Activities in the Research Group on Satellite Geodesy at AIUB

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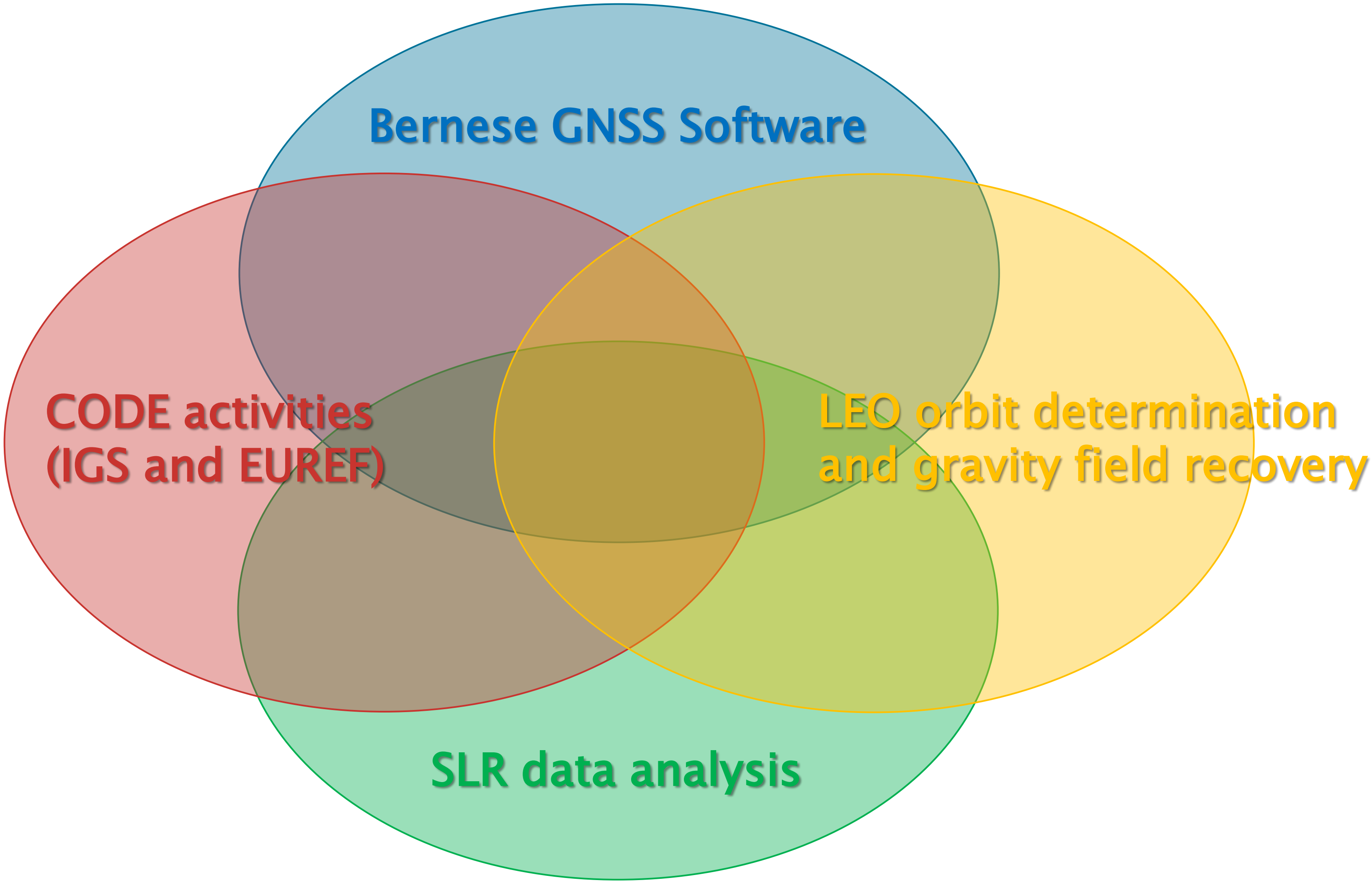
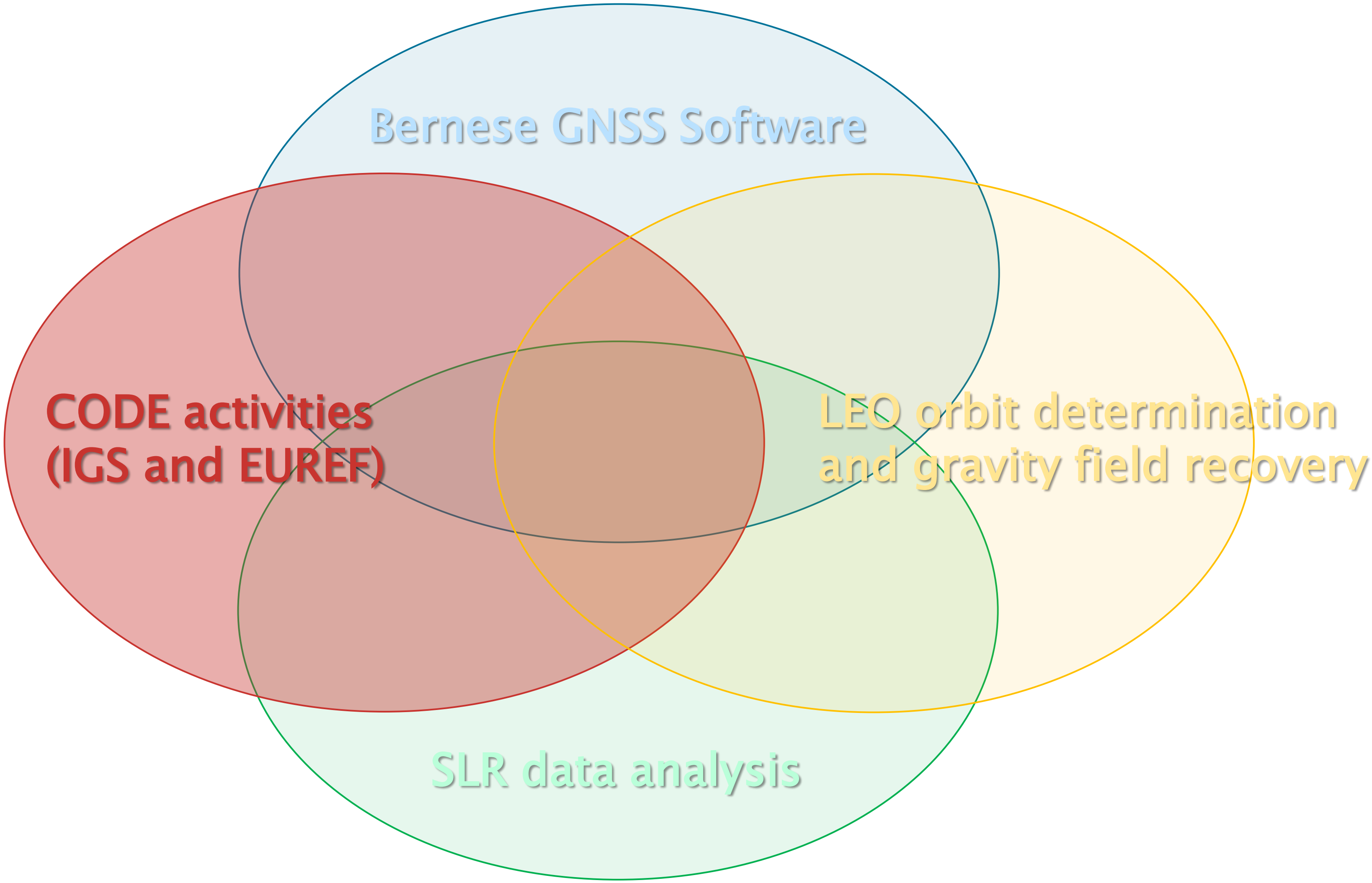
Astronomisches Institut

Satellite Geodesy Research Group



Satellite Geodesy Research Group



Updates from the CODE analysis center

CODE@AIUB in the IGS

- Stefan Schaer:
  Chair Working Group on Biases and Calibration
- Editor of the IGS annual report:
  transfer from Yoomin Jean to Arturo Villiger
- Rolf Dach:
  Member of the Executive Committee of the IGS
- Arturo Villiger:
  Chair of Antenna Working Group

News from CODE analysis center

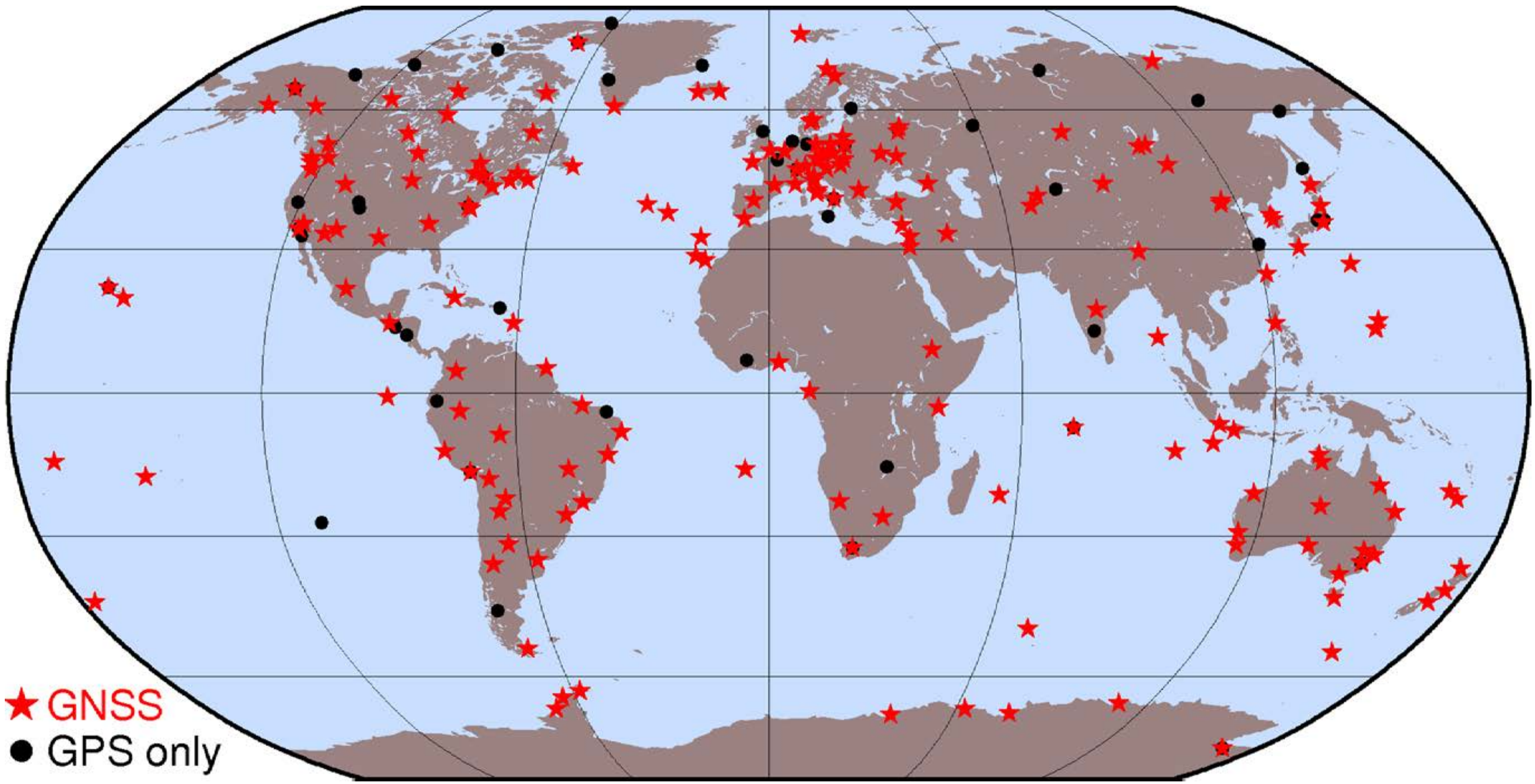
- New URL to access the anonymous FTP:
  ftp://ftp.aiub.unibe.ch/...
  instead of ftp://ftp.unibe.ch/aiub/...

- August: Publication of the EGSIEM repro results:

	GPS	GLONASS
GNSS orbits	since 1994	since 2002
GNSS satellite clocks: 30s	since 2000	since 2008
GNSS satellite clocks: 5s	since 2003	since 2010

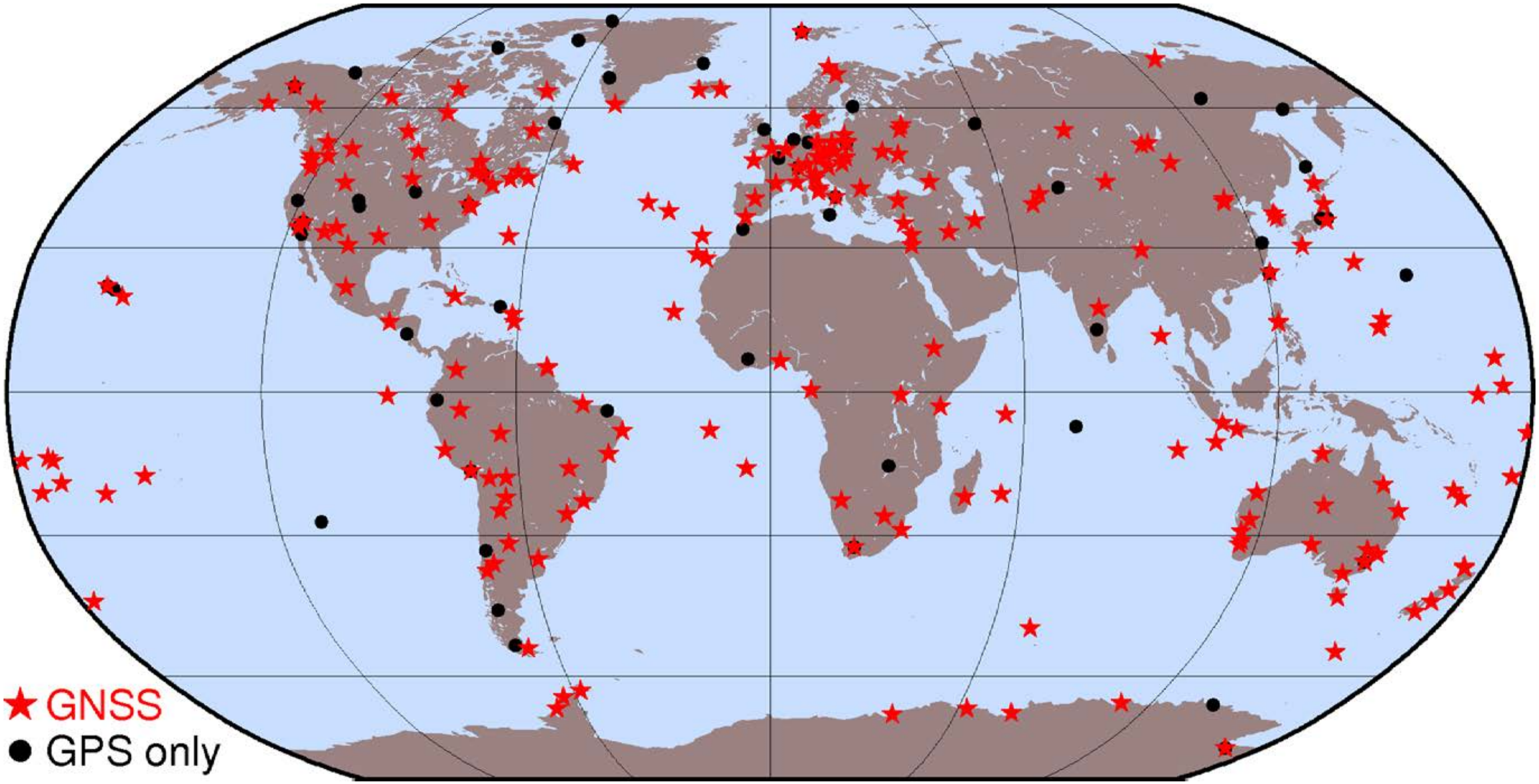
  ftp://ftp.aiub.unibe.ch/REPRO_2015
  (report on results already in 2016)

IGS14 reference frame/PCV since 29. Jan. 2017



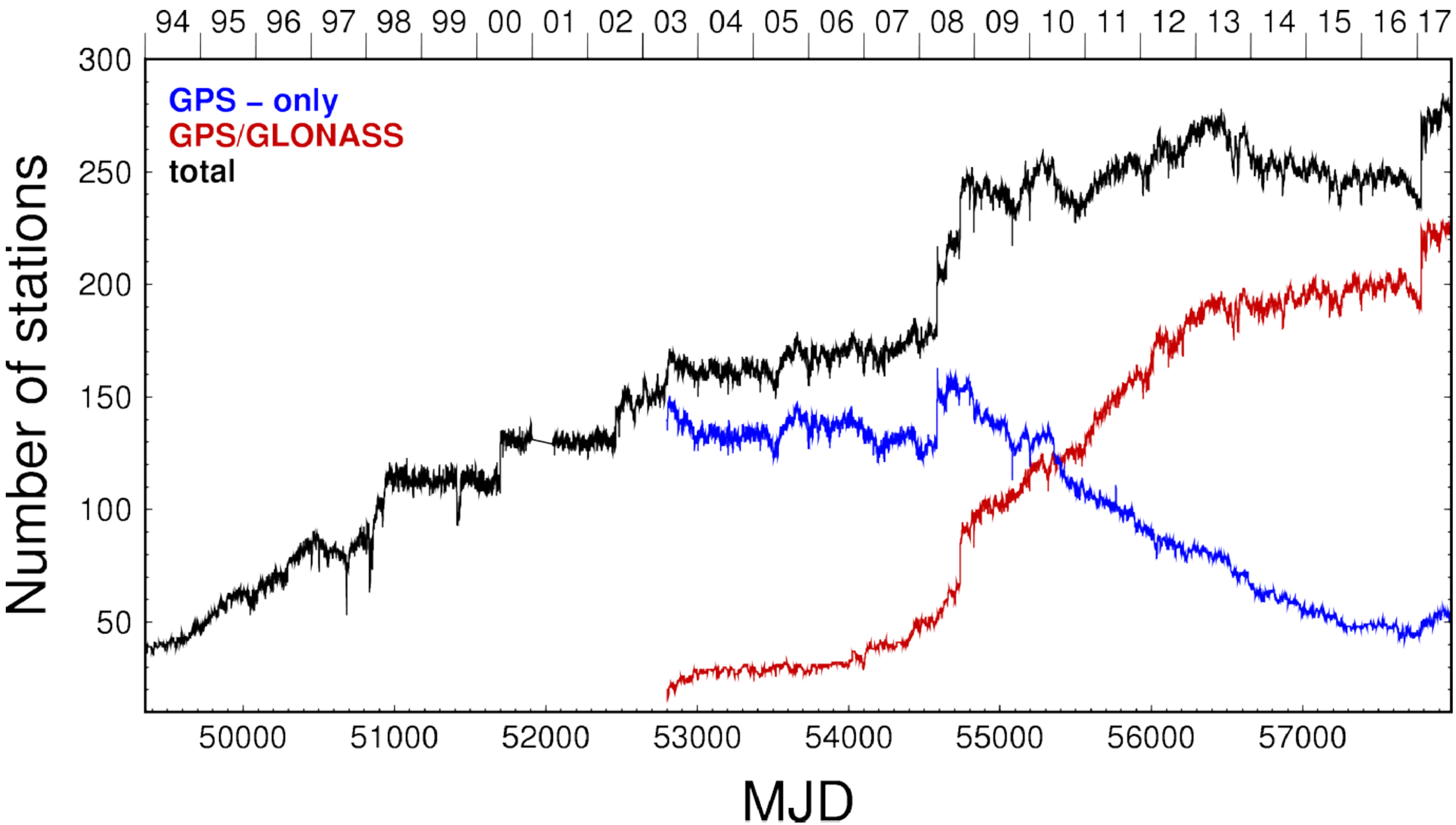
GNSS stations processed for the IGS final series at CODE: Status December 2016

IGS14 reference frame/PCV since 29. Jan. 2017



GNSS stations processed for the IGS final series at CODE: Status March 2017

IGS14 reference frame/PCV since 29. Jan. 2017



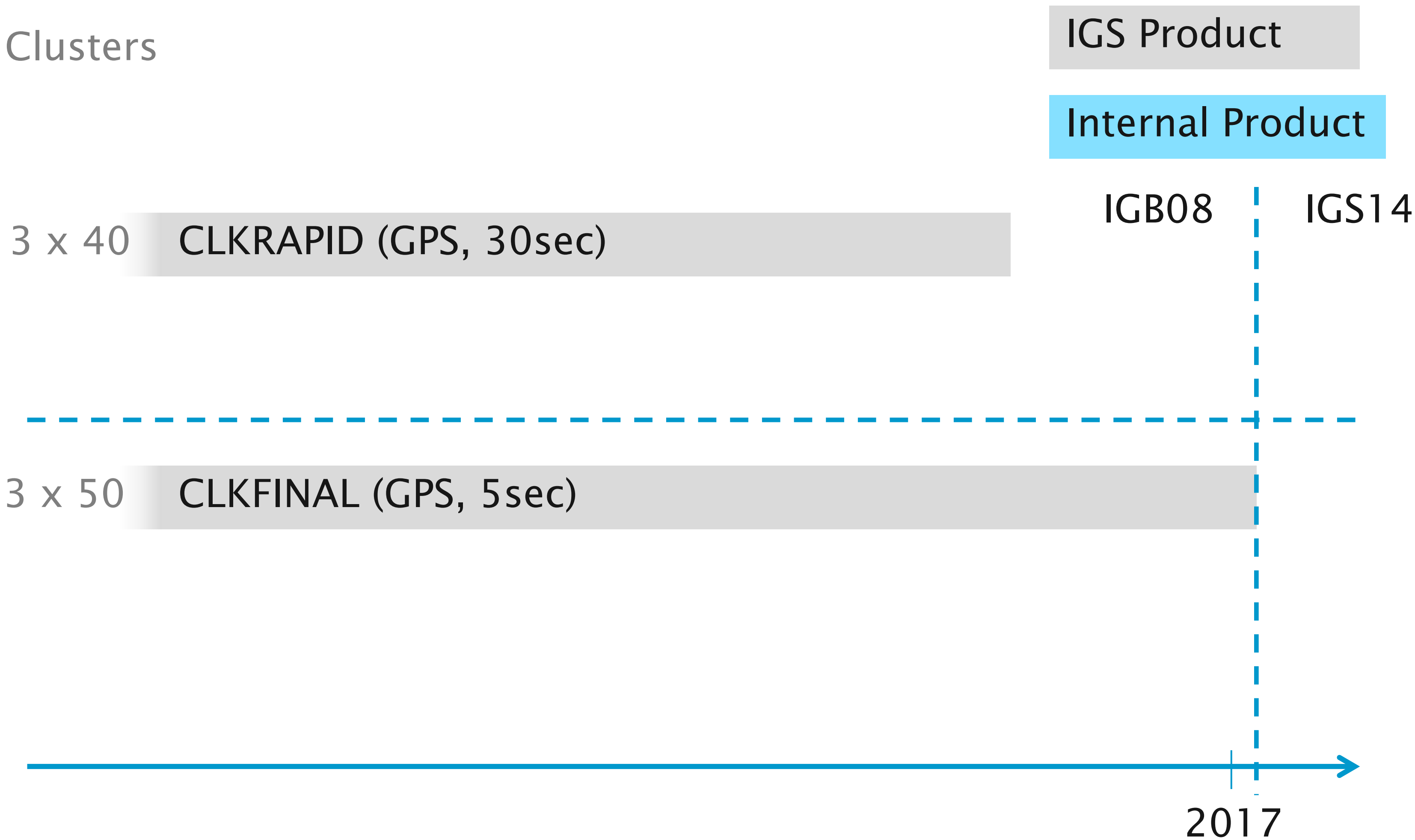
GNSS stations processed for the IGS final series at CODE

News from the CODE analysis center

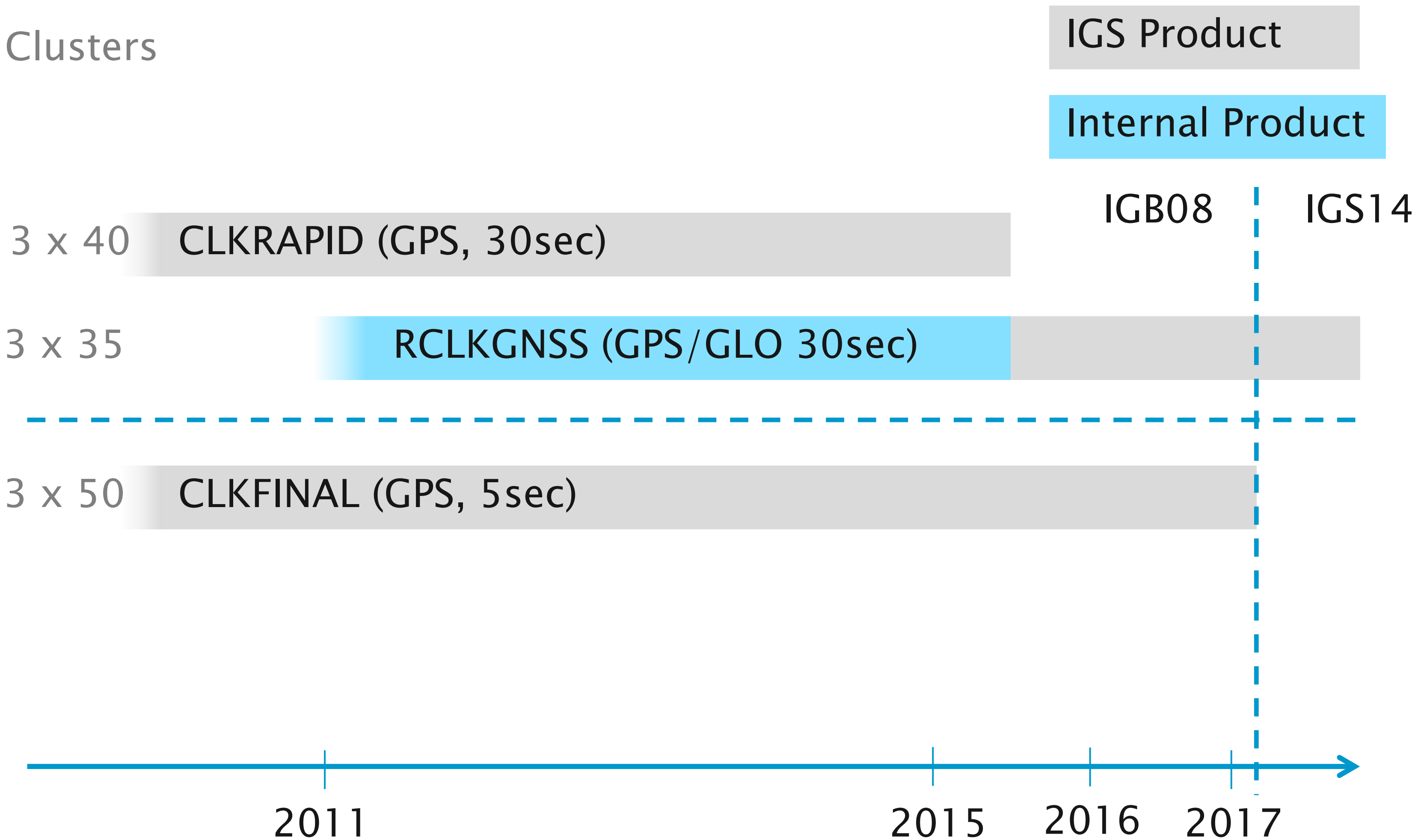
- Preparation for introducing ITRF2014/IGS14 reference frame by January 2017:
  - Diverse updates of the Bernese GNSS Software
  - Updating the list of stations in the final processing
  - Processing starts with RINEX3 file where available
- Improve the robustness of generating clock products («lessons learned» from EGSIEM reprocessing project).

New IGS Final CLOCK Product

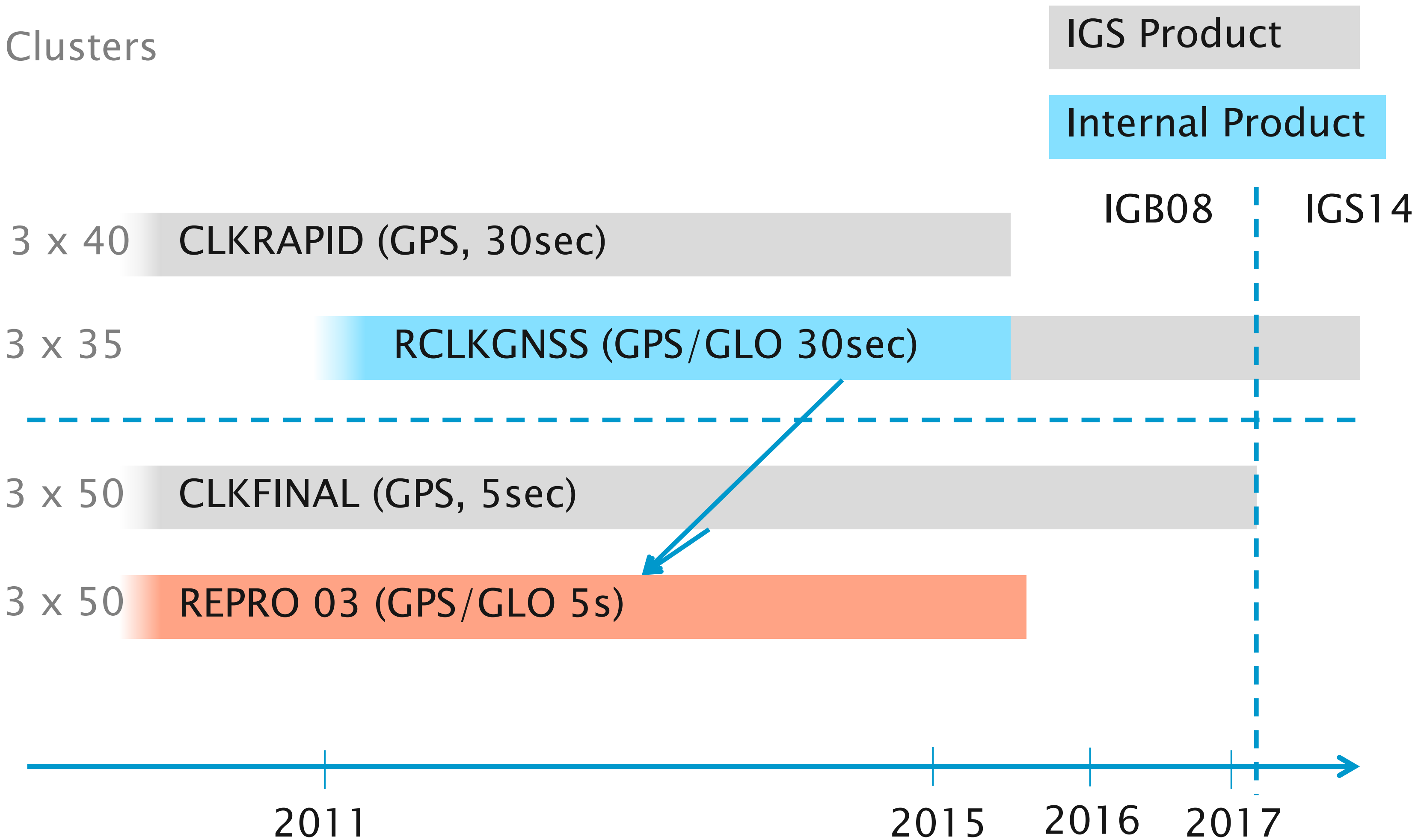
History of Clock Estimation at CODE



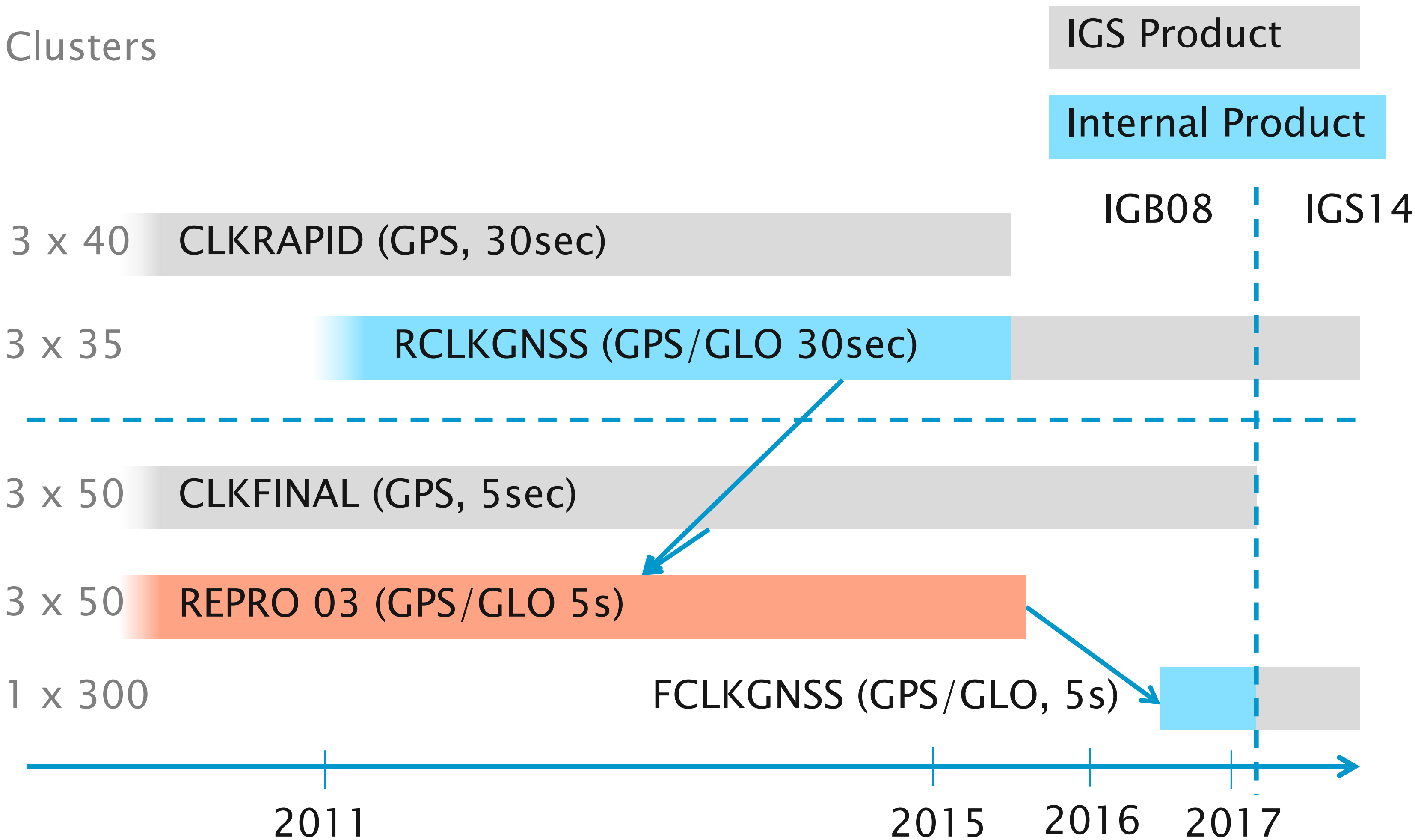
History of Clock Estimation at CODE



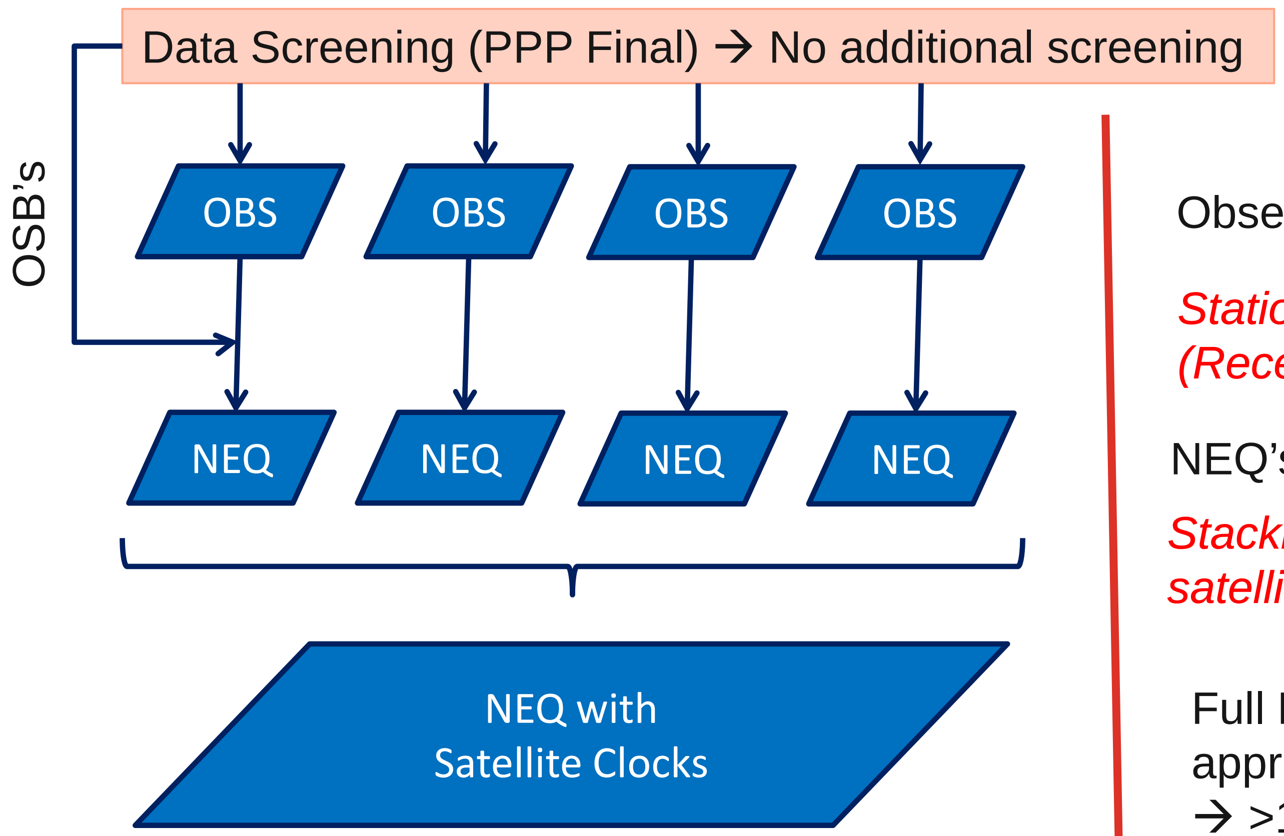
History of Clock Estimation at CODE



History of Clock Estimation at CODE



New Clock Estimation Approach



Observation files from PPP

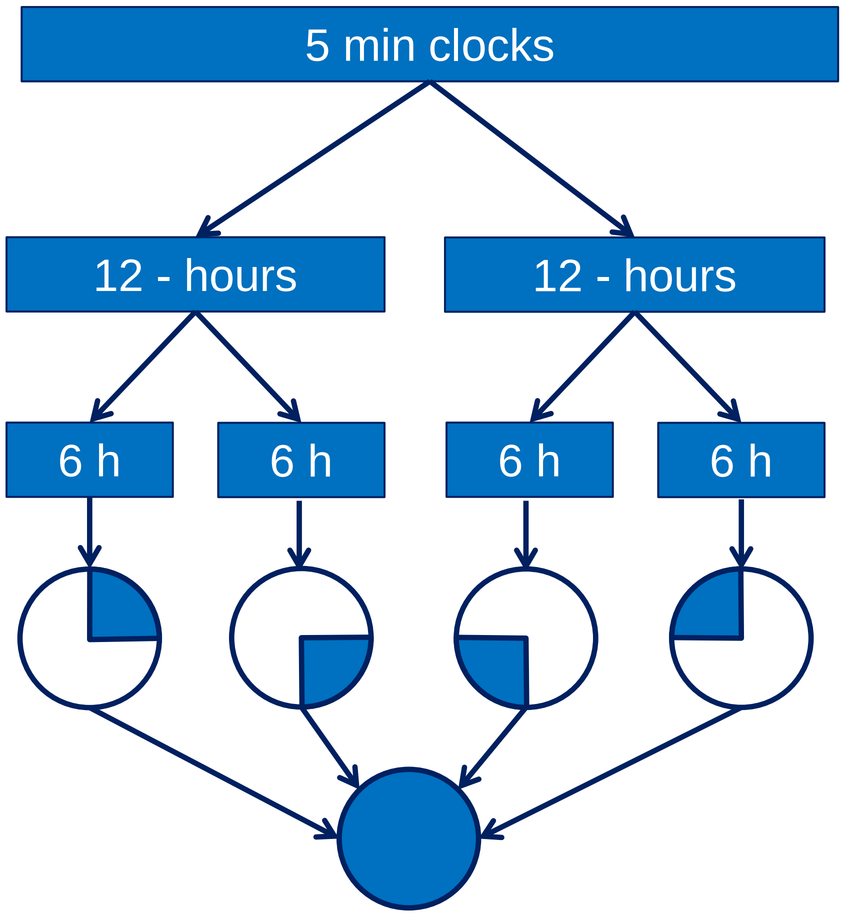
Station-wise clock setup (Receiver clocks pre-eliminated)

