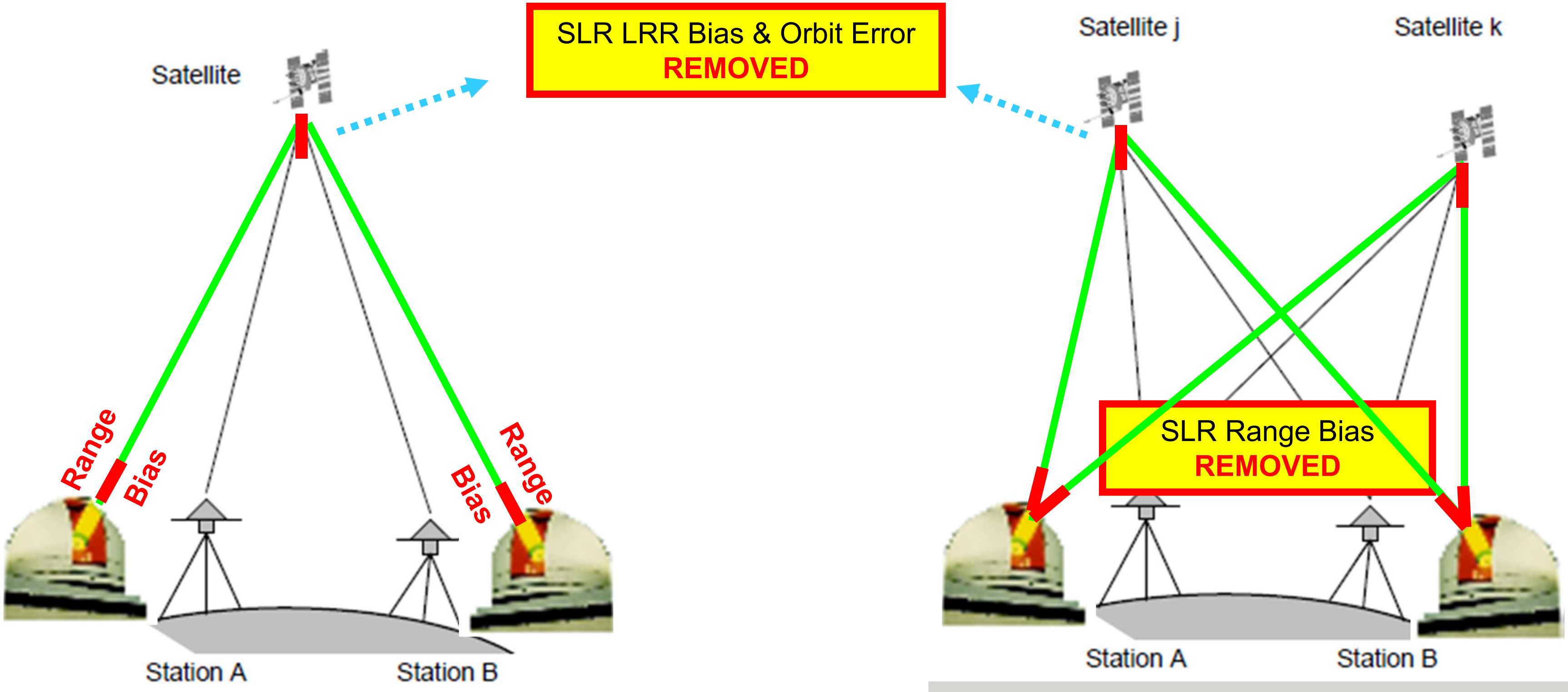
LEO network: SWARM, JASON-2, GRACE…

GPS+SLR+DORIS

# SLR Double-Differences

”SLR Baseline” vs. GPS Baseline

Normal points @ common epoch: Interpolation over e.g. 10-20 min



**Single-Differences**
(Normal Points)

**Double-Differences**
(Normal Points)

SLR LRR Bias & Orbit Error
**REMOVED**

SLR Range Bias
**REMOVED**

SLR Range Bias
**NOT REMOVED**

$$DD_{AB}^{jk}(GPS) = \rho_{AB}^{jk} + \delta\rho_{AB}^{jk}(TRP_{\mu wawe})$$

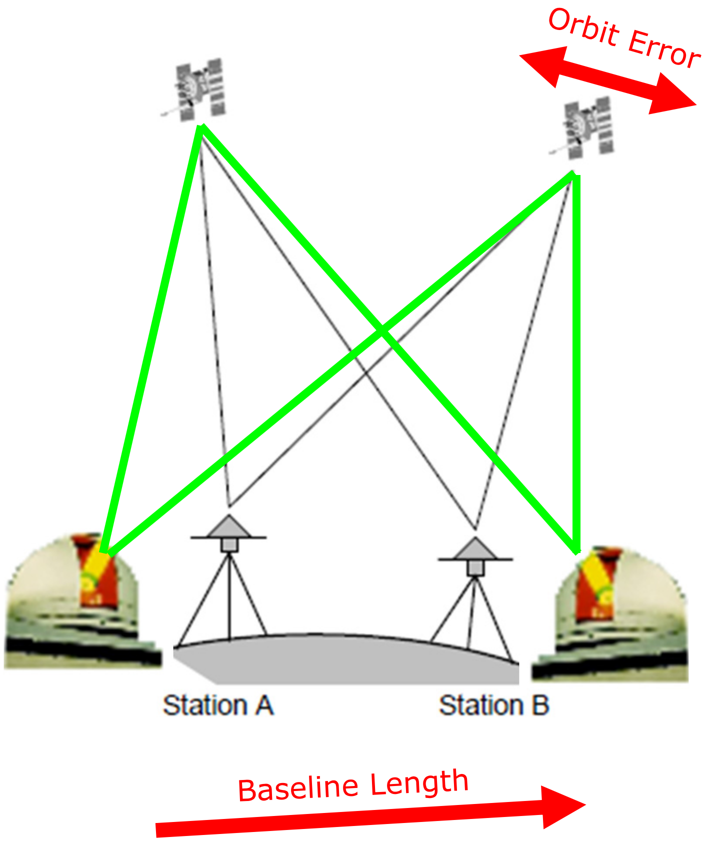
$$DD_{AB}^{jk}(SLR) = \rho_{AB}^{jk} + \delta\rho_{AB}^{jk}(TRP_{optical}) + local\ tie$$

# SLR Double-Differences

”orbit-free & bias-free”

**New Tool for Local Ties, Ref. Frames, Troposphere**

”orbit-free & bias-free”



## “Bauersima Rule of Thumb”

*baseline error*
$(x, y, z)$

*orbit error*

$$\delta\rho_{xyz} = \frac{l}{R}\,\delta r$$

$$\frac{\text{baseline length}}{\text{orbit altitude}}$$

$$\delta r(GNSS\ orbit\ RMS) = 1cm$$

$$l = 500\ km \rightarrow \delta\rho_{xyz} = 0.2\ mm$$

$$l = 1000\ km \rightarrow \delta\rho_{xyz} = 0.4\ mm$$

