Federal Agency for
Cartography and Geodesy

SLR – An Overview and General Aspects

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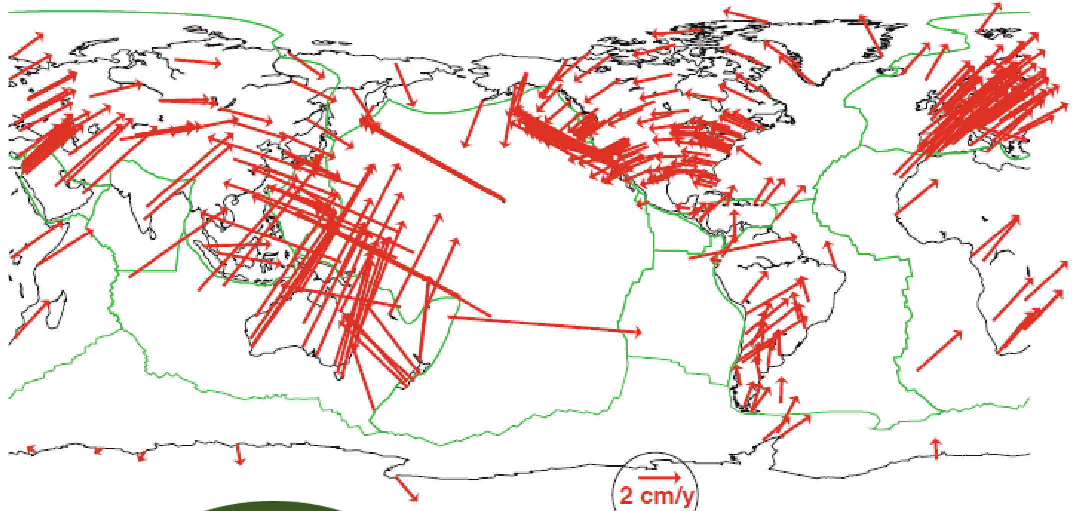
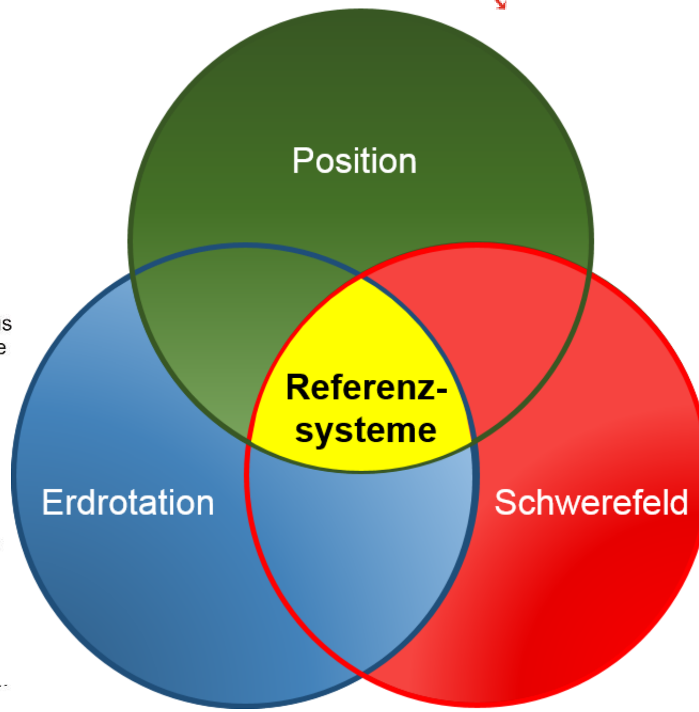
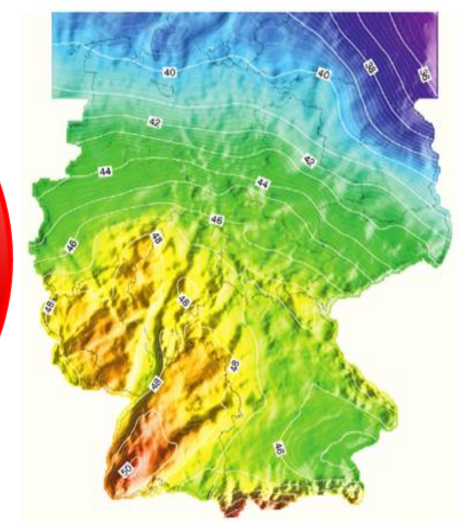
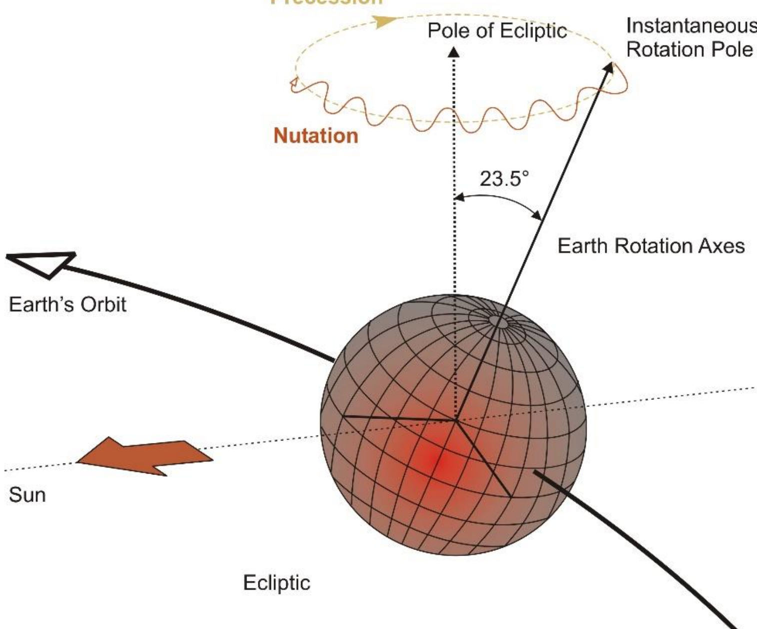
The 3 Pillars of Geodesy

