Introduction
Satellite Laser Ranging (SLR) provides a powerful tool to validate satellite orbits of Global Navigation Satellite Systems (GNSS) that are solely computed from microwave data. So far, only two GPS satellites are equipped with laser retroreflectors. In contrast, all GLONASS, Galileo, BeiDou, and QZSS spacecraft can be tracked via SLR. The Center for Orbit Determination in Europe (CODE) is an Associate Analysis Center of the International Laser Ranging Service (ILRS). Since 2004 CODE has been computing the SLR residuals with respect to CODE’s 3-day rapid orbits (i.e., GPS and GLONASS orbits) on a daily basis.

Principle of SLR validation
The principle of validating GNSS orbits using SLR is simple: the SLR observations (‘observed’) are directly compared against the geometry based on the coordinates of the SLR stations and the microwave-based orbit (‘computed’) without estimating any parameter. The residuals (‘observed minus computed’) indicate how well the orbits agree with the SLR observations. Note that since the maximum angle of incidence of a laser pulse to a GNSS satellite does not exceed 14°, SLR data are mainly sensitive to the radial component of microwave-based GNSS orbits.

Validation of GLONASS orbits
GLONASS satellites are equipped with laser retroreflector arrays (LRAs) of different types. Whereas the shape of old satellites’ LRAs was irregular planar (SVN 779, 791) or a hollow greek cross (SVN 789, 790), all LRAs of the GLONASS-M fleet have a rectangular shape. Those of the new GLONASS-K satellites form a ring (cf. Figure 1 and Table 1). The SLR residuals (cf. Table 1) were computed w.r.t. 1-day (F1) and 3-day orbits (F3), which result both from a reprocessing campaign at the Center for Orbit Determination in Europe (CODE) – Repro15 (time span: Jan 2006 to Dec 2012).

For the K-type satellite SVN 801, an elevation-dependent center of mass (CoM) correction is provided (cf. Table 2). For the moment, however, a CoM correction of 1470 mm is applied within the Bernese Software for all elevation angles; this correction is optimal for elevation angles between 70° and 80° (cf. Table 2). Figure 2 shows that (1) the residuals are indeed smallest for elevation angles around 80° and that (2) the residuals approximately follow the elevation-dependent CoM corrections.

Validation of GPS orbits
Up to this date only two GPS satellites are equipped with laser retroreflectors. The standard deviation of the SLR residuals w.r.t. GPS orbits is significantly smaller for 3-day orbits (F3), see Table 3.

Validation of MGEX orbits
Figure 3 shows the SLR residuals for Galileo, BeiDou, and QZSS satellites, which were computed w.r.t. CODE MGEX orbits. The larger residuals for BeiDou and QZSS occur when the attitude mode is switched from yaw-steering to orbit-normal. No significant differences in the SLR residuals for Galileo I/OV/FOC and for BeiDou IGSO/MEO have been detected so far. More details of MGEX are given in the talk by L. Prange (Orbit Modelling Session).

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Astronomical Institute of the University of Bern in the framework of the EGSIPI project (see poster by Šušnij et al.). Mean value \( \nu \) and standard deviation \( \sigma \) are typically smaller for the 3-day orbits, which are more consistent at day boundaries. Averaged over all satellites, \( \nu \) and \( \sigma \) are -9.7 mm and 38.4 mm for the 1-day orbits and -8 mm and 34.7 mm for the 3-day orbits. The standard deviation decreases from 50.1 mm for the old satellites to 33.5 mm for the M-fleet.

Table 1: Elevation-dependent center of mass (CoM) corrections for SVN 801.

<table>
<thead>
<tr>
<th>SVN Slot</th>
<th>COSPAR ID</th>
<th>Launch</th>
<th>Num. of obs.</th>
<th>( \nu ) (in mm)</th>
<th>( \sigma ) ( \nu ) (in mm)</th>
<th>( \nu ) (in mm)</th>
<th>( \sigma ) ( \nu ) (in mm)</th>
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