NEQ's with satellite clocks

Stacking station-wise satellite clocks

Full NEQ with all satellite clocks approx. (32+24)*288 clocks
→ >16'000 parameters

Satellite Clock Estimation



After 2 hours finished

Full Inversion: > 6 hours

Pre-elimination

12-hours NEQs

Pre-elimination

6-hours NEQs

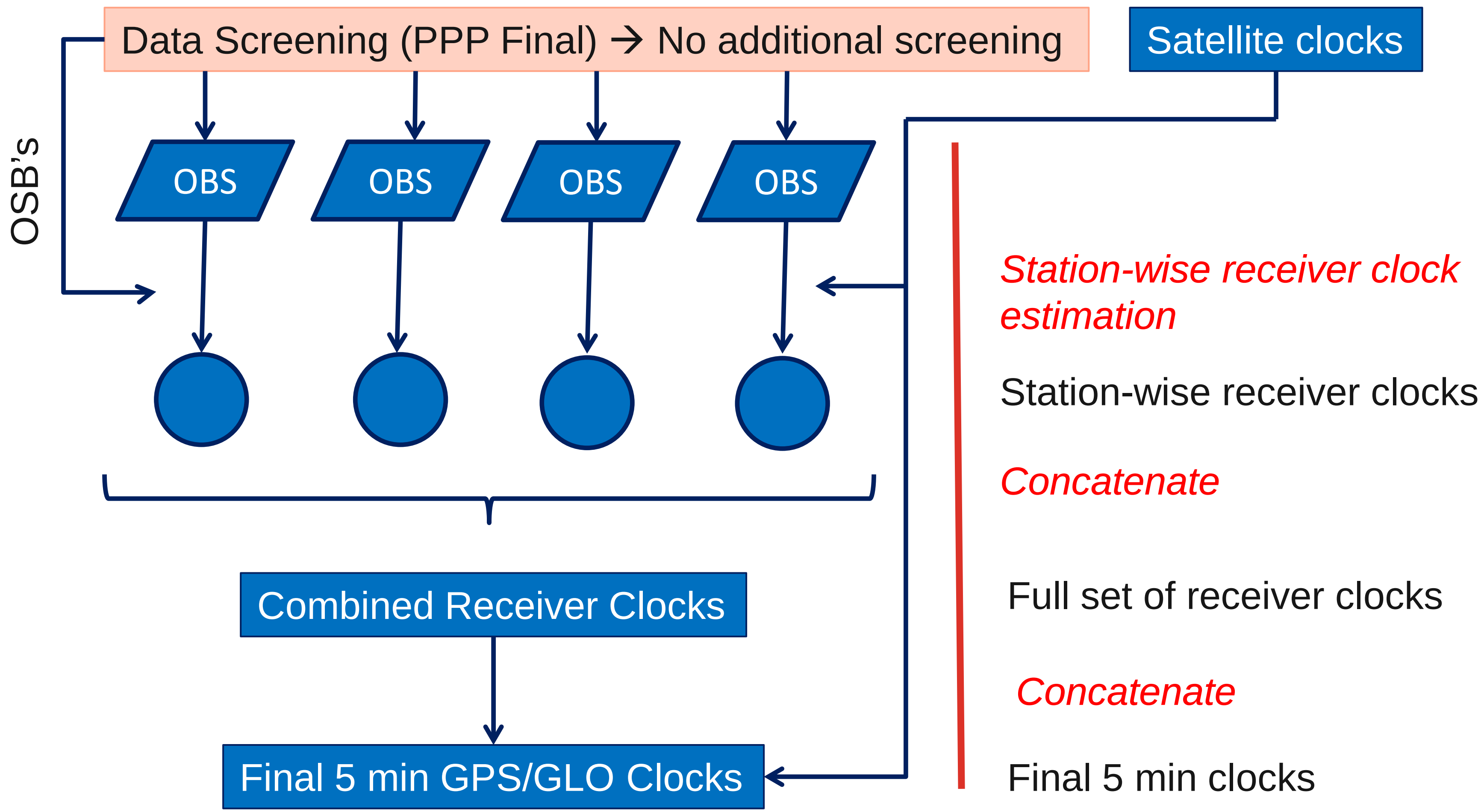
Inversion

6-hours clocks

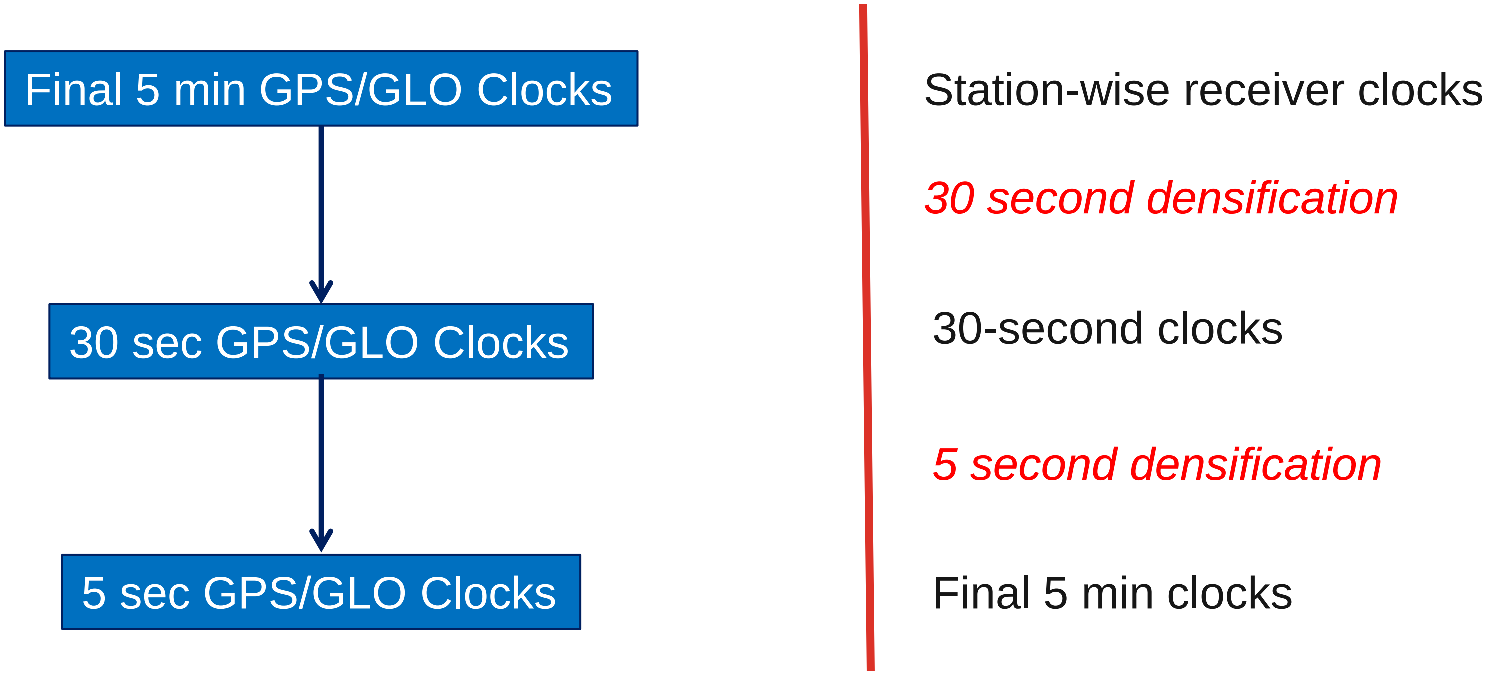
Concatenate

Full set of satellite clocks

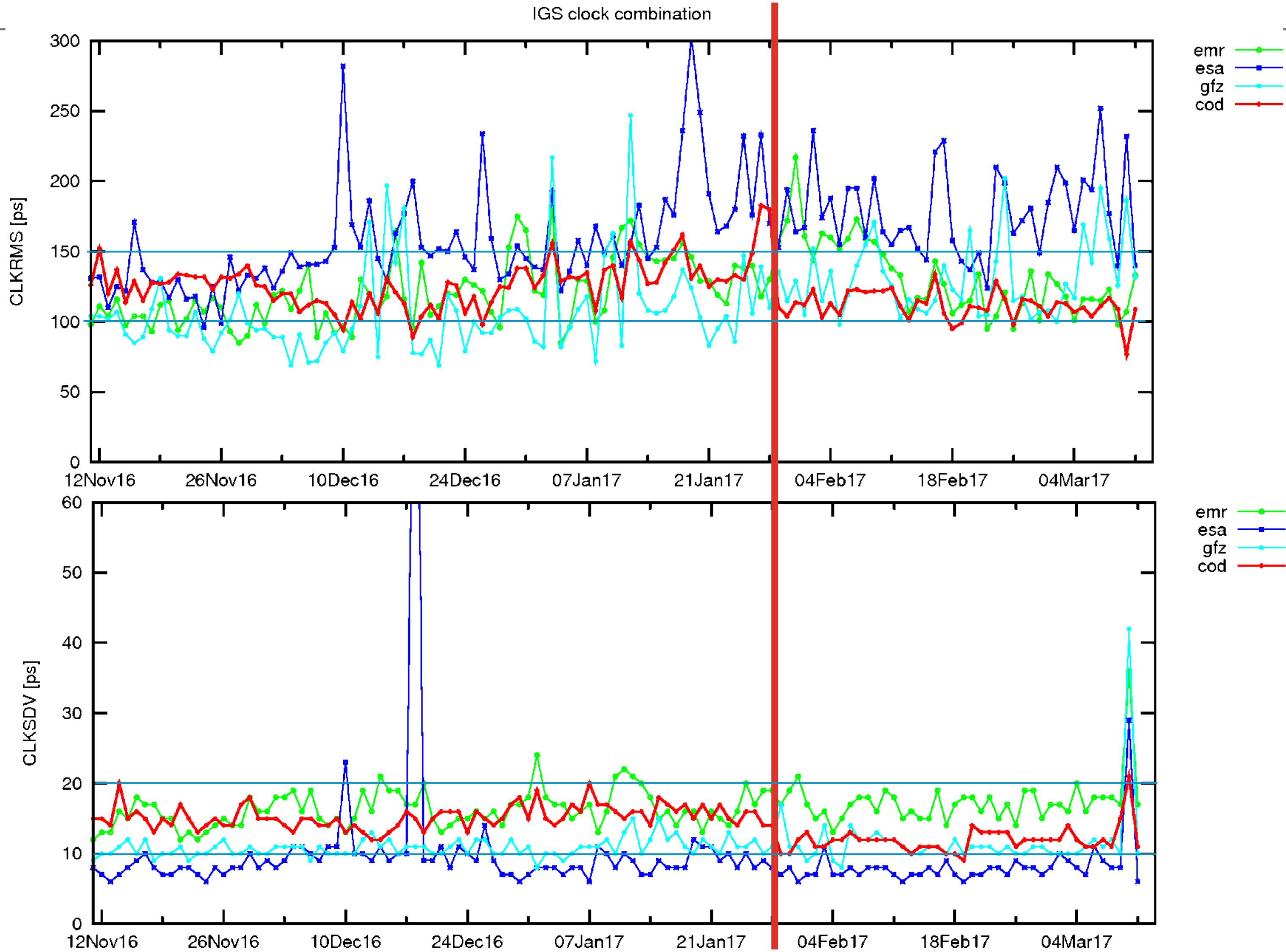
Receiver Clock Estimation



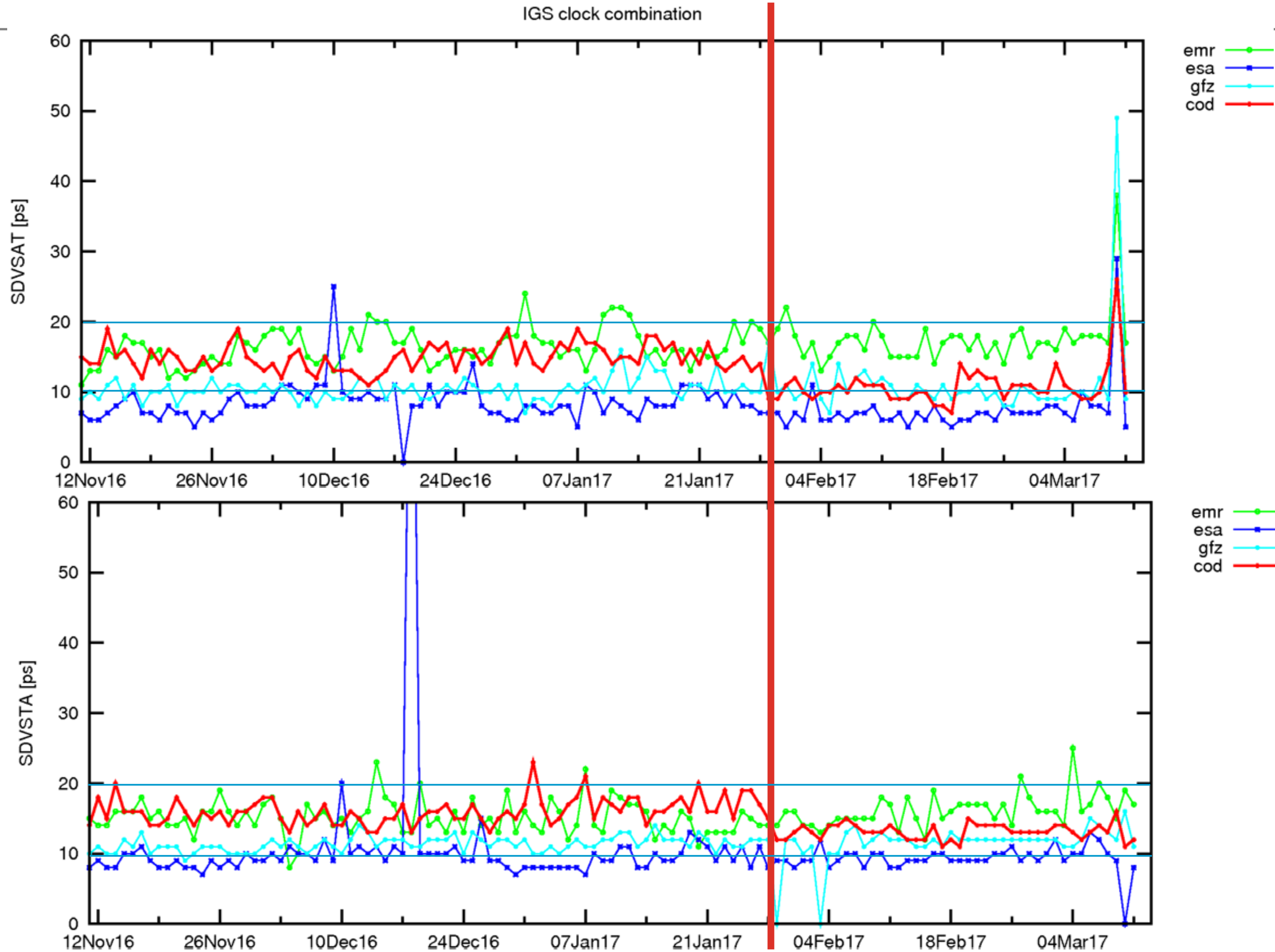
Clock Densification



IGS Combination Statistics

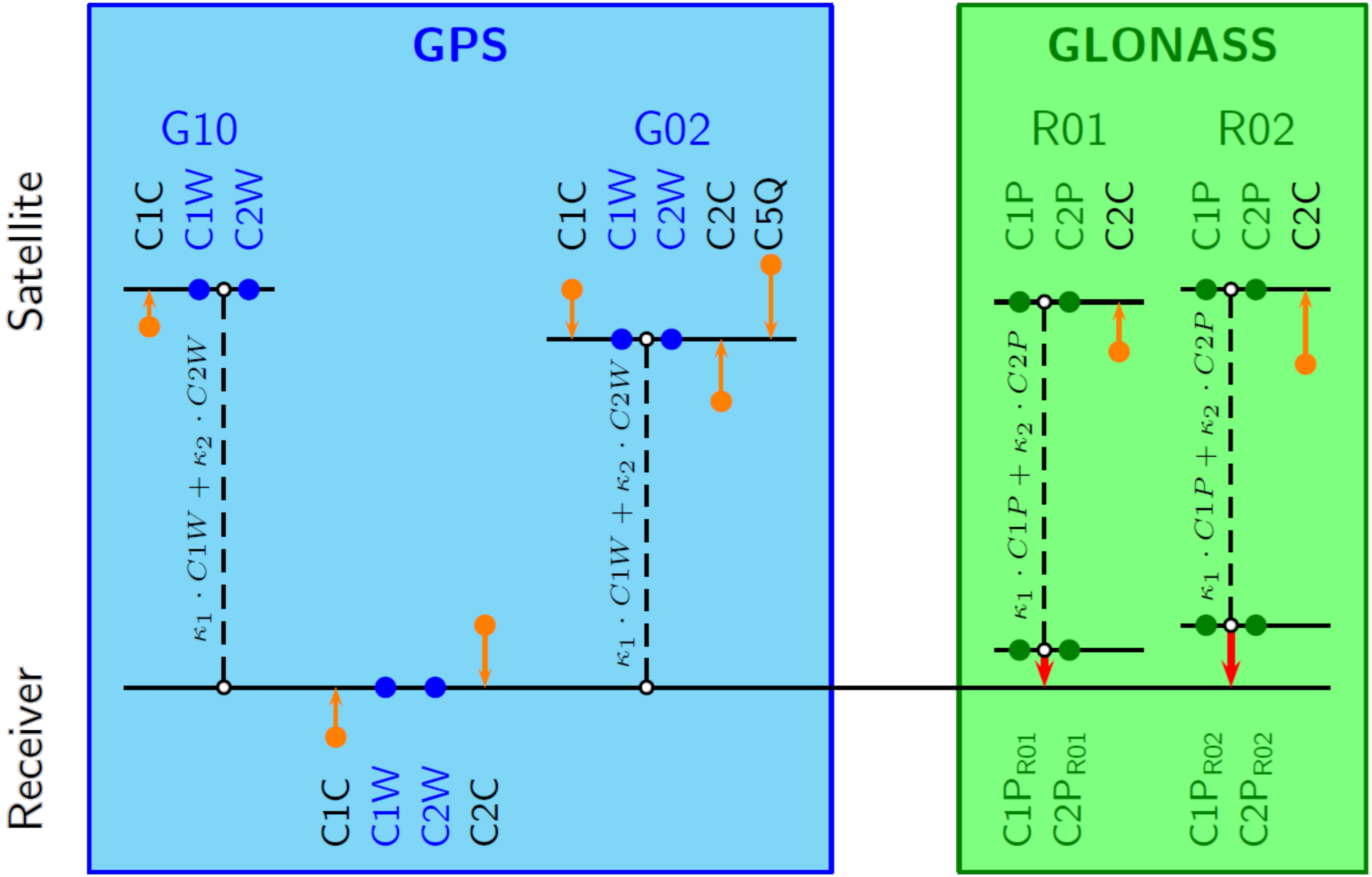


IGS Combination Statistics

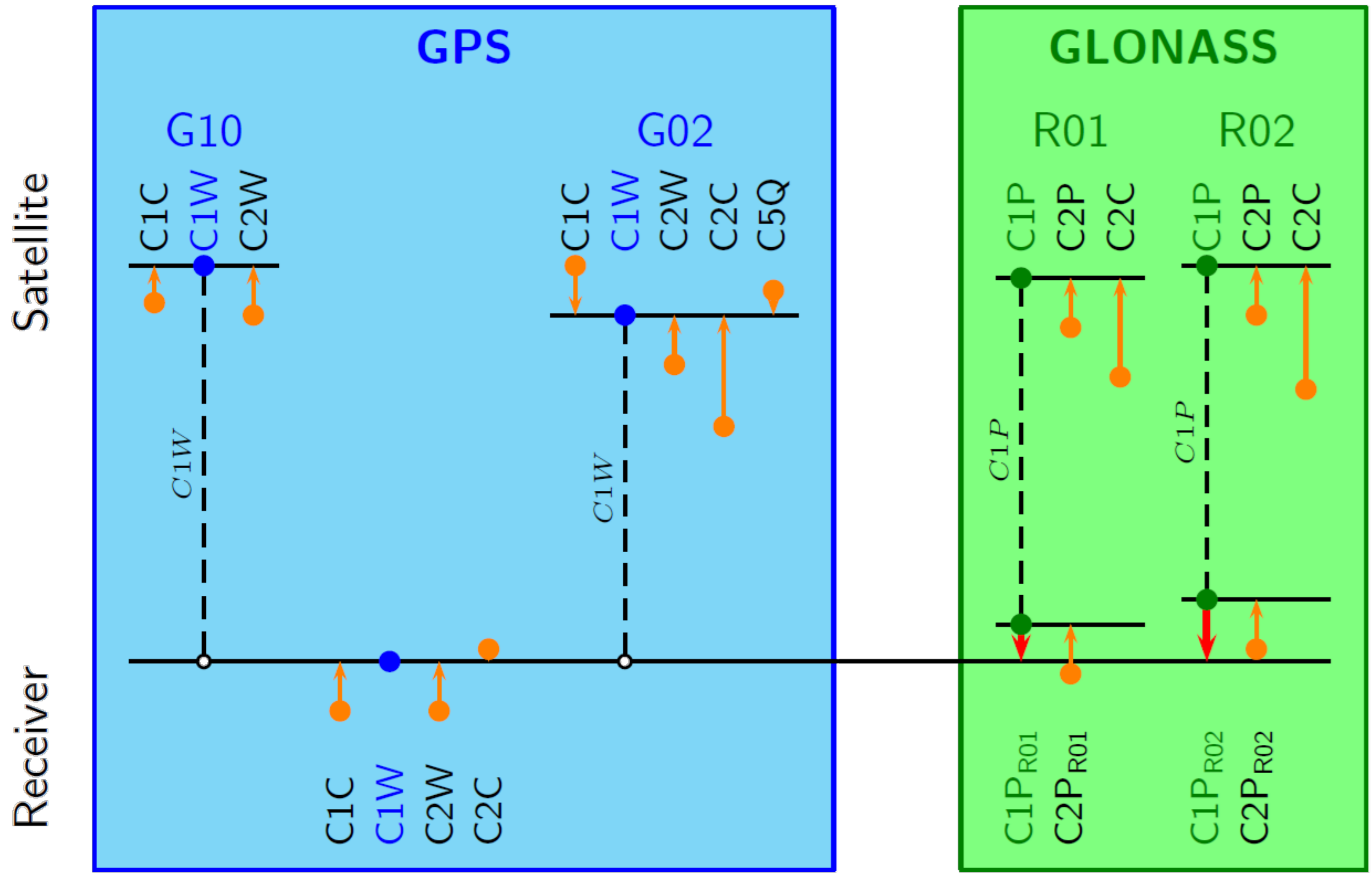


Reprocessing of GNSS code biases based on the new bias handling scheme in the Bernese GNSS Software

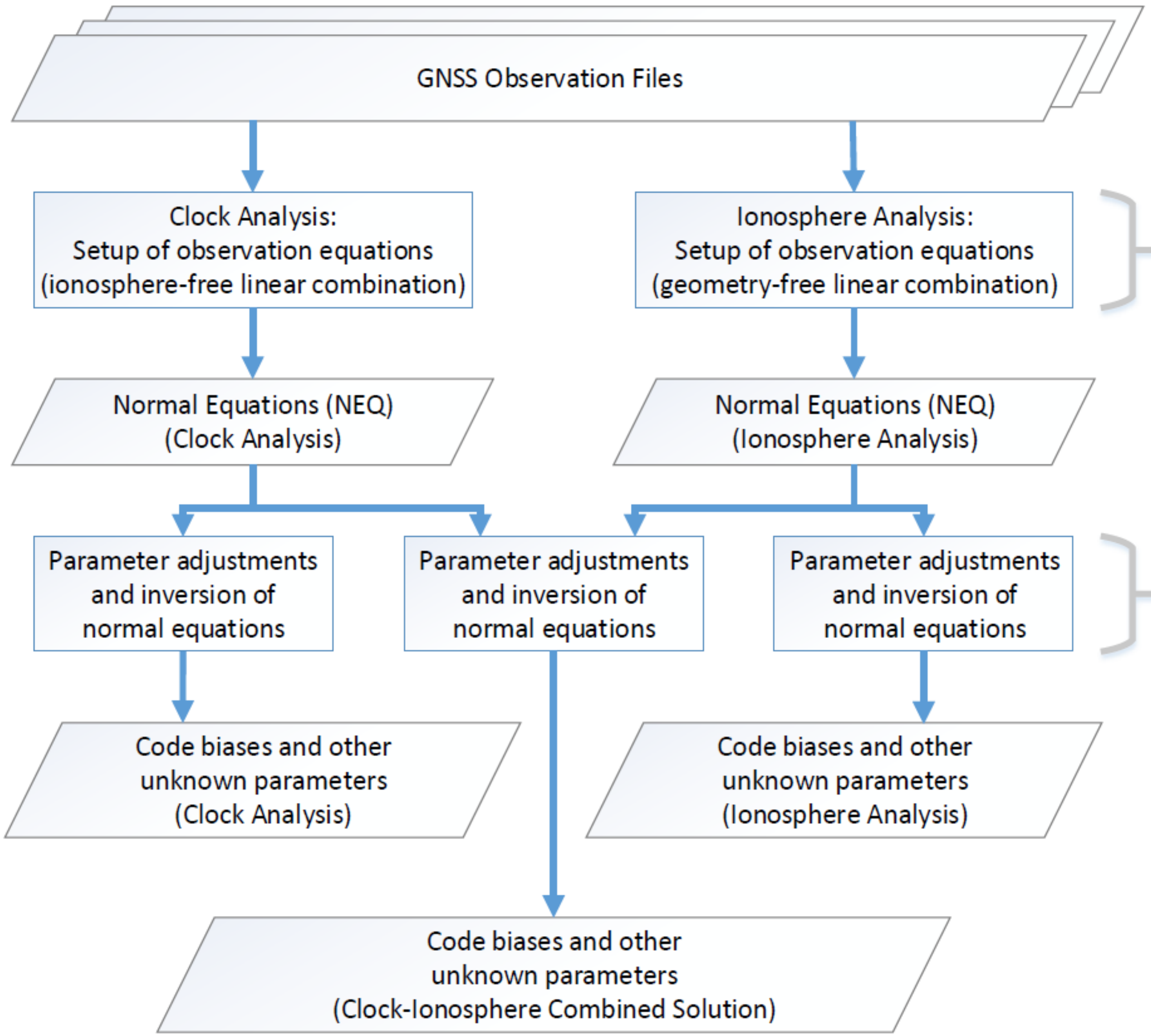
Pseudo–Absolute Code Biases: CLK



Pseudo-Absolute Code Biases: CLK+ION



CODE's new Bias Estimation Workflow

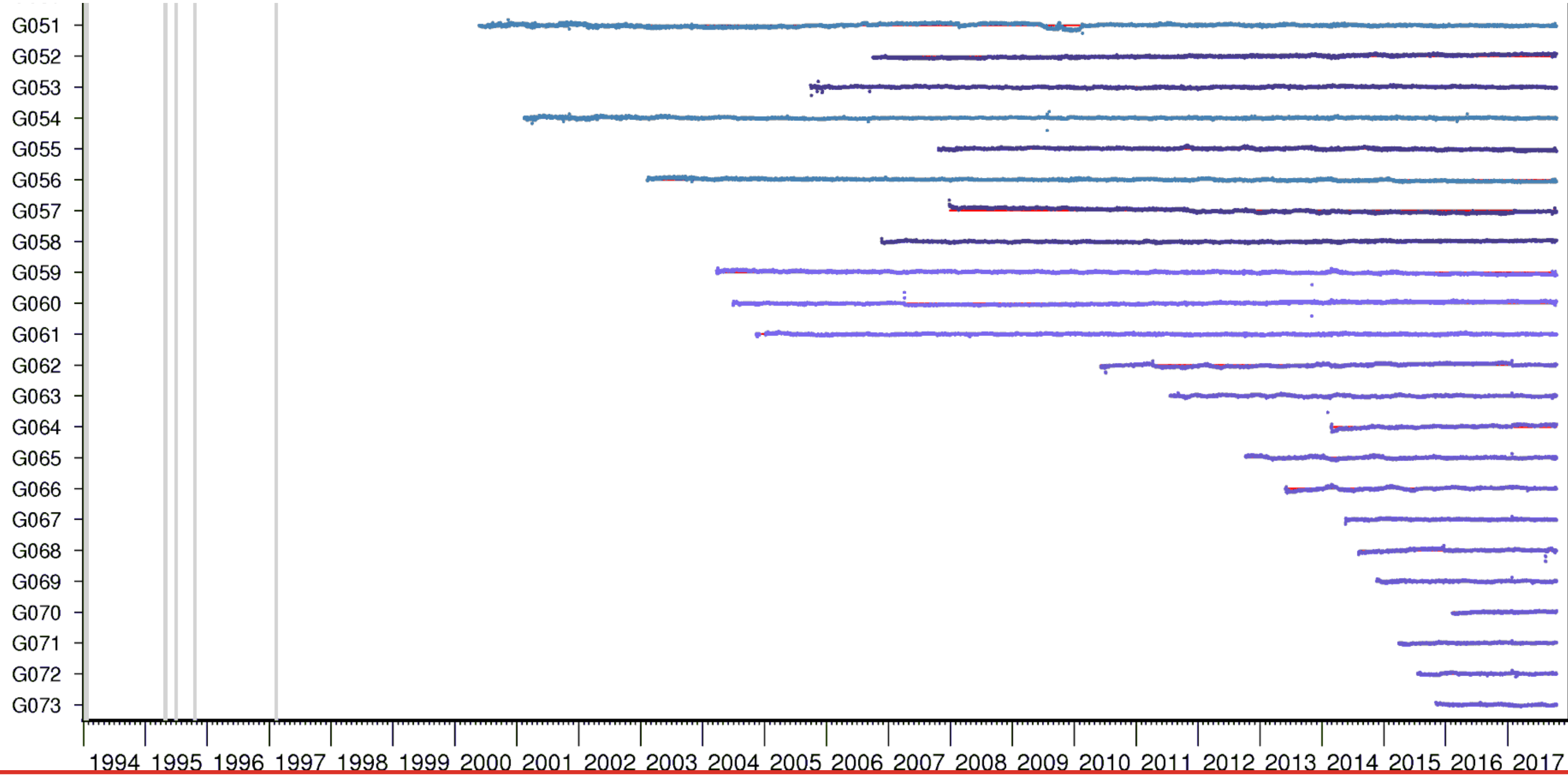


- Code bias parameters specific to each observable
- Without code bias datum definition.

- Selection of reference observables for the current IGS clock convention.
- Bias datum definition imposed on (combined) NEQ-system.

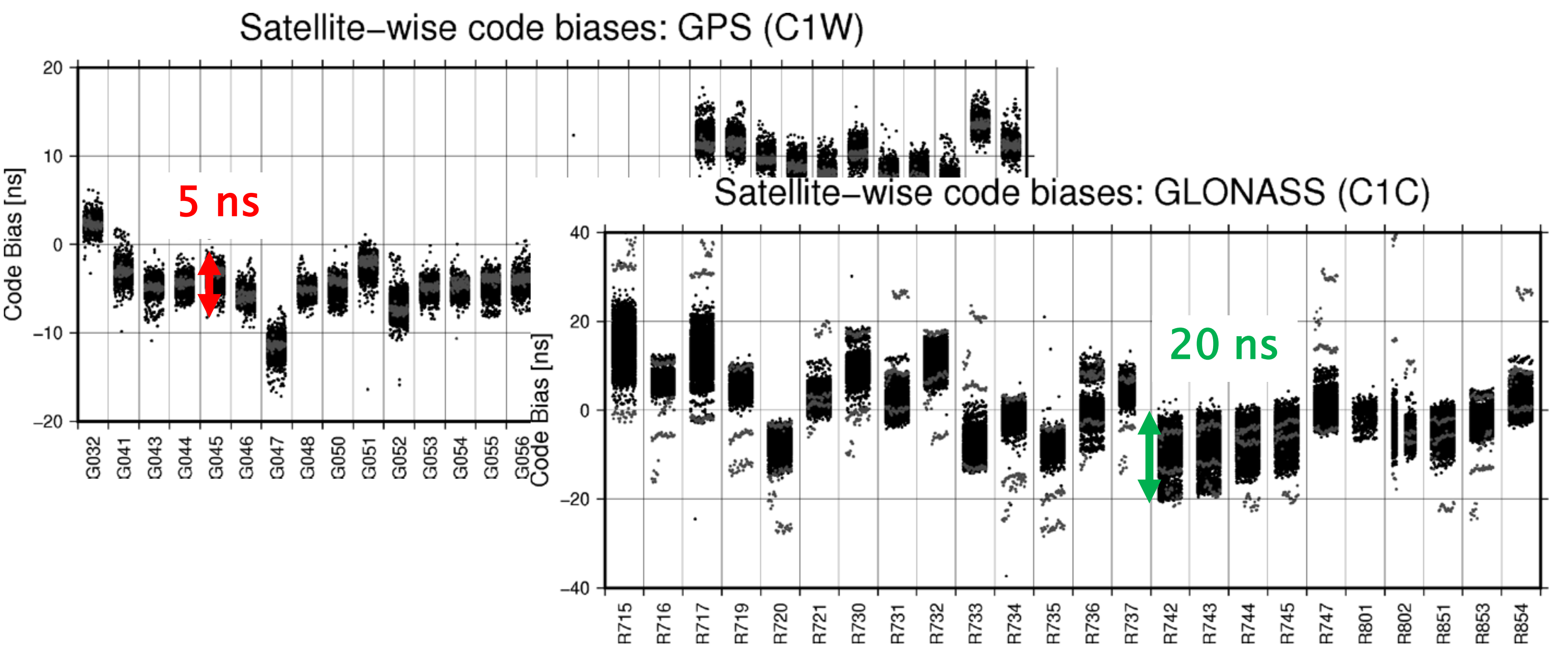
Estimation of GNSS Code Biases

- Estimation of observable-specific code biases (OSB)
- Reprocessing from 1994 to 2016 finished →
- Long-time OSB product is estimated at CODE (and updated with each IGS Rapid and Final process, internal product)



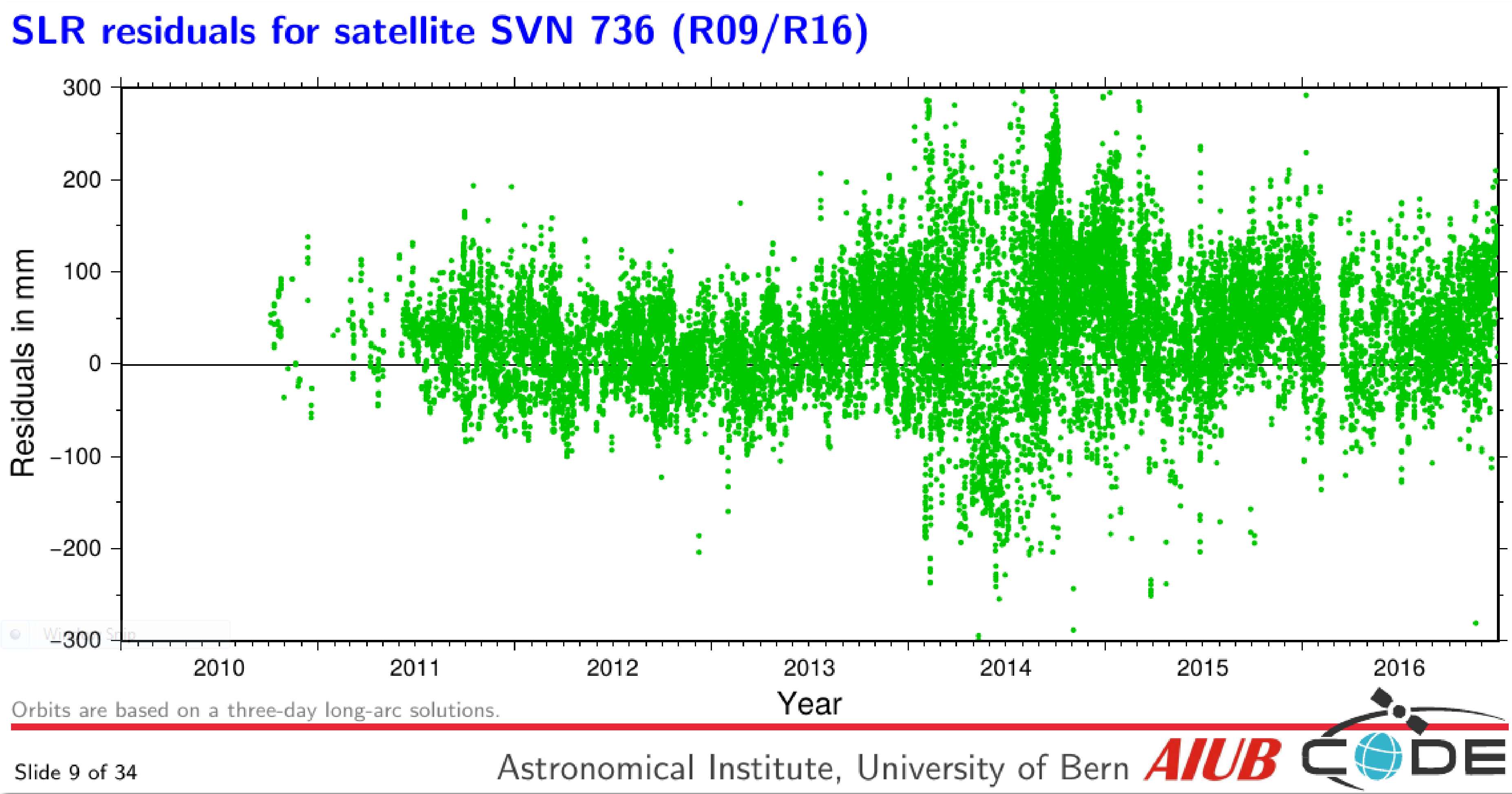
CDMS (GPS) vs FDMS (GLO): Code bias estimation

- GPS and GLONASS setup as receiver-satellite biases
- OSB station-wise detrended (removing receiver bias)
- System-wise GLONASS biases do improve solutions, but satellite-receiver parametrization more feasible