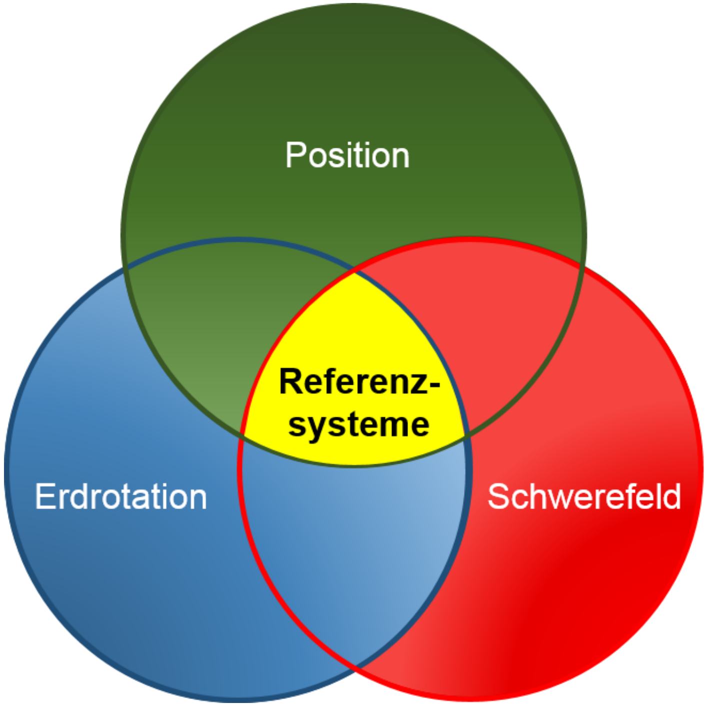








The 3 Pillars of Geodesy



<u>**Earth geometry and kinematics**</u>:

Shape of the Earth and its variation

<u>**Earth orientation and rotation**</u>:

Earth rotation and its variation

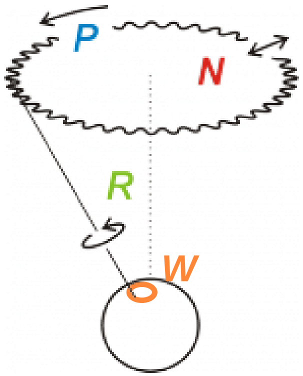
<u>**Earth gravitational field**</u>:

Static (mean) and variable gravity field

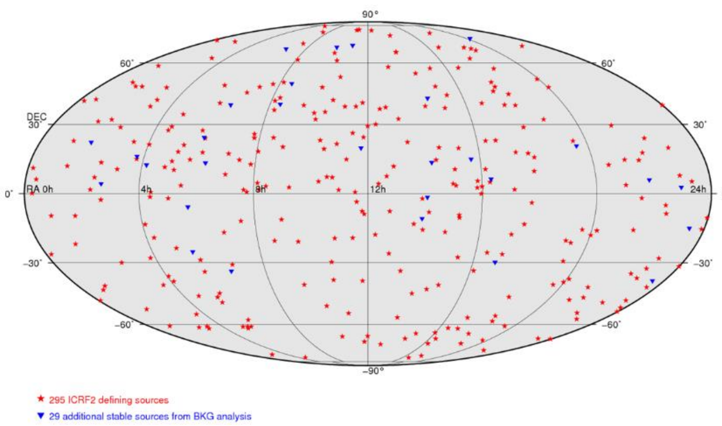
❑ Requirement for integrated estimation:
highly accurate, homogeneous, long-term stable reference frame

