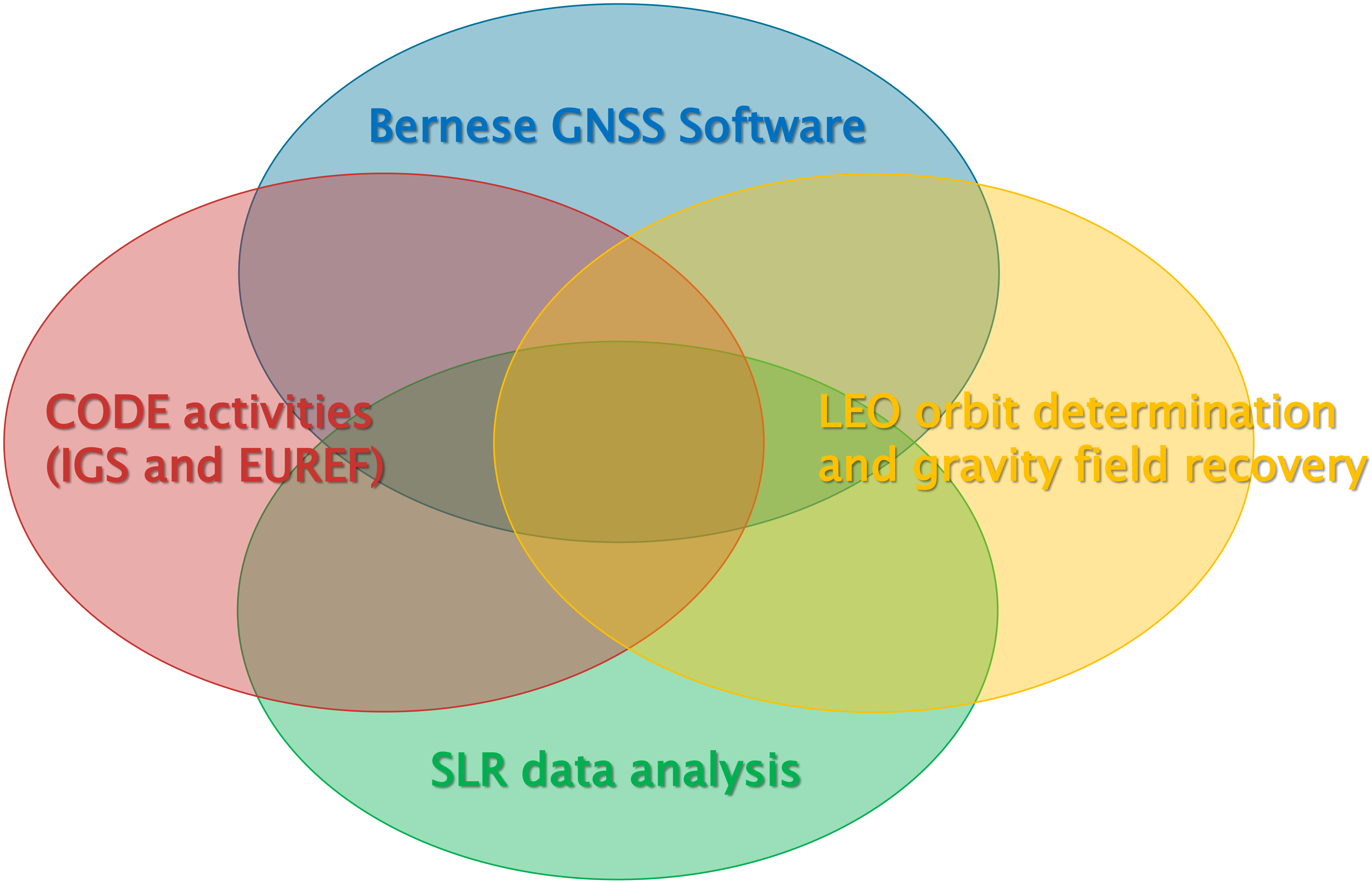
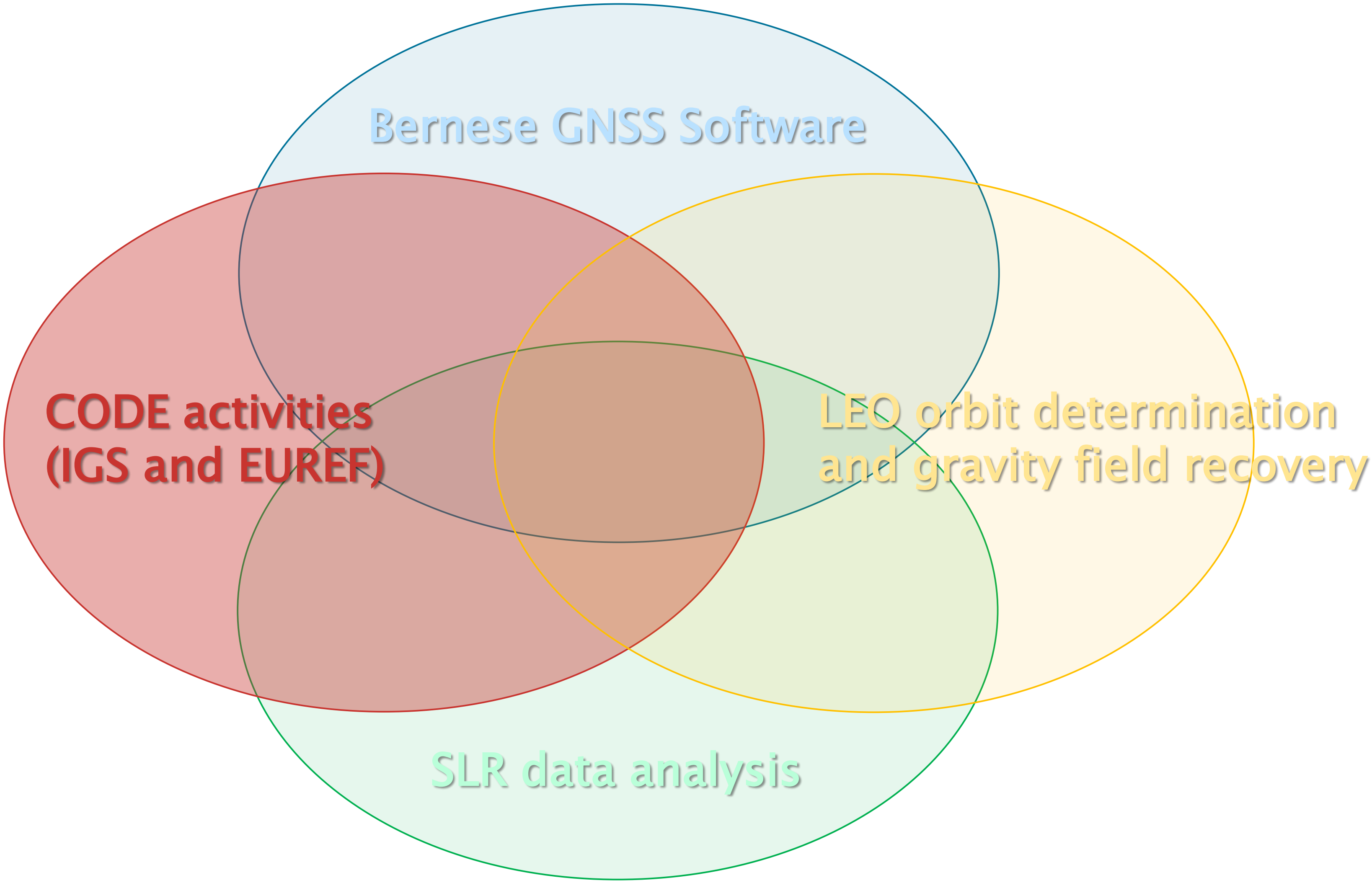
Activities in the Research Group on Satellite Geodesy at AIUB

Astronomisches Institut

Satellite Geodesy Research Group



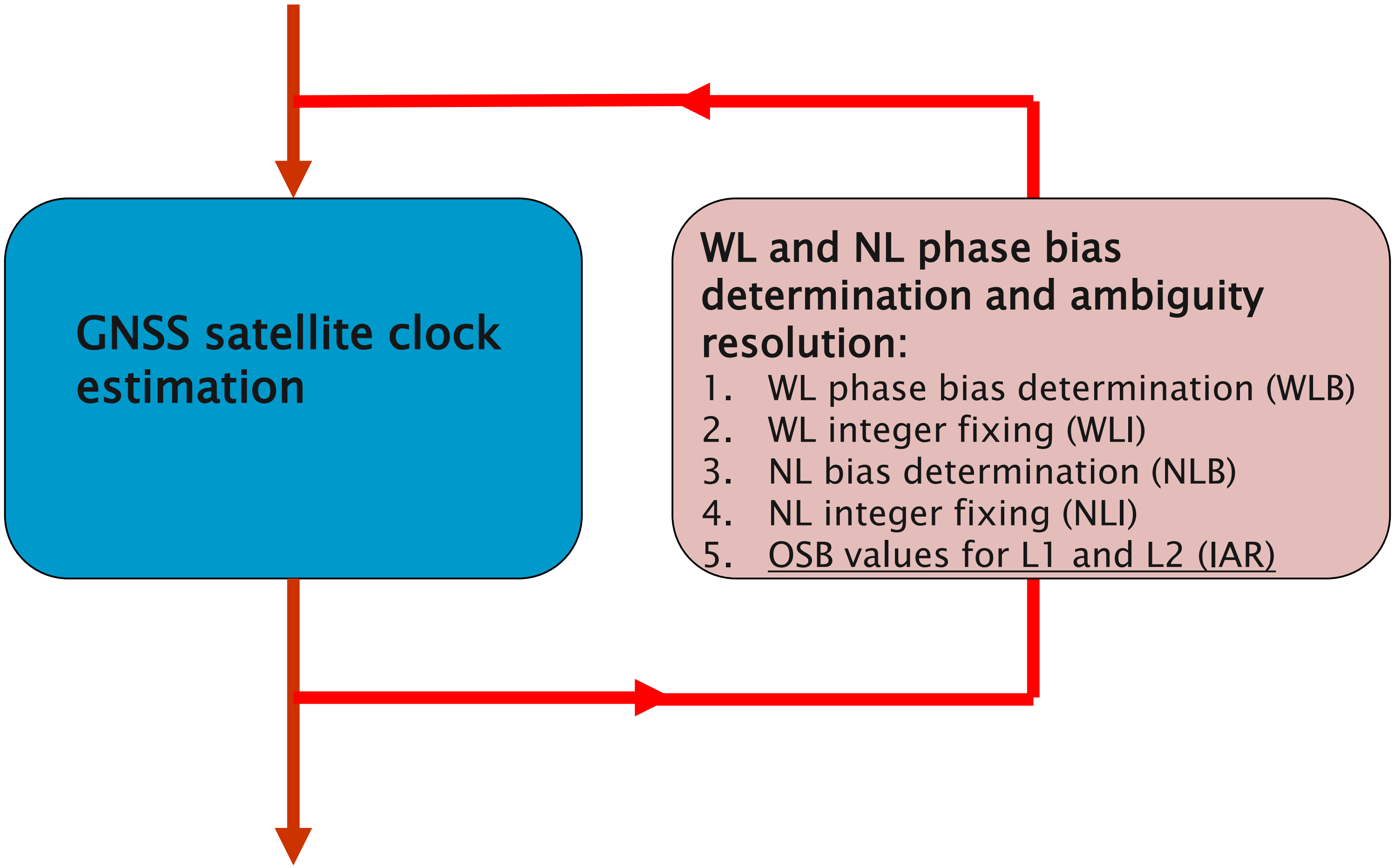
Satellite Geodesy Research Group



Clock products with resolved ambiguities

S. Schaer, A. Villiger, D. Arnold, R. Dach, A. Jäggi, L. Prange: **New ambiguity-fixed IGS clock analysis products at CODE.** Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Procedure for clock estimation with ambiguity resolution

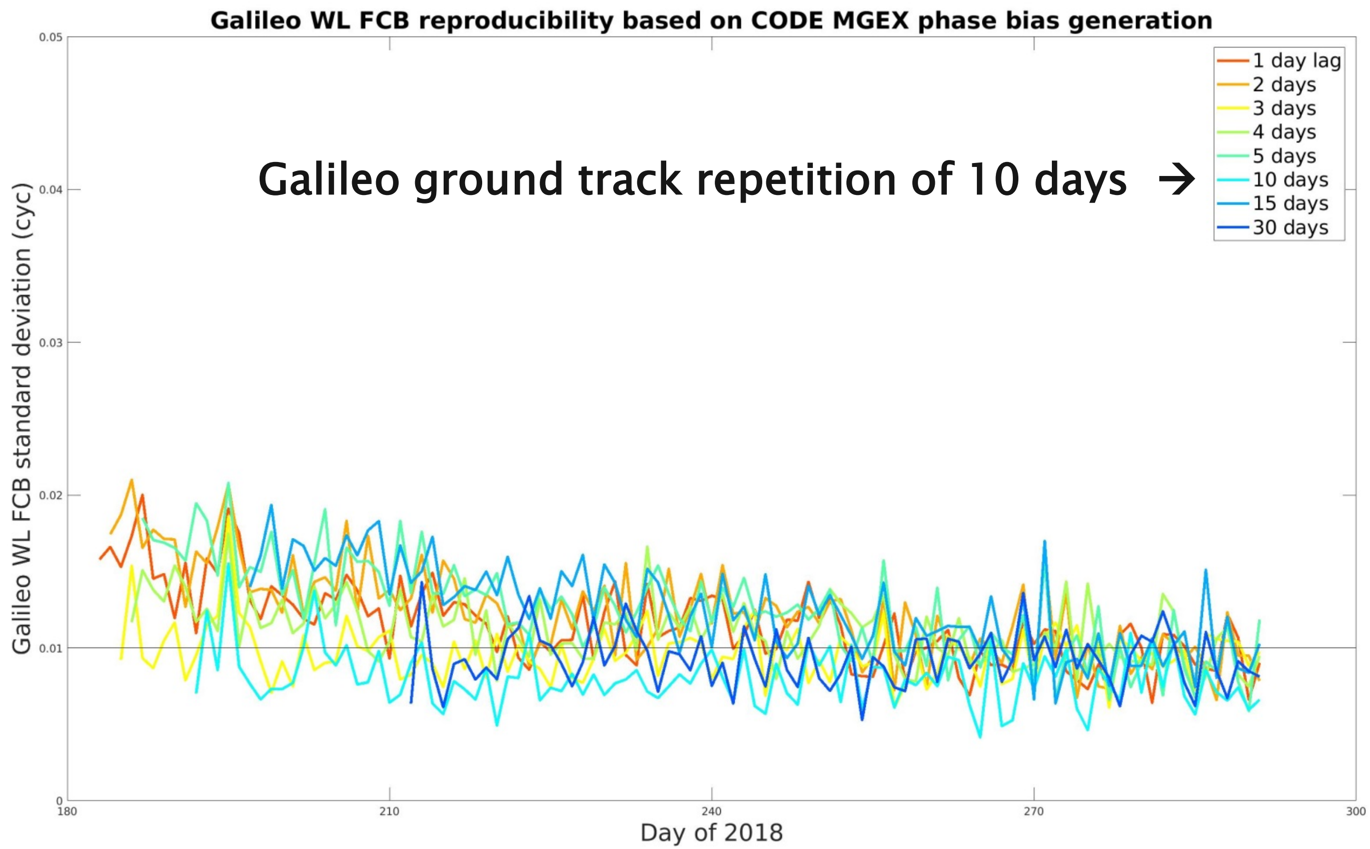


Activated for rapid, final, and MGEX clocks in July 2018

S. Schaer, A. Villiger, D. Arnold, R. Dach, A. Jäggi, L. Prange: **New ambiguity-fixed IGS clock analysis products at CODE.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Galileo satellite widelane fractional bias results

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



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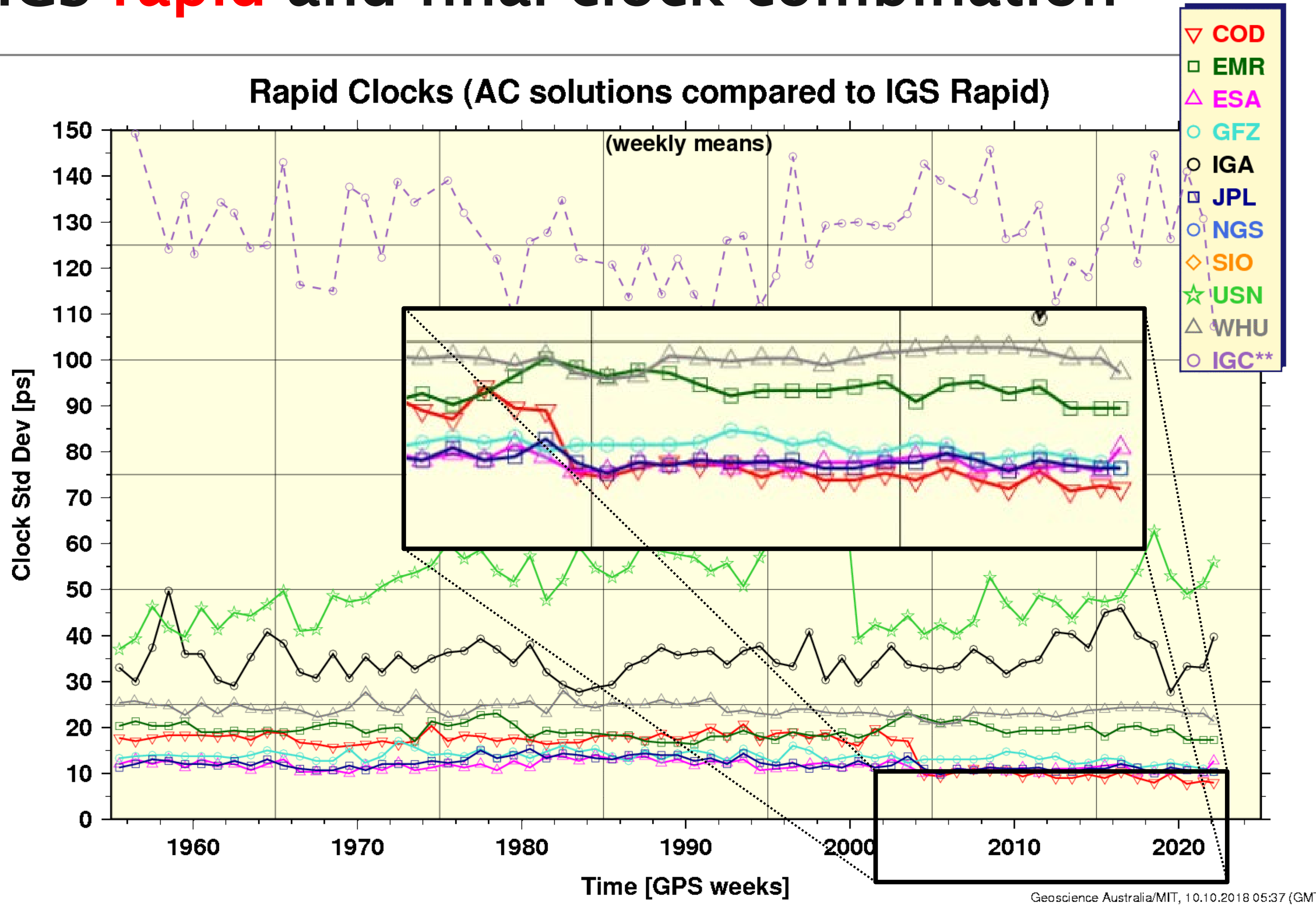
IGS rapid and final clock combination



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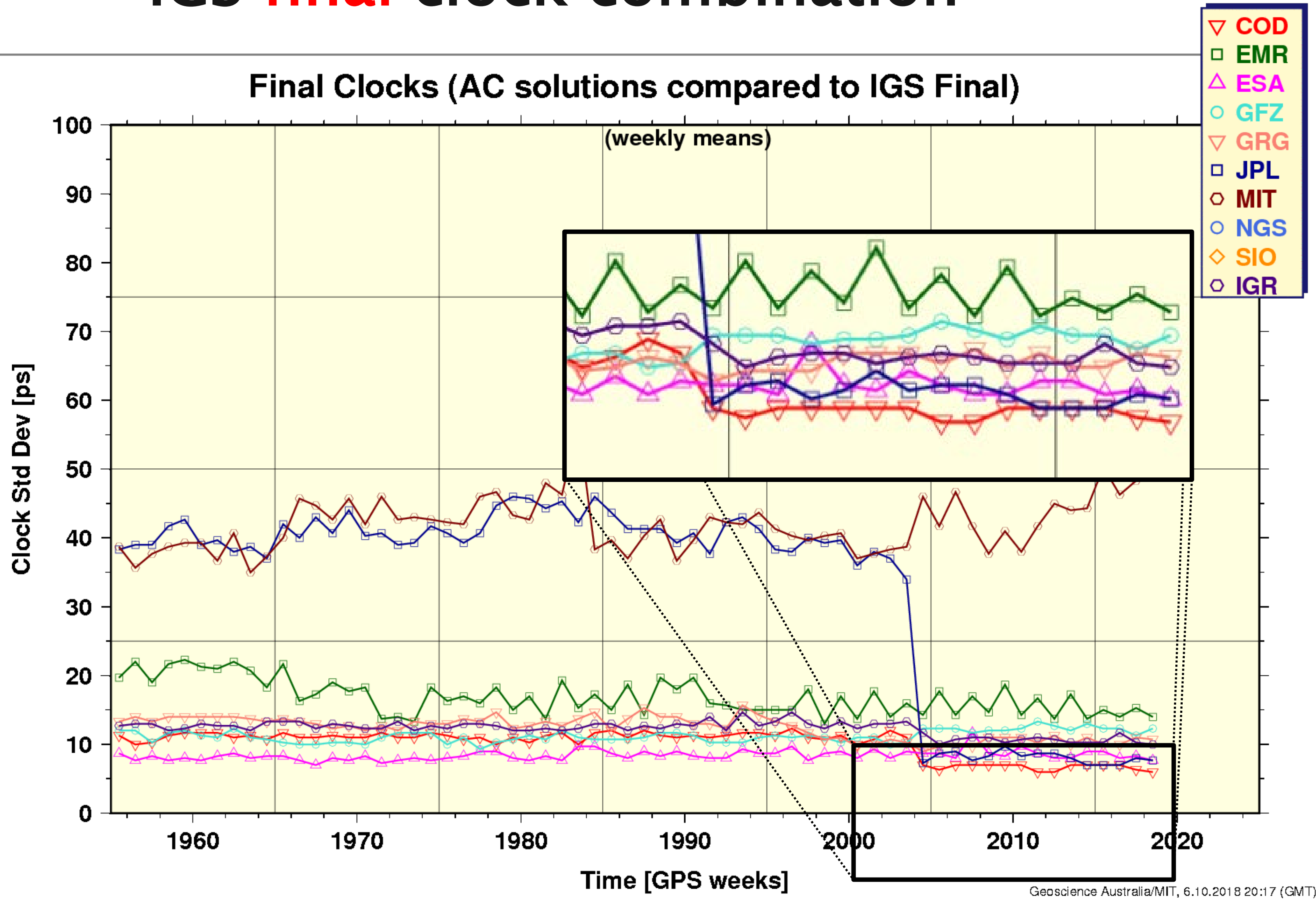
IGS final clock combination



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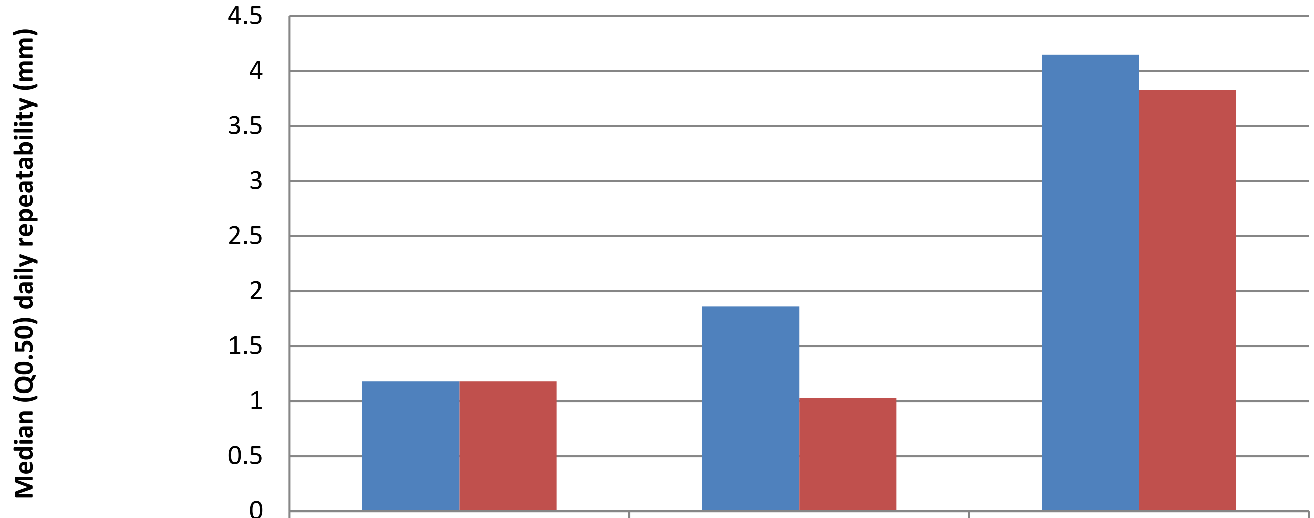
Daily PPP vs. daily IPPP

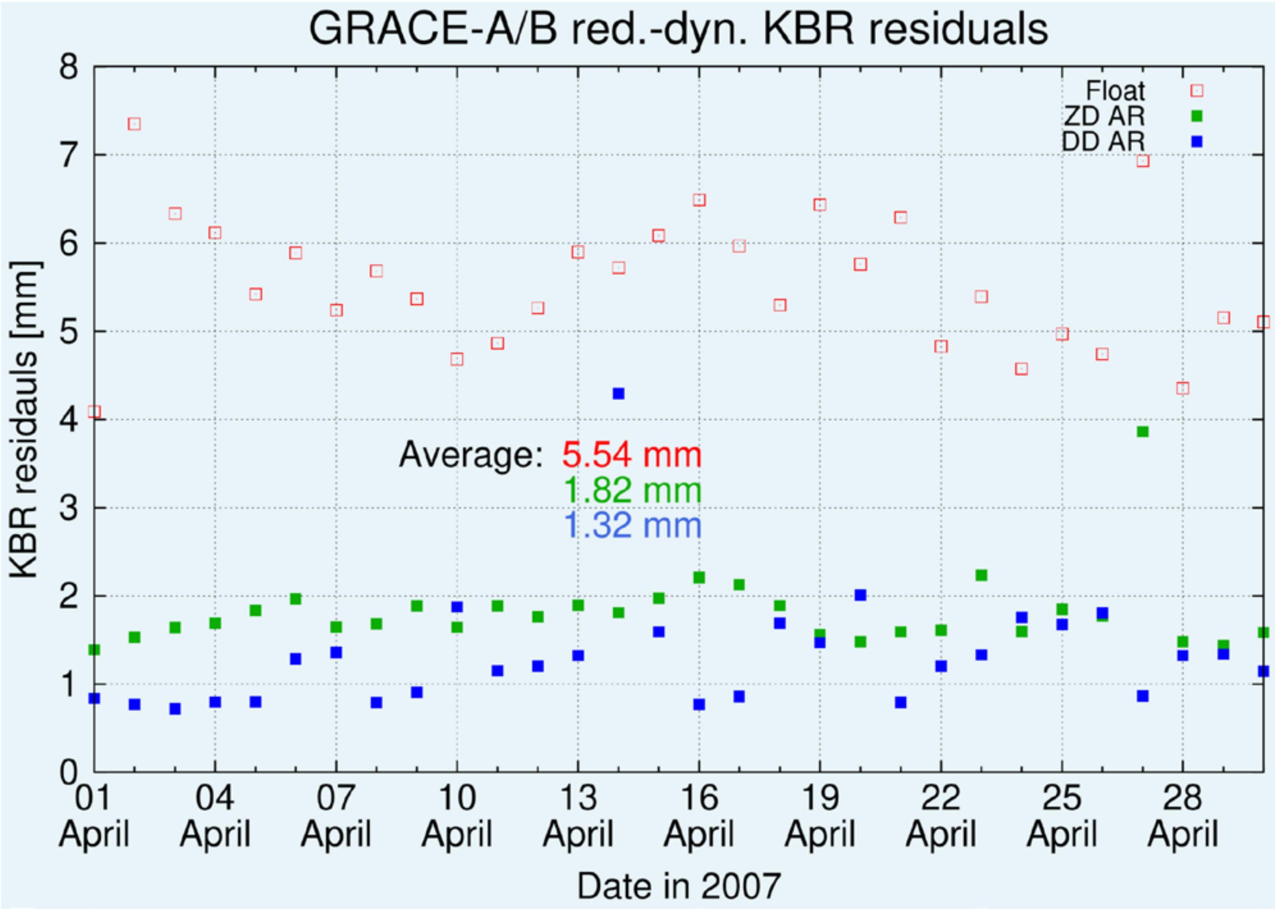
Daily PPP; CODE final product; September 2018; 295 (of 337) stations



	N	E	U
Ambiguity-float PPP	1.18	1.86	4.15
Ambiguity-fixed PPP	1.18	1.03	3.83

S. Schaer, A. Villiger, D. Arnold, R. Dach, A. Jäggi, L. Prange: **New ambiguity-fixed IGS clock analysis products at CODE.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

IPPP for LEO POD



Daily RMS values of K-band residuals.