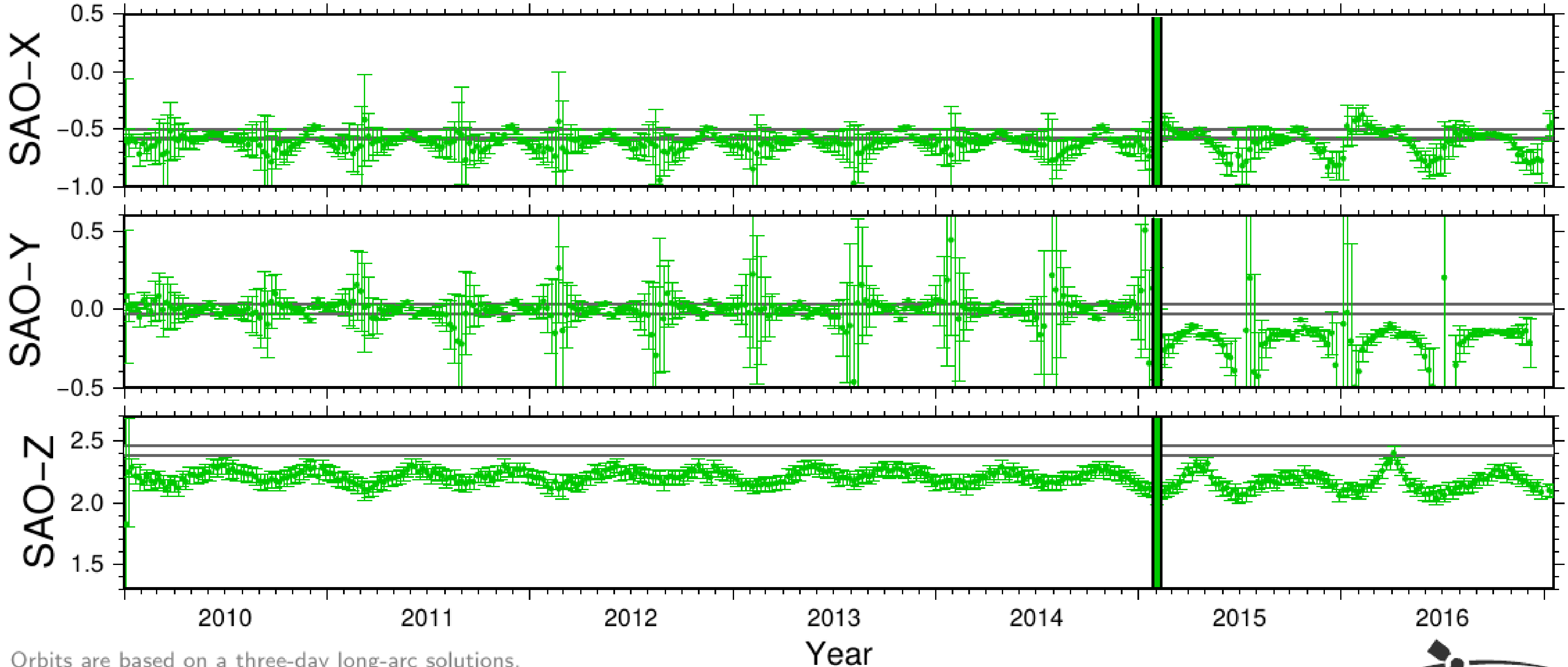
Solving the GLONASS miracle

The GLONASS-miracle: SLR residuals



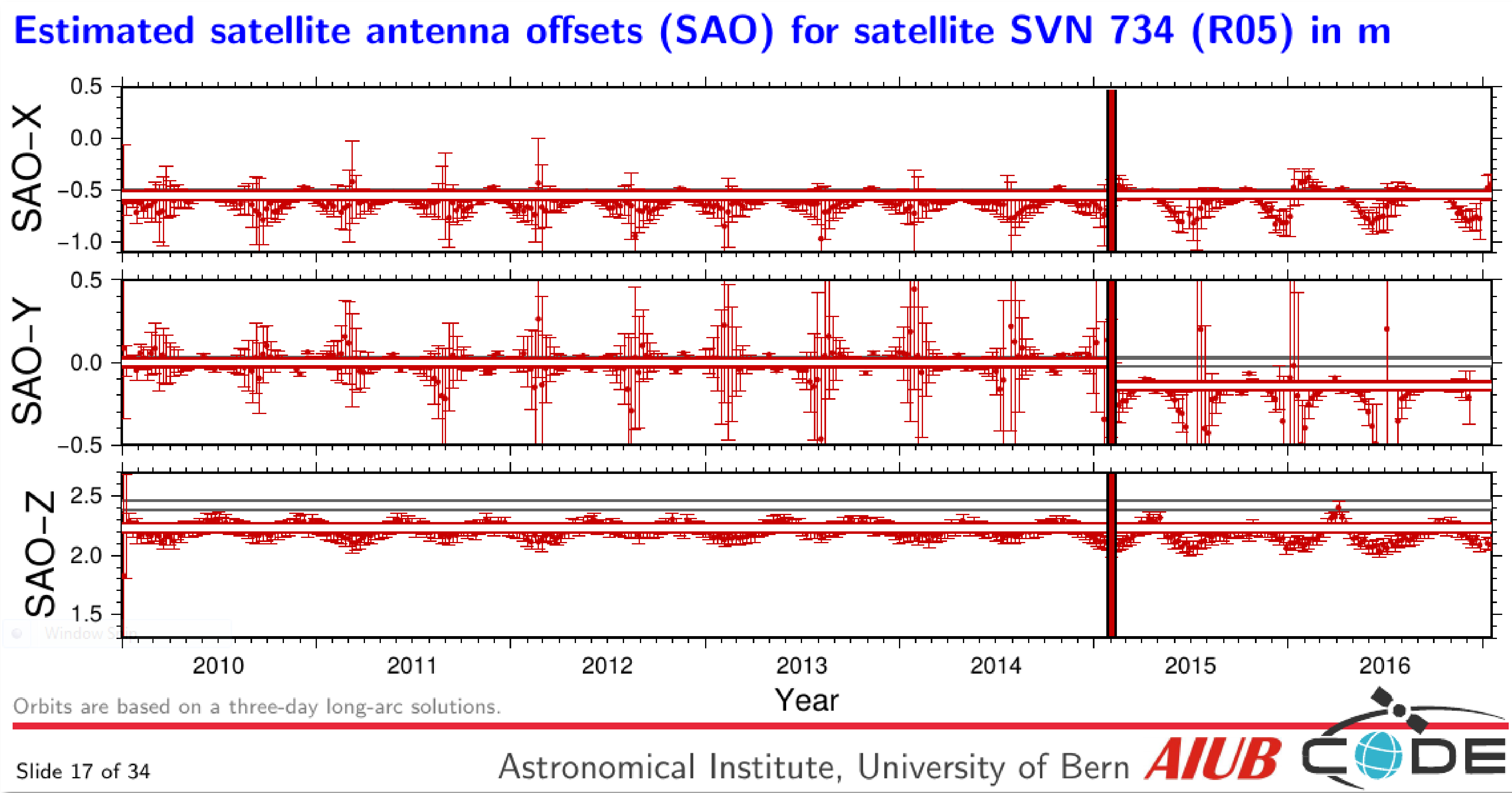
Estimating satellite antenna offsets

Estimated satellite antenna offsets (SAO) for satellite SVN 734 (R05) in m

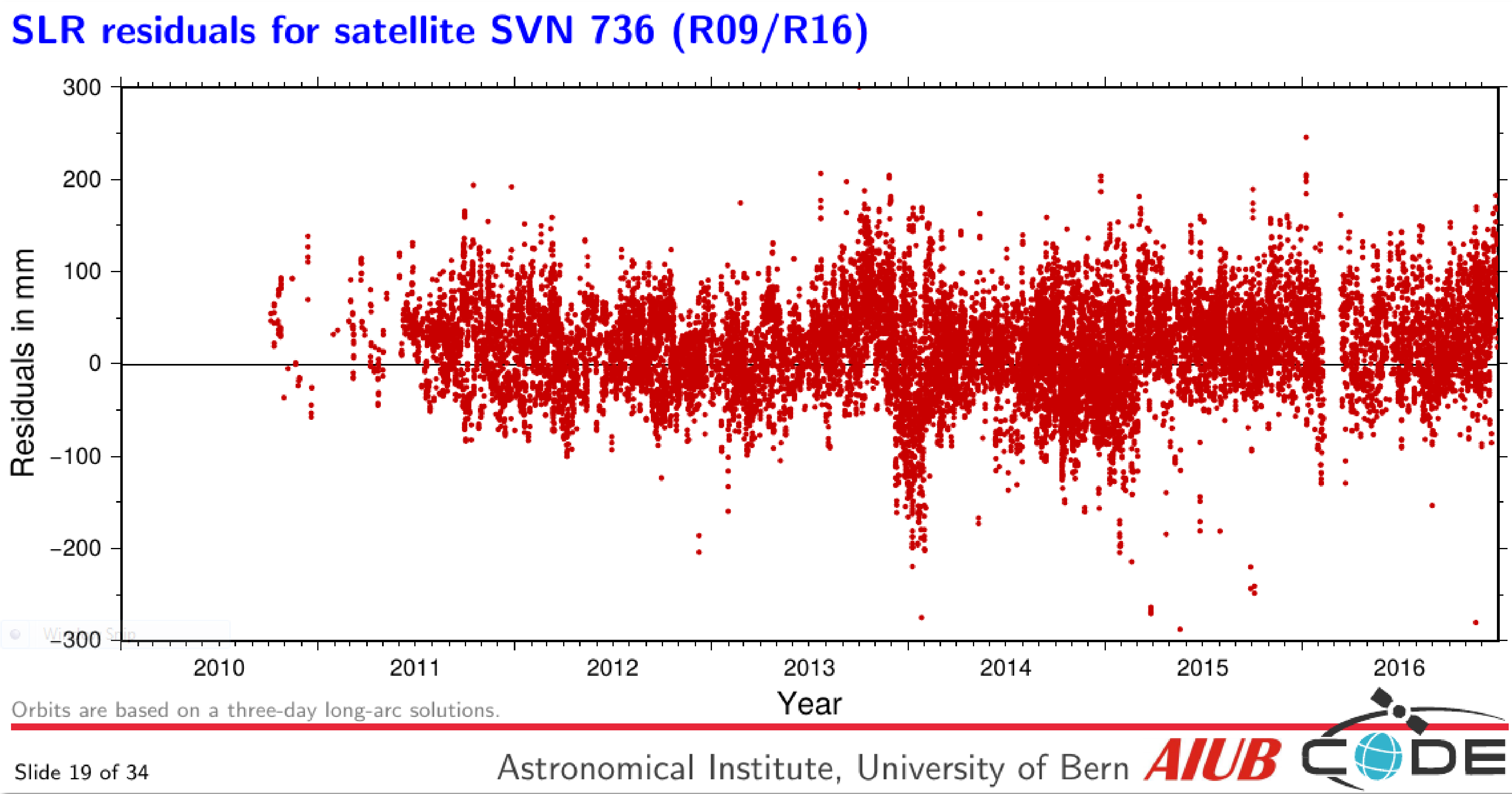


Orbits are based on a three-day long-arc solutions.

Estimating satellite antenna offsets

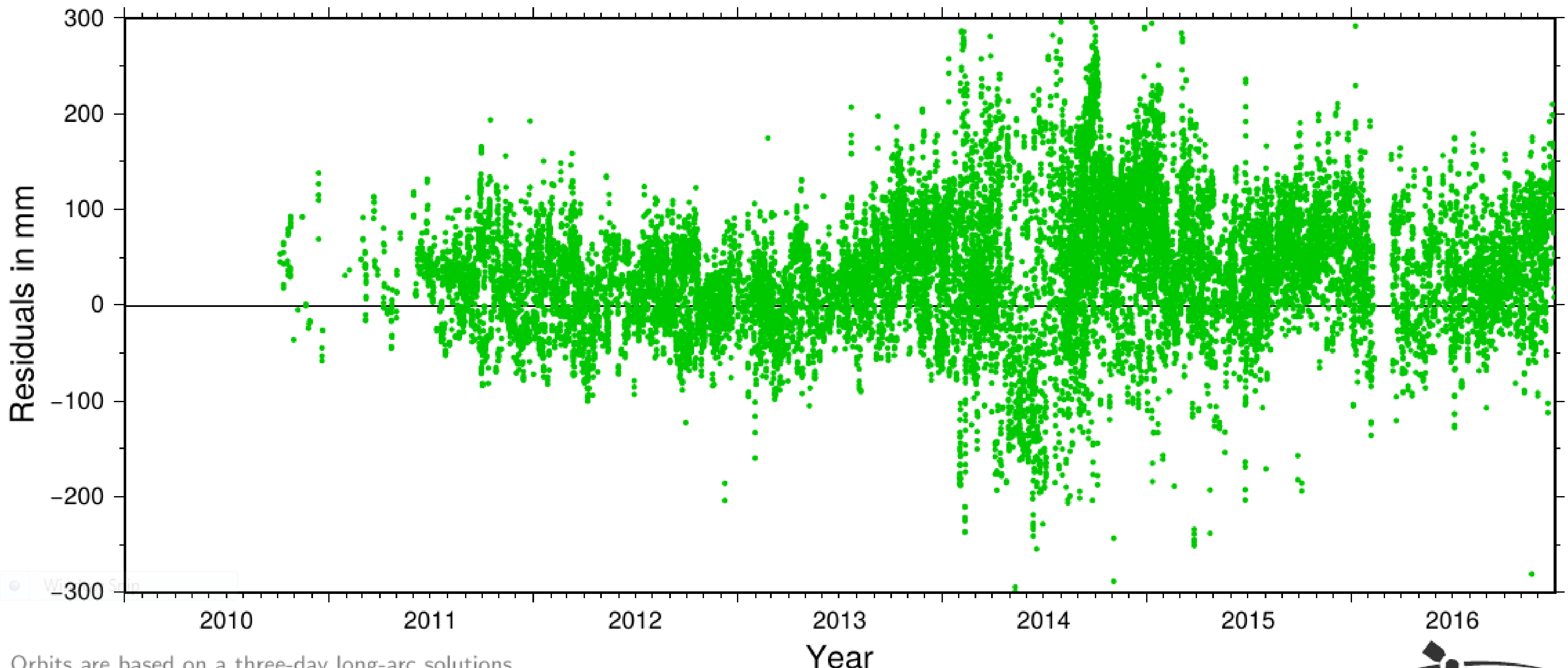


SLR residuals with re-estimated SAO



SLR residuals with original SAO

SLR residuals for satellite SVN 736 (R09/R16)



Orbits are based on a three-day long-arc solutions.

Discussion: option 1

What could be the reason at the spacecraft?

Shift of the center of mass:

If the satellite has roughly a mass of 1500 kg, 150 kg need to be shifted by 1 m in order to generate a COM shift of 10 cm.

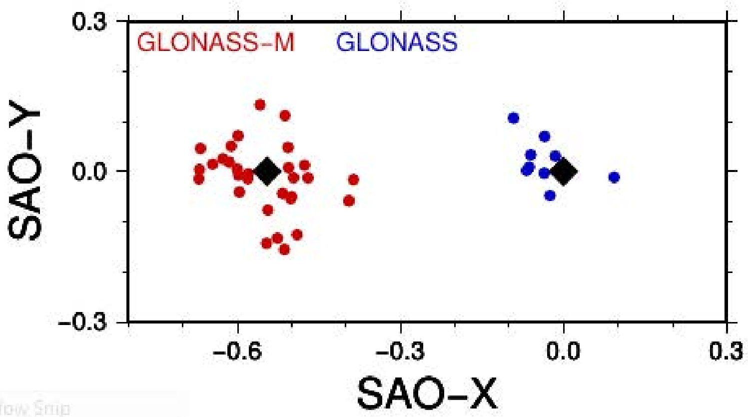
http://spaceflight101.com/spacecraft/glonass-m/

Discussion: option 2

What could be the reason at the spacecraft?

Issue with satellite antenna:

Not likely because SAO-Z is not affected in most cases and the SAO-X/Y estimates do not show a pattern



http://spaceflight101.com/spacecraft/glonass-m/

Discussion: option 3

What could be the reason at the spacecraft?

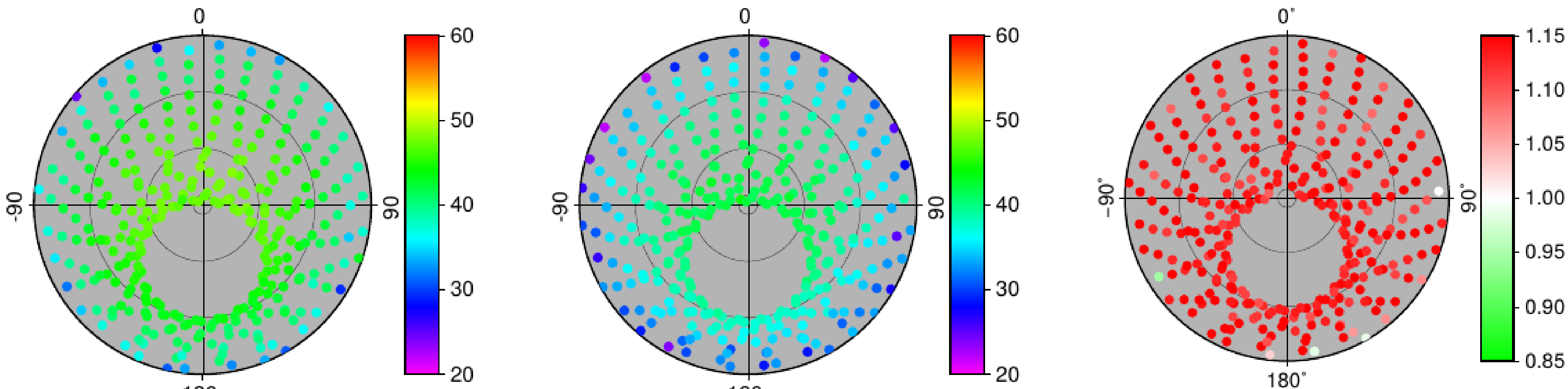
Satellite attitude misorientation:
The satellite plane with the navigation antenna and the SLR reflector is about 2 m away from the center of mass.
A shift of 10 to 15 cm results in a tilt of the 3 to 4 degree of the satellite body.

http://spaceflight101.com/spacecraft/glonass-m/

Discussing signal strength measurements

Signal strength measurements S2 in dbHz for satellite SVN 732 (R23)

(Station Casey, Antartica (CAS1; rec: `TRIMBLE NETR9`; ant: `LEIAR25.R3 LEIT`)



before event
2014: 341-349

after event
2015: 084-091

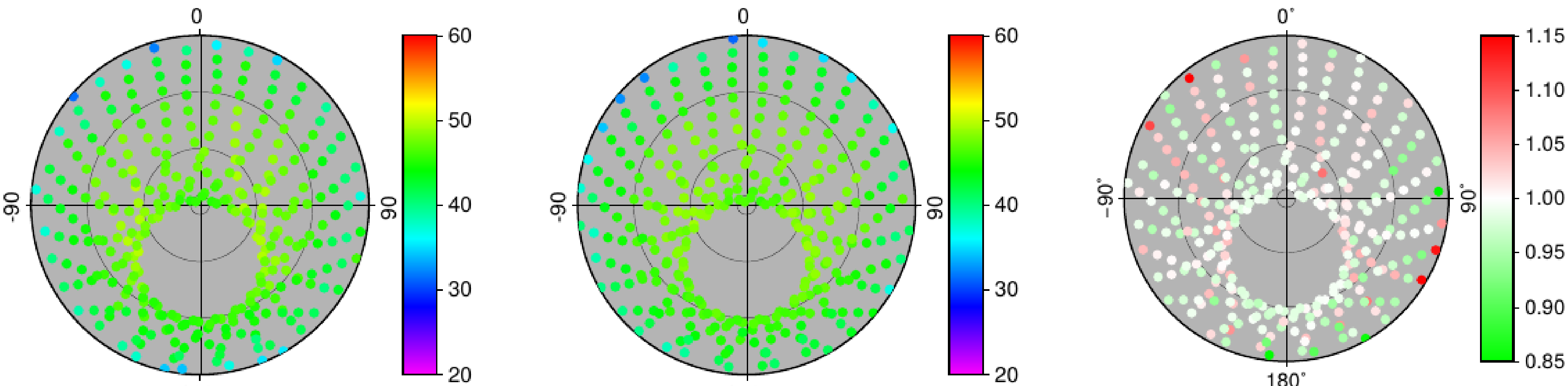
ratio (before/after)
median 1.140 (0.040)

Signal strength measurements extracted from RINEX observation files.

Discussing signal strength measurements

Signal strength measurements S1 in dbHz for satellite SVN 732 (R23)

(Station Casey, Antartica (CAS1; rec: `TRIMBLE NETR9`; ant: `LEIAR25.R3 LEIT`)



before event 2014: 341-349 | after event 2015: 084-091 | ratio (before/after) median 0.994 (0.033)

Signal strength measurements extracted from RINEX observation files.

Summary and conclusions

What could be the reason at the spacecraft?

- Shift of the center of mass:
  If the satellite has roughly a mass of 1500 kg, 150 kg need to be shifted by 1 m in order to generate a COM shift of 10 cm.
- Issue with satellite antenna or related electronic components:
  Not likely because SAO-Z is not affected in most cases and the SAO-X/Y estimates do not show a pattern; but strong effect in the signal strength in about two third of the cases.
- Satellite attitude misorientation:
  A shift of 10 to 15 cm results in a tilt of the 3 to 4 degree of the satellite body.

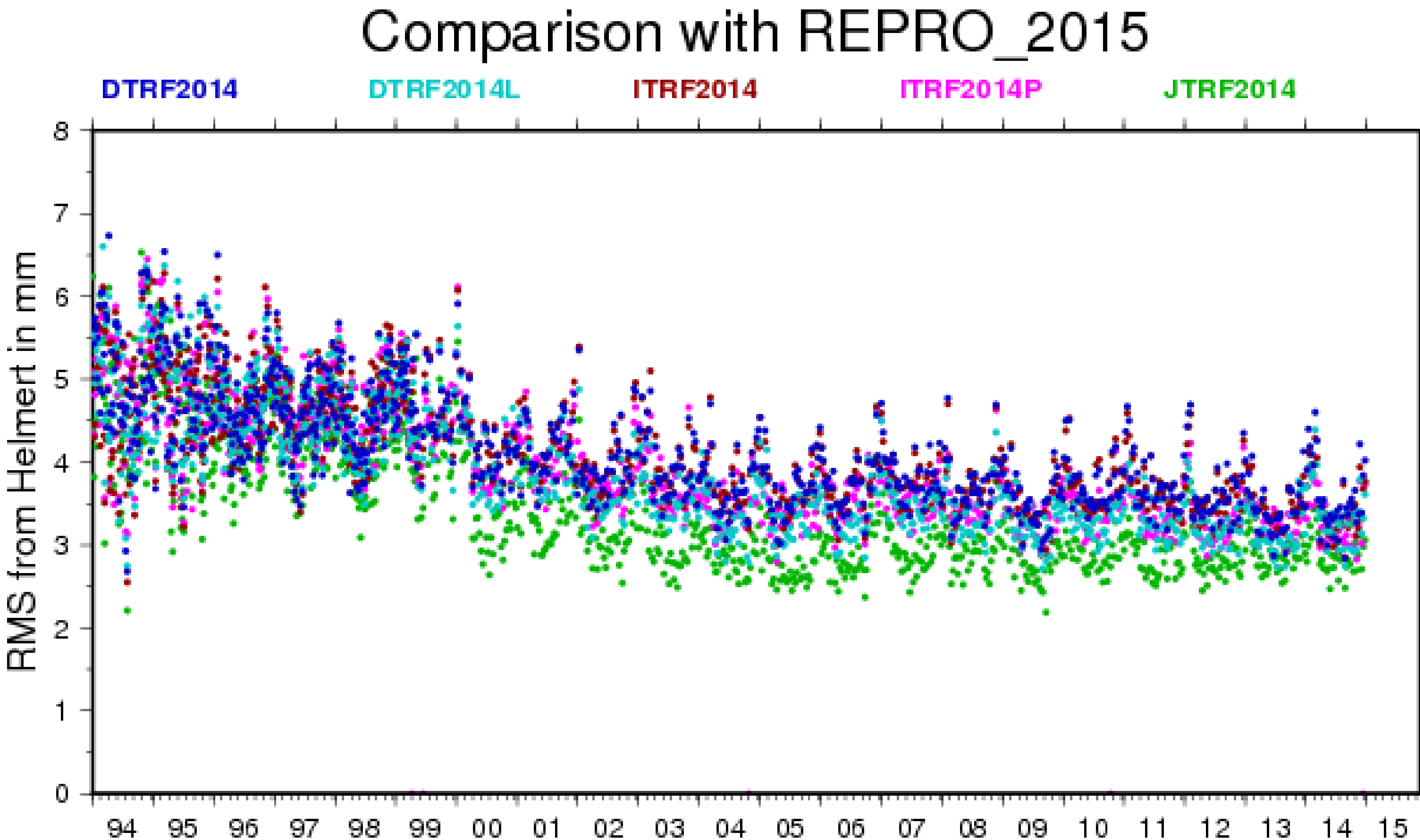
The usage of the estimated SAOs obviously helps to reduce the SLR residuals.

Introducing ITRF2014

ITRF2014 solutions

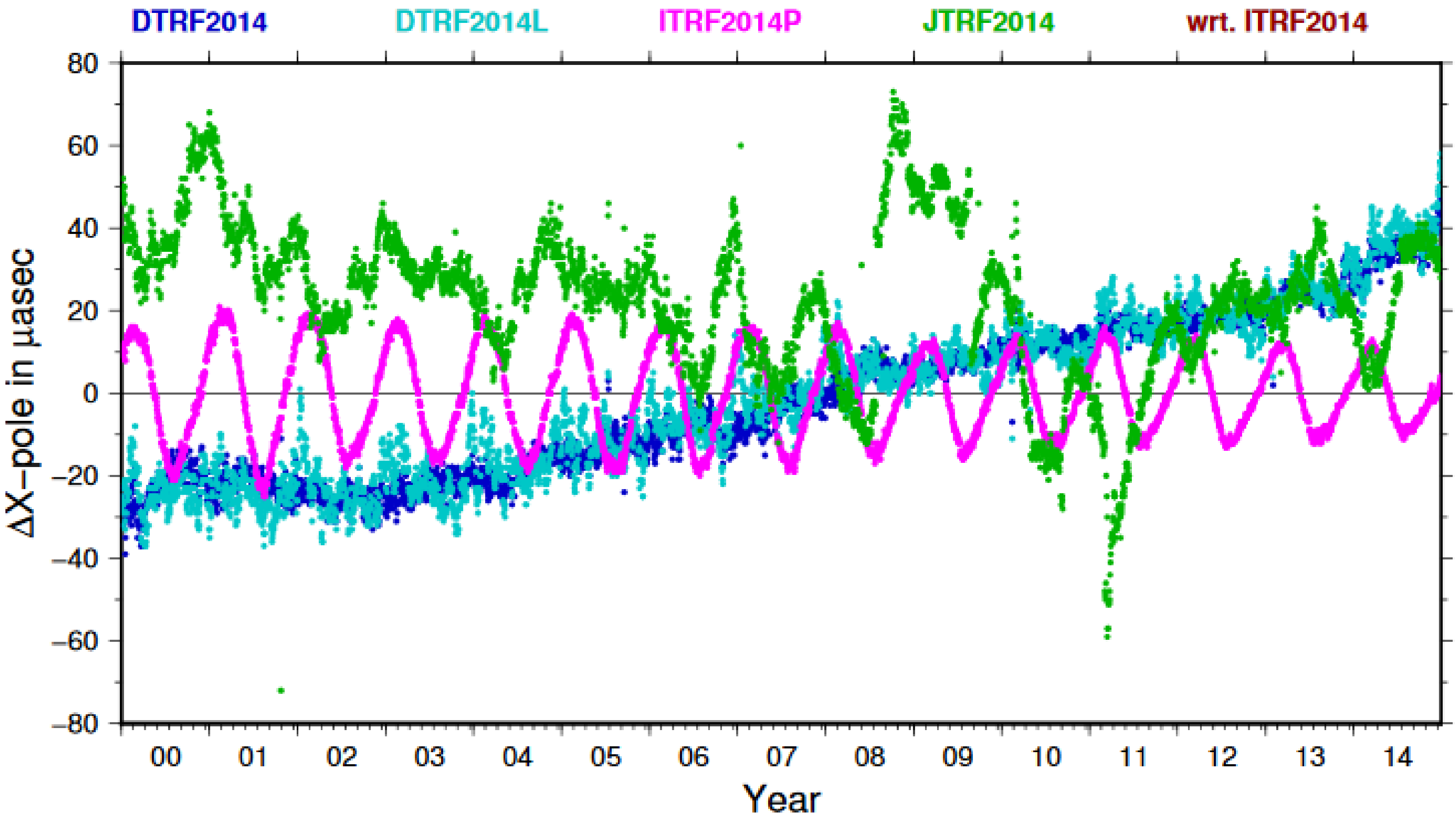
- TUM-DGFI
  - DTRF2014: based on a classical coordinate+linear velocity solution
  - DTRF2014L: ATM+Hydro.-loading applied
- IGN
  - ITRF2014: based on coordinate+linear velocities+ empirical post-seismic deformation corrections (+annual/semi-annual periodic functions)
  - ITRF2014P: periodic functions recovered
- JPL
  - JTRF2014: **based on a filter approach**

Comparison of the ITRF2014 solutions

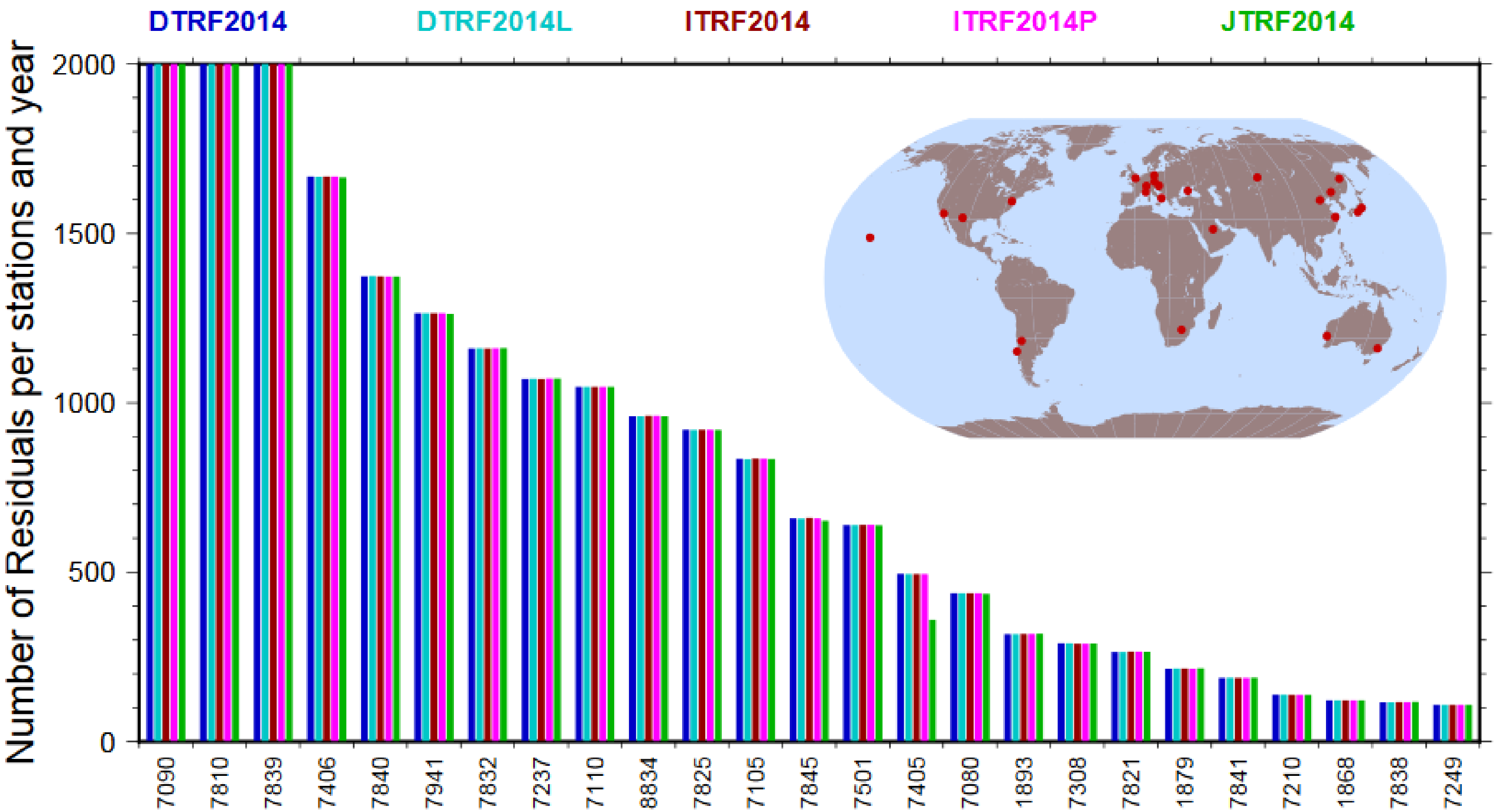


Comparison of the ITRF2014 solutions

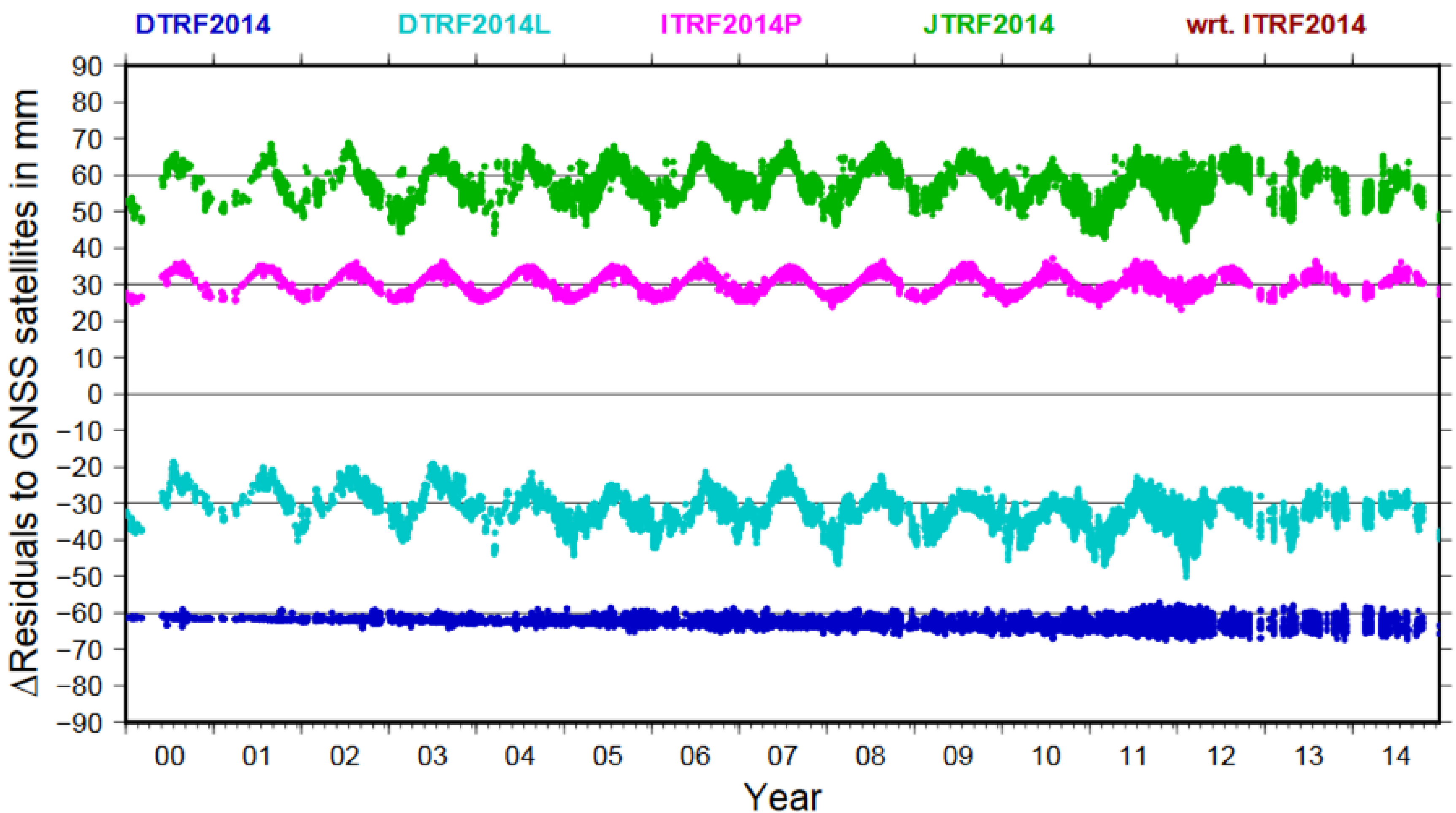
Five series of GNSS solutions have been generated.
Difference of the ERP-estimates wrt. ITRF2014:



Comparison of the ITRF2014 solutions



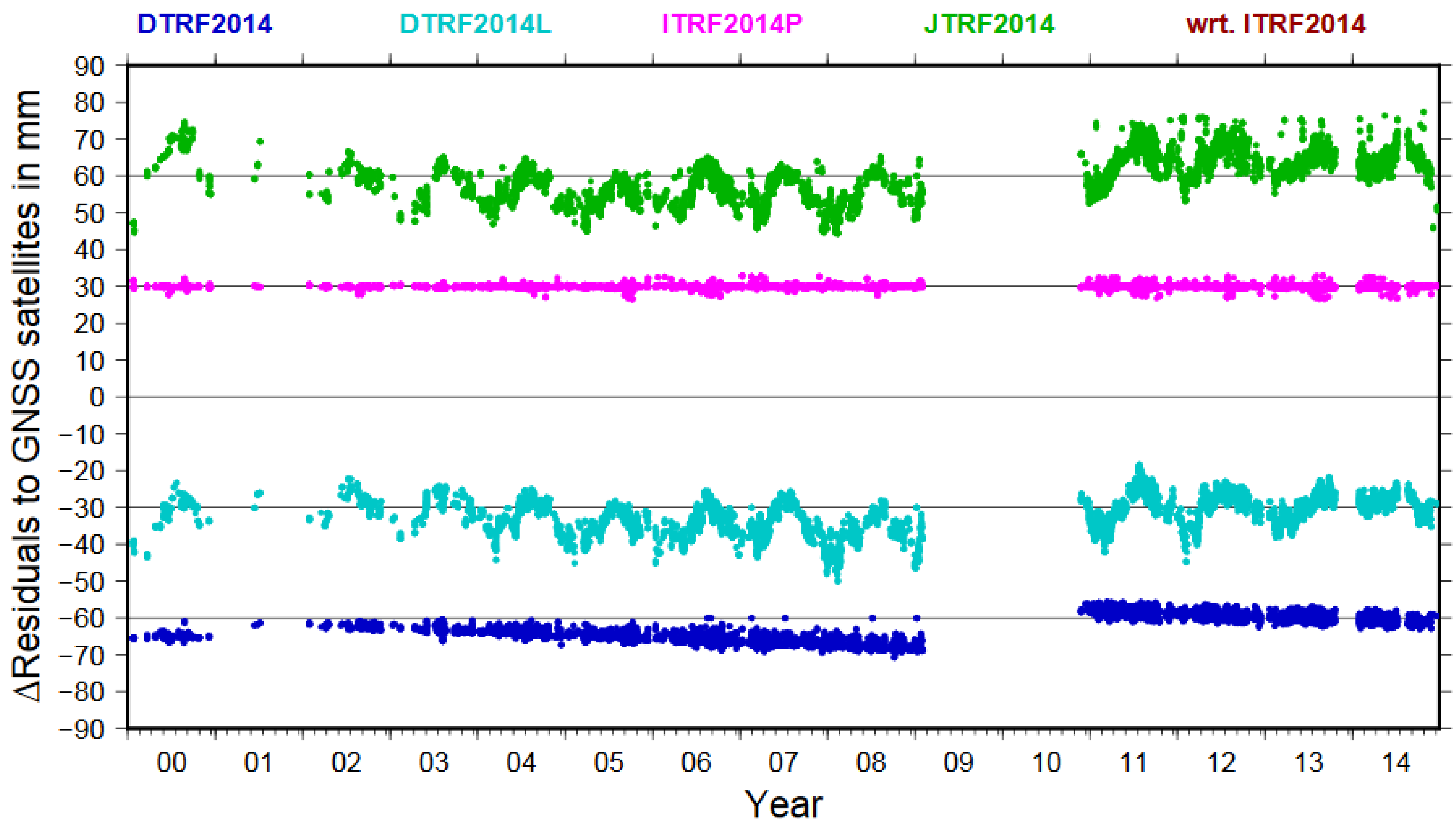
Comparison of the ITRF2014 solutions



c) SLR station: Graz, Austria (number 7839)

The reference ITRF2014 was arbitrary chosen.

