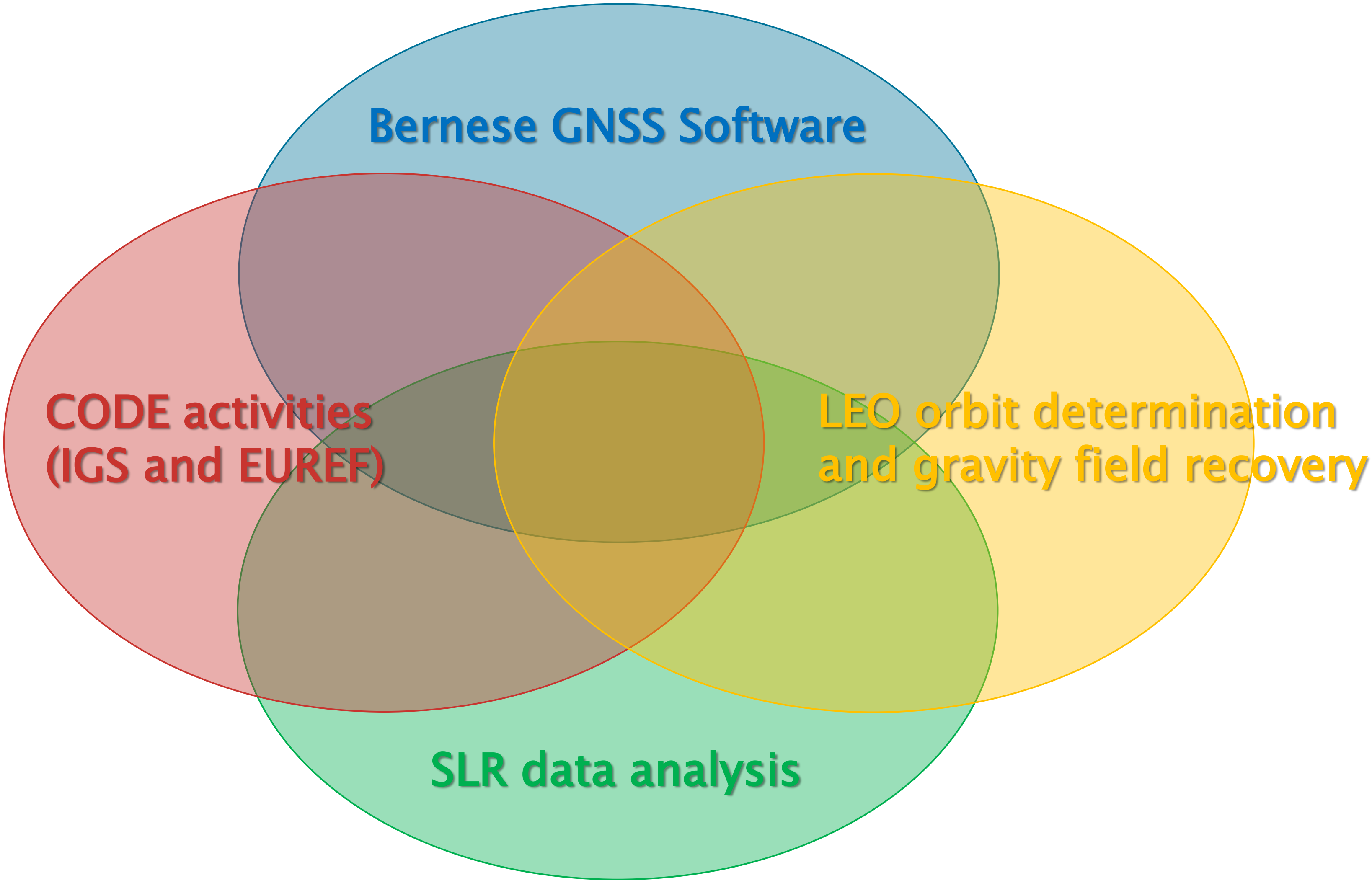
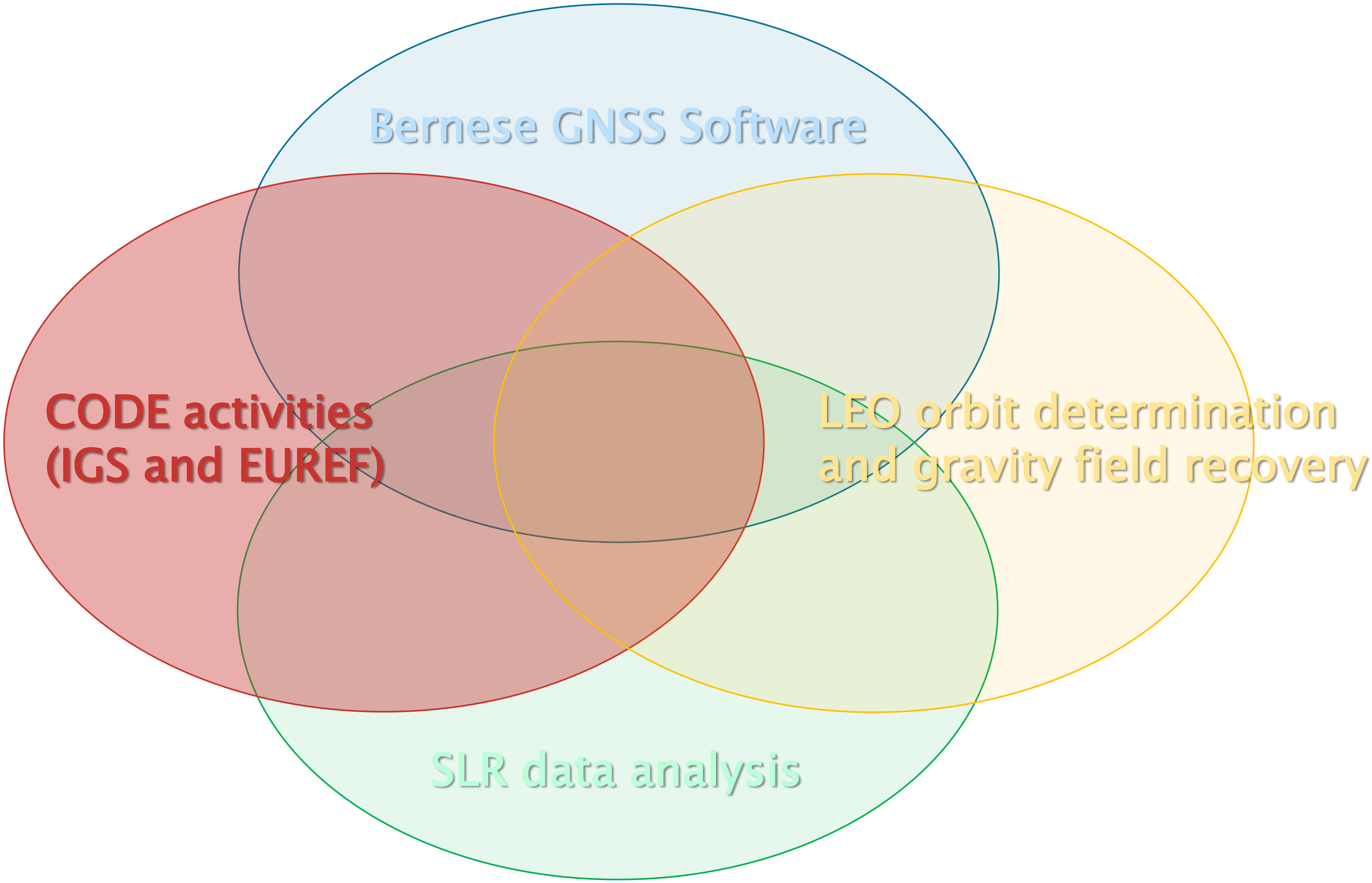
Activities in the Satellite Geodesy Research Group

Astronomisches Institut

Satellite Geodesy Research Group



Satellite Geodesy Research Group



CODE is providing as the first of the IGS analysis centers a combined

GPS+GLONASS+Galileo

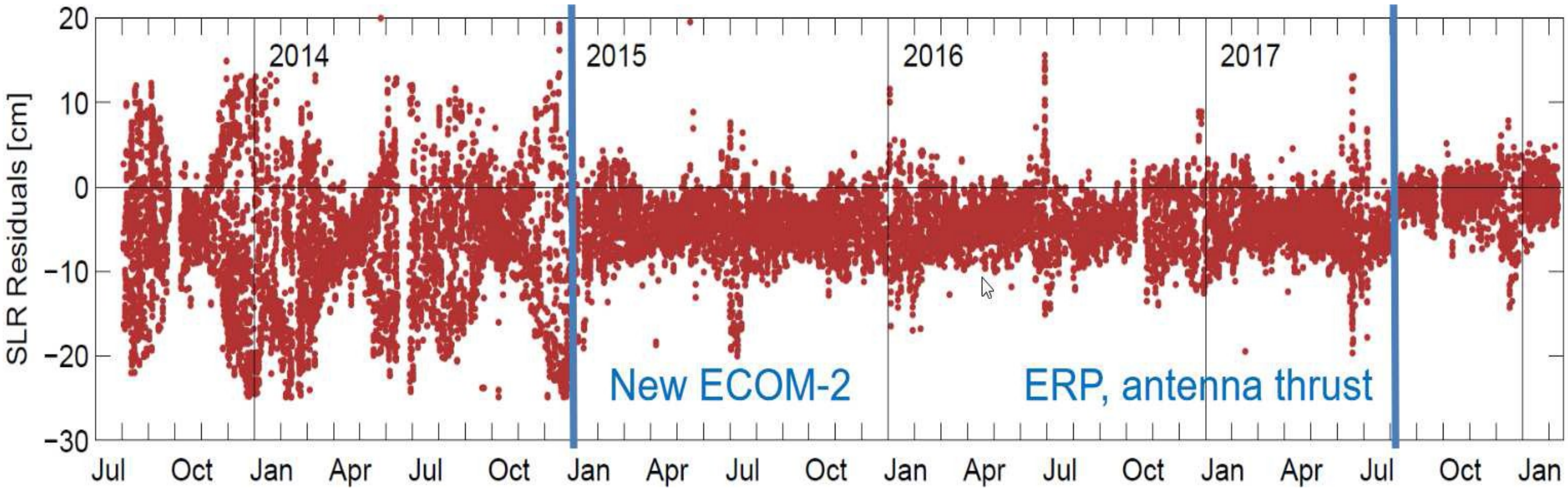
orbit and clock product

in its legacy rapid and ultra-rapid processing chains since September 23rd, 2019.

Galileo Orbit Modelling

Processing of Galileo Data at CODE

- Galileo observations are processed at CODE since 2012 in the frame of the IGS MGEX project.
- In that time several improvements have been introduced:



- SLR residuals to satellite SVN E102 in the CODE MGEX solution

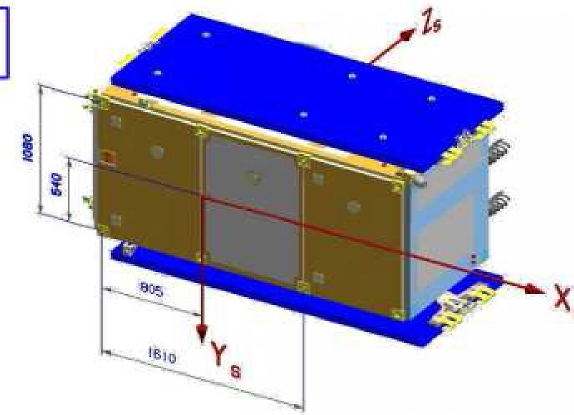
Montenbruck, O., R. Dach, P. Steigenberger; 2018: New Constellations for Geodesy: The IGS Multi-GNSS Pilot Project (MGEX). EUREF 2018 Symposium, Amsterdam, Netherlands, 30 May – 01 June, 2018.

Processing of Galileo Data at CODE

- Thermal radiation modelled since June 2019 in the CODE MGEX solution
- Radiators at Galileo satellites are installed on
  IOV satellites: +X, +Y , −Y; FOC satellites: +X, +Y , −Y , −Z

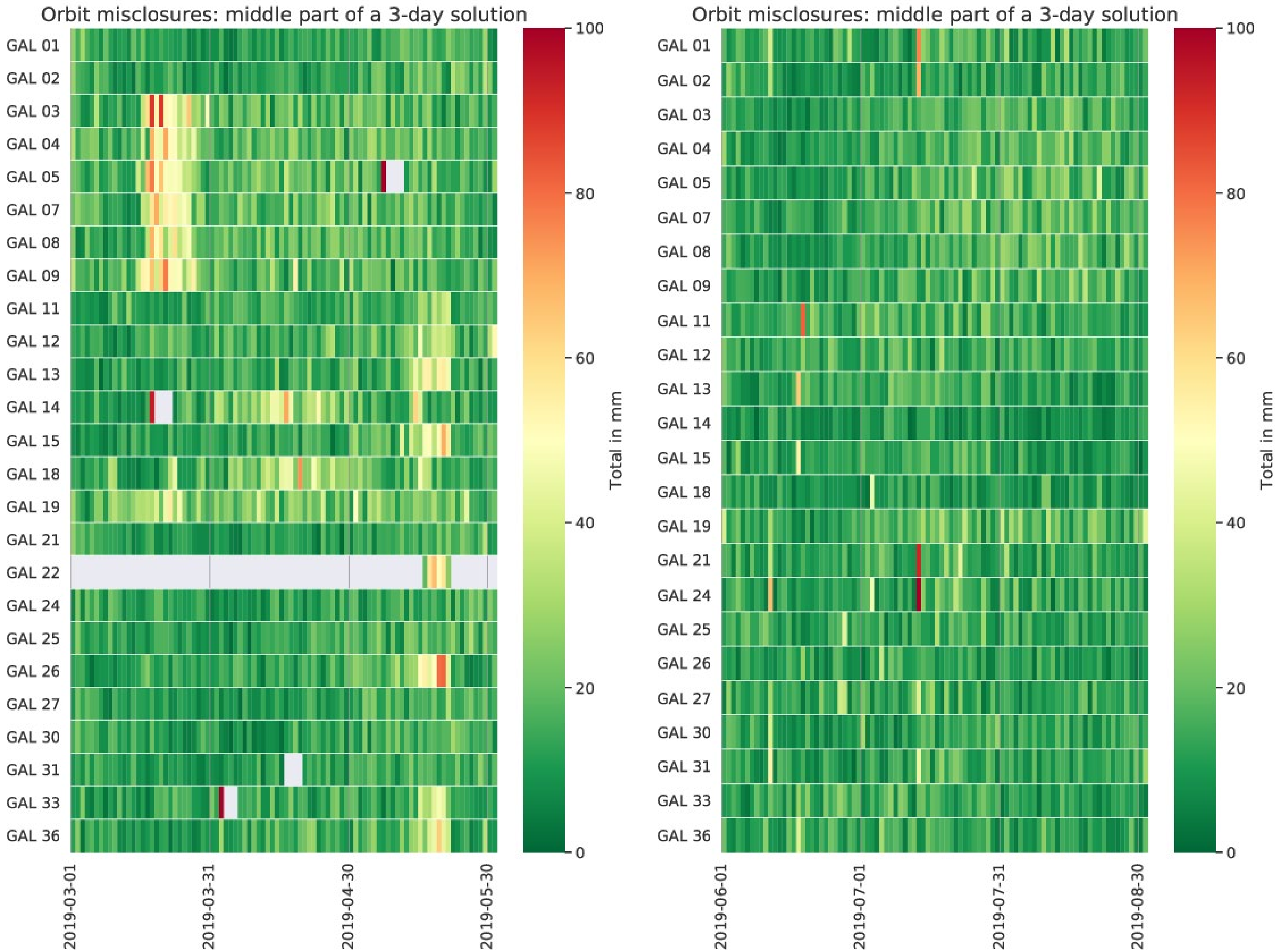
IOV

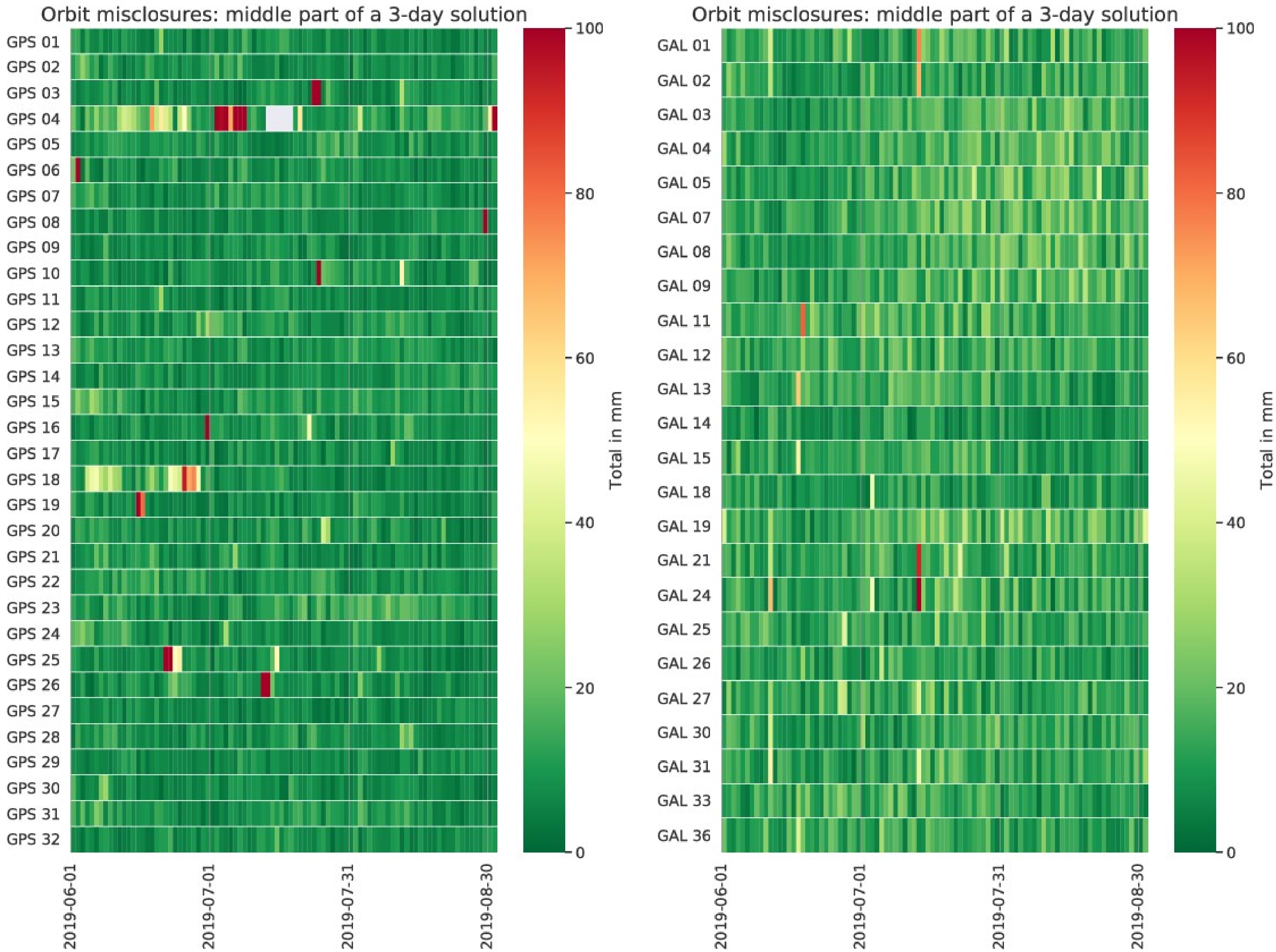
FOC



- Galileo satellites (Galileo Satellite Metadata, URL: https://www.gsceuropa.eu).

D. Sidorov, R. Dach, L. Prange, A. Jäggi; 2018: Improved Orbit Modelling of Galileo Satellites During Eclipse Seasons. Presented at IGS workshop, Wuhan, China, 29 October – 02 November, 2018.


Orbit misclosures: middle part of a 3-day solution
GAL 01
GAL 02
GAL 03
GAL 04
GAL 05
GAL 07
GAL 08
GAL 09
GAL 11
GAL 12
GAL 13
GAL 14
GAL 15
GAL 18
GAL 19
GAL 21
GAL 22
GAL 24
GAL 25
GAL 26
GAL 27
GAL 30
GAL 31
GAL 33
GAL 36
2019-03-01
2019-03-31
2019-04-30
2019-05-30
Total in mm
0
20
40
60
80
100
Orbit misclosures: middle part of a 3-day solution
GAL 01
GAL 02
GAL 03
GAL 04
GAL 05
GAL 07
GAL 08
GAL 09
GAL 11
GAL 12
GAL 13
GAL 14
GAL 15
GAL 18
GAL 19
GAL 21
GAL 24
GAL 25
GAL 26
GAL 27
GAL 30
GAL 31
GAL 33
GAL 36
2019-06-01
2019-07-01
2019-07-31
2019-08-30
Total in mm
0
20
40
60
80
100



Orbit misclosures: middle part of a 3-day solution
GPS 01
GPS 02
GPS 03
GPS 04
GPS 05
GPS 06
GPS 07
GPS 08
GPS 09
GPS 10
GPS 11
GPS 12
GPS 13
GPS 14
GPS 15
GPS 16
GPS 17
GPS 18
GPS 19
GPS 20
GPS 21
GPS 22
GPS 23
GPS 24
GPS 25
GPS 26
GPS 27
GPS 28
GPS 29
GPS 30
GPS 31
GPS 32
2019-06-01
2019-07-01
2019-07-31
2019-08-30
Total in mm
0
20
40
60
80
100
Orbit misclosures: middle part of a 3-day solution
GAL 01
GAL 02
GAL 03
GAL 04
GAL 05
GAL 07
GAL 08
GAL 09
GAL 11
GAL 12
GAL 13
GAL 14
GAL 15
GAL 18
GAL 19
GAL 21
GAL 24
GAL 25
GAL 26
GAL 27
GAL 30
GAL 31
GAL 33
GAL 36
2019-06-01
2019-07-01
2019-07-31
2019-08-30
Total in mm
0
20
40
60
80
100

Implementation in the Bernese GNSS Software

Flexible Selection of Empirical Models

- Does the satellite flying in ON-mode?
  - ECOM-TBM for BDS2 (IGSO)
  - ECOM-TB for BDS2 (MEO)&QZS
- Do we need parameters active during eclipse?
  - ECOM2-D1 for Galileo IOV
  - ECOM2-YD1 for Galileo FOC
- Otherwise use ECOM2 as it is.

Flexible Selection of Empirical Models

- Updated output of ORBGEN:

```
 -------------------------------------------------------------------------------
 RPR PARAMETERS AND RMS ERRORS   ARC NUMBER:  1                    ITERATION:  3
 -------------------------------------------------------------------------------
 SAT       PAR_1     RMS           PAR_2     RMS           PAR_3     RMS        EMP MODEL
        (M/S**2*1.D-7)          (M/S**2*1.D-7)          (M/S**2/D*1.D-7)
 ---   -----------------   -----------------   -----------------  ----------

   1   -1.07756  0.00016    0.00034  0.00002   -0.00411  0.00
   2   -1.01908  0.00020    0.00140  0.00002   -0.00024  0.00
   3   -1.07574  0.00027    0.00002  0.00003   -0.00282  0.00
   4   -0.99304  0.00051   -0.00365  0.00006   -0.00692  0.00
   ⋮
 203   -1.12630  0.00035   -0.00648  0.00010    0.00440  0.00
 204   -1.12455  0.00033   -0.00186  0.00012    0.01077  0.00
 205   -1.11033  0.00056   -0.00777  0.00018    0.00608  0.00
 207   -1.11789  0.00083   -0.00625  0.00032    0.00208  0.00
 208   -1.11835  0.00051   -0.00521  0.00018    0.00441  0.00
 209   -1.13070  0.00060   -0.00496  0.00022    0.00776  0.00
 211   -1.11737  0.00024   -0.00091  0.00005    0.00208  0.00
 212   -1.10887  0.00024    0.00046  0.00005    0.00320  0.00
 214   -1.19495  0.00021   -0.01169  0.00014    0.00645  0.00
 218   -1.19557  0.00019   -0.00993  0.00012    0.00166  0.00
 219   -1.13409  0.00034    0.00460  0.00010    0.00248  0.00
 224   -1.09805  0.00018   -0.00714  0.00004    0.00009  0.00
   ⋮
```

```
   ⋮
 USED EMPIRICAL MODELS
 ------------------------------------------------------------------------------
      EMP MODEL            SATELLITES
      --------------------  -----------------------------------------------------
 EMP: ECOM2                   1   2   3   4   5   6   7   8   9  10  11  12  13
 EMP: ECOM2                  14  15  16  17  18  19  20  21  22  23  24  25  26
 EMP: ECOM2                  27  28  29  30  31  32 101 102 103 104 105 106 107
 EMP: ECOM2                 108 109 110 111 113 114 115 116 117 118 119 120 121
 EMP: ECOM2                 122 123 124 201 202 211 212 214 218 224 226 230 406
 EMP: ECOM2                 409 410 411 412 502
 EMP: ECOM2-D1              219
 EMP: ECOM2-YD1             203 204 205 207 208 209
 EMP: ECOM-TB               413 414 501
 EMP: ECOM-TBM              407 408

 ------------------------------------------------------------------------------
 PARAMETERS OF EMPIRICAL MODELS
 ------------------------------------------------------------------------------
   PAR_1    PAR_2    PAR_3    PAR_4    PAR_5    PAR_6    PAR_7    PAR_8    PAR_9
 ------------------------------------------------------------------------------
 MODEL NAME: ECOM2
      D0       Y0       B0      D2C      D4C      B1C      D2S      D4S      B1S

 MODEL NAME: ECOM2-D1
      D0       Y0       B0      D2C     *D1C      B1C      D2S     *D1S      B1S

 MODEL NAME: ECOM2-YD1
      D0      *Y0       B0      D2C     *D1C      B1C      D2S     *D1S      B1S

 ...

 ------------------------------------------------------------------------------
```

Flexible Selection of Empirical Models

- **Orbit model description (STD/ELE files):**

Currently used:

