SLR – An Overview and General Aspects

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The 3 Pillars of Geodesy
The 3 Pillars of Geodesy

**Earth geometry and kinematics:**
Shape of the Earth and its variation

**Earth orientation and rotation:**
Earth rotation and its variation

**Earth gravitational field:**
Static (mean) and variable gravity field

- Requirement for integrated estimation:
  highly accurate, homogeneous, long-term stable reference frame
The 3 Pillars of Geodesy: Relationships

Earth Orientation

Celestial Reference Frame

Terrrestrial Reference Frame

EOP
Reference System and Reference Frame

**Reference System**

**Geodetic Observations**

**Reference Frame**

**REALIZATION**
Realization of Geometric Reference Systems: Space Geodetic Techniques

For the determination of the geometry and rotation/orientation of the Earth, the following space-geodetic techniques are used:

- **GNSS**: Global Navigation Satellite Systems
- **SLR**: Satellite Laser Ranging
- **VLBI**: Very Long Baseline Interferometry
- **DORIS**: Doppler Orbitography and Radiopositioning Integrated by Satellites
Space Geodetic Techniques

Level 5: Quasars
Level 4: Moon, Planets
Level 3: MEO / GEO
Level 2: LEO
Level 1: Stations

GPS / GLONASS / GALILEO

Planets

Moon

Earth
The 3 Pillars of Geodesy: Contributions by the Space Geodetic Techniques

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<th>VLBI</th>
<th>SLR</th>
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<td>XG</td>
<td>XV</td>
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<td>Satellite orbits</td>
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<td>Polar motion + rates</td>
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<td>Universal Time (dUT)</td>
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<td>Length of Day (LOD)</td>
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<td>Nutation (+ nutation rates)</td>
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<td>Geocenter</td>
<td>(X)</td>
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<td>Earth's gravity field</td>
<td>(x)</td>
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<td>X</td>
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<tr>
<td>Troposphere</td>
<td>X</td>
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<td>X</td>
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<td>Ionosphere</td>
<td>X</td>
<td></td>
<td>(x)</td>
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<tr>
<td>Technique-specific parameters</td>
<td>xG</td>
<td>xV</td>
<td>xS</td>
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The 3 Pillars of Geodesy: SLR

Contributions by SLR:

(1) Geometry:
- Coordinates of SLR stations
- Position variations due to, e.g., plate tectonics, loading deformation

(2) Earth Rotation:
- Polar motion
- Length of Day (LOD)

(3) Gravity Field:
- Geocenter
- Low-degree harmonics of Earth’s gravity field: depending on satellites
Satellite Laser Ranging: Measurement Principle

- Transmitting of the laser pulse by the station
- Reflection of the laser pulse at the satellite
- Detection of the reflected laser pulse at the station

➢ Two-Way travel time of the laser pulse as basic observable
Satellite Laser Ranging: Measurement Principle
The core element of a laser ranging system is the high energy laser (Light Amplification by Stimulated Emission of Radiation).

The laser is characterized by the high coherence, high degree of collimation of the beam, and the high power density. Therefore, these very high-energy, sharply defined pulses can be transported over large distances.

Most of the SLR stations use Nd:Yag 10 Hz laser systems with pulse energies of 20-100 mJ and pulse-widths of 50-100 ps.

10 Hz laser systems are used, e.g., in Yarragadee, Hartebeesthoek, Greenbelt, Monument Peak, McDonald, and Tahiti.

Recent developments to kHz SLR stations (Graz, Herstmonceux, etc.)

The primary frequency is doubled and, with a wavelength of 532 nm (green), instead of 1064 nm (infrared), produces better conditions for the reception of return pulses.

Several other configurations are in use, see Sosnica (2014)
Satellite Laser Ranging: Measurement Principle

**TIMER**

State-of-the-art timers are essential for SLR. An error of 1ns (=1000ps) would imply an error of 300 mm. Two timing methods are currently in use:

**Interval counter**

Time interval counters measure the time-of-flight of the laser pulse. Interval timers have a resolution up to 10 ps.

**Event timer**

largely used now, due to need to handle multiple laser shots in flight with kHz laser systems. They calculate time-of-flight of the laser pulse by differencing the laser fire epoch and the pulse reception epoch.

Event Timers have a resolution up to 0.5 ps with 3 ps jitters and 12 kHz repetition rates (Artyukh et al., 2012) (3 ps corresponds to 0.9 mm by means of light travel or to 0.45 mm for two-way ranging).

Some of the SLR stations are equipped with ultra-stable clocks, e.g., active or passive Hydrogen Masers or Cesium Fountain frequency sources supplying frequencies stable at about $10^{-15}$ s per second.
Satellite Laser Ranging: Measurement Principle

DETECTOR

To detect a return signal of a few or single photons from satellites, stations use either a micro-channel plate (MCP) or an avalanche diode, typically a single photon avalanche diode (SPAD, Prochazka et al., 2012).

MCP detectors have far less dark noise than SPAD of around 30-300 Hz and the efficiency level reaching 40%.

The SPAD detectors are effective and widely used. The SPAD detectors exhibit an error dependence on incident signal intensity, termed 'time-walk'. The latest SPAD is designed for kHz operations and has the 'dark' noise at the level of 200-300 kHz and the ability to detect single photon events (Prochazka et al., 2012). The typical SPAD detectors have quantum efficiencies of >20%.