Comparison of the ITRF2014 solutions

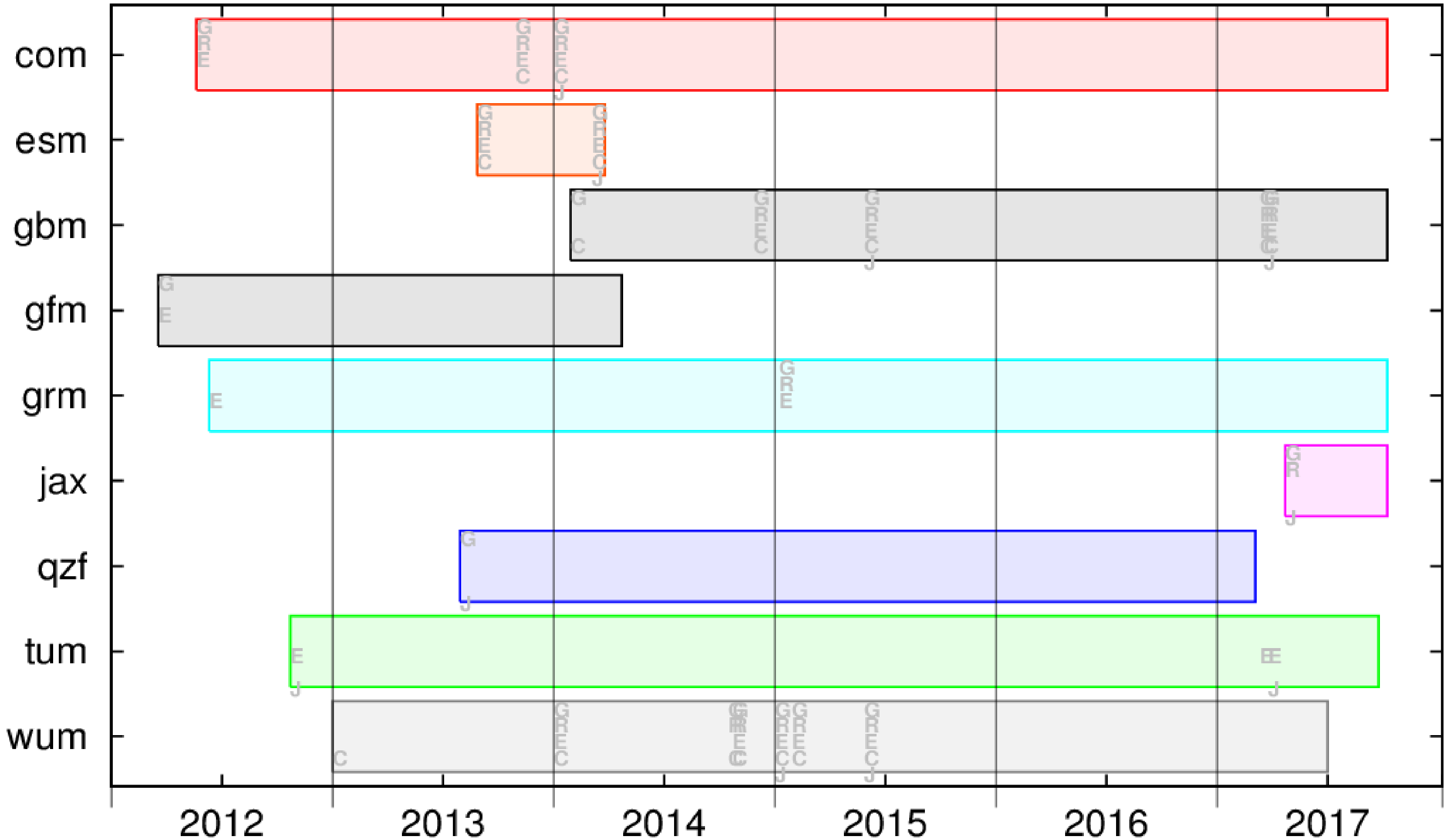


d) SLR station: Wettzell, Germany (number 8834)

The reference ITRF2014 was arbitrary chosen.

CODE contribution to IGS MGEX

MGEX products availability



Status: October 2017

Satellite system IDs according to the content of the precise orbit files at ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/

Release of satellite meta data …

- Missing satellite meta data is a limiting factor for accuracy of estimated orbits and clocks, therefore …

- Disclosure of Galileo IOV (Dec. 2016) and FOC (Oct. 2017) meta data by the GSA
- Disclosure of QZS-1 and QZS-2 information by JAXA in several steps in 2017

⇒ … are very appreciated!

… triggered some of the latest model changes

- Observation biases:
  - Change from differential code biases (DCB) to observable-specific biases (OSB) => mainly internal impact (e.g., on ambiguity resolution, multi-GNSS clock solution)

- Antenna calibrations:
  - Use of disclosed antenna phase center offset (PCO) for Galileo IOV and QZS-2
  - Values included or to be included in IGS14-ANTEX file
  - Impact of ANTEX changes analyzed for Galileo IOV (=> Villiger et al. at IGS Workshop 2017)

- Attitude models:
  - Use of disclosed Galileo IOV model for all Galileo SC

- Earth albedo and transmit antenna thrust:
  - Activated for Galileo and QZS-1 (see following slides)

Experiment: Impact of satellite meta data on POD

Test	Galileo					QZS-1		
Name	Al-bedo	Ant. Thr.	Atti-tude	Pulses	Median SLR [cm]	Albedo	Ant. Thr. (244 W)	Median SLR [cm]
OPER	–	–	–	–	–3.8 (–+4.5)	–	–	–7.8
ALB1	x	–	–	–	–2.0	m= 1800 kg	–	–2.6
AAT1	x	260 W	–	–	+0.6	m= 1800 kg	m= 1800 kg	+0.3
AAT2	x	130 W	–	–	–0.7	m= 3600 kg	m= 3600 kg	–3.7
EAT	x	200 W	x	–	0.0	m= 1950 kg	m= 1950 kg	–0.3
EATP	x	200 W	x	R, S, W; 12h	+0.6	m= 1950 kg	m= 1950 kg	–0.3
EATU (upd...)	x	I: 130 W F:200 W	X	–	–0.2 (–+4.6)	m= 2000 kg	m= 2000 kg	–1.8
EATUP (...BW)	x	I: 130 W F:200 W	X	R, S, W; 12h	+0.5 (–+3.5)	m= 2000 kg	m= 2000 kg	–1.6 (w. PLS)

Experiment: Impact of satellite meta data on POD

Test	Galileo					QZS-1		
Name	Al-bedo	Ant. Thr.	Atti-tude	Pulses	Median SLR [cm]	Albedo	Ant. Thr. (244 W)	Median SLR [cm]
OPER	-	-	-	-	-3.8 (-+4.5)	-	-	-7.8
ALB1	x				-2.0	m= 1800 kg	-	-2.6
AAT1	x	260 W	-	-	+0.6	m= 1800 kg	m= 1800 kg	+0.3
AAT2	x	1[illegible]			-0.7	m= [illegible]	m= [illegible]	-3.7
EAT	x	200 W	x	-	0.0			-0.3
EATP	x	200 W	x	R, S, W; 12h	+0.6	[illegible]	[illegible]	-0.3
EATU (upd...)	x	I: 130 W [illegible]	X	-	-0.2 (-+4.6)	m= 2000 kg	m= 2000 kg	-1.8
EATUP (...BW)	x	F:200 W		[illegible] S, W; 12h	+0.5 (-+3.5)	m= 2000 kg	m= 2000 kg	-1.6 (w. PLS)

Impact albedo: +1.8 cm

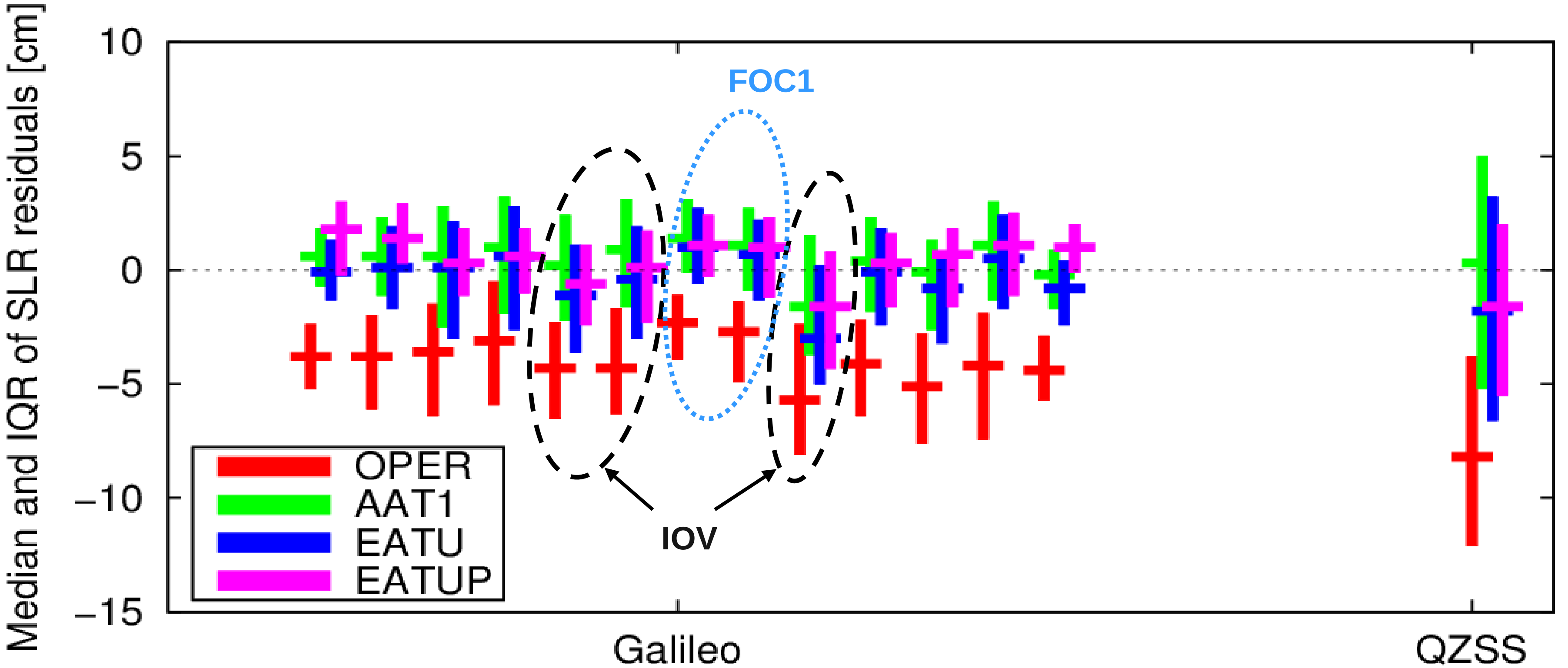
Impact antenna thrust: 1 cm/100 W

Impact SC mass: 2.2 cm/1000 kg

(macro model over-scaled)

Pulses might shift the SLR offset

Experiment: Impact of satellite meta data on POD

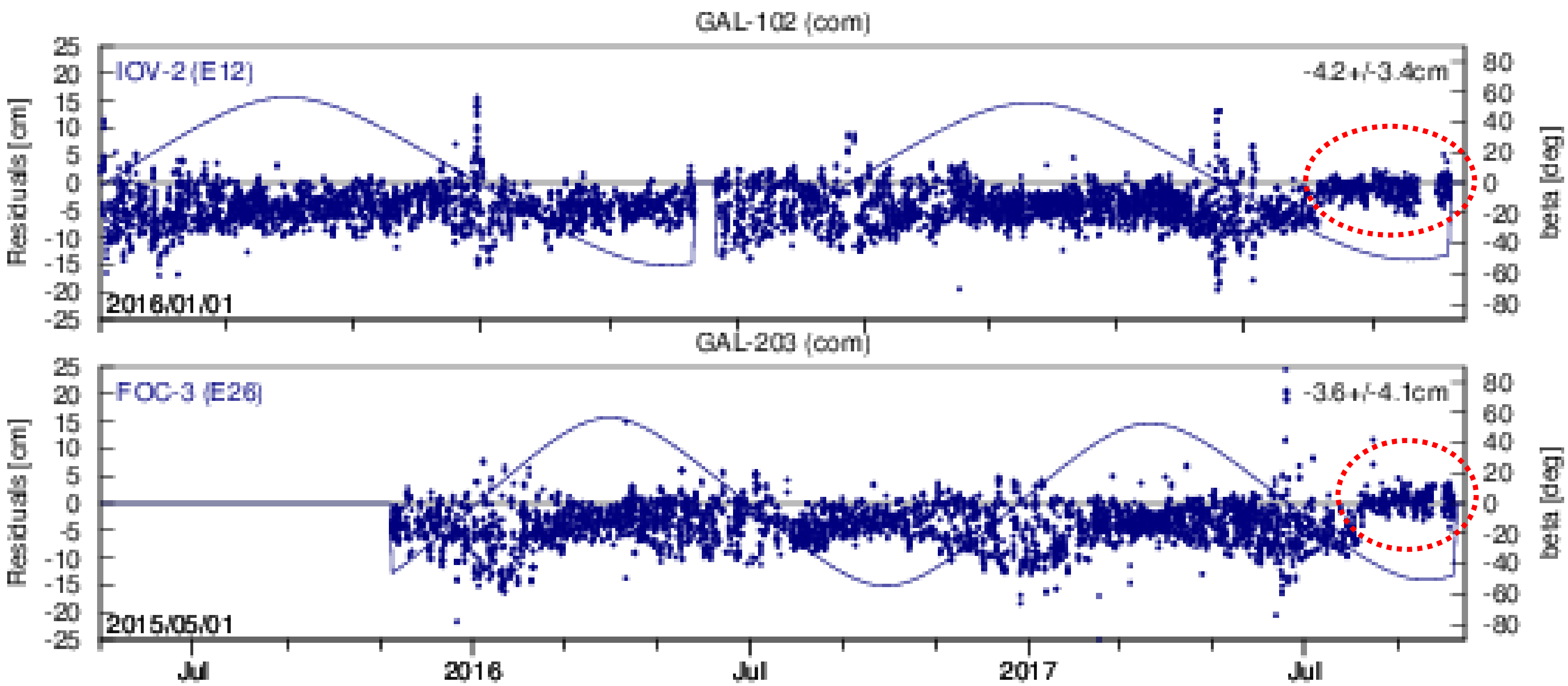


⇒ Consideration of albedo and antenna thrust reduces SLR offset

⇒ Uncertainties remain:

- Satellite macro model is rough and sometimes needs corrections (e.g., absorption of SP)
- True satellite mass and CoM not always known
- Uncertainties w.r.t. transmit power
- Antenna calibration also impacts orbit scale

Experiment: Impact of satellite meta data on POD



(SLR validation provided by the IGS MGEX: http://mgex.igs.org)

⇒ Model changes active in CODE MGEX solution since GPSWEEK 1962

⇒ Expected orbit improvement confirmed by external validation

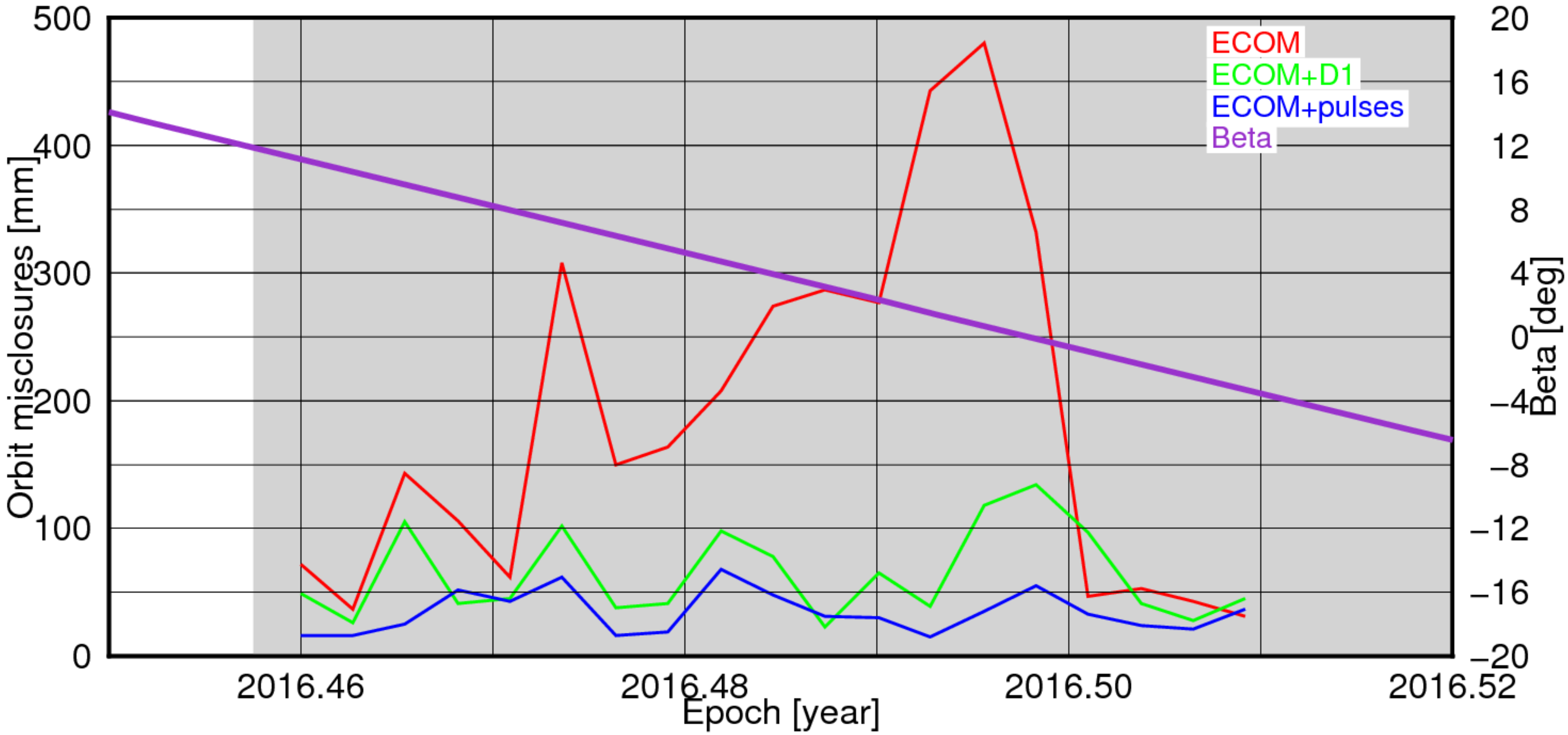
Orbit modelling during eclipse

SRP/thermal re-radiation modelling

- Problem:
  - Difficulties in Galileo orbit modelling during eclipse phases:
    - Elevated orbit misclosures
    - Degradation in satellite clock modelling
    - Degradations of SLR residuals
- Potential solutions:
  - New terms in ECOM (e.g., once-per-rev sin/cos terms in D)
  - Stochastic pulses at specific orbit position of a satellite (e.g., in the middle of eclipse)

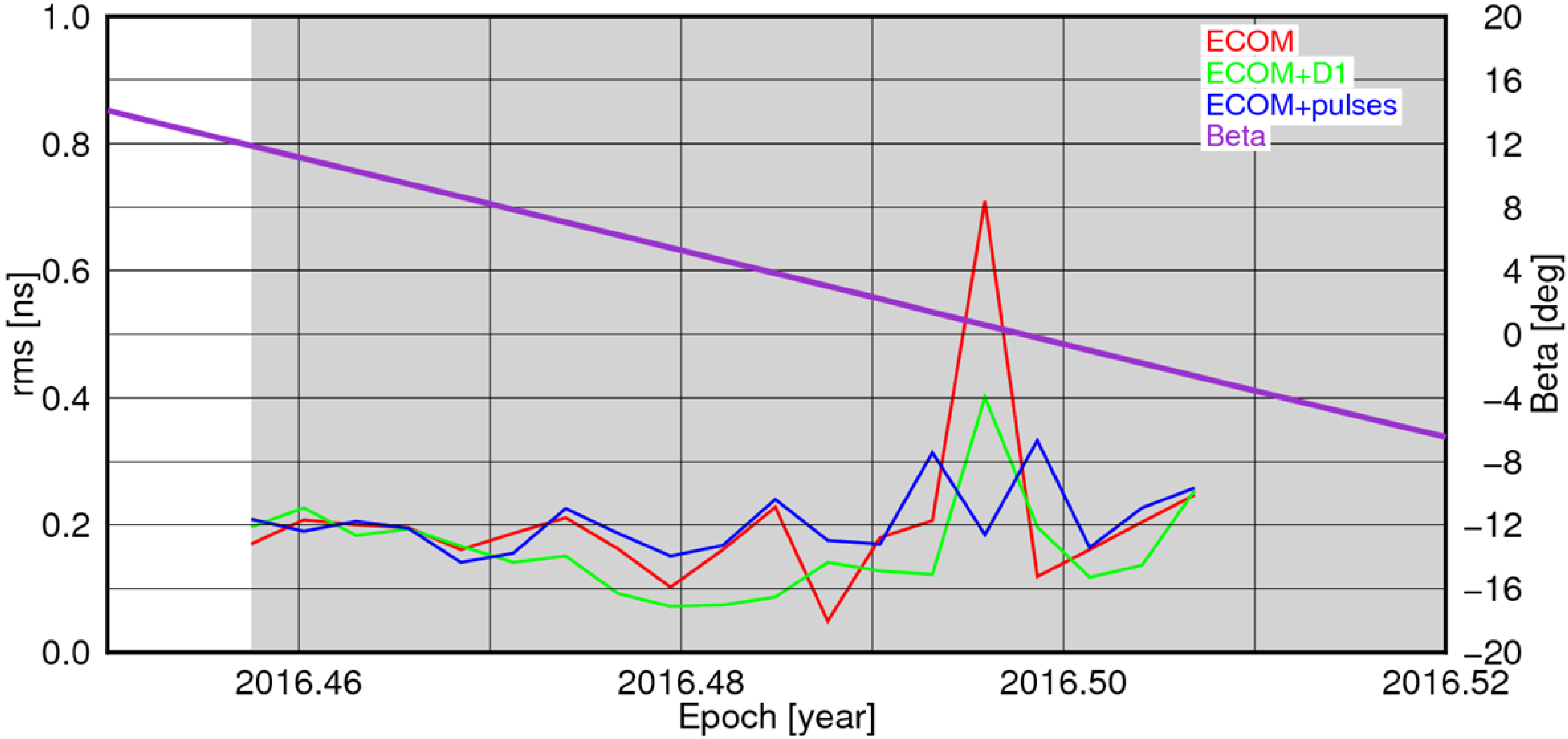
SRP/thermal re-radiation modelling

- **Orbit misclosures for Galileo E22 during 16/06/2017 – 04/07/2017 using ECOM, ECOM+D1SC, ECOM+pulses in the middle of eclipse**



SRP/thermal re-radiation modelling

- **RMS of linear clock fit for Galileo E22 during 16/06/2017 – 04/07/2017 using ECOM, ECOM+D1SC, ECOM+pulses in the middle of eclipse**



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

Influence and Availability of Antennas Calibrations

- IOV (2016) and FOC (2017) disclosed by ESA
- IGS:
  - IOV pattern accepted during IGS Workshop 2017
  - Included into the IGS ANTEX file as of 23. October 2017
  - FOC patterns: Currently under investigation (and preparation to include into the IGS ANTEX file)

Antenna/System	GPS	Galileo
Satellite	✘	✓
Receiver Robot (IGS standard): Chamber:	 ✓ (L1/L2) ✓ (L1/L2)	 ✘ ✓

Midnight orbit overlaps

- Overlap between midnight epochs of one day arcs
- Comparison between MGEX solution and IOV pattern solution

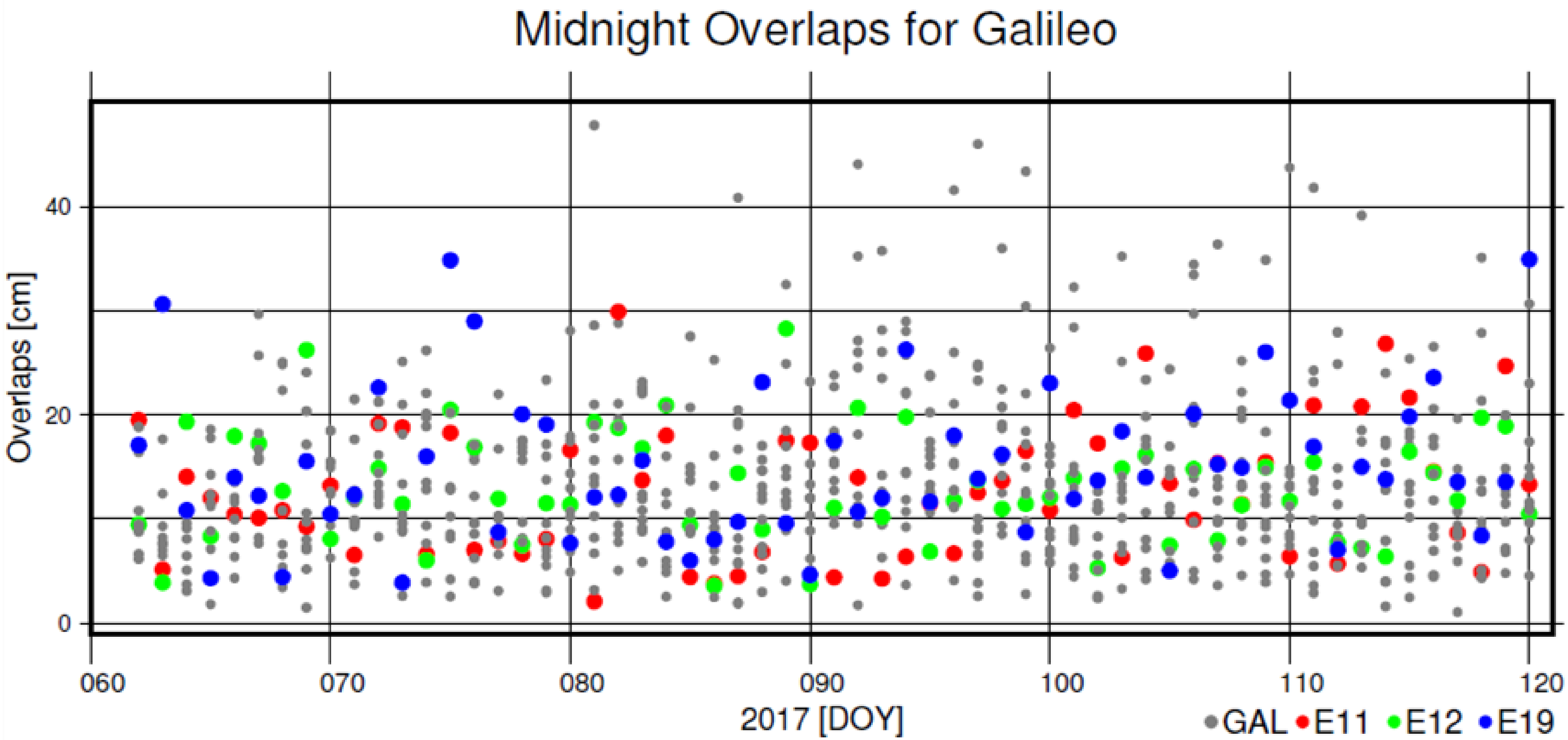


Figure: Midnight overlap of all Galileo satellites (using IGS PCOs)

Midnight orbit overlaps

- Overlap between midnight epochs of one day arcs
- Comparison between MGEX solution and IOV pattern solution

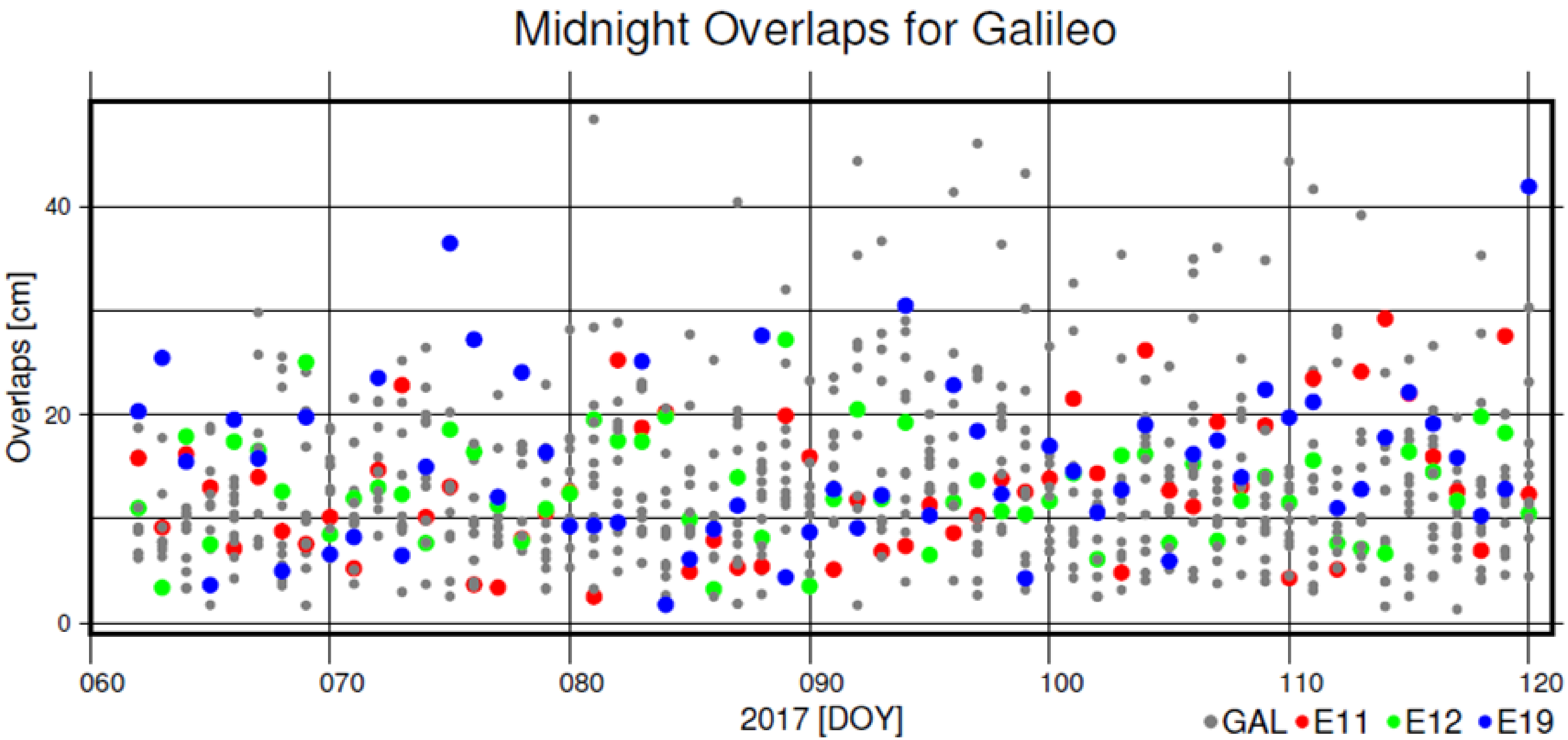
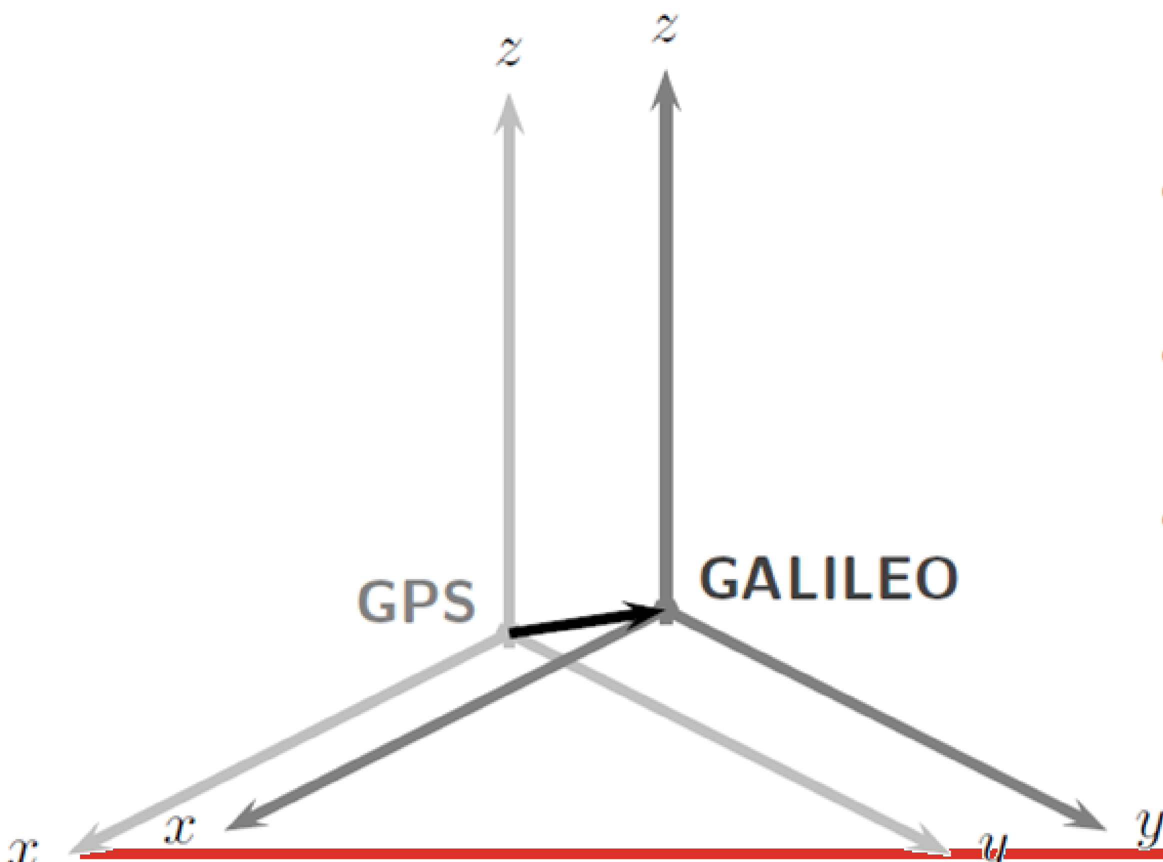


Figure: Midnight overlap of all Galileo satellites (using IOV PCOs and PCVs)

GPS–Galileo antenna bias: Coordinates

- Orbit-Solution (double-difference): Zero mean condition applied: translation and rotation
- PPP-Solutions: No constrains applied



- Station coordinates from GPS-only
- Station coordinates from GALILEO–only
- **Vector between GPS– and GALILEO–coordinates**

Estimated translation biases for rec. antennas

Average GTRA estimates for Galileo (except IOV) in cm

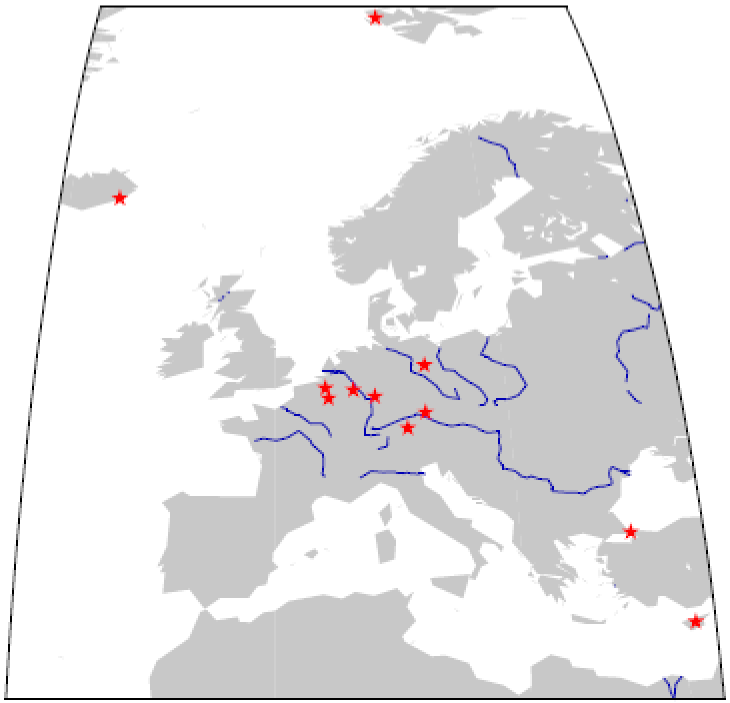
Sol	East	North	Up	*East*	*North*	*Up*
IGS	−0.97	−0.53	−5.83	*20.37*	*8.51*	*15.97*
IOV	−0.92	−0.53	−5.83	*20.76*	*8.62*	*16.01*
DIF[%]	5.0	−0.7	0.1	*−1.9*	*−1.3*	*−0.3*

Average GTRA estimates for IOV satellites (E11,E12,E19) in cm

Sol	East	North	Up	*East*	*North*	*Up*
IGS	−2.19	−0.15	2.27	*32.02*	*16.56*	*33.10*
IOV	−0.96	−0.23	1.70	*22.54*	*11.47*	*19.69*
DIF[%]	56.1	−59.1	24.9	*29.6*	*30.7*	*40.5*

Fully calibrated antennas in a PPP environment

- Individual calibrated EUREF ANTEX file contains 12 chamber calibrated antennas with frequency L5
- Impact of using L5 antenna pattern instead of L2
- Estimation of Inter-System Translation Bias for Galileo and IOV satellites using either L1/L2 or L1/L5 pattern.