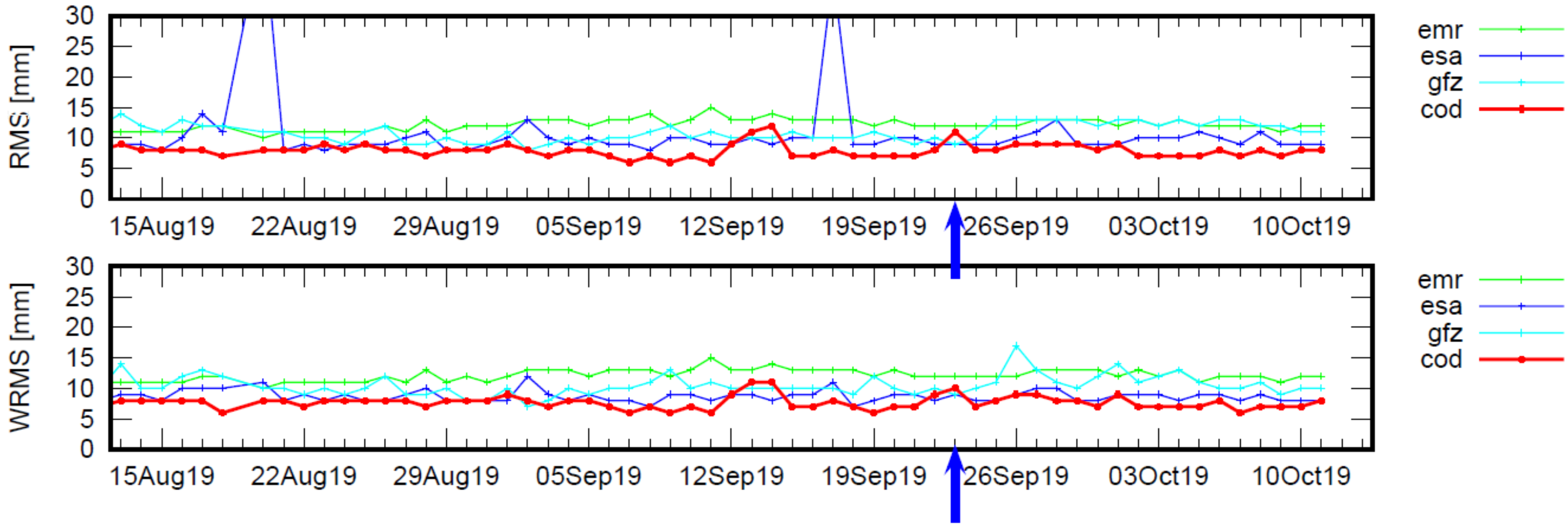
```
IGSR_Q: RQ_18078, FINAL 1-DAY SOLUTION (CONSTRAINED)
--------------------------------------------------------------------------------
FORMAT:      1    17
TITLE : Create Tabular Orbit File using Precise Ephemeris
CREATE: 23-MAR-18 05:54
INTEG2:      3600   10     21600   12
NUTSUB: IAU2000R06      IERS2010         BIAS
GRAVIT: EGM2008           12           MEANPOLE IERS2010
TIDPOT: IERS2000    ELAS STEP_1+2      POLTID   IERS2010 K20=0.30
OTIDES: ICGEM fes2004    IERS2003      XMIN     0.00000 DEG   8
JPLEPH: DE421
PLANET: JUPITER VENUS MARS
RELATV: PPN IERS1996 P
EMPIRI: D2X ONCE-PER-REV NONE
SHADOW: STEP SPHERE MOON
OTLOAD: FES2004          CMC: Y     HARLOAD: 342 tides
ERPMOD: NUMERICAL
ANTTHR: YES
TIMSYS: GPS
ATTIMD: KOUBA/DILSSNER
------------------------------------------------------------------
```

Will be updated to:

```
IGSR_Q: RQ_18078, FINAL 1-DAY SOLUTION (CONSTRAINED)
--------------------------------------------------------------------------------
FORMAT:      2    25
TITLE : Create Tabular Orbit File using Precise Ephemeris
CREATE: 22-JAN-19 17:06
INTEG2:      3600   10     21600   12
NUTSUB: IAU2000R06      IERS2010         BIAS
GRAVIT: EGM2008           12           MEANPOLE IERS2010
TIDPOT: IERS2000    ELAS STEP_1+2      POLTID   IERS2010 K20=0.30
OTIDES: ICGEM fes2004    IERS2003      XMIN     0.00000 DEG   8
JPLEPH: DE421
PLANET: JUPITER VENUS MARS
RELATV: PPN IERS1996 P
EMPIRI: SPC ECOM2                  1   2   3   4   5   6   7   8   9  10  11  12
EMPIRI: SPC ECOM2                 13  14  15  16  17  18  19  20  21  22  23  24
EMPIRI: SPC ECOM2                 25  26  27  28  29  30  31  32 101 102 103 104
EMPIRI: SPC ECOM2                105 106 107 108 109 110 111 113 114 115 116 117
EMPIRI: SPC ECOM2                118 119 120 121 122 123 124 201 202 211 212 214
EMPIRI: SPC ECOM2                218 224 226 230 409 410 411 412 502
EMPIRI: SPC ECOM2-D1             219
EMPIRI: SPC ECOM2-YD1            203 204 205 207 208 209
EMPIRI: SPC ECOM-TB              413 414 501
EMPIRI: SPC ECOM-TBM             407 408
SHADOW: STEP SPHERE MOON
OTLOAD: FES2004          CMC: Y     HARLOAD: 342 tides
ERPMOD: NUMERICAL
ANTTHR: YES
TIMSYS: GPS
ATTIMD: KOUBA/DILSSNER
--------------------------------------------------------------------------------
```

CODE rapid with Galileo in the IGS combination

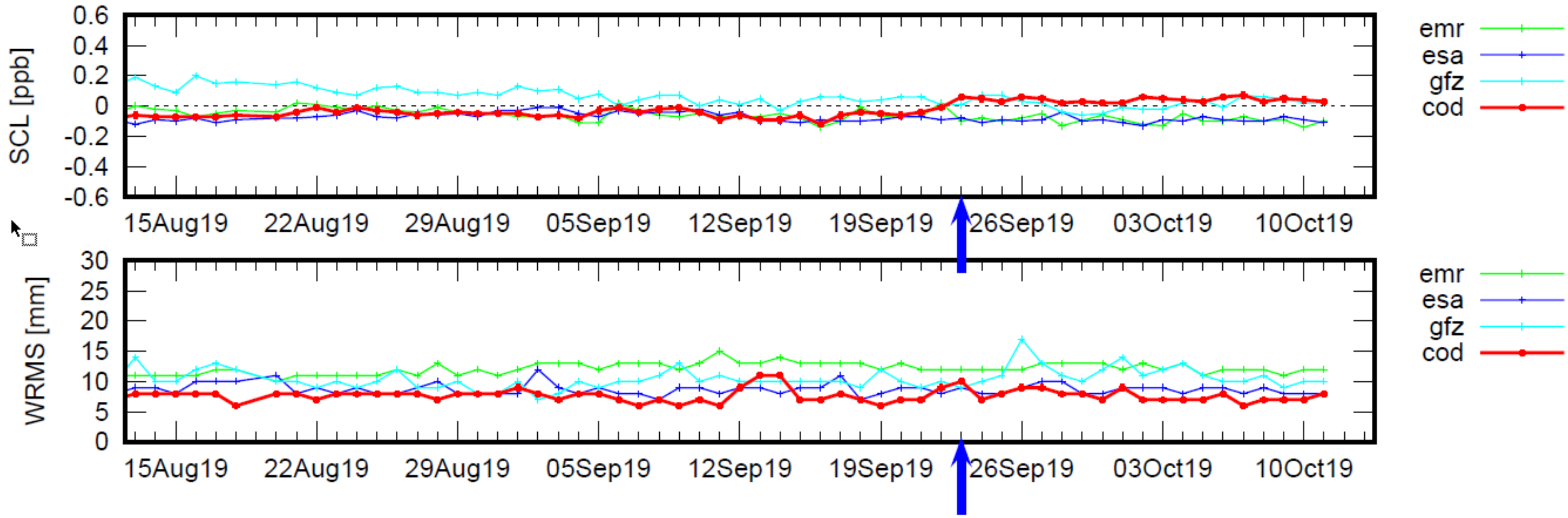
CODE rapid with Galileo



Extract from the ACC combination protocols:
IGS rapid (GPS)

- No effect on the RMS (quality) of the GPS orbit product

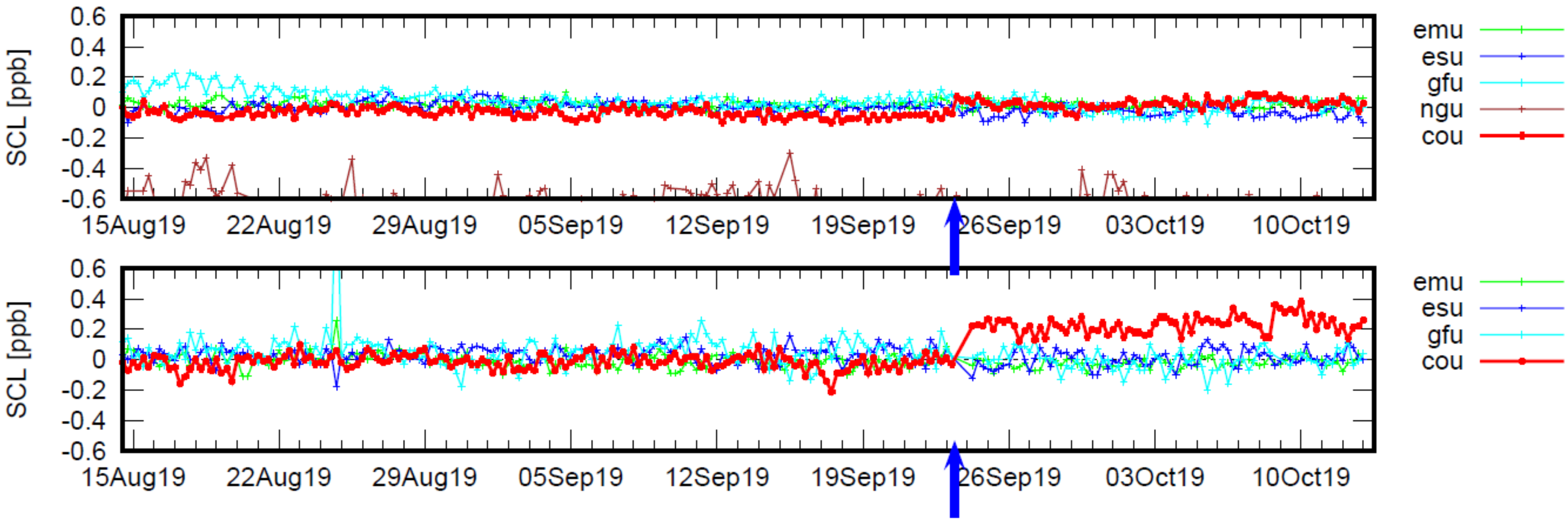
CODE rapid with Galileo



Extract from the ACC combination protocols:
IGS rapid (GPS)

- No effect on the RMS (quality) of the GPS orbit product
- No effect on the transformation parameters apart from the scale!

CODE ultra-rapid with Galileo



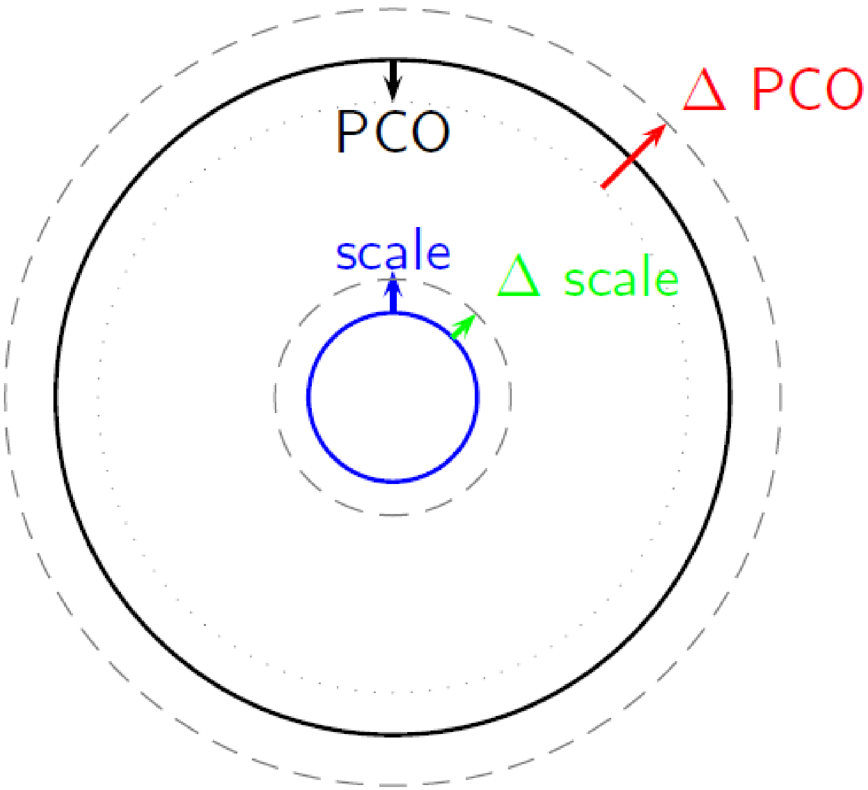
Extract from the ACC combination protocols:
IGS ultra-rapid (GPS and GLONASS)

- No effect on the RMS (quality) of the GPS orbit product
- No effect on the transformation parameters apart from the scale! More pronnounced for GLONASS in the ultra-rapid combination

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

Relation PCO and scale determination

Why do we need calibrated antennas?



- PCO to Scale:
  [Zhu et al. 2002]
  1m $\hat{=}$ -7.8 ppb
  1 ppb $\hat{=}$ -0.13 m
- PCO's: -4 m Δ PCO
- Stations: 20 cm offset

Antenna calibrations

Traditional (operational) situation with IGS14.atx

GNSS	Frq	Sat.	Rob.
GPS	L1		
	L2		
	L5		
GLO	G1		
	G2		
	G3		
GAL	E1		L1
	E5a		L2
	E5b		
	E5		
	E6		

GNSS	Frq	Sat.	Rob.
BDS	B1		L1
	B2		L2
	B3		
QZSS	L1		
	L2		
	L5		

unknown	estimated	calibrated	approx.

Rob. : roboter receiver antenna calibrations

Antenna calibrations

Current situation for repro3 (IGS14r3.atx)

GNSS	Frq	Sat.	Rob.	Cha.
GPS	L1			
	L2			
	L5			
GLO	G1			
	G2			
	G3			
GAL	E1		L1	
	E5a		L2	
	E5b			
	E5			
	E6			

GNSS	Frq	Sat.	Rob.	Cha.
BDS	B1		L1	
	B2		L2	
	B3			
QZSS	L1			
	L2			
	L5			

unknown	estimated	calibrated	approx.

Rob. : roboter receiver antenna calibrations
Cha. : chamber receiver antenna calibrations

Receiver antenna calibrations

	Geo++ (robot)	BONN (chamber)
Individual	–	~250
Type-mean	37	35

Which one shall be used?

- **IGS decided to use robot calibrations and extend them by chamber calibrations (>5 individual calibrations)**
  IGS AC Workshop in Potsdam, 2019

Consistency of the multi-GNSS calibrations

- Inter-system translation bias (ISTP):
  vector between GPS and another
- GTRP: troposphere bias between GPS and another GNSS

		IGS14	Galileo Scale		
GNSS	Sol.	ISTP	ISTP	ISTP	GTRP
GLONASS	ROB	-1.22	-0.88	0.80	-0.4
	CHA	-3.58	-0.73	1.29	-0.5
GALILEO	ROB	6.31	0.58	0.43	0.11
	CHA	7.40	1.08	0.21	0.44

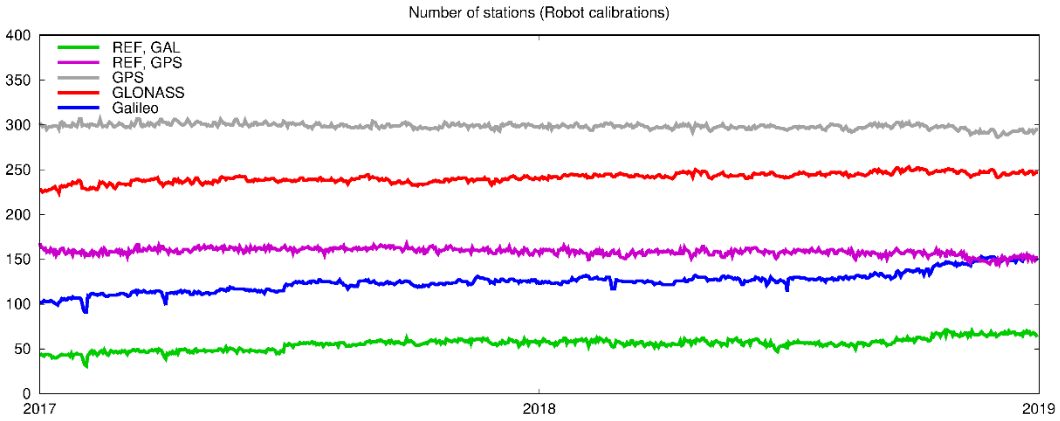
← nadir dependent consistency

→ Robot calibration consistent to ITRF 2014

→ When adjusting scale to either robot or chamber calibrations the consistency is bellow 1.5mm for GLONASS and Galileo → good

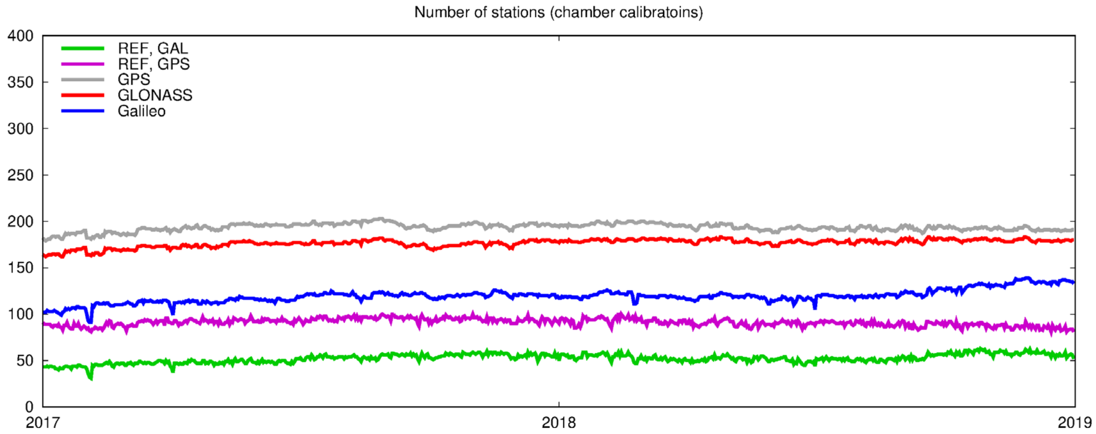
Coverage

Stations used for CODE's test solution for years 2017 and 2018



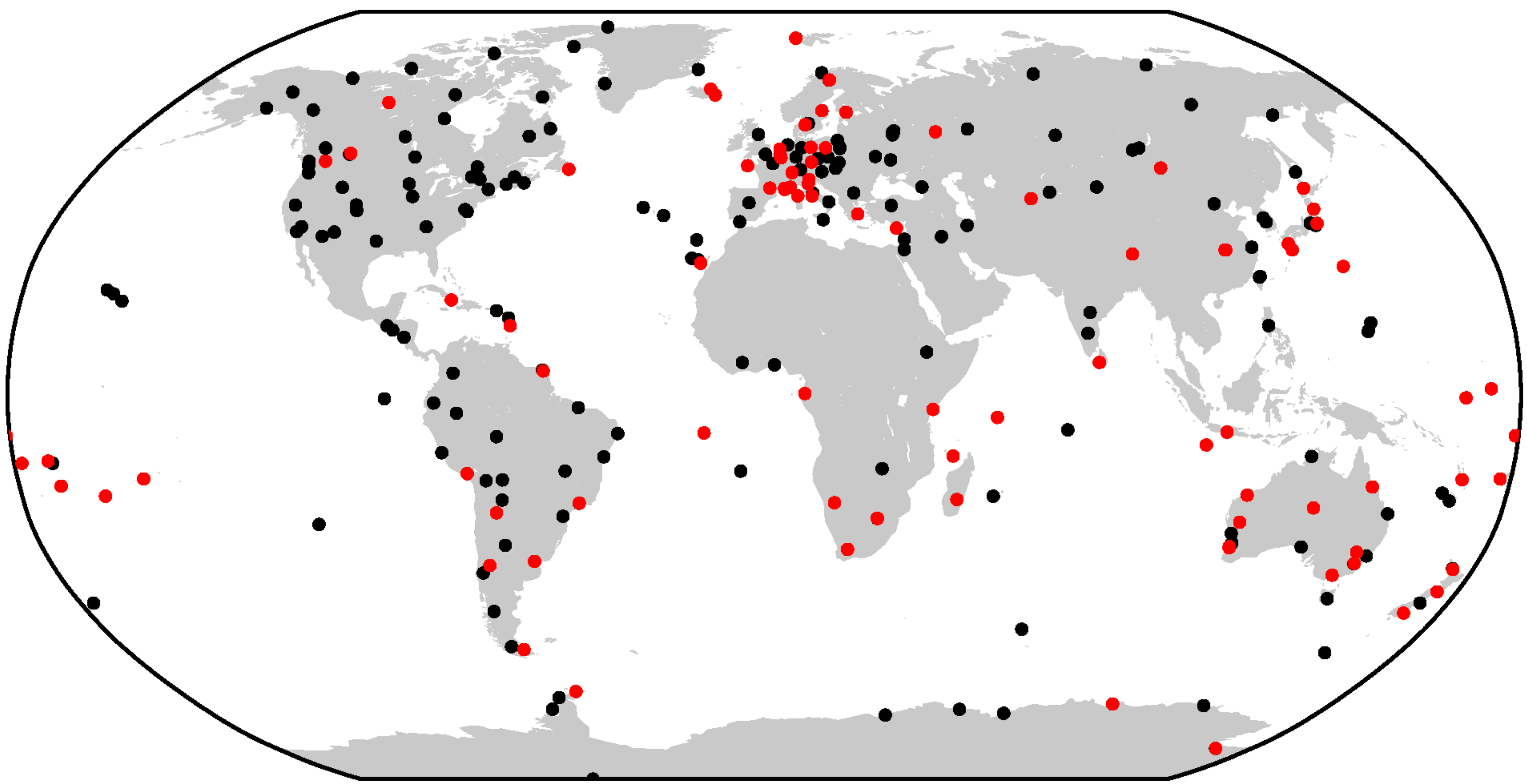
Robot calibrations

Chamber calibrations



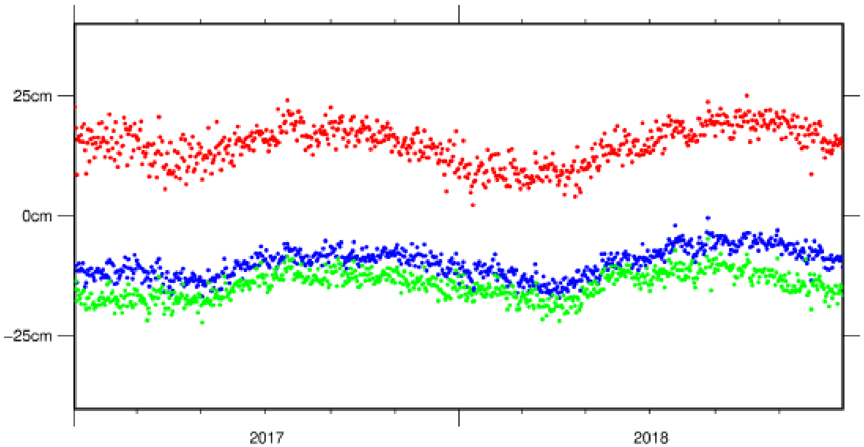
Coverage

Stations used for CODE's test solution for years 2017 and 2018

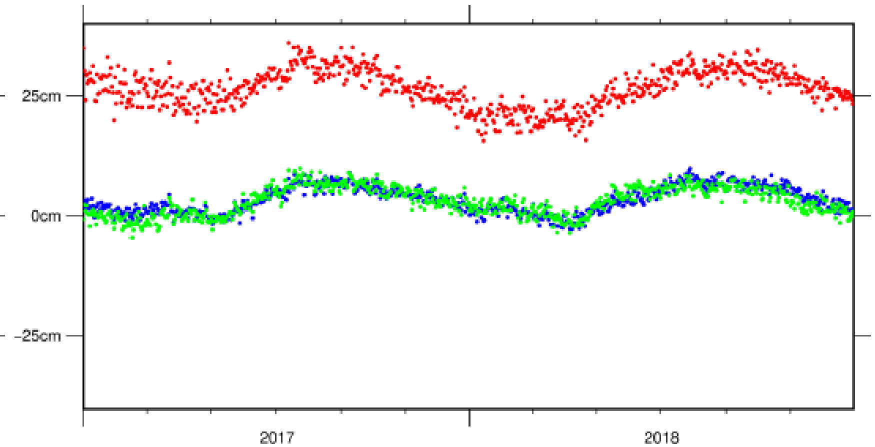


Scale determination

Code solution: ITRF 2014 scale fixed

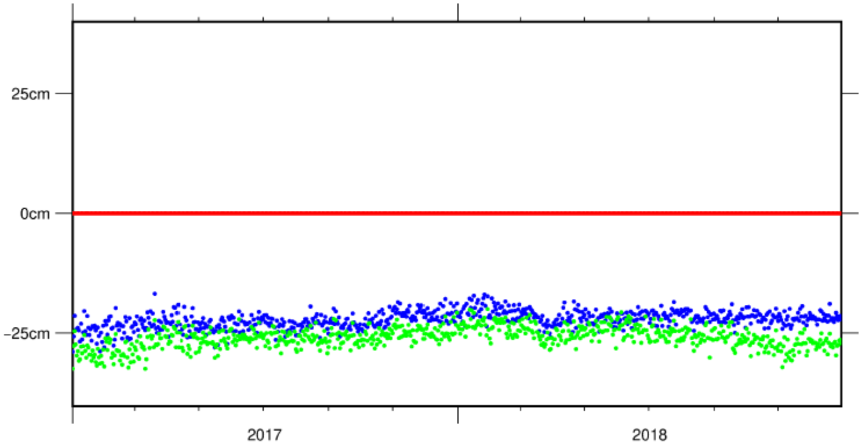


(a) Chamber calibrations: Scale fixed to ITRF 2014.

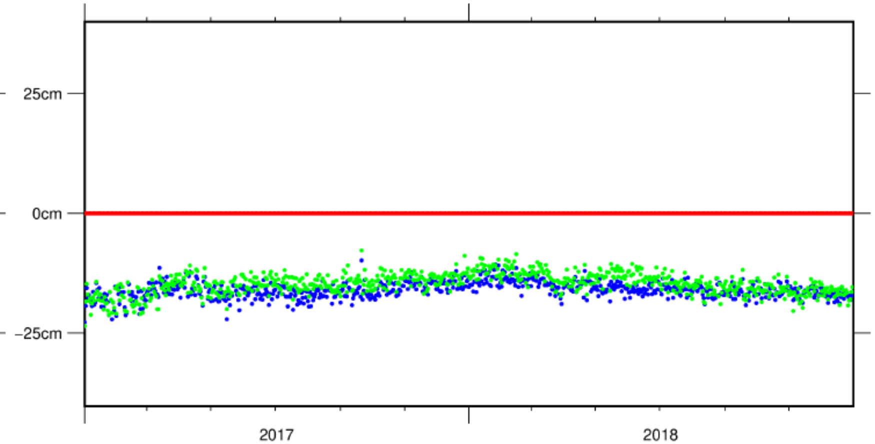


(d) Robot calibrations: Scale fixed to ITRF2014.