The 3 Pillars of Geodesy: Relationships

Earth Orientation

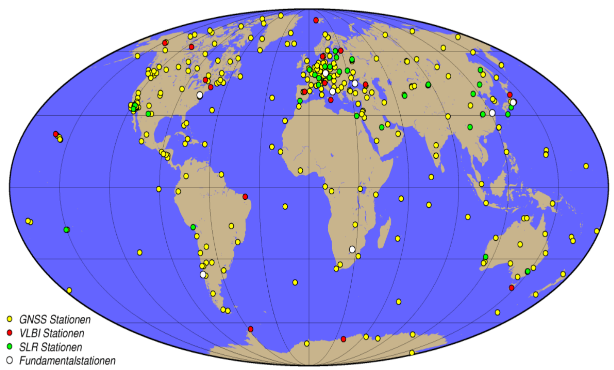


Celestial Reference Frame

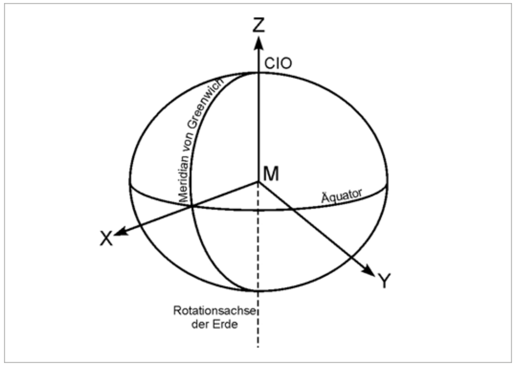


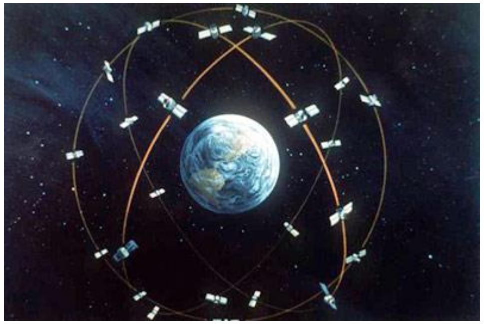
EOP

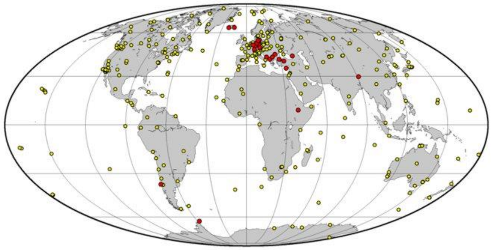
Terrstrial Reference Frame

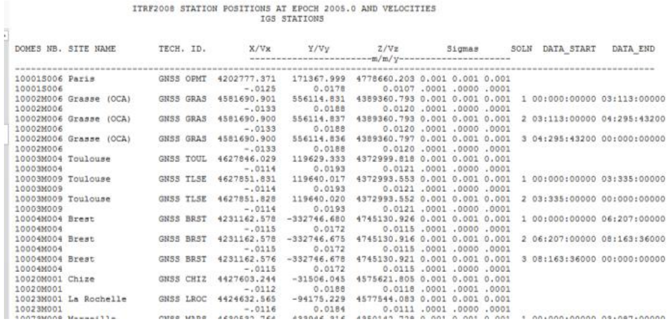


Reference System and Reference Frame









ITRF2008 STATION POSITIONS AT EPOCH 2005.0 AND VELOCITIES
IGS STATIONS

DOMES NB.	SITE NAME	TECH.	ID.	X/Vx	Y/Vy	Z/Vz	Sigmas			SOLN	DATA_START	DATA_END
				m/m/y								
10001S006	Paris	GNSS	OPMT	4202777.371	171367.999	4778660.203	0.001	0.001	0.001			
10001S006				-.0125	0.0178	0.0107	.0001	.0000	.0001			
10002M006	Grasse (OCA)	GNSS	GRAS	4581690.901	556114.831	4389360.793	0.001	0.001	0.001	1	00:000:00000	03:113:00000
10002M006				-.0133	0.0188	0.0120	.0001	.0000	.0001			
10002M006	Grasse (OCA)	GNSS	GRAS	4581690.900	556114.837	4389360.793	0.001	0.001	0.001	2	03:113:00000	04:295:43200
10002M006				-.0133	0.0188	0.0120	.0001	.0000	.0001			
10002M006	Grasse (OCA)	GNSS	GRAS	4581690.900	556114.836	4389360.797	0.001	0.001	0.001	3	04:295:43200	00:000:00000
10002M006				-.0133	0.0188	0.0120	.0001	.0000	.0001			