$$l = 5000\ km \rightarrow \delta\rho_{xyz} = 2.2\ mm$$

**Orbit Error is negligible for baselines up to 5 000 km!**

**Recommendation:**

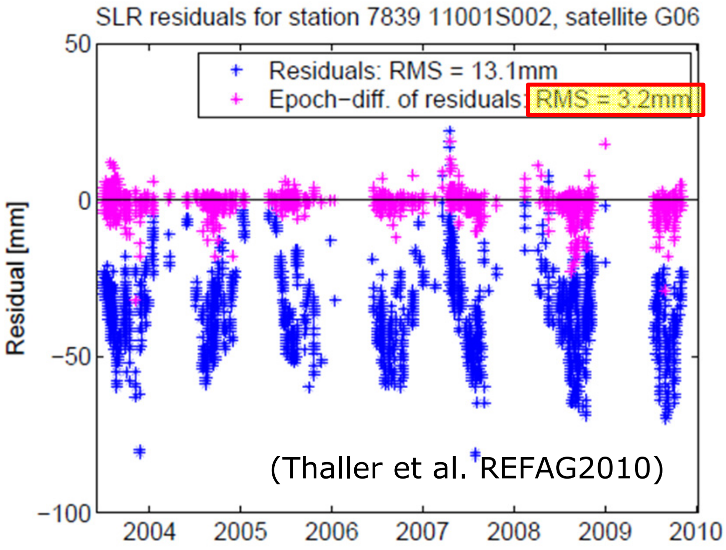
**Why not to observe GNSS satellites in pairs?**

# First SLR Double-Difference Baseline

## Simulation: Wettzell-Zimmerwald

Test of the concept proposed to Wettzell, Graz, HERS and TIGO

### What is the noise level of SLR double-differences?



(Thaller et al. REFAG2010)

SLR epoch-wise RMS

GPS(G06): **3.2 mm** $/\sqrt{2} = \mathbf{2.2\ mm}$

GLONASS(R07): 8.5 mm $/\sqrt{2} = \mathbf{6.0\ mm}$

GLONASS SLR noise is significantly higher

SLR double-difference RMS

$\sigma(DD) \approx 4.4\ \mathrm{mm}$ **GPS**

$\sigma(DD) \approx 12.0\ \mathrm{mm}$ **GLONASSS**

### SLR Baseline WETL-ZIML (≈500 km)

**What is removed?**

**Station SLR range bias**

**Common Satellite LRR bias**

**GNSS Orbit Error (baselines up to 5000 km)**

| | **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 |

**GPS GLONASS**

With just two SLR double-differences SLR coordinates **(local tie)** estimated at mm-level!