Code solution: Galileo PCO fixed

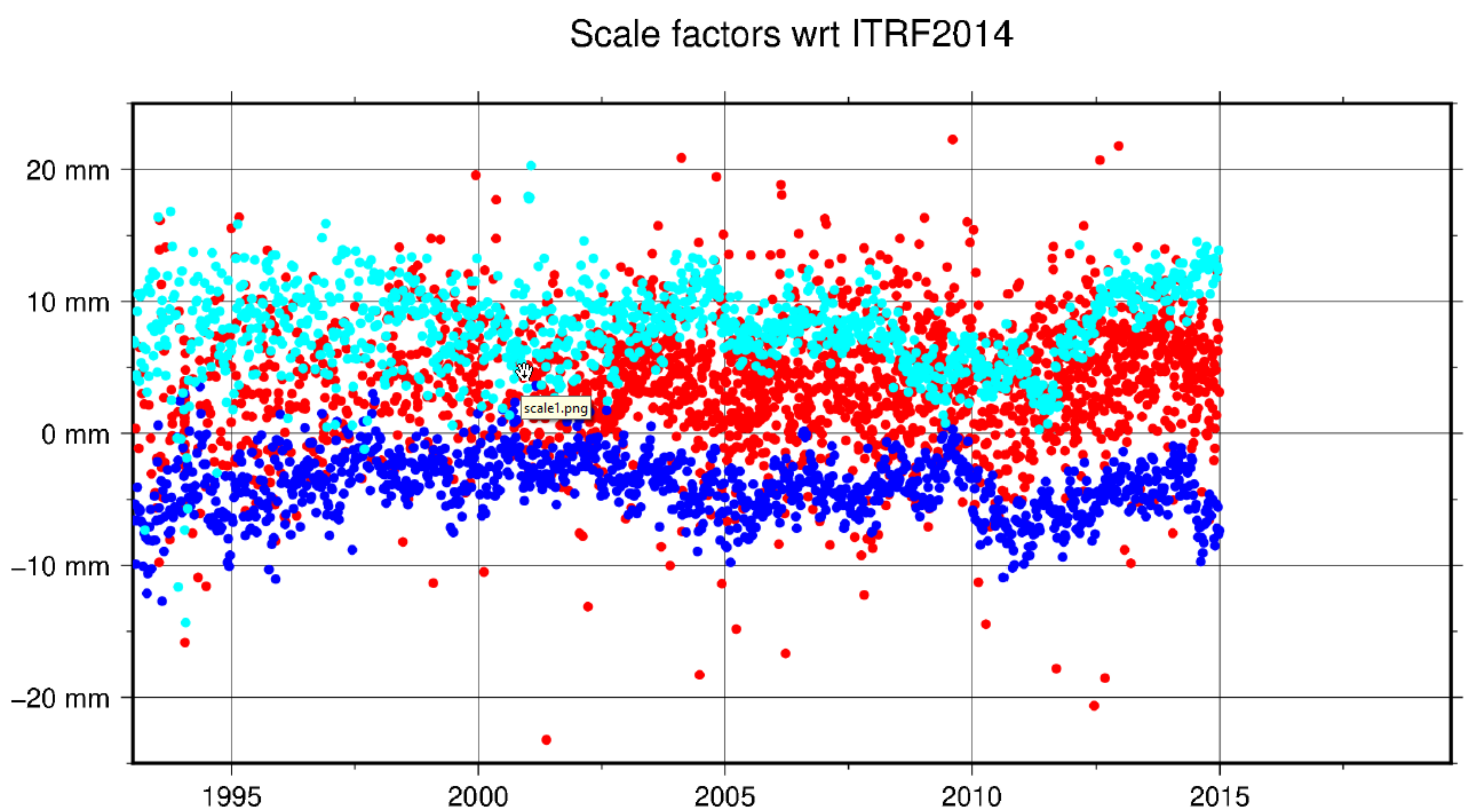


(c) Chamber calibrations: Scale fixed to GAL PCO.



(f) Robot calibrations: Scale fixed to GAL PCO.

Impact on terrestrial scale



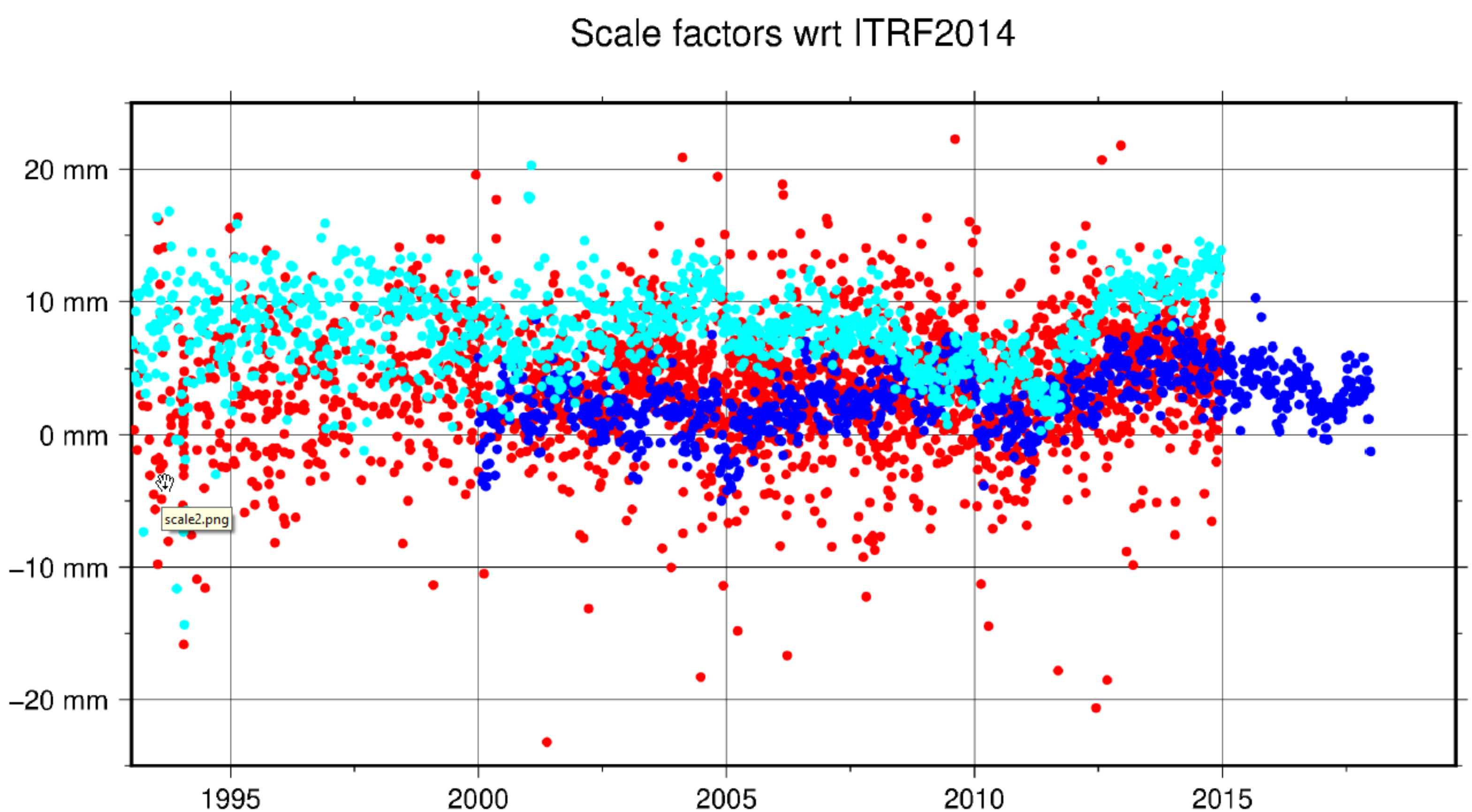
●●● VLBI contribution to ITRF2014 + 4.4 + 0.11 (t – 2010) mm

●●● SLR contribution to ITRF2014 – 4.4 – 0.08 (t – 2010) mm

●●● DORIS contribution to ITRF2014 + 7.2 – 0.11 (t – 2010) mm

P. Rebischung; 2019: Possible contribution of GNSS the definition of the ITRF2020 scale based on the Galileo satellite PCOs. Presented at UAW workshop, Paris, France, 02 October – 04. October, 2019.

Impact on terrestrial scale



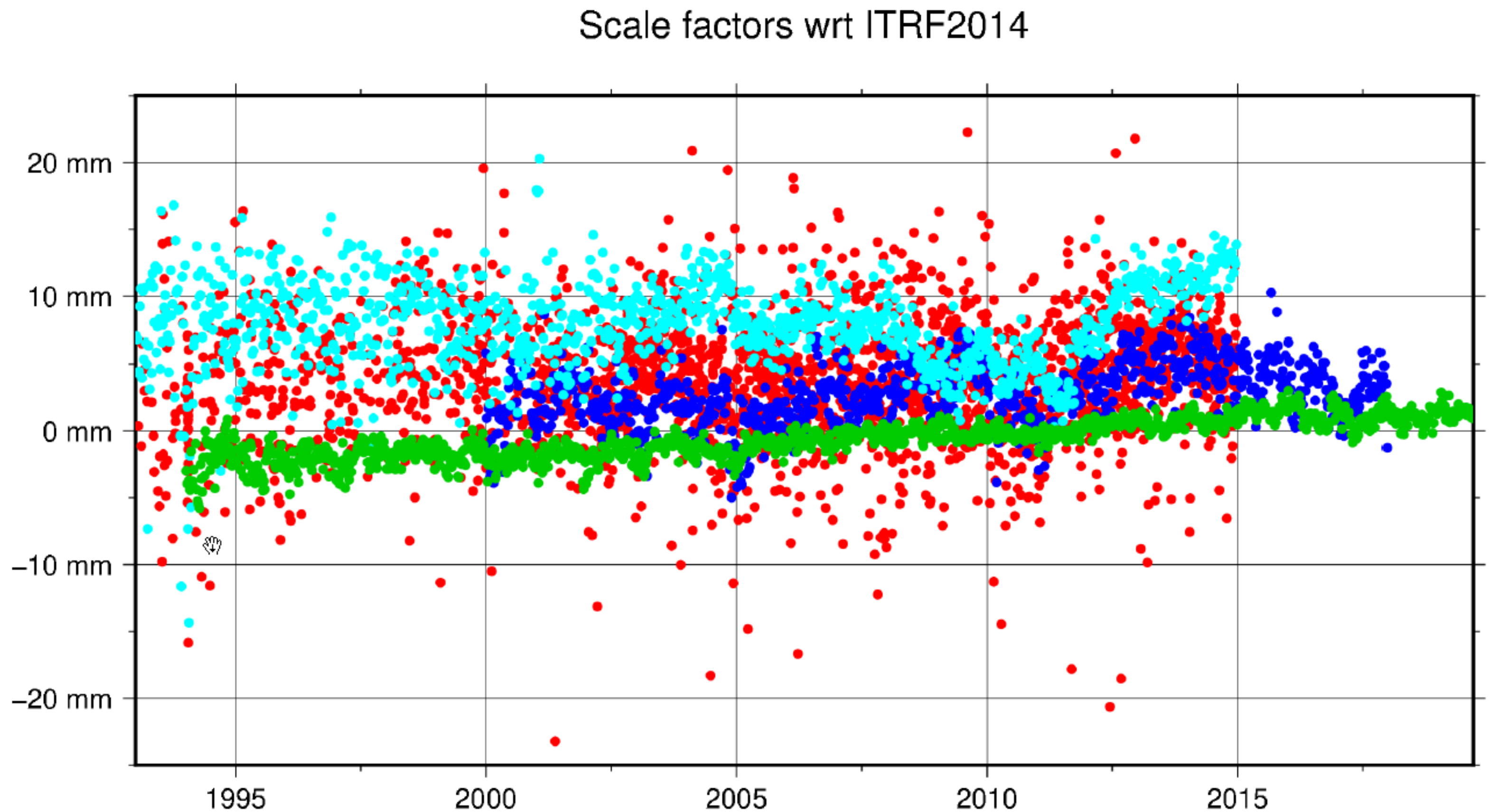
••• VLBI contribution to ITRF2014 + 4.4 + 0.11 (t – 2010) mm

••• SLR ASI solution – new range biases + 2.9 + 0.16 (t – 2010) mm

••• DORIS contribution to ITRF2014 + 7.2 – 0.11 (t – 2010) mm

P. Rebischung; 2019: Possible contribution of GNSS the definition of the ITRF2020 scale based on the Galileo satellite PCOs. Presented at UAW workshop, Paris, France, 02 October – 04. October, 2019.

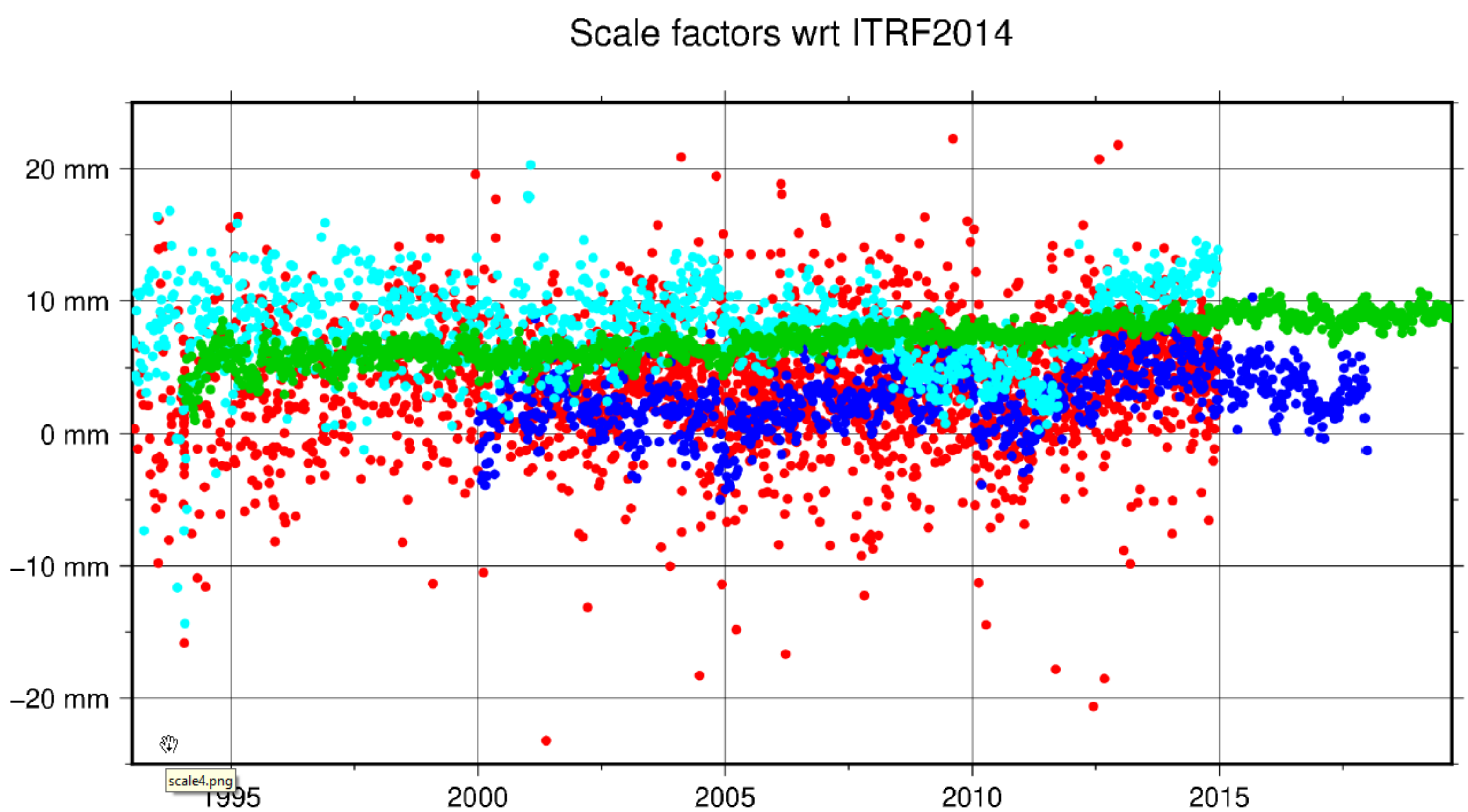
Impact on terrestrial scale



- ●●● VLBI contribution to ITRF2014 — + 4.4 + 0.11 (t – 2010) mm
- ●●● SLR ASI solution – new range biases — + 2.9 + 0.16 (t – 2010) mm
- ●●● DORIS contribution to ITRF2014 — + 7.2 – 0.11 (t – 2010) mm
- ●●● igs14.atx-based IGS combined solutions — – 0.1 + 0.18 (t – 2010) mm

P. Rebischung; 2019: Possible contribution of GNSS the definition of the ITRF2020 scale based on the Galileo satellite PCOs. Presented at UAW workshop, Paris, France, 02 October – 04. October, 2019.

Impact on terrestrial scale



●●● VLBI contribution to ITRF2014 — + 4.4 + 0.11 (t – 2010) mm

●●● SLR ASI solution – new range biases — + 2.9 + 0.16 (t – 2010) mm

●●● DORIS contribution to ITRF2014 — + 7.2 – 0.11 (t – 2010) mm

●●● igsR3.atx-based IGS combined solutions — + 7.7 + 0.17 (t – 2010) mm

P. Rebischung; 2019: Possible contribution of GNSS the definition of the ITRF2020 scale based on the Galileo satellite PCOs. Presented at UAW workshop, Paris, France, 02 October – 04. October, 2019.

CODE contribution to IGS MGEX

Overview of CODE's MGEX solution (with the focus on Galileo)

L. Prange[1], A. Villiger[1], D. Sidorov[1], S. Schaer[1,2],
G. Beutler[1],R. Dach[1], A. Jäggi [1]

Astronomisches Institut

CODE MGEX (COM) orbit solution

GNSS considered:	**GPS + GLONASS + Galileo + BDS2** (MEO+IGSO) + **QZSS** (>90 SV)
Processing mode:	Post-processing (≈2 weeks latency)
Timespan covered:	GPS-weeks 1689 - today
Number of stations:	140 (GPS), 130 (GLONASS), 100 (Galileo); 80 (BDS2); 40 - 50 (QZSS)
Processing scheme:	**Double-difference** network processing (observable: phase double differences; ambiguity-fixed)
Signal frequencies:	L1+ L2 (GPS + GLO+ QZSS); E1 (L1) + E5a (L5) Galileo; B1 (L2) + B2 (L7) BDS2
Orbit characteristic:	3-day long arcs; SRP: ECOM2, ECOM-TB (during ON)
Reference frame:	IGS14
IERS conventions:	IERS2010
Product list:	Daily orbits (SP3; 300s) and ERPs
Distribution:	ftp://cddis.gsfc.nasa.gov/gnss/products/mgex/ and ftp://ftp.aiub.unibe.ch/CODE_MGEX/
Designation:	COD0MGXFIN_YYYYDDD...gz

CODE MGEX (COM) clock solution

GNSS considered:	**GPS + GLONASS + Galileo + BDS2 + QZSS** (>90 SV)
Processing mode:	Post-processing (≈2 weeks latency)
Timespan covered:	GPS-weeks 1710 - today
Number of stations:	140 (GPS), 130 (GLO), 100 (Galileo); 50 (BDS2); 40 (QZSS)
Processing scheme:	**Zero-difference** processing (code+phase undifferenced; ambiguity-fixed for G,E,C,J)
Signal frequencies:	L1+ L2 (GPS + GLO+ QZSS); E1 (L1) + E5a (L5) Galileo; B1 (L2) + B2 (L7) BDS2
A priori information:	Orbits, ERPs, coordinates, and troposphere from CODE MGEX orbit solution introduced as known
Reference frame:	IGS14
IERS conventions:	IERS2010
Product list:	Epoch-wise (30s) clock corrections for satellites and stations in daily CLK-RINEX files; daily observable-specific (OSB) code biases for satellites and stations in BIAS-SINEX-format
Distribution:	ftp://cddis.gsfc.nasa.gov/gnss/products/mgex/ and ftp://ftp.aiub.unibe.ch/CODE_MGEX/

Summary

- **CODE's** point of view:

  Galileo is ready for IGS legacy products

- **IGS** decision is expected soon:

  Galileo to be potentially included in IGS REPRO3

Outlook for COM

- Further improvement of radiation pressure modelling ((semi-) analytical SRP models, thermal radiation models, …)
- Attitude (models for Asian systems, ORBEX format, quaternions?)
- MGEX SINEX files
- MGEX ionosphere and bias product (containing phase biases and considering all signals)
- New systems and satellites (BDS3, IRNSS, GEOs)?
- Further improvements of clock products (sampling, midnight epoch, …)

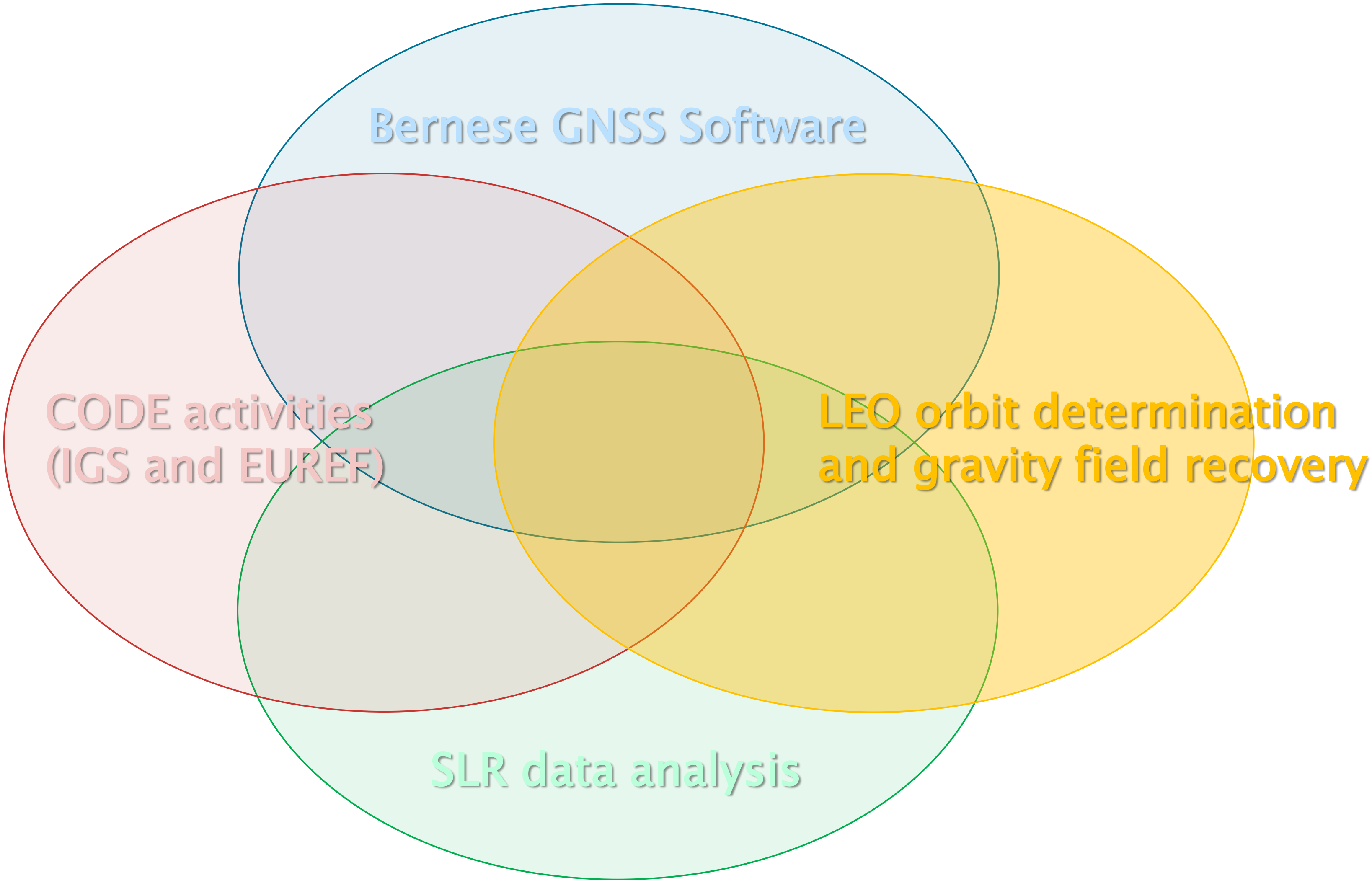
ESA project related to GNSS activities

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)

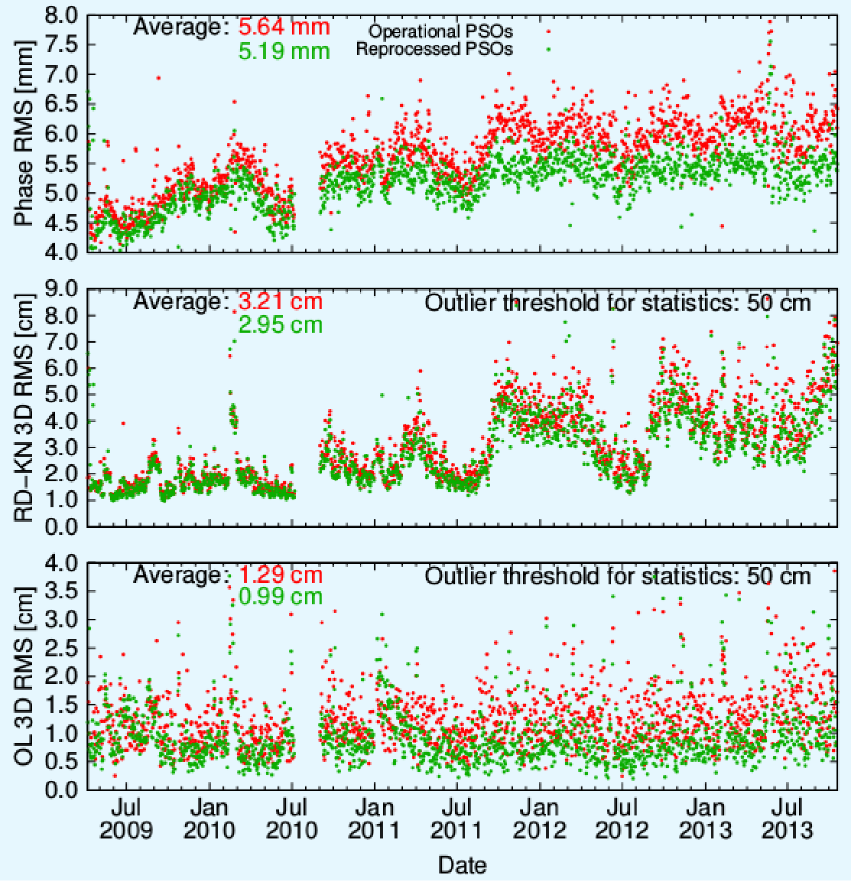
Satellite Geodesy Research Group



GOCE PSO Reprocessing

GOCE PSO reprocessing – Orbits

In the frame of an ESA-funded reprocessing of GOCE data, AIUB was responsible for the re-generation of the GOCE Precise Science Orbits (PSOs) → successfully finished