D. Arnold, S. Schaer, A. Villiger, R. Dach, A. Jäggi: **Undifferenced ambiguity resolution for GPS-based POD of LEO using the new CODE bias and clock product.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

IPPP for LEO POD

	Float		ZD AR	
Orbits	red.-dyn.	kin.	red.-dyn.	kin.
GRACE-A	+0.5/15.5	+1.5/16.6	+2.5/12.4	+2.6/12.0
GRACE-B	+0.9/12.1	-0.5/16.9	+3.8/8.5	+3.7/9.6
Sentinel-3A	-6.0/11.5	-6.5/14.7	-5.7/10.7	-5.4/11.9
Sentinel-3B	-2.9/12.4	-4.3/15.2	-3.5/10.4	-3.3/11.1

Table 1: Mean values and standard deviations in mm of SLR residuals over April 2007 (GRACE) and September 2018 (Sentinel-3), respectively.

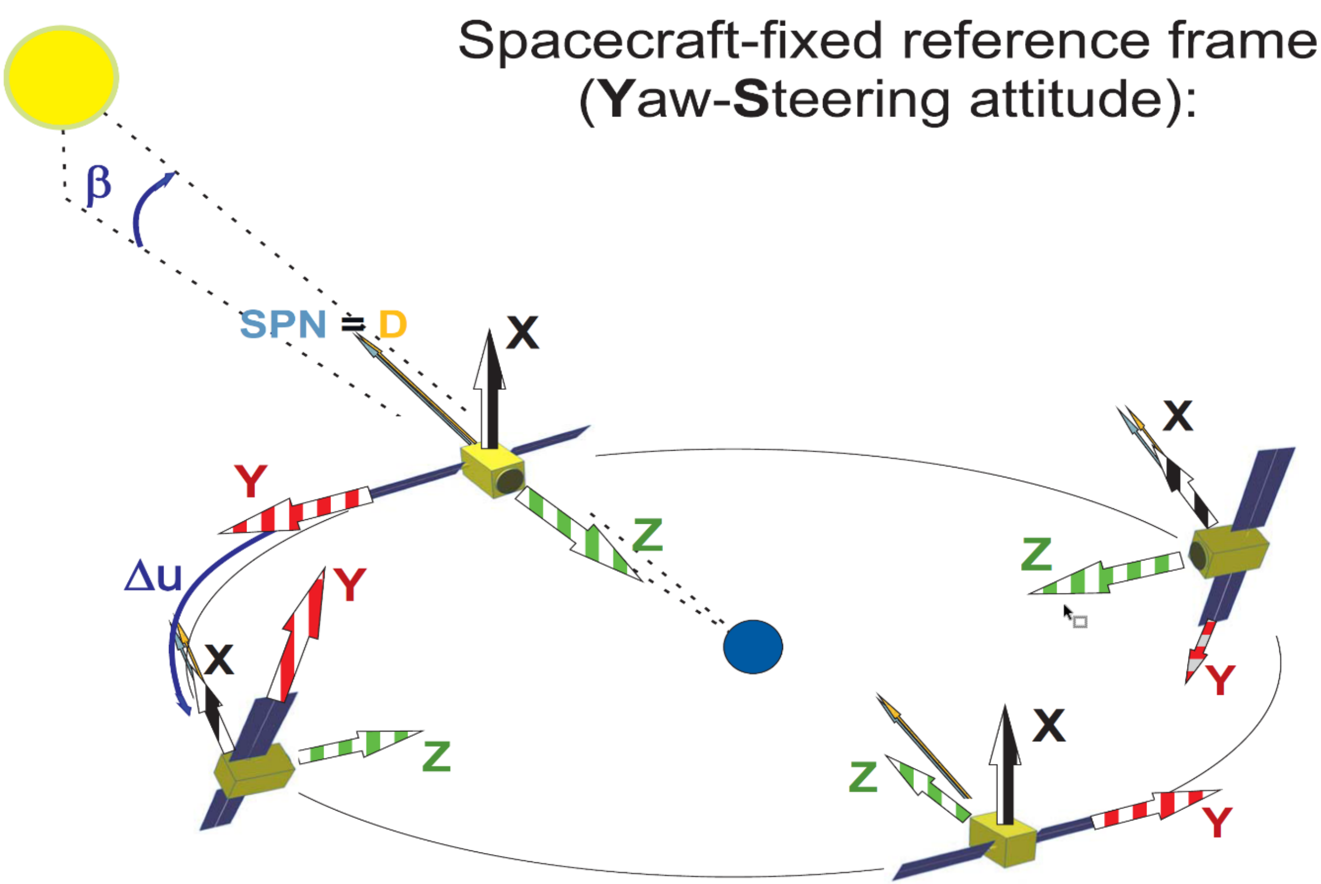
D. Arnold, S. Schaer, A. Villiger, R. Dach, A. Jäggi: **Undifferenced ambiguity resolution for GPS-based POD of LEO using the new CODE bias and clock product.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

CODE contribution to IGS MGEX

Recent Improvements in the CODE MGEX

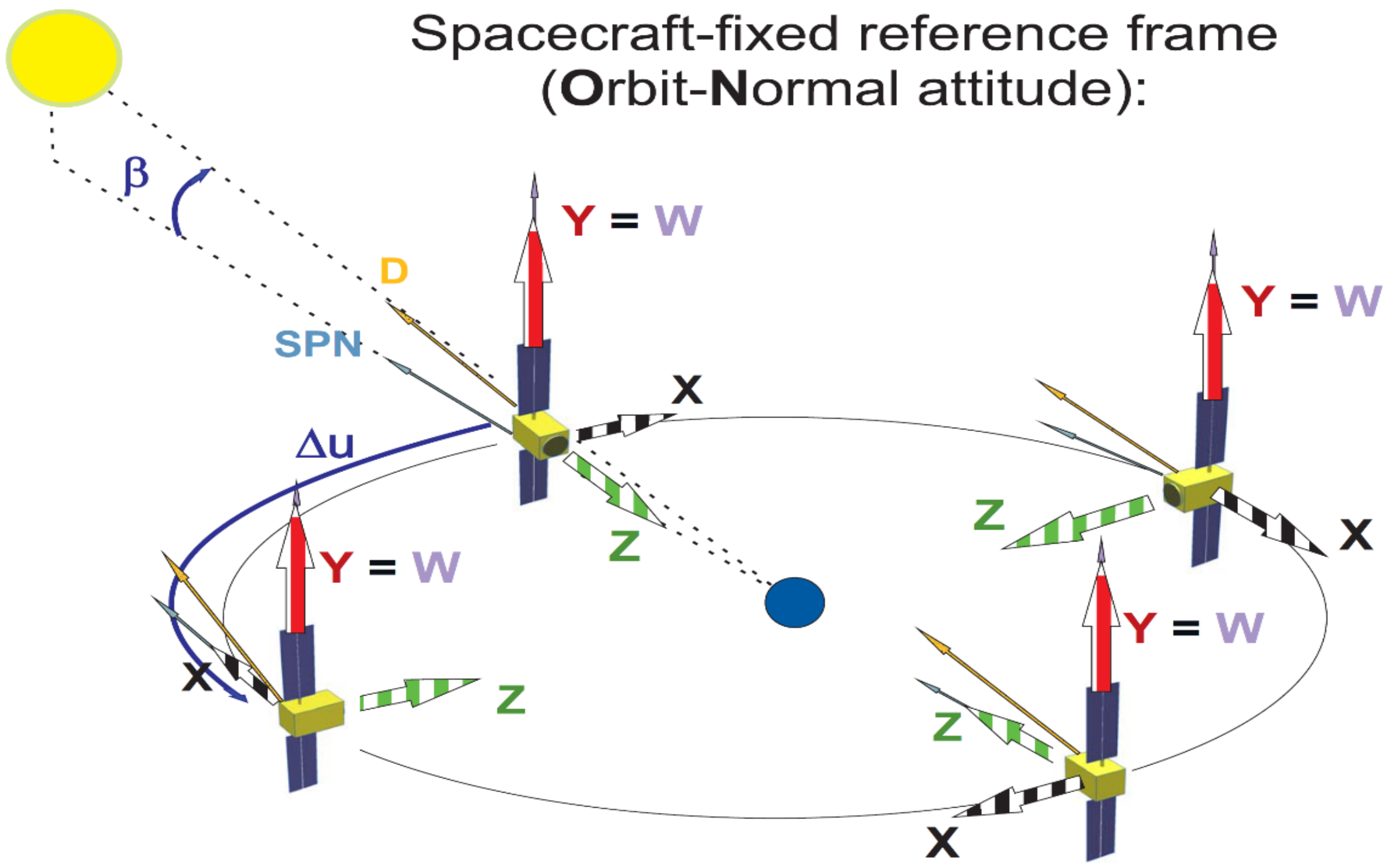
- Improved ambiguity resolution for orbit product, based on CODE's OSB product
- Activation of eclipse attitude law for Galileo
- Albedo and antenna thrust models for Galileo and QZSS
- Higher sampling of orbit (5 min) and clock products (30 s)
- Zero-diff. ambiguity resolution for clock product
- Activation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

Orientation of the spacescraft



L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Orientation of the spacescraft



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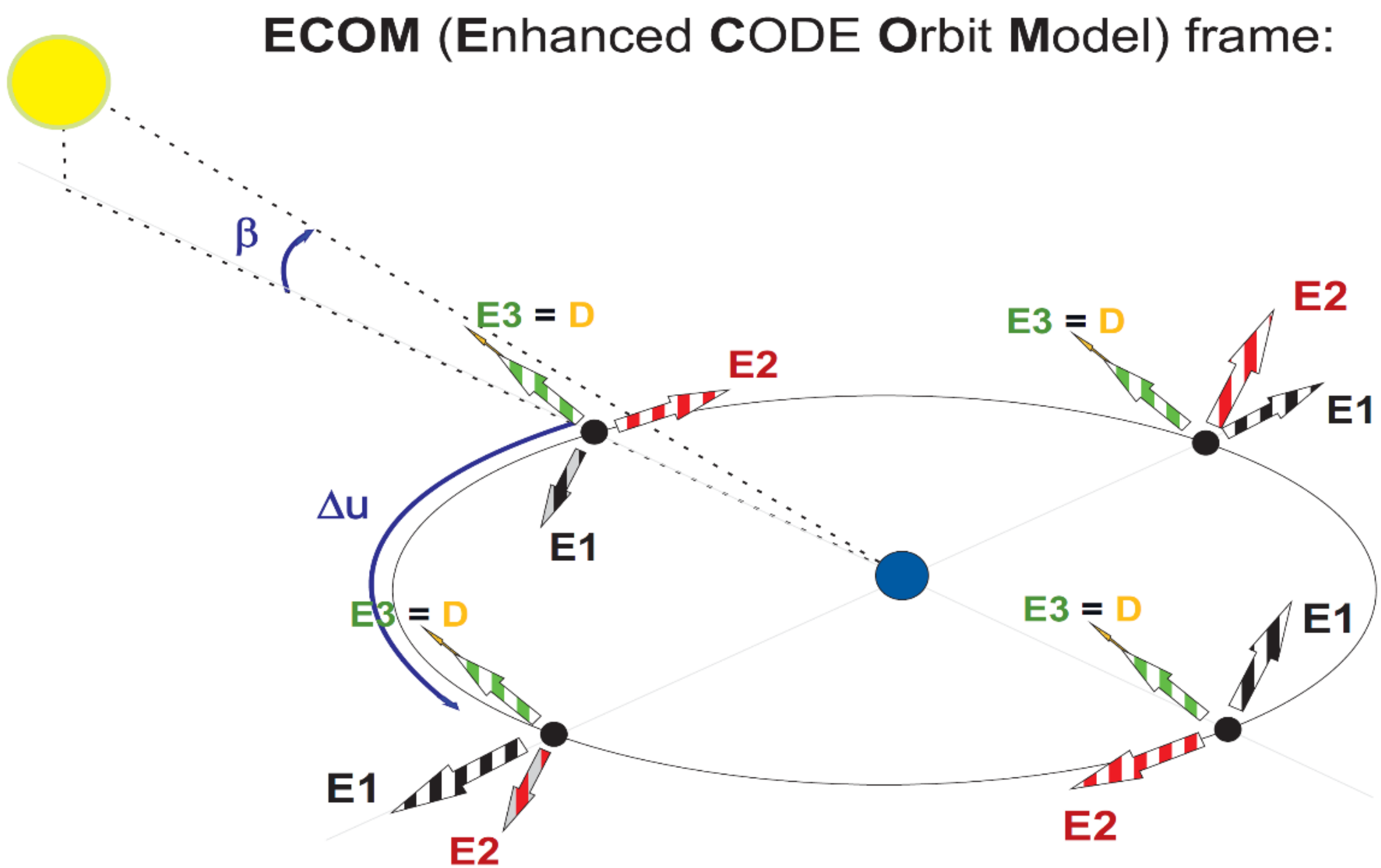
Orientation of the coordinate system



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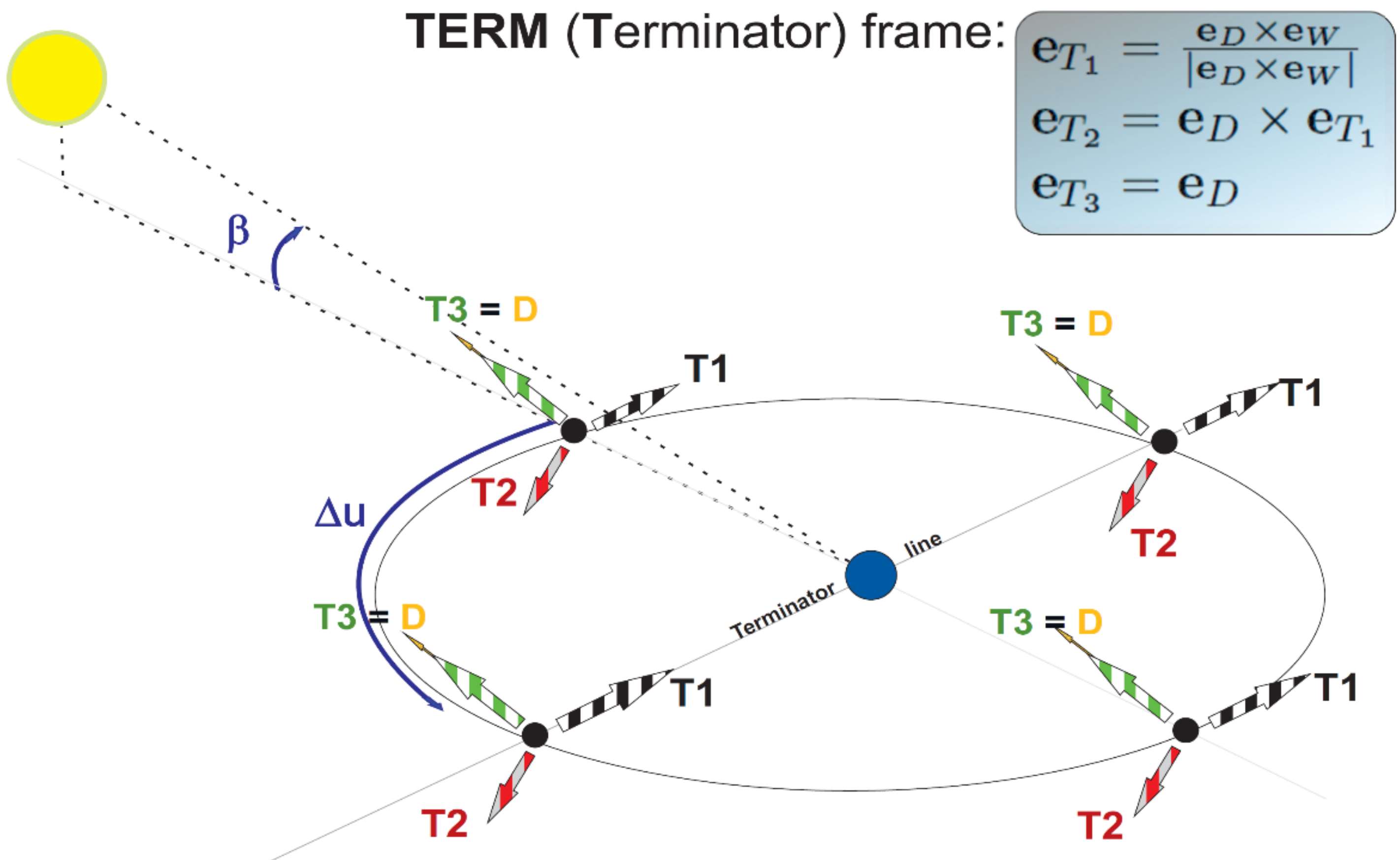

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ECOM updated for orbit normal mode

RMS from SLR residuals (IQR):

	BDS2-MEO	BDS2-IGSO	QZSS-1
Old model	20.5 cm	21.0 cm	62.0 cm
New model	12.2 cm	12.2 cm	15.2 cm
Improvement	40.5 %	41.9%	75.5%

Median of a linear fit of the satellite clock corrections:

	BDS2-MEO	BDS2-IGSO	QZSS-1
Old model	1.72 ns	1.61 ns	1.43 ns
New model	0.72 ns	0.69 ns	0.35 ns
Improvement	58.1%	57.1%	75.5%

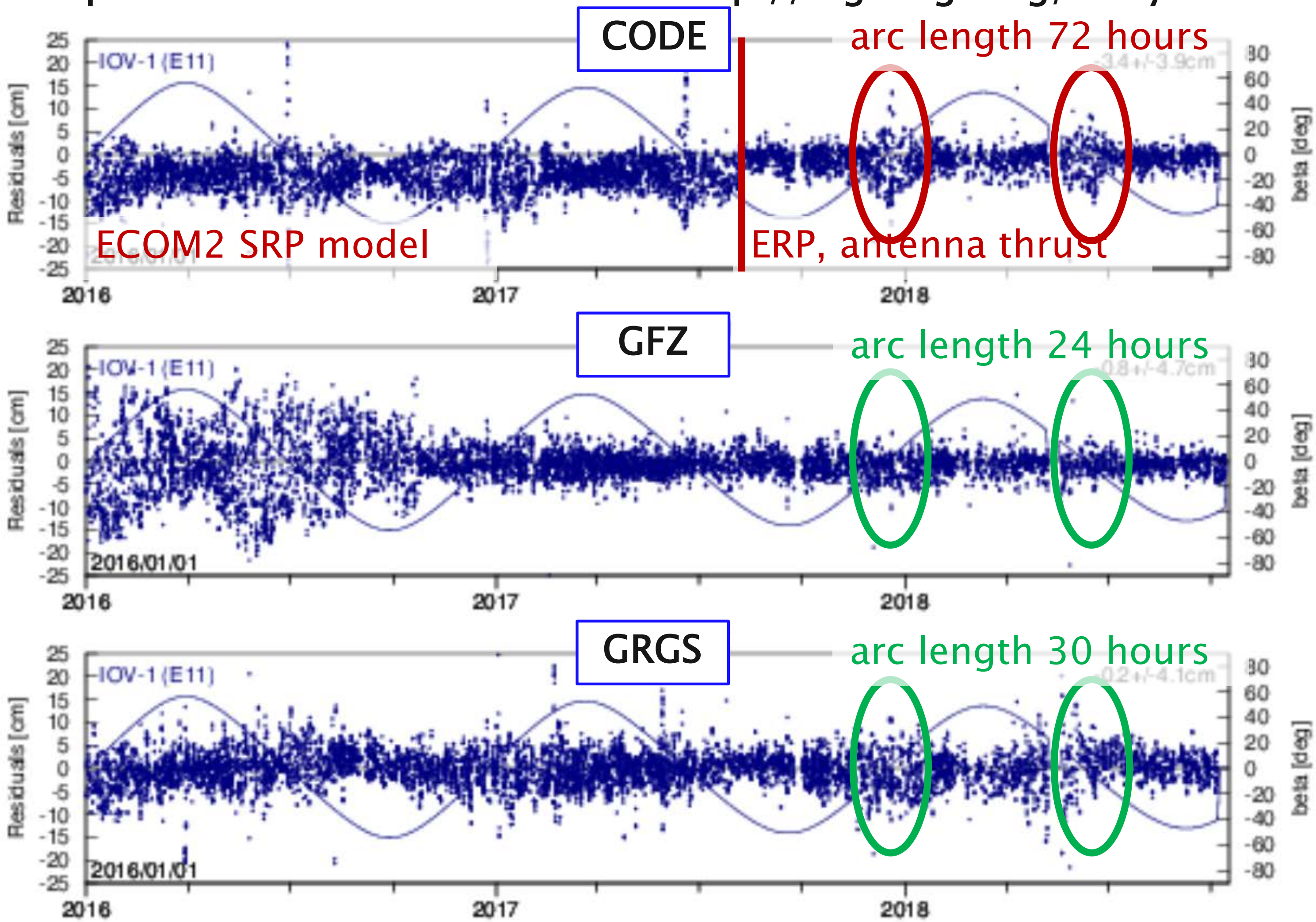
L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Orbit modelling during eclipse

D. Sidorov, R. Dach, L. Prange, A. Jäggi: **Improved orbit modelling of Galileo satellites during eclipse seasons.**
Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

SLR residuals for SVN 101

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

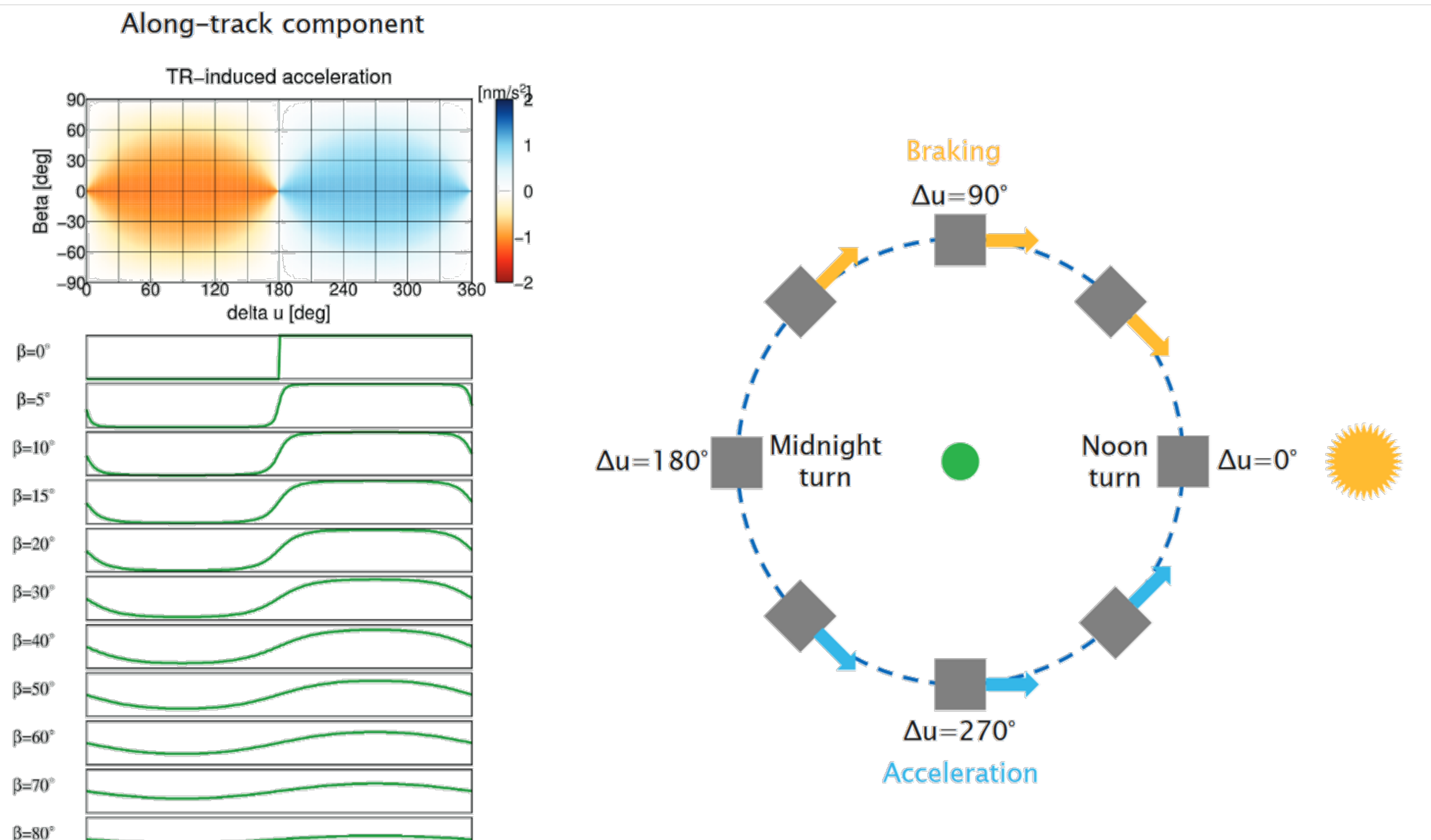


Consequences of the satellite design

- 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.