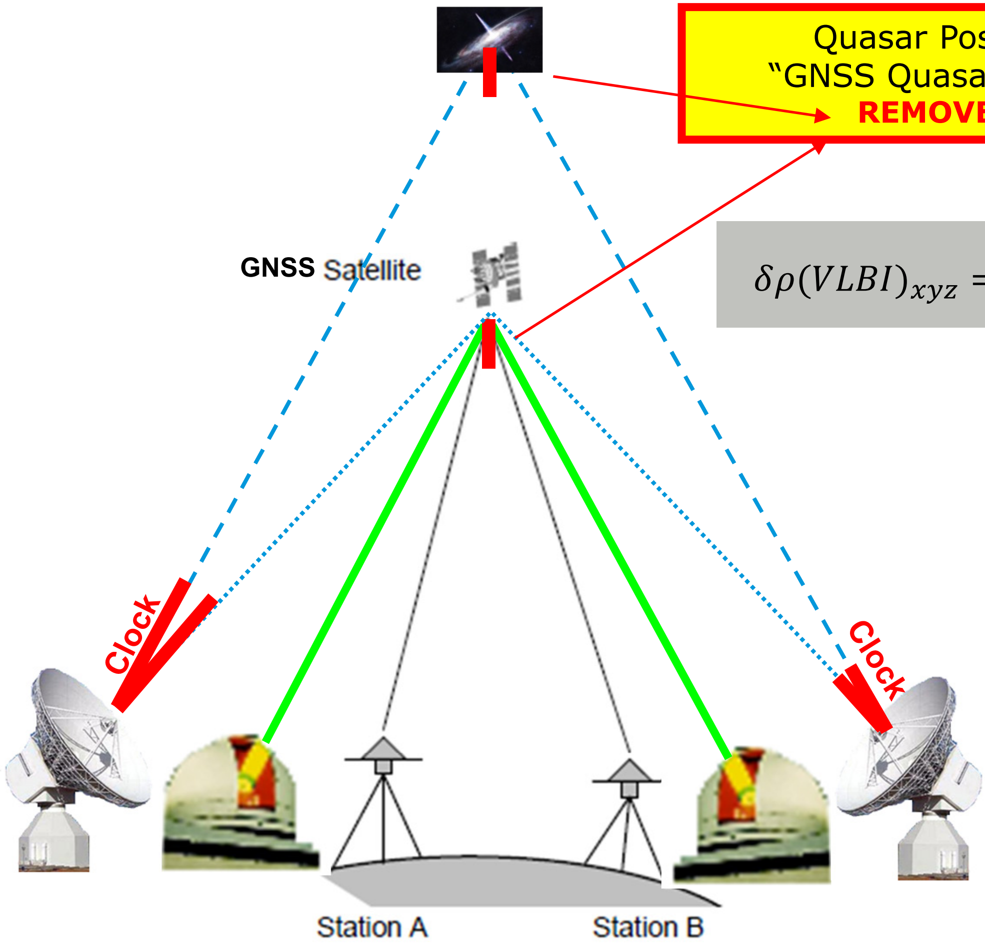
Any random effect nicely averages out, not the case with undifferenced SLR (LAGEOS)!

# SLR/VLBI/GPS Double-Differences

”SLR Baseline” and ”VLBI Baseline” vs. GPS Baseline

## VLBI Single-Differences

to Nearby Quasar or GNSS



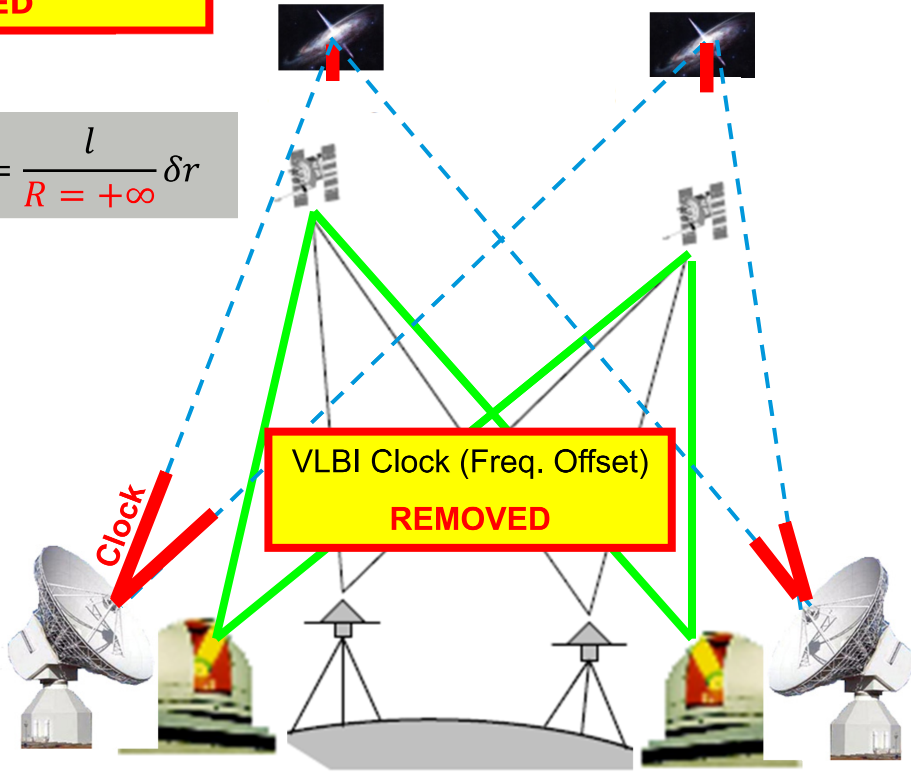
Quasar Position
“GNSS Quasar Orbit”
**REMOVED**