10003M004	Toulouse	GNSS	TOUL	4627846.029	119629.333	4372999.818	0.001	0.001	0.001			
10003M004				-.0114	0.0193	0.0121	.0001	.0000	.0001			
10003M009	Toulouse	GNSS	TLSE	4627851.831	119640.017	4372993.553	0.001	0.001	0.001	1	00:000:00000	03:335:00000
10003M009				-.0114	0.0193	0.0121	.0001	.0000	.0001			
10003M009	Toulouse	GNSS	TLSE	4627851.828	119640.020	4372993.552	0.001	0.001	0.001	2	03:335:00000	00:000:00000
10003M009				-.0114	0.0193	0.0121	.0001	.0000	.0001			
10004M004	Brest	GNSS	BRST	4231162.578	-332746.680	4745130.926	0.001	0.001	0.001	1	00:000:00000	06:207:00000
10004M004				-.0115	0.0172	0.0115	.0001	.0000	.0001			
10004M004	Brest	GNSS	BRST	4231162.578	-332746.675	4745130.916	0.001	0.001	0.001	2	06:207:00000	08:163:36000
10004M004				-.0115	0.0172	0.0115	.0001	.0000	.0001			
10004M004	Brest	GNSS	BRST	4231162.576	-332746.678	4745130.921	0.001	0.001	0.001	3	08:163:36000	00:000:00000
10004M004				-.0115	0.0172	0.0115	.0001	.0000	.0001			
10020M001	Chize	GNSS	CHIZ	4427603.244	-31506.045	4575621.805	0.001	0.001	0.001			
10020M001				-.0112	0.0188	0.0118	.0001	.0001	.0001			
10023M001	La Rochelle	GNSS	LROC	4424632.565	-94175.229	4577544.083	0.001	0.001	0.001			
10023M001				-.0116	0.0184	0.0111	.0001	.0000	.0001			