D. Sidorov, R. Dach, L. Prange, A. Jäggi: **Improved orbit modelling of Galileo satellites during eclipse seasons.** Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Expected effect of the +X radiator



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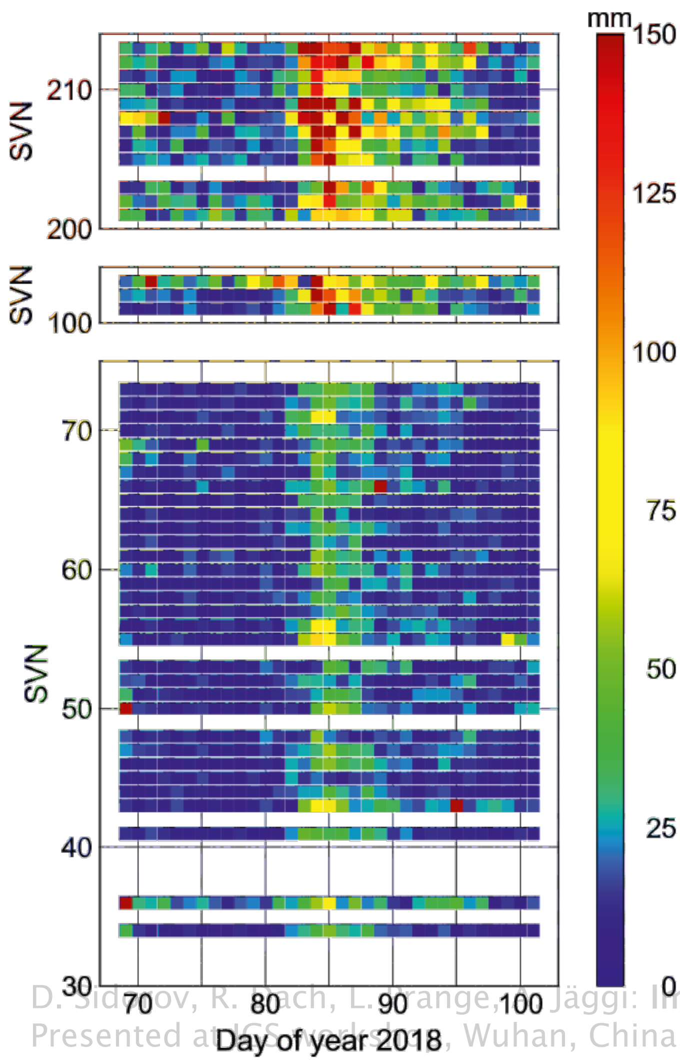
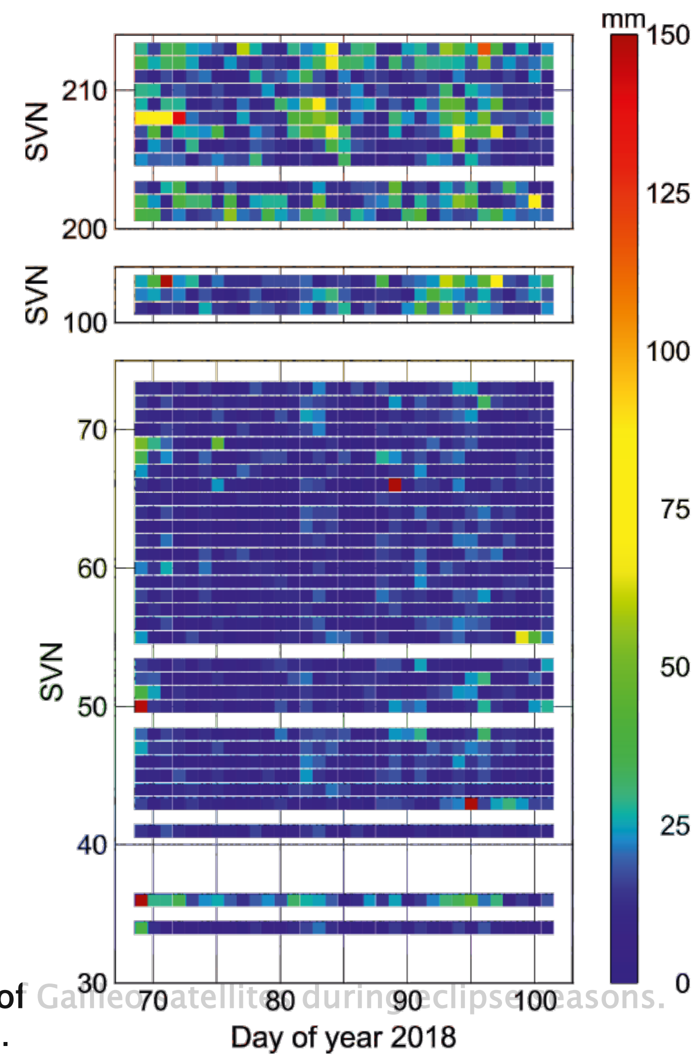
Orbit misclosures at midnight





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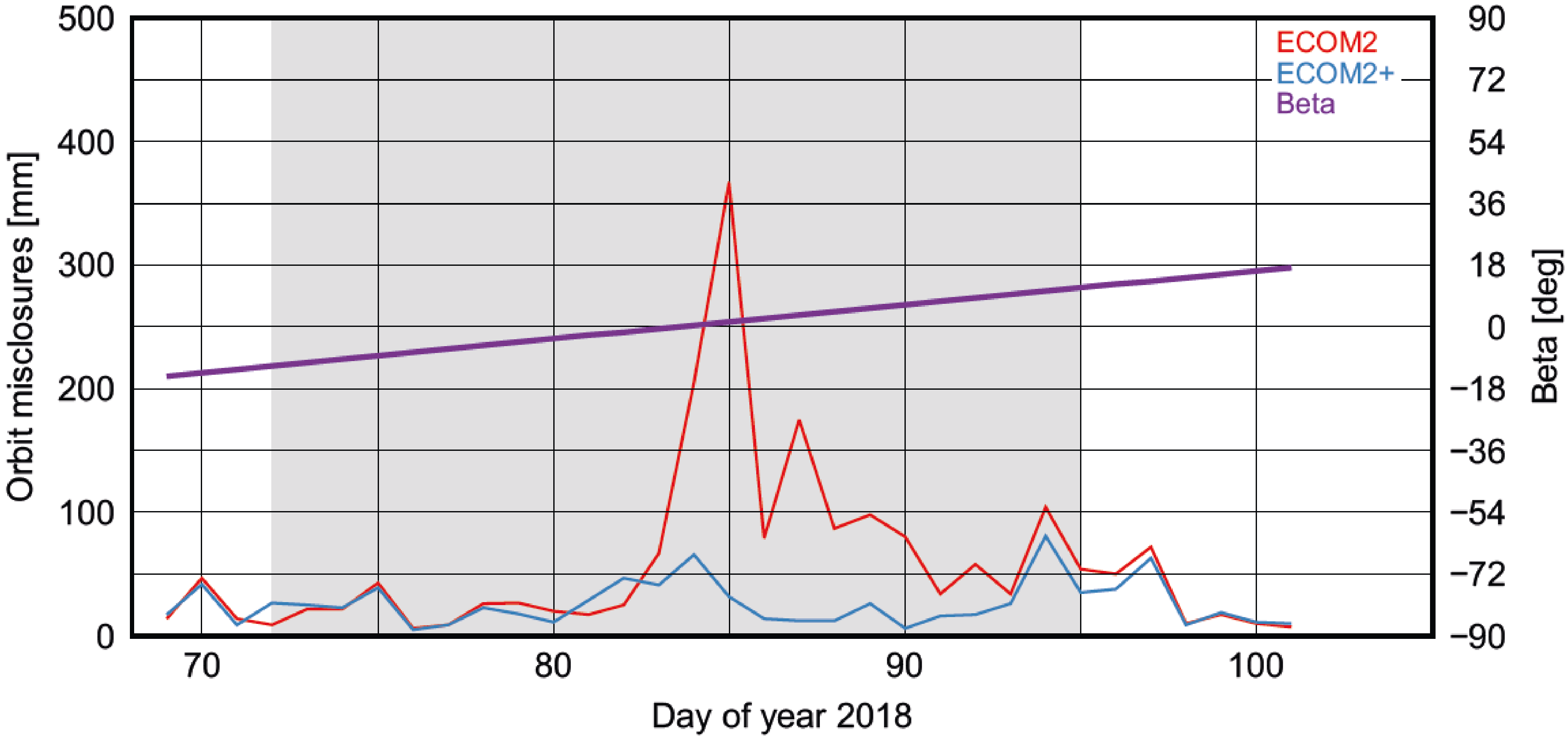
Example: IOV satellite E11



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Scaling factors for box-wing models

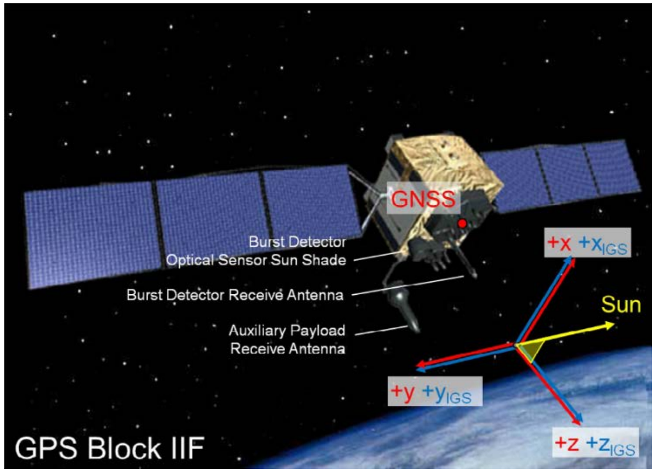
L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.**
Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

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.



[Montenbruck et al, 2015. Adv. In Space Research]

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

Plate	Mod	Area (A) [m²]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
2	1	5.720	[−1, 0, 0]	0.112	0.448		−X
3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
4	1	7.010	[0, −1, 0]	0.112	0.448		−Y
5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
6	1	5.400	[0, 0, −1]	0.000	0.000		−Z
7	0	22.250	[+1, 0, 0]	0.195	0.035	+SUN: [0,+1, 0]	Solar panels front
8	0	22.250	[−1, 0, 0]	0.196	0.034	−SUN: [0,+1, 0]	Solar panels back

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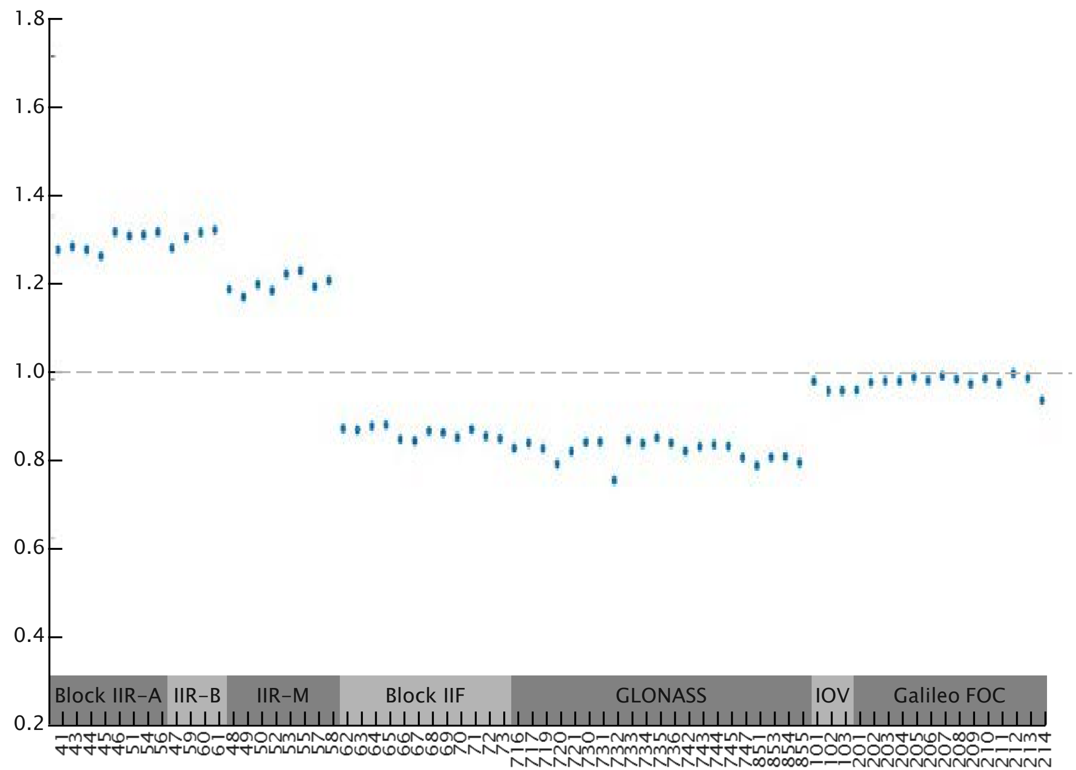
Yearly Scale Factors: Monoscale



Monoscale:
(one factor per satellite)

The scale factors show clearly the different types of satellites.

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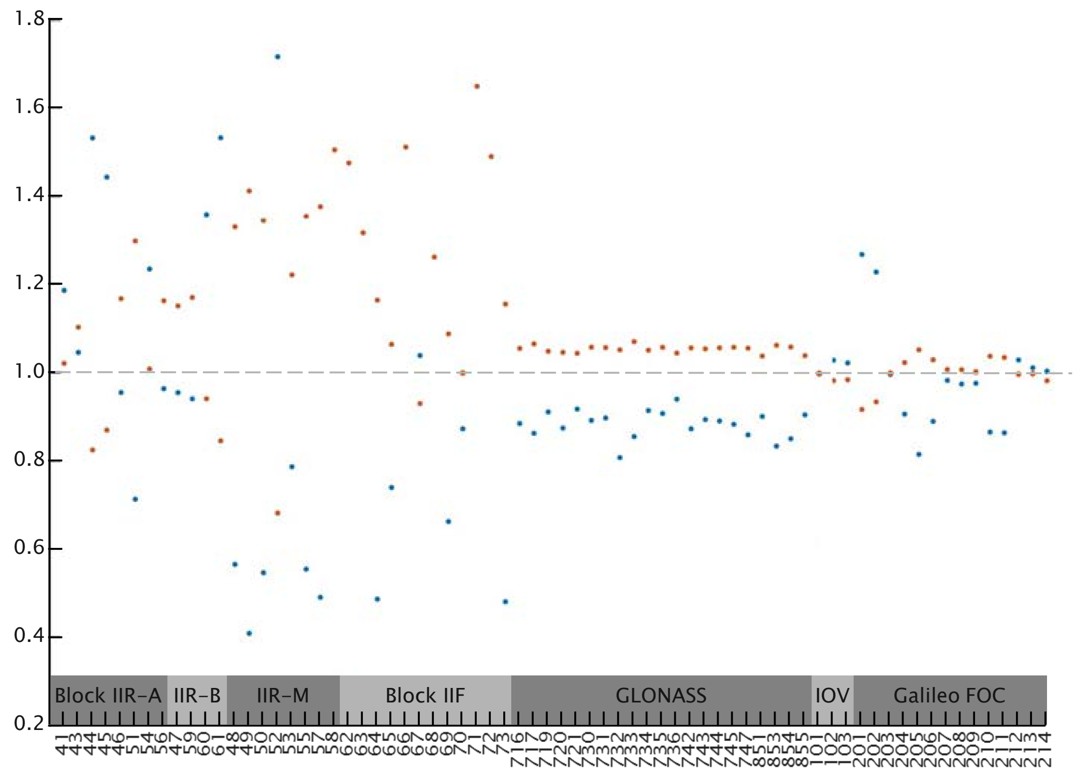
Yearly Scale Factors: Smartscale-2



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.

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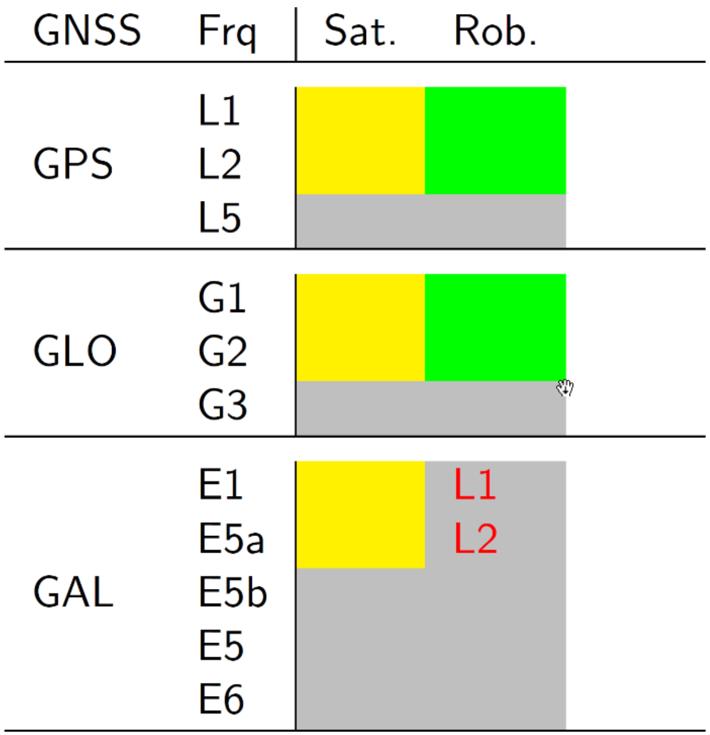
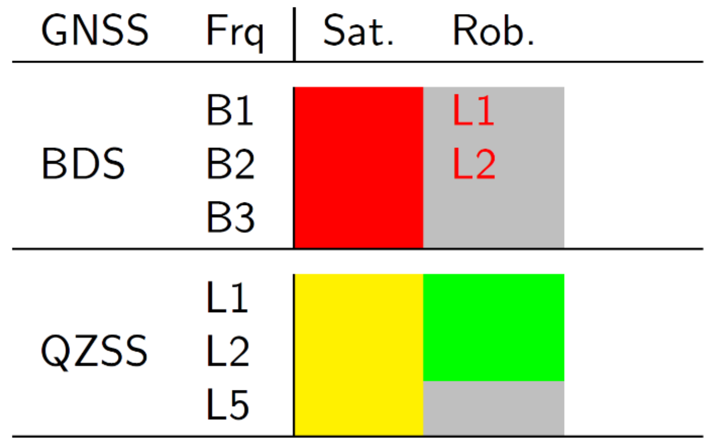
Deficiencies in the Receiver Antenna Calibration in an multi-GNSS environment

A. Villiger, L. Prange, R. Dach, F. Zimmermann, H. Kuhlmann, A. Jäggi: **Consistency of antenna products in the MGEX environment.** Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

IGS antenna pattern

Before Galileo and QZSS disclosed the satellite antenna corrections





unknown | estimated | calibrated | guess

Rob. : roboter calibrations

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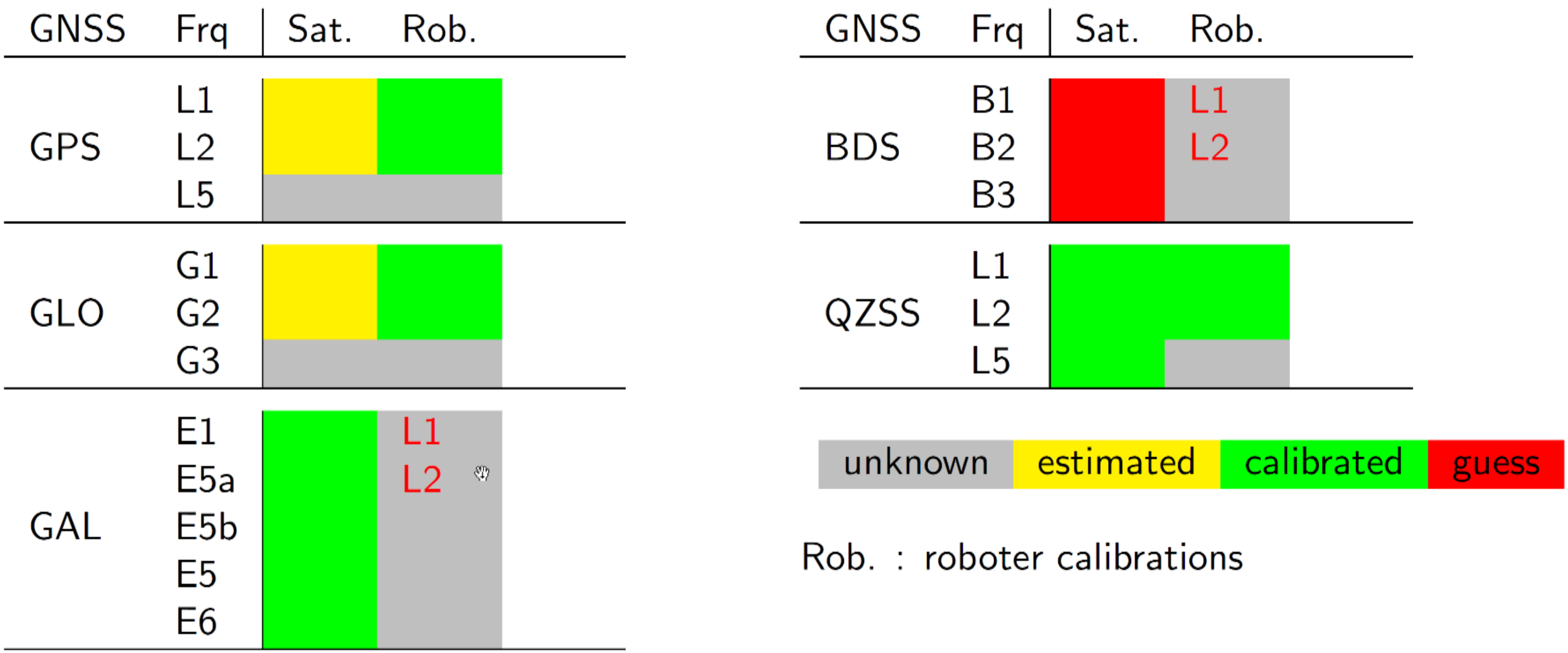

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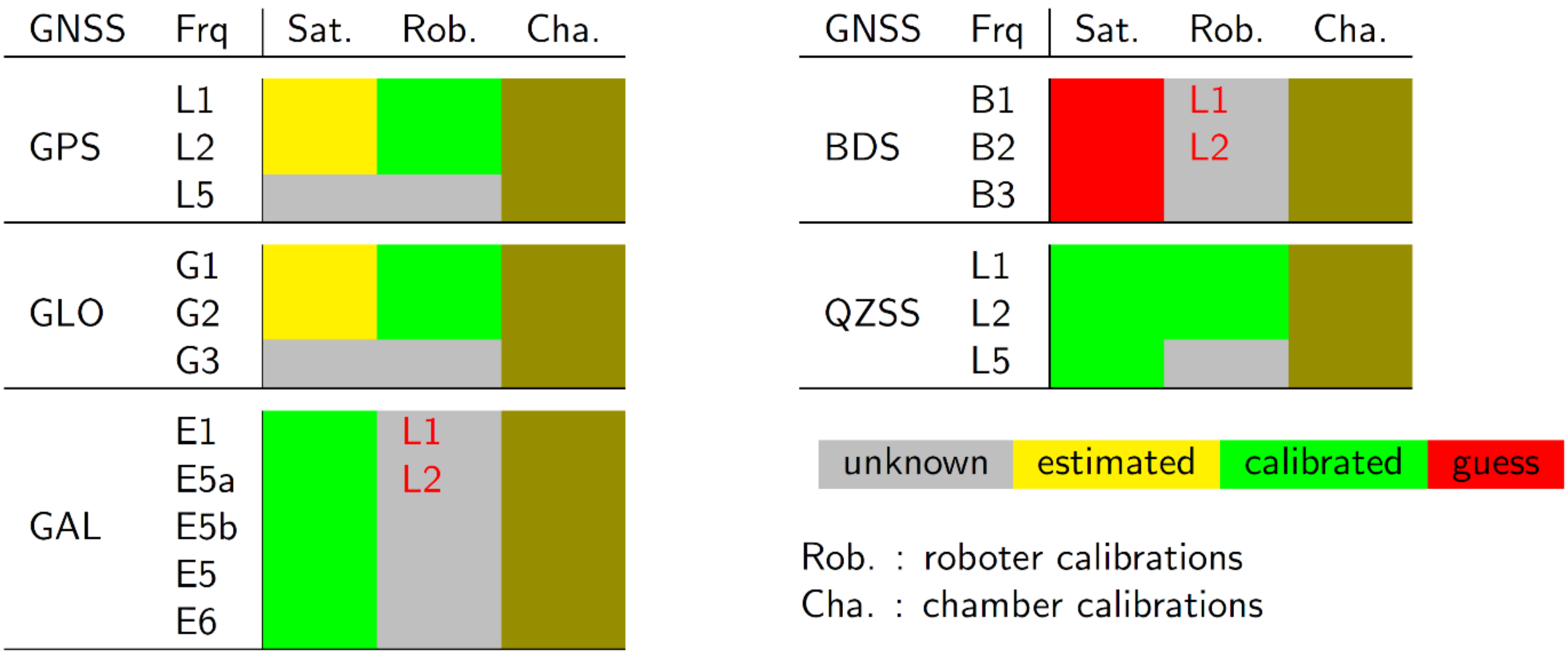