$$\delta\rho(VLBI)_{xyz} = \frac{l}{R = +\infty}\delta r$$

VLBI Clock (Freq. Offset)
**NOT REMOVED**

## VLBI Double-Differences

to Nearby Quasar or GNSS



VLBI Clock (Freq. Offset)
**REMOVED**

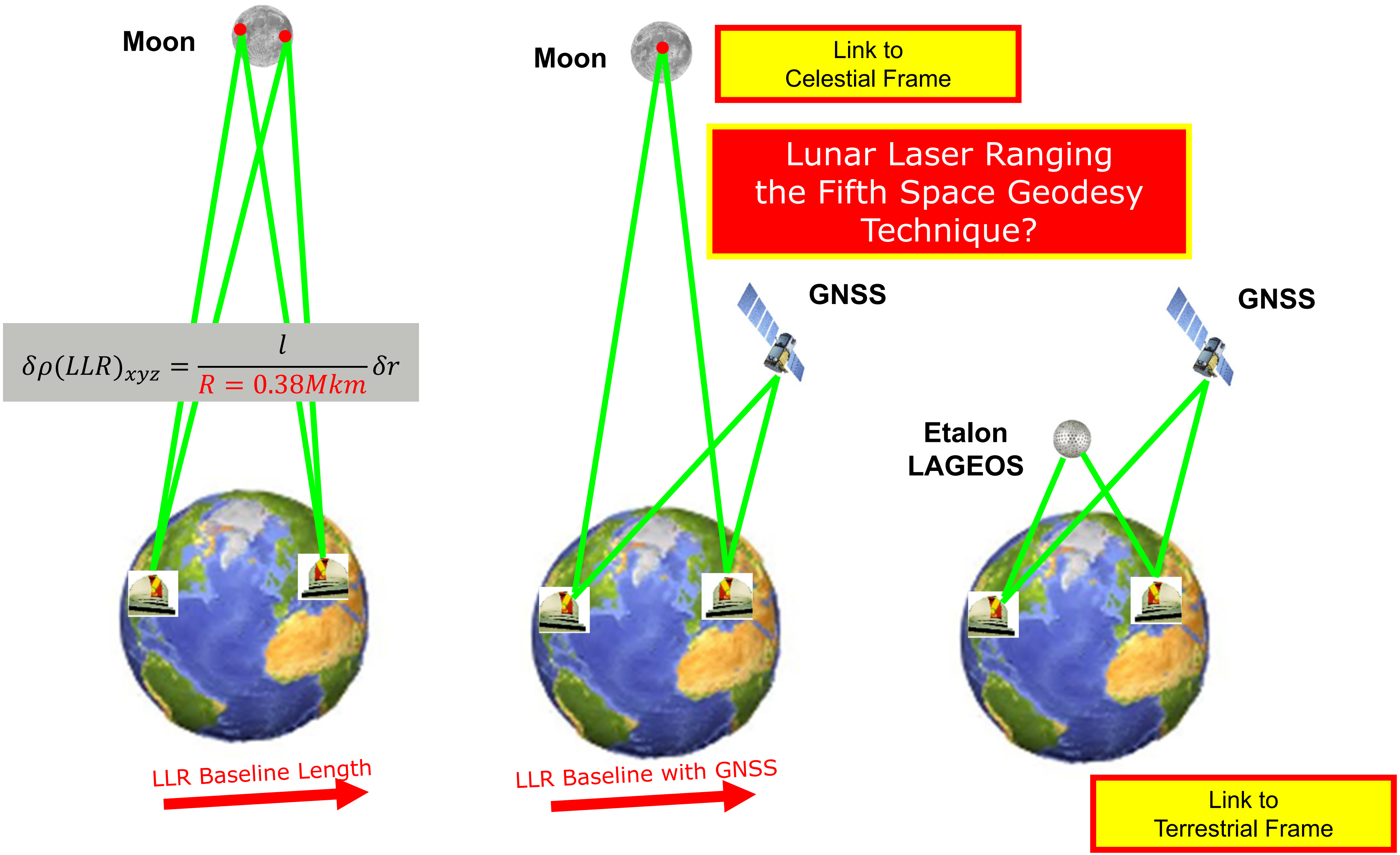
$$DD_{A\,B}^{jk}(GNSS) = \rho_{A\,B}^{jk} + \delta\rho_{A\,B}^{jk}(TRP_{\mu wave})$$