Reference System   Geodetic Observations   Reference Frame

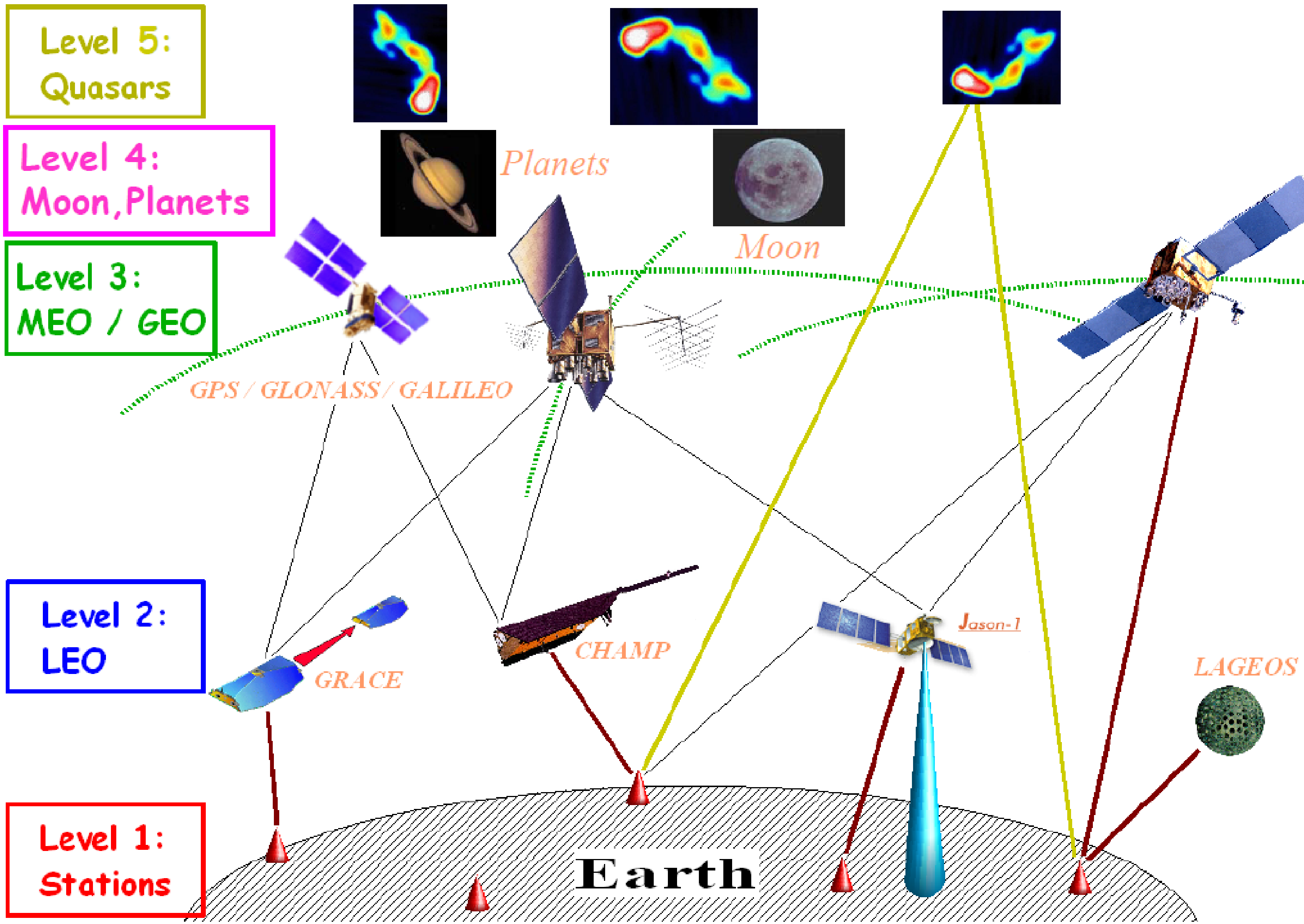
REALIZATION

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



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

	GNSS	VLBI	SLR
Station coordinates + velocities	XG	XV	XS
Satellite orbits	X		X
Quasar coordinates		X	
Polar motion + rates	X	X	X
Universal Time (dUT)		X	
Length of Day (LOD)	X	X	X
Nutation (+ nutation rates)	(x)	X	(x)
Geocenter	(X)		X
Earth's gravity field	(x)		X
Troposphere	X	X	
Ionosphere	X	(x)	
Technique-specific parameters	xG	xV	xS