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Collection of chamber calibrations

- 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

A. Vill[illegible]ger [illegible] [illegible]lmann, A. Jäggi: **Consistency of antenna products in the MGEX environment.** Presented at IG[illegible] workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

ESA project related to GNSS activities

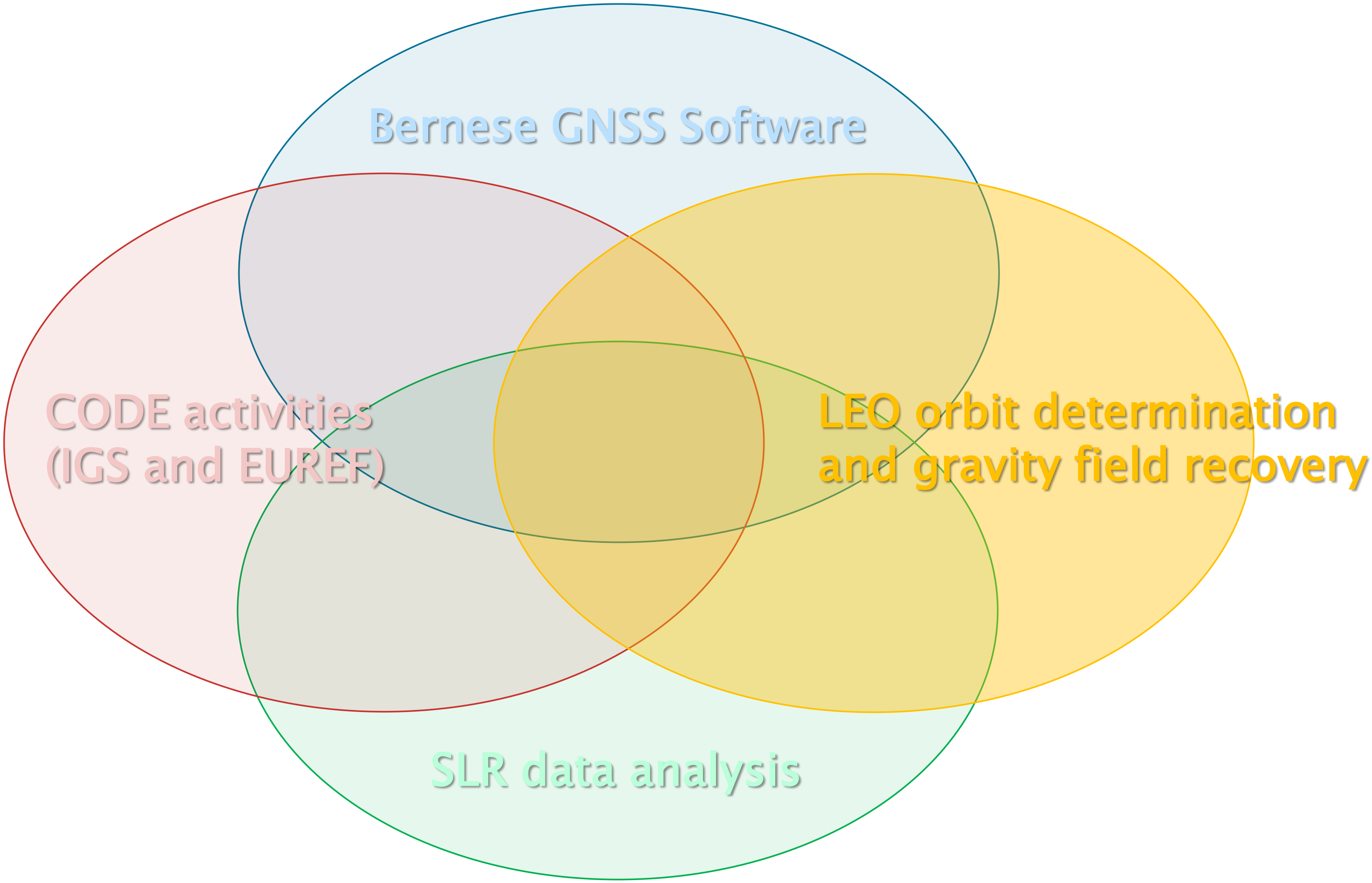
Other projects:

- **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)

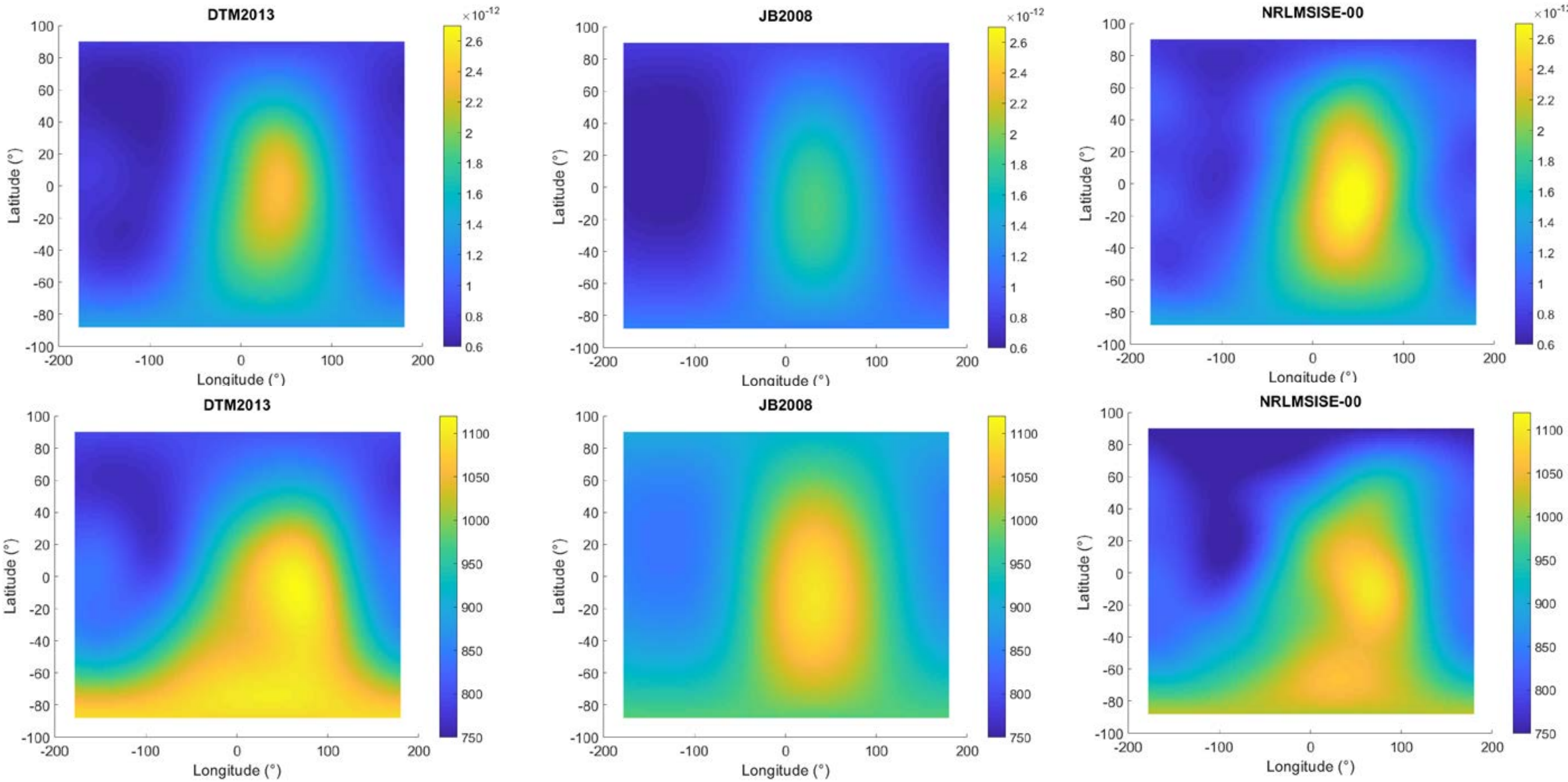
Satellite Geodesy Research Group



Atmospheric density models in LEO non-gravitational force modeling

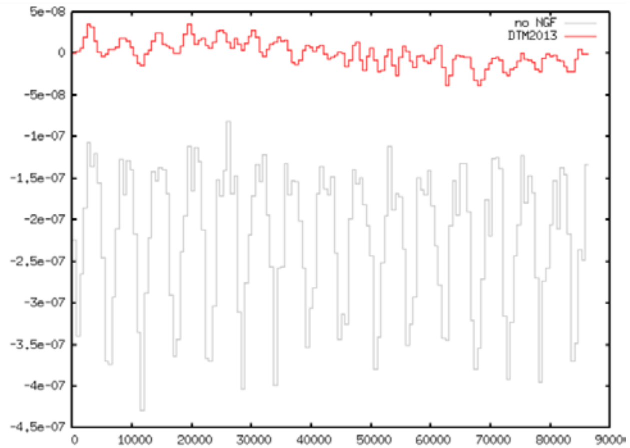
Thermospheric models

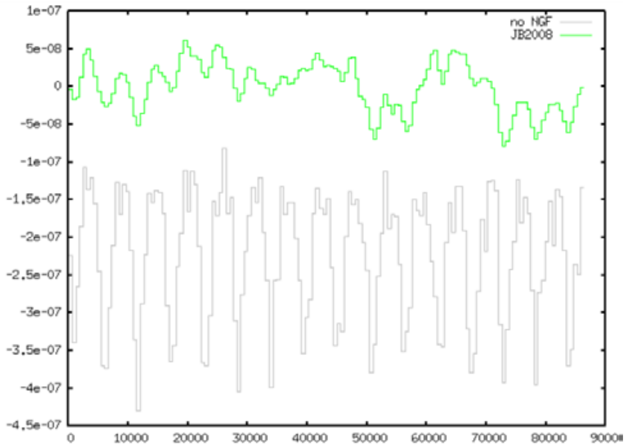
Atmospheric densities (top, kg/m^3) and temperatures (bottom, K) provided by three different models at an altitude of 425 km (GRACE):

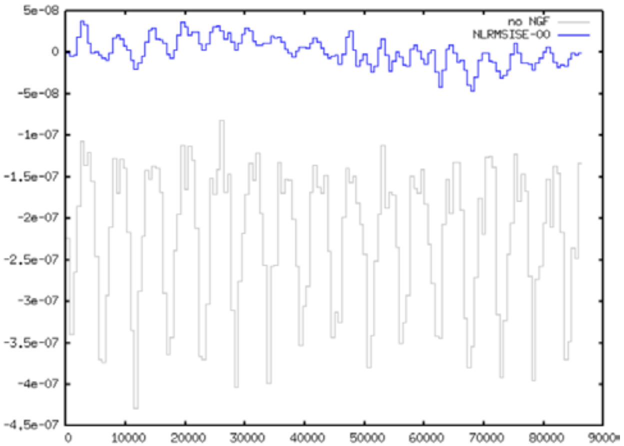


Piecewise-constant accelerations

Estimated along-track 10-min piecewise-constant accelerations (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:



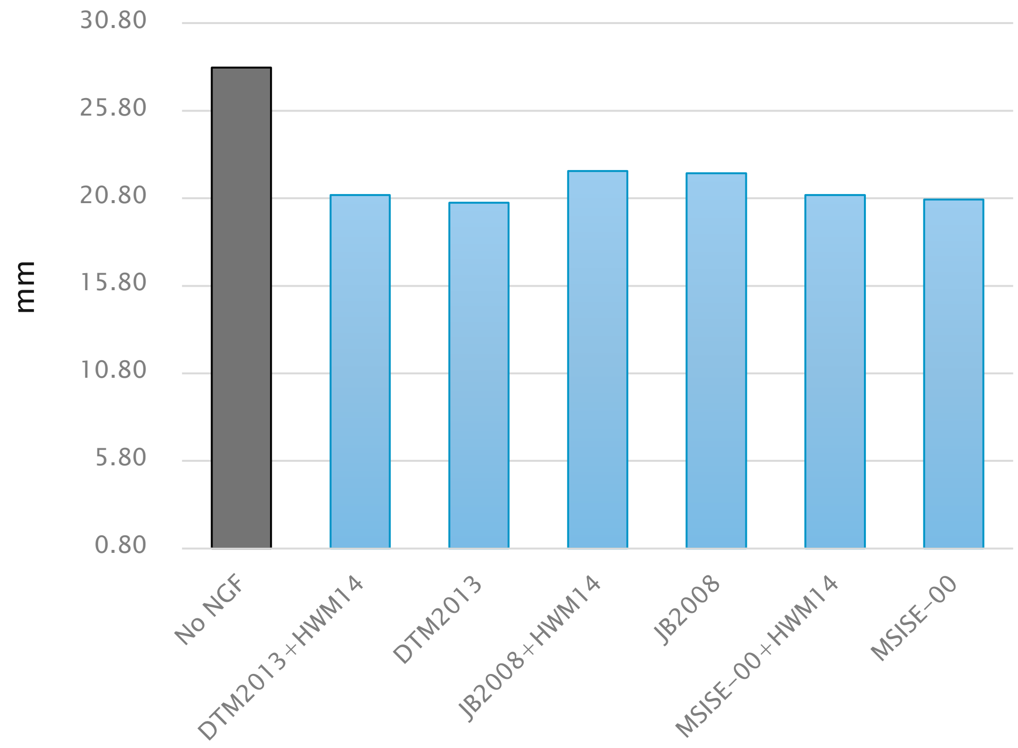




s since midnight

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

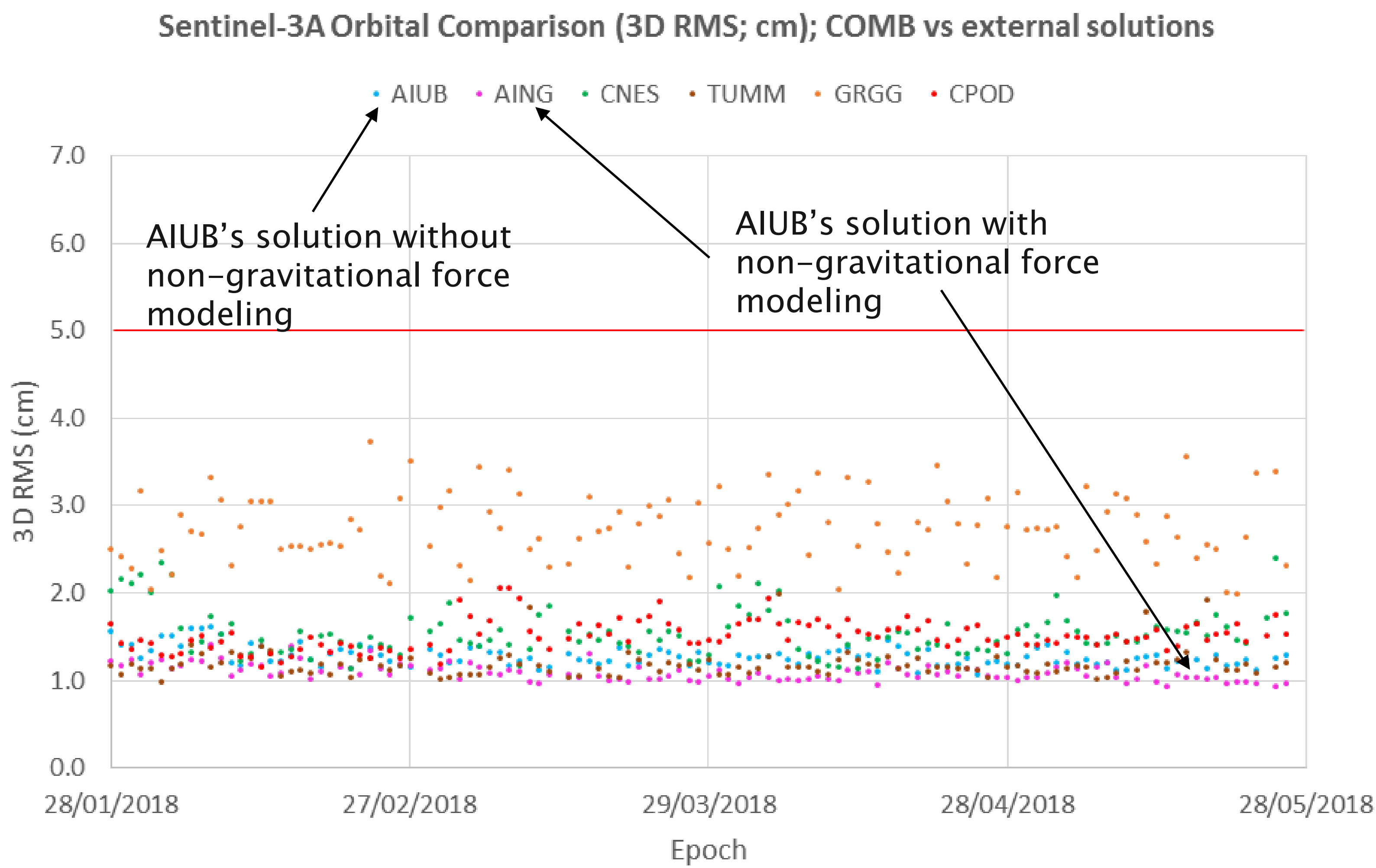
Sentinel-2A
Sentinel-2B

Sentinel-3A
Sentinel-3B

Copernicus
Europe's eyes on Earth

Courtesy: ESA

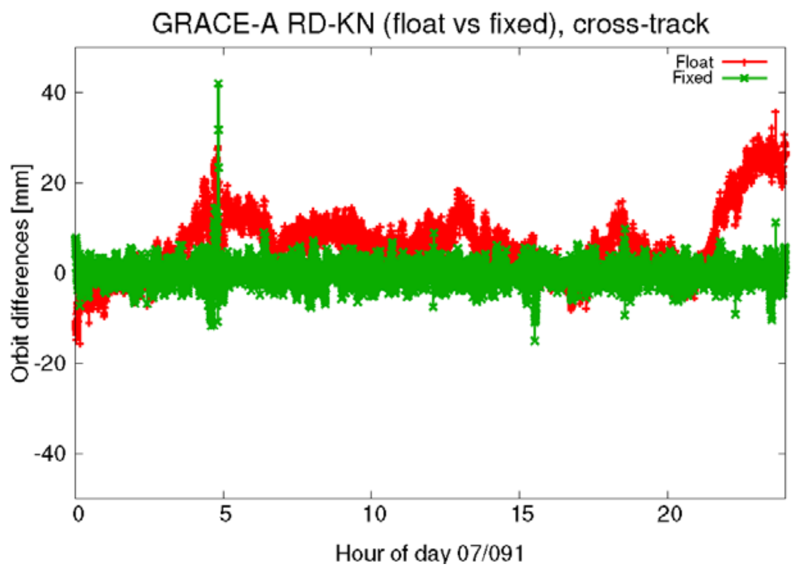
Sentinel-3A orbit comparisons

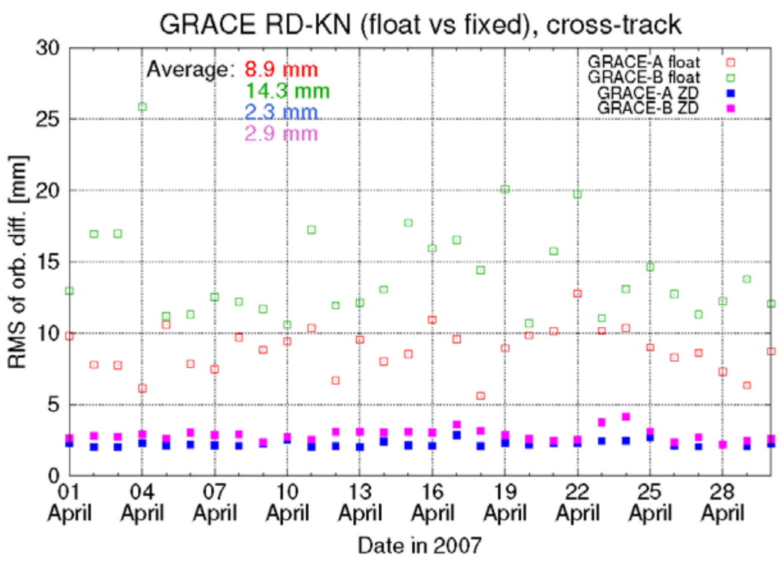


Zero-difference ambiguity resolution in LEO POD

Internal orbit consistency

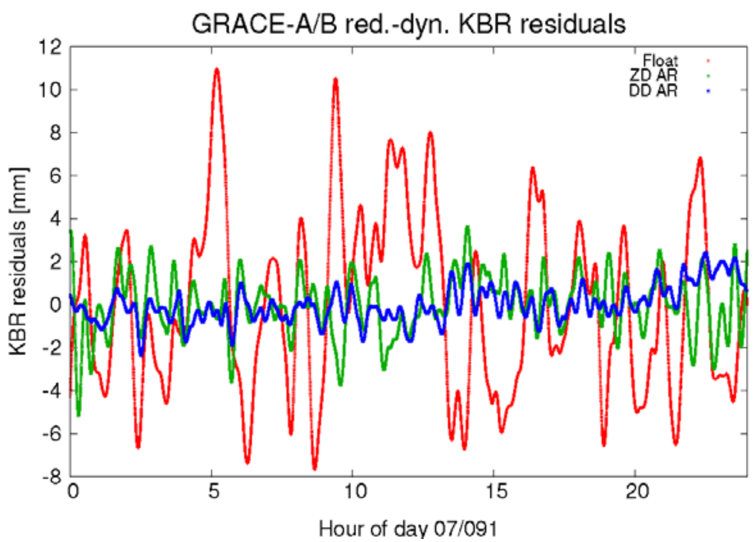
Based on CODE's new phase bias and clock product, zero-difference ambiguities can be resolved in LEO POD. This significantly improves the consistency between reduced-dynamic and kinematic orbit…

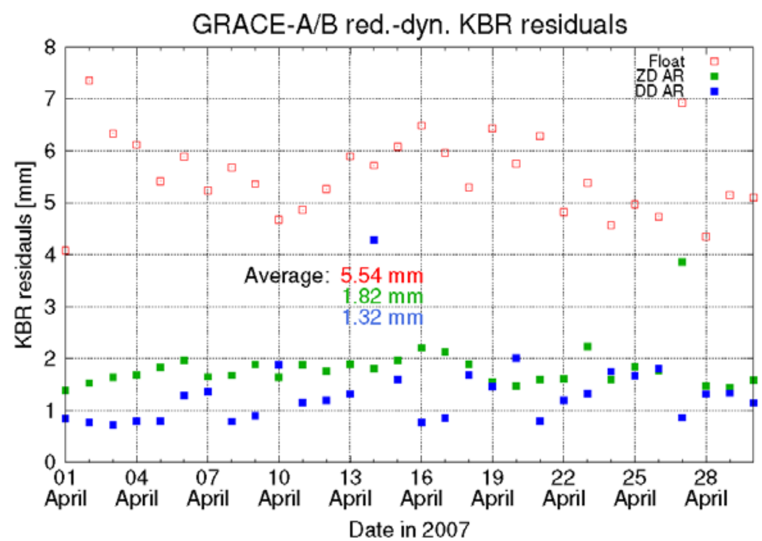




K-band validation

… and the K-band residuals (GRACE)



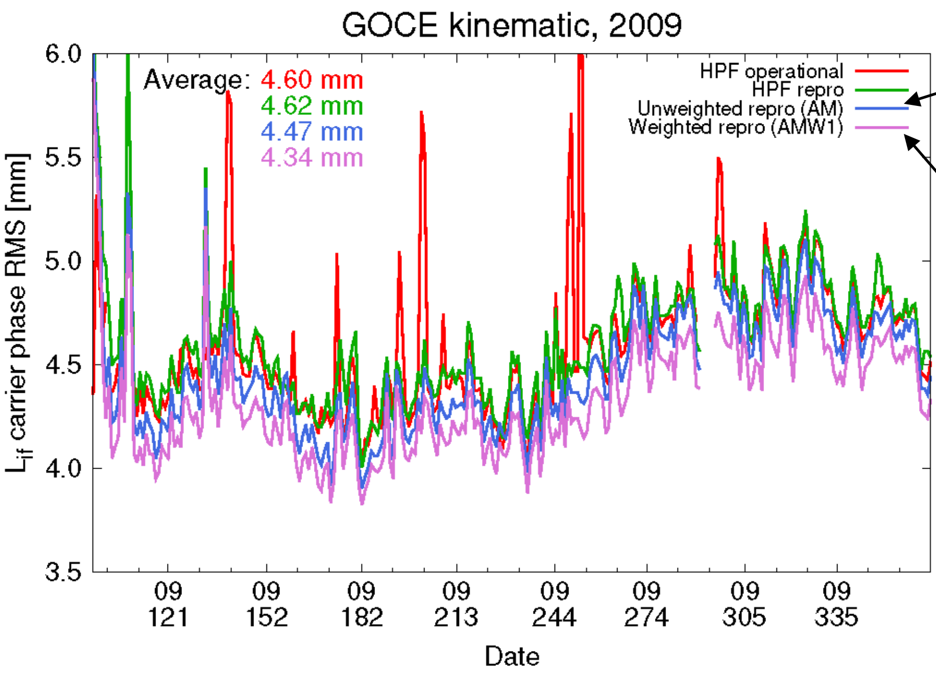


K-band residuals are comparable to what is obtained in a double-difference baseline processing with ambiguity resolution.

