Activities in the Research Group on Satellite Geodesy at AIUB

Astronomisches Institut
Satellite Geodesy Research Group

- Bernese GNSS Software
- CODE activities (IGS and EUREF)
- SLR data analysis
- LEO orbit determination and gravity field recovery
Satellite Geodesy Research Group

Bernese GNSS Software

CODE activities (IGS and EUREF)

LEO orbit determination and gravity field recovery

SLR data analysis
Clock products with resolved ambiguities

Procedure for clock estimation with ambiguity resolution

Activated for rapid, final, and MGEX clocks in July 2018

WL and NL phase bias determination and ambiguity resolution:
1. WL phase bias determination (WLB)
2. WL integer fixing (WLI)
3. NL bias determination (NLB)
4. NL integer fixing (NLI)
5. OSB values for L1 and L2 (IAR)
Galileo satellite widelane fractional bias results

Differences in the bias between day n and n+1, n+2, n+3, ...

Galileo ground track repetition of 10 days

IGS rapid and final clock combination

Rapid Clocks (AC solutions compared to IGS Rapid)

IGS final clock combination

Final Clocks (AC solutions compared to IGS Final)

Clock Std Dev [ps]


Time [GPS weeks]

Daily PPP vs. daily IPPP

<table>
<thead>
<tr>
<th></th>
<th>Daily PPP; CODE final product; September 2018; 295 (of 337) stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median (Q0.50) daily repeatability (mm)</td>
<td>N</td>
</tr>
<tr>
<td>Ambiguity-float PPP</td>
<td>1.18</td>
</tr>
<tr>
<td>Ambiguity-fixed PPP</td>
<td>1.18</td>
</tr>
</tbody>
</table>

### IPPP for LEO POD

<table>
<thead>
<tr>
<th></th>
<th>Float</th>
<th>ZD AR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>red.-dyn.</td>
<td>kin.</td>
</tr>
<tr>
<td>Orbits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRACE-A</td>
<td>+0.5/15.5</td>
<td>+1.5/16.6</td>
</tr>
<tr>
<td>GRACE-B</td>
<td>+0.9/12.1</td>
<td>-0.5/16.9</td>
</tr>
<tr>
<td>Sentinel-3A</td>
<td>-6.0/11.5</td>
<td>-6.5/14.7</td>
</tr>
<tr>
<td>Sentinel-3B</td>
<td>-2.9/12.4</td>
<td>-4.3/15.2</td>
</tr>
</tbody>
</table>

**Table 1**: Mean values and standard deviations in mm of SLR residuals over April 2007 (GRACE) and September 2018 (Sentinel-3), respectively.
CODE contribution to IGS MGEX
Recent Improvements in the CODE MGEX

- Improved ambiguity resolution for orbit product, based on CODE’s OSB product
- Activation of eclipse attitude law for Galileo
- Albedo and antenna thrust models for Galileo and QZSS
- Higher sampling of orbit (5 min) and clock products (30 s)
- Zero-diff. ambiguity resolution for clock product
- Activation of the orbit normal mode modelling
Orientation of the spacecraft

Spacecraft-fixed reference frame (Yaw-Steering attitude):

Orientation of the spacecraft

Spacecraft-fixed reference frame (Orbit-Normal attitude):

Orientation of the coordinate system

ECOM (Enhanced CODE Orbit Model) frame:

Orientation of the coordinate system

TERM (Terminator) frame:

\[ e_{T_1} = \frac{e_D \times e_W}{|e_D \times e_W|} \]
\[ e_{T_2} = e_D \times e_{T_1} \]
\[ e_{T_3} = e_D \]

ECOM updated for orbit normal mode

RMS from SLR residuals (IQR):

<table>
<thead>
<tr>
<th></th>
<th>BDS2–MEO</th>
<th>BDS2–IGSO</th>
<th>QZSS–1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Old model</strong></td>
<td>20.5 cm</td>
<td>21.0 cm</td>
<td>62.0 cm</td>
</tr>
<tr>
<td><strong>New model</strong></td>
<td>12.2 cm</td>
<td>12.2 cm</td>
<td>15.2 cm</td>
</tr>
<tr>
<td><strong>Improvement</strong></td>
<td>40.5 %</td>
<td>41.9%</td>
<td>75.5%</td>
</tr>
</tbody>
</table>