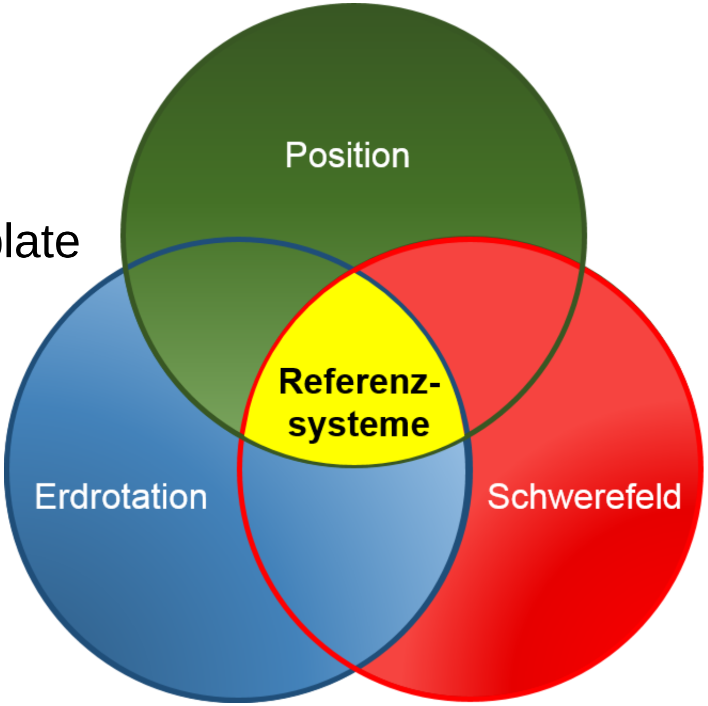
The 3 Pillars of Geodesy: SLR

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

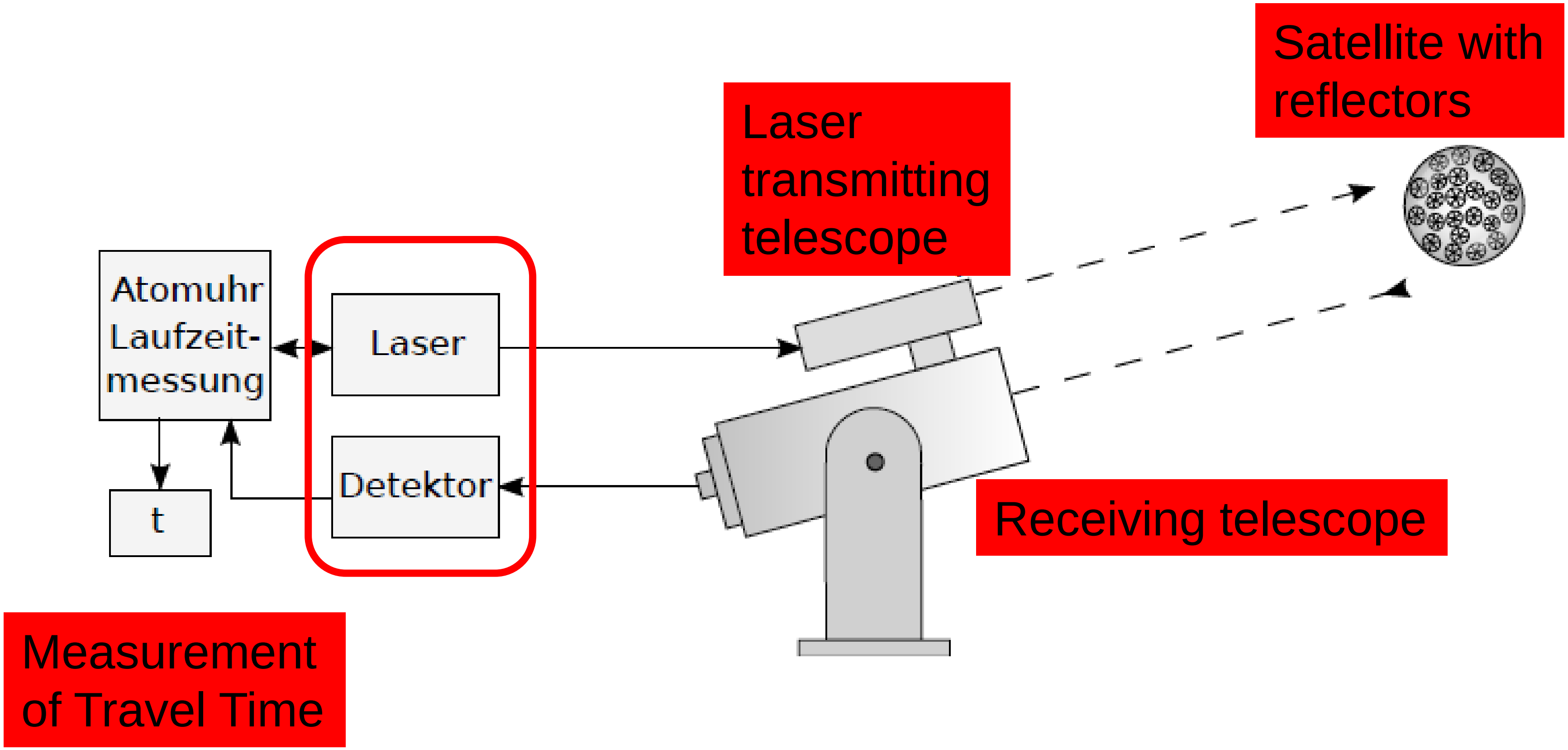


Satellite Laser Ranging: Measurement Principle

- 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



Satellite Laser Ranging: Measurement Principle
LASER

- The core element of a laser ranging system is the high energy laser (Light Amplication 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 11^{-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

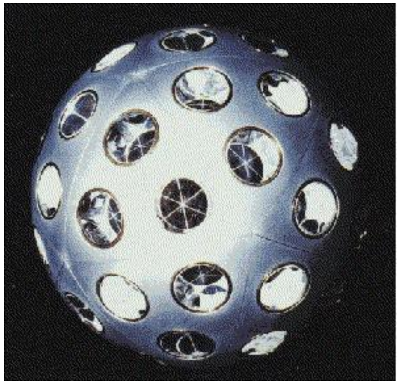
Most important satellites for global terrestrial reference frame: **LAGEOS-1** and **LAGEOS-2**:

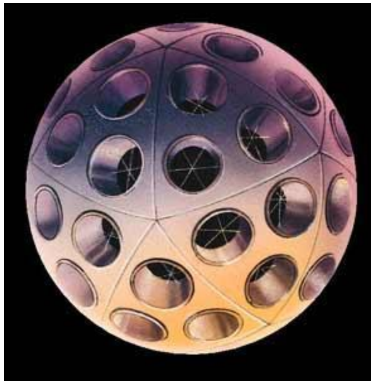
60 cm Diameter
407 kg Mass
426 Corner reflectors
5.800 km Orbital height (above Earth‘s surface)
225 Minutes per revolution

First tracked:

LAGEOS-1: May 10, 1976
LAGEOS-2: October 24, 1992

Geodetic / Spherical Satellites: Overview

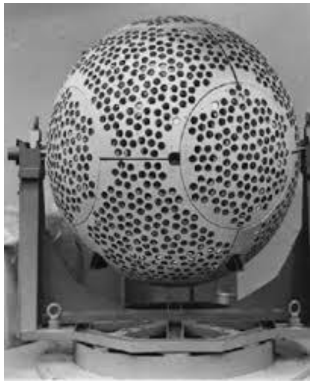

Starlette


Stella

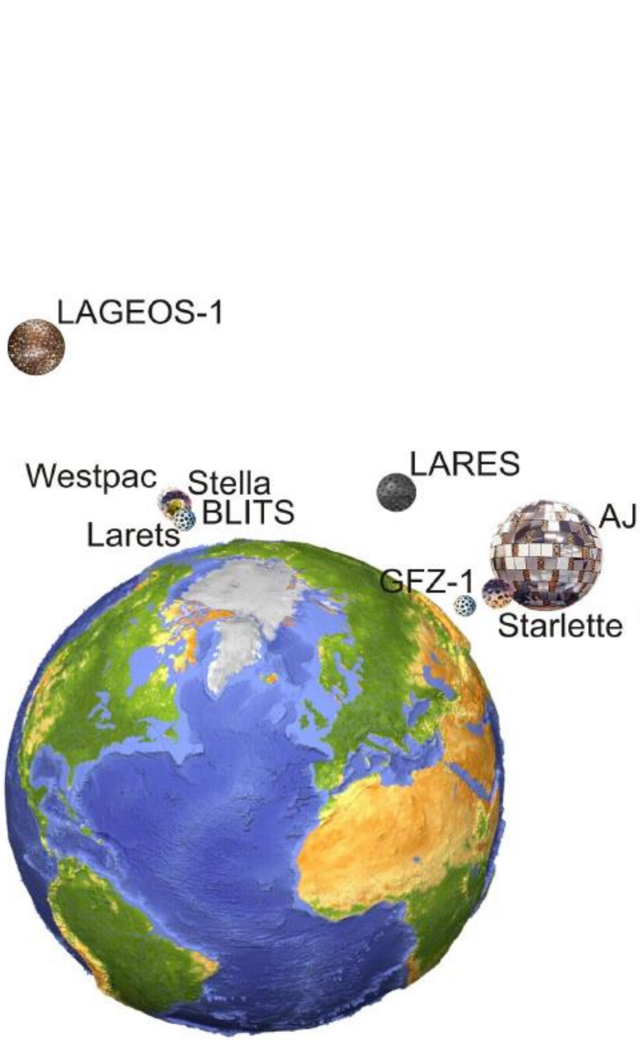

LARES


Ajisai


LAGEOS


Etalon

Geodetic / Spherical Satellites: Overview



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

[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

Satellite type/purpose Satellite name	Launch [year]	Decommission [year]	Altitude [km]	Inclination [deg]
Geodetic				
Starlette	1975	-	800-1100	49.84
LAGEOS-1	1976	-	5860	109.90
AJISAI	1986	-	1500	50.04
Etalon-1	1989	-	19140	65
Etalon-2	1989	-	19140	65
LAGEOS-2	1992	-	5620	52.67
Stella	1993	-	830	98.57
GFZ-1	1995	1999	398	51.6
Westpac-1	1998	2001	835	98.8
Larets	2003	-	691	98.2
BLITS	2009	2013	832	98.8
LARES	2012	-	1450	69.5
Gravity				
CHAMP	2000	2010	474	87
GRACE-A, -B	2002	-	485	89
GOCE	2009	2013	255	96.7
Remote sensing				
ERS-1	1991	2000	780	98
ERS-2	1995	2011	780	98
ENVISAT	2002	2012	780	98
ICESAT	2003	2010	600	94
TerraSAR-X	2007	-	514	97.4
TanDEM-X	2010	-	514	97.4
Cryosat-2	2010	-	720	92
Altimetry				
TOPEX/Poseidon	1992	2005	1350	66
Jason-1	2001	2013	1336	66
Jason-2	2008	-	1336	66
Navigation				
GPS-35, GPS-36	1993/1994	2011/-	20200	55
GLONASS	1989	-	19140	65
Galileo/GIOVE	2005	-	23220	56
Beidou (COMPASS)	2007	-	42160/21530	55
QZSS	2010	-	32000-42000	45
Other scientific satellites				
Beacon-C	1965	-	927	41
Gravity Probe B	2004	2006	650	90
ANDE P/C	2009	2010	350	51.6
PROBA-2	2010	2010	757	98.4