$$DD_{A\,B}^{jk}(SLR) = \rho_{A\,B}^{jk} + \delta\rho_{A\,B}^{jk}(TRP_{optical}) + local\ tie$$

$$DD_{A\,B}^{jk}(VLBI) = \rho_{A\,B}^{jk} + \delta\rho_{A\,B}^{jk}(TRP_{\mu wave}) + local\ tie$$

# Lunar Laser Ranging Double-Differences

”LLR Baseline” and Cascade LLR/SLR/GNSS Baseline



**Moon**

$$\delta\rho(LLR)_{xyz} = \frac{l}{R = 0.38Mkm}\delta r$$

LLR Baseline Length

**Moon**

Link to
Celestial Frame

Lunar Laser Ranging
the Fifth Space Geodesy
Technique?

**GNSS**

LLR Baseline with GNSS

**GNSS**

**Etalon**
**LAGEOS**

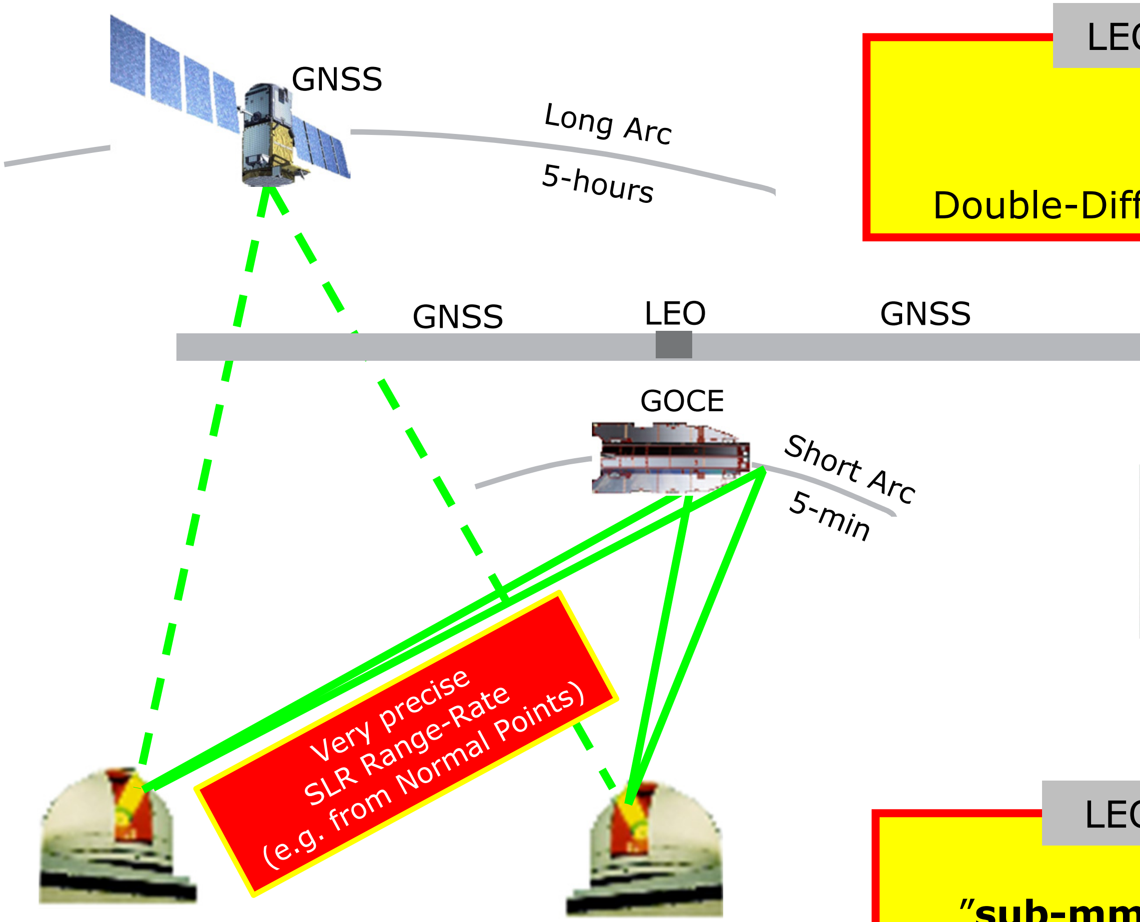
Link to
Terrestrial Frame

# LEO Single-Differences in Time
# LEO-GNSS Double-Differences

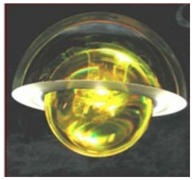
## LEO-GNSS Double-Differences

Orbit/Bias-free

Double-Differences with LEO (GOCE, Lageos)