Fully calibrated antennas in a PPP environment

STA	Antenna type *Used PCO and PCV:*	GTRA L1/L2 [mm]	L1/L5 [mm]	Δ GTRA [mm]	Δ PCO [mm]
BRUX	JAVRINGANT_DM NONE	3.7	15.0	-11.3	-8.56
POTS	JAV_RINGANT_G3T NONE	4.9	15.9	-11.0	-9.22
OBE4	JAV_RINGANT_G3T NONE	5.6	17.1	-11.5	-9.90
NYA2	JAV_RINGANT_G3T NONE	-0.8	7.1	-7.9	-9.23
BADH	LEIAR10 NONE	10.2	13.5	-3.3	-1.49
WRLG	LEIAR25.R3 LEIT	7.6	15.7	-8.1	-2.84
DOUR	LEIAR25.R3 NONE	-	-	-	-3.04
REYK	LEIAR25.R4 LEIT	2.3	10.3	-8.0	-4.36
HOFN	LEIAR25.R4 LEIT	2.9	10.1	-7.2	-4.20
NICO	LEIAR25.R4 LEIT	7.9	16.2	-8.3	-4.54
EUSK	LEIAR25.R4 LEIT	10.0	18.1	-8.1	-4.32
ISTA	LEIAR25.R4 LEIT	6.5	14.6	-8.1	-6.53

Advancing ECOM for satellite in orbit normal mode

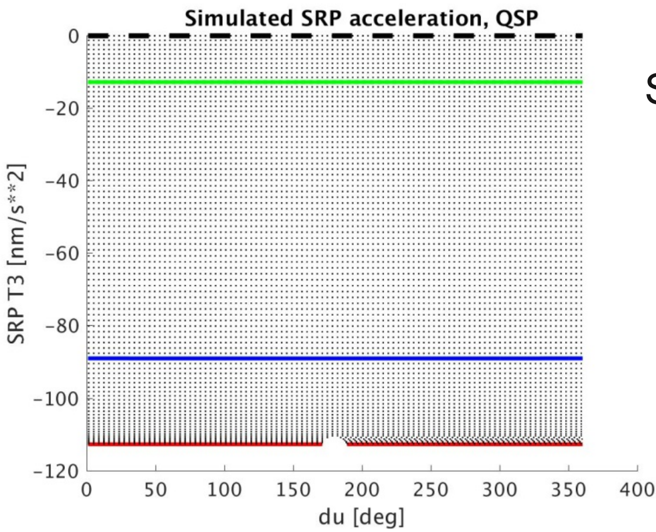
Development steps

- Based on the available meta information for the QZSS–satellite a «simlation» environment has been established:

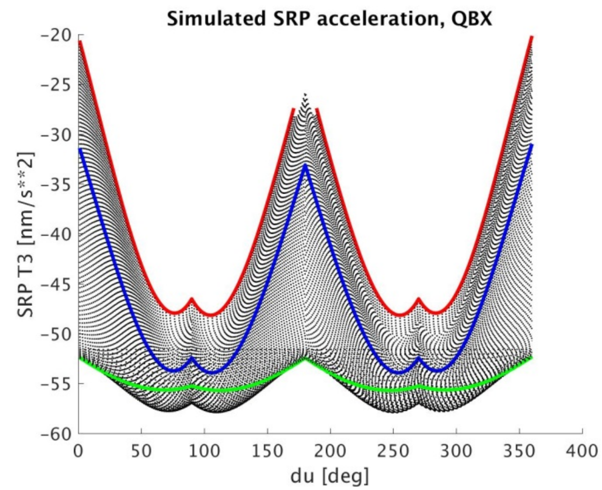
  1. SRP effect can be estimated for all potential locations of the Sun
  2. This SRP effect is represented by different sets of orbit parameters in various coordinate systems
  3. Residuals, numerical stability, correlations have been evaluated

SRPSIM – Terminator system – SP vs. box

Simulated SRP acceleration; T3 component; Beta: **-90 .. +90** deg

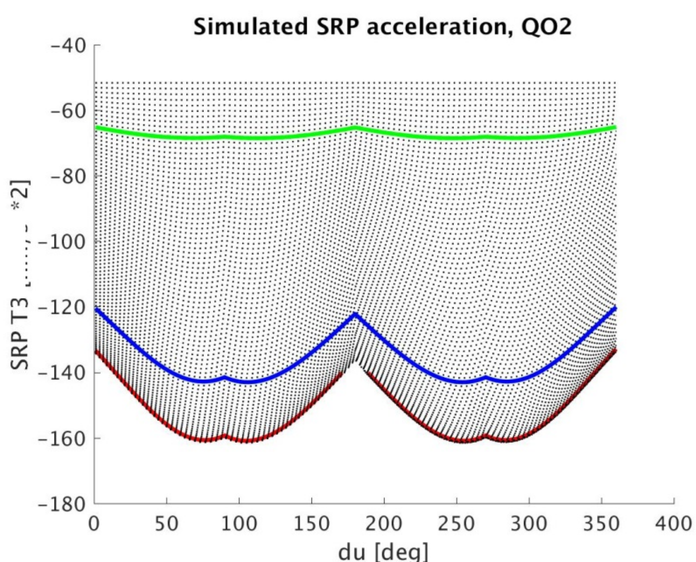


SP



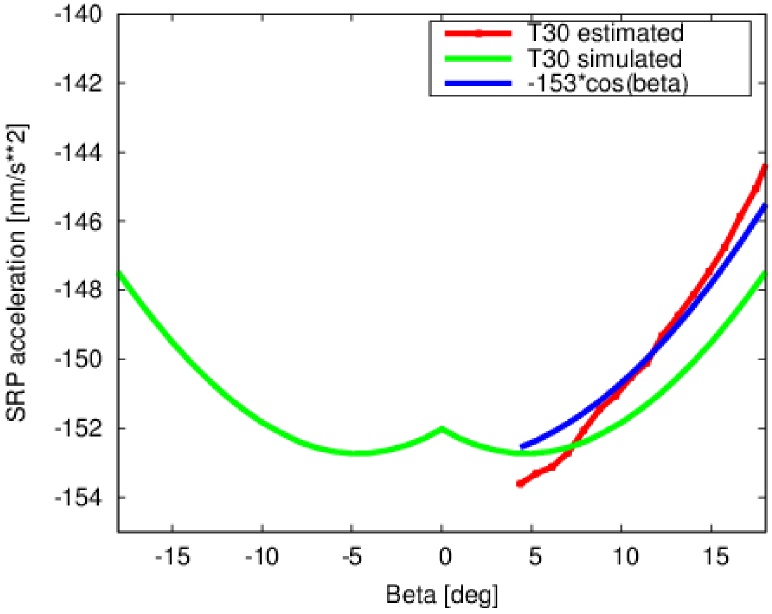
Box

SP + box

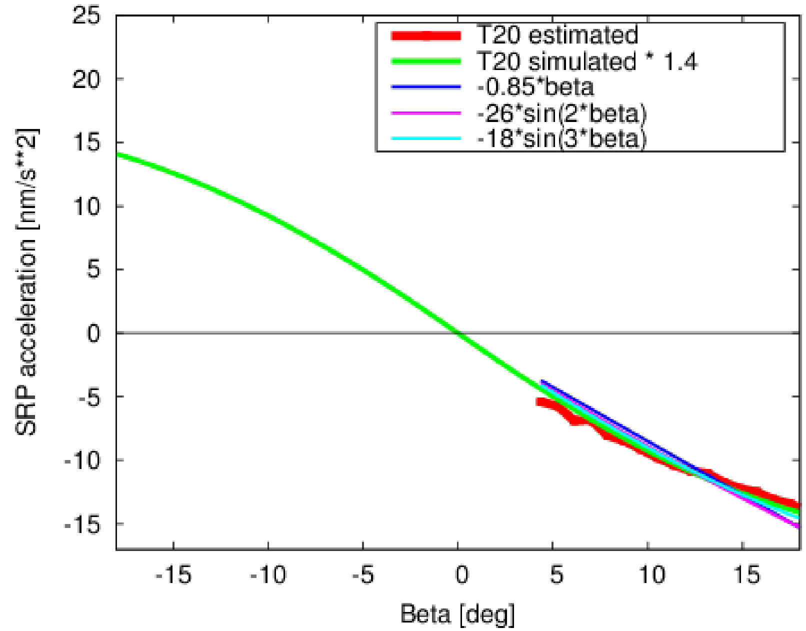


- du-constant part mainly from SP
- du-periodic part from box
- Both are Beta-dependent

SRPSIM – reality check (vs. ECOM2–TM)

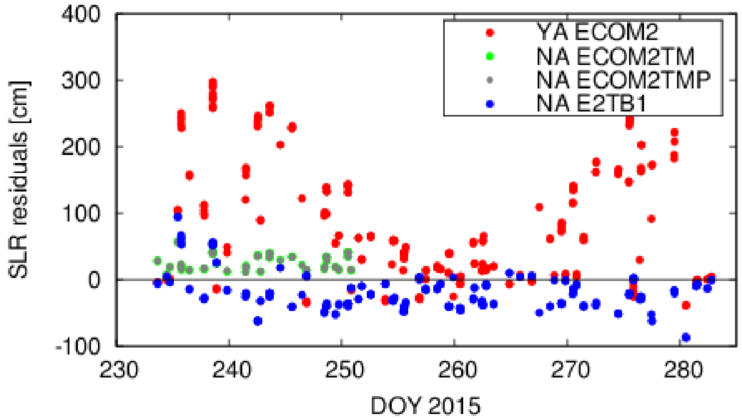


T30 coefficient from ECOM2–TM 1–day solution fits relatively well to simulation and proposed n*cos(Beta) fit function



T20 coefficient curve from ECOM2–TM 1–day solution fits to shape of simulated signal and proposed fit functions

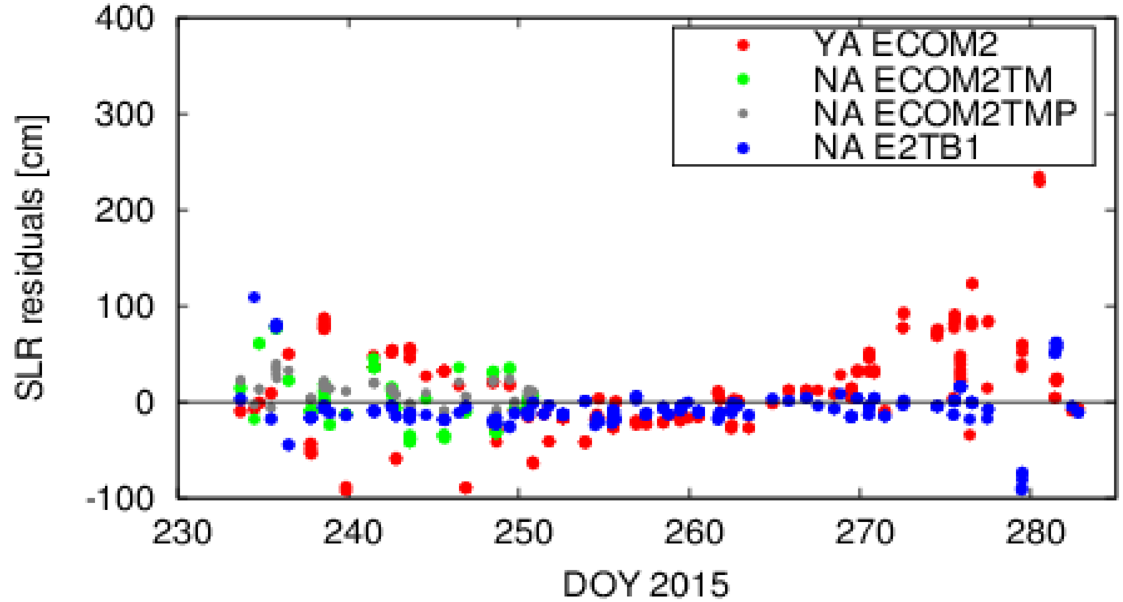
Orbit validation: E2TB1 – SLR residuals

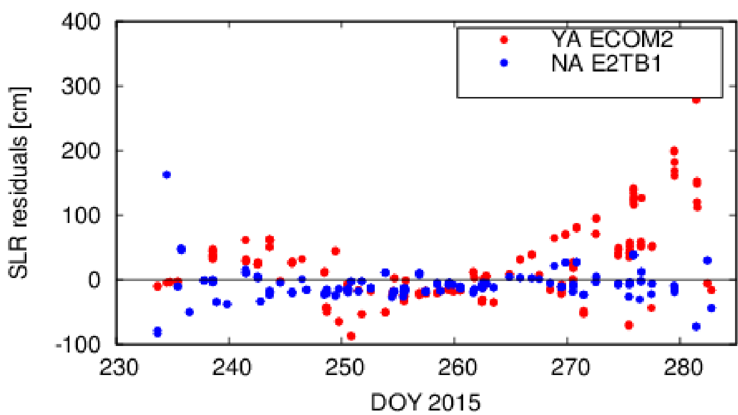


1-day arc

⇒ E2TB1 solution (blue) performs better than solutions without Beta-dependency (w.r.t. SLR offset and STD)

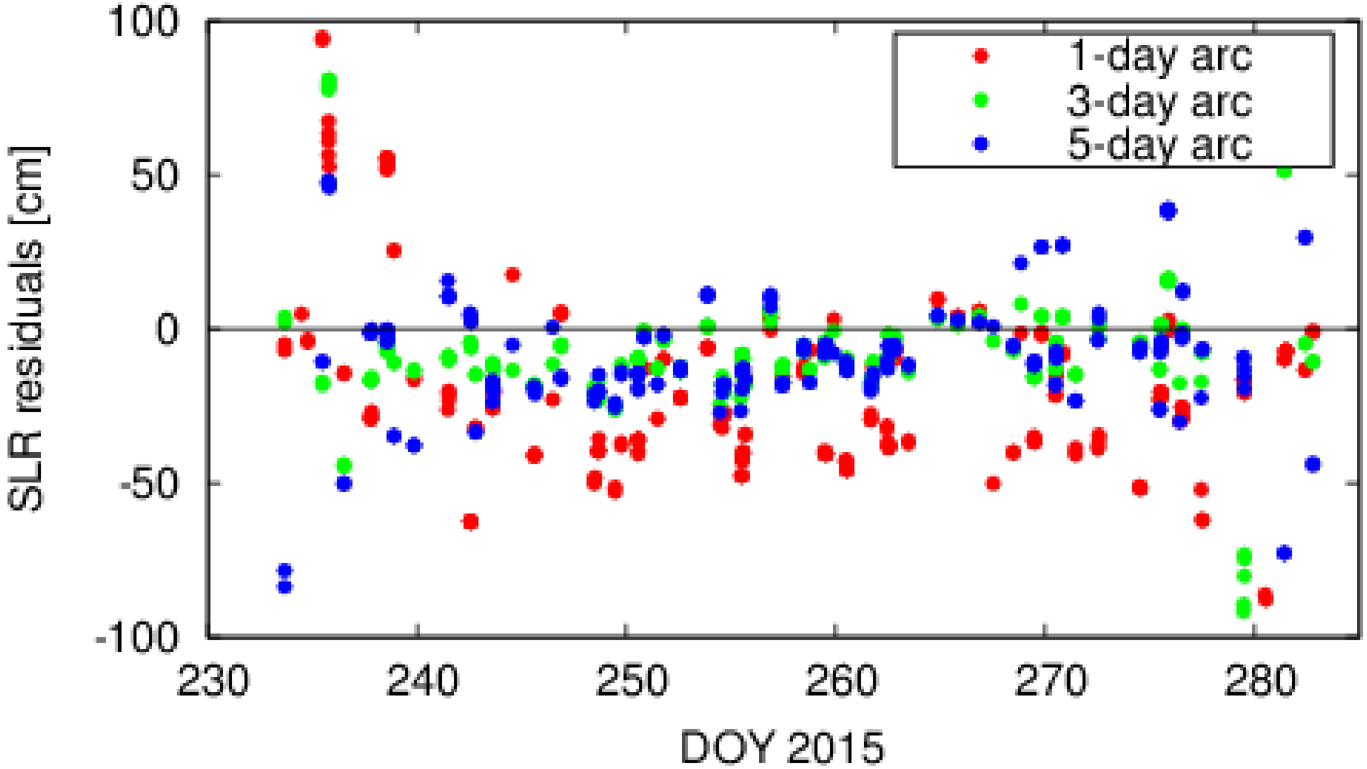
3-day arc





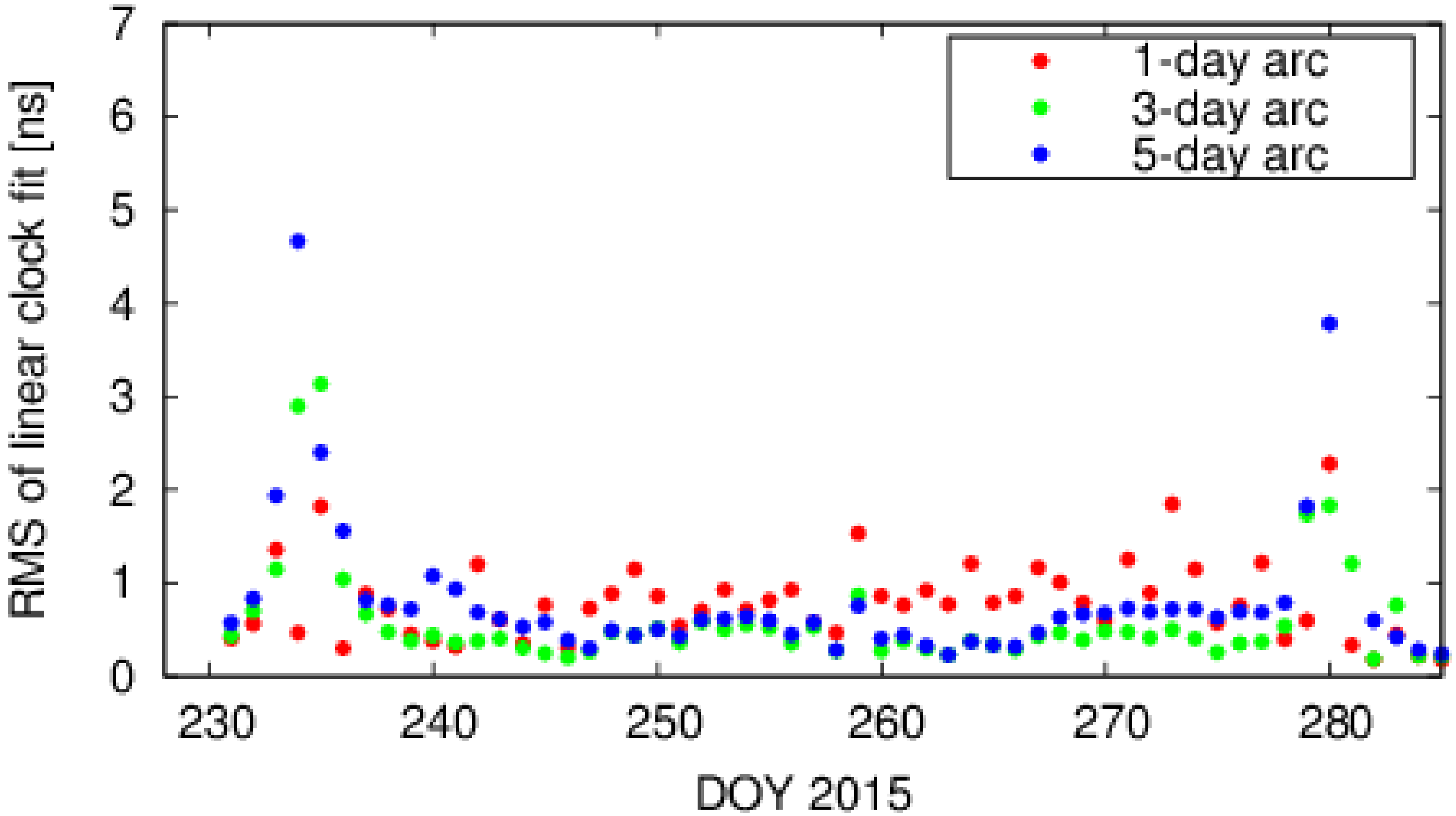
5-day arc

Orbit validation: E2TB1 – SLR residuals



⇒ Long-arc solutions perform better than 1-day arc solution (especially 3-day solution)
⇒ Size of SLR residuals is relatively constant over whole NA time interval - in spite of varying Beta-angle
⇒ SLR offset of 3-day solution is similar to that of the ECOM2-based solution with YA
⇒ **E2TB1 is a suitable SRP model for NA**

Clock validation: E2TB1 – RMS of linear fit



⇒ Long-arc solutions perform better than 1-day arc solution (especially 3-day solution)

⇒ Size of SLR residuals is relatively constant over whole NA time interval - in spite of varying Beta-angle

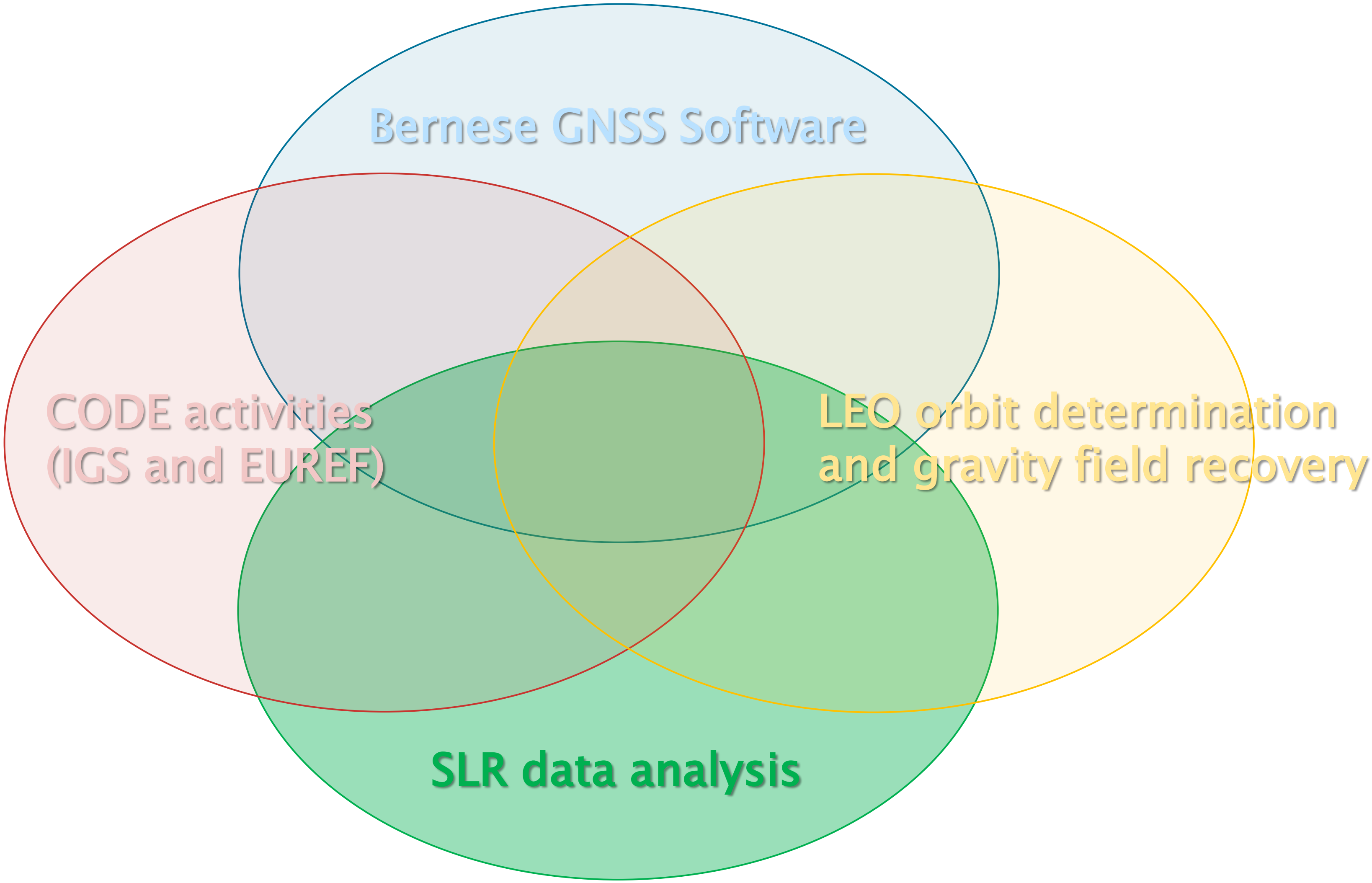
⇒ **E2TB1 is a suitable SRP model for NA**

ESA project related to GNSS activities

Other projects:

- **TGVF/OVF: «Ground truth» for Galileo GMS**
  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

Satellite Geodesy Research Group

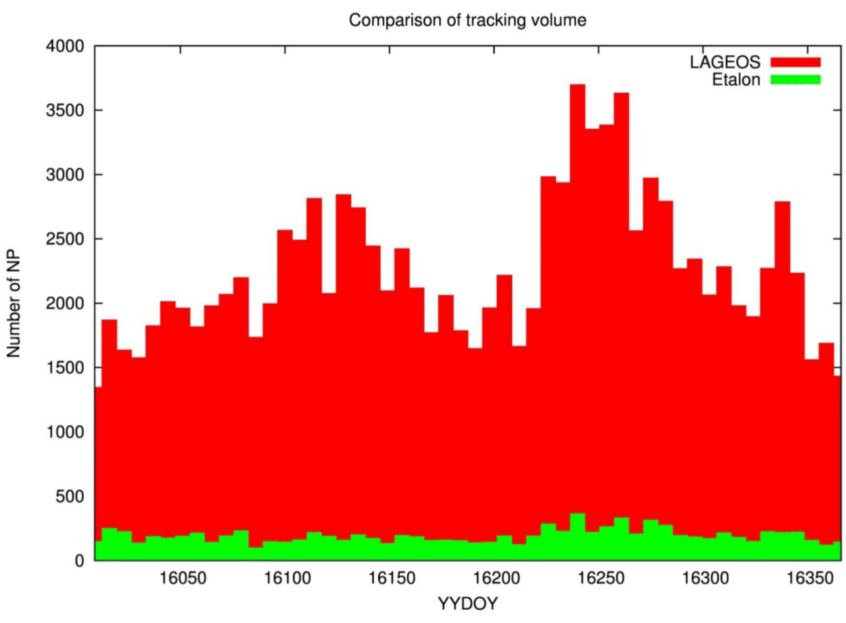


Simulating SLR Data:
Target: optimizing the observation scenarios at SLR tracking stations

Number of NPs

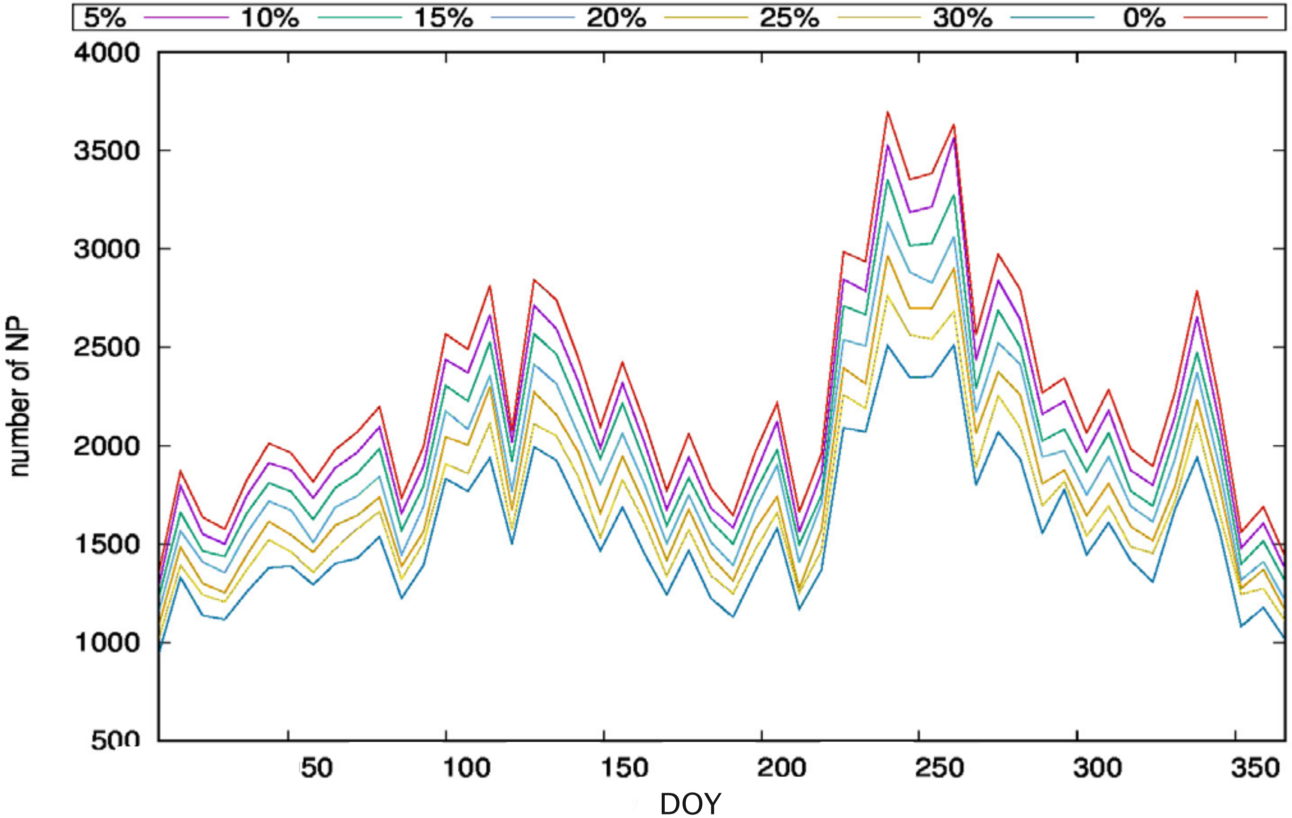
In 2016:

- In average 130000 NPs/month in total.
- 13000 NPs of those to LAGEOS.
  - 10% of total NP to only 2 of 100 satellites.
- 1200 NPs to Etalon.
  - Only 10% of the ILRS solution for the ITRF comes from Etalon



Experiment: Reducing LAGEOS NPs

- Impact of number and distribution of observations on the LAGEOS and Etalon satellites.
  - Comparison of different scenarios:

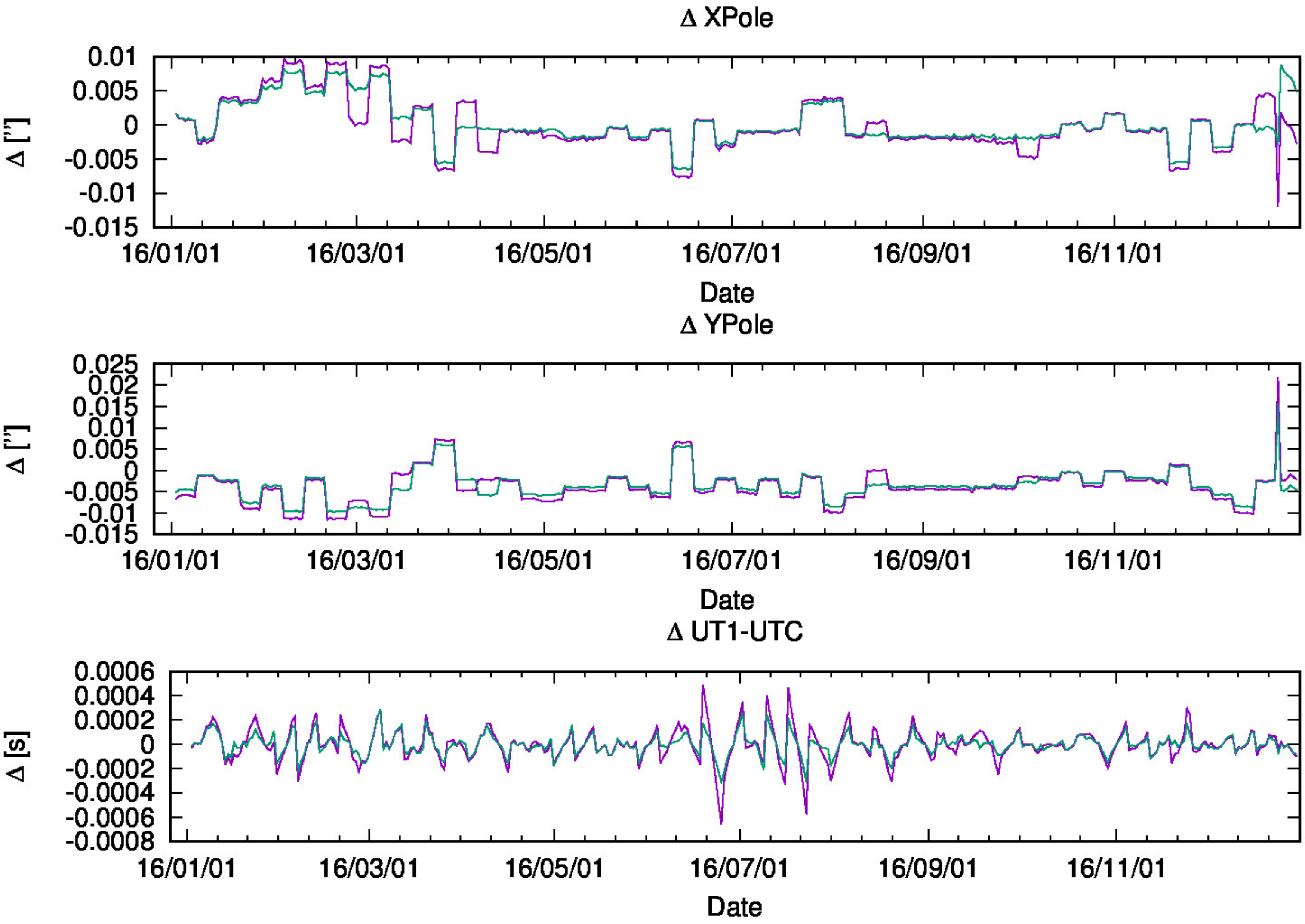


Summary

- **RMS of Helmert:** increases when reducing LAGEOS observations. Up to 20% Reduction the RMS stays within the simulation noise RMS threshold.
- **ERP, translation/rotation**: insignificant difference.
- **Orbits**: Average residuals of LAGEOS orbits slightly increase but remain at the same maximum level of ~10cm.
- **Scale factor, geocenter**: Scenarios clearly show a decrease beyond 20% reduction.

=> **20% of LAGEOS NPs could go to other targets**.

Increasing NPs to Etalon – ERPs



Reference
10% more Etalon

Summary

- **RMS of station coordinates**: on the same level as with LAGEOS.

- **Translation/Rotation**: not significant.

- **Orbits**:
  - LAGEOS: Slightly bigger average differences, but still on the same ~10cm level.
  - Etalon: Vastly improved orbits.

- **ERPs improved by 10%**

Satellite Laser Ranging to Low Earth Orbiters – Orbit and Network validation

SLR residuals

SLR residuals for various publicly available GPS-based LEO orbit products, using all contributing SLR stations and a subset of 12 high-quality SLR stations.

Mission	Orbit product	Year	Residuals (mean $\pm$ σ [mm])	
			All stations	High-quality stations
CHAMP	AIUB red. dyn. (Prange et al 2010)	2007	$+2.6 \pm 23.0$	$+1.5 \pm 18.2$
	AIUB kinematic (Prange et al 2010)	2007	$+0.6 \pm 34.4$	$+0.8 \pm 31.4$
GRACE-A	JPL GNV1B (Bettadpur 2012; Bertiger et al 2010)	2010	$+2.3 \pm 24.4$	$+3.1 \pm 12.3$
ICEsat	UT/CSR 2011 reprocessing (Rim et al 2013)	2008	$+2.4 \pm 15.4$	$+2.0 \pm 15.2$
Jason-2	CNES GPS+DORIS GDR-E (CNES 2015; IDS 2015)	2016	-6.1 ± 25.3	$+0.6 \pm 12.5$
GOCE	AIUB PSO red. dyn. (Bock et al 2014)	2010	$+2.6 \pm 21.0$	$+2.6 \pm 13.8$
	AIUB PSO kinematic (Bock et al 2014)	2010	$+2.7 \pm 23.3$	$+2.9 \pm 17.1$
TerraSAR-X	DLR red. dyn. (Hackel et al 2017)	2016	$+3.5 \pm 25.4$	$+3.4 \pm 15.3$
Swarm-B	TU Delft PSO red. dyn. (van den IJssel et al 2015)	2016	$+0.3 \pm 25.5$	$+0.3 \pm 15.2$
	TU Delft PSO kinematic (van den IJssel et al 2015)	2016	$+0.7 \pm 31.2$	$+0.8 \pm 24.3$
Sentinel-3A	CPOD (Peter et al 2016)	2016	$+1.8 \pm 27.2$	$+2.6 \pm 15.7$

1.5-2.5 cm consistency of reduced-dynamic orbit solutions with SLR measurements.

Orbit errors

Analysis of SLR residuals allows the estimation of systematic LEO orbit offsets

Estimated offsets in radial (R), along-track (T) and cross-track (N) direction for three different Sentinel-3A POD products of 2016:

Solution	SLRF2008				SLRF2014				Notes
	R	T	N	Res	R	T	N	Res	
AIUB	−1.5	−3.9	+4.6	13.6	−5.5	−3.3	+5.0	12.4	Float ambiguity, free accel. in RTN
CPOD	+4.7	−7.1	+8.5	14.5	+0.8	−6.5	+8.9	13.8	Float ambiguity, macro model
DLR	+4.7	−0.4	+0.7	11.5	+0.7	+0.2	+1.1	10.6	Ambiguity-fixed, macro model

- SLR residuals are not only sensitive to orbit errors in radial, but also in along- and cross-track direction.
- AIUB solution shows a different radial offset compared to the other two solutions due to its more empirical parametrization.
- Residuals smaller in SLRF2014, although this is formally inconsistent with the IGb08-based GPS orbits.

SLR station parameters

Analysis of SLR residuals of LEOs allows the estimation of SLR station-specific parameters

Estimated SLRF2014 station coordinate corrections in east (E), north (N), and up (U) direction and range biases (B) based on SLR residuals for Swarm-C, TerraSAR-X, Sentinel-3A, and Jason-2 orbits in 2016:

Station	SOD	E [mm]	N [mm]	U [mm]	B [mm]	n_{np}	Residuals [mm]
Arequipa	74031306	2.7 ± 0.6	4.0 ± 0.6	12.9 ± 2.0	12.7 ± 1.2	3674	5.8 ± 11.9 / -0.0 ± 11.4
Arkhyz	18869601	6.9 ± 1.6	-4.9 ± 1.8	-143.8 ± 4.8	-87.9 ± 2.9	614	-16.4 ± 28.5 / -0.0 ± 14.3
Badary	18900901	-3.7 ± 0.8	-3.4 ± 0.7	6.6 ± 2.6	5.4 ± 1.7	2455	1.7 ± 17.6 / -0.0 ± 17.3
Beijing	72496102	3.8 ± 1.1	6.0 ± 1.2	20.7 ± 3.3	5.1 ± 2.1	1105	-7.9 ± 15.6 / 0.0 ± 14.8

- Station parameter estimation removes mean bias and reduces standard deviations for SLR residuals
- Some stations show very large height corrections (up to 20 cm!), confirmed by LAGEOS-based coordinate estimations

SLR station parameters

Submitted to special issue on SLR-processing

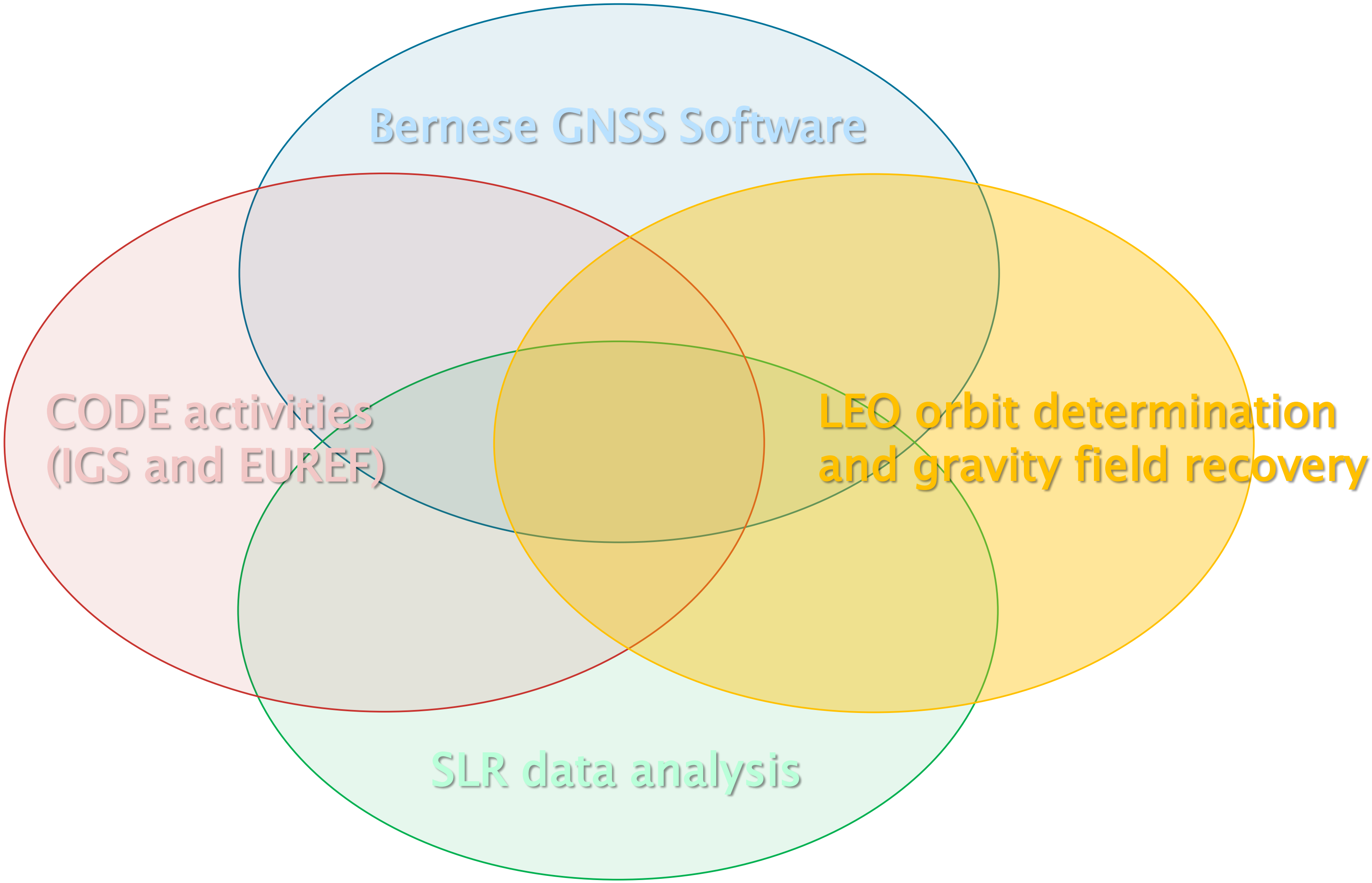
Journal of Geodesy manuscript No.
(will be inserted by the editor)