Carrier phase residuals

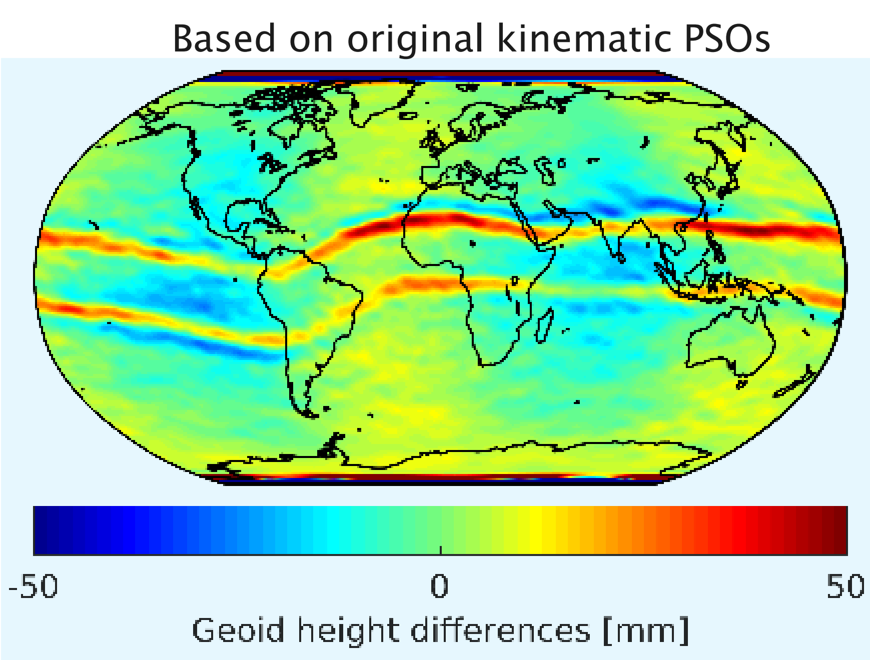
3D differences between reduced-dynamic and kinematic PSOs

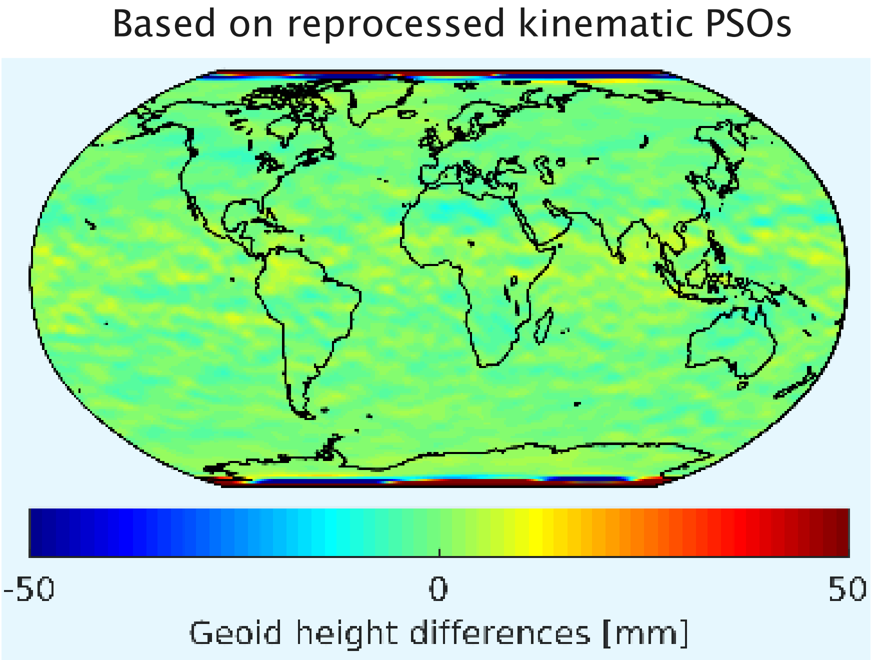
3D orbit overlaps (6h) for reduced-dynamic PSOs

for original and reprocessed GOCE PSOs

GOCE PSO reprocessing – Gravity field

Downweighting of GPS data affected by large ionospheric dynamics significantly reduces artifacts in GPS-only gravity field solutions along geomagnetic equator:





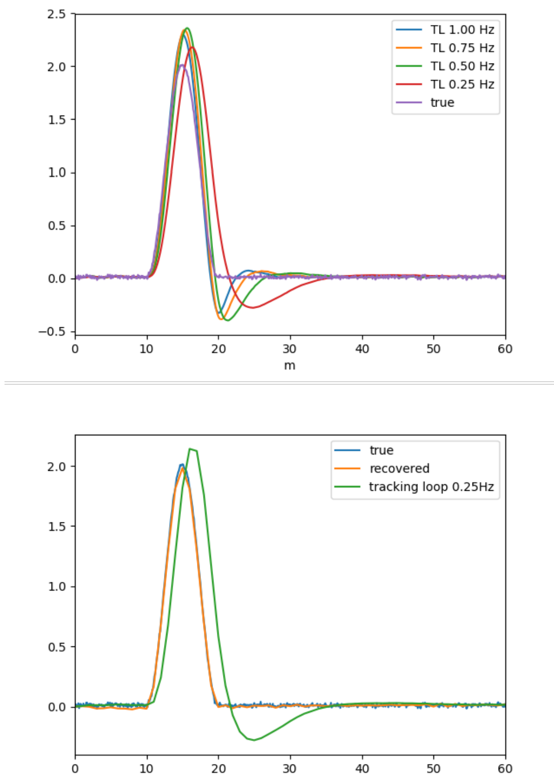
Geoid height differences of GPS-only solution for November 2009–July 2012 w.r.t. ITG-GRACE2016, 300km Gauss filter applied.

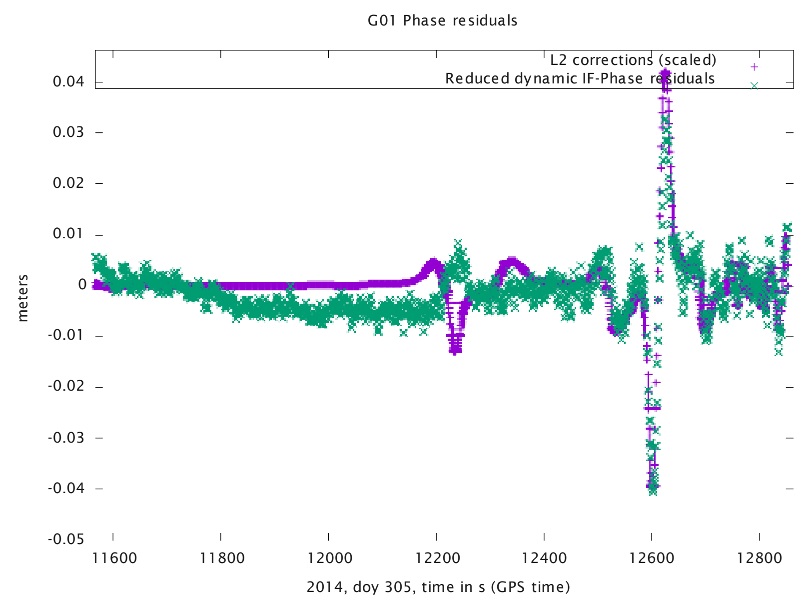
AIUB kinematic PSOs were used for generation of official GOCE-TIM6 gravity field solution

Swarm Tracking Loop and Sentinel TEC

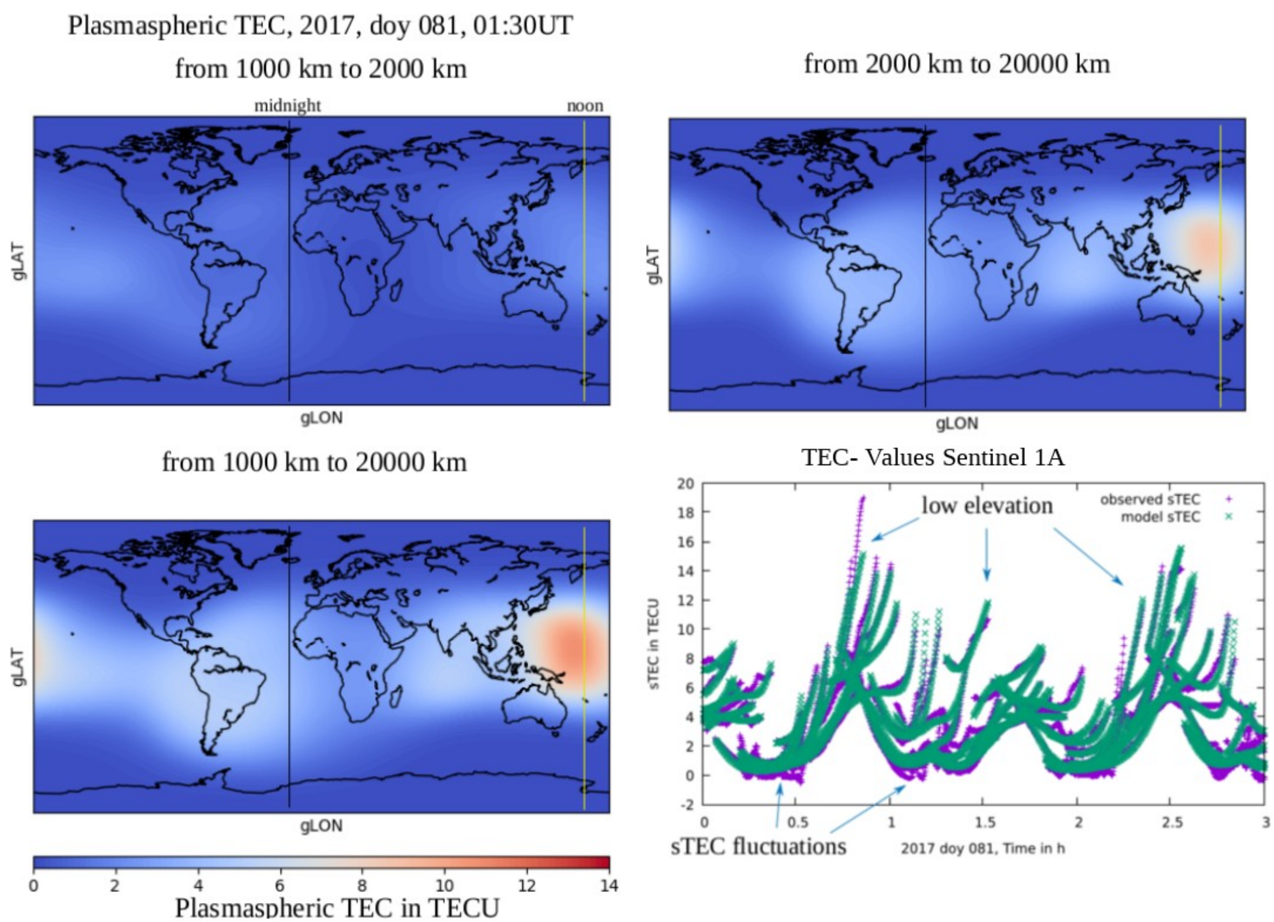
Tracking Loop Simulations

Left: Const. 0-signal with 1cm white noise and cosine shaped 10 s puls with amplitude 2.
Right: IF Phase residuals and corrections





TEC as seen by Sentinel



Copernicus POD Service

Copernicus satellite fleet

At AIUB precise orbits of all Sentinel satellites are computed

Sentinel-1A
Sentinel-1B

Sentinel-2A
Sentinel-2B

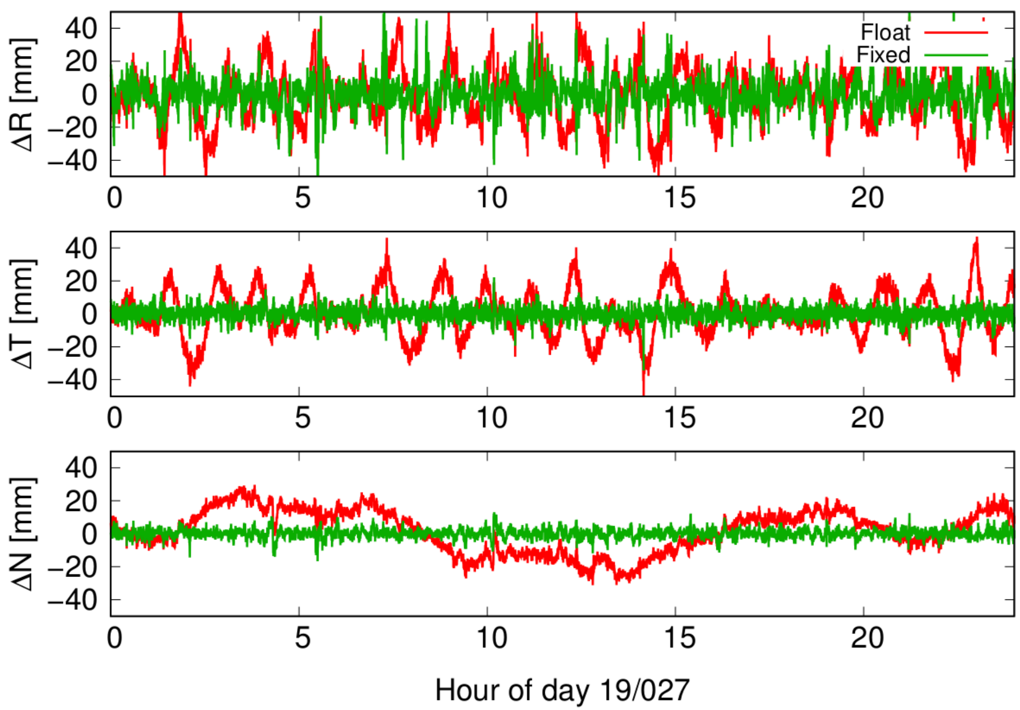
Sentinel-3A
Sentinel-3B

Copernicus
Europe's eyes on Earth

Courtesy: ESA

Undifferenced ambiguity fixing

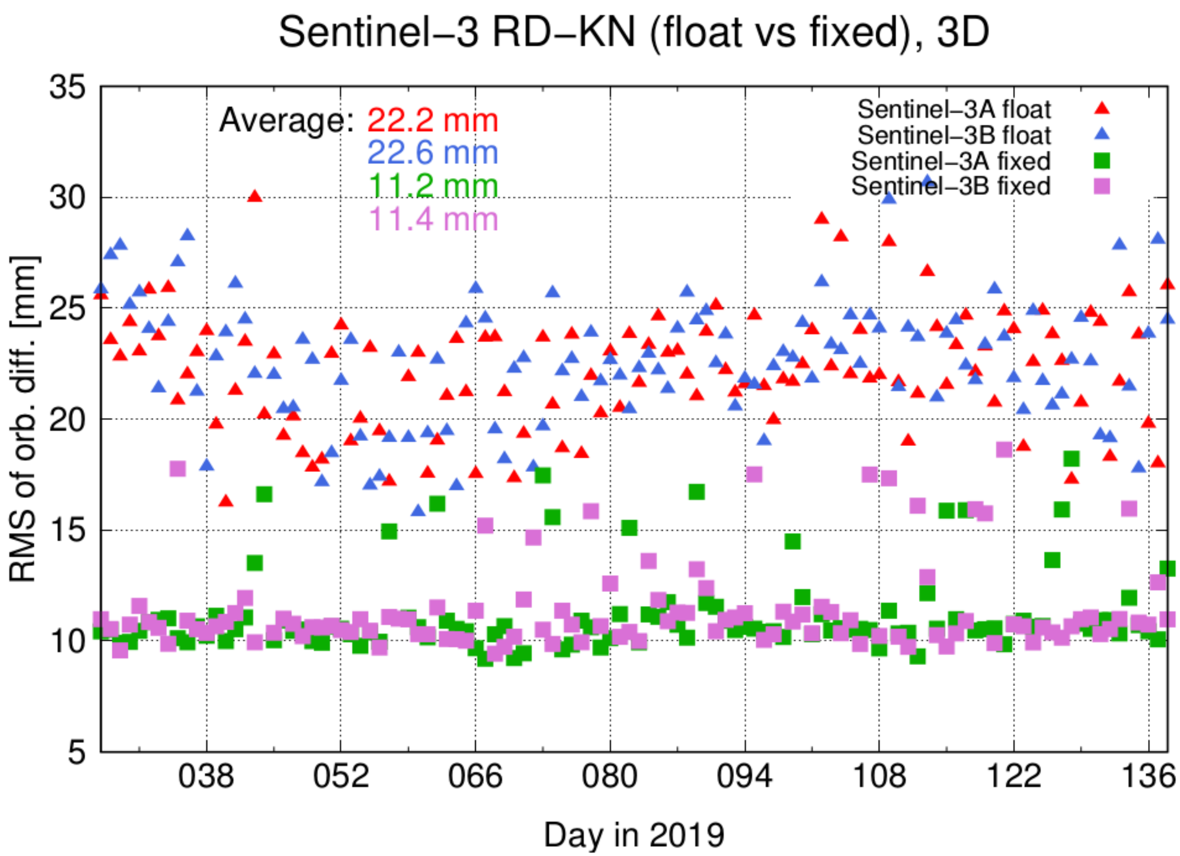
Starting from Regular Service Review #14 (covering January 28 – May 18, 2019) all AIUB orbit solutions for all Sentinels are based on undifferenced ambiguity fixing (using CODE's new phase bias and ambiguity-fixed clock products)



Example: Differences between reduced-dynamic and kinematic Sentinel-3A orbits for one day in radial, tangential and normal direction (ambiguity-float and ambiguity-fixed)

Undifferenced ambiguity fixing

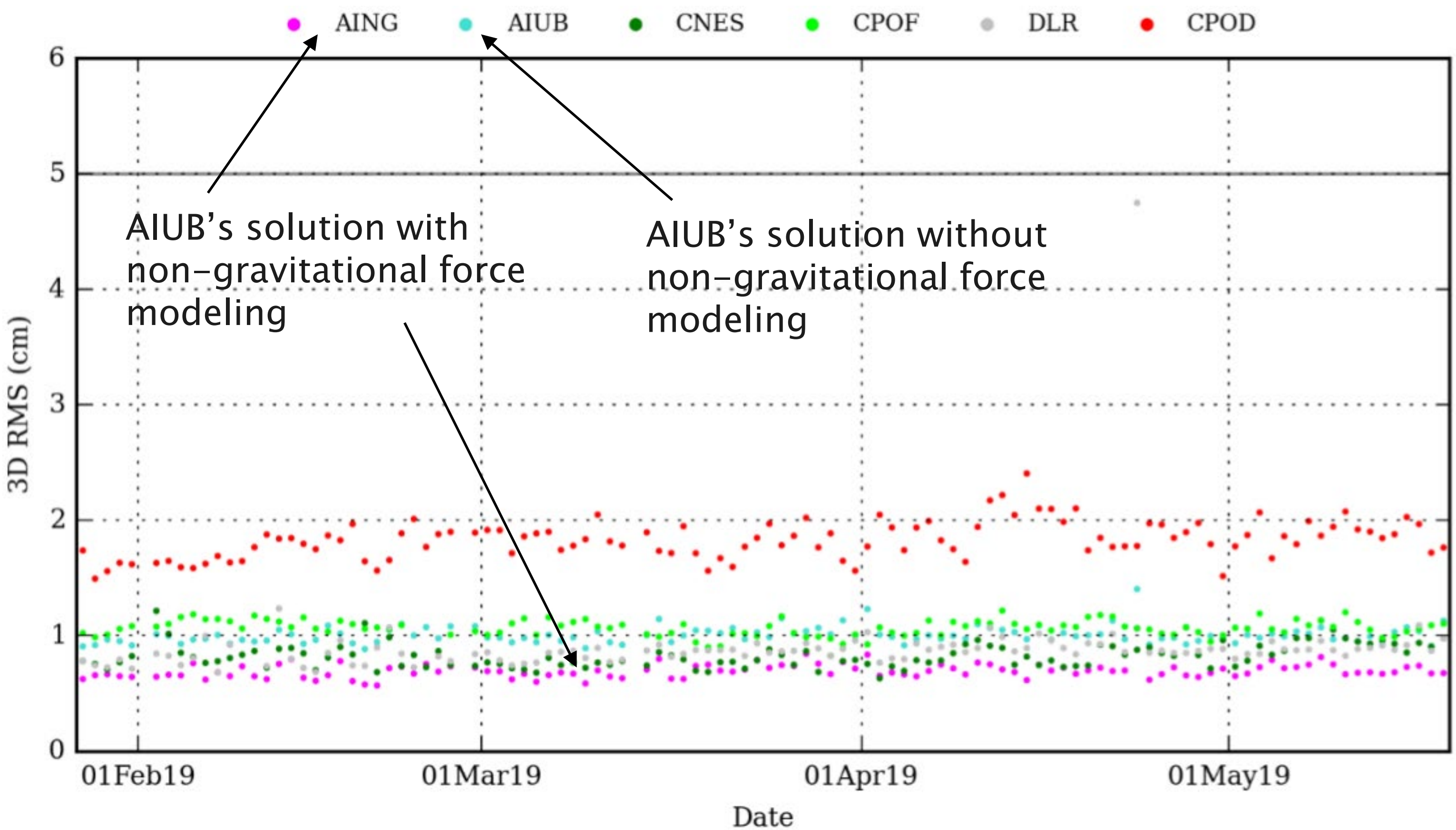
3D differences between reduced-dynamic and kinematic Sentinel-3 orbits for entire RSR #14



 Astronomical Institute University of Bern AIUB

Sentinel-3A orbit comparisons

Besides ambiguity fixing, AIUB delivers Sentinel-3 orbits both with and without non-gravitational force modeling



Combination of precise S3A orbit solutions using variance component estimation

- 1 September 2017 – 27 January 2018
- Combined solutions and individual solutions were validated for this time period

[cm]	AIUB	GMV	TUM	CNES	DLR	TUD	ESOC	EUM	VCE(1)	VCE(10)
Mean	-0.61	-0.07	-0.27	-0.05	-0.45	-0.54	0.03	-0.28	-0.32	-0.36
Std	1.16	1.23	1.32	1.38	1.17	1.10	1.27	1.69	1.03	1.03
RMS	1.31	1.23	1.35	1.38	1.26	1.23	1.28	1.71	1.08	1.09

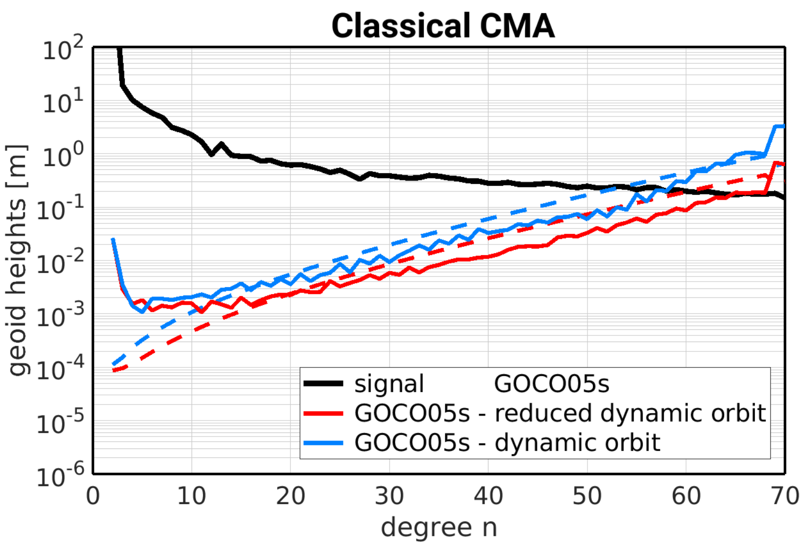
SLR validation
AIUB = Astronomical Institute, University of Bern
GMV = Grupo Mecánica del Vuelo
TUM = Technical University of Munich
CNES = Centre National d'Etudes Spatiales
DLR =German Aerospace Center
TUD = Delft University of Technology
ESOC = European Space Operations Center of ESA
EUM = European Organisation for the Exploitation of Meteorological Satellites
VCE = Combined solution, *(1)=1 Iteration, (2) = 10 Iterations*

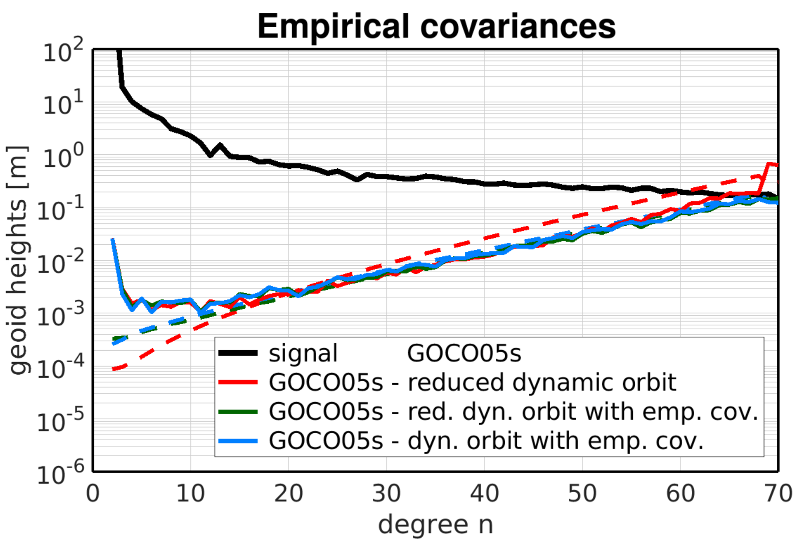
Noise modelling for GRACE/GRACE-FO

GPS-only (GRACE)

Modelling of the noise of kinematic positions either with

- pseudo-stochastic parameters
- an estimation of a covariance function from orbit residuals
- applying both





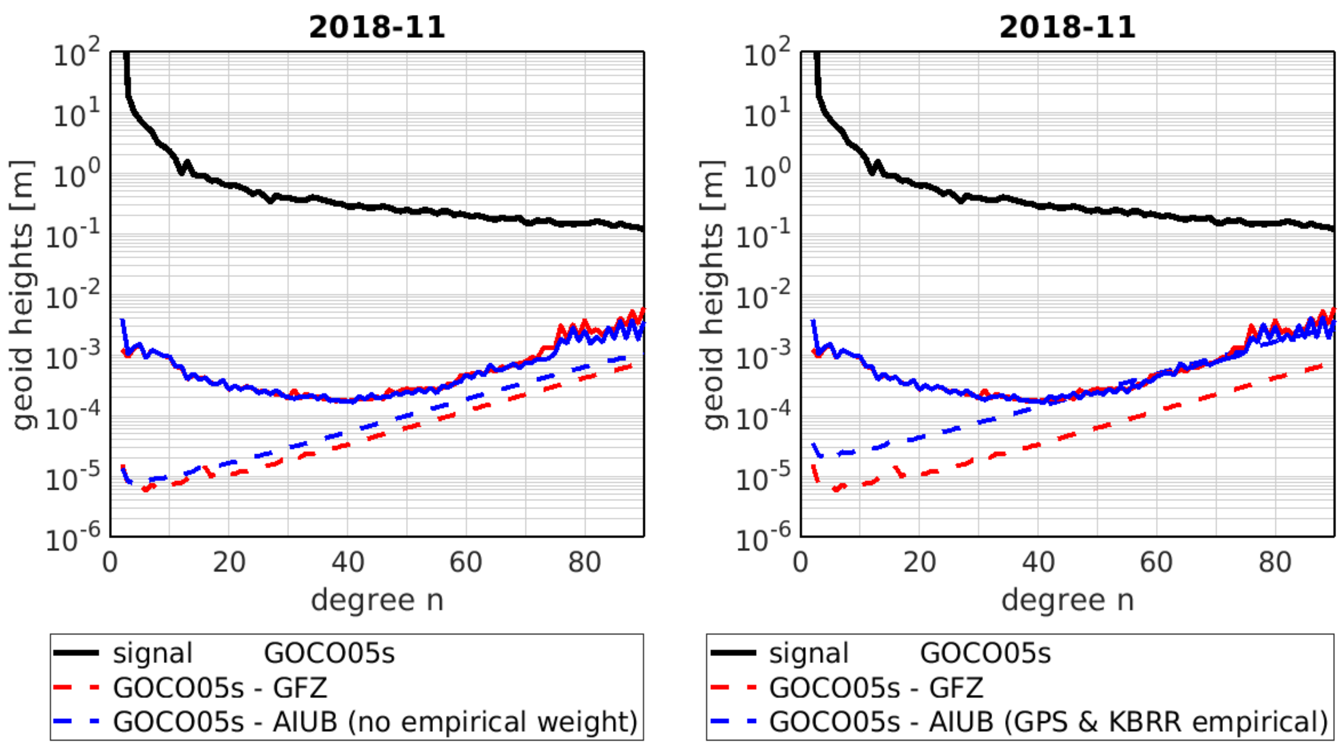
Dynamic orbit parametrisation features imperfect force model -> solution degraded
PCA are able to absorb deficiencies (done so far in the CMA)

Empirical covariances are able to describe the deficiencies in case of dynamic and reduced dynamic parametrisation
-> better formal errors

GPS & K-band (GRACE-FO)

GRACE-FO solutions on the level of SDS centres
First Laser-link (LRI) gravity fields at the level of KBR solutions

GPS noise modelling together with K-band



Formal errors too optimistic. Only PCA introduce empirical modelling.