Very precise SLR Range-Rate (e.g. from Normal Points)



With BLITS retro-reflector “SLR noise” is only 0.2 mm!!

## LEO Single-Differences in Time

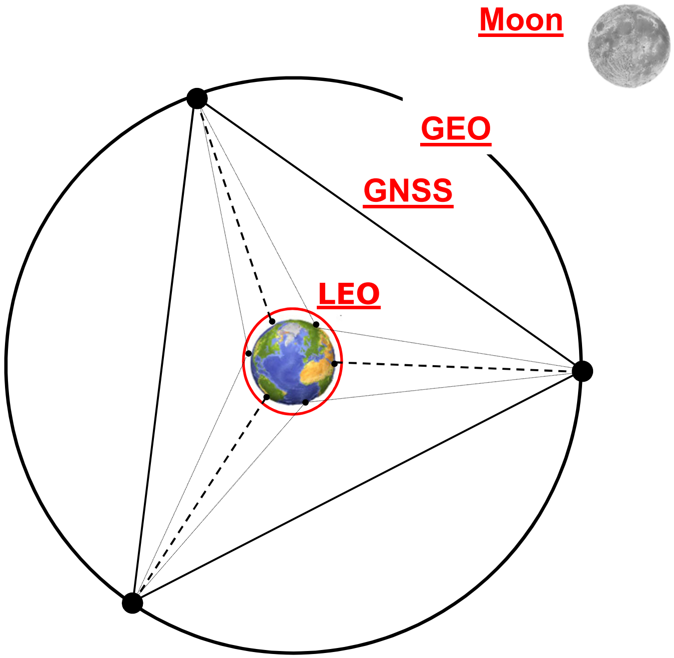
”**sub-mm-orbit perturbations**” Bias-free

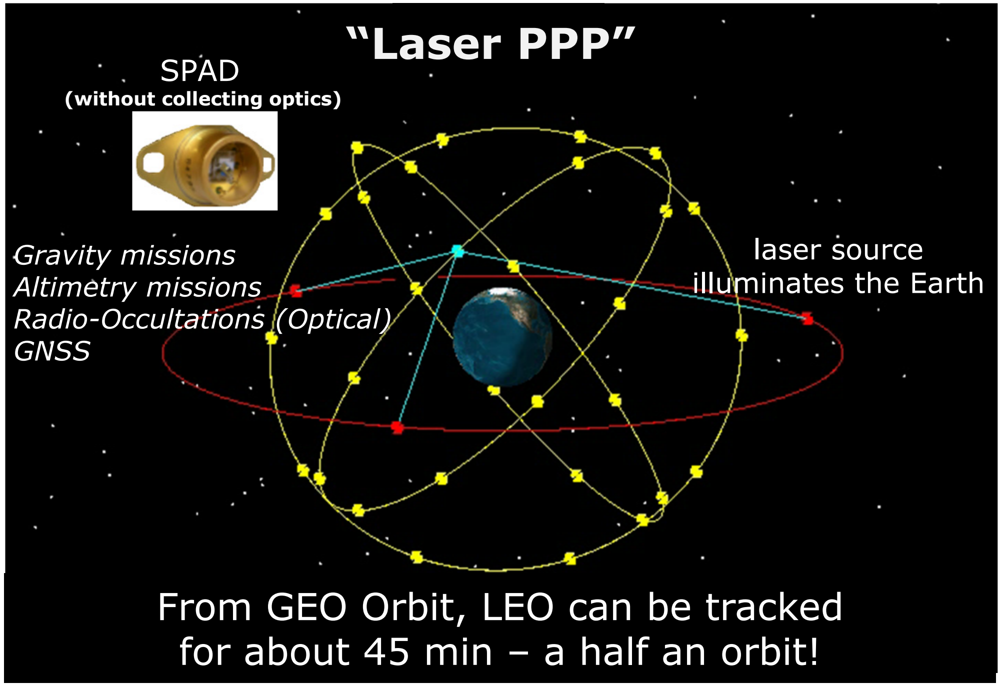
Can SLR support GOCE/GRACE gravity?
Using epoch-wise differences (“Laser Doppler”)

An additional gravity/POD observation equation for SLR “Laser Doppler’’?