Satellite Laser Ranging to Low Earth Orbiters – Orbit and Network Validation

Daniel Arnold · Oliver Montenbruck · Stefan Hackel · Krzysztof Sośnica

Collaboration between AIUB, DLR and University of Wroclaw

Satellite Geodesy Research Group



Copernicus POD Service

Copernicus satellite fleet

At AIUB precise orbits of all Sentinel satellites are computed

Sentinel-1A
Sentinel-1B

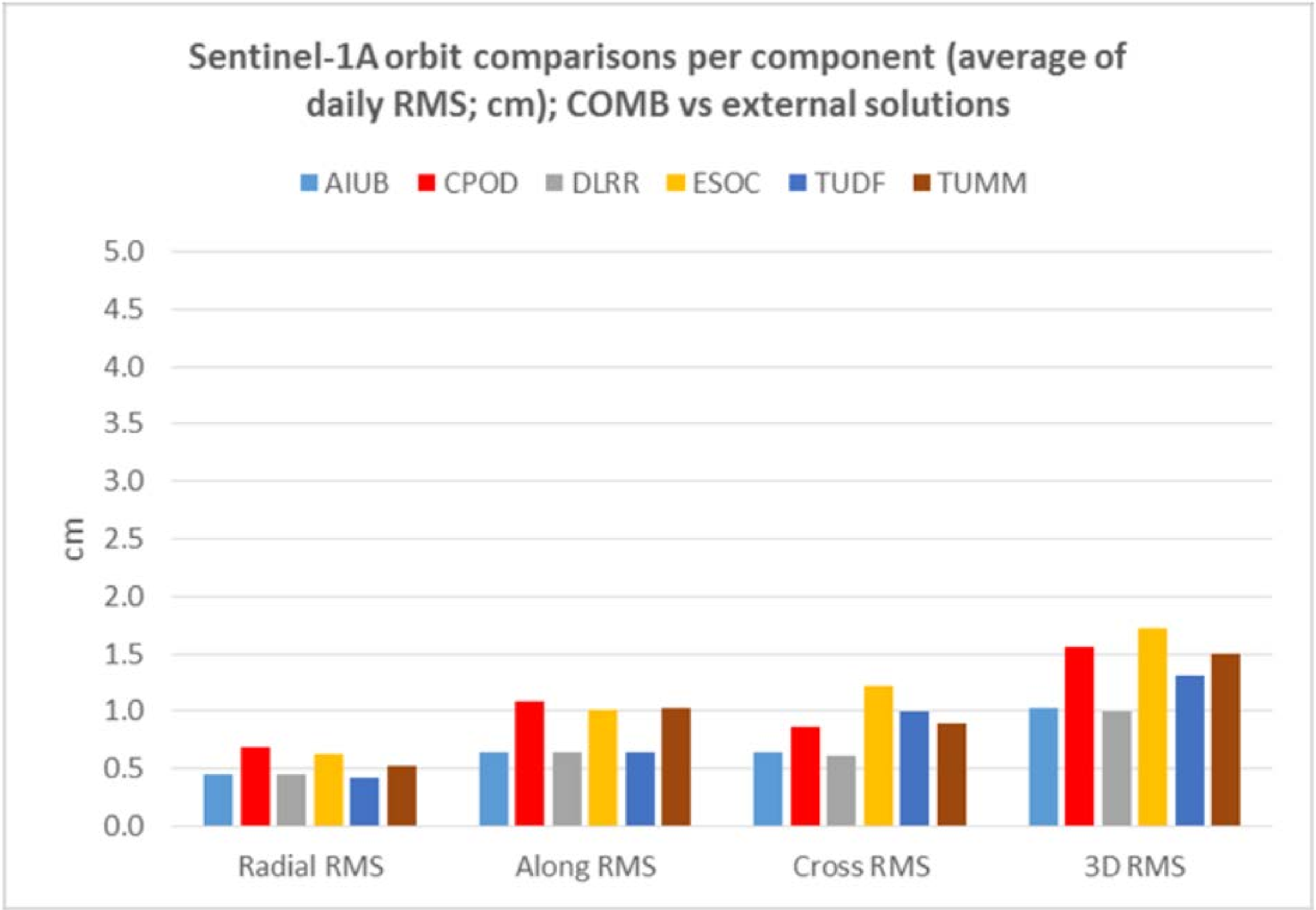
Sentinel-2A
Sentinel-2B

Sentinel-3A

copernicus
Europe's eyes on Earth

Courtesy: ESA

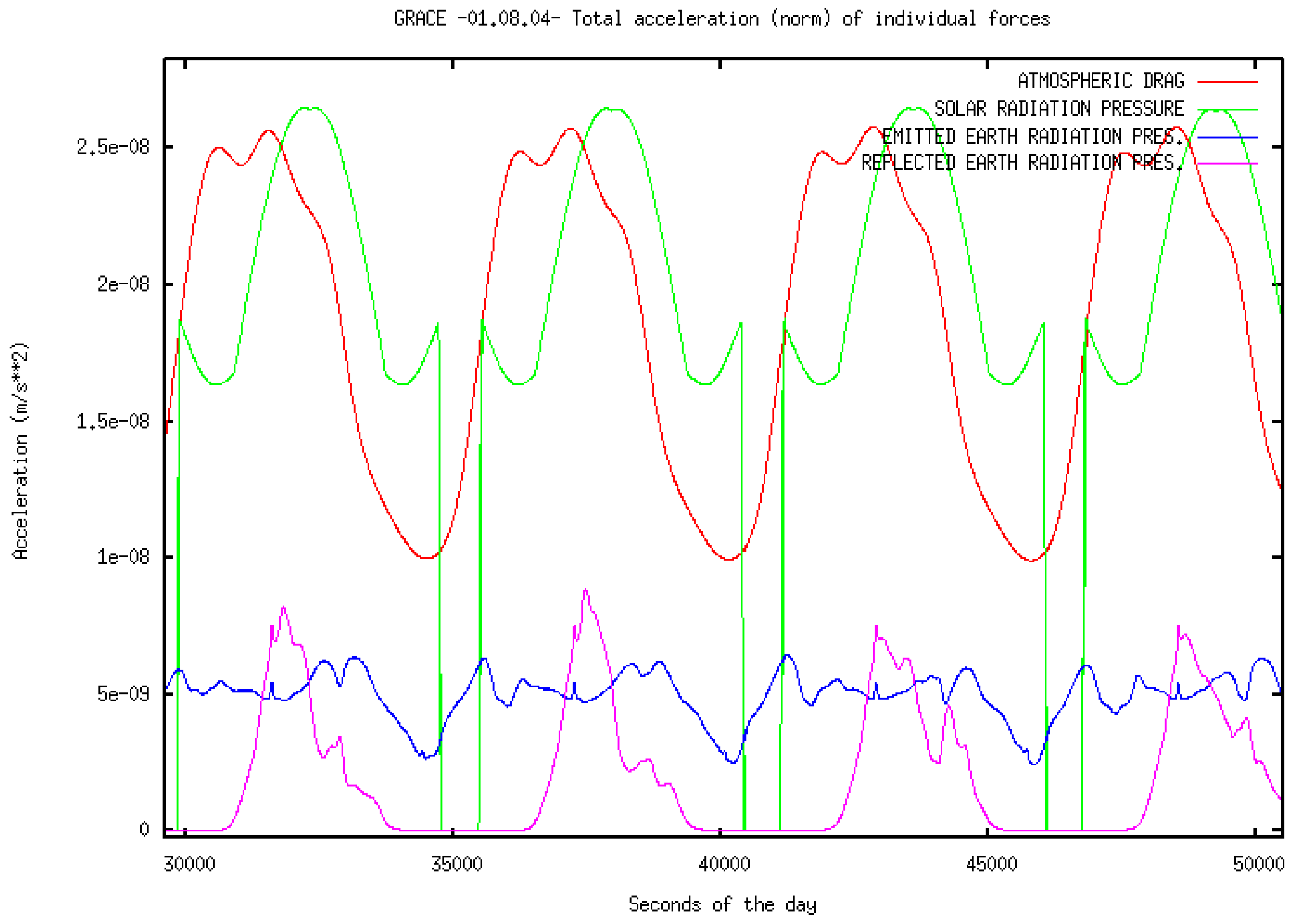
Sentinel orbit comparisons



LEO non-gravitational force modeling

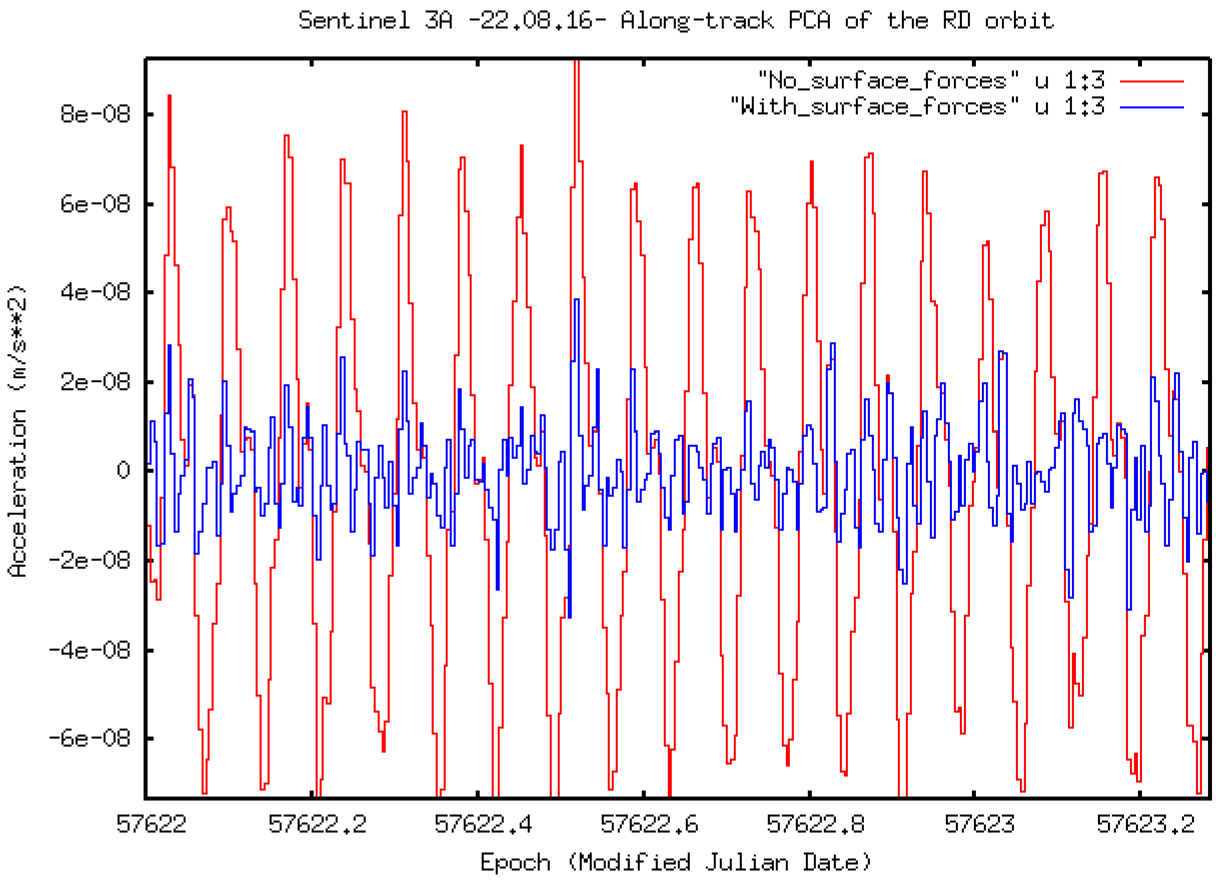
GRACE surface forces

Non-gravitational accelerations acting on GRACE-A



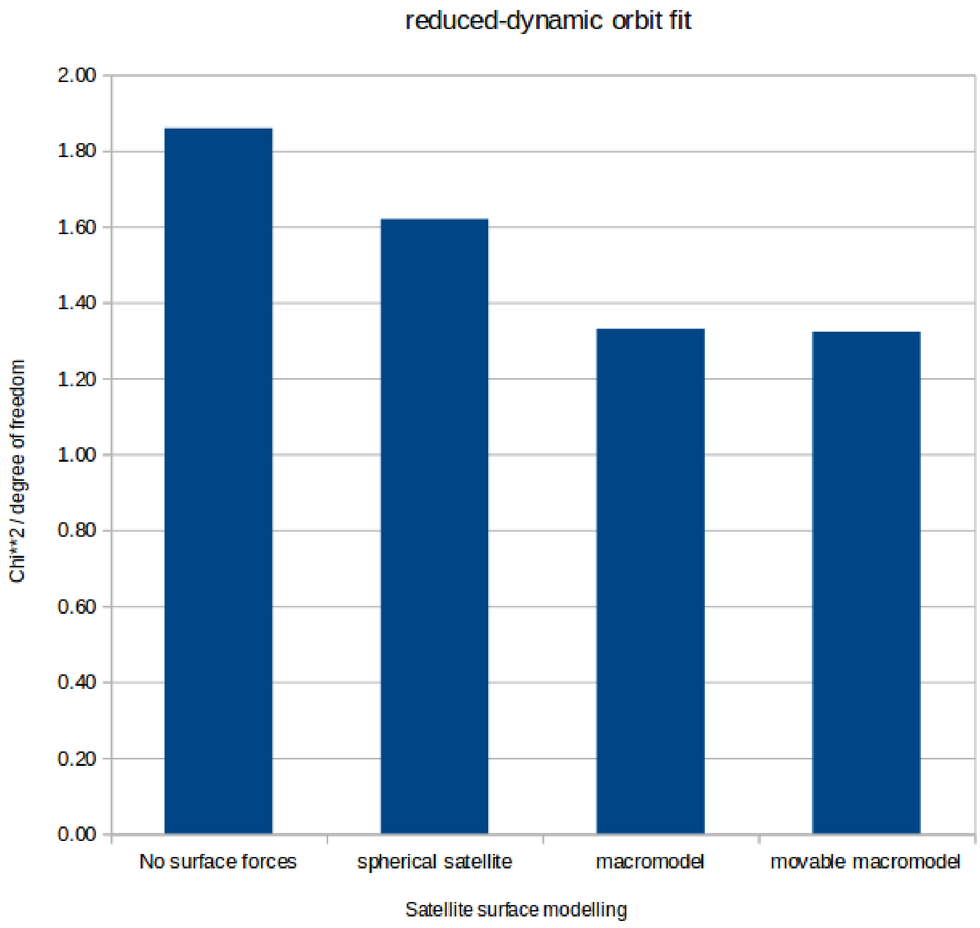
Sentinel-3A

Modeling of non-gravitational forces significantly reduces estimated piecewise-constant accelerations. E.g., in along-track:



Sentinel-3A

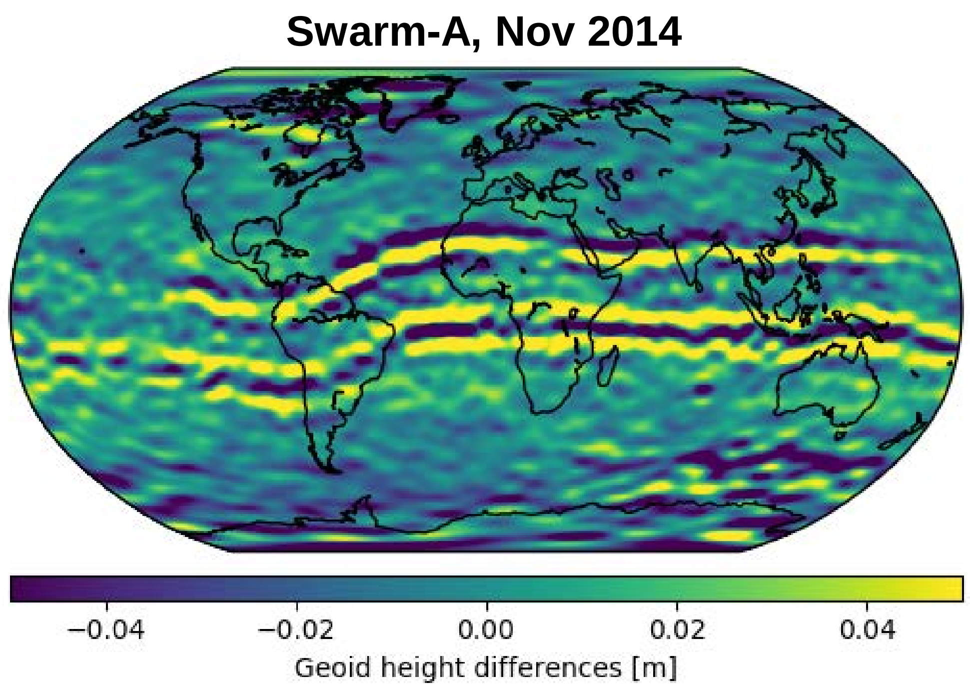
Quality of Sentinel-3A GPS data fit in reduced-dynamic POD for August 2016, using different degrees of sophistication for satellite model



Ionosphere-induced artifacts in Swarm and GOCE GPS gravity fields

Swarm gravity field

Geoid height differences (400 km Gauss filtered) of a Swarm-A monthly gravity field and the static field GRACE-AIUB03S:



- Artifacts along geomagnetic equator: Known to be caused by non-optimal GPS receiver settings
- Similar artefacts for GOCE

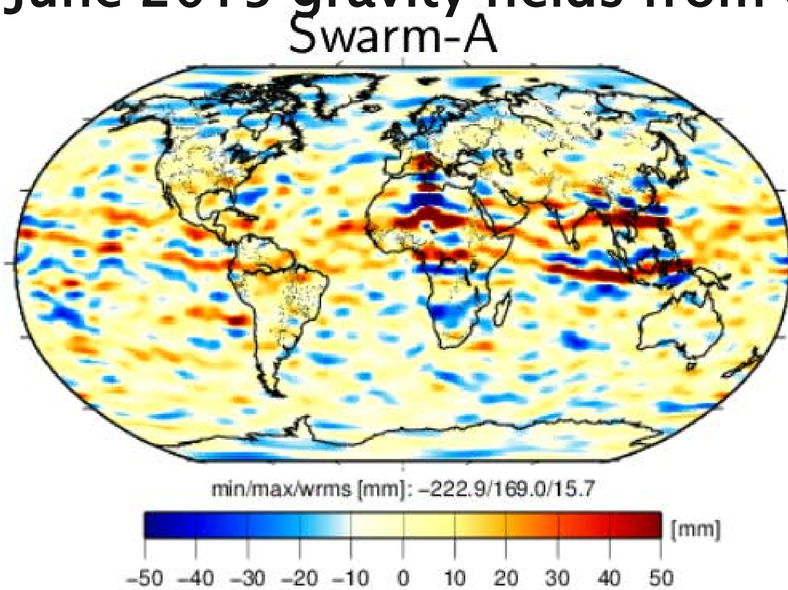
Tracking loop updates

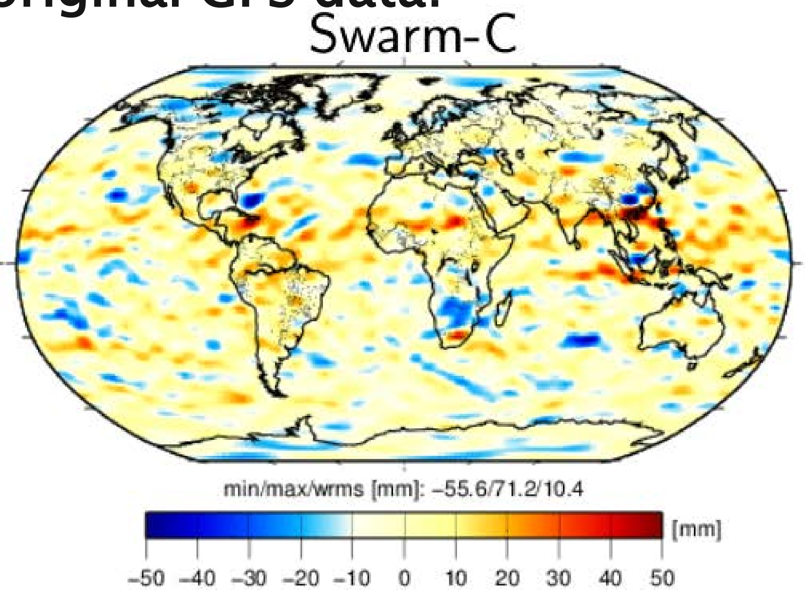
The tracking loop settings of the Swarm GPS receivers have been changed several times:

Date	Satellite	Tracking loop update
06 May 2015	Swarm-C	L_1: 10 Hz $\rightarrow$ 15 Hz L_2: 0.25 Hz $\rightarrow$ 0.5 Hz
08 Oct 2015	Swarm-A	L_1: 10 Hz $\rightarrow$ 15 Hz L_2: 0.25 Hz $\rightarrow$ 0.5 Hz
10 Oct 2015	Swarm-B	L_1: 10 Hz $\rightarrow$ 15 Hz L_2: 0.25 Hz $\rightarrow$ 0.5 Hz
23 Jun 2016	Swarm-C	L_2: 0.5 Hz $\rightarrow$ 0.75 Hz
11 Aug 2016	Swarm-A Swarm-C	L_2: 0.5 Hz $\rightarrow$ 0.75 Hz L_2: 0.75 Hz $\rightarrow$ 1 Hz

Tracking loop updates

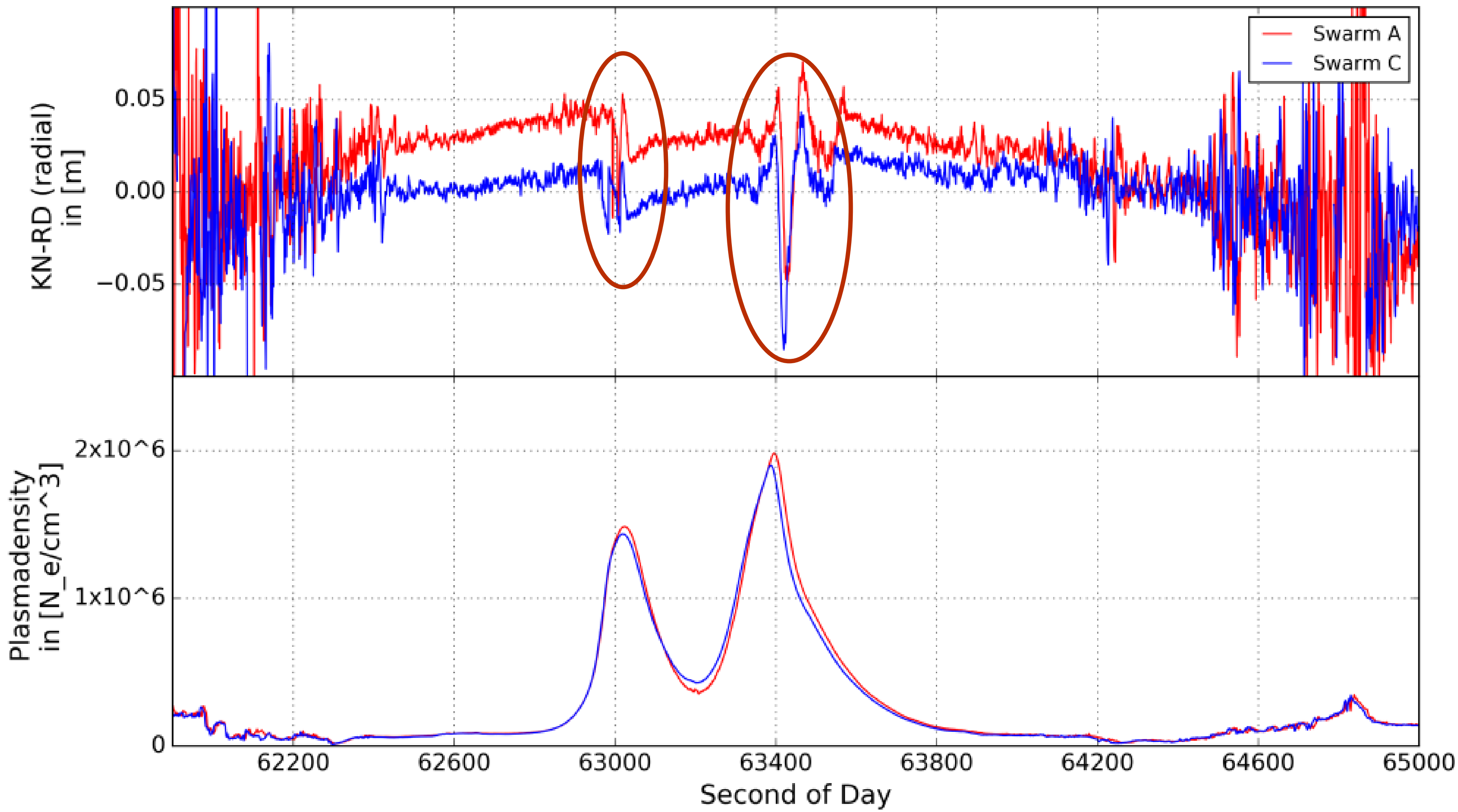
- Swarm–A and –C are in very similar orbits
- Between May and October 2015 Swarm–A had the old TL settings and Swarm–C the new ones
- June 2015 gravity fields from original GPS data:



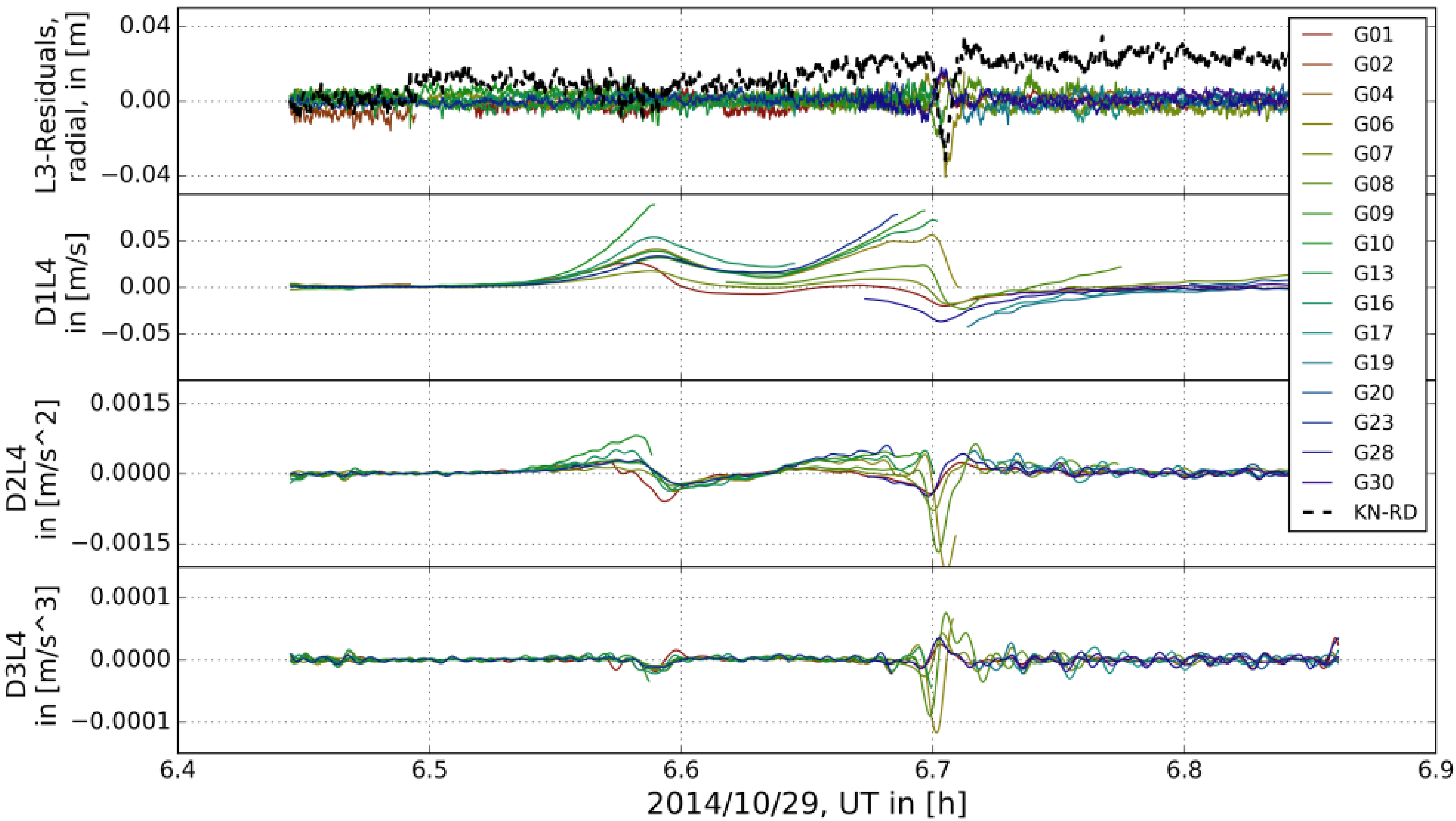


- TL upate significantly mitigates the artefacts
- To process older Swarm data and in the frame of the upcoming *GOCE orbit reprocessing*, better screening and weighting strategies are needed

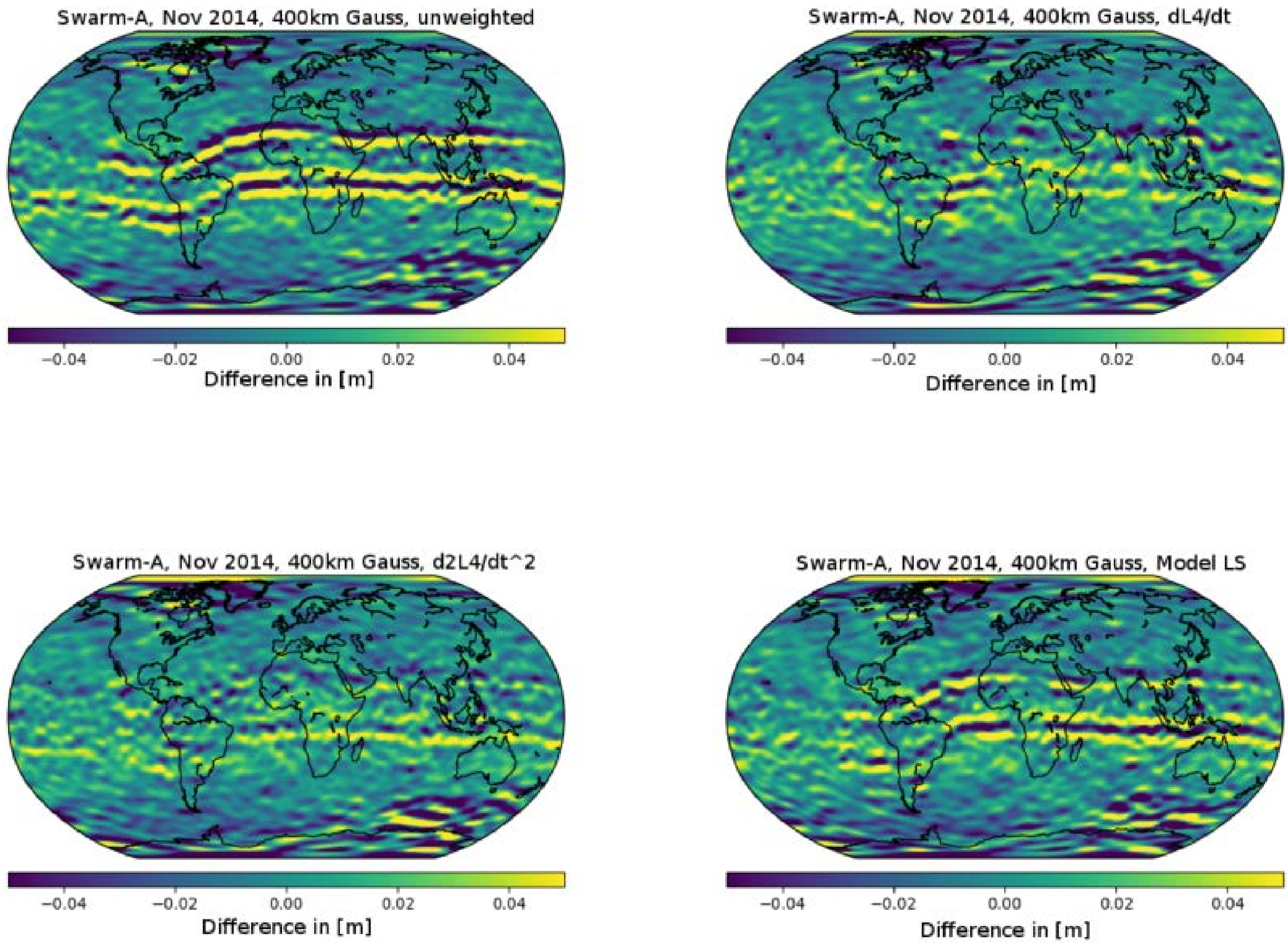
Artifacts and Swarm plasma density



Artifacts and time derivatives of L4



Downweighting GPS data

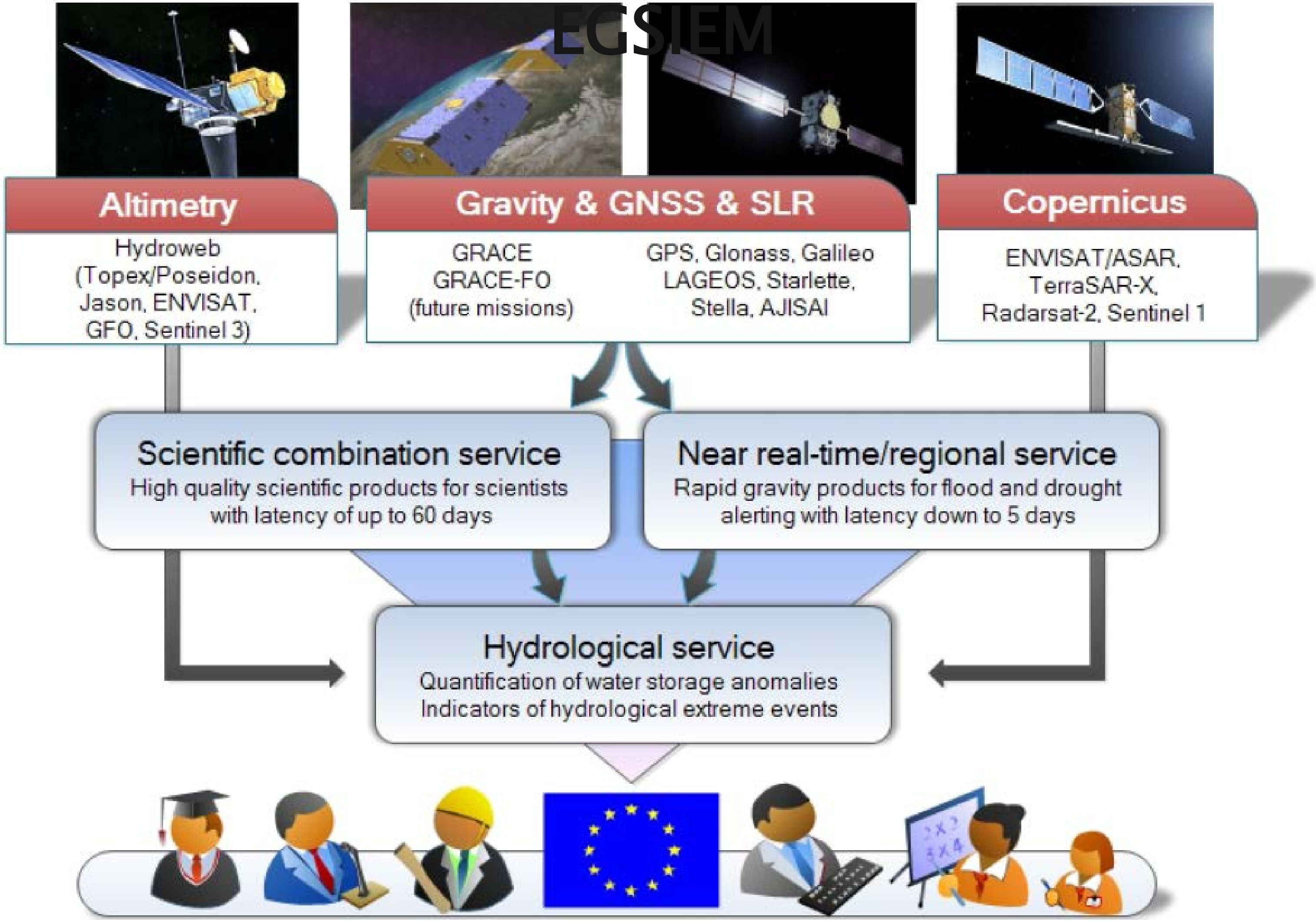


Activities in the frame of EGSIEM

EGSIEM European Gravity Service for Improved Emergency Management

is a project of the Earth Observation Space Calls of the Horizon 2020 Framework Program for Research and Innovation of the European Commission.

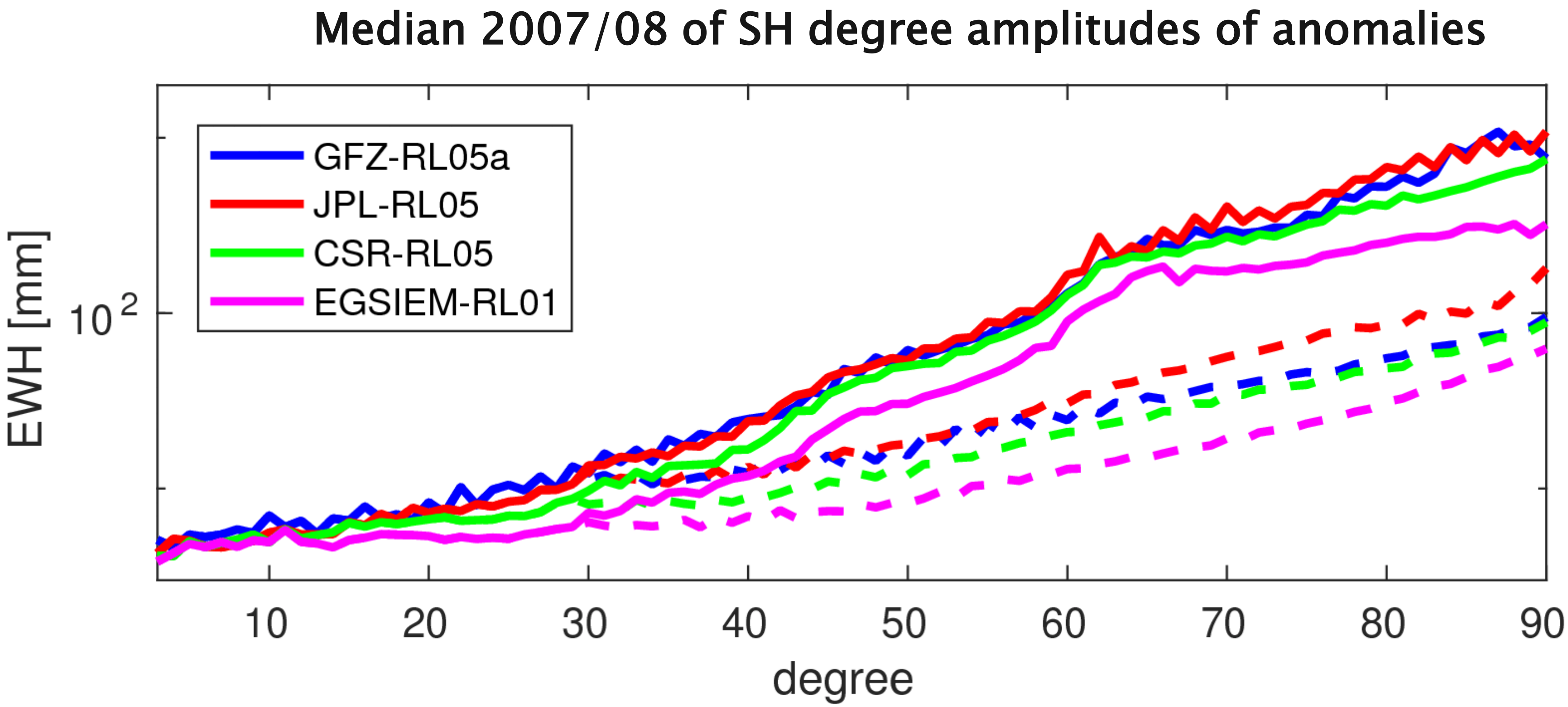
EGSIEM



Services will be tailored to the needs of governments, scientists, decision makers, stakeholders and engineers. Special visualisation tools will be used to inform, update, and attract also the large public.

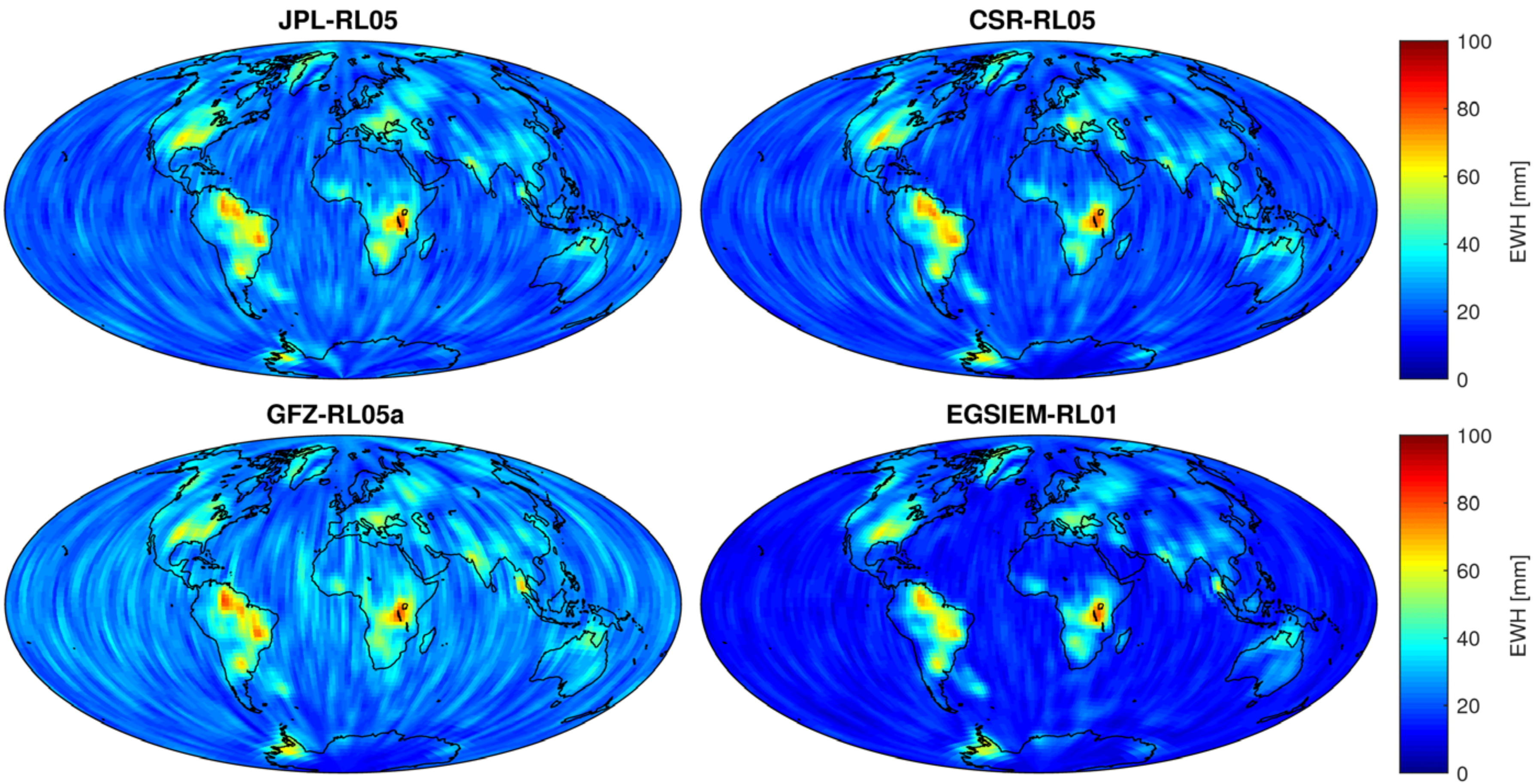
EGSIEM: Scientific Combination Service of monthly GRACE gravity fields

Noise assessment of monthly gravity fields.