Median of a linear fit of the satellite clock corrections:

<table>
<thead>
<tr>
<th></th>
<th>BDS2–MEO</th>
<th>BDS2–IGSO</th>
<th>QZSS–1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Old model</strong></td>
<td>1.72 ns</td>
<td>1.61 ns</td>
<td>1.43 ns</td>
</tr>
<tr>
<td><strong>New model</strong></td>
<td>0.72 ns</td>
<td>0.69 ns</td>
<td>0.35 ns</td>
</tr>
<tr>
<td><strong>Improvement</strong></td>
<td>58.1%</td>
<td>57.1%</td>
<td>75.5%</td>
</tr>
</tbody>
</table>

Orbit modelling during eclipse

SLR residuals for SVN 101

Comparison of MGEX solutions from http://mgex.igs.org/analysis

ECOM2 SRP model

CODE arc length 72 hours

ERP, antenna thrust

GFZ arc length 24 hours

GRGS arc length 30 hours
Consequences of the satellite design

- The thermal radiation from the radiators on the +Y/−Y plates cause forces compensating each other (or introducing a Y-bias).

- For Galileo we have more radiators causing additional forces (+X and −Z for FOC).

- Because of the low weight of Galileo satellites they are more sensitive to non-gravitational forces.

- Thermal radiation from the radiators are also active during eclipse periods where empirical SRP parameters are switched off.

Expected effect of the +X radiator

Orbit misclosures at midnight

Example: IOV satellite E11

Scaling factors for box-wing models

Validate boxwing model

Macromodel defines:
- Plates of the satellite with its areas and surface properties

Used to compute forces acting on the satellite because of solar radiation pressure.

Whether these models are correct can be assessed by estimating scale factors for the resulting force:

<table>
<thead>
<tr>
<th>Plate</th>
<th>Mod</th>
<th>Area (A) [m²]</th>
<th>Normal (\vec{e}_n)</th>
<th>Specularity (\rho)</th>
<th>Diffusivity (\delta)</th>
<th>Rotation Sys.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5.720</td>
<td>[+1, 0, 0]</td>
<td>0.112</td>
<td>0.448</td>
<td>+X</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>5.720</td>
<td>[-1, 0, 0]</td>
<td>0.112</td>
<td>0.448</td>
<td>-X</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>7.010</td>
<td>[0, +1, 0]</td>
<td>0.112</td>
<td>0.448</td>
<td>+Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>7.010</td>
<td>[0, -1, 0]</td>
<td>0.112</td>
<td>0.448</td>
<td>-Y</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5.400</td>
<td>[0, 0, +1]</td>
<td>0.112</td>
<td>0.448</td>
<td>+Z</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>5.400</td>
<td>[0, 0, -1]</td>
<td>0.000</td>
<td>0.000</td>
<td>-Z</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>22.250</td>
<td>[+1, 0, 0]</td>
<td>0.195</td>
<td>0.035</td>
<td>+SUN: [0,+1, 0]</td>
<td>Solar panels front</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>22.250</td>
<td>[-1, 0, 0]</td>
<td>0.196</td>
<td>0.034</td>
<td>-SUN: [0,+1, 0]</td>
<td>Solar panels back</td>
</tr>
</tbody>
</table>


L. McNair, A. Villiger, R. Dach, A. Jäggi: Validation of boxwing models for GNSS satellites.
Yearly Scale Factors: Monoscale

Monoscale: (one factor per satellite)

The scale factors show clearly the different types of satellites.

Yearly Scale Factors: Smartscale–2

Smartscale–2:
(two factor per satellite: solar panel and body)

GLONASS & Galileo:
stable scale factors for all satellites in same block
→ close to 1

GPS:
more variation between satellites in same block
→ farther away from 1.