GOCE PSO Reprocessing

GOCE PSO reprocessing – Orbits

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)

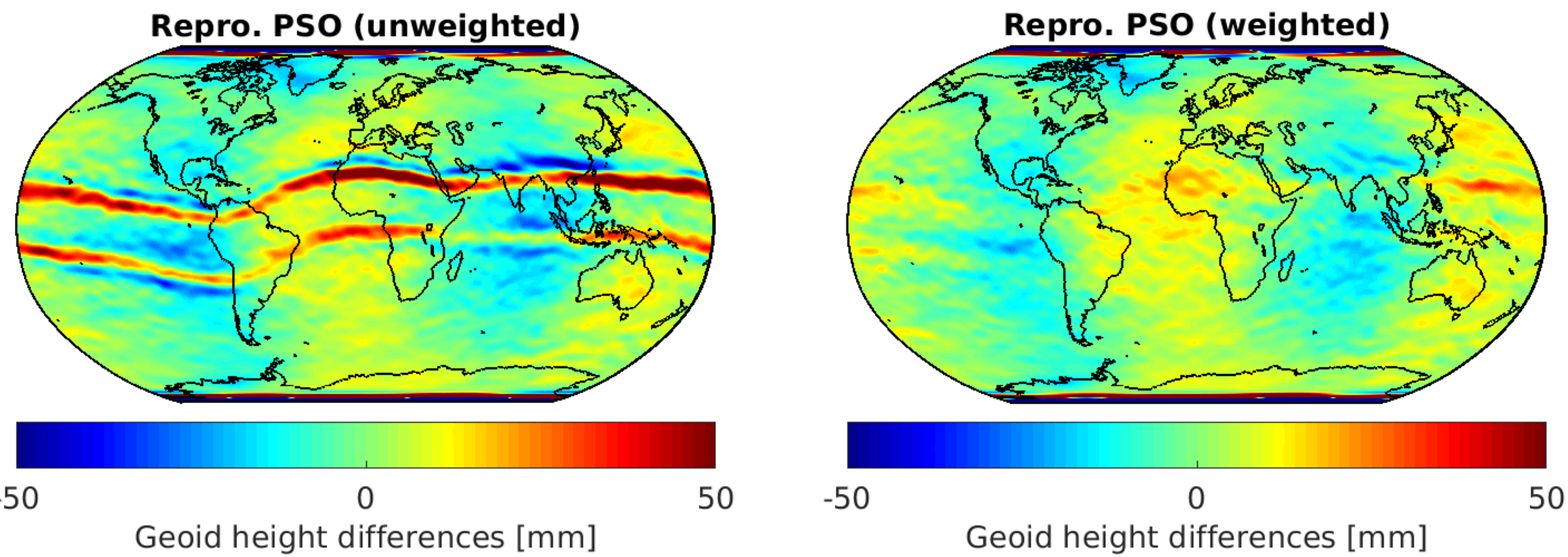


New PSOs, based on latest version of Bernese GNSS Software and homogeneous GNSS products from EGSIEM repro

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:

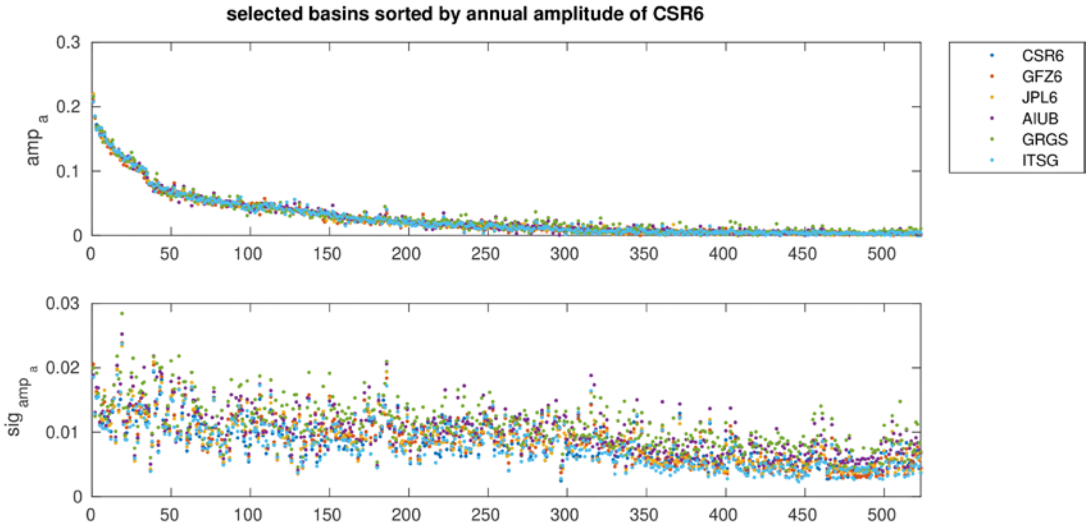


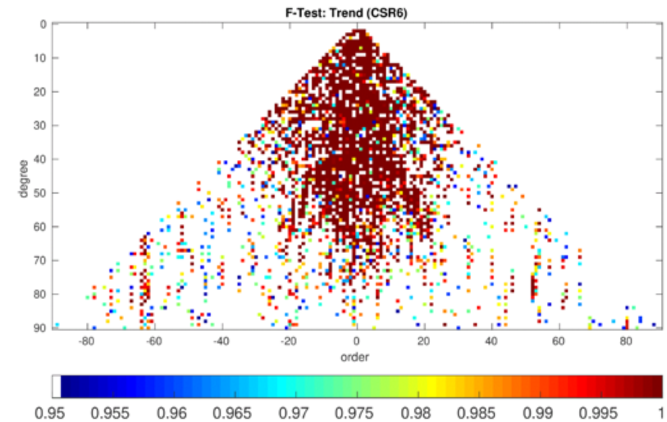
Geoid height differences of 2011 yearly GPS-only solution w.r.t. ITG-GRACE2010, 300km Gauss filter applied.

Follow-up activities from the EGSIEM project

Product Center of the IAG

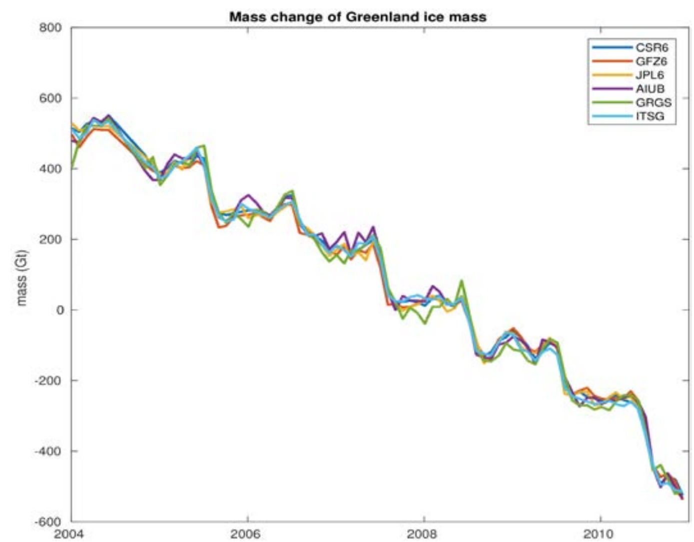
COST-G
Combination Service for Time-variable Gravity Models





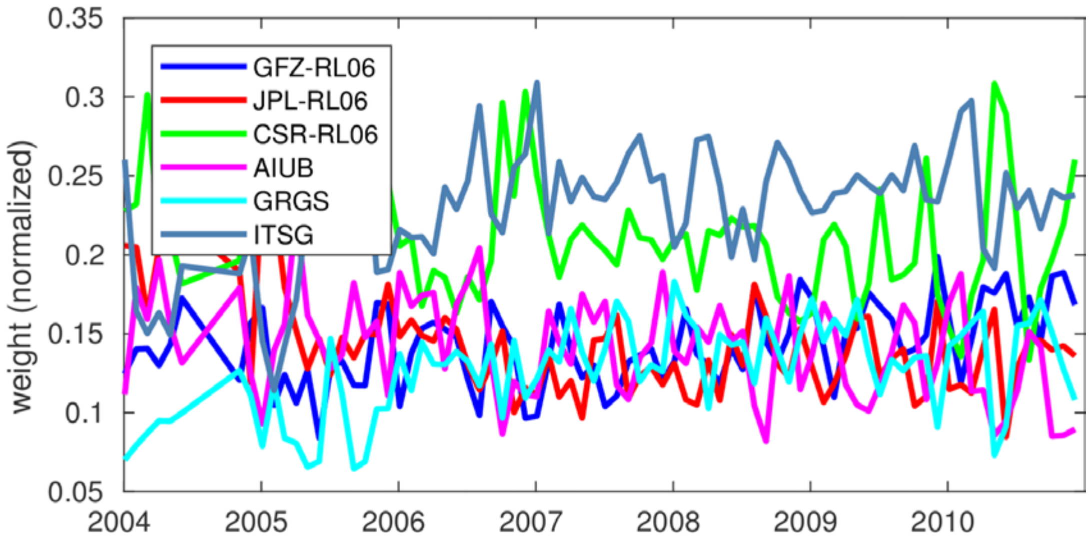
COST-G: Quality control

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

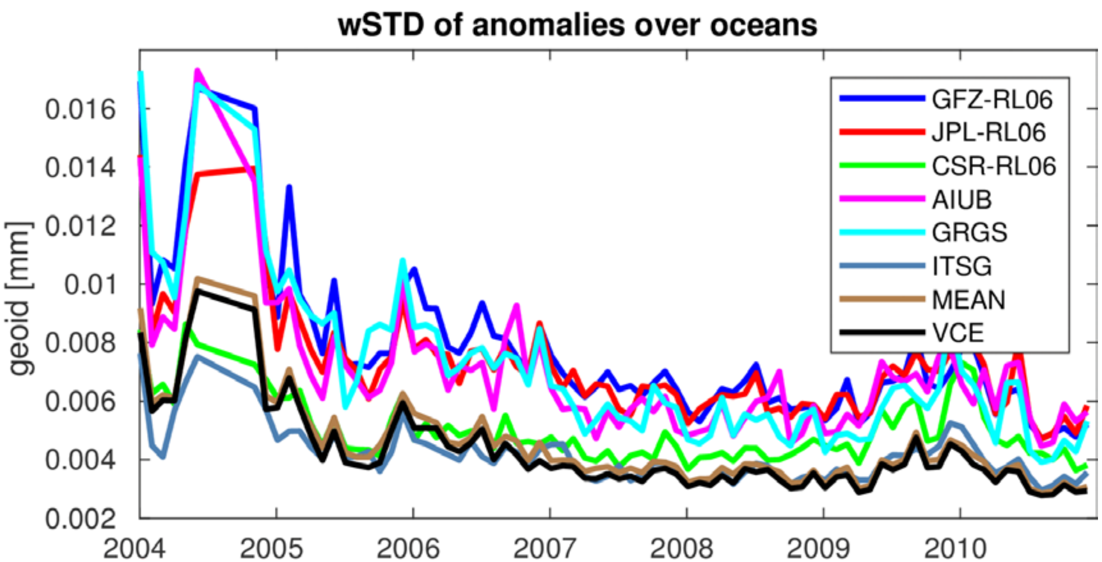


Product Center of the IAG

COST-G
Combination Service for Time-variable Gravity Models



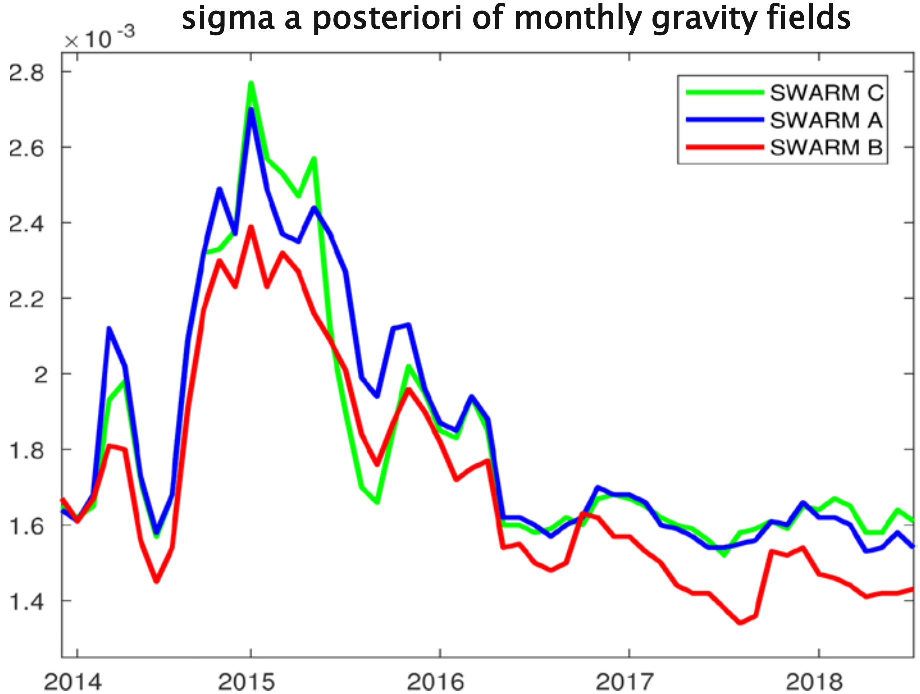
Weighted combination of monthly gravity fields based on variance component estimtion.

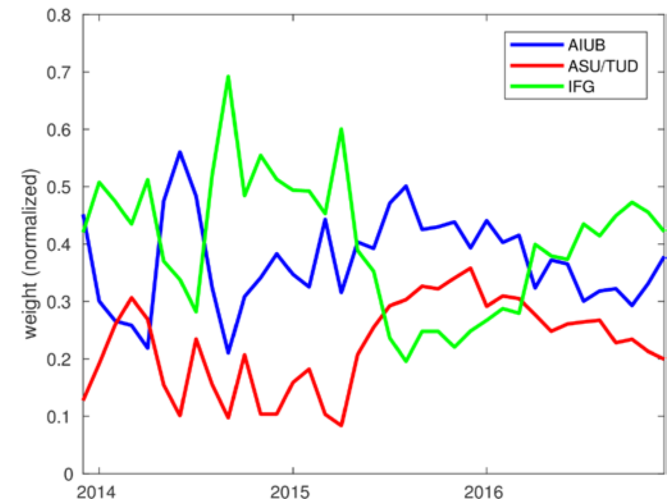


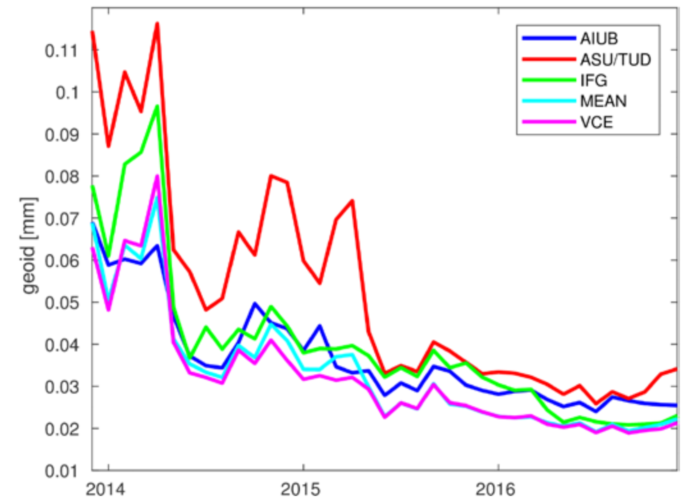
Quality control of individual time-series and their combination in terms of variability over the oceans.

SWARM Combination

sigma a posteriori of monthly gravity fields





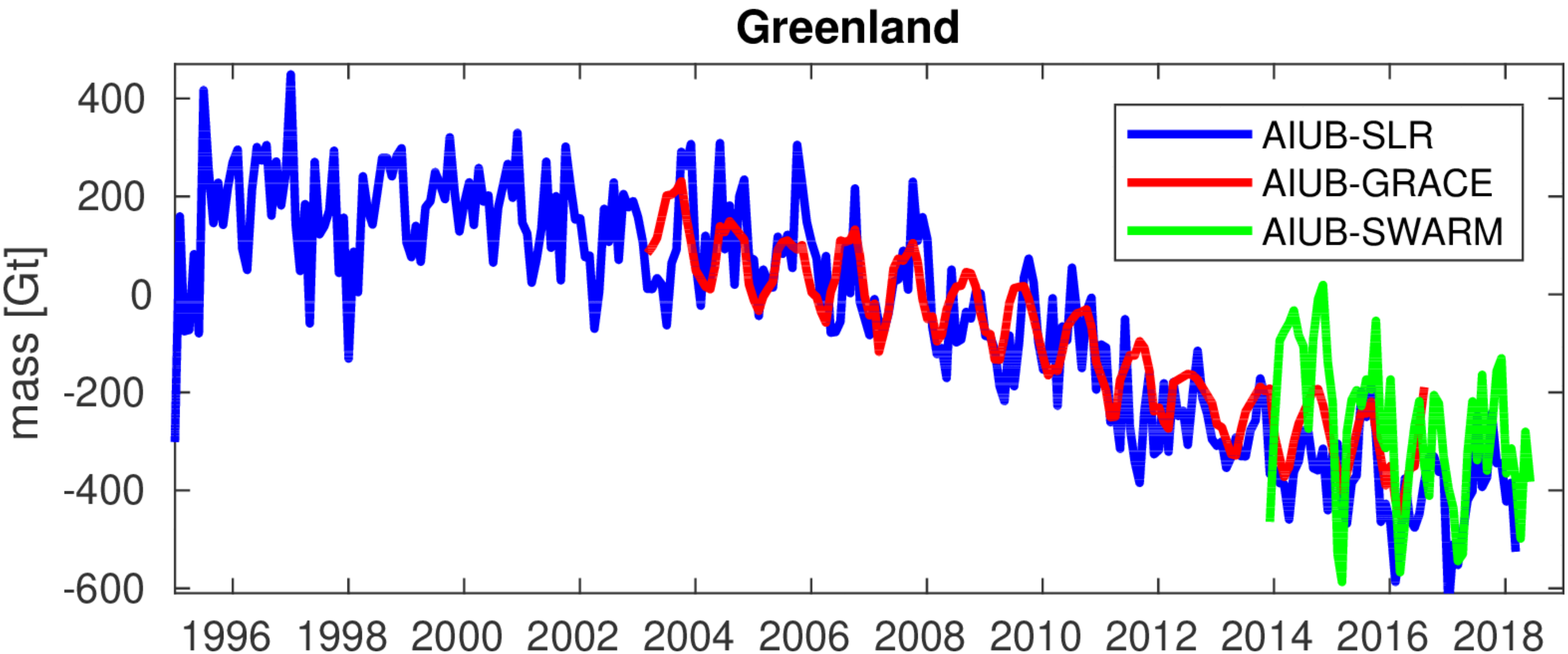


SWARM monthly gravity field

- processing,
- combination,
- quality control

in the frame of SWARM DISC.

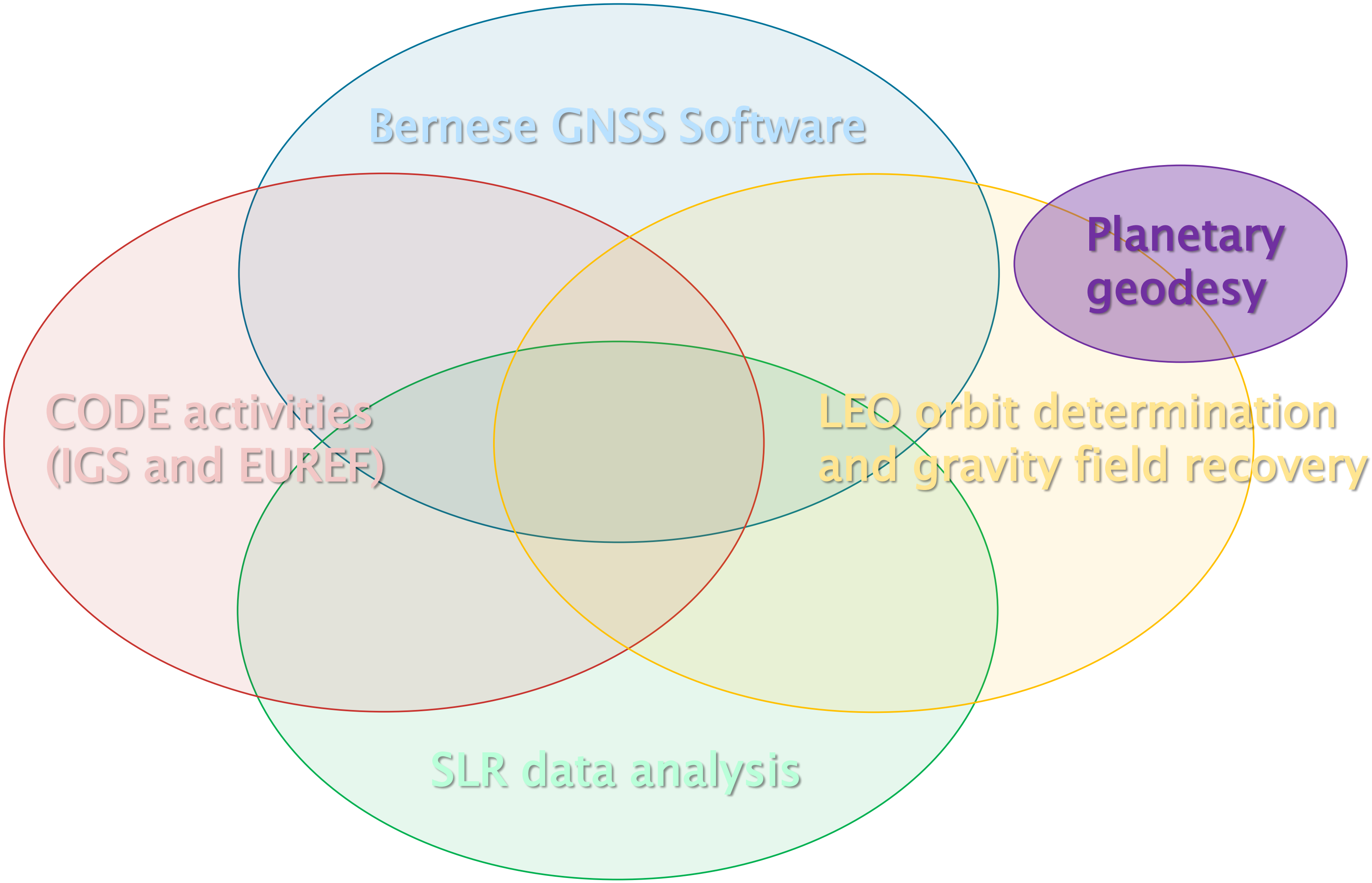
Satellite Laser Ranging



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.