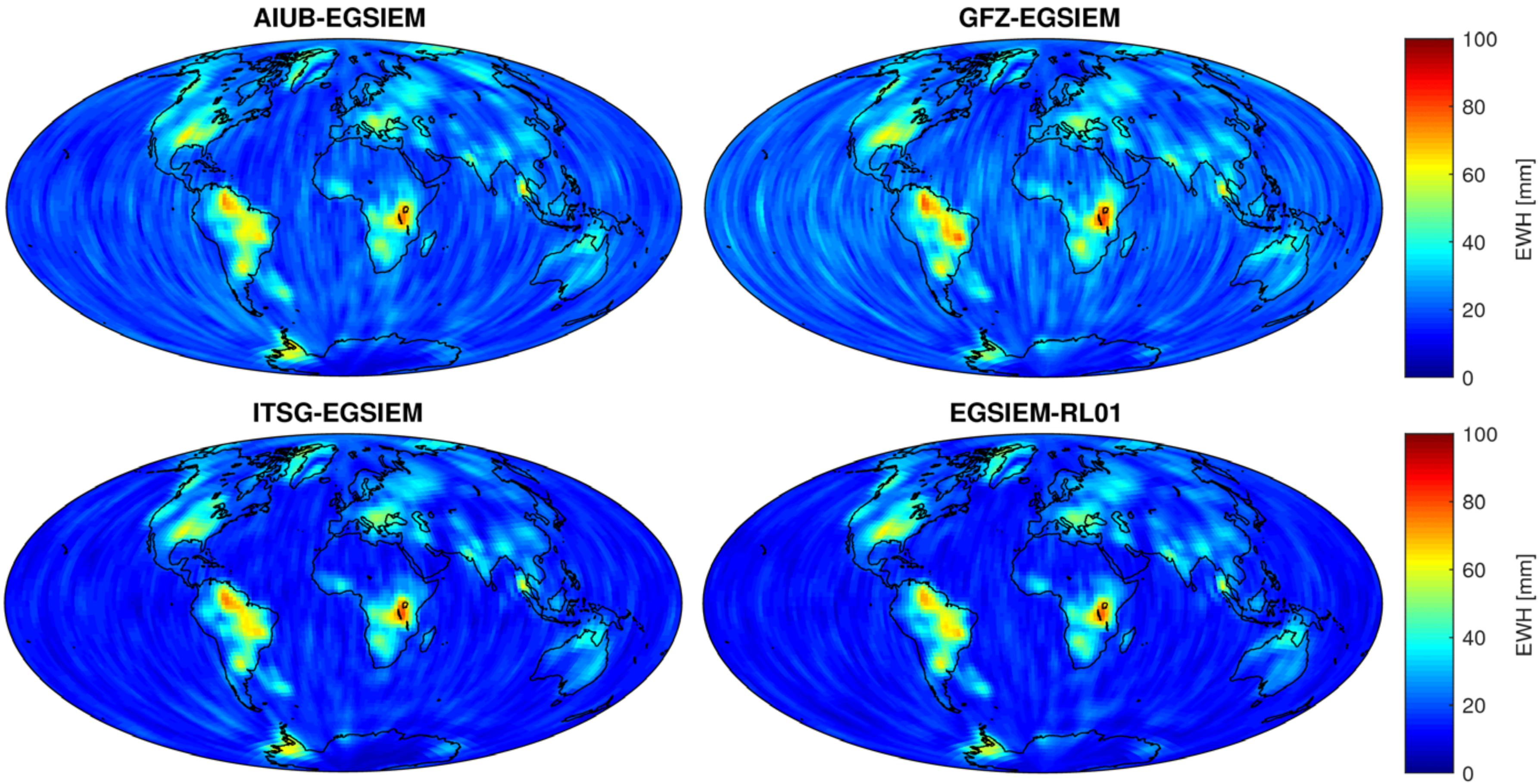
The signal content of monthly gravity fields is modeled by a best fit of seasonal and secular variations. The residuals (anomalies) at small scales (high SH degrees) are interpreted as noise. Dashed lines are truncated to physically most meaningful SH orders 1..29.

Non-seasonal EWH variability 2006/07



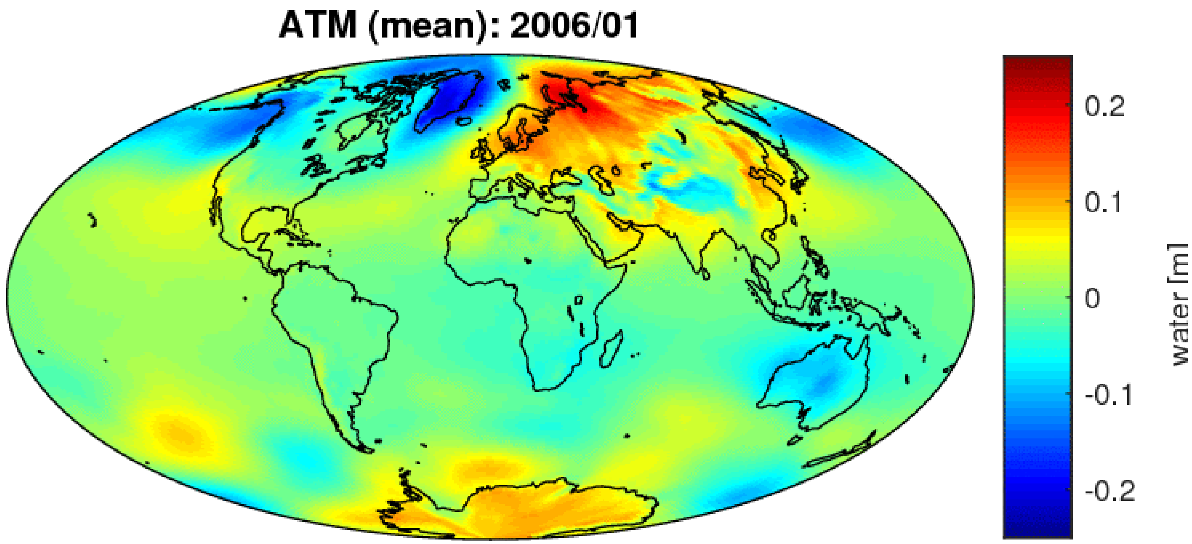
Non-seasonal EWH variability over the oceans is an indicator for noise in the monthly gravity fields.

Individual contributions

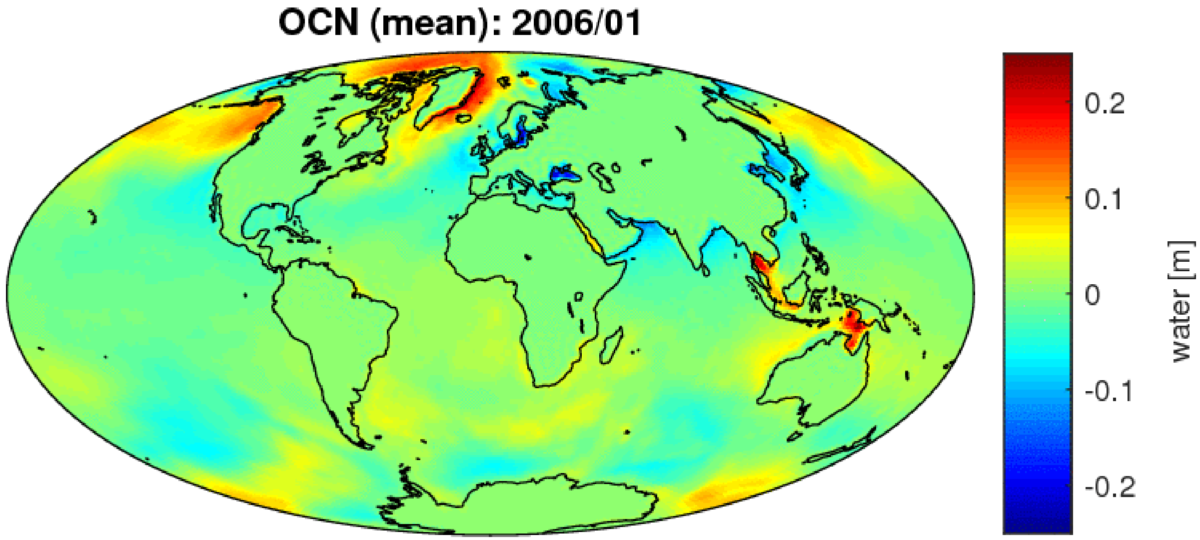


Non-seasonal EWH variability over the oceans is an indicator for noise in the monthly gravity fields.

Monthly mean of de-aliasing products

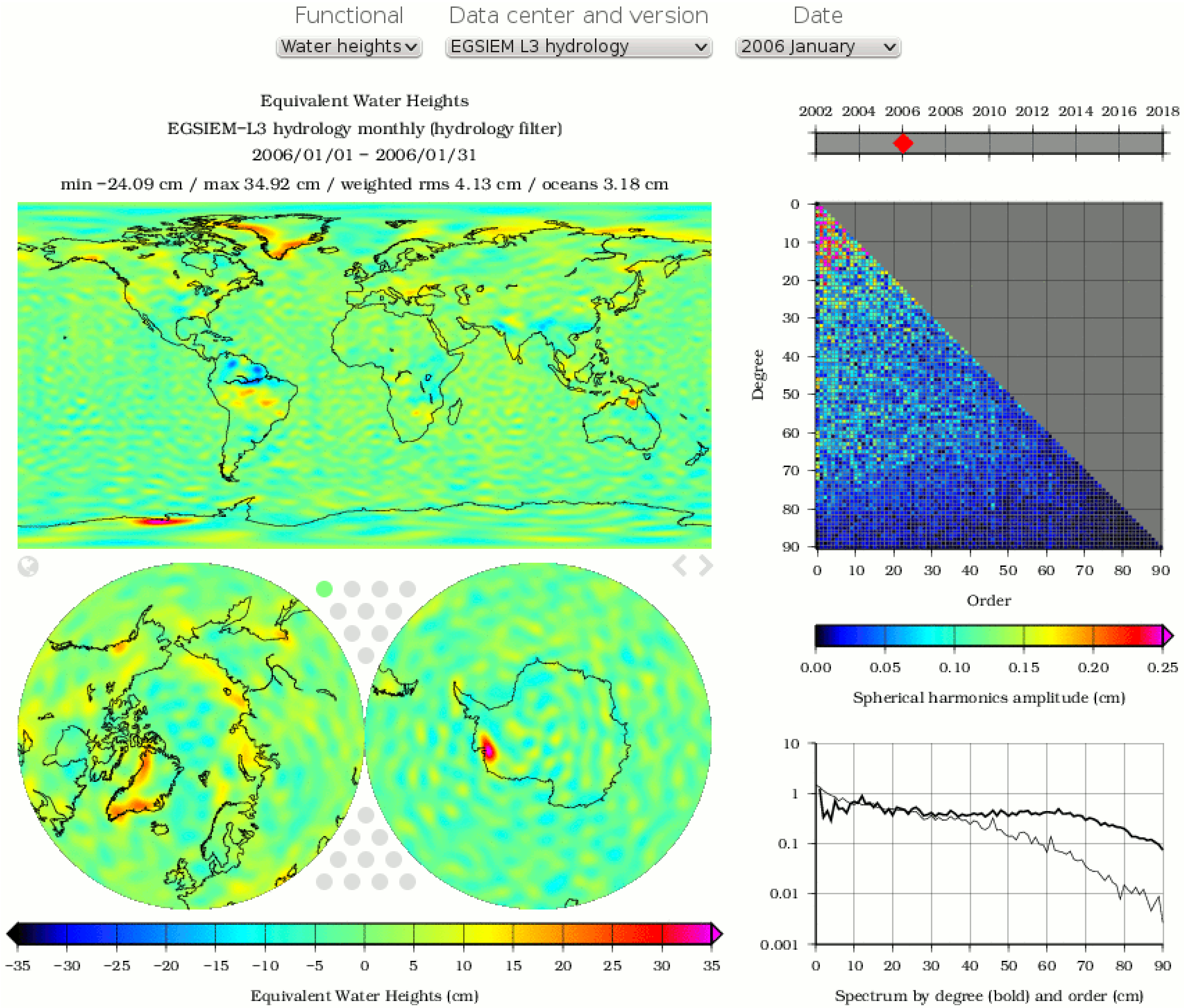


Monthly mean of short-term atmosphere mass variations.

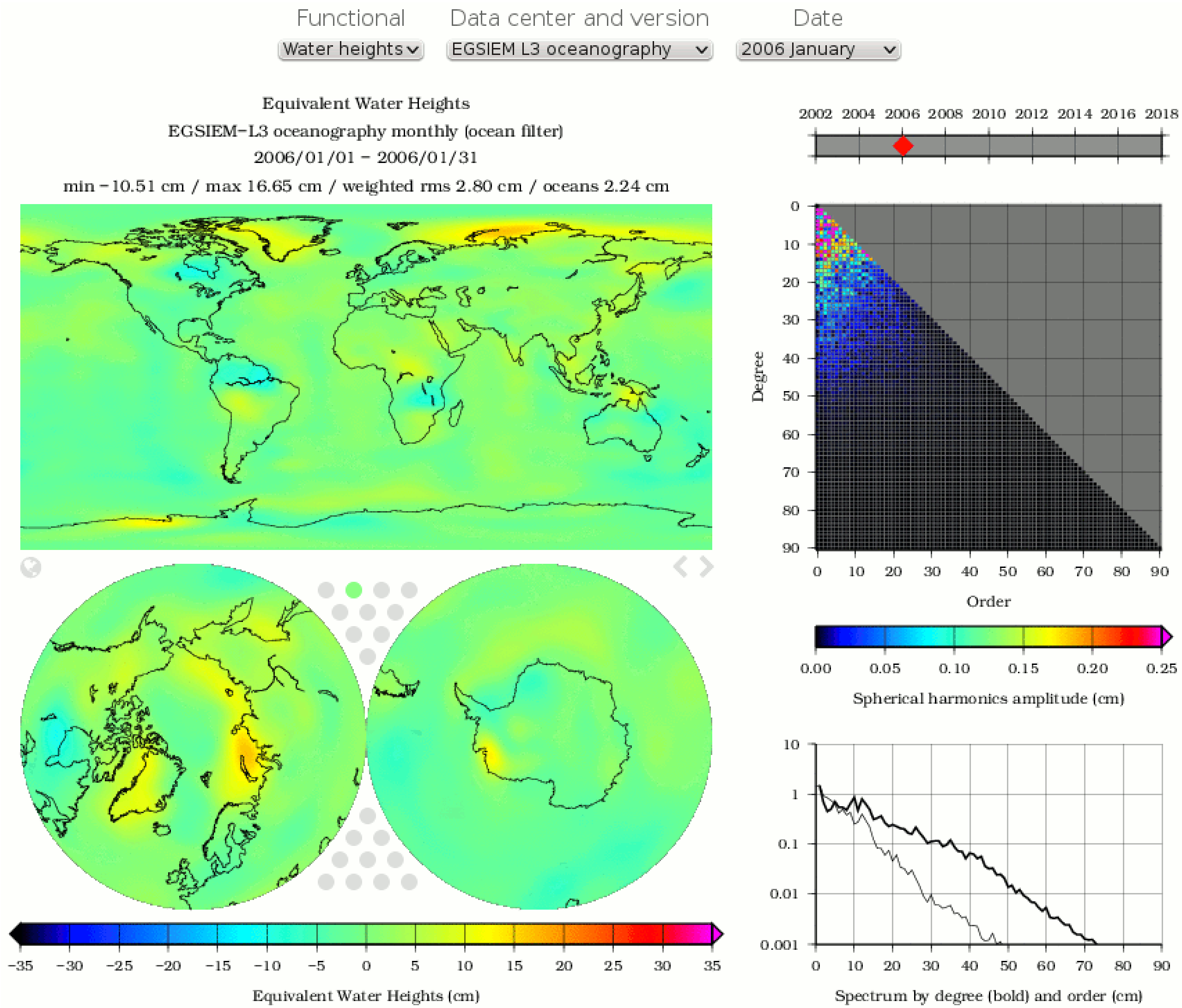


Monthly mean of short-term ocean mass variations.

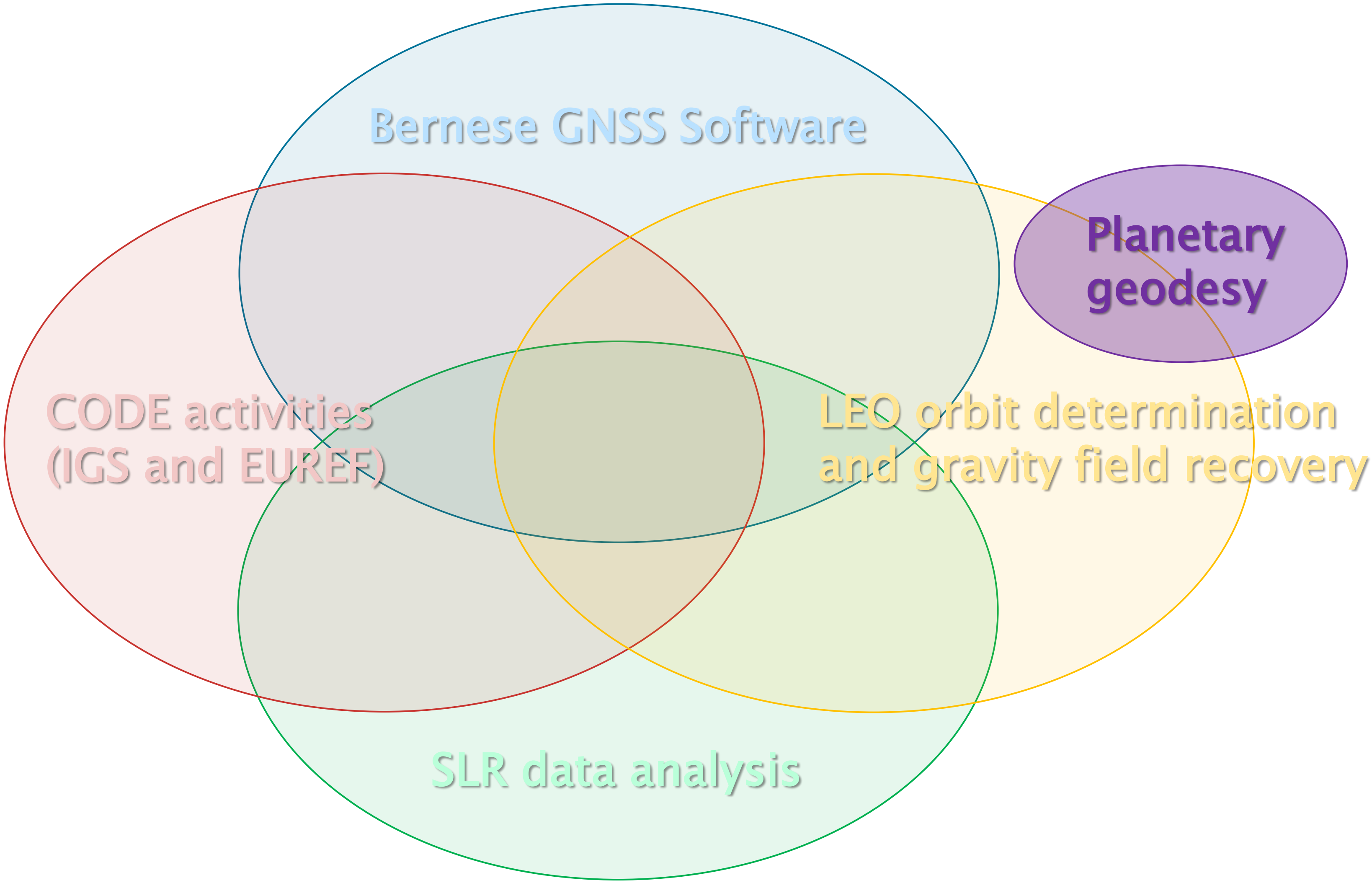
Gridded L3-products: pre-filtered for hydrology applications



Gridded L3-products: pre-filtered for oceanographic applications



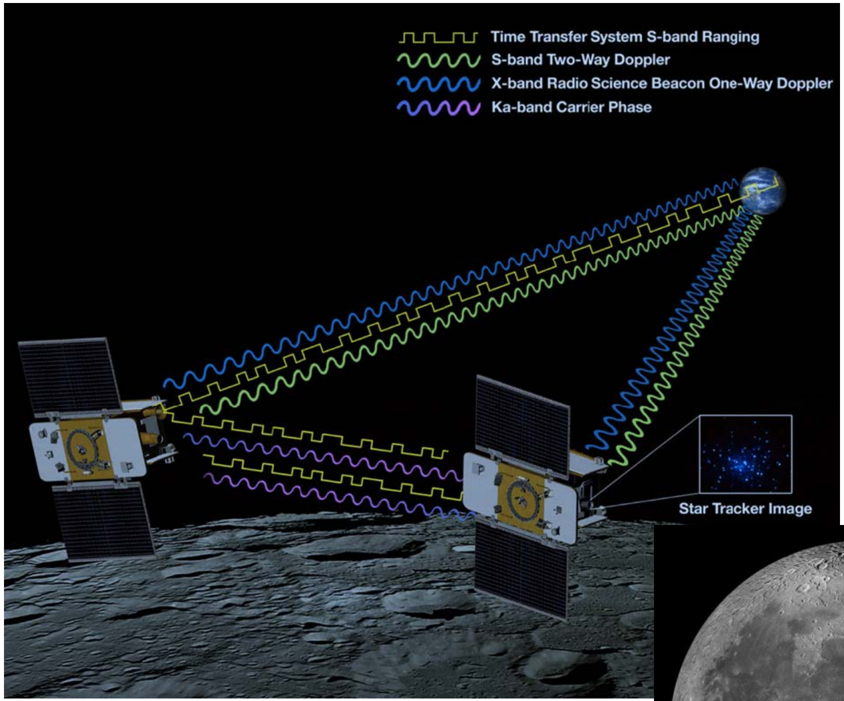
Satellite Geodesy Research Group



GRAIL – Lunar Geodesy

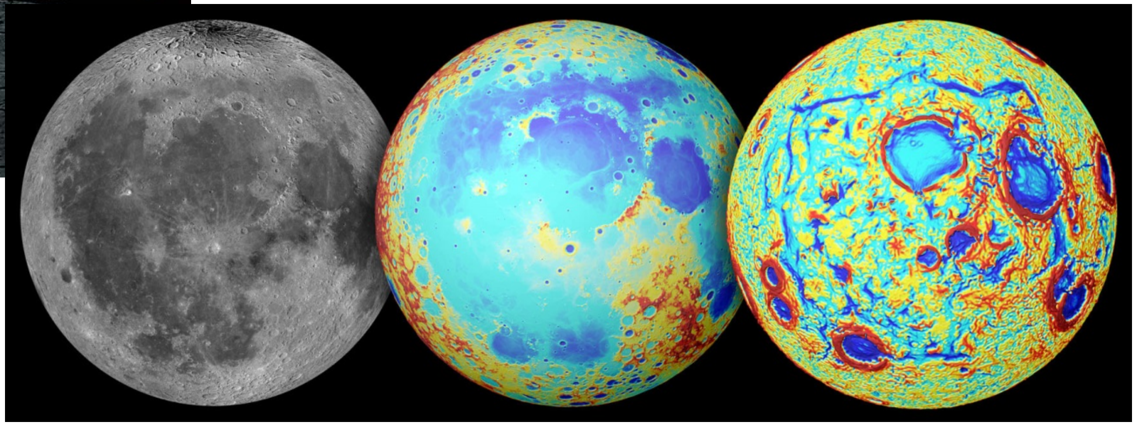
GRAIL – Lunar geodesy

Precise orbits of GRAIL probes around the Moon are computed at AIUB



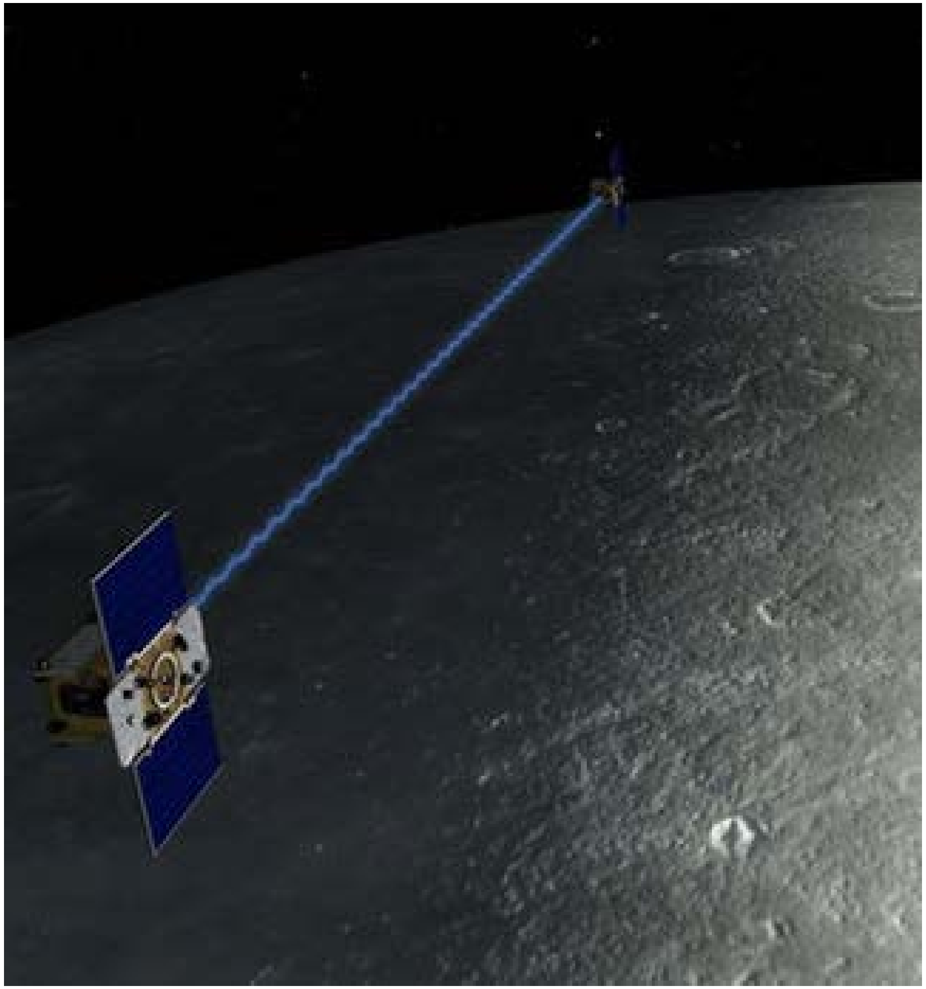
Datasets:

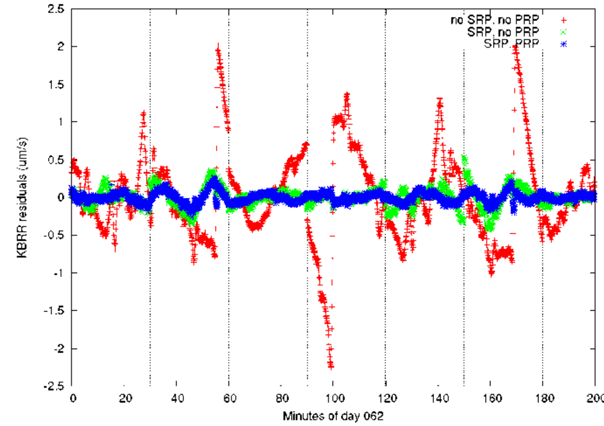
- 2-way S-band Doppler
- 1-way X-band Doppler
- Intersatellite Ka-band range rate data

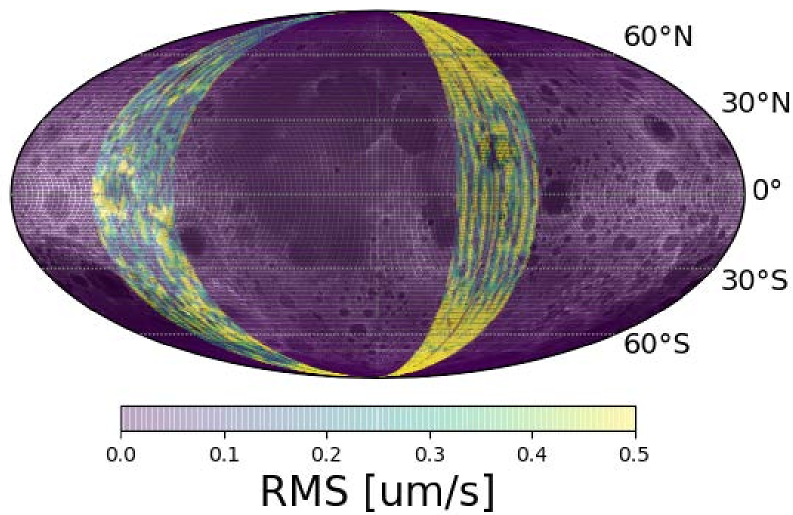


Courtesy: NASA

Precise modeling of solar eclipses

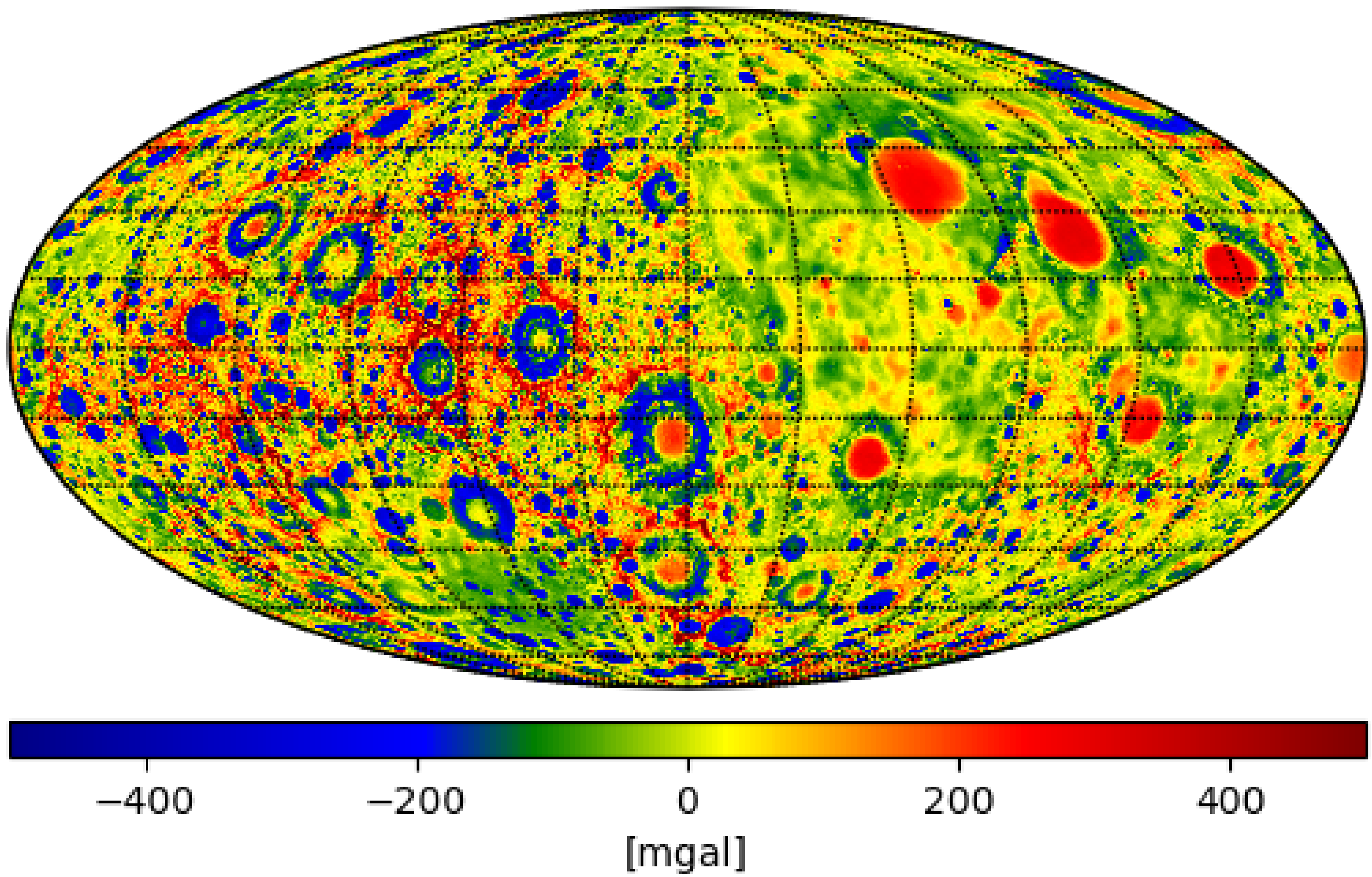






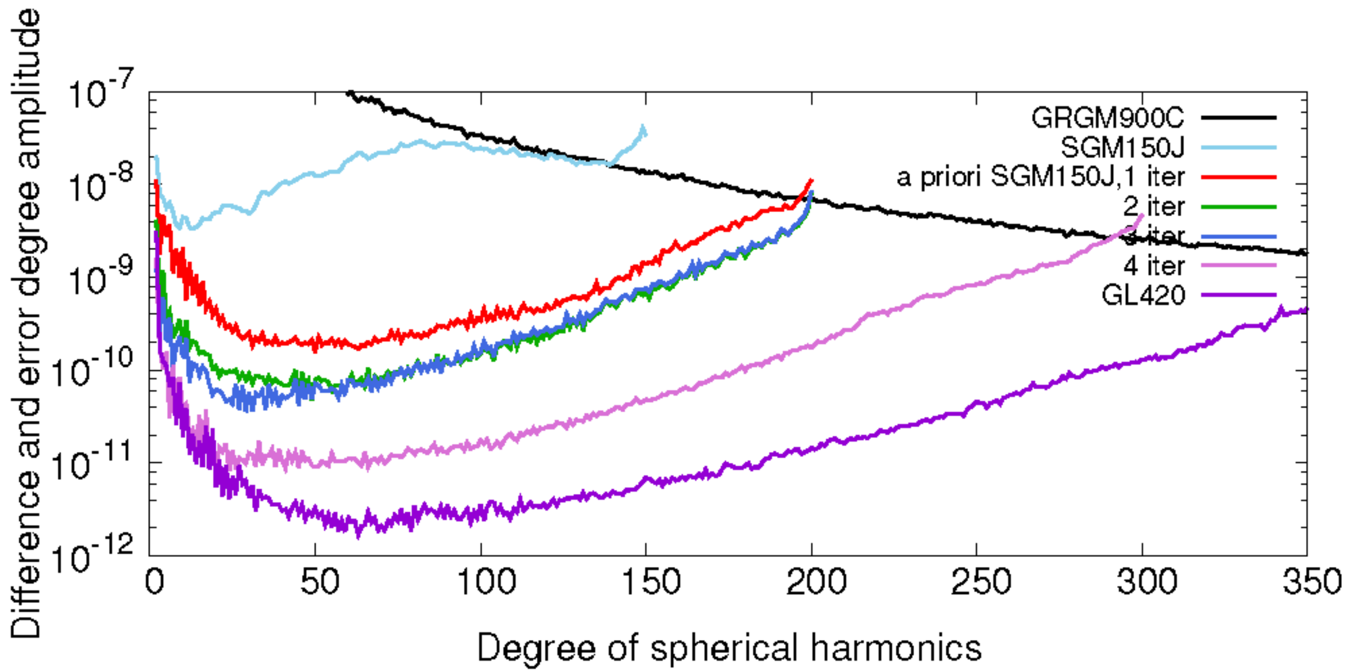
No modeling of Non gravitational forces

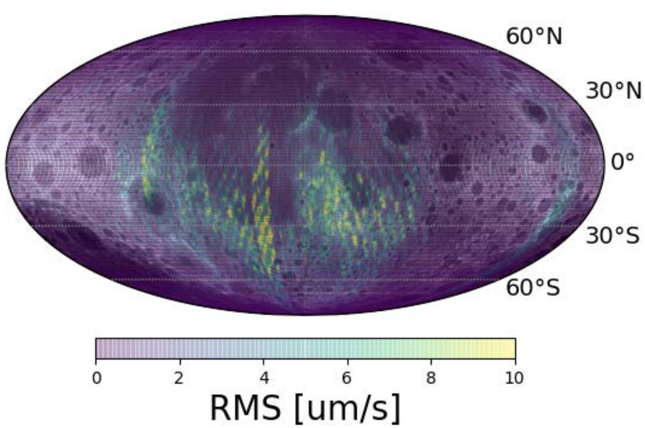
Lunar gravity field solutions

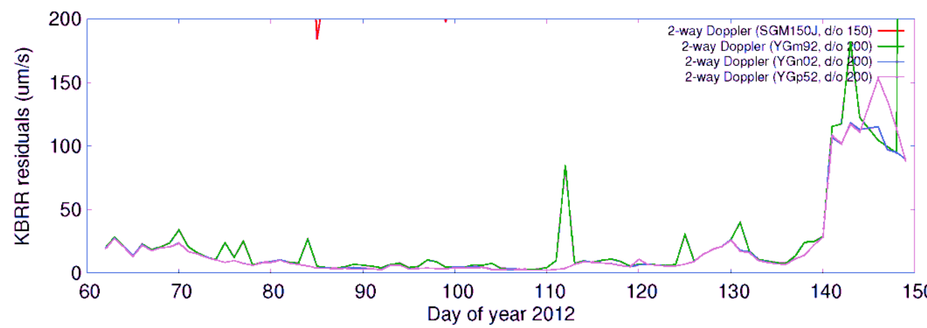


AIUB-GRL350B gravity anomalies

Lunar gravity field solutions
(iterations from SGM150J pre-GRAIL solution)



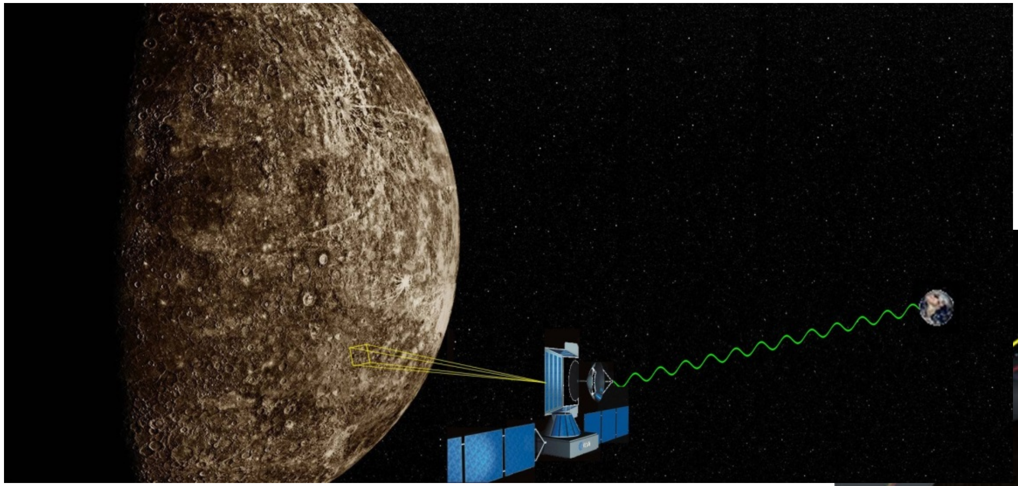


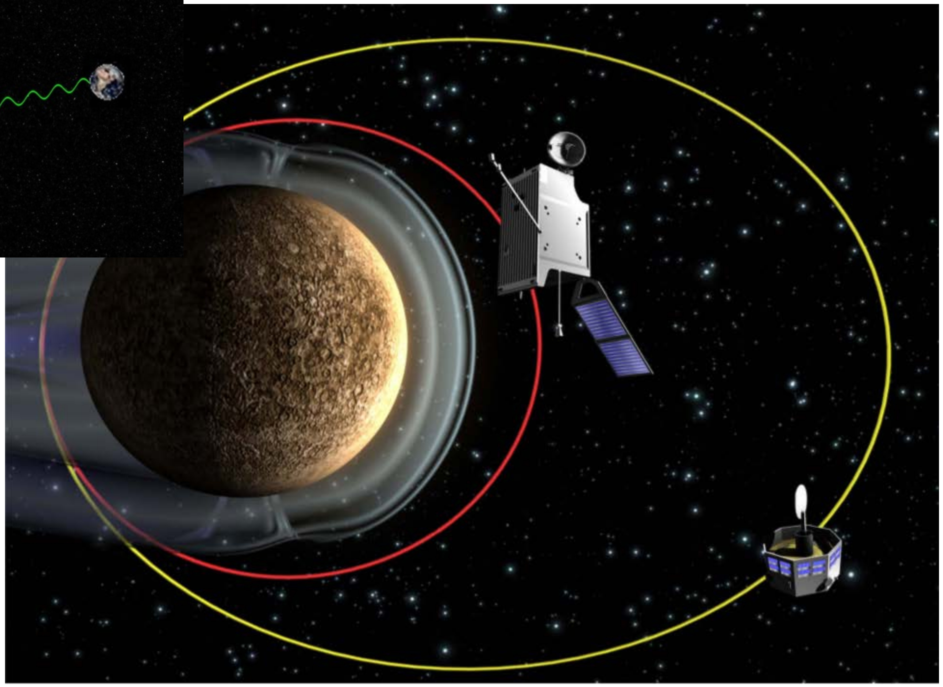


BELA (BepiColombo Laser Altimeter) orbit simulations

BepiColombo and BELA

BepiColombo: First European mission to Mercury
BELA : first European altimeter on a planetary mission



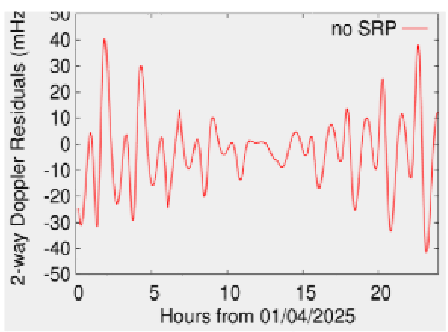


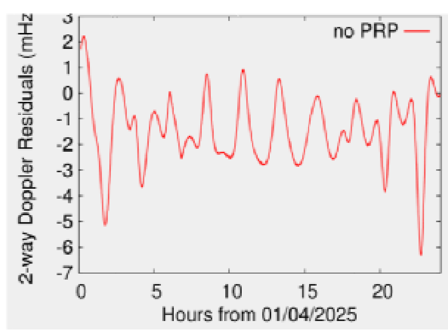
- **Developed and tested at Unibe (WP) and DLR**
- **Collaboration for accurate in-orbit simulations (PhD thesis)**

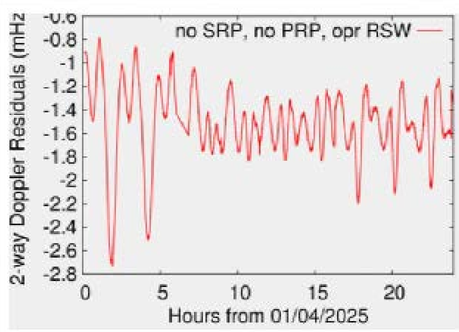
Sensitivity studies

Impact of several mismodelings on orbit recovery performances from Doppler simulated data

Doppler RMS over 60 days				
Iter	GRV d/o 25	No SRP	NO PRP	No SRP, NO PRP Opr empirical accelerations
1	4.4 mHz	79 mHz	13 mHz	54 mHz
5	1.3 mHz	15 mHz	2 mHz	0.9 mHz







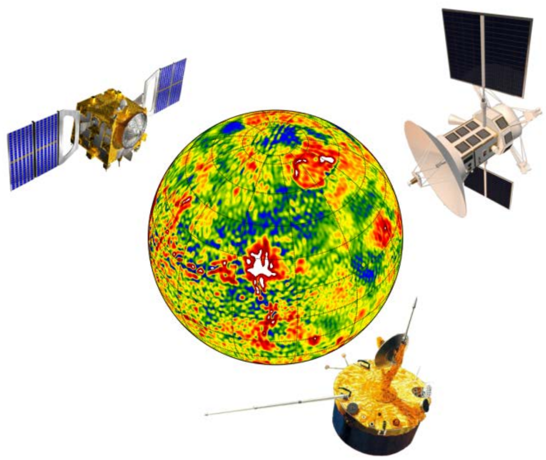
Reduced gravity field resolution

No Solar Radiation Pressure

No Mercury albedo / IR radiation

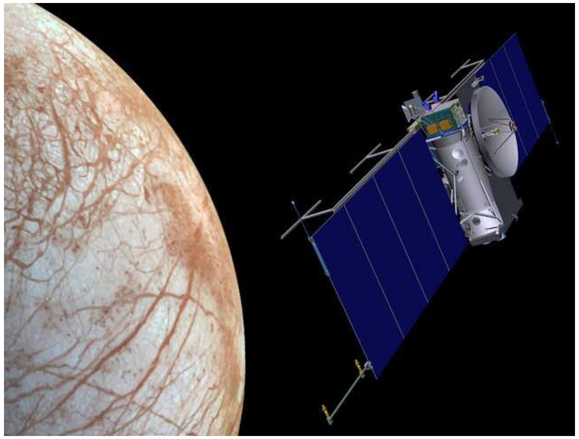
No non-gravitational forces + empirical acc.