# SLR/VLBI Collocation in Space

## LEO or Higher Earth Orbit?





From GEO Orbit, LEO can be tracked for about 45 min – a half an orbit!

(Svehla et al. 2007)

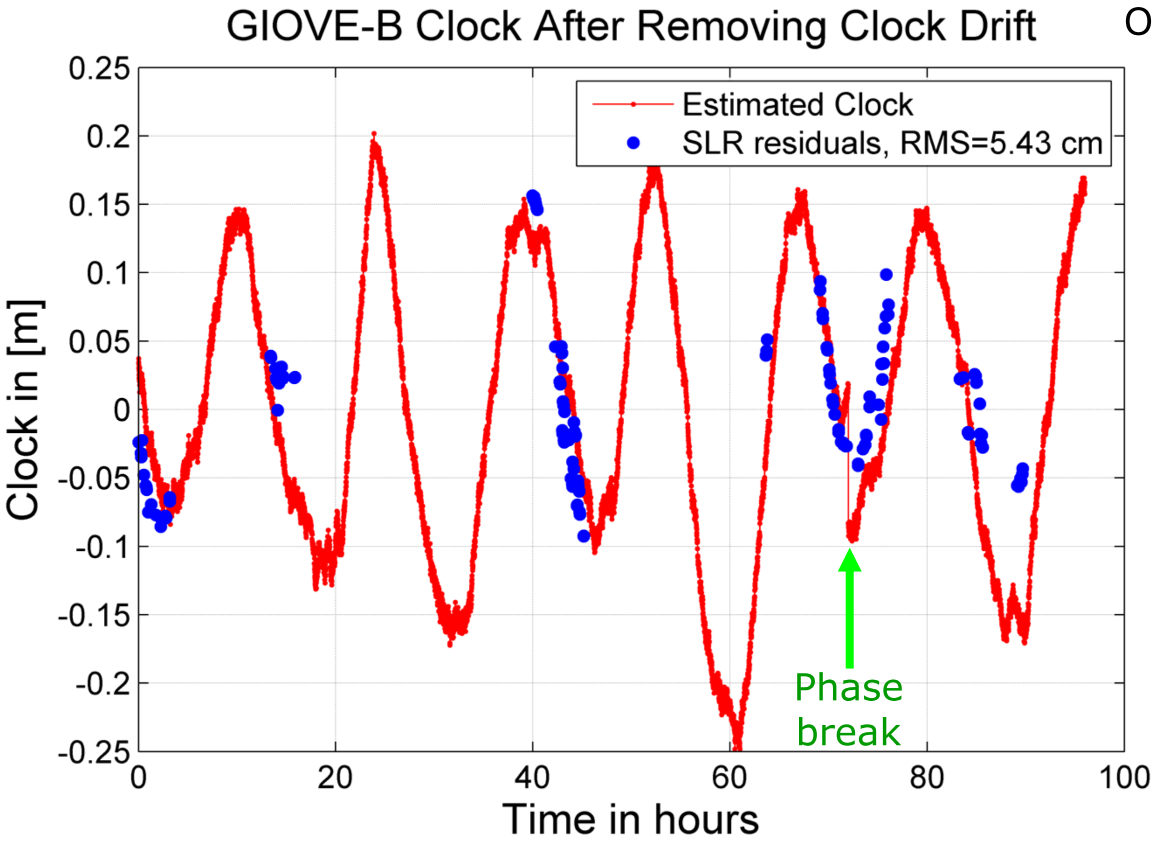
SLR/VLBI Collocation:
- Higher Earth Orbit (GEO)
- Moon

GRAS (JPL), "MARKUSAT" (ETH) all target LEO Orbit. However, only higher Earth Orbit can properly be observed by VLBI

# How GNSS Clock can Compare all SLR Stations?

## Geometrical Mapping of the Orbit Error (Antipodal SLR Stations)

SLR Residuals and Estimated GIOVE-B Clock Parameters (30 s)



Only time bias and time drift removed!