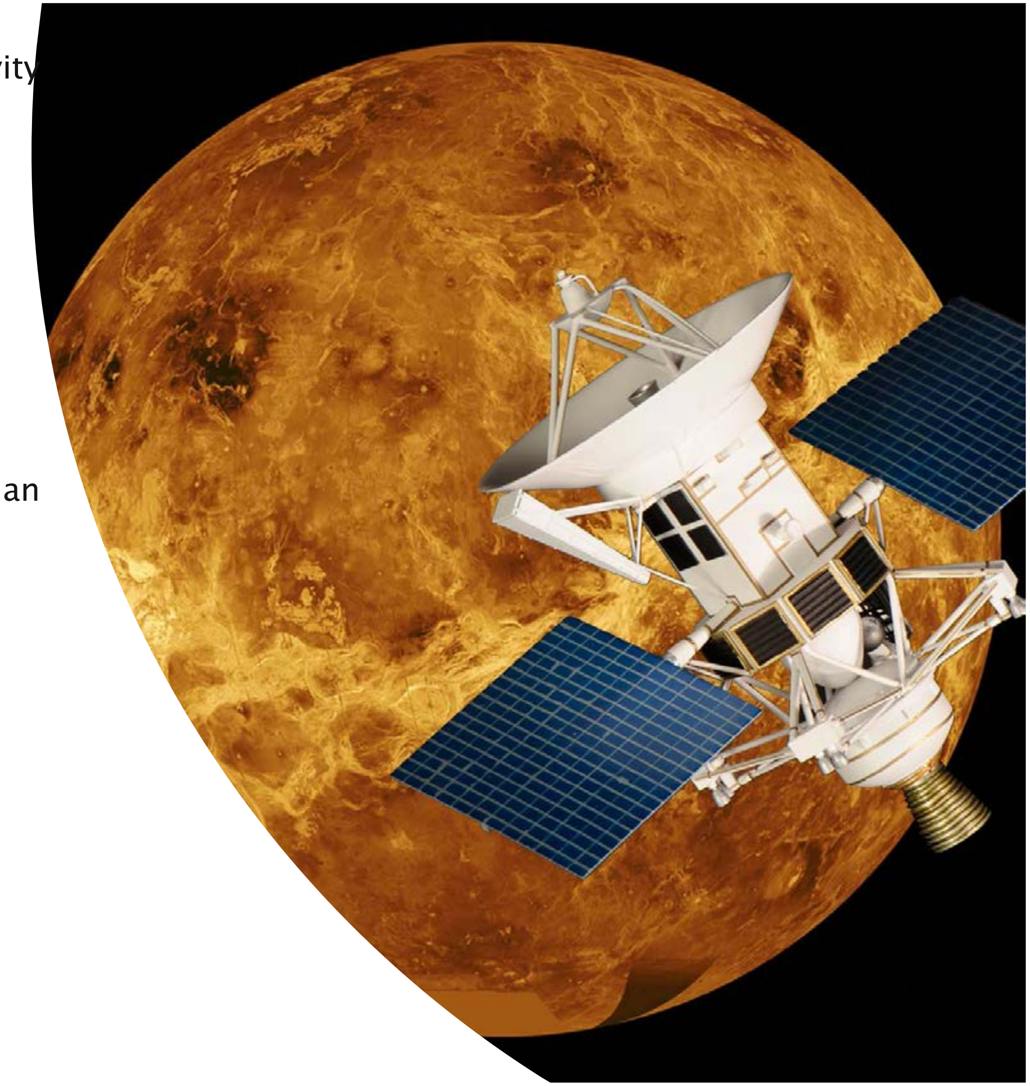
Satellite Geodesy Research Group



Non-gravitational forces for Magellan orbit determination

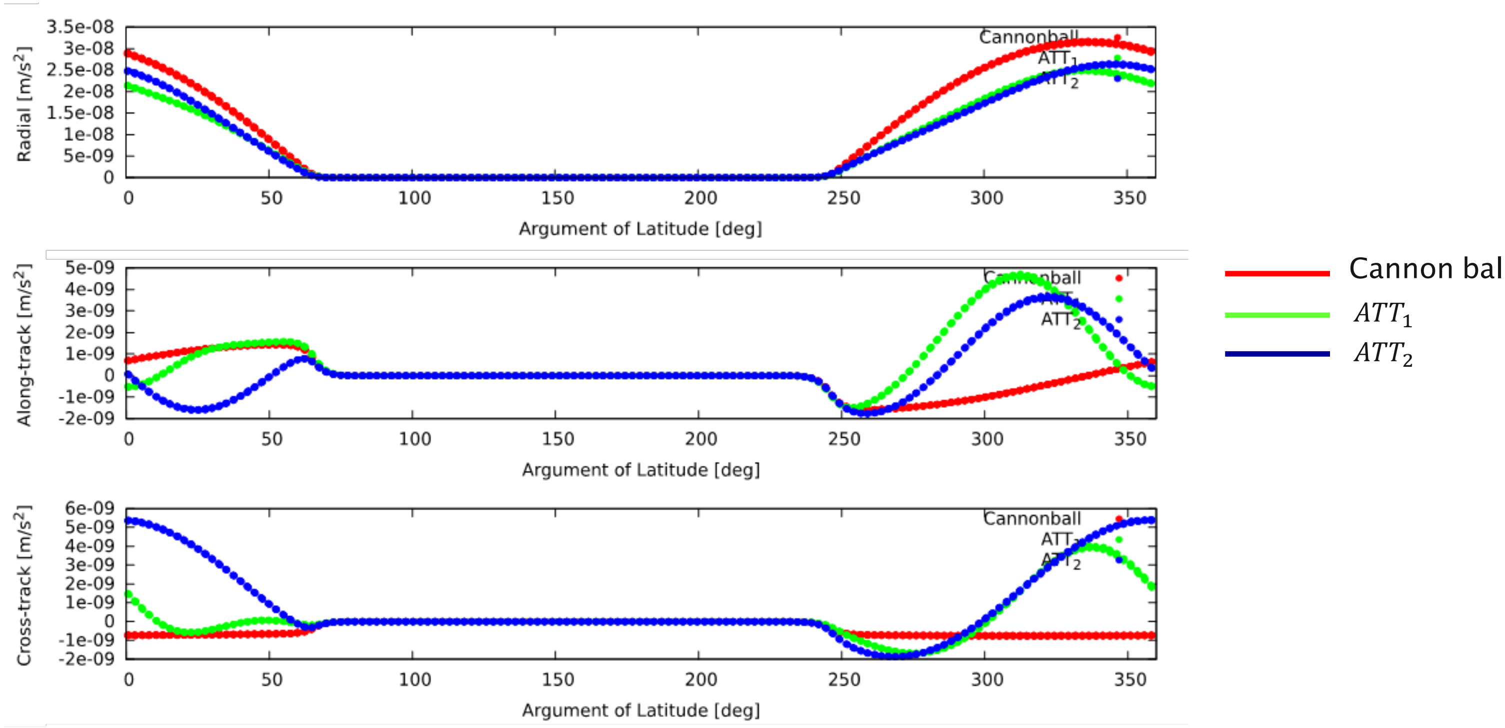
Magellan mission

- NASA mission to Venus,1990-1994
- 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



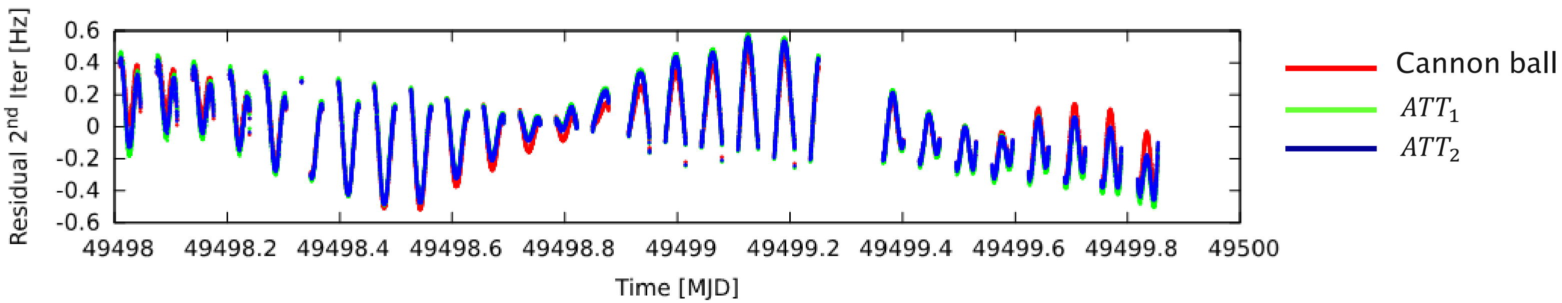
Modeled non-gravitational accelerations

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

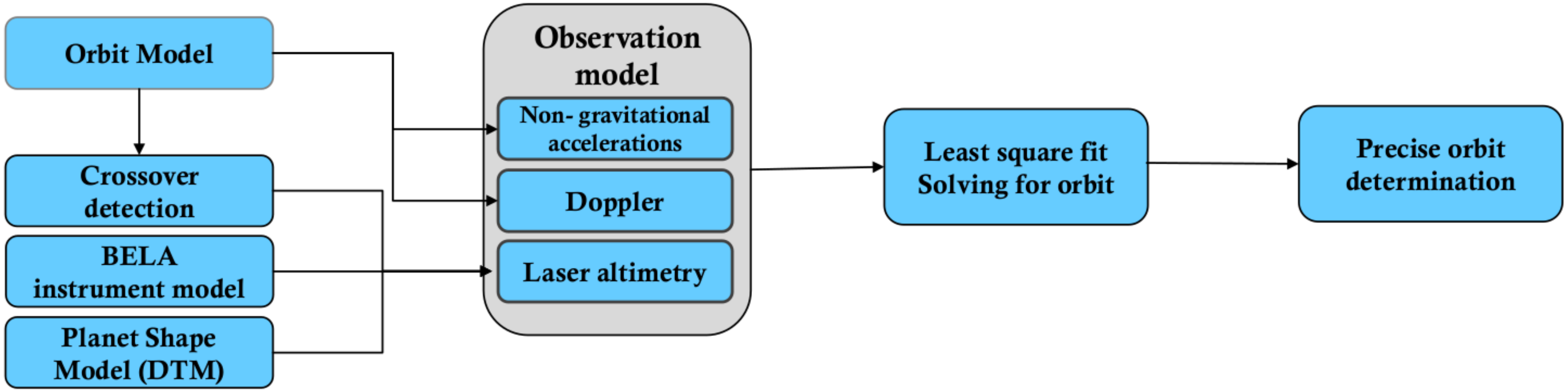
Doppler residuals after 2 iteration of Doppler-based Magellan POD on doys 146 and 147 of 1994:



Statistics	No Surface Forces	Cannonball	ATT_1	ATT_2
Mean (Hz)	−0.00114	0.00027	0.00024	0.00019
Standard Deviation (Hz)	2.06433	0.22392	0.23624	0.21425
RMS (Hz)	2.06420	0.22391	0.23623	0.21425

BepiColombo MPO orbit reconstruction simulation

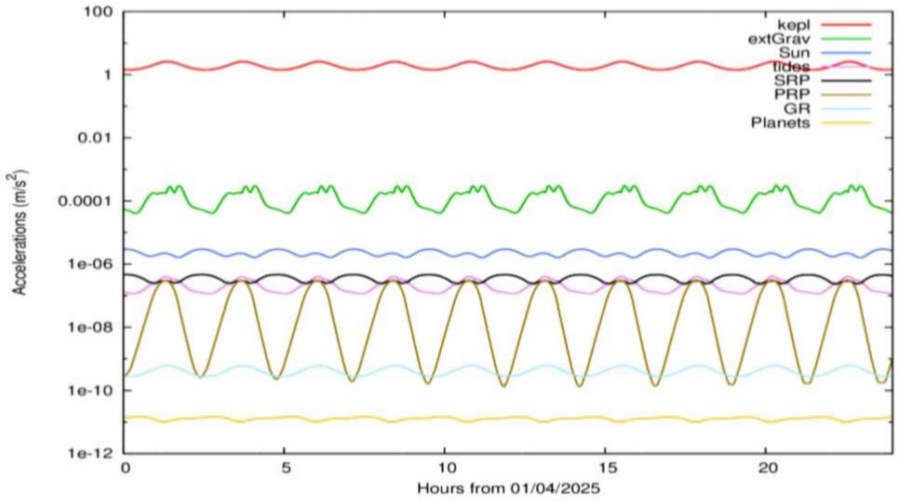
MPO orbit determination

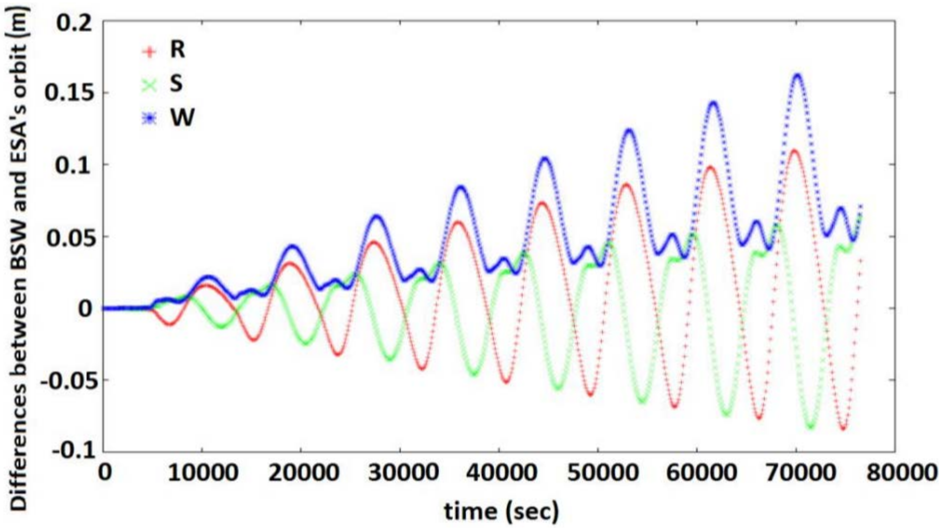


- Simulation study for precise orbit determination of BepiColombo Mercury Planetary Orbiter (MPO) using Doppler, accelerometer and altimetry data and development version of Bernese GNSS Software.
- PhD project at Space Research and Planetary Sciences Division, University of Bern, co-supervised by AIUB

Modeling

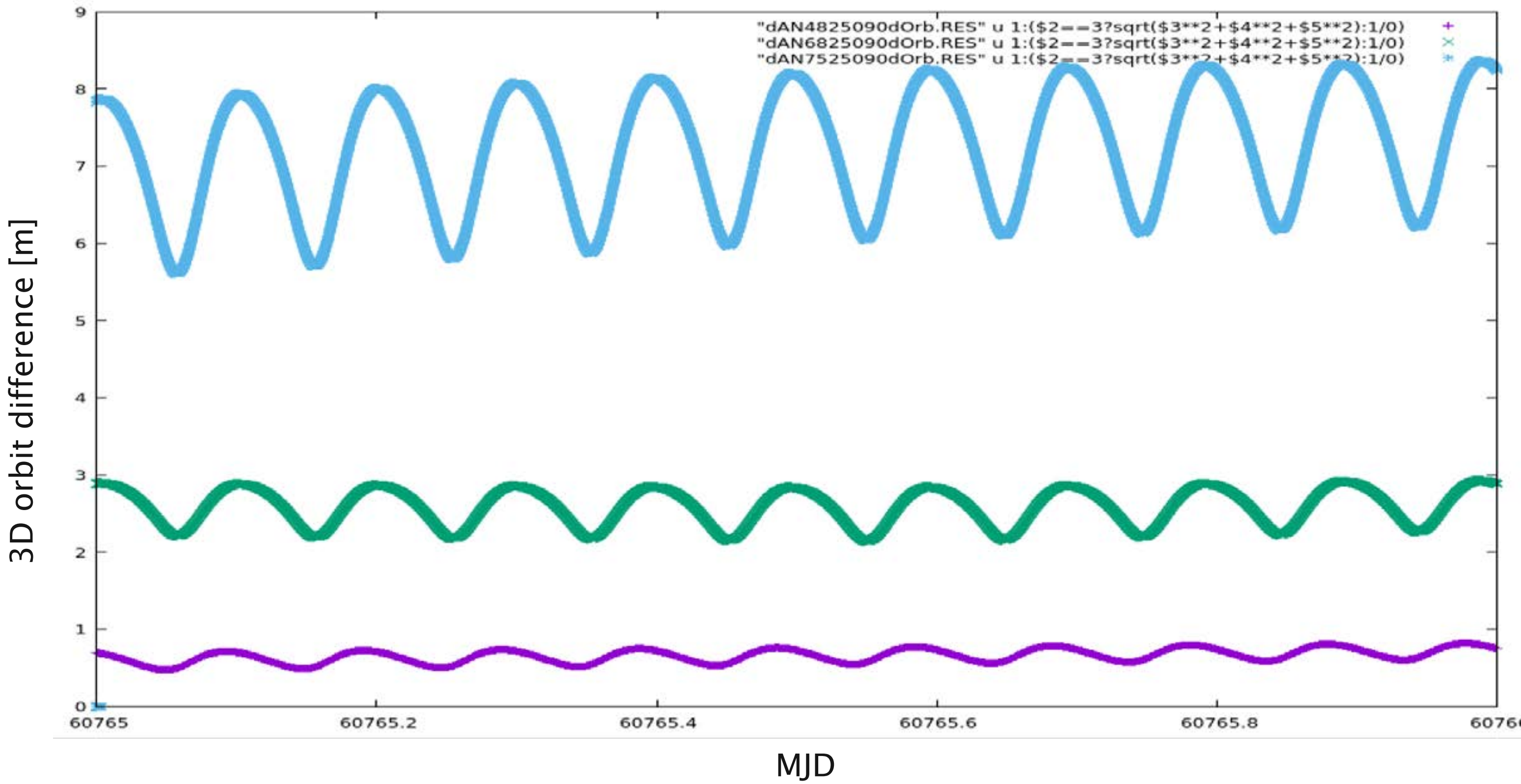
- Force model: gravitational forces (Mercury gravity field to d/o 50, Sun, and planets), non-gravitational forces (solar and planetary radiation pressure), relativistic corrections
- Visibility conditions (occulatation, elevation over Earth horizon, ground station availability)
- 15-16h tracking period 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:



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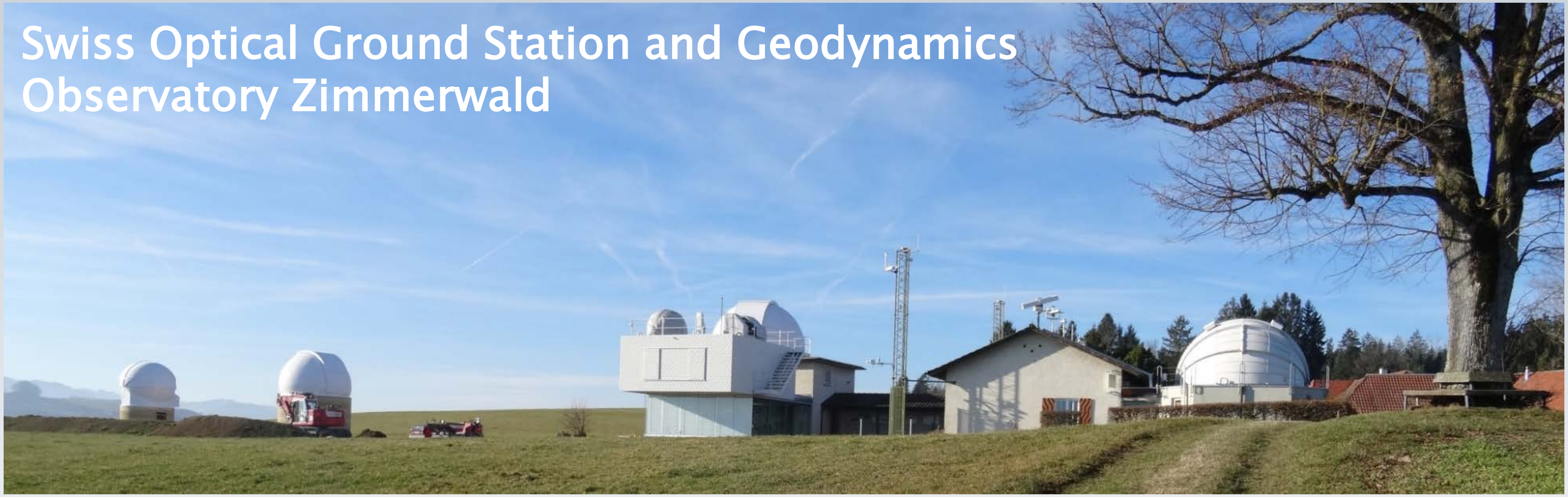
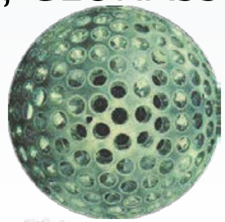
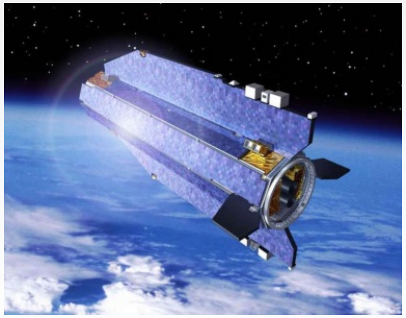
24/7 Betrieb

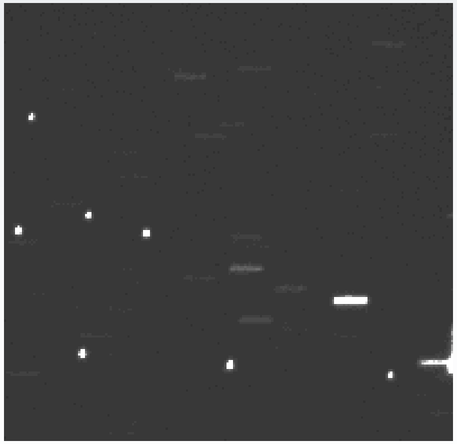


24/7 Operations

- **Optical Observations**
  space debris (SSA), asteroids, comets
- **Satellite Laser Ranging**
- **Satellite-Receivers** (GPS-, GLONASS- and Galileo)