Other ongoing projects in planetary geodesy



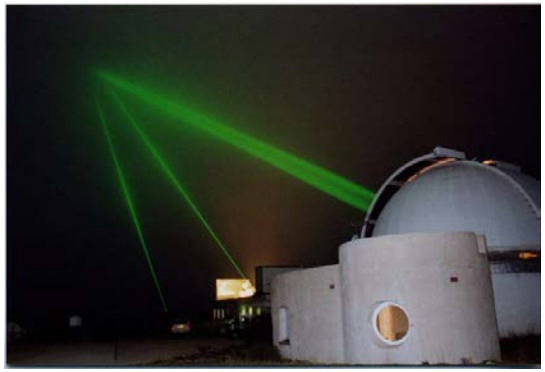
Improved Venus gravity field from data reprocessing

(Master thesis Jayraj Inamdar, TU DELFT)



Joint Europa Mission orbit and gravity recovery simulations

(internship William Desprats, ISAE)



Analysis of Lunar Laser Ranging + GRAIL combined solutions

Combining
Observations &
Modeling to
Promote
upper Atmospheres
Research
& Exploitation

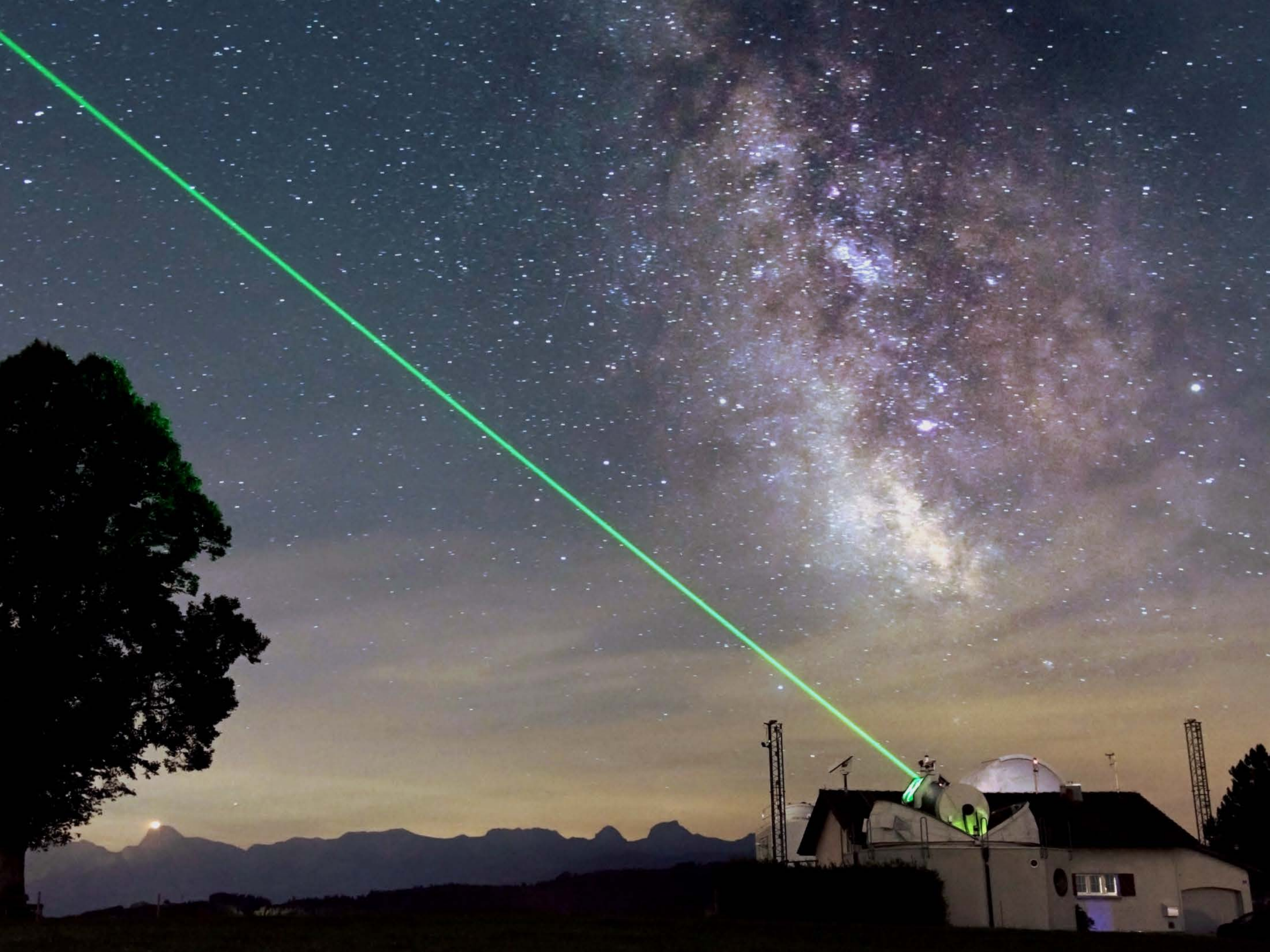
Participation to international projects and H2020 proposals

Astronomisches Institut der Universität Bern – Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald

Astronomical Institute, University of Bern, Switzerland

Activities at the Zimmerwald Observatory

- **Optical Observations** (CCD) Space Debris, Asteroids, Comets
- **Satellite Laser Ranging** to dedicated satellites
- **GNSS-Receivers** (GPS-, GLONASS- and Galileo-signals; swisstopo)
- **Earth Tide Gravimeter** Institute for Geodesy and Photogrammetry ETH Zürich
- **Various microwave instruments for atmospheric research** Institute of Applied Physics Bern



SLR Operations

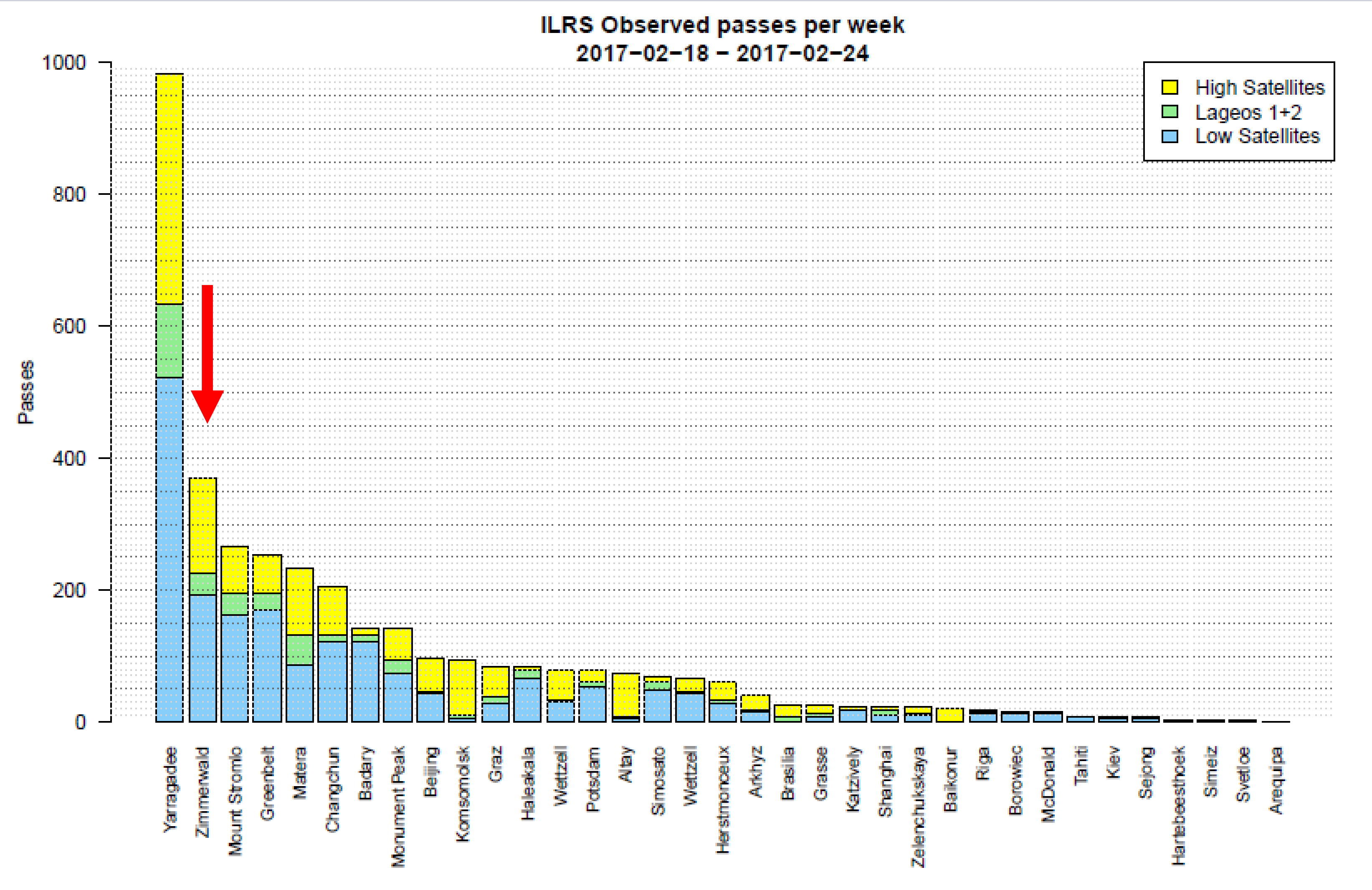
- Laser fully operational again since January 2017!
  - new laser head from Thales
    (no replacement hardware available)
  - high voltage power supply repaired

  → tracking of LEO, LAGEOS and GNSS o.k.
- February 27, 2017 successful ILRS qualification
  - required after long outage period

  → same data quality as in 2015/16

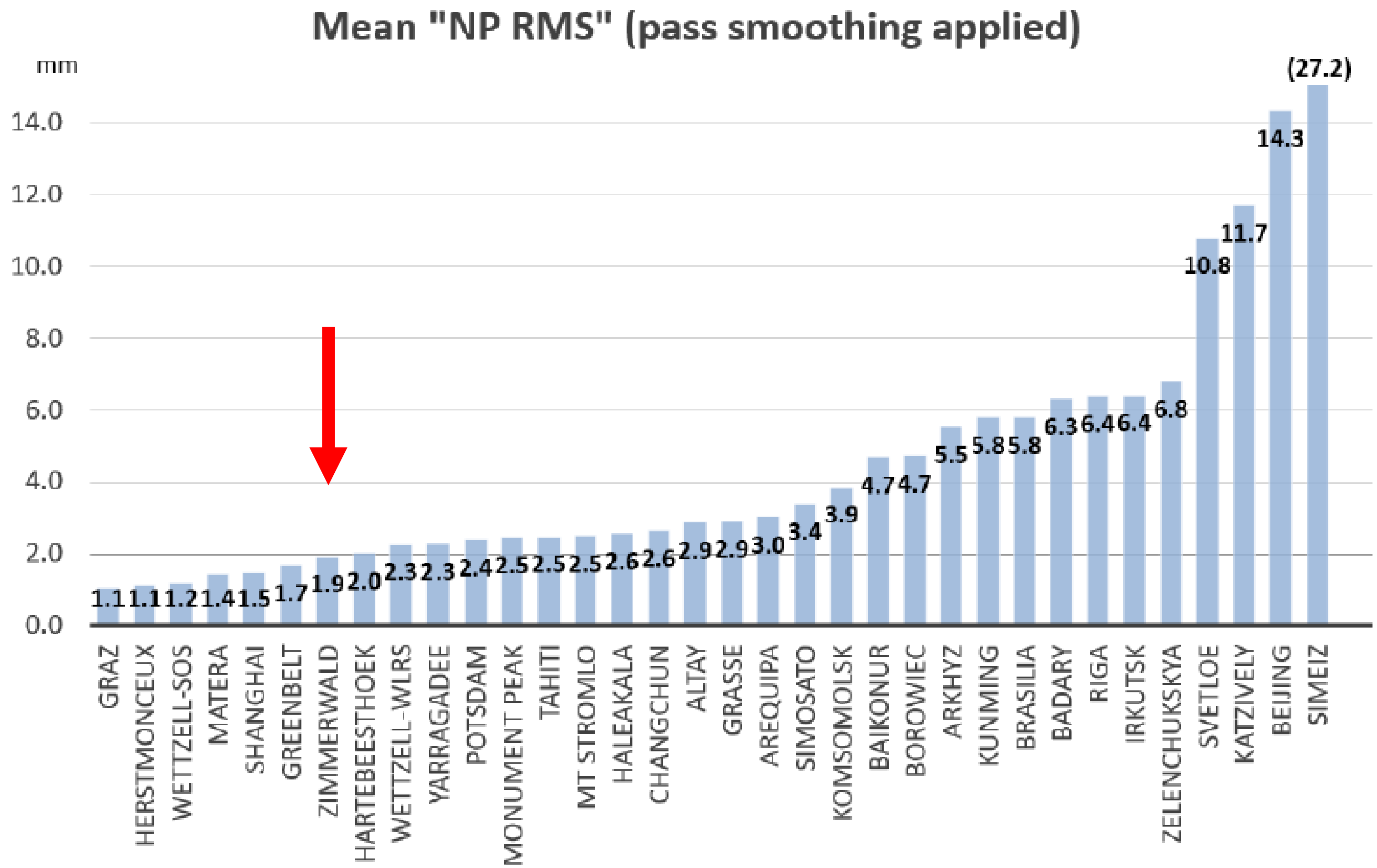
  → very good performance
- Sentinel-3A tracking qualification
  - March 21, 2017 (finally)

ILRS Station Performance



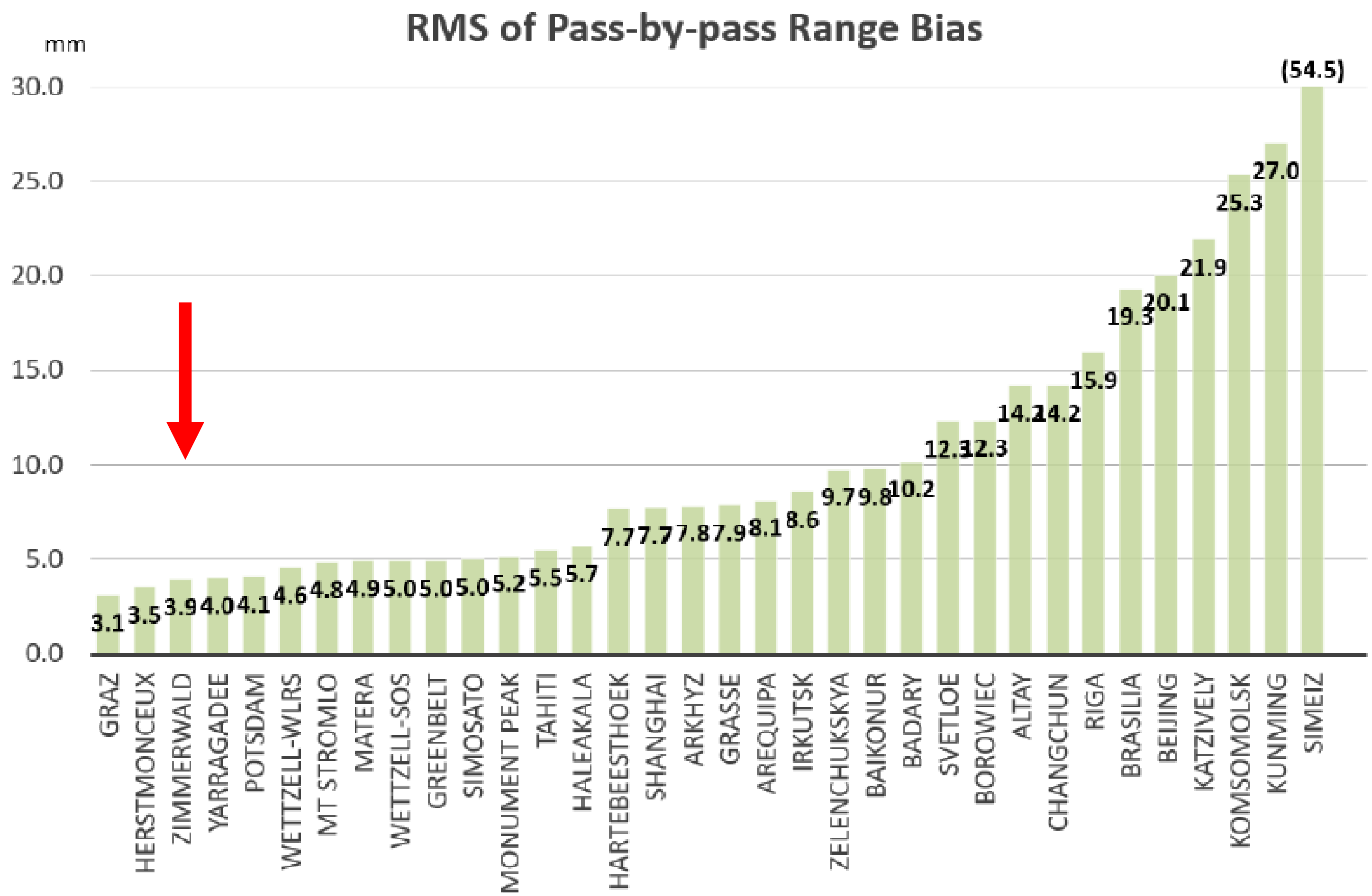
ILRS NP RMS

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.

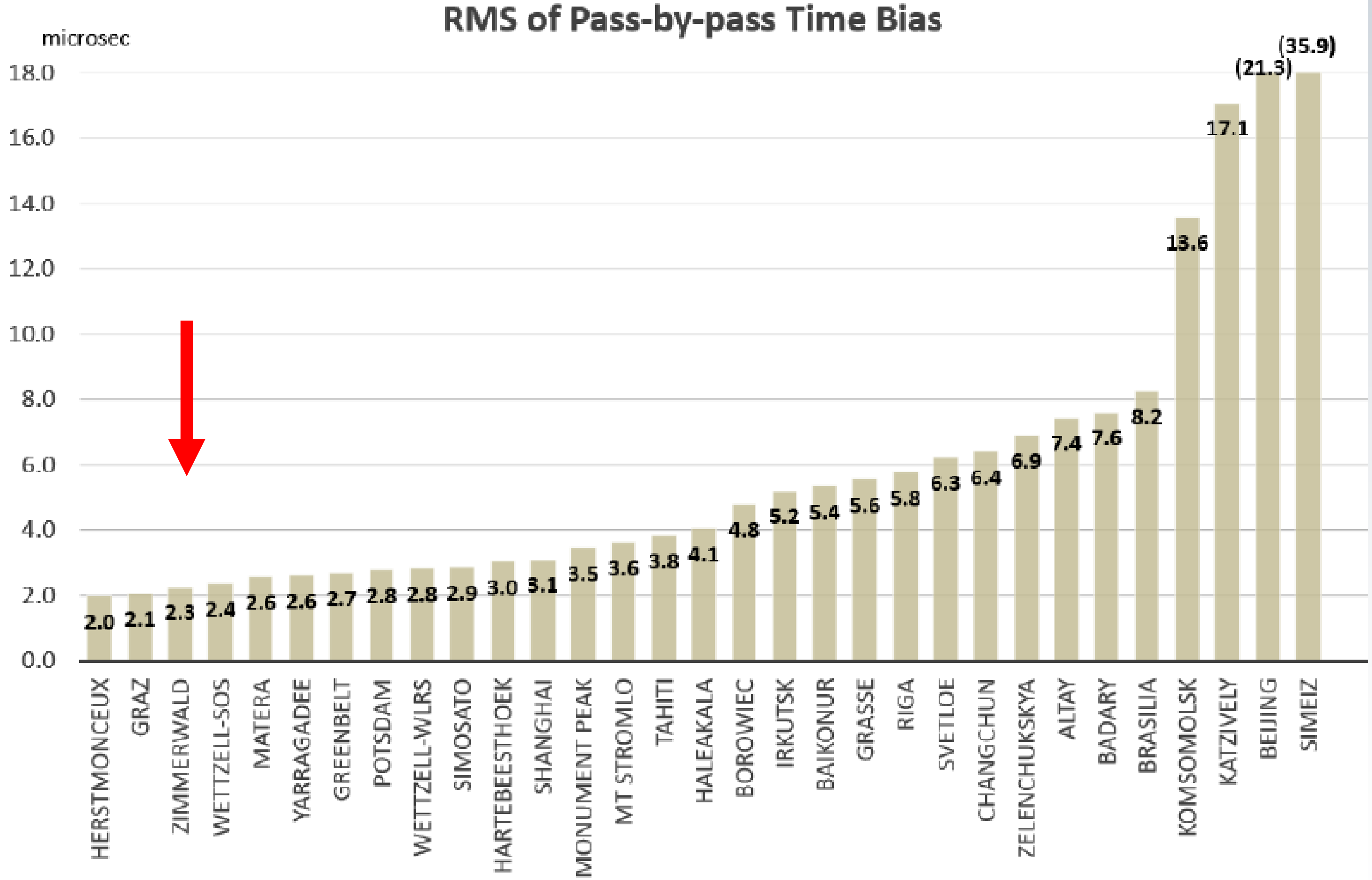


T. Schildknecht (2017.10)
Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald

ILRS Time Bias

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

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



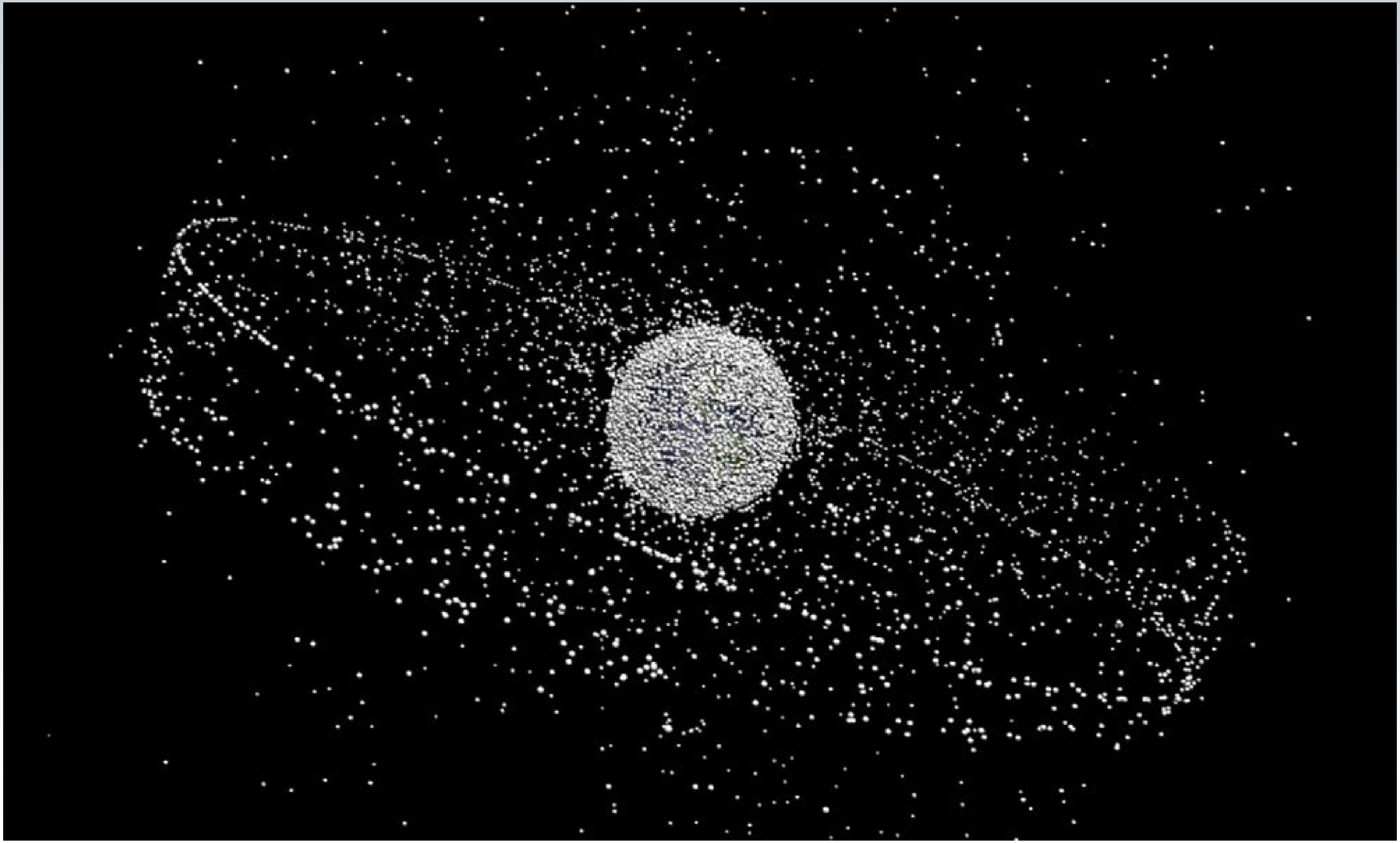
T. Schildknecht (2017.10)
Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald

Astronomical Institute University of Bern AIUB

SLR Operations & Developments

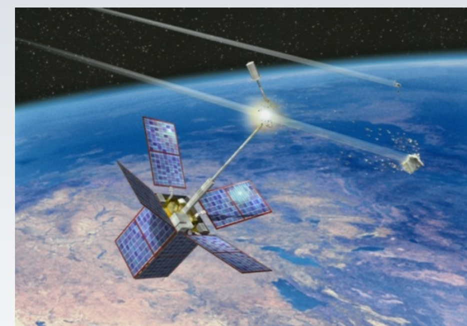
- New SLR projects
  - New high-altitude satellite campaigns
  - European Laser Time Transfer project (ELT)(ACES experiment on ISS)
    - definition of hardware requirements
    - analysis of software requirements
  - Space Debris laser campaigns (new ILRS Space Debris Study Group)
- Definition/evaluation of new laser
  - 100Hz/kHz...?
  - Two lasers? Debris SLR on new 0.8m telescope
  - Final evaluation 2018
  - Procurement 2019
- Main technical developments
  - EFOS-8 Maser is operational frequency standard for SLR since 9.8.2016
  - usability of sCMOS tracking camera improved

Space Debris



Space Debris Research

- **Open Questions**
  - **Population**
    - how many?
    - size distribution?
    - orbit regions?
    - nature of objects?
    - sources, sinks?
  - **Physics/Mechanisms**
    - creation
    - evolution of orbits
    - long-term evolution: → models
- **Approach**
  - **Search for debris** (surveillance)
  - **Determine orbits**
  - **Characterize**



Optical Sensors

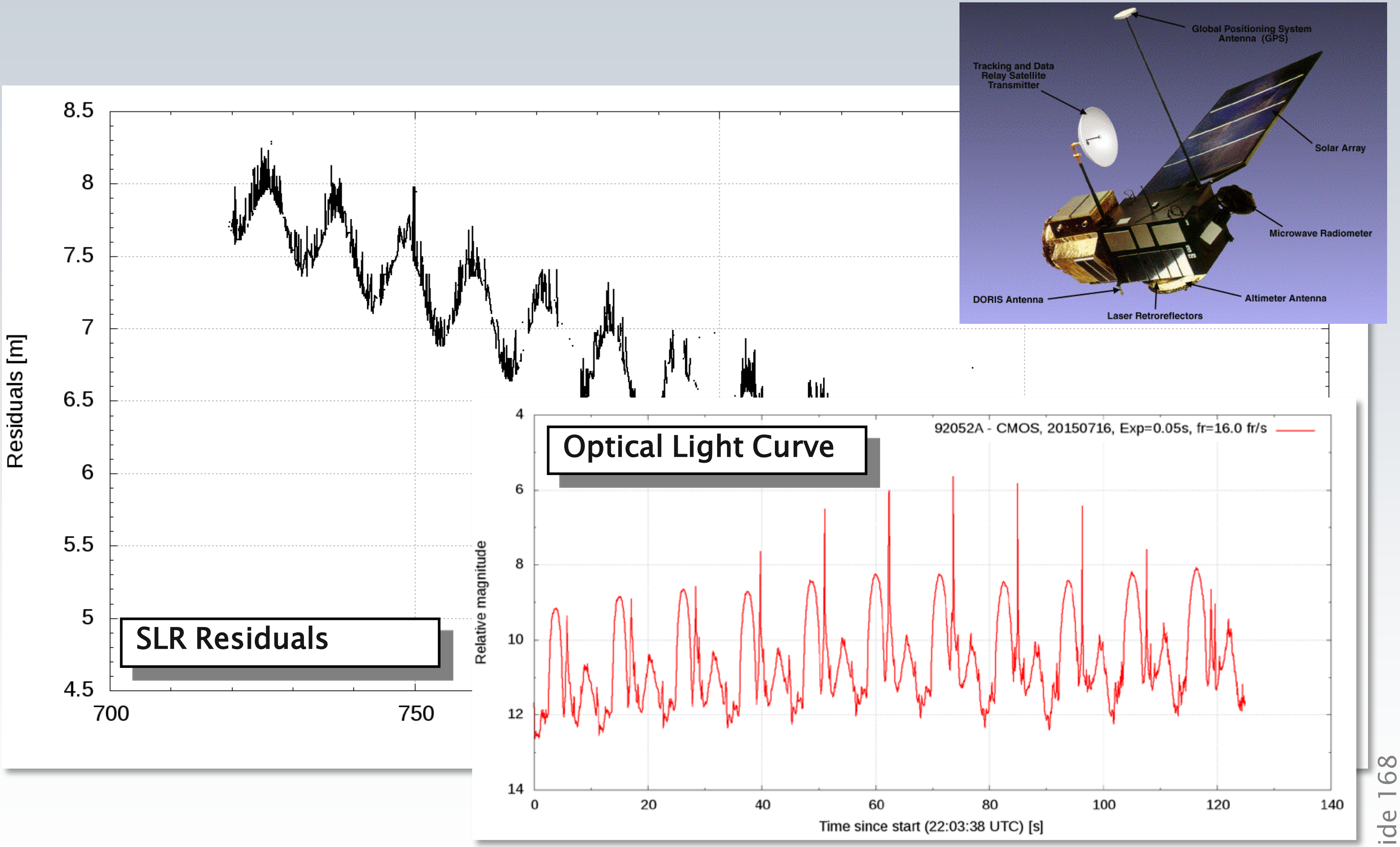
Optical Sensors

ZimTWIN (2 x 0.4m wide field)

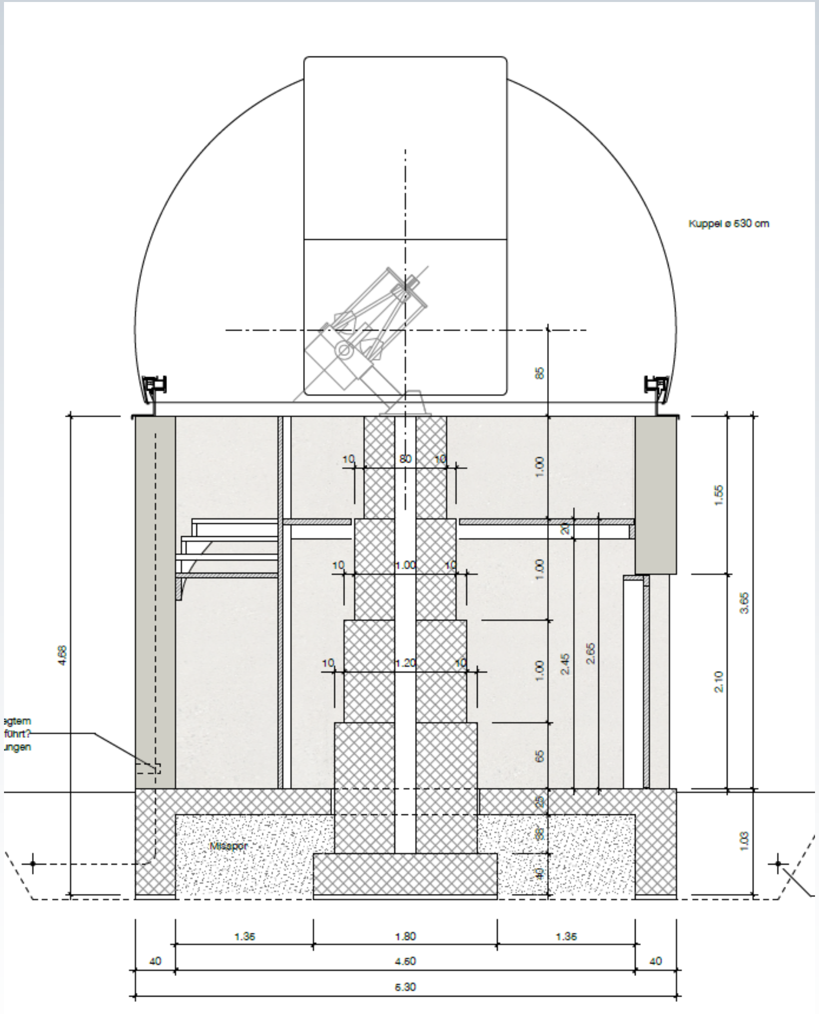
New 0.8m (Dec 2017)

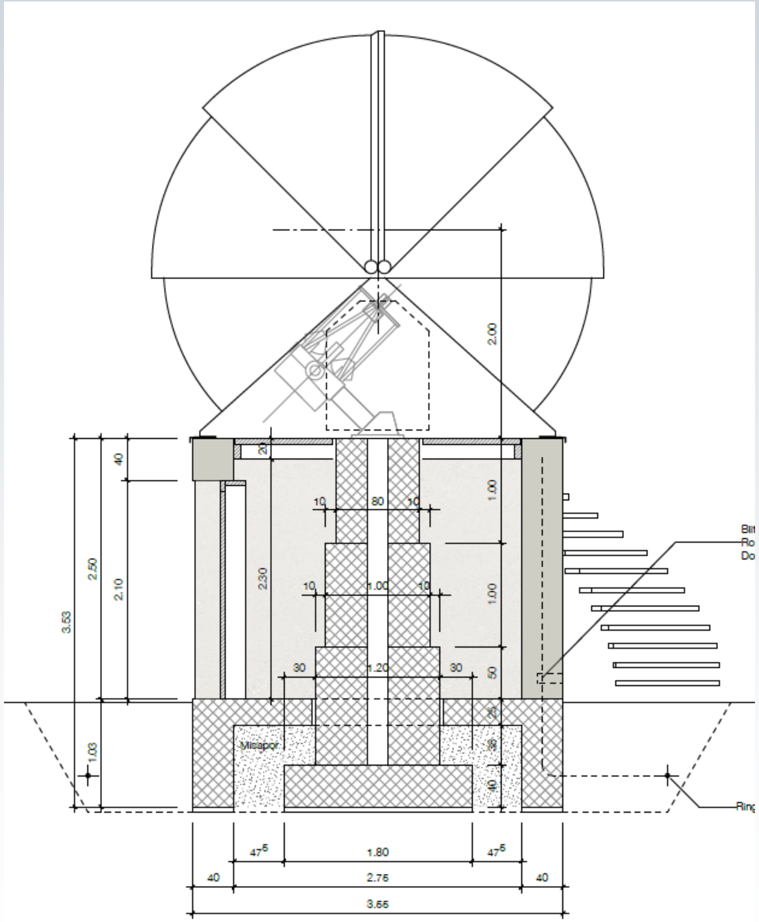
- 0.8m telescope
- Space debris research (AIUB)
- Offload ZIMLAT
- Space Debris SLR?

Attitude Motion of Topex



New Domes (Spring 2016)





New Domes October 2016

New Domes 2017

New Domes 2017

New Domes 2017

Einweihung der neuen Teleskope:
14./15. oder 8./9. Juni 2018
(Einladung folgt)