More realistic formal errors. Noise characterisation mainly due to GPS contribution.

Follow-up activities from the EGSIEM project

COST-G

Combination Service for Time-variable Gravity Fields

COST-G: the new Product Center of the International Gravity Field Service of the IAG

U. Meyer[1], J.-M. Lemoine[2], F. Flechtner[3], T. Mayer-Gürr[4], S. Bettadpur[5], S. Bourgogne[6], A. Jäggi[1]

Unified Analysis Workshop

Paris, France

2 – 4 October, 2019

UNIVERSITÄT BERN
cnes
GFZ Helmholtz Centre Potsdam
TU Graz Graz University of Technology
CSR Center for Space Research The University of Texas at Austin
STELLAR SPACE STUDIES

International Gravity Field Service (IGFS)

Gravity and geoid metadata

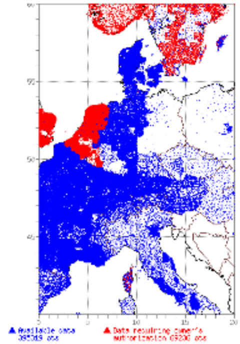
Online applications for the creation of metadata for gravity and geoid data. Service for searching the metadata database.

g–μeta
the gravity metadata editor
(v0.2.6 – beta edition)

N–μeta
the geoid metadata editor
(v0.1.3 – alpha edition)

Gravity data

Land, marine, airborne gravity data as point and gridded values. Absolute and relative gracity data, WGM



SG and Earth tide data

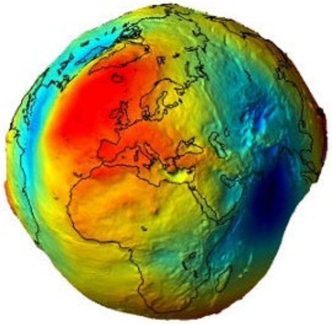
Temporal variations of the Earth gravity field through long-term records from ground gravimeters, SG data, Earth tide data.

DEM data

Digital Elevation Models, relevant software for DEM creation, assessment, manipulation and display, global relief and crustal models and spherical harmonic data sets.

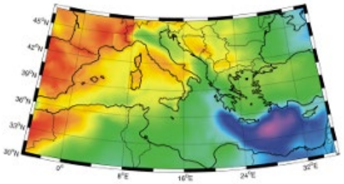
Global Earth Models

Collection and archive of all existing global gravity field models, web interface for access to GEMs, model visualization and service.



Geoid

Geoid models and geoid determination software, geoid modeling processing methodologies



Time-variable GEMs

Combined gravity field solutions in SH coefficients and spatial grids for hydrological, oceanic and polar ice sheets applications.

COST-G is a new product center of the

International Association of Geodesy

IAG

I G F S

COST-G

Unified Analysis Workshop

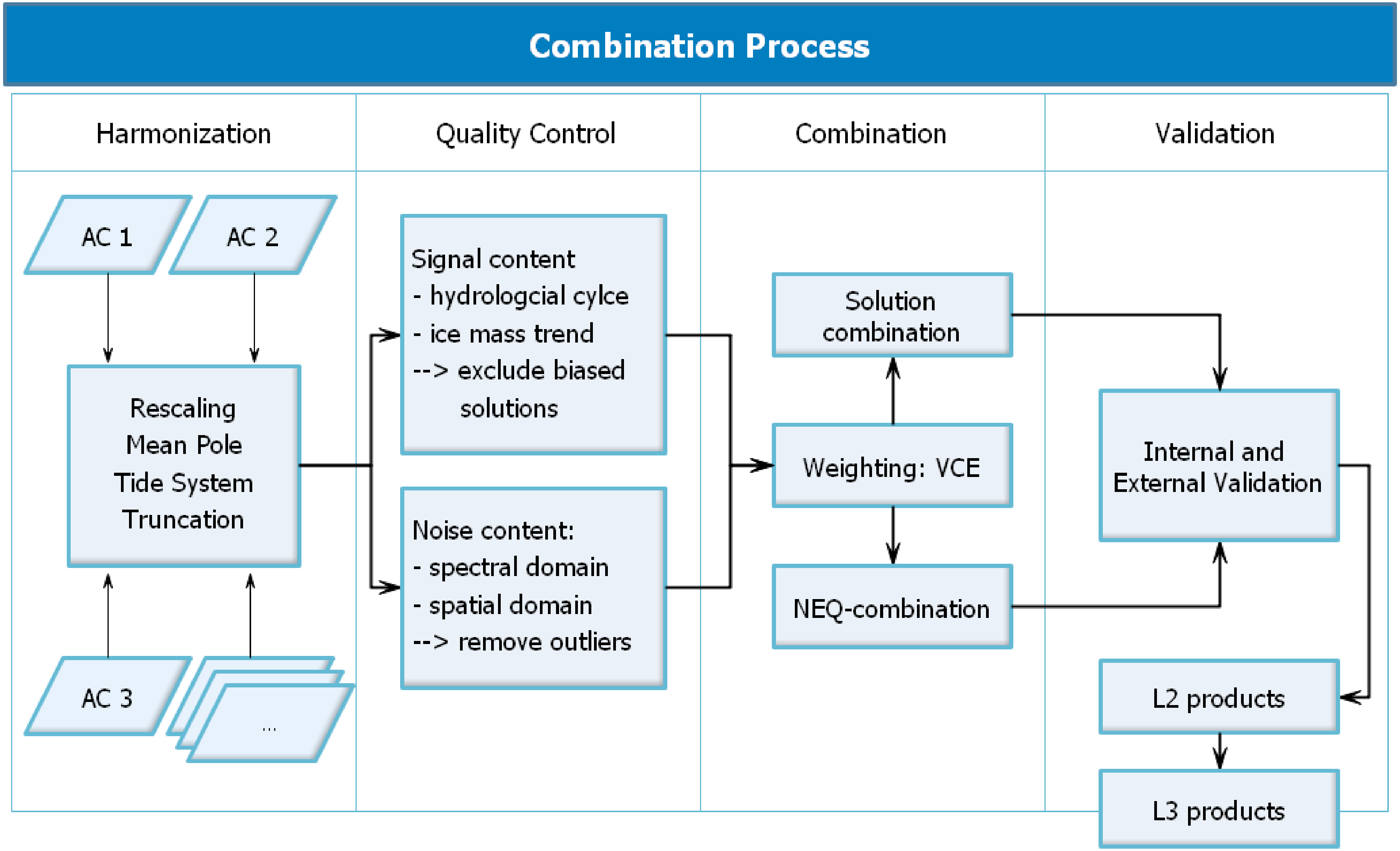
Paris, 2 – 4 October, 2019

Permanent Components of COST-G

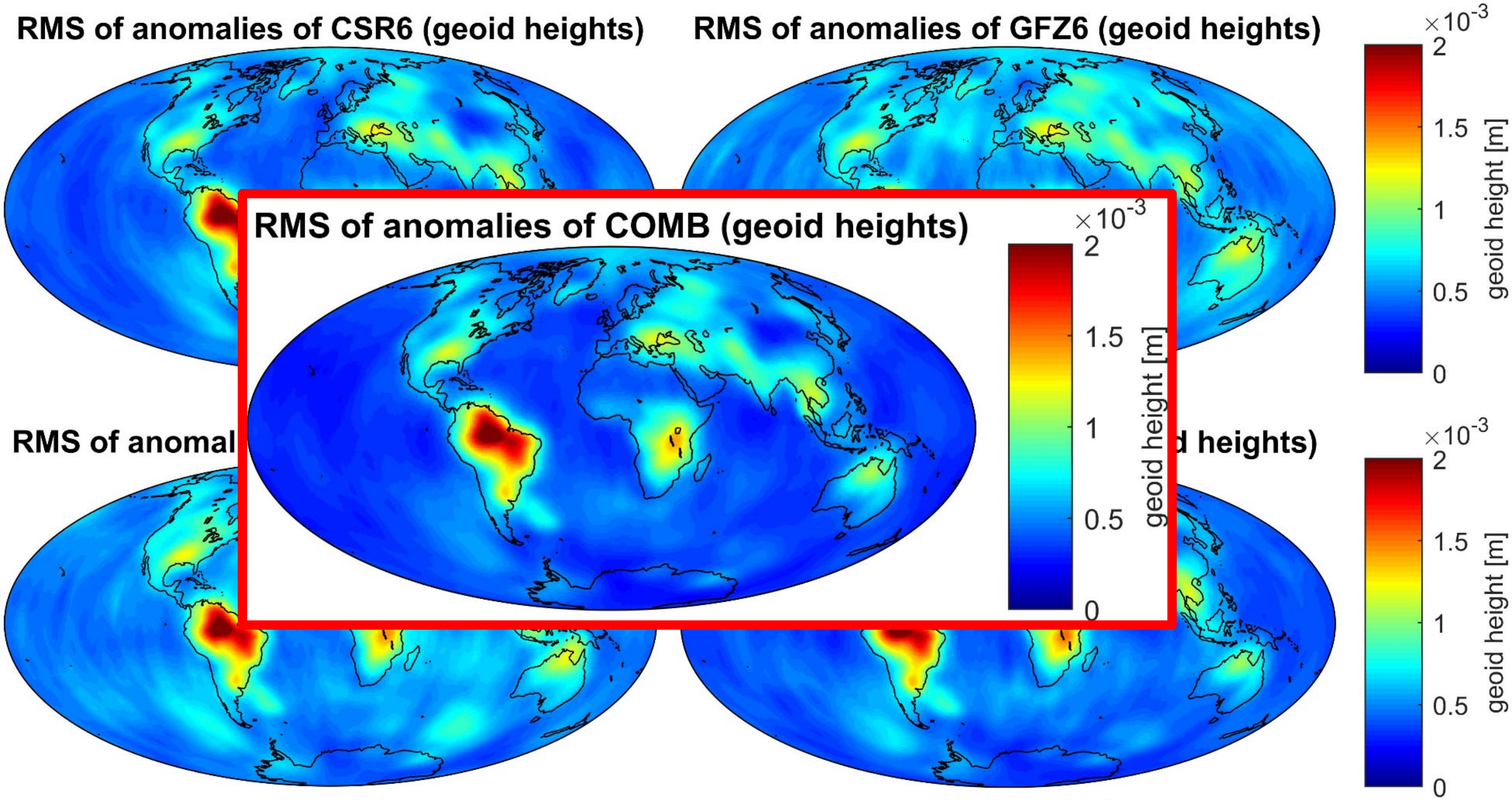
- **Central Bureau (CB):** AIUB
- **Analysis Centers (ACs):** AIUB, CNES, GFZ, TUD
- **Analysis Center Coordinator (ACC):** AIUB
- **Validation Center (VC):** GRGS, GFZ
- **Product Evaluation Group (PEG):**

  A. Eicker, A. Groh, L. Longuevergne, B. Meyssignac
- **Level-3 Center (L3C):** GFZ

COST-G: Workflow

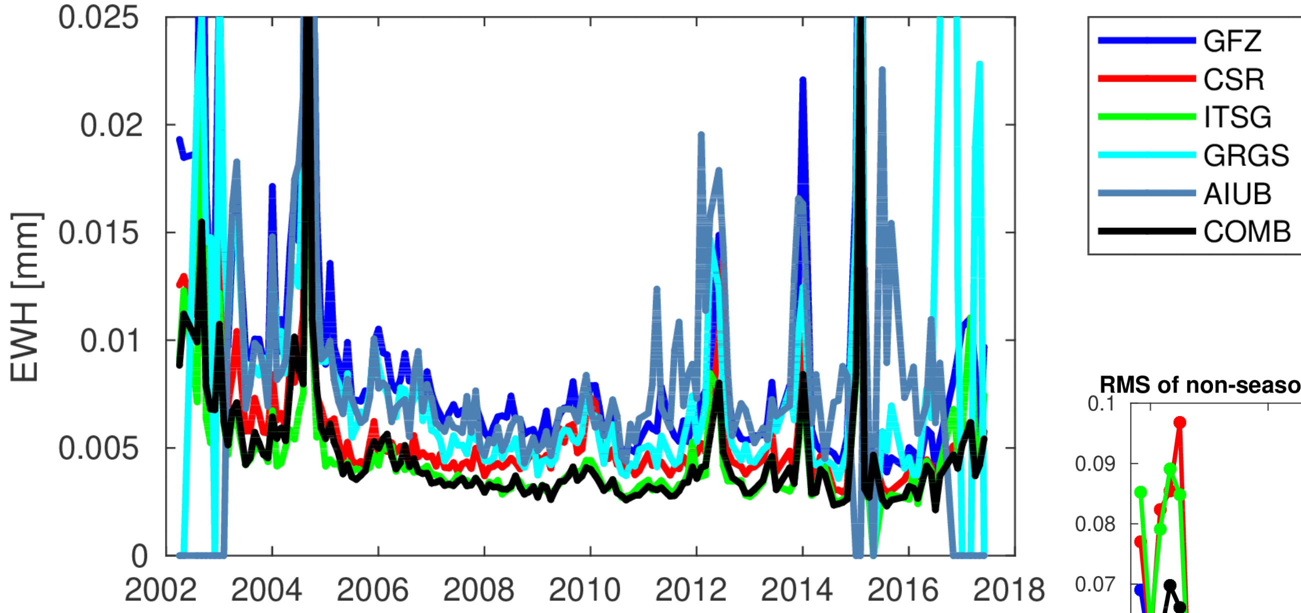


Internal Validation: Noise Levels of GRACE

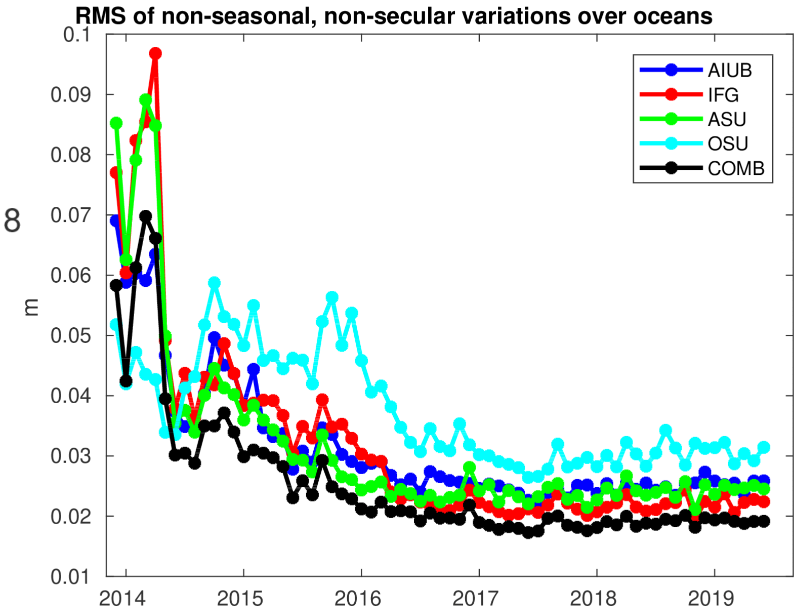


Internal Validation: Monthly Noise Level

GRACE



Swarm



Product Availability

Cost-G went on-line at the occasion of the IUGG 2019. Products are available at ICGEM:

- Monthly combined GRACE gravity field models:
  - 04/2002 to 06/2017 (reprocessing):

    http://icgem.gfz-potsdam.de/series/03_COST-G/GRACE

    ftp://icgem.gfz-potsdam.de/03_COST-G/GRACE

- Monthly combined Swarm gravity field models:
  - 12/2013 to 06/2019 (operational, 3 months latency):

    http://icgem.gfz-potsdam.de/series/03_COST-G/Swarm

    ftp://icgem.gfz-potsdam.de/03_COST-G/Swarm

COST-G: Products

COST-G

Combination Service for Time-variable Gravity Fields

Home | Introduction | Consortium | Service | Products | Documents | Contact | The COST-G Plotter

Products

COST-G provides a number of products via different platforms and channels:

GRACE

Level 2 – Products are sets of spherical harmonic coefficients which stem from the combination on solution or normal equation level. The coefficients need to be processed by a spherical harmonic synthesis in order to derive gridded data. They are available at the International Center for Global Gravity Earth Models (ICGEM): http://icgem.gfz-potsdam.de/series/03_COST-G/GRACE

Level 2b – Products will be available soon.

Level 3 – Products will be available soon.

GRACE Follow-On

Level 2 – Products will be available soon.

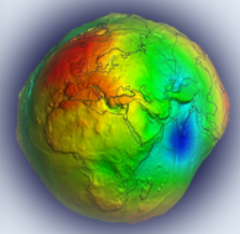
Level 2b – Products will be available soon.

Level 3 – Products will be available soon.

Swarm

Level 2 – products are a combination of different kinematic orbit products and various gravity field recovery approaches. Data is available at the International Center for Global Gravity Earth Model (ICGEM): http://icgem.gfz-potsdam.de/series/03_COST-G/Swarm

Product Dissemination



I C G E M

- ICGEM Home

Gravity Field Models

- Static Models
- Temporal Models
- Topographic Gravity Field Models

Calculation Service

- Regular grids
- User-defined points

3D Visualisation

- Static Models
- Temporal Models
- Trend & Amplitude
- Spherical Harmonics

Evaluation

- Spectral domain
- GNSS Leveling

Documentation

- FAQ

Tongji-Grace2018		(GRACE monthly solutions from the Tongji University, Shanghai, PR China)
ULux		(CHAMP monthly solutions from the University of Luxembourg)
WHU RL01	DOI	(GRACE monthly solutions from the GNSS Research Center of Wuhan University, PR China)
XISM&SSTC_GRACE01		(GRACE monthly solutions from Xi'an Research Institute of Surveying and Mapping (XISM) and Space Star Technology co., LTD. (SSTC))

COST-G (International Combination Service for Time-variable Gravity Field)

GRACE	(Monthly GRACE solutions from the International Combination Service for Time-variable Gravity Field (COST-G), see also here here)
Swarm	(Monthly Swarm solutions, more information can be found here here and here)

GRACE weekly solutions

GFZ Release 05	(GFZ GRACE Level-2 Processing, Revised Edition, January 2013)

GRACE daily solutions

ITSG-Grace2014	(more information can be found here)
ITSG-Grace2016	(more information can be found here)
ITSG-Grace2018	(more information can be found here)

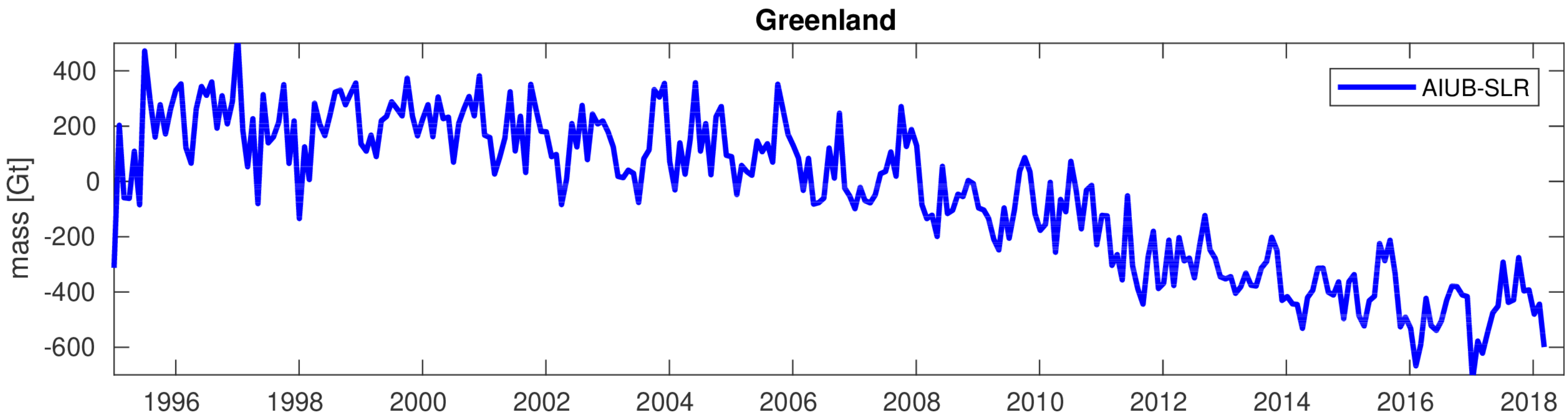
SLR_monthly

SLR-only monthly solutions from AIUB

Non-isotropic smoothing

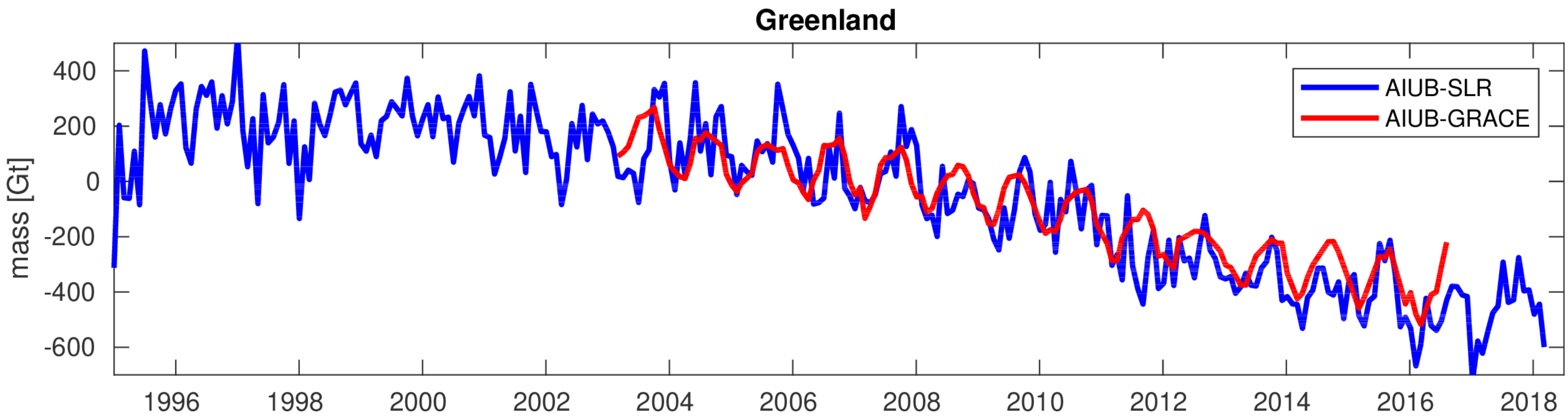
AIUB Release 02		(more information can be found here)
CSR Release 05		(UTCSR Level-2 Processing Standards Document, Rev 4.0 May 29, 2012)
GFZ Release 05		(GFZ GRACE Level-2 Processing, Revised Edition, January 2013)
HUST-Grace2016	DOI	(GRACE monthly solutions from the Huazhong University of Science and Technology, Wuhan, PR China)
ITSG-Grace2014		(GRACE monthly solutions from the ITSG, TU Graz; more information can be found here)
ITSG-Grace2016	DOI	(GRACE monthly solutions from the ITSG, TU Graz; more information can be found here)
JPL Release 05		(PL Level-2 Processing Standards Document, Release 05.1 November 3, 2014)
Tongji Release 01		(GRACE monthly solutions from the Tongji University, Shanghai, PR China)
Tongji Release 02 new version		(GRACE monthly solutions from the Tongji University, Shanghai, PR China)
Tongji Release 02 old version		(GRACE monthly solutions from the Tongji University, Shanghai, PR China)

Monthly SLR gravity fields (d/o 6)



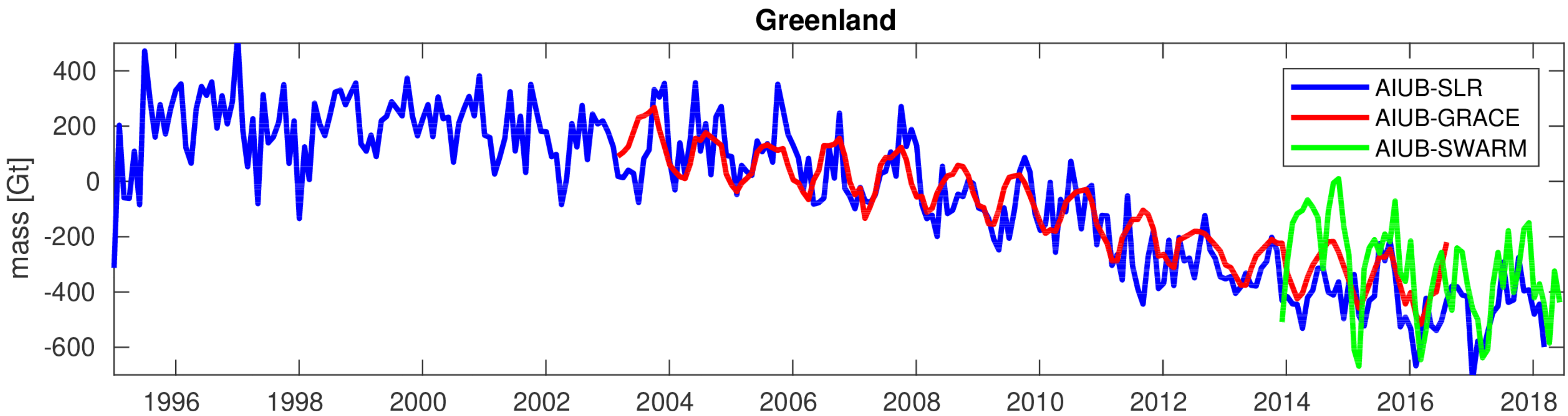
- LAGEOS 1+2: 30 d solutions based on 10 d arcs.
- SLR-LEOS (Beacon-C, Ajisai, Starlete, Stella, Larets, Lares): 30 d solutions based on 1 d arcs.
- Gravity field: 5 x 5 + C_{61} and S_{61}; C_{50} constrained.
- A priori gravity: static 7 y GRACE (AIUB-APR).
- A priori orbits: LAGEOS own predictions, LEOS CPF

Monthly GRACE gravity fields (d/o 90->6)



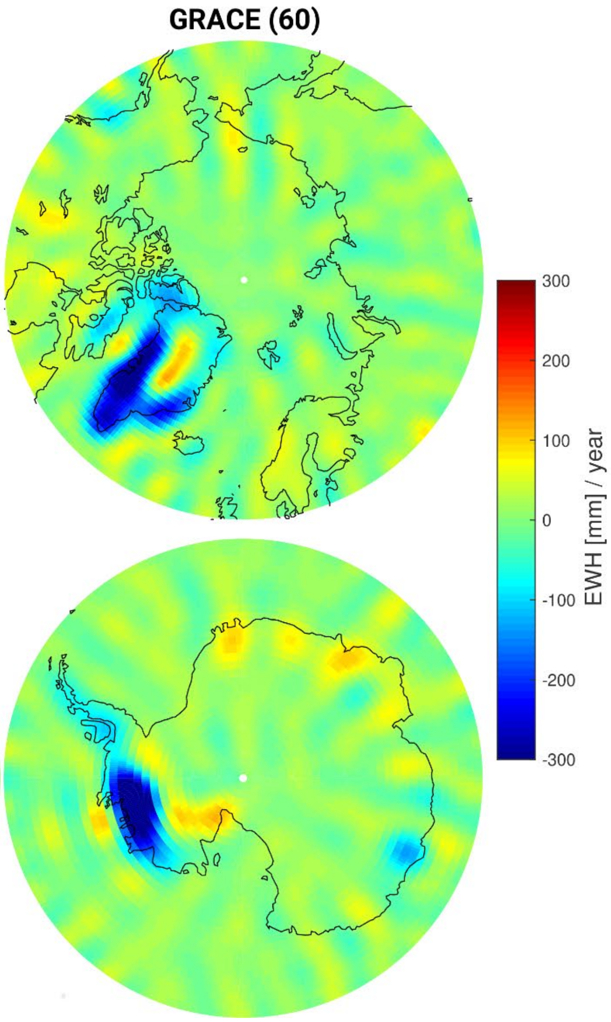
- GRACE GPS+K-band: monthly 90 x 90 gravity field solutions, truncated at degree / order 6.
- Degree 2 excluded.
- Degree 1 fixed to 0.
- No filter applied.