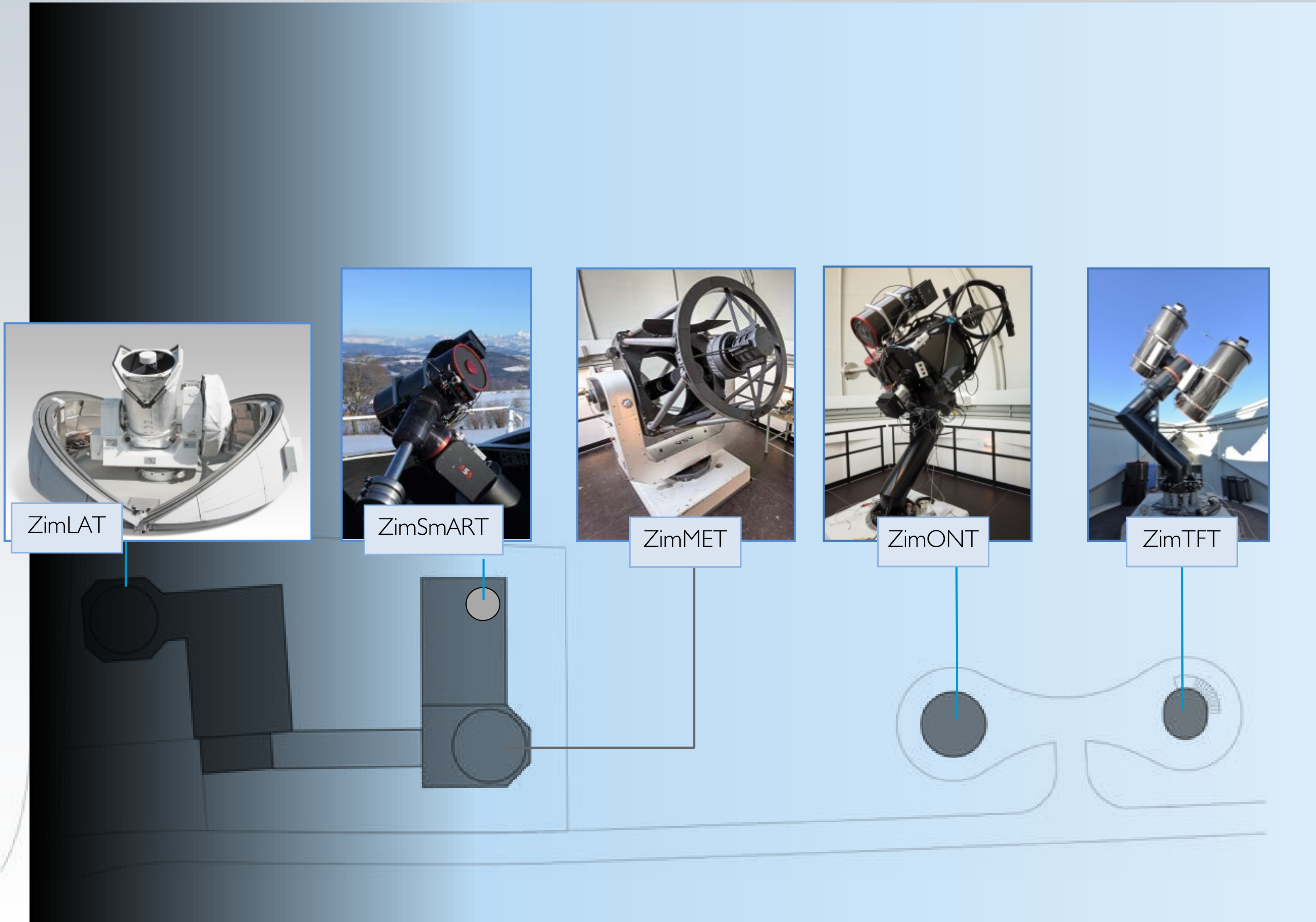


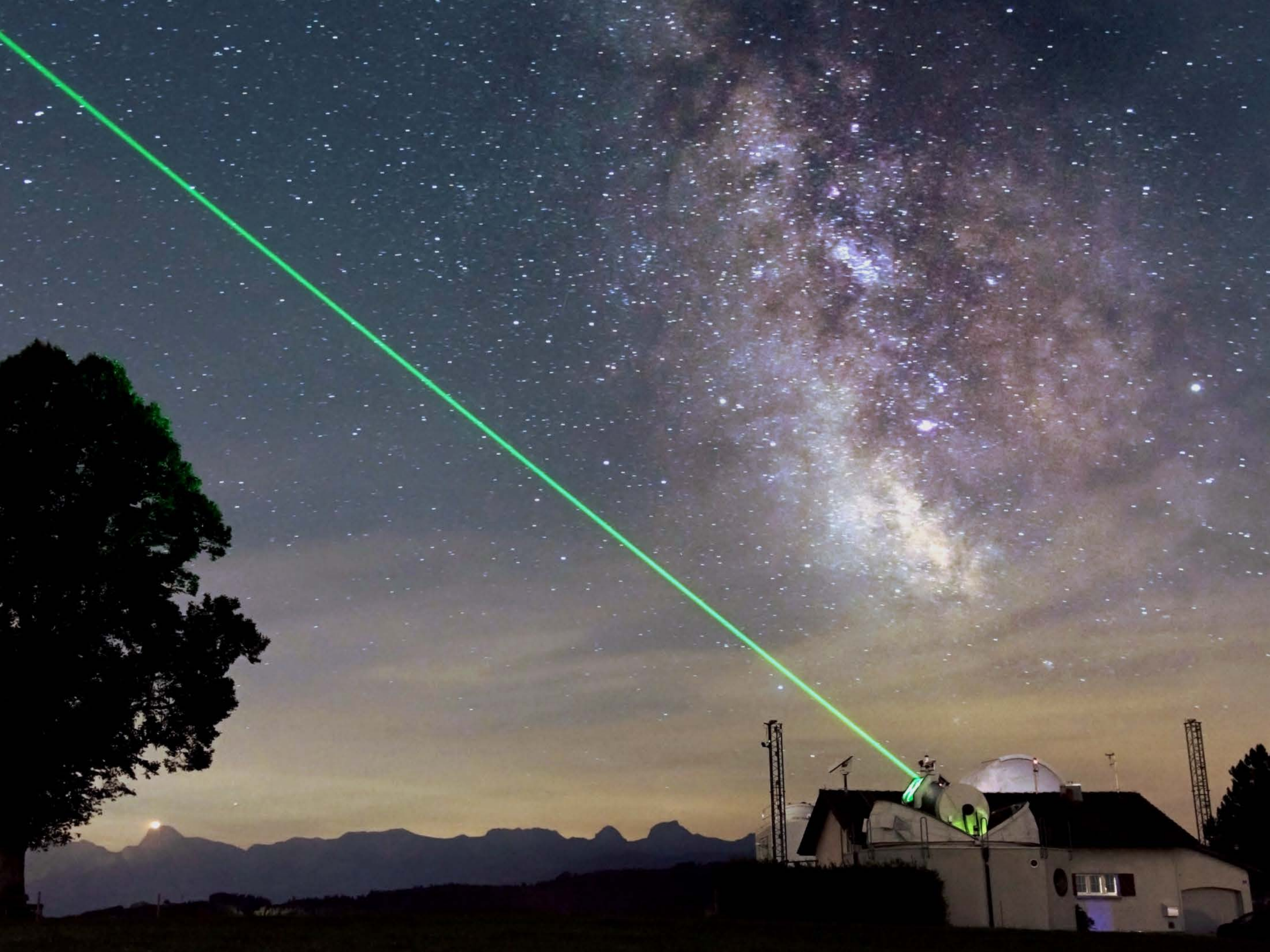


Telecopes

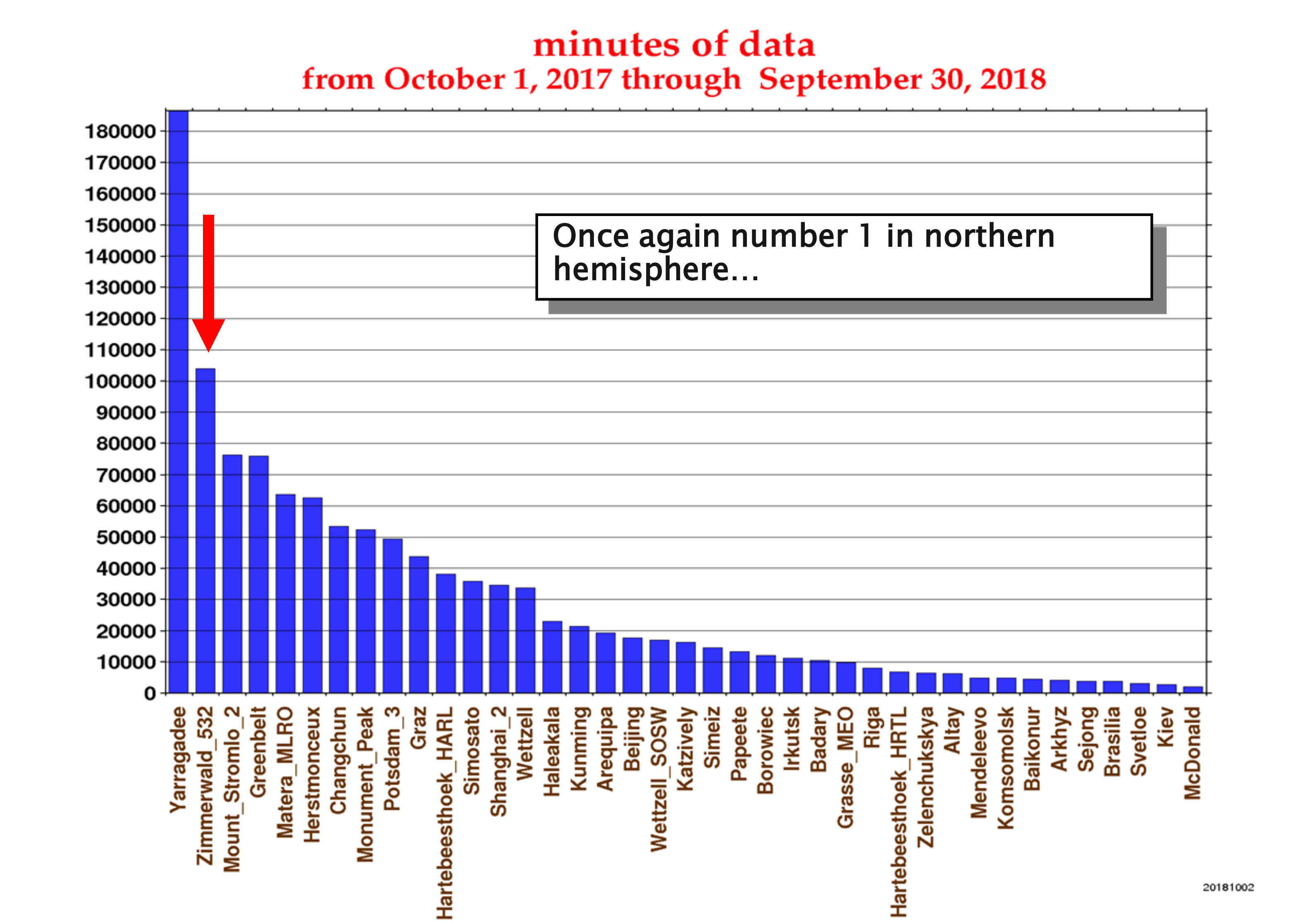

NEW DOMES/TELESCOPES
Official inauguration event on May 29
Public Day on June 2

6 Operational Telescopes!

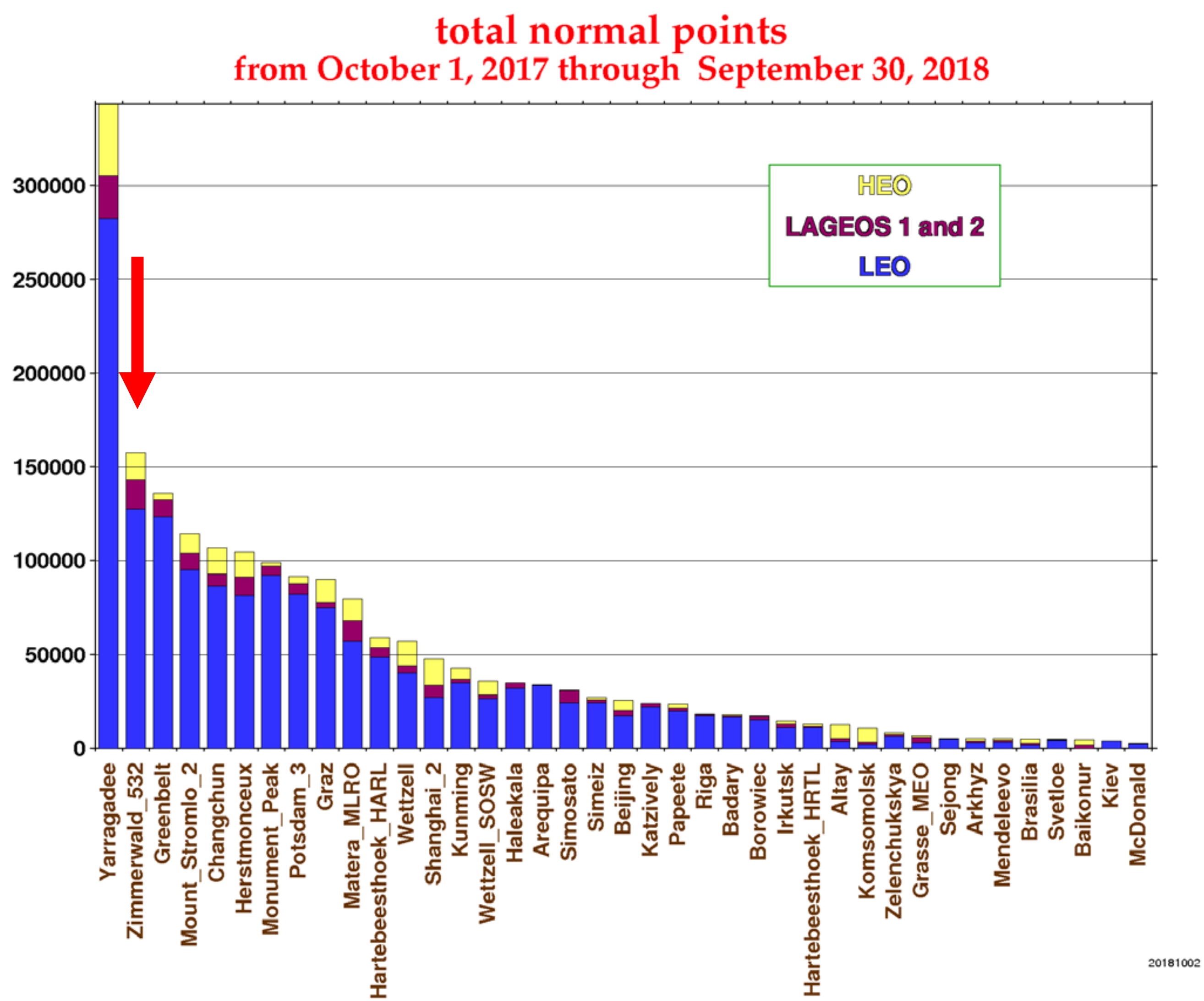




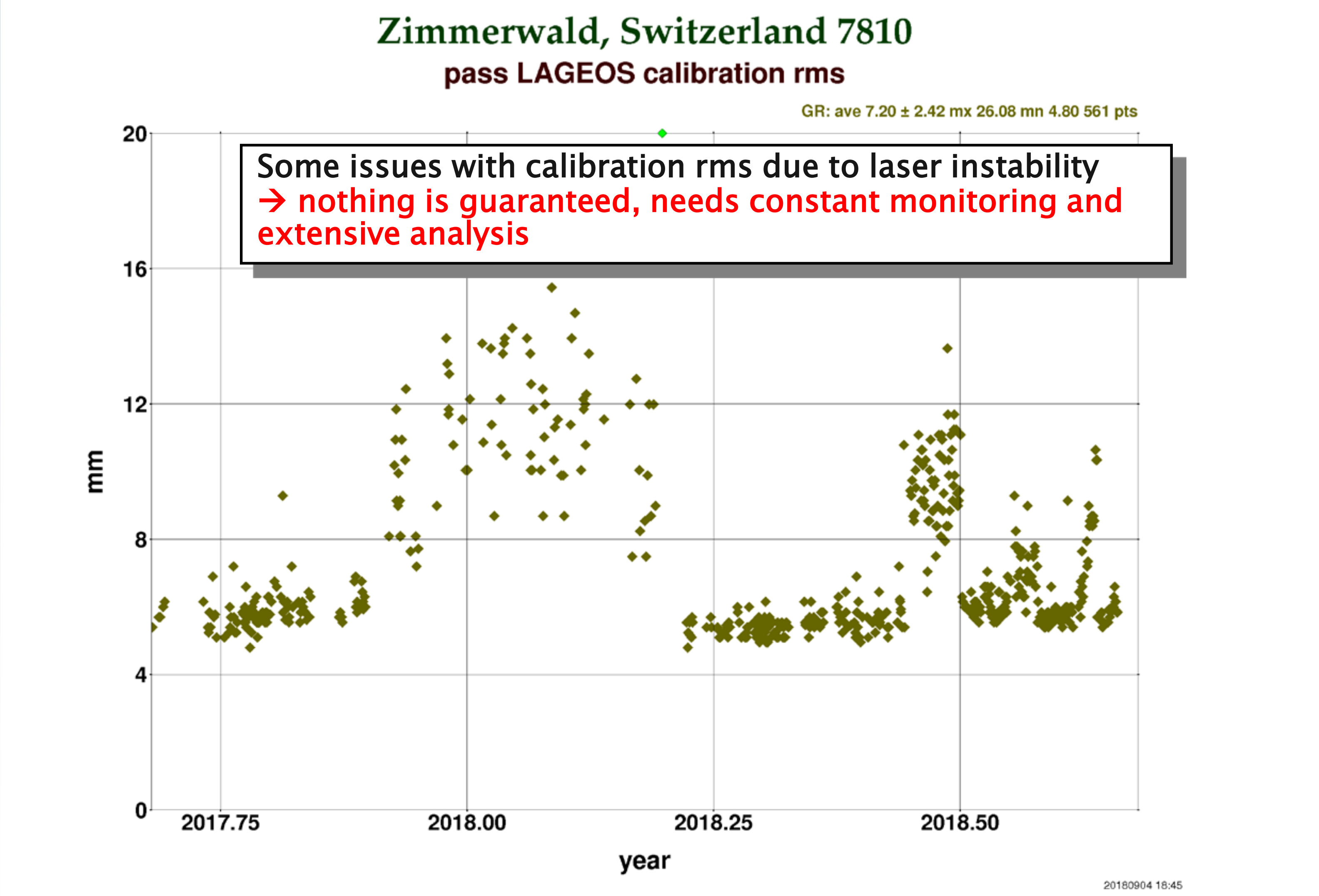
ILRS Station Performance



ILRS Station Performance



LAGEOS Calibration rms



Some issues with calibration rms due to laser instability
→ nothing is guaranteed, needs constant monitoring and extensive analysis

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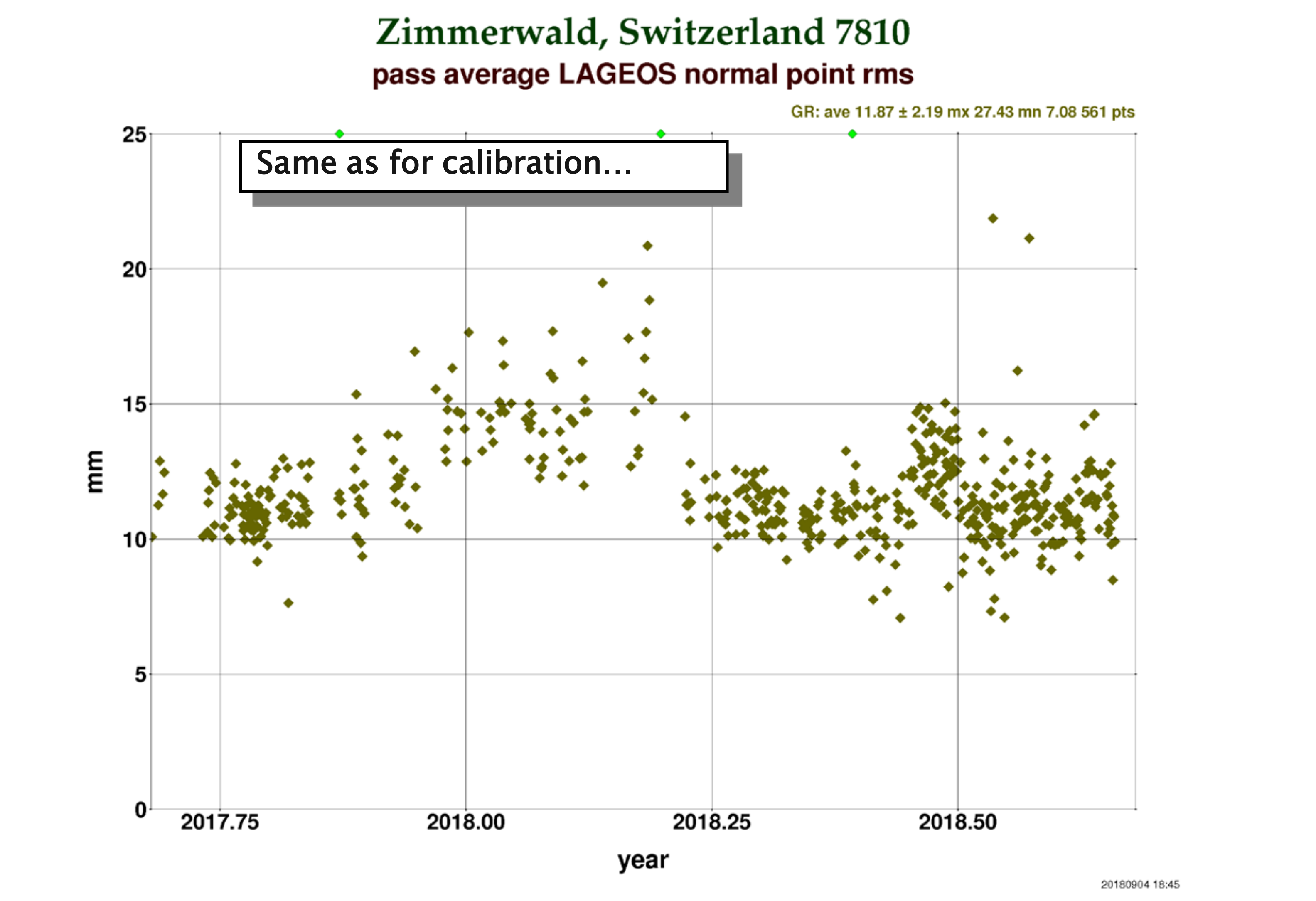
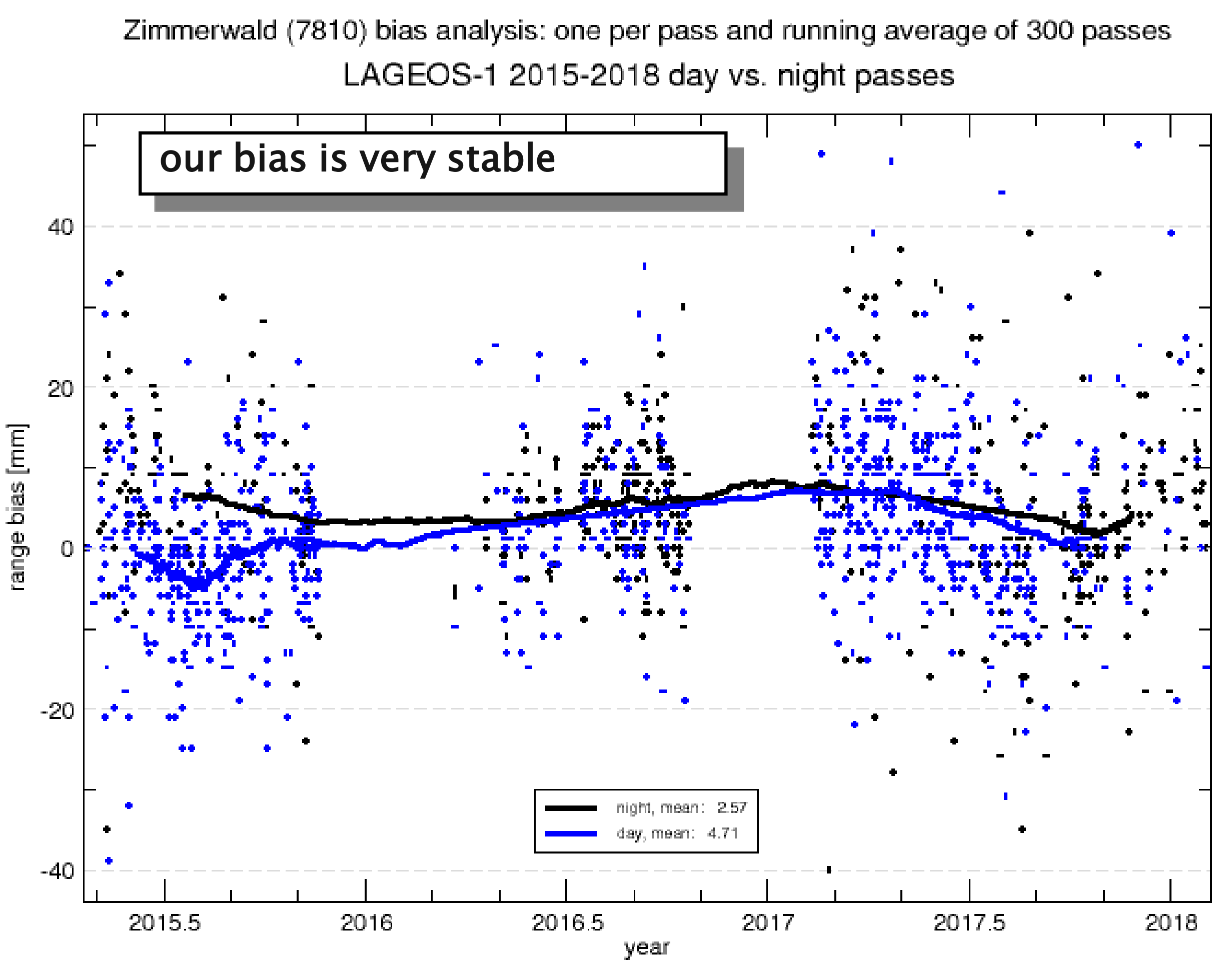
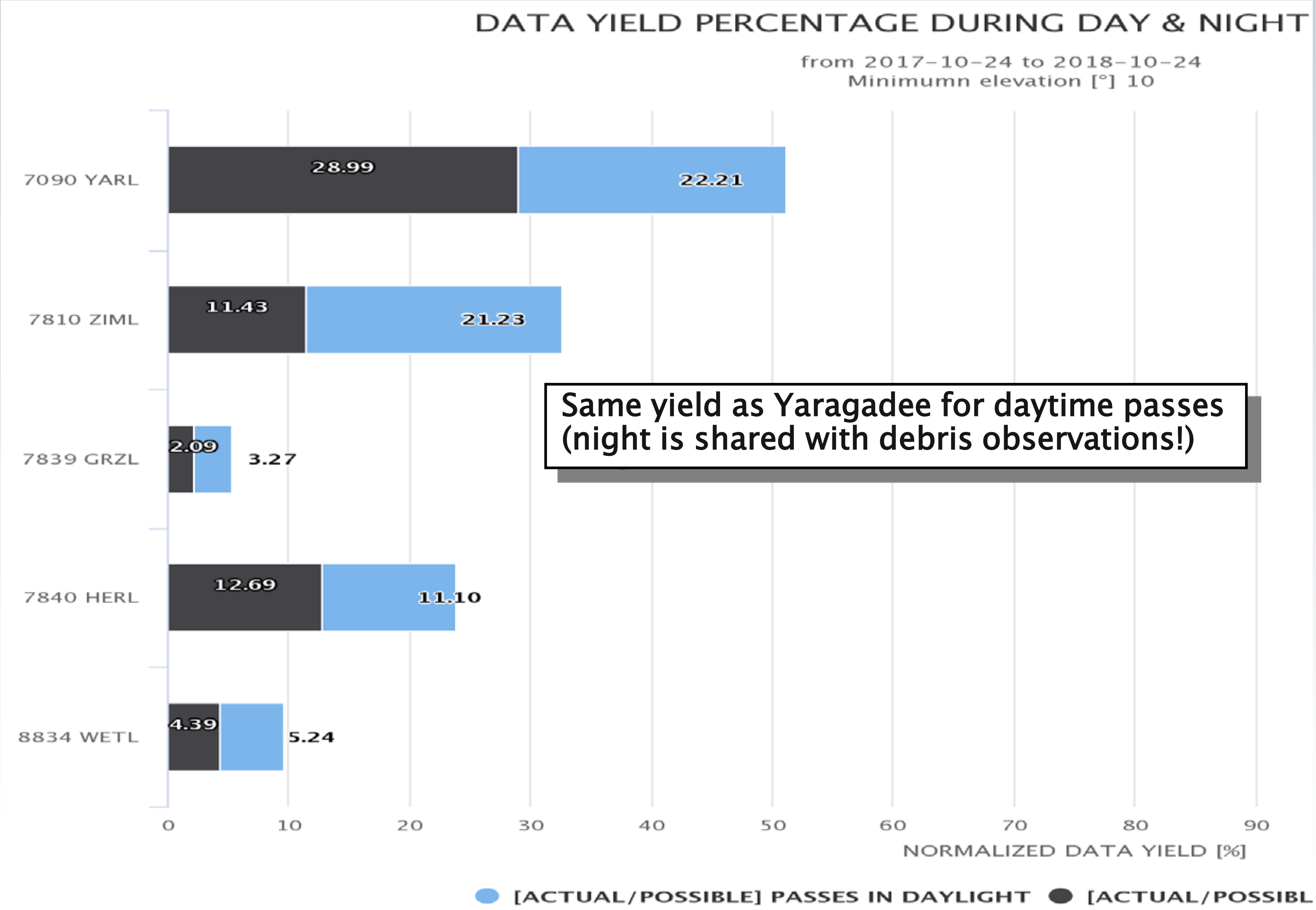
LAGEOS NPT rms



LAGEOS Bias Analysis



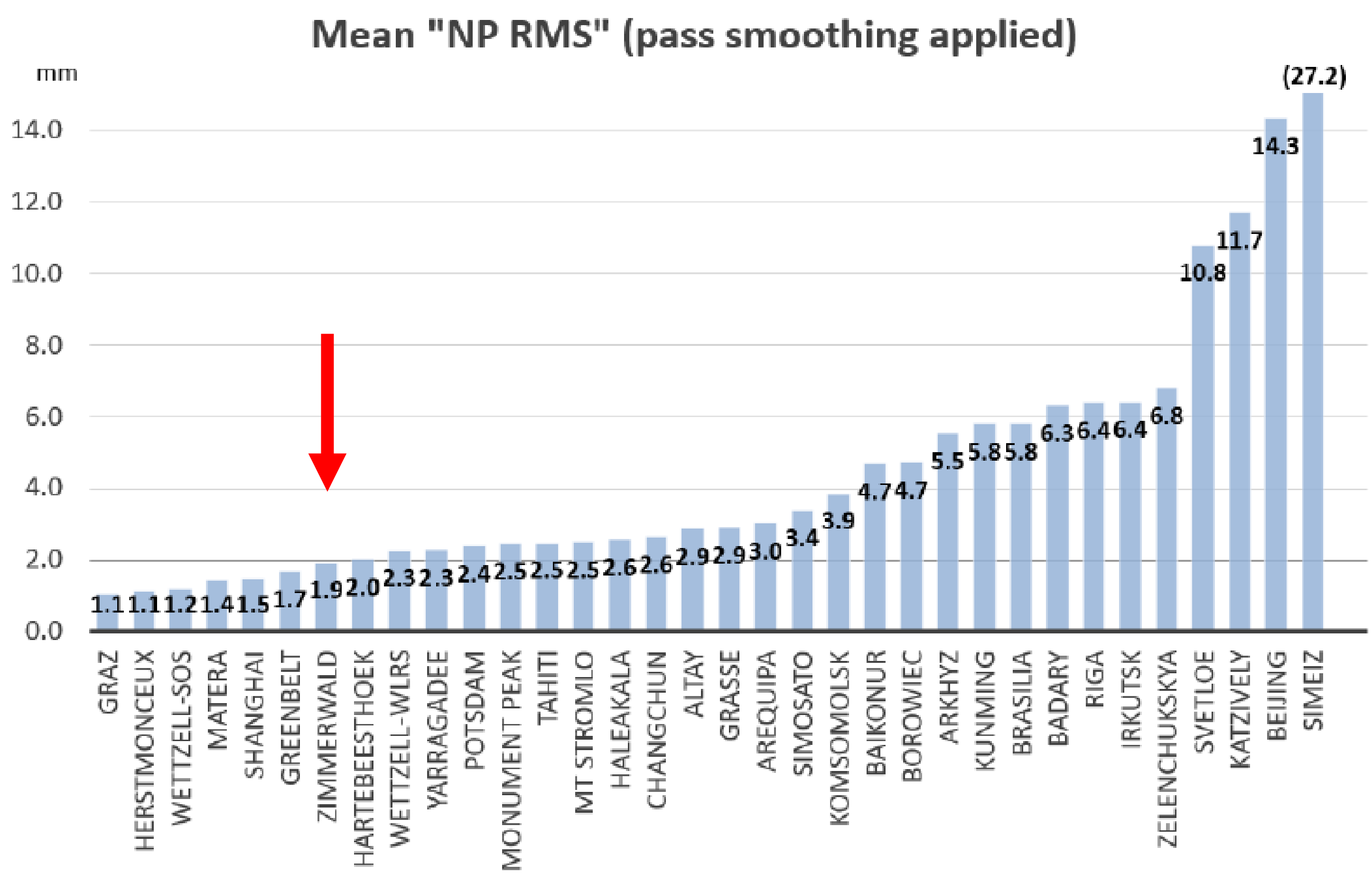
LAGEOS Day/Night Yield



Same yield as Yaragadee for daytime passes
(night is shared with debris observations!)