In order to perform daytime SLR observations, sophisticated bandwidth filters are required to handle the large noise ratios. Optics with laser wavelength specific transmission bands of typically 0.3 nm are introduced with a 'blocking filter' in front of the detector. Some filters are oven controlled and tuned to the desired wavelength.
Satellite Laser Ranging

Most important satellites for global terrestrial reference frame: **LAGEOS-1** and **LAGEOS-2**:

- Diameter: 60 cm
- Mass: 407 kg
- Corner reflectors: 426
- Orbital height (above Earth’s surface): 5,800 km
- Time per revolution: 225 Minutes

**First tracked:**

- LAGEOS-1: May 10, 1976
- LAGEOS-2: October 24, 1992
Geodetic / Spherical Satellites: Overview

Starlette

Stella

LARES

Ajisai

LAGEOS

Etalon
Geodetic / Spherical Satellites: Overview

<table>
<thead>
<tr>
<th></th>
<th>AJISAI</th>
<th>Starlette/Stella</th>
<th>LAGEOS-1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [m]</td>
<td>2.15</td>
<td>0.24</td>
<td>0.60</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>685</td>
<td>47/48</td>
<td>407/405</td>
</tr>
<tr>
<td>Area-to-mass [m²kg⁻¹]</td>
<td>58.0e-4</td>
<td>9.6e-4/9.4e-4</td>
<td>6.9e-4/7.0e-4</td>
</tr>
<tr>
<td>Radiation coeff. $C_R$</td>
<td>1.03</td>
<td>1.134/1.131</td>
<td>1.13</td>
</tr>
<tr>
<td>Semi-major axis [km]</td>
<td>7.866</td>
<td>7.335/7.176</td>
<td>12.274/12.158</td>
</tr>
<tr>
<td>Orbit altitude [km]</td>
<td>1.500</td>
<td>800-1.100/830</td>
<td>5.860/5.620</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.0016</td>
<td>0.0205/0.0010</td>
<td>0.0039/0.0137</td>
</tr>
<tr>
<td>Inclination [deg]</td>
<td>50.04</td>
<td>49.84/98.57</td>
<td>109.90/52.67</td>
</tr>
<tr>
<td>Drift of node [days]</td>
<td>116.77</td>
<td>90.97/364.7</td>
<td>1050.1/569.5</td>
</tr>
<tr>
<td>Drift of perigee [days]</td>
<td>141.1</td>
<td>108.7/122</td>
<td>1680.3/822.7</td>
</tr>
<tr>
<td>Draconitic year [days]</td>
<td>89</td>
<td>72.8/182</td>
<td>560/222</td>
</tr>
<tr>
<td>$S_2$ alias period [days]</td>
<td>44.5</td>
<td>36.5/91</td>
<td>280/111</td>
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<tr>
<td>A priori CoM corr.</td>
<td>1010 mm</td>
<td>78 mm</td>
<td>CoM¹</td>
</tr>
</tbody>
</table>

¹ station-specific CoM (Appleby et al. 2012)
Satellites Tracked by SLR: Overview

**Geodetic satellites:**
Passive satellites;
Only equipped with retro-reflectors

**Other satellites:**
Platform for a variety of instruments;
Active instruments;
Retro-reflectors in addition to other equipment
SLR Data Analysis: Basic Observation Equation

\[ d_{rec}^{sat}(t) = \frac{1}{2} \cdot c \cdot \Delta t_{rec}^{sat} \]

Distance SLR Station – Satellite at Measurement Epoch \( t \)

2-Way Travel Time of Laser Pulse
SLR Data Analysis: Extended Observation Equation

\[
d(t_r) = \frac{1}{2} c \Delta t_r^a + \delta_{rel} + \delta_{rot} + \delta_r - \delta_{RB} + \delta_{CoM} + \delta_Z m_f + \epsilon,
\]

(2.51)

- \(d(t_r)\) - one-way range between the observatory and the satellite at time \(t_r\),
- \(t_r\) - time epoch of the observation tied to universal time UTC,
- \(c\) - speed of light,
- \(\Delta t_r^a\) - light time travel,
- \(\delta_{rel}\) - relativistic correction,
- \(\delta_{rot}\) - correction due to Earth’s rotation and satellite motion in the inertial system,
- \(\delta_r\) - correction due to the station eccentricity w.r.t. the reference point,
- \(\delta_{RB}\) - station range bias,
- \(\delta_{CoM}\) - satellite Center-of-Mass correction or satellite laser array offset,
- \(\delta_Z m_f\) - tropospheric signal delay in the zenith direction multiplied by the corresponding mapping function,
- \(\epsilon\) - remaining systematic or random system errors.

Optical (different from microwave, e.g. GNSS, VLBI)
Normal points are the basic SLR data product. They replaced full-rate data as the primary station data product.

Forming normal points:
- decreases the noise of observations
- reduces the size of observation files
- reduces the number of observations, which are typically strongly correlated and thus do not introduce any further important information for most of the SLR applications.

Full-rate data are also used for special purposes, e.g., for the studies concerning the satellite's spin period (Kucharski et al., 2012).
SLR Data: „Normal Points“ vs. „Full Rate“

**Defined Intervals** vary from few seconds for low satellites, up to several minutes for high orbiting satellites.
- Etalon: 5 minutes
- LAGEOS: 2 minutes
- Stella, Starlette: 30 seconds
- GRACE: 5 seconds

For a normal point formation, a **minimum data requirement** has been established, i.e., a certain number of individual measurements to a target in a **defined interval**, which are combined into one normal point:
- 6 data points (single shots) for day-time observations
- 3 data points for night-time observations for single photoelectrons systems with high data yield.
- Fewer data points are acceptable on lower satellites (e.g., GOCE, GRACE) for those ranging systems with lower pulse repetition rates, where these minimum requirements are not practical.
Thank you for your kind attention!

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