Monthly SWARM gravity fields (d/o 70->6)

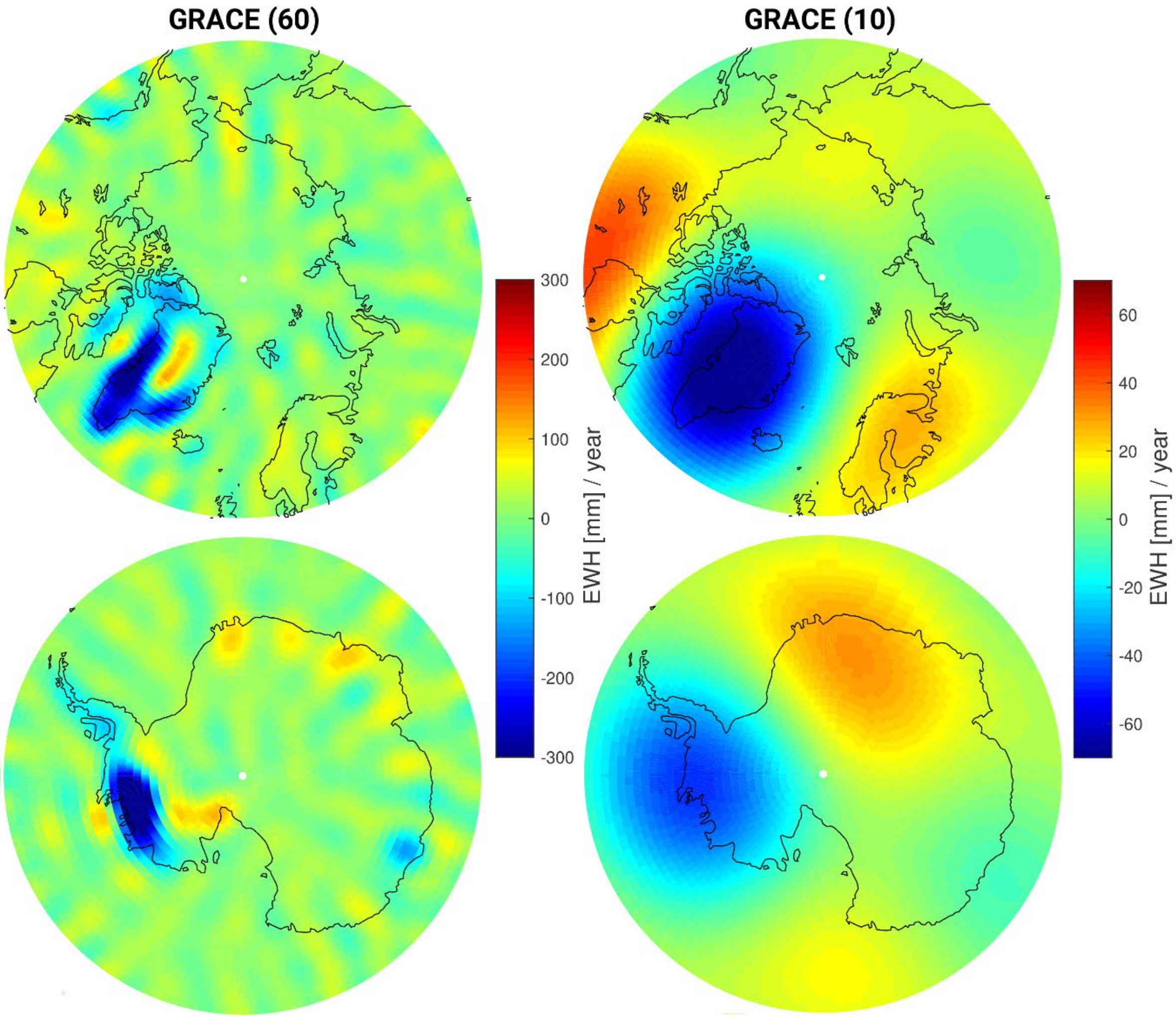


- SWARM GPS: monthly 70 x 70 gravity field solutions, truncated at degree / order 6.
- Degree 2 excluded.
- Degree 1 fixed to 0.
- No filter applied.

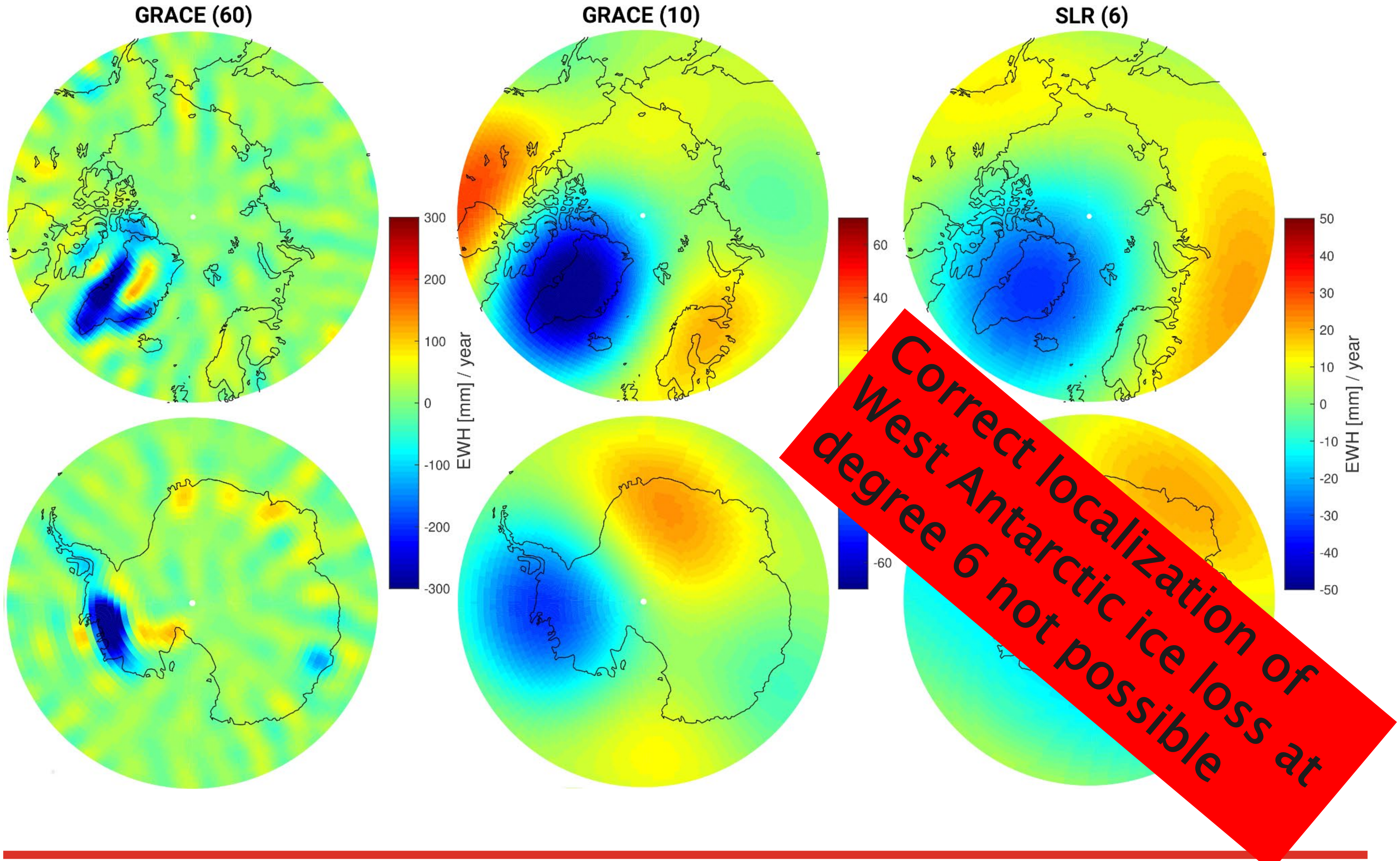
Localization of mass change



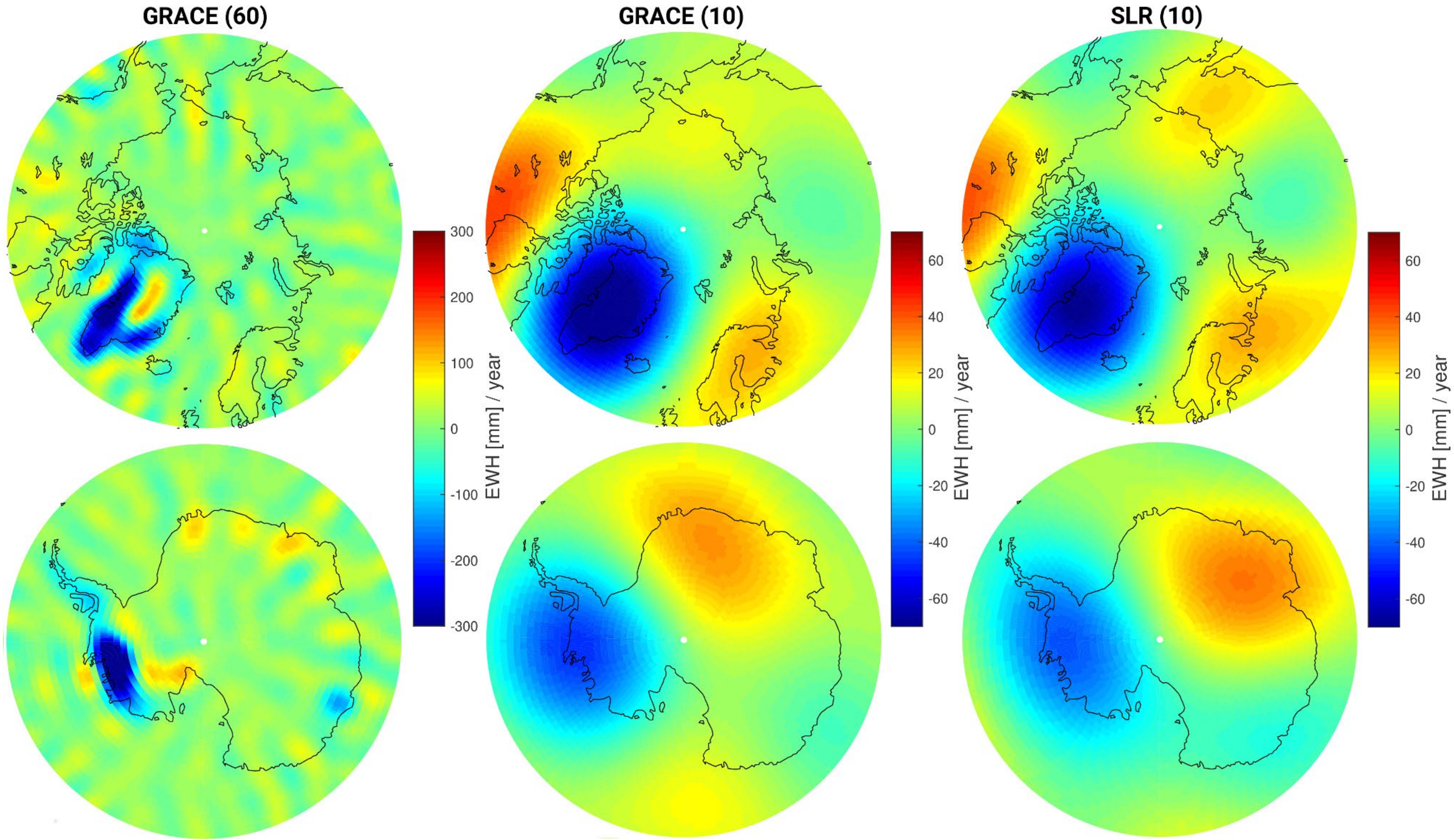
Localization of mass change



Localization of mass change



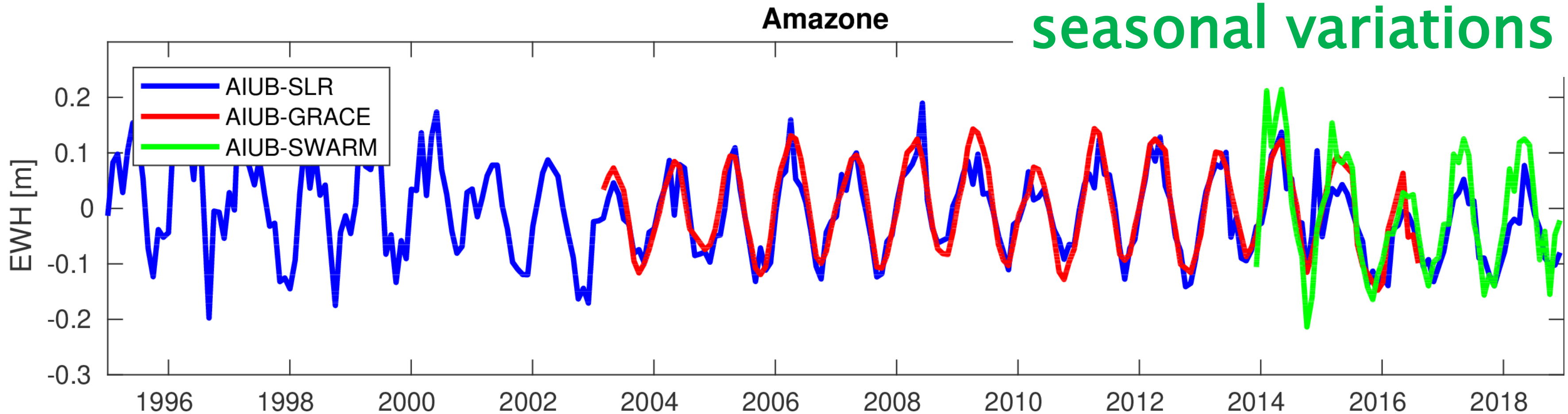
Localization of mass change

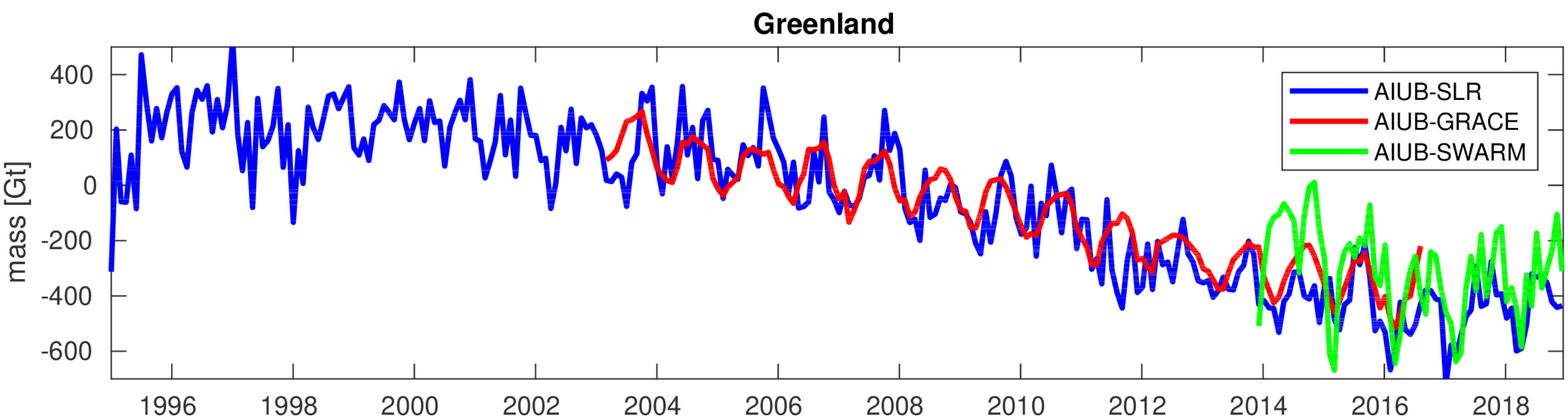


regularized

Quantification of mass change

over-estimation of seasonal variations

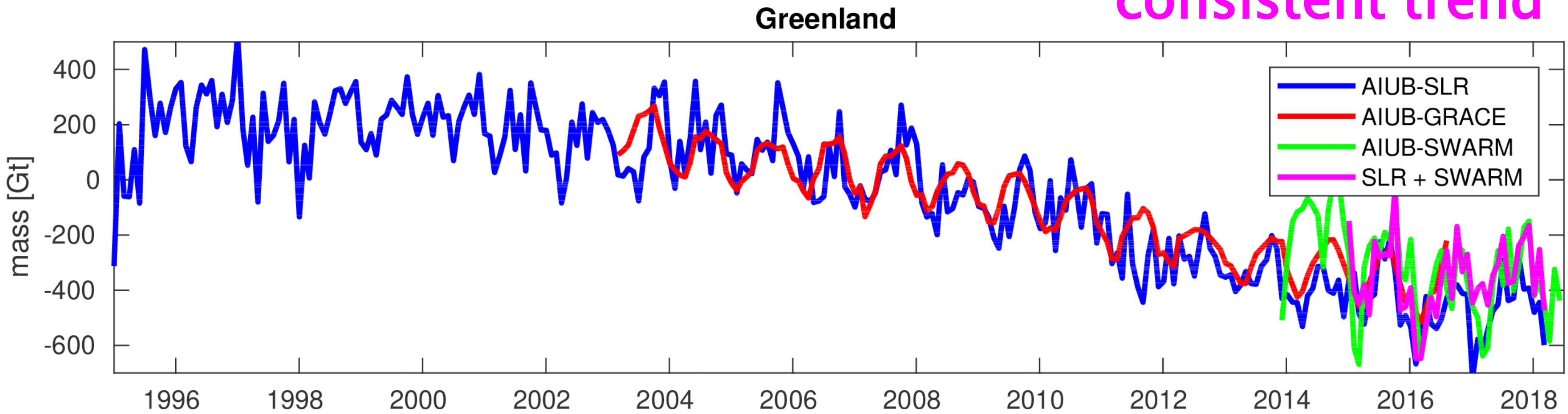


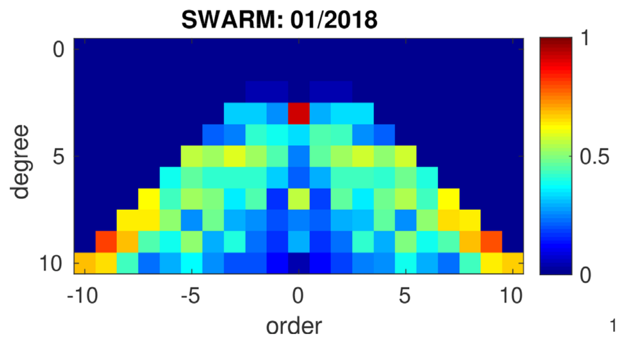


diverging trend after 2014

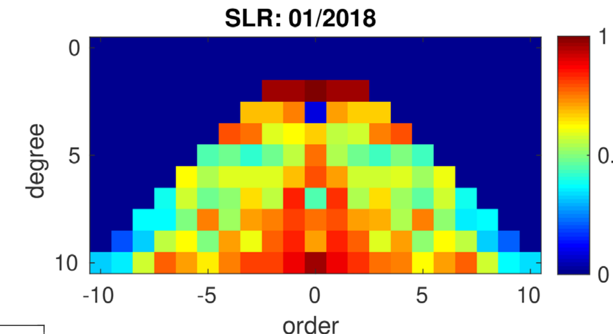
Combination of NEQs: SWARM + SLR

consistent trend

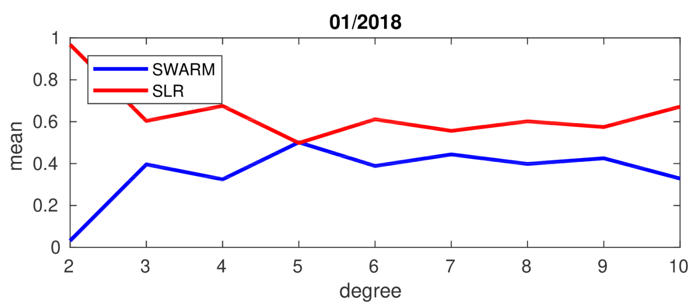




Contribution analysis per spherical harmonic coefficient.



Mean contribution per degree.