**First time: GNSS clock maps the radial orbit error!!!**

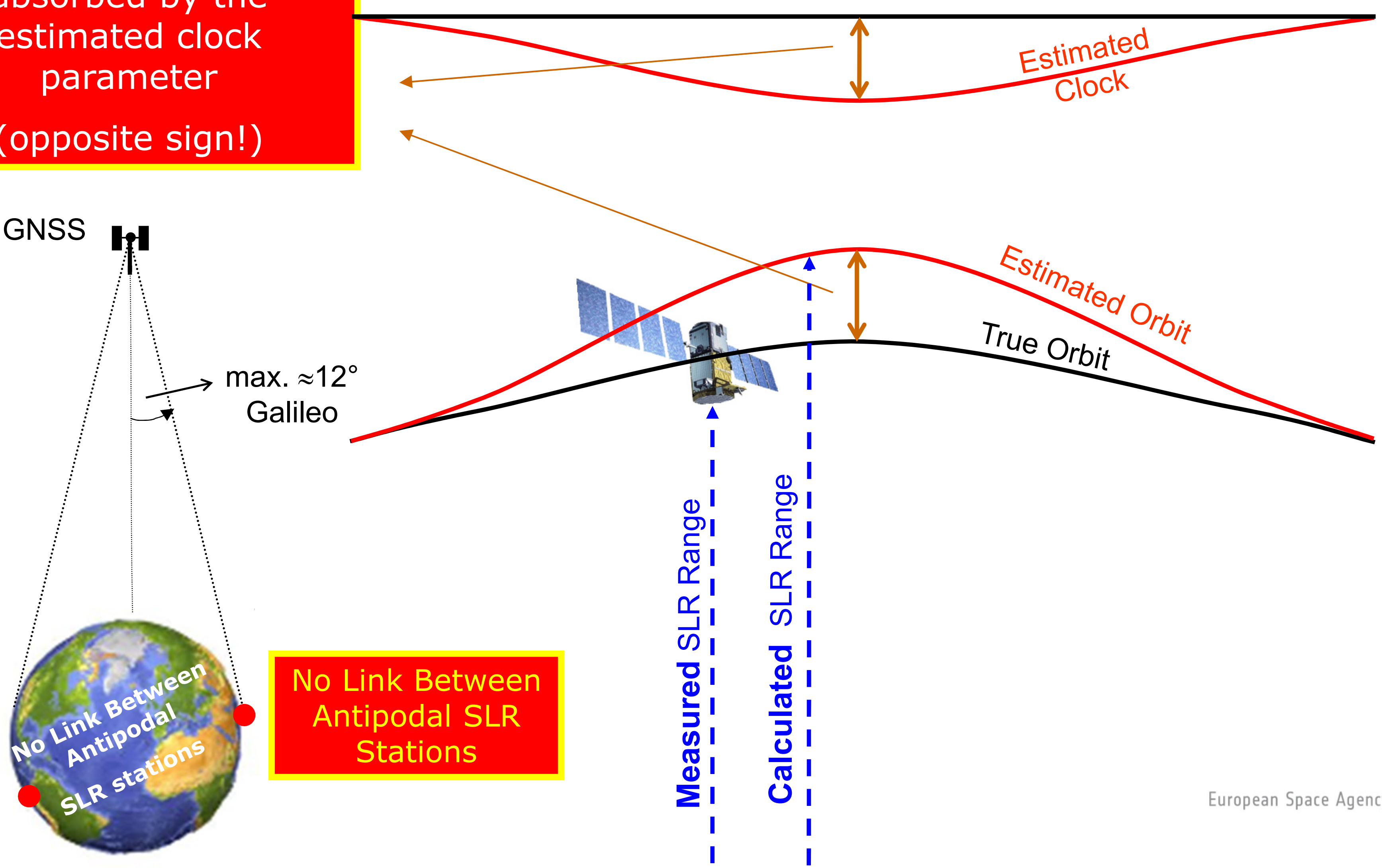
**First time: GNSS Clock Consistently Connects all SLR Stations**

Agreement between GIOVE-B clock and SLR is fantastic **1-2 cm only!!!**

(Svehla et al. 2010)
Figure authorised for the publication by the Galileo Project

European Space Agency

# Orbit and Clock Dependency



Radial orbit error absorbed by the estimated clock parameter

(opposite sign!)

No Link Between Antipodal SLR Stations

# Conclusions

- The “GFZ Laser Retro-Reflector” to be embarked onboard SWARM constellation and the two Sentinel-3 satellites.
- Place to develop “standard LRR” for gravity/altimetry missions and reference frames (with zero signature like BLITS).
- “ILRS ANTEX” format is used for the validation of GOCE Precise Science Orbit.
- Potential SLR tracking restrictions for the two Sentinel-3 satellites to be engineered before the launch (OLCI instrument).
- SLR double-differences remove station range biases, common satellite signature effects and orbit errors for baselines up to 5000 km (GNSS), thus any random effect is averaged out.
- GNSS satellites should be observed in pairs in order to get better SLR/GNSS reference frame realization for gravity and altimetry missions.
- SLR double-difference approach is potentially new approach for the local tie estimation, reference frames and troposphere. Scale is preserved by forming double-differences!
- Double-Difference Space Geodesy: First GNSS/SLR/LLR/VLBI Double-Difference Baseline.
- New generation GNSS clocks offer novel combination strategies with SLR.
- Lunar Laser Ranging (Lunar Geodesy) - the 5th Space Geodesy Technique?

# Acknowledgements

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