ILRS NP RMS

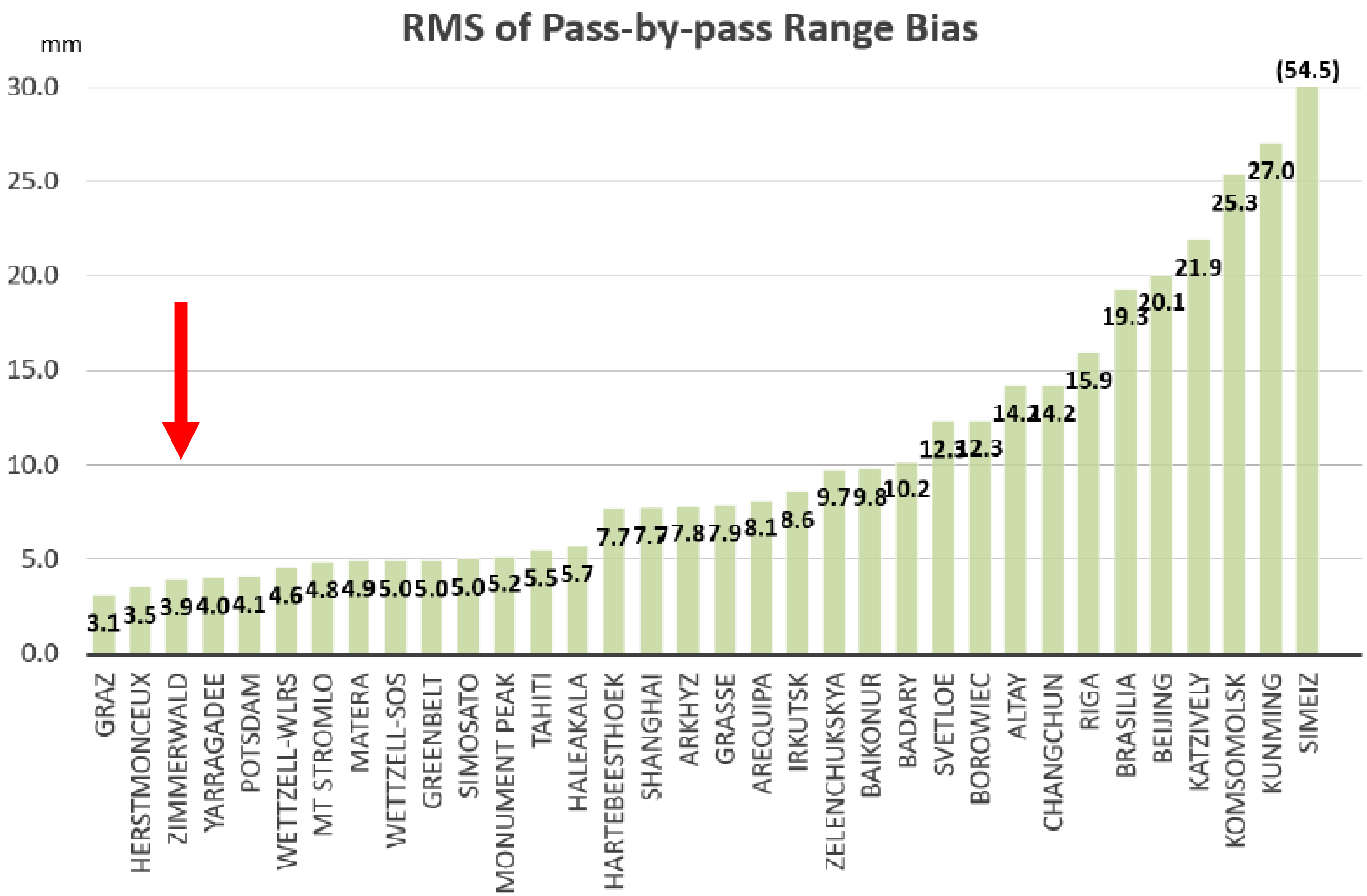
1 year (July 2016-June 2017), LAG1+LAG2.
RB only or RB+TB smoothing applied for POD (c5++) post-fit residuals.



ILRS Range Bias

1 year (July 2016-June 2017), LAG1+LAG2.

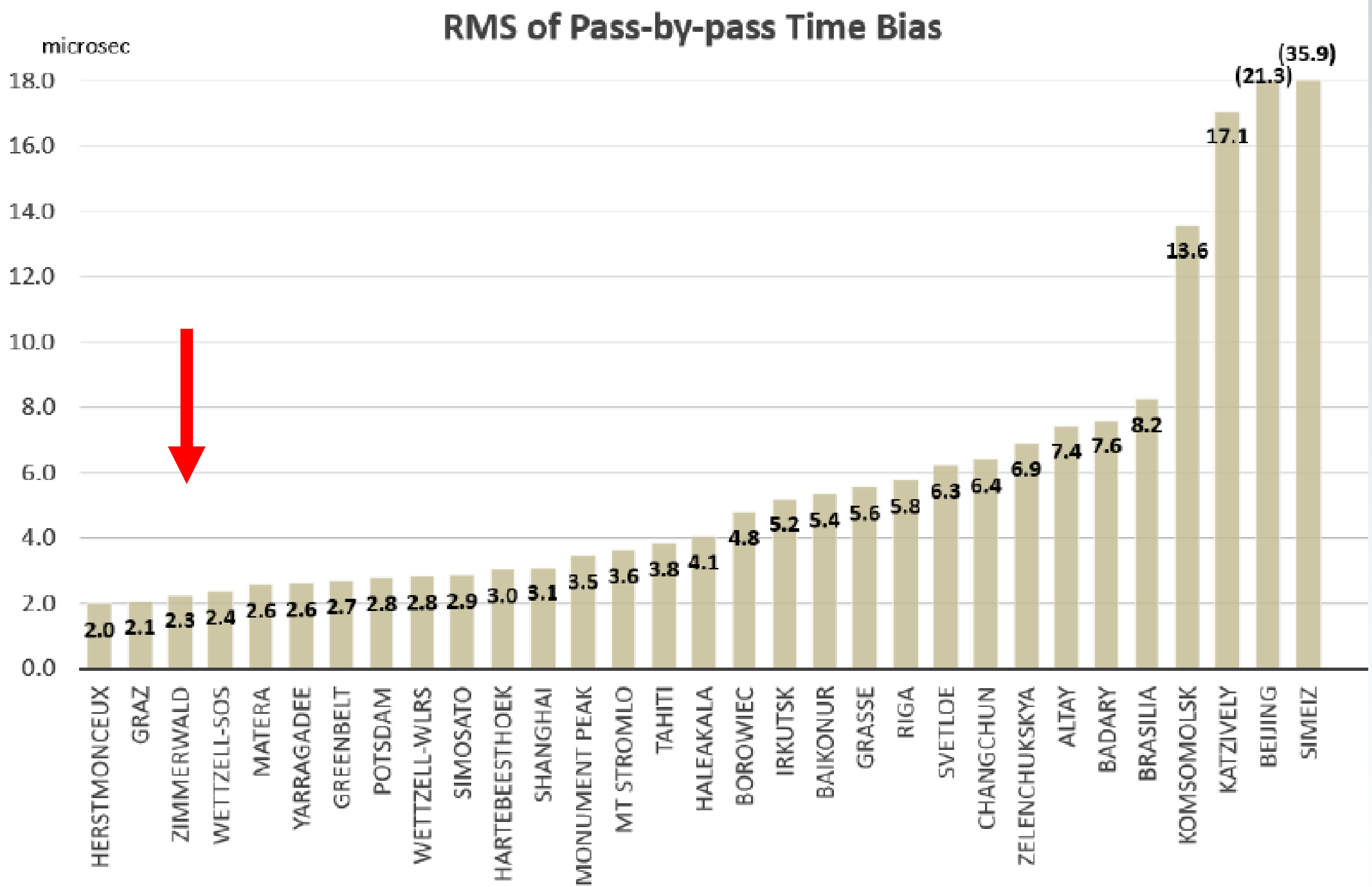
POD (c5++): station pos solved for. U-Strasbg atm+hyd loading applied.



ILRS Time Bias

1 year (July 2016-June 2017), LAG1+LAG2.

POD (c5++): station pos solved for. U-Strasbg atm+hyd loading applied.



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SLR Operations

- ILRS pass statistics
  - again #1 in the northern hemisphere
  - very good performance
  - station range bias often at ≤ 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

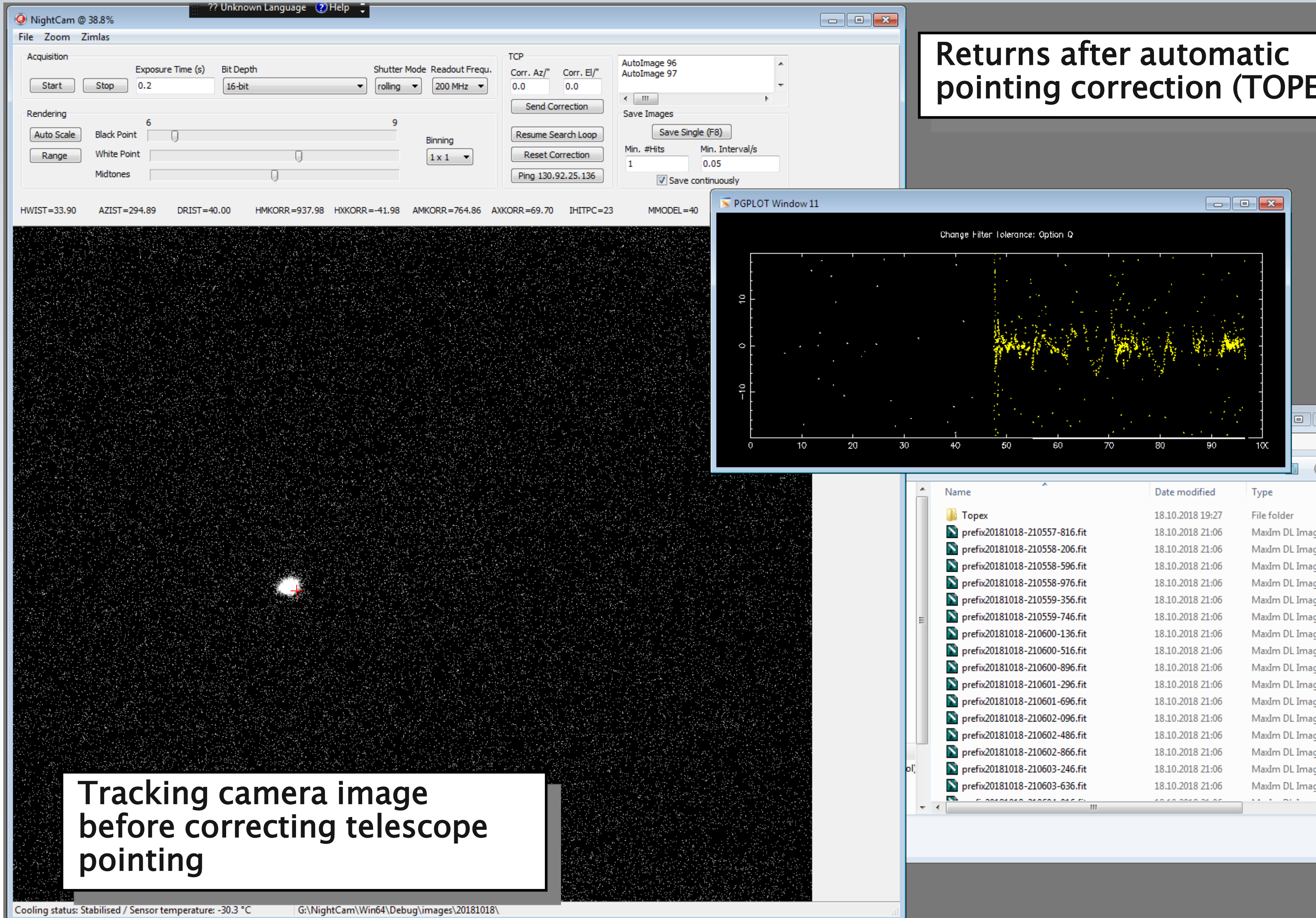
SLR Operations

- 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 on-going

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?

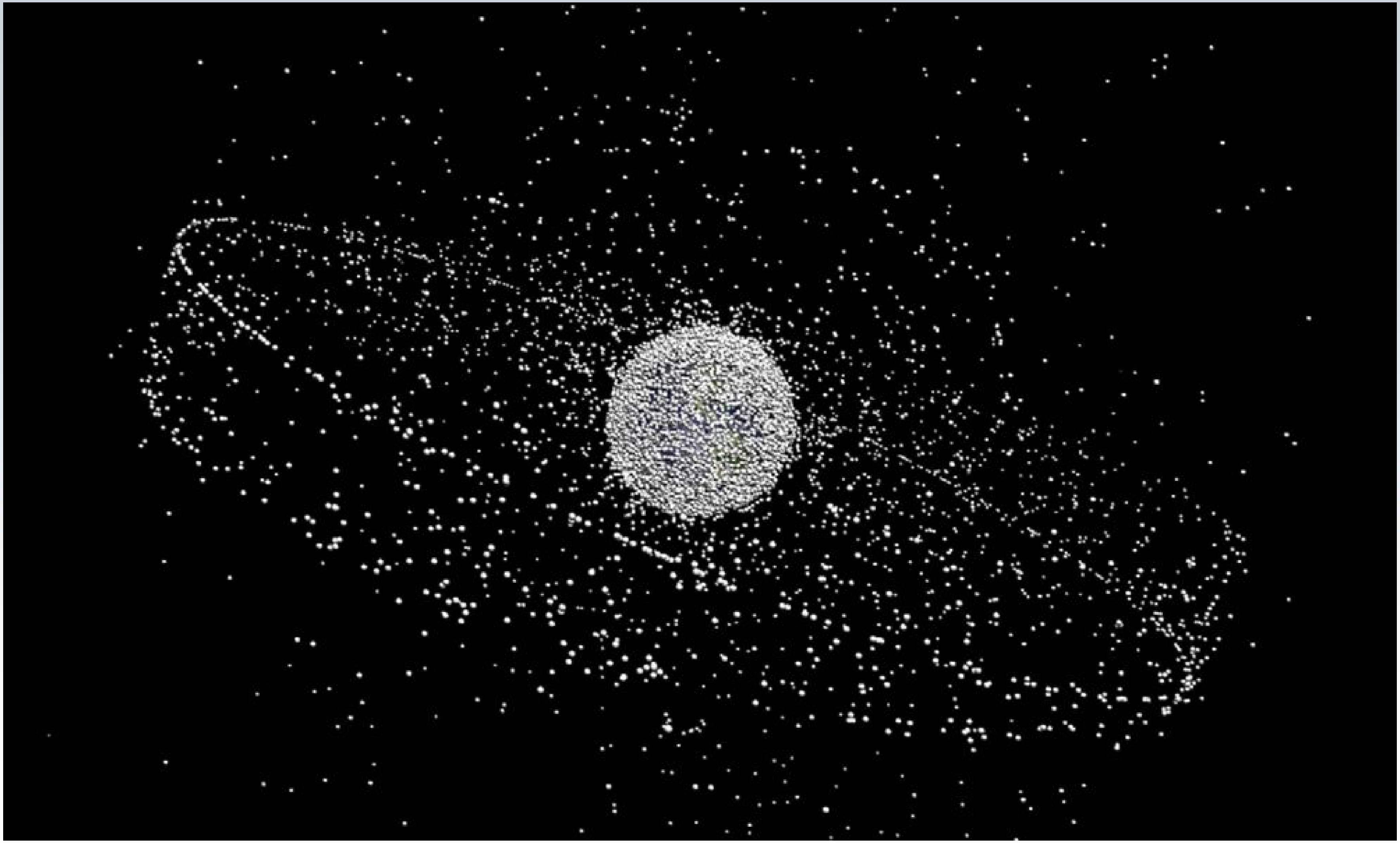
Stare and Chase



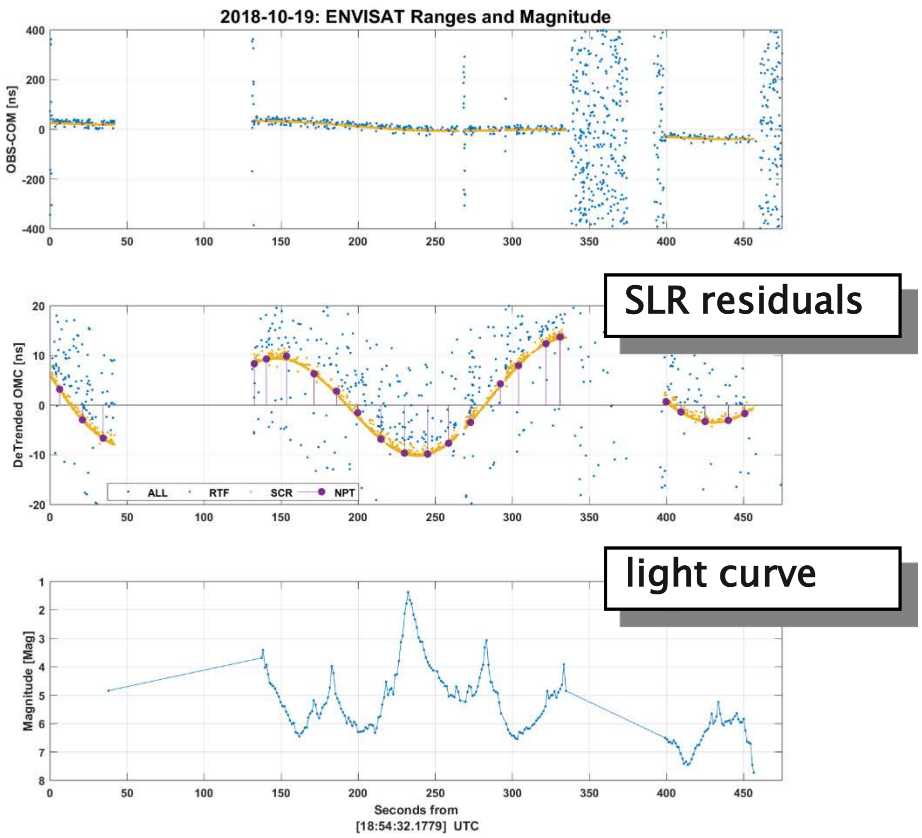
Returns after automatic pointing correction (TOPEX)!

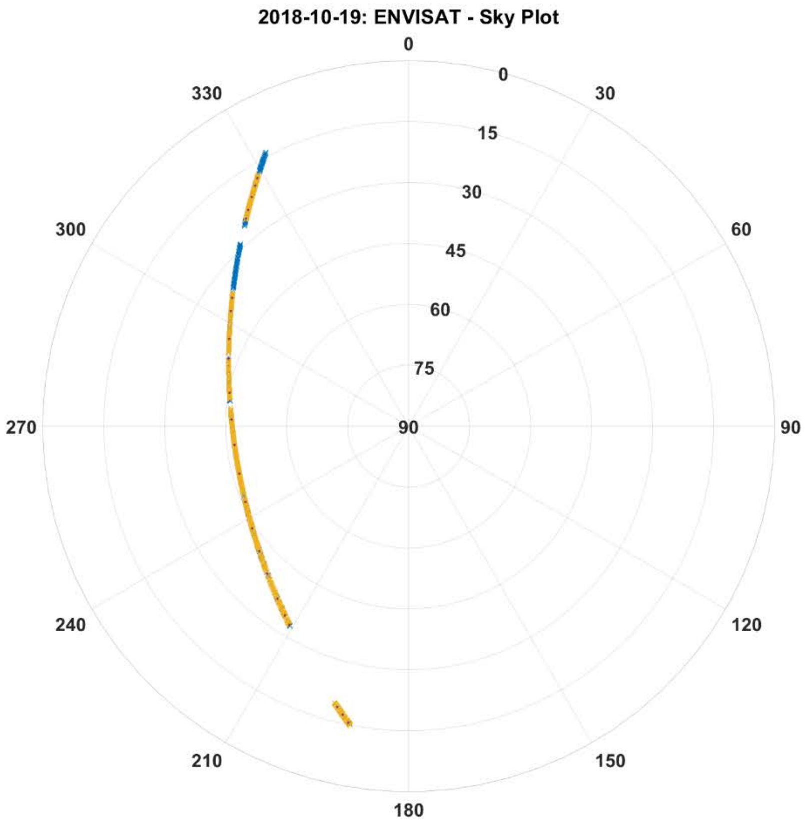
Tracking camera image before correcting telescope pointing

Space Debris



Simultaneous Light Curves and SLR Measurements – ENVISAT





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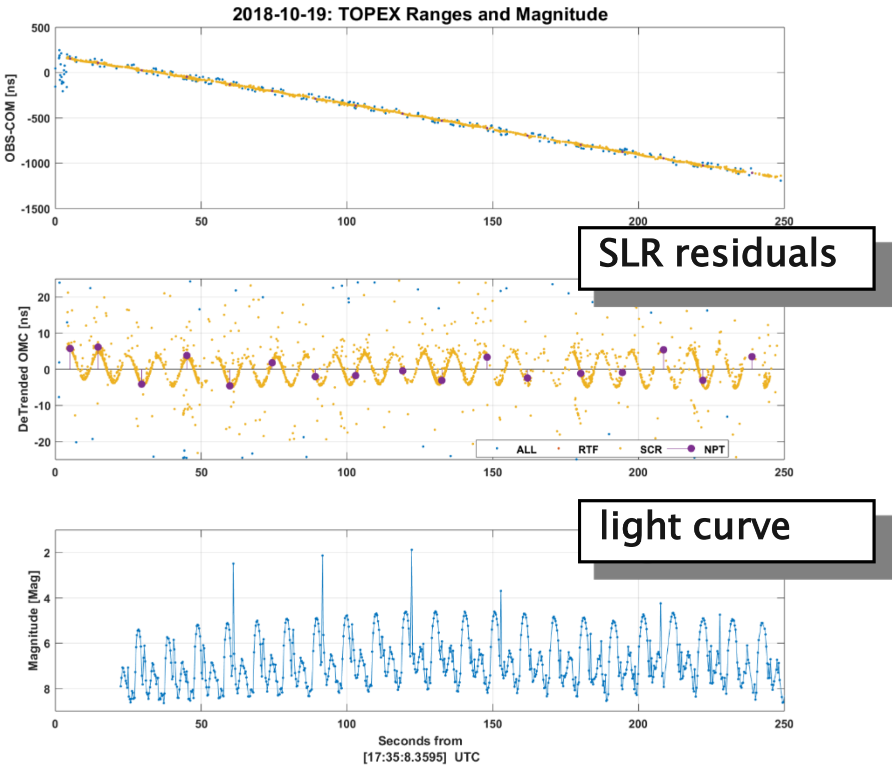
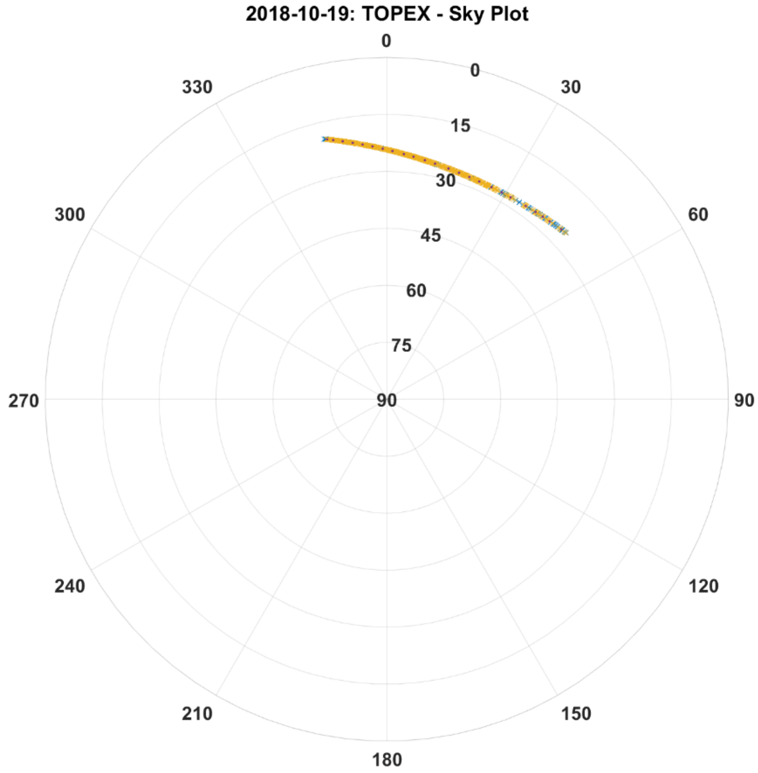
Simultaneous Light Curves and SLR Measurements – TOPEX





Simultaneous Light Curves and SLR Measurements – GLONASS (decommissioned)