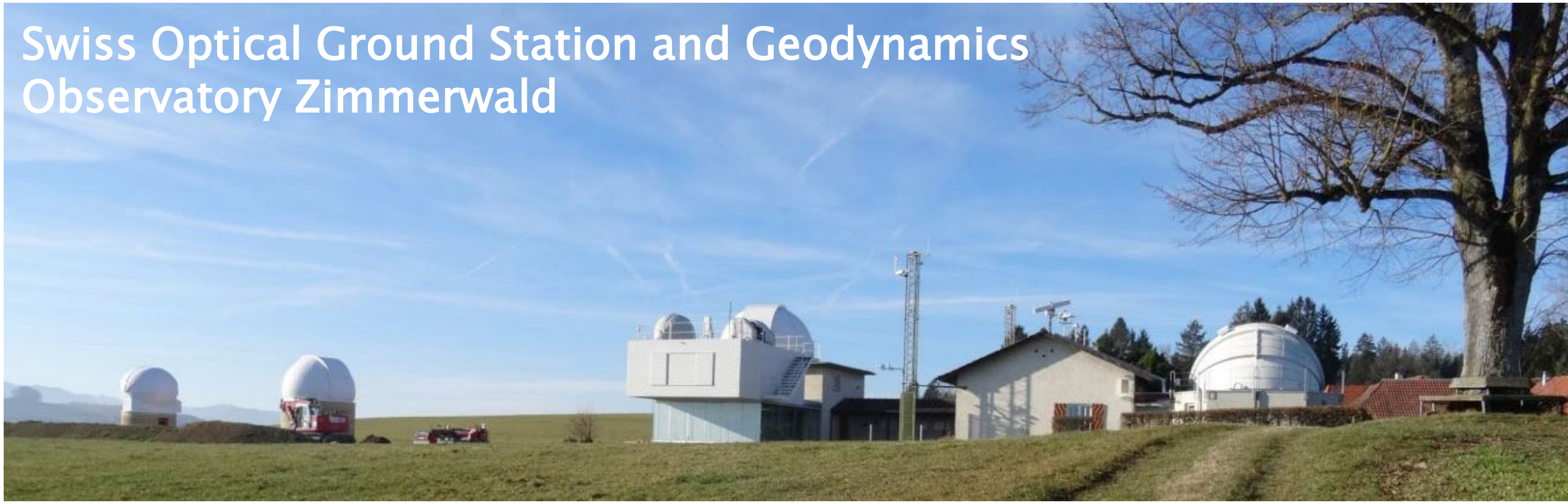
UNIVERSITÄT BERN

Astronomisches Institut der Universität Bern

Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald

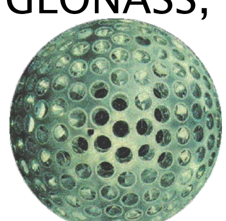
AIUB

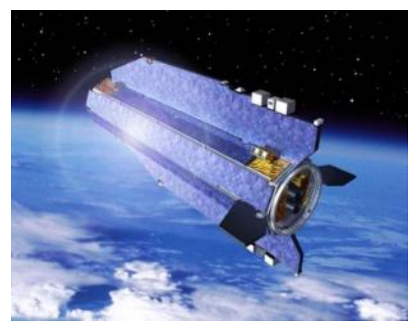
24/7 Betrieb

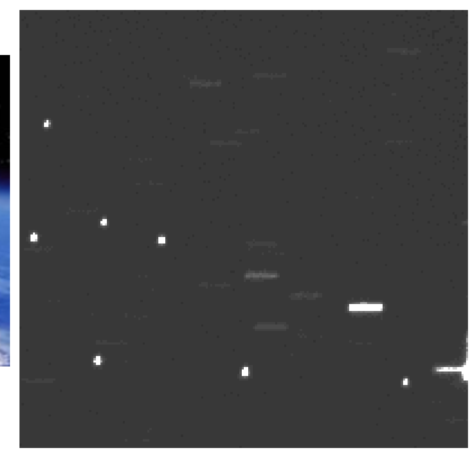


24/7 Operations

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

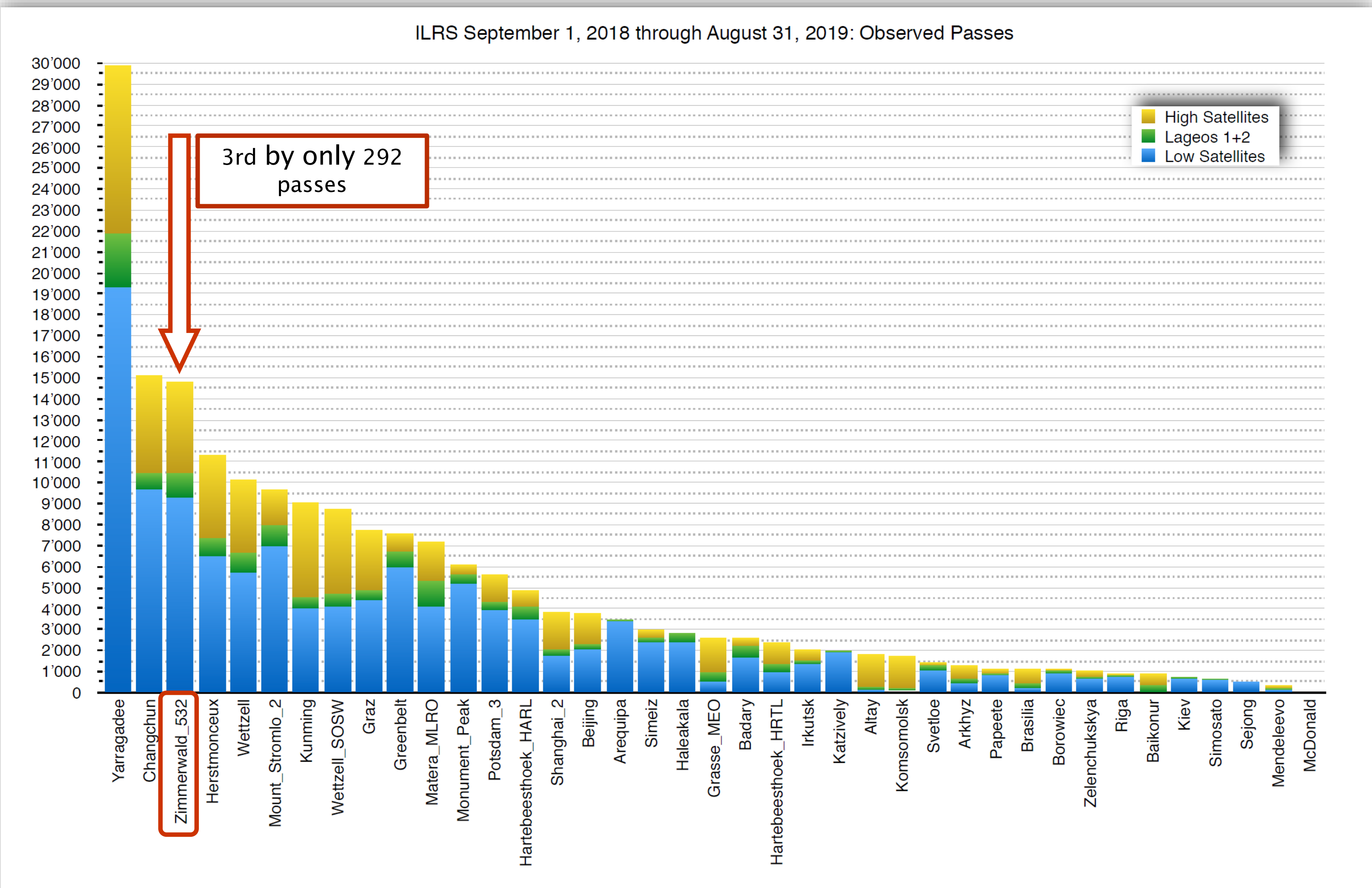




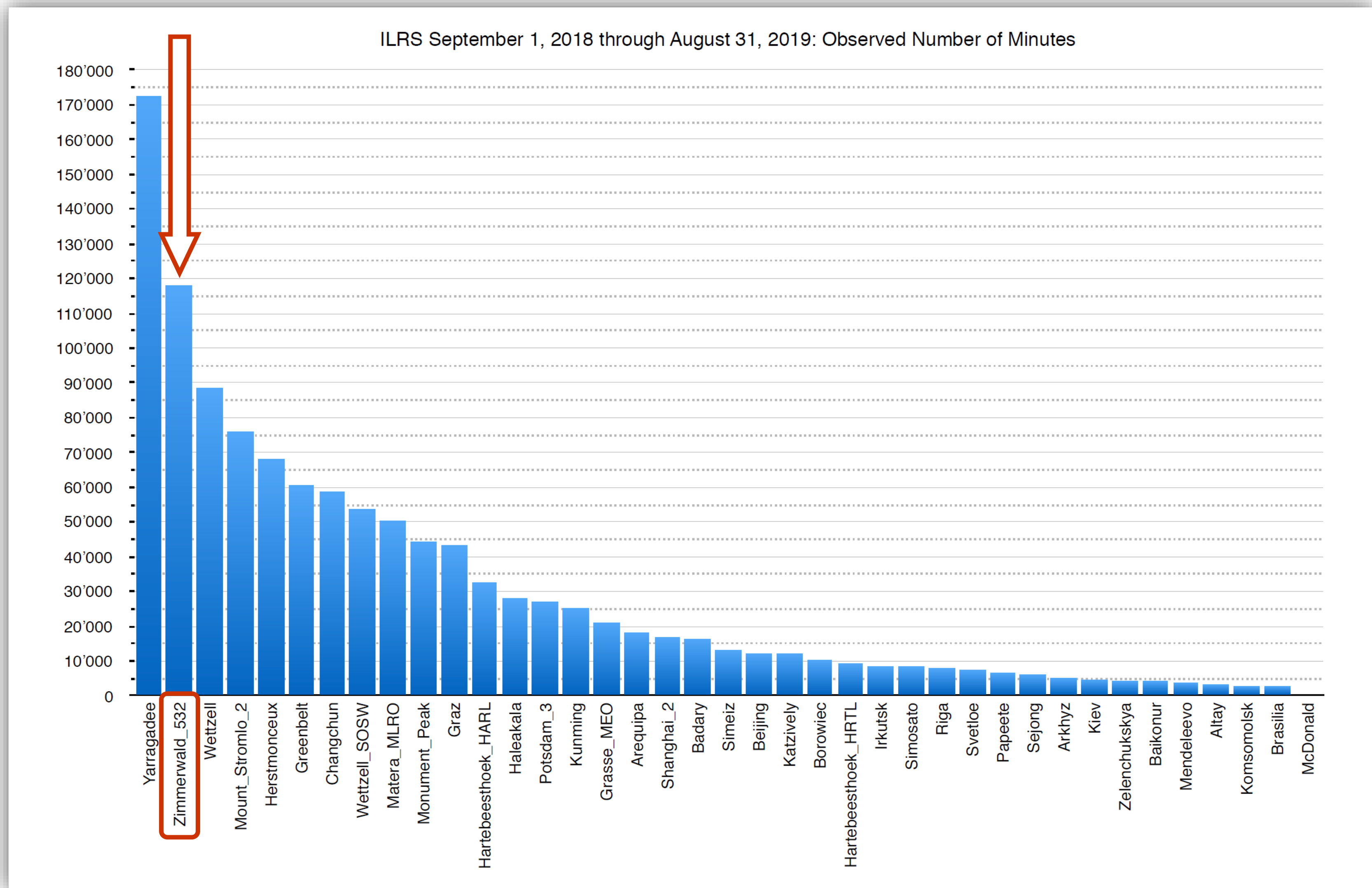


Satellite Laser Ranging

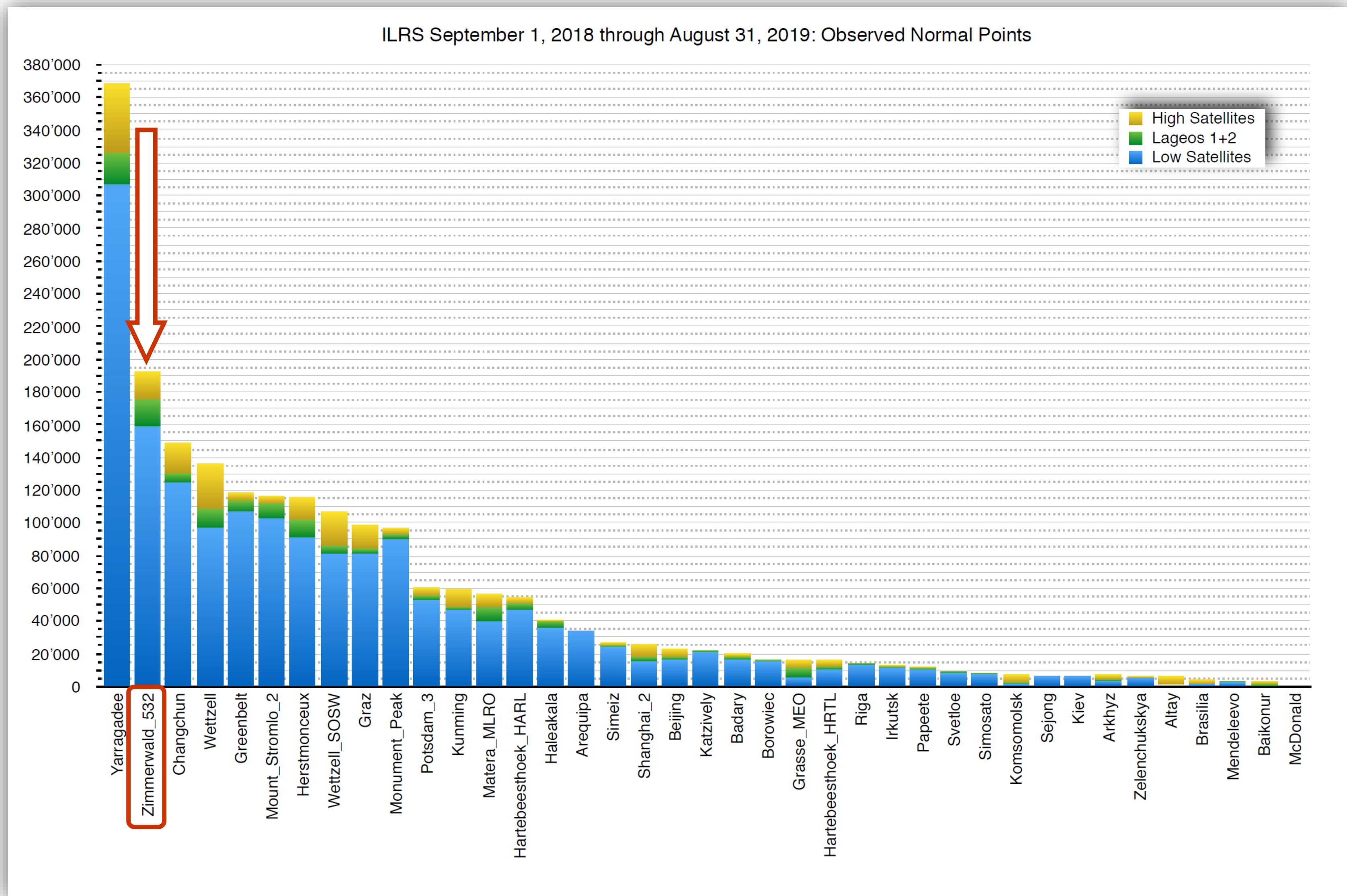
SwissOGS – SLR Performances



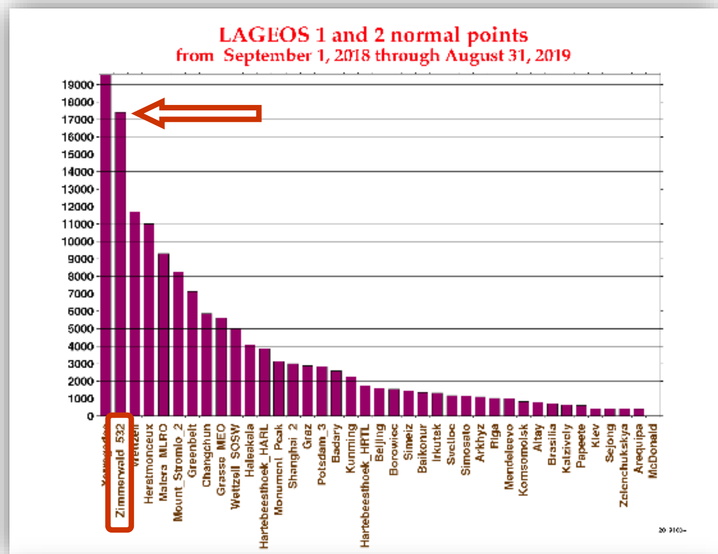
SwissOGS – SLR Performances

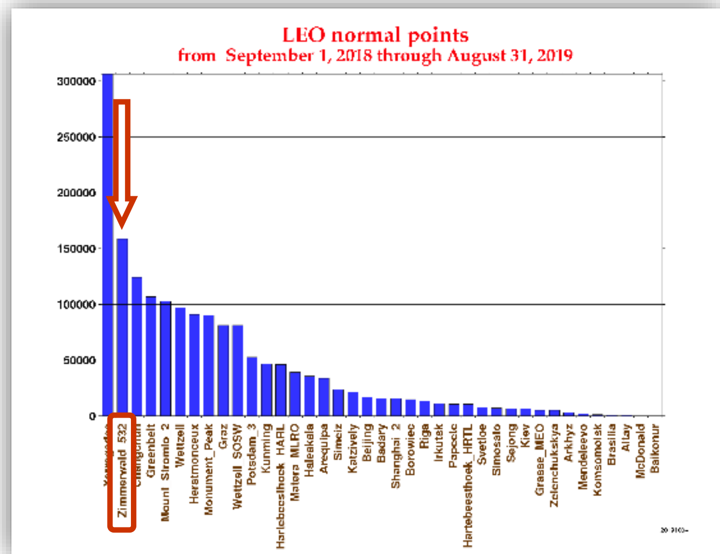


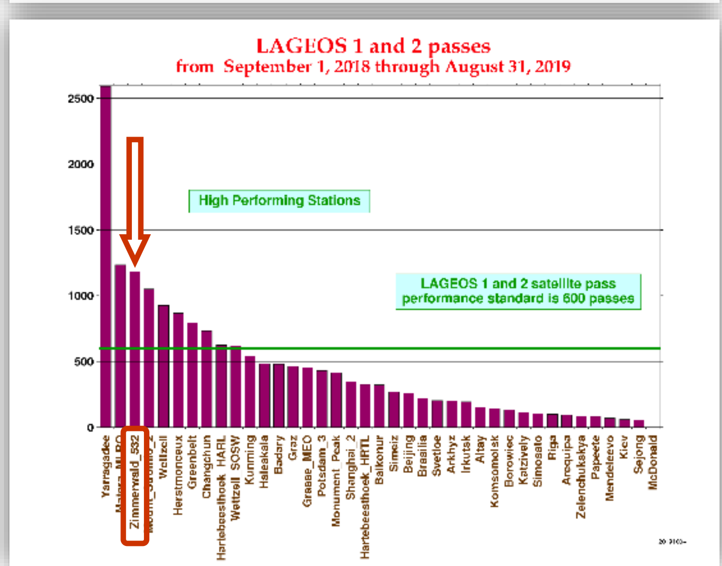
SwissOGS – SLR Performances

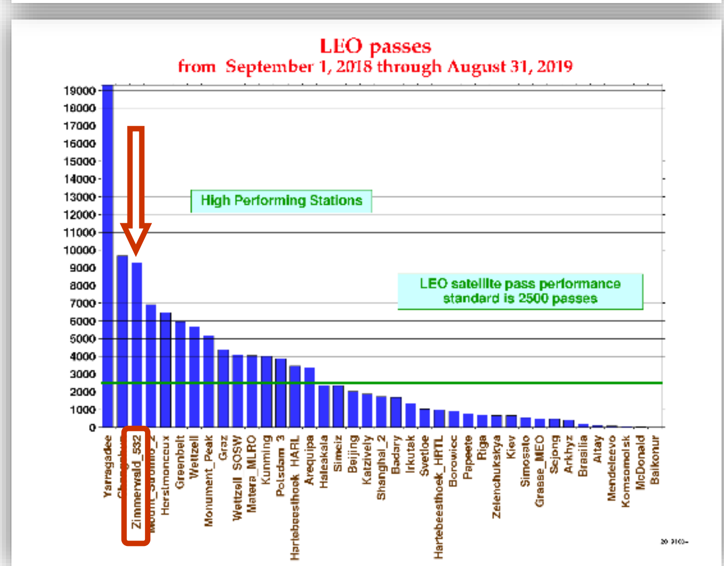


SwissOGS Performance for LEO & LAGEOS

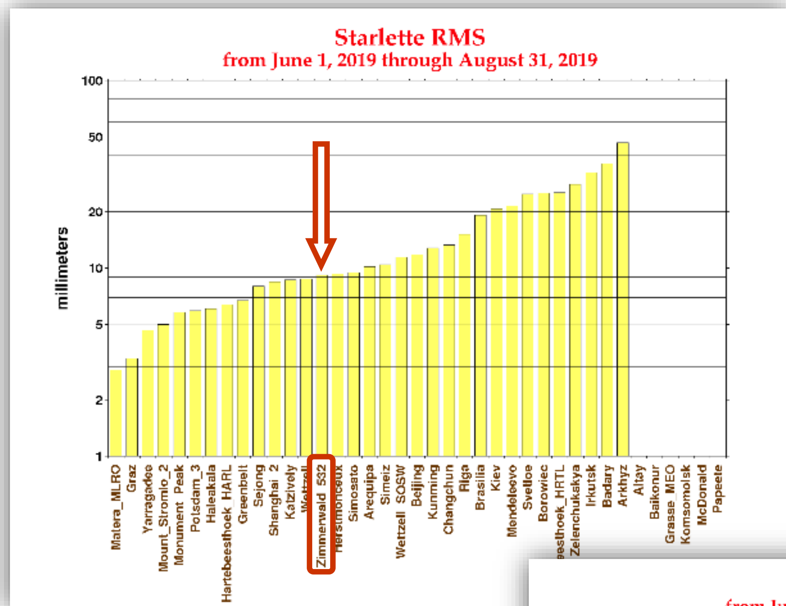


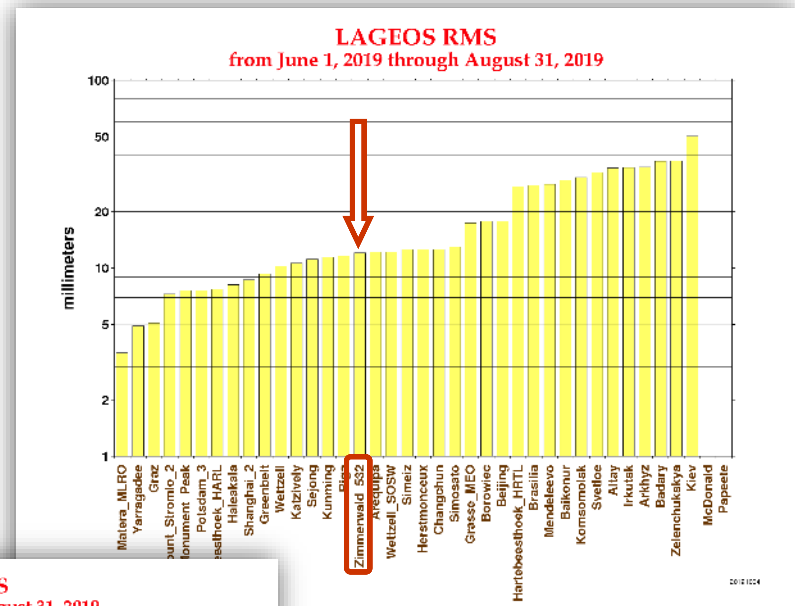


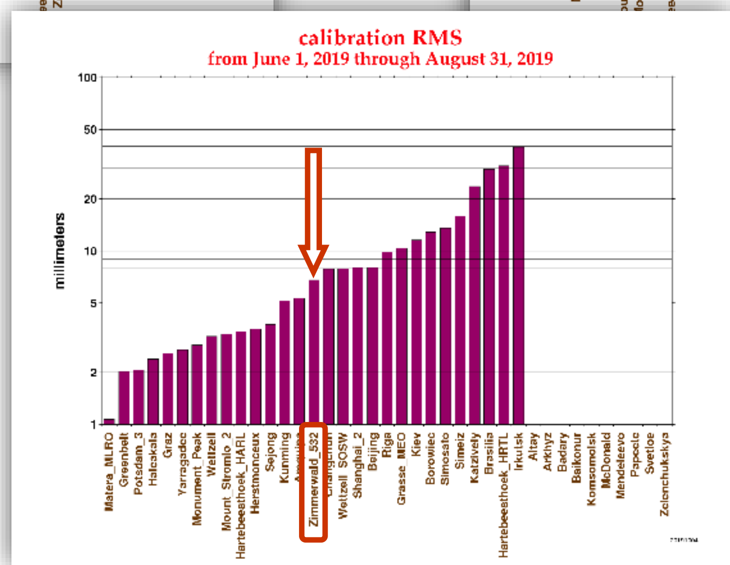




SwissOGS – Measurement Accuracy

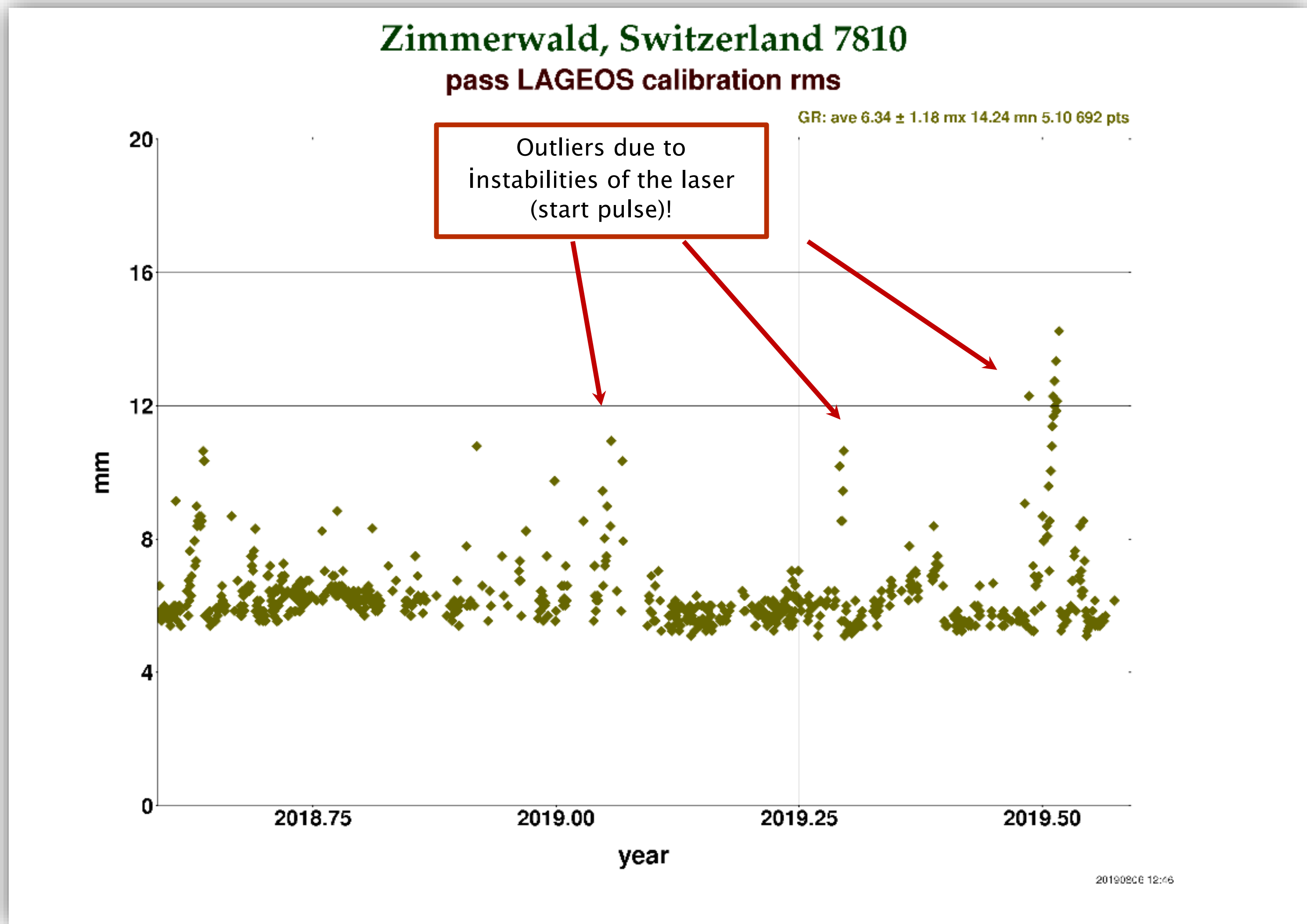






The accuracy is limited by our current laser system

LAGEOS Calibration rms



SUCCESS – GALILEO SLR Observation campaign

Observation Campaign Outcomes:

- SLR contribute to improvement of Galileo orbit accuracy when combining radiometric tracking data (>10%)
- Station coordinate estimation difference w.r.t. SLRF2014 < 1 cm
- SLR Only Orbit detemrination 0.1 m (3D-RMS) w.r.t. radiometric orbit
- SLR can be used as backup for Galileo POD
- Improved orbit modelling during eclipses
- SLR residuals against satellite clock estimates are not necessarily caused by radial orbit errors
- SLR full rate can be used to determine yaw state of satellite during eclipse maneuver

Station	Total Number of NPs			Number of Passes > X NPs	
	GSAT0102	GSAT0220	Sum	>5	>10
Grasse	63	126	189	14	3
Zimmerwald	65	89	154	12	6
Herstmonceux	77	53	130	9	5
Wettzell	17	63	80	9	4
Mt. Stromlo	57	15	72	6	2
Yarragadee	175	149	324	5	0
Wettzell	18	23	41	5	1
Graz	3	67	70	4	3
Potsdam	19	8	27	2	0
Matera	21	15	36	1	0
Greenbelt	4	10	14	1	0
Brazilia	8	0	8	1	0
Kunming2	12	10	22	0	0
Papeete	14	0	14	0	0
Changchun	7	6	13	0	0
Beijing	0	4	4	0	0
Monument Peak	3	0	3	0	0
Svetloe	2	0	2	0	0
Altay	1	0	1	0	0
Sum	**566**	**638**	**1204**	**69**	**24**
Daily average	25.7	29.0	54.7	3.1	1.1

Source:
ESA technical Note – SUCCESS Data Analyses
Reference: DOPS-SYS-TN-0505-OPS-GN
Date of Issue: 18/09/2019
Prepared by ESA SLR Analysis Team