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

Federal Agency for
Cartography and Geodesy

SLR Data Analysis: Extended Observation Equation

Optical (different from micro-wave, e.g. GNSS, VLBI)

$$d(t_r) = \frac{1}{2}c\Delta t_r^s + \delta_{rel} + \delta_{rot} + \delta_r - \delta_{RB} + \delta_{CoM} + \delta_Z m_f + \epsilon, \qquad (2.51)$$

- $d(t_r)$ - 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,
- Δt_r^s - light time travel,
- δ_{rel} - relativistic correction,
- δ_{rot} - correction due to Earth's rotation and satellite motion in the inertial system,
- δ_r - correction due to the station eccentricity w.r.t. the reference point,
- δ_{RB} - station range bias,
- δ_{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,
- ϵ - remaining systematic or random system errors.

SLR Data: „Normal Points“ vs. „Full Rate“

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).

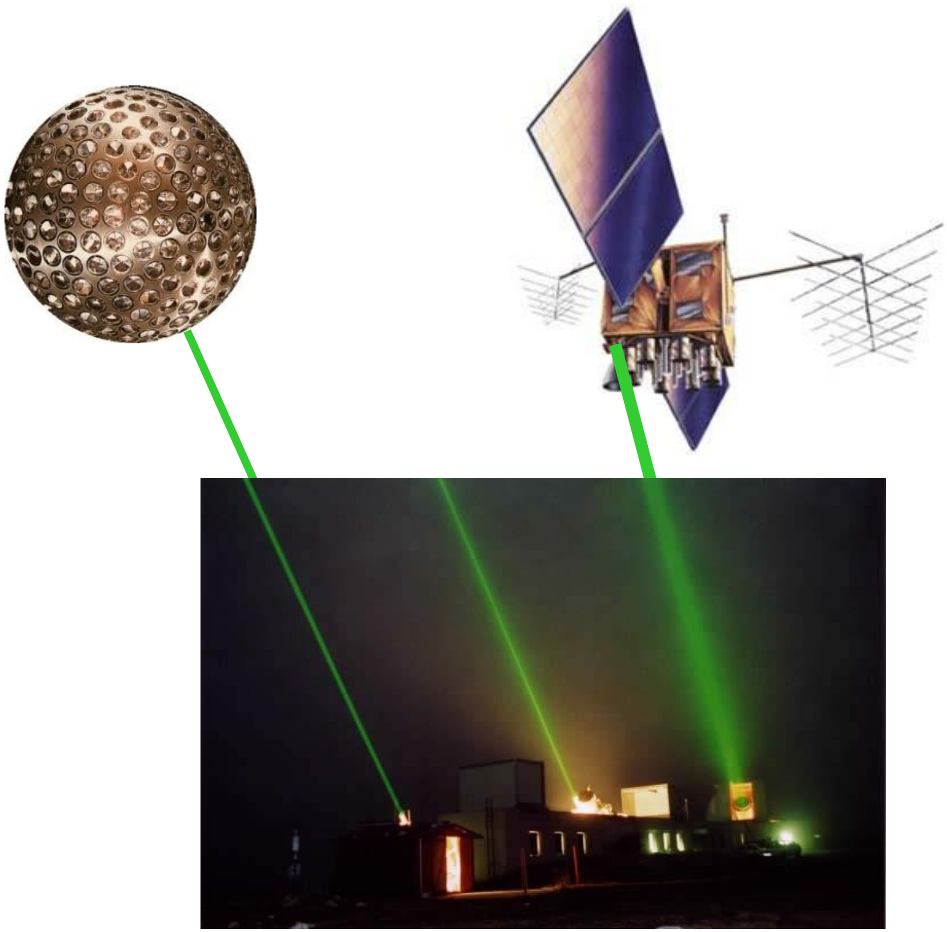
SLR Data: „Normal Points“ vs. „Full Rate“

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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