L. McNair, A. Villiger, R. Dach, A. Jäggi: Validation of boxwing models for GNSS satellites.
Deficiencies in the Receiver Antenna Calibration in an multi-GNSS environment

Before Galileo and QZSS disclosed the satellite antenna corrections

<table>
<thead>
<tr>
<th>GNSS</th>
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<tbody>
<tr>
<td>GPS</td>
<td>L1</td>
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<td>L2</td>
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<td>GAL</td>
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<tr>
<td>QZSS</td>
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Rob. : roboter calibrations

### IGS antenna pattern

After Galileo and QZSS disclosed the satellite antenna corrections

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Rob. : roboter calibrations

IGS antenna pattern

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<tr>
<td>GPS</td>
<td>L1</td>
<td>![Yellow]</td>
<td>![Green]</td>
<td>![Brown]</td>
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<tr>
<td></td>
<td>L2</td>
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<tr>
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<td>![Yellow]</td>
<td>![Green]</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>![Red]</td>
<td>![Green]</td>
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</tr>
<tr>
<td></td>
<td>B3</td>
<td>![Red]</td>
<td>![Green]</td>
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</tr>
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<td>![Brown]</td>
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<td>L2</td>
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</tr>
<tr>
<td></td>
<td>L5</td>
<td>![Green]</td>
<td>![Brown]</td>
<td>![Yellow]</td>
</tr>
</tbody>
</table>

Rob. : roboter calibrations
Cha. : chamber calibrations

Collection of chamber calibrations

- Antenna working group (A. Villiger, AIUB): call for chamber calibrations

- Great response from various institutions:
  - Vermessungsamt Mecklenburg-Vorpommern, Germany
  - Vermessung und Geoinformation Schleswig-Holstein, Germany
  - BKG
  - ESA
  - EUREF (publicly available)
  - GFZ
  - IGE University of Bonn
ESA project related to GNSS activities
Other projects:

- **TGVF/OVF**: «Ground truth» for Galileo GMS (continued with the label GRSP)
  GSA–project with ESOC, BKG, GFZ, IGN

- **ORBIT/SRP Modelling for Long Term Prediction**
  ESA–project with Airbus (defense and space)

- **Improved GNSS–Based Precise Orbit Determination by using highly accurate clocks**
  ESA–project with ETH Zurich and TU Munich (finished in 2018)
Satellite Geodesy Research Group

- Bernese GNSS Software
- CODE activities (IGS and EUREF)
- LEO orbit determination and gravity field recovery
- SLR data analysis
Atmospheric density models in LEO non-gravitational force modeling
Thermospheric models

Atmospheric densities (top, kg/m$^3$) and temperatures (bottom, K) provided by three different models at an altitude of 425 km (GRACE):
Piecewise–constant accelerations

Estimated along-track 10-min piecewise–constant accelerations \((\text{m/s}^2)\) for GRACE –A (doy 222 of 2014) when using no non-gravitational force modeling, and DTM2013, JB2008, or NRLMSISE–00 for aerodynamic acceleration modeling:
SLR residuals

Standard deviations of GRACE – A SLR residuals over 3 months when using different atmospheric density models, as well as with and without Horizontal Wind Model HWM14:
Copernicus POD Service
Copernicus satellite fleet

At AIUB precise orbits of all Sentinel satellites are computed

Sentinel-1A
Sentinel-1B

Sentinel-2A
Sentinel-2B

Sentinel-3A
Sentinel-3B

Courtesy: ESA
Sentinel–3A orbit comparisons

Sentinel-3A Orbital Comparison (3D RMS; cm); COMB vs external solutions

- AIUB’s solution without non-gravitational force modeling
- AIUB’s solution with non-gravitational force modeling
Zero-difference ambiguity resolution in LEO POD
Internal orbit consistency

Based on CODE’s new phase bias and clock product, zero-difference ambiguities can be resolved in LEO POD. This significantly improves the consistency between reduced-dynamic and kinematic orbit...
K–band validation

... and the K–band residuals (GRACE)

K–band residuals are comparable to what is obtained in a double-difference baseline processing with ambiguity resolution.
GOCE PSO Reprocessing
In the frame of an ESA-funded reprocessing of GOCE data, AIUB is responsible for the re-generation of the GOCE Precise Science Orbits (PSOs).