SLR Operations

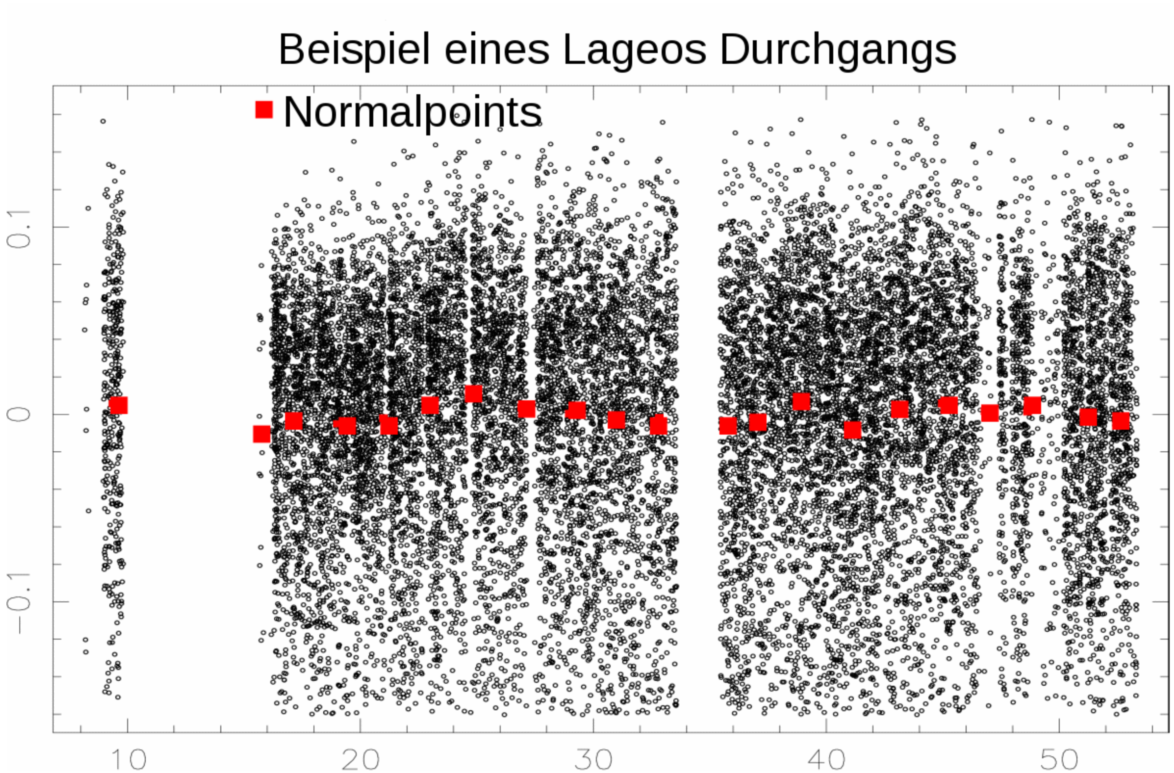
- ILRS pass statistics
  - Still very good performance

- Special Satellites/Restricted Tracking
  - Low Energy measurements
    - Sentinel-3A/B on a routine basis again
    - ICESat-2 tried but has to many restrictions: time bias extremely high and highly varying + low elevation + low power requirements + GoNoGo + weather
  - Space debris targets (ILRS space debris study group)

- System
  - laser, electronics, and mechanics perform reliably
  - SLR dome: discussion with Canton for new dome due to a possible safety issue, but new standard domes do not fit well

Normal Point Generation

- review and improvement of strategy/algorithm for Normal Point generation
- PhD started June 2019 (Linda Geisser)



SLR Development

- **Definition/evaluation of new laser**
  - still no quantum leap in technology in sight
  - go now for 2 lasers:
    - one for high precision geodetic applications and
    - one for space debris
  - laser parameters
    - high precision: rep.-rate 2..3 kHz and pulse width 10..15ps, keep avg. power
    - space debris: rep.-rate 100 Hz..1kHz and pulse width <= 5ns, increased avg. power

- **Software for higher rep.-rates (data-PC)**
  - porting from MSDOS to Linux in principle done but the Linux scheduler multitasking breaks the real time requirements of the old software completely.
  - trying to run main process without the time scheduler time slicing; there are still Linux kernel specials and bugs

  Alternatives
  - use foreign software packages, e.g. from DIGOS, Graz, ...
  - redesign Zimmerwald software

SLR Development

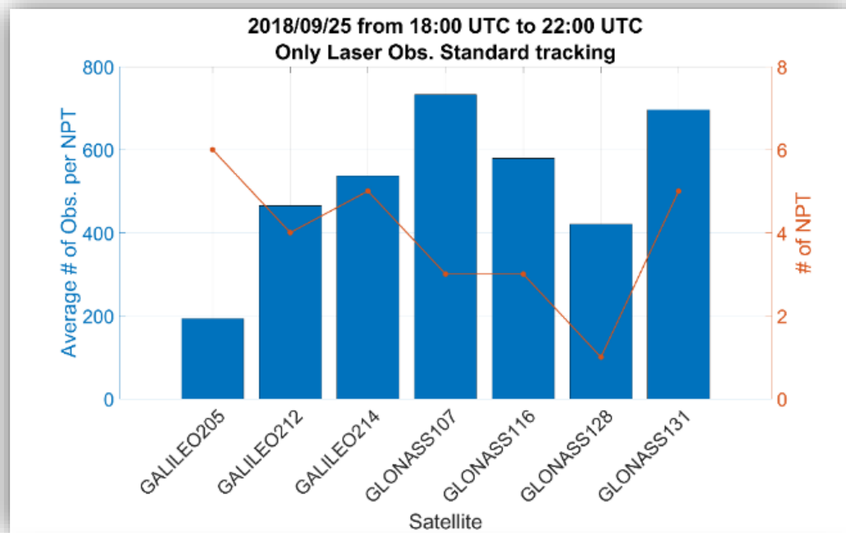
- Quantum experiments
  - setting up a link in the green with an adjustment laser worked in principle but already here high energy loss; reason might be higher atmospheric attenuation than assumed
  - project postponed due to administrative reasons (scientist had to leave, funding etc.)

- European Laser Time Transfer project (ELT) (ACES experiment on ISS):
  - Performed campaign with Prague University to determine one-way calibration constants
  - Improved UTC time scale precision from 100 ns to 15 ns via new GPS receiver
  - Improved local time derived from maser from 30 ns to 1 ns
  - Time tag of SLR measurements with 15 ns precision
  - Software for time triggering in development

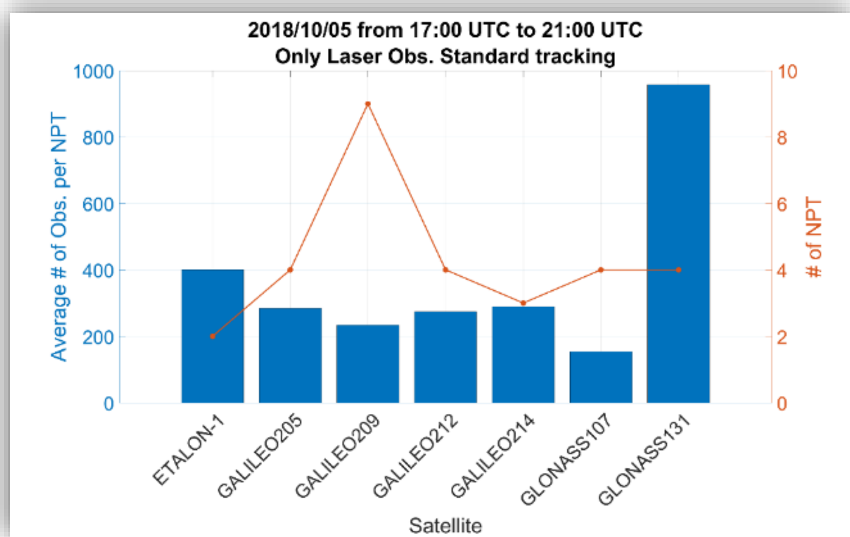
Space Debris Observations – Highlights

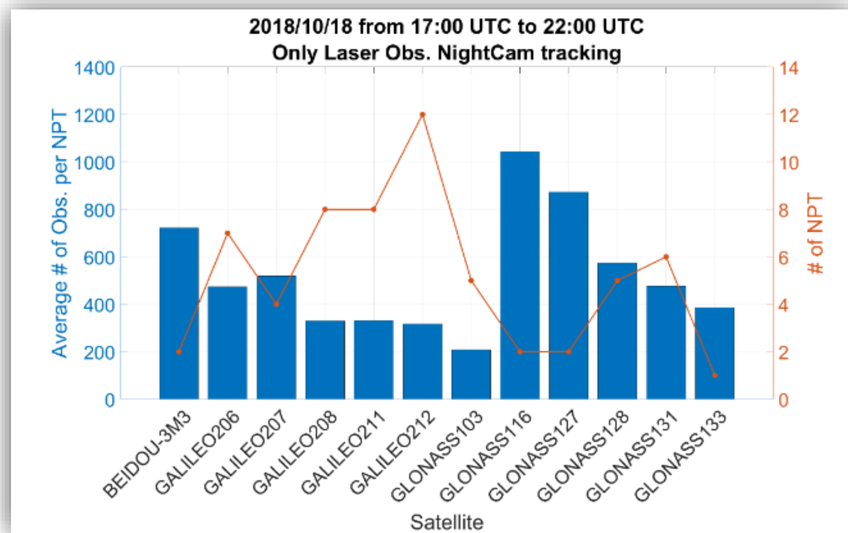
- Deep survey for discovery of faint breakup fragments (ZimTWIN, ZimMAIN, and ZIMLAT)
- Object color indices (CI), simultaneous color light curve acquisition (ZimTWIN)
- Results with Night-tracking camera (ZIMLAT):
  - improved SLR tracking
  - high resolution light curve
  - Near Earth Asteroid light curve
  - influence on station efficiency
  - orbit determination (OD) with short observation arc
- Photon Counter for high temporal resolution light curves (ZIMLAT)

ZIMLAT – Tracking Camera: Performance Analysis



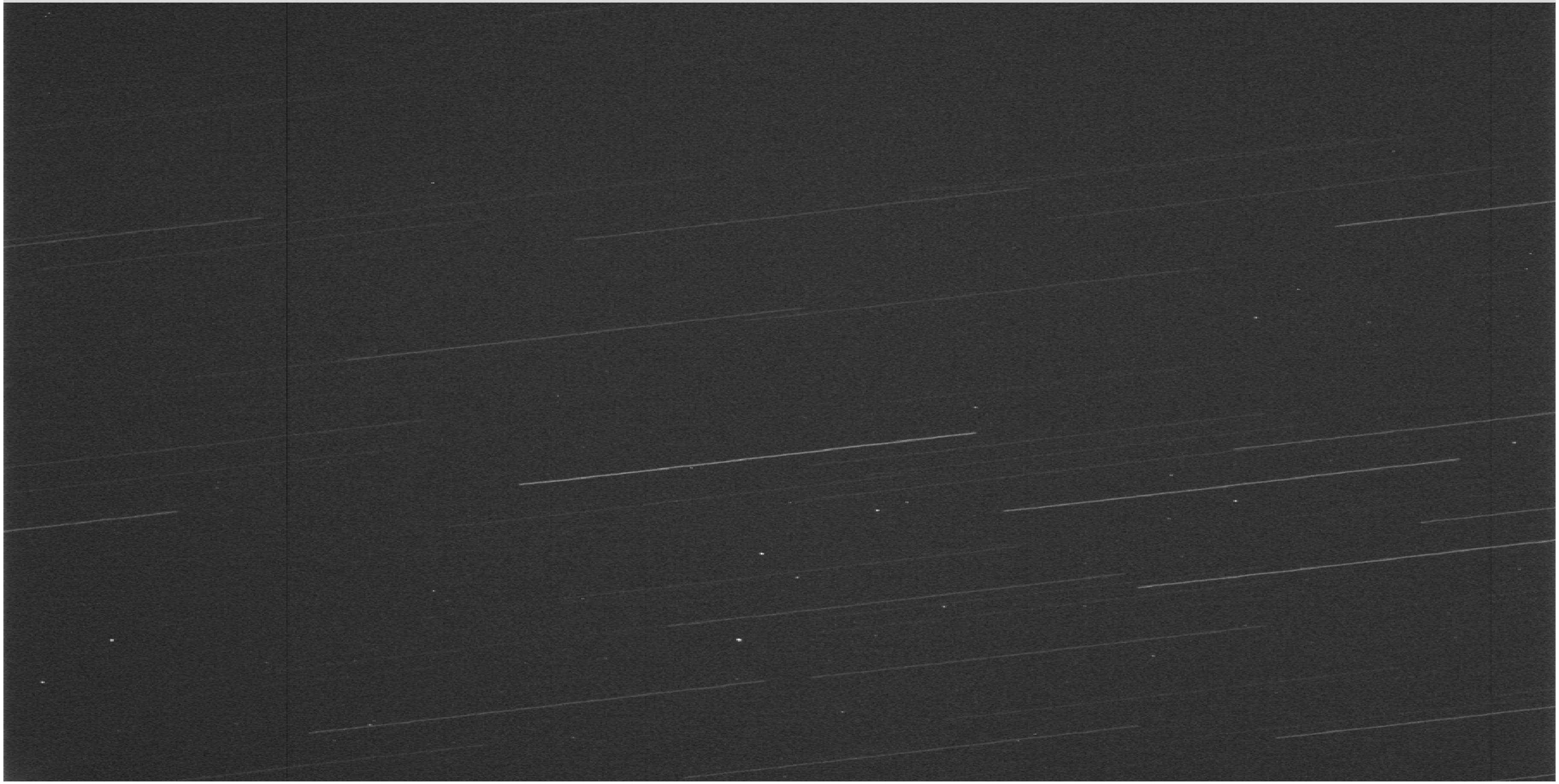
	Date	Hour of Obs.	MEO NPT/Hour	Obs./MEO NPT	Ave. NPT/MEO
Normal Tracking	2018/09/25	4	6,75	517	3,86
	2018/10/05	4	7,5	370	4,28
Tracking Camera	2018/10/17	4	10	855	3,78
	2018/10/18	5	12,4	522	5,17





Breakup Event: Results from New Telescopes (ZimTWIN & ZimMAIN)

- 20190325 discovered
- 20190326 first observations at Swiss Optical Ground Station and Geodynamics Observatory



2009-047B
Breakup

Fragments from three break-up events in HEO (June 2019)

Observations Analysis – Light Curve of Artificial Objects

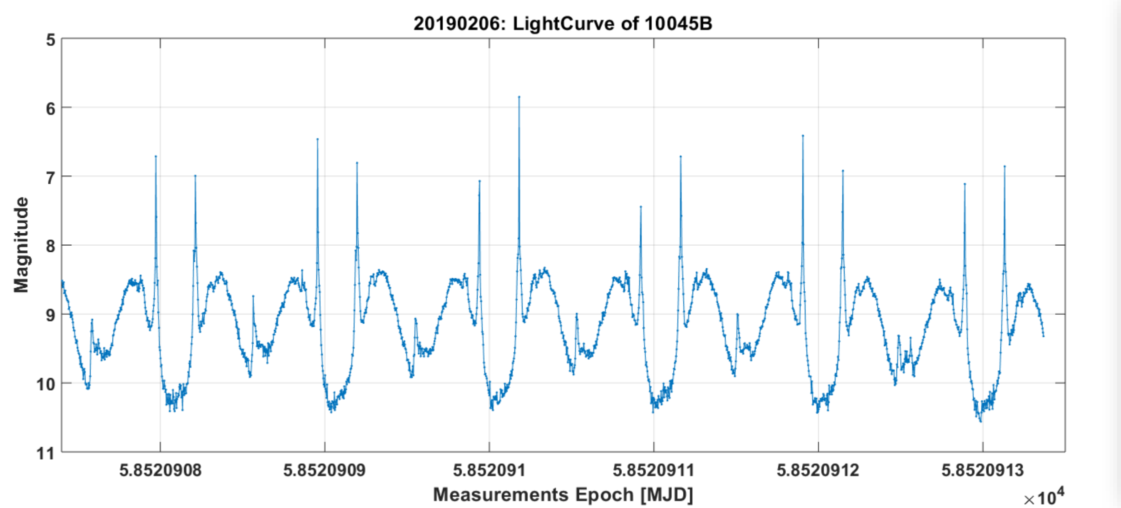
- AIUB Light Curve Database

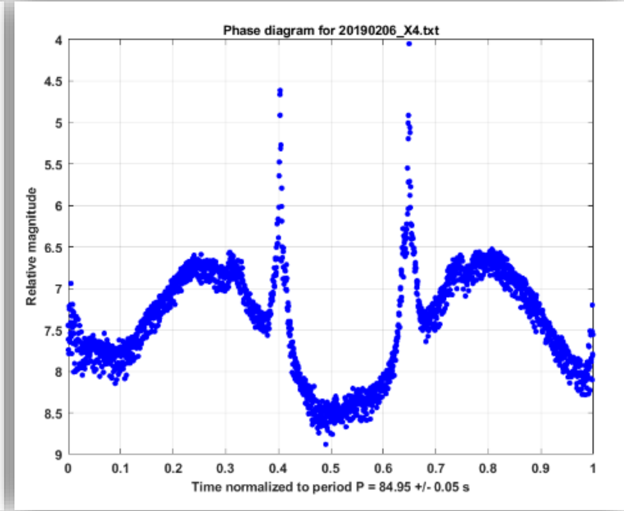
- Telescope: ZIMLAT
- Both CCD and sCMOS

- # of light curves: > 3500
- # of observed objects: ~520

Attitude Characterization

Rotation period estimation
Rotation axis direction
Environmental studies



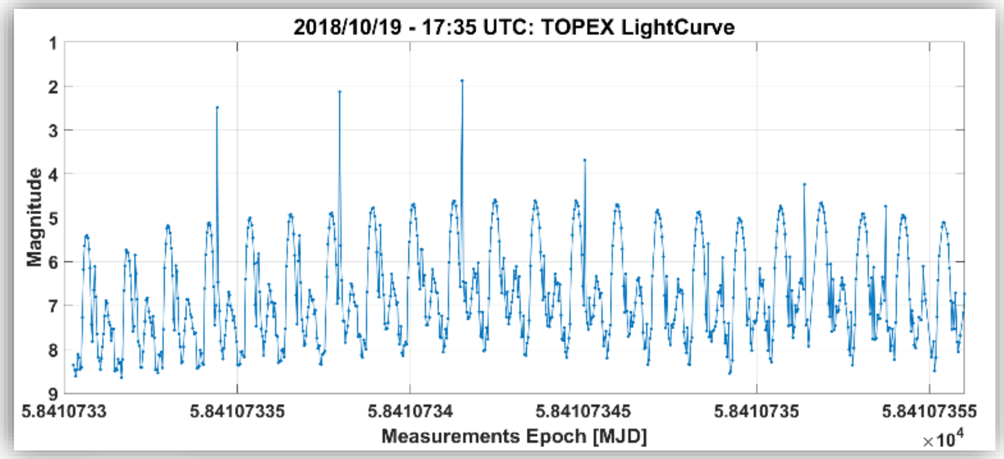


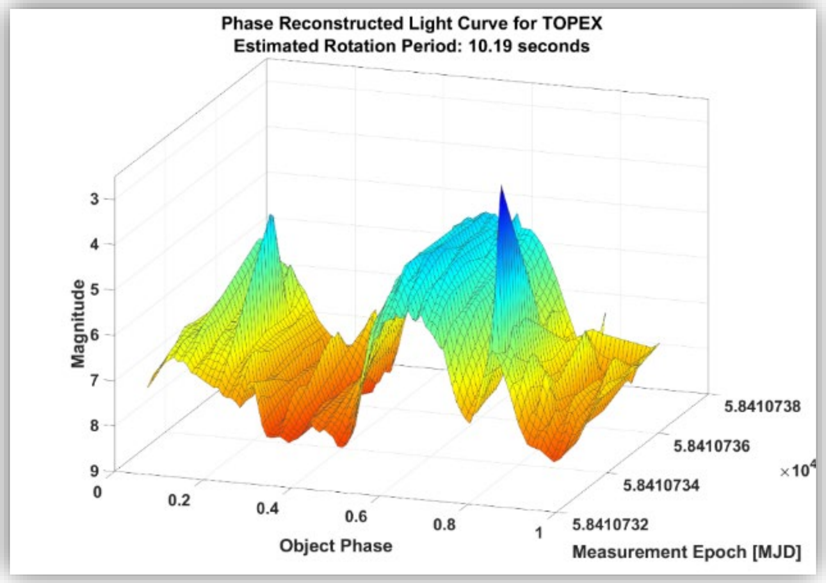
ZIMLAT – Tracking Camera: Attitude Determination Results – TOPEX

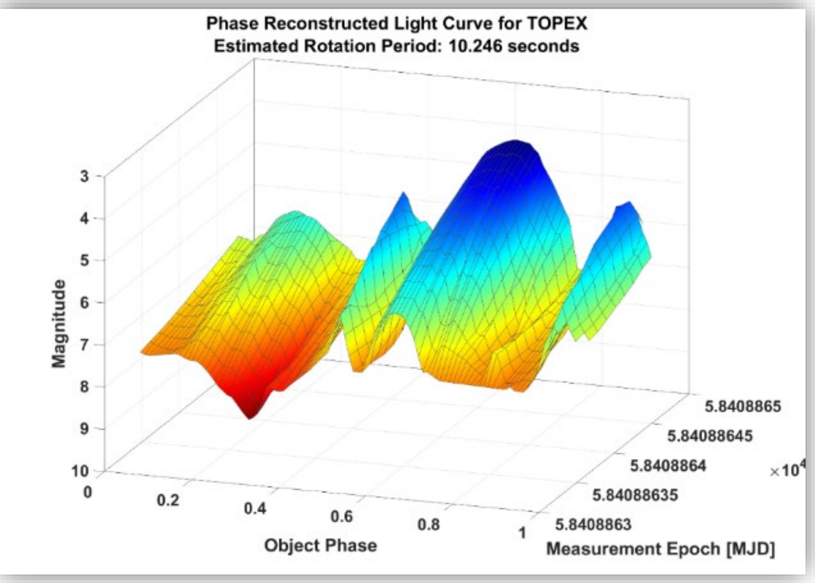
Target: TOPEX
COSPAR-ID: 92052A

Exp. Time: 0.1 sec

Observation Date		Rot. Period
2018/09/25		10.235 sec
2018/10/09		10.207 sec
2018/10/17	1° Pass	10.188 sec
2018/10/17	2° Pass	10.246 sec
2018/10/19	1° Pass	10.189 sec
2018/10/19	2° Pass	10.215 sec







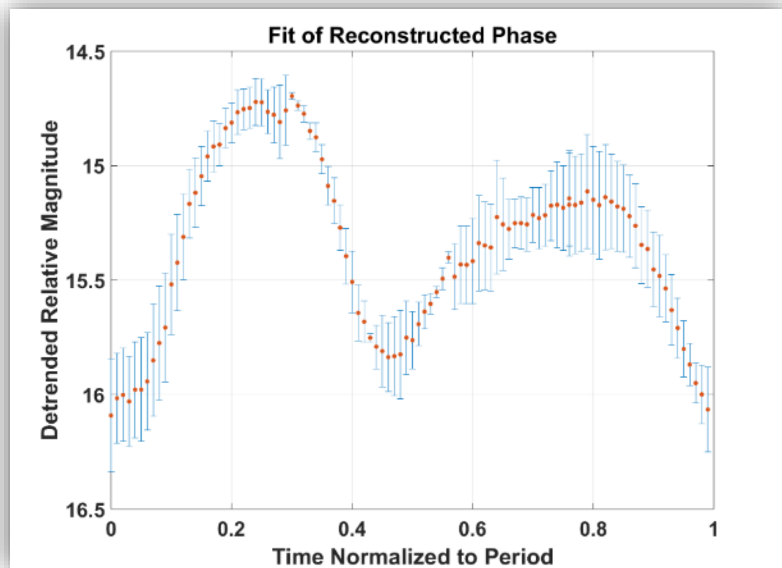
ZIMLAT – NEO Observations

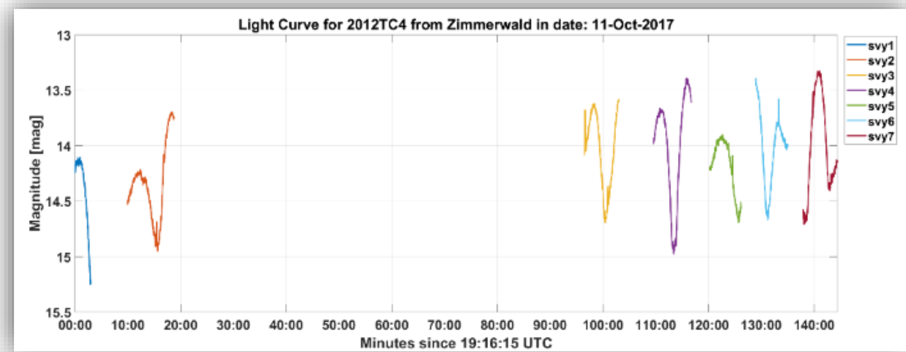
Phase Reconstructed Light Curve

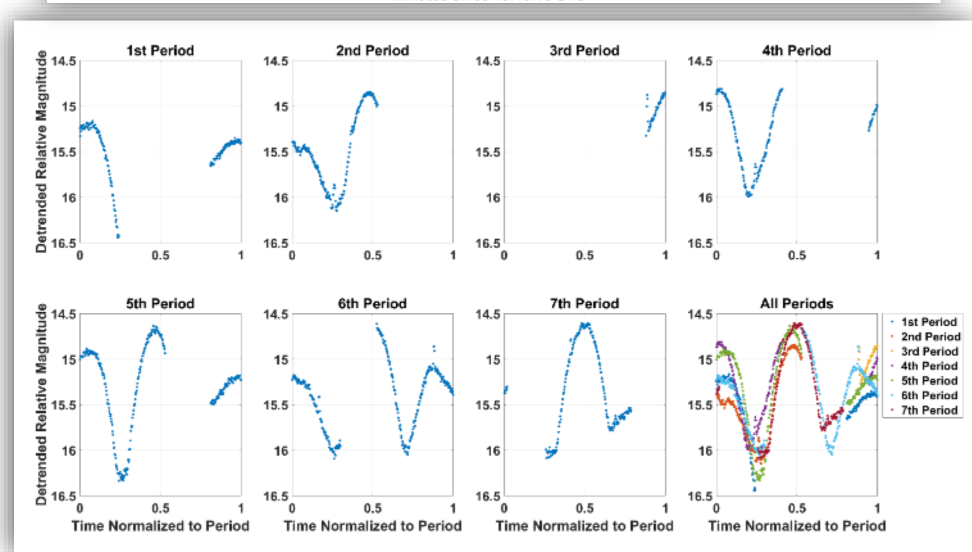
- Close encounter of asteroid: 2012-TC4
- Closest distance to Earth: ~44000 km (GEO altitude ~36000 km)
- Exposure time: 2s
- # of series: 7; # of images per series: ~200
- Total observation time: 140 minutes

Extracted Period: 735 ± 5 seconds
0.204 ± 0.001 hours

In agreement with [1-2-3]







[1] A. B. Sonka, A. I. Gornea, S. Anghel and M. Birlan, "Photometric Observations of Near Earth Asteroid 2012 TC4," *Romanian Astronomical Journal,* vol. 27, no. 3, pp. 223-231, 12 2017.

[2] C. E. Odden, J. C. Verhaegh, D. G. McCullough and J. W. Briggs, "Lightcurve Analysis for Near-Earth Asteroid 2012 TC4," *The Minor Planet Bulletin,* vol. 40, no. 3, pp. 176-177, 2013.

[3] D. Polishook, "Fast Rotation of the NEA 2012 TC4 Indicates a Monolithic Structure," *The Minor Planet Bulletin,* vol. 30, no. 1, pp. 42-43, 2013.