Ranging the GNSS Constellation

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GPS SLR Residuals

-6 cm
Influence of Earth Albedo

- Earth albedo causes a radial GNSS orbit error of 1-2 cm
- Antenna thrust causes a radial orbit error at a level of 1 cm

Rodriguez et al., 2010
Improvements in Orbit Modeling and LRA Offsets

Urschl et al., 2007
SLR reveals significant systematic orbit errors

GPS SLR residuals in Sun-fixed reference frame, ROCK radiation pressure a priori model.

Flohrer et al., 2008
Current GPS SLR residuals

SLR bias below 1 cm for IGS CODE reprocessed orbits
What about new GNSS constellations?

Montenbruck et al. 2013

Montenbruck et al. 2013
SLR Residuals of Galileo IOV Satellites

Montenbruck et al. 2015
Cause: different shape of satellites
Galileo SLR residuals

SLR residuals for plane: ALL, 1day-sol. no boxwing

SLR residual [cm]

epoch [mjd]
Galileo SLR residuals

SLR residuals for plane: ALL, 1 day-sol. with boxwing
Galileo SLR residuals

Classical ECOM radiation pressure model

New ECOM2 radiation pressure model

IGS MGEX project: http://mgex.igs.org/analysis/slrres.php
Conclusions 1

- SLR ranging to GPS and GLONASS has a long history. Independent orbit validation helped to improve orbit models.
- Radiation pressure modelling crucially depends on details of satellite structure and surface properties.
- SLR to satellites of the new GNSS constellations and satellites on new orbit types thus plays an essential role for calibrating such models.
- For GEO the determination of satellite longitude with GNSS tracking data is highly susceptible to biases. SLR can play an important role.
- For IRNSS satellites currently SLR are the only public tracking data allowing the determination of precise orbits.
Monitoring of Satellite Clock Behaviour

![Graph showing SLR residuals over time (doy 2012)]
Gravitational Redshift

E11
\[ a = 29'600 \text{ km}, \quad e = 0.00002, \quad i = 55.4^\circ \]

E14/18
\[ a = 27980 \text{ km}, \quad e = 0.15725, \quad i = 50.0^\circ \]
Laser Time Transfer to Galileo

- SLR as tool for high precision time synchronization of stable GNSS clocks combining Laser one-way with two-way, similar to ELT concept.
- Convince ESA for Galileo.
Conclusions 2

- GNSS satellites are equipped with clocks of higher and higher stability.
- As GNSS-derived satellite clock corrections are highly correlated with radial orbit errors.
- SLR thus plays an important role to separate temperature-induced variations of the apparent satellite clocks from orbit errors and to characterize the physical behavior of the clocks.
- This is also crucial for improving the determination of the gravitational redshift parameter $\alpha$ beyond Gravity Probe A using the clocks onboard the two Galileo satellites misplaced to eccentric orbits (Delva et al., 2015).
- It is time that SLR time synchronization of GNSS clocks plays a more important role.
GNSS is expanding

- Soon more than 100 satellites in the sky
- All equipped with SLR reflectors (GPS beginning with Block III SV-9)
Simple Simulation

- GNSS constellation is expanding, and in future all satellites will be equipped with SLR reflectors.
- How to observe GNSS satellites with SLR to derive precise orbits?
- Covariance analysis with simulated SLR observations from
  - 1, 6, and 17 SLR stations,
  - three sets of normal points, at 30° elevation rising, culmination if elevation above 60°, and at 30° elevation setting,
  - or one set of normal points per station at high elevation,
  - of full 24-satellite Galileo constellation.
- Good weather situation, observations of stations uncoordinated.
Simulation: 1 SLR Station
Simulation: 6 SLR Station
Simulation: 17 SLR Station
Range of E01 for one SLR Station
Ranges of all Galileo Satellites for one SLR Station
Simulated SLR Observations: $E=30^\circ$, Culmination
Simulated SLR Observations: E=30°, Culmination
Simulated SLR Observations: 1 Station, 1 Day
Simulated SLR Observations: 1 Station, 1 Day

1 sta 1 day
Simulated SLR Observations: 1 Station, 1 Day
Simulated SLR Observations: 1 Station, 1 Day

1 sta 1 day
Simulated SLR Observations: 1 Station, 3 Days
Simulated SLR Observations: 6 Stations, 1 Day

6 sta 1 day
Simulated SLR Observations: 6 Stations, 3 Days

E03

6 sta 3 day
Simulated SLR Observations: 17 Stations, 1 Day

E03

17 sta 1 day
Simulated SLR Observations: 17 Stations, 3 Days

17 sta 3 day
Formal Orbit Errors: 1 Station, 1 Day
Formal Orbit Errors: 1 Station, 3 Days

![Graph showing formal orbit errors over 3 days for different components: radial, alongtrack, and crosstrack.](image)
Formal Orbit Errors: 6 Stations, 1 Day
Formal Orbit Errors: 6 Stations, 3 Day

![Graph showing formal orbit errors over time]
Formal Orbit Errors: 6 Stations, 1 Day, Culminations
Formal Orbit Errors: 6 Stations, 3 Days, Culminations
Formal Orbit Errors: 17 Stations, 1 Day
Formal Orbit Errors: 17 Stations, 3 Days

![Graph showing formal orbit errors for radial, alongtrack, and crosstrack directions over a 3-day period.](image)
Conclusions 3

• Simple simulations demonstrate the capability of precise orbit determination for GNSS satellites using a limited number of observations per station.

• Coordination of the observations between the stations is crucial to make economic use of the observing system.

• Eventually SLR observations should not only be used for orbit validation but combined with GNSS observations for determining precise orbits.
Space Geodetic Techniques

SLR

GNSS

DORIS

VLBI
Space Geodetic Techniques

SLR

GNSS

DORIS

VLBI
Space Geodetic Techniques

SLR

GNSS

DORIS

VLBI
Conclusions

- SLR plays an important role since decades for validating GNSS derived satellite orbits.
- For new GNSS constellations and new orbit types SLR proves to be essential to calibrate new radiation pressure models.
- SLR allows to separate orbit- and temperature-induced variations of stable onboard GNSS clocks.
- Eventually the role of SLR becomes even more important by contributing to precise orbit determination of GNSS satellites.
- Coordination of the observation schedule between stations is crucial to optimize the benefit-to-cost ratio.
- Integration of GNSS and SLR observations for precise product generation has to be forced in the context of GGOS.
How to track GNSS?

• For validation and calibration of radiation pressure models?
  – one satellite block for a range of Sun-beta angles, i.e., one satellite block per orbital plane
  – good coverage along the orbit

• For determination of gravitational redshift parameter using Galileo E14/E18:
  – good coverage of orbits of both satellites (as long as clock running on H-maser)

• For BeiDou GEO satellites:
  – coverage of all satellites

• For contributing to precise orbit products combined with GNSS
  – coverage of full constellation
  – coordination of observation schedule among SLR stations
Many thanks for your attention!