New PSOs, based on latest version of Bernese GNSS Software and homogeneous GNSS products from EGSIEIM repro.

In addition: Downweighting of GPS data affected by large ionospheric dynamics.
GOCE PSO reprocessing – Gravity field

Data downweighting significantly reduces artifacts in GPS–only gravity field solutions along geomagnetic equator:

Geoid height differences of 2011 yearly GPS–only solution w.r.t. ITG–GRACE2010, 300km Gauss filter applied.
Follow-up activities from the EGSIEM project
Product Center of the IAG

COST–G: Quality control

- Amplitudes of seasonal mass variations in river basins,
- Ice mass trends in polar regions,
- Significance tests for time variations in the spherical harmonic domain.
Product Center of the IAG

Weighted combination of monthly gravity fields based on variance component estimation.

Quality control of individual time-series and their combination in terms of variability over the oceans.
SWARM Combination

**sigma a posteriori of monthly gravity fields**

- SWARM monthly gravity field
  - processing,
  - combination,
  - quality control
in the frame of SWARM DISC.
Long time-series of SLR processing (LAGEOS, SLR–LEOs)

- provide information on geocenter, Earth rotation, and the scale of the geodetic reference frame,
- extend the GRACE time-series of mass variations back to the 90s,
- and help to bridge the gap to GRACE–FO.
Satellite Geodesy Research Group

- Bernese GNSS Software
- Planetary geodesy
- LEO orbit determination and gravity field recovery
- CODE activities (IGS and EUREF)
- SLR data analysis
Non-gravitational forces for Magellan orbit determination
Magellan mission

- Best source of knowledge about Venus gravity field
- State-of-the art Venus gravity field model (MGNP180U):
  - is 20 years old
  - was derived in a non-optimal multi-step approach
  - is based on simplified modeling of non-gravitational forces
- Goal: Establish detailed spacecraft macro model and attitude laws to study impact of non-gravitational force modeling on Magellan POD
Modeled non-gravitational accelerations

Modeled reflected planetary pressure accelerations acting on Magellan for April 16, 1994 when using a cannon ball satellite model or a 16-plate macro model with two different attitude laws (solar panel axis along velocity or solar panel perpendicular to satellite–Sun direction, while high gain antenna is pointing towards Earth):
Doppler residuals

Doppler residuals after 2 iteration of Doppler–based Magellan POD on doys 146 and 147 of 1994:

Statistics

<table>
<thead>
<tr>
<th></th>
<th>No Surface Forces</th>
<th>Cannonball</th>
<th>$ATT_1$</th>
<th>$ATT_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (Hz)</td>
<td>-0.00114</td>
<td>0.00027</td>
<td>0.00024</td>
<td>0.00019</td>
</tr>
<tr>
<td>Standard Deviation (Hz)</td>
<td>2.06433</td>
<td>0.22392</td>
<td>0.23624</td>
<td>0.21425</td>
</tr>
<tr>
<td>RMS (Hz)</td>
<td>2.06420</td>
<td>0.22391</td>
<td>0.23623</td>
<td>0.21425</td>
</tr>
</tbody>
</table>

Time [MJD]
BepiColombo MPO orbit reconstruction simulation
MPO orbit determination

- Simulation study for precise orbit determination of BepiColombo Mercury Planetary Orbiter (MPO) using Doppler, accelerometer and altimetry data and development version of Bernese GNSS Software.
- PhD project at Space Research and Planetary Sciences Division, University of Bern, co-supervised by AIUB
Modeling

- Force model: gravitational forces (Mercury gravity field to d/o 50, Sun, and planets), non-gravitational forces (solar and planetary radiation pressure), relativistic corrections
- Visibility conditions (occultation, elevation over Earth horizon, ground station availability)
- 15–16h tracking period and dark period
- Desaturation maneuvers (every 12h)
- Accelerometer error model
Doppler–based orbit determination

Differences to ref. orbit in a Doppler–based orbit determination when using error–free accelerometer, accelerometer noise model, and accelerometer noise model together with desaturation maneuvers introduced:
Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald
24/7 Betrieb

Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald

24/7 Operations
- Optical Observations
  space debris (SSA), asteroids, comets
- Satellite Laser Ranging
- Satellite–Receivers (GPS–, GLONASS– and Galileo)
NEW DOMES/TELESCOPES
Official inauguration event on May 29
Public Day on June 2
6 Operational Telescopes!
ILRS Station Performance

minutes of data
from October 1, 2017 through September 30, 2018

Once again number 1 in northern hemisphere...
ILRS Station Performance

total normal points
from October 1, 2017 through September 30, 2018

Yarragadee, Zimmernwald, Greenbelt, Stromlo, Herschimoneux, Monument Peak, Potsdam, Graz, Hartebeesthoek, Hari, LAGEOS 1 and 2, LEO, Bejing, Katively, Papeete, Riga, Badary, Borowiec, Inkutsk, Hartebeesthoek, Altay, Komsomolsk, Zelenchukskaya, Grasse, MEO, Sejong, Arkhyz, Mendeleev, Brasilia, Svetloe, Balkonur, Kev, McDonald.
Some issues with calibration rms due to laser instability
→ nothing is guaranteed, needs constant monitoring and extensive analysis
LAGEOS NPT rms

Zimmerwald, Switzerland 7810
pass average LAGEOS normal point rms

Same as for calibration...

GR: ave 11.87 ± 2.19 mx 27.43 mn 7.08 561 pts
LAGEOS Bias Analysis

Zimmerwald (7810) bias analysis: one per pass and running average of 300 passes
LAGEOS-1 2015-2018 day vs. night passes

our bias is very stable
LAGEOS Day/Night Yield

Same yield as Yaragadee for daytime passes (night is shared with debris observations!)
1 year (July 2016-June 2017), LAG1+LAG2. RB only or RB+TB smoothing applied for POD (c5++) post-fit residuals.

Mean "NP RMS" (pass smoothing applied)
1 year (July 2016-June 2017), LAG1+LAG2.
POD (c5++): station pos solved for. U-Strasbg atm+hyd loading applied.
1 year (July 2016-June 2017), LAG1+LAG2.
POD (c5++): station pos solved for. U-Strasbg atm+hyd loading applied.
SLR Operations

- **ILRS pass statistics**
  - again #1 in the northern hemisphere
  - very good performance
  - station range bias often at $\leq 1$ mm, location of error source narrowed

- **Special Satellites/Restricted Tracking**
  - Sentinel–3A/B on a routine basis (Low Energy)
  - ICESat–2 upcoming (GoNoGo)
  - decommissioned satellites: # of debris targets increasing

- **System**
  - laser, electronics and mechanics perform reliably
  - mechanics: expect some refurbishments after 20 years of operation for dome
SLR Operations

- Definition/evaluation of new laser
  - 100Hz/kHz…? (quantum jump of technology not in sight)
  - two lasers? debris SLR on new 0.8m telescope?
  - new targets (nano, debris satellites) might affect choice

- European Laser Time Transfer project (ELT) (ACES experiment on ISS)
  - Trimble GPS–Receiver 1PPS 15 ns wrt UTC integrated
  - determination of internal calibration delays ongoing
SLR Operations

- **Tracking camera / stare and chase**
  - find target in full frame image → correct telescope pointing (automatically!) → track satellite with laser

- **Quantum experiments**
  - telescope optics in the infrared fits requirements for entangled photons experiment with IAP (Hasler Stiftung project)
  - first to calibration target, later to a satellite?
Stare and Chase

Tracking camera image before correcting telescope pointing

Returns after automatic pointing correction (TOPEX)!
Space Debris
Simultaneous Light Curves and SLR Measurements – ENVISAT

**SLR residuals**

**light curve**
Simultaneous Light Curves and SLR Measurements – TOPEX

**SLR residuals**

**light curve**
Simultaneous Light Curves and SLR Measurements – GLONASS (decommissioned)