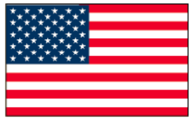
Federal Agency for
Cartography and Geodesy

SLR tracking of GNSS constellations – Many synergies to be explored

Daniela Thaller

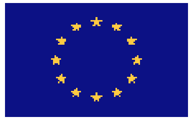
SLR tracking of GNSS

- 4 Global Navigation Satellite Systems are operating:



  - GPS

  - GLONASS



  - Galileo

  - BeiDou
- Additionally: regional systems (e.g., QZSS, IRNS)
- All satellites are equipped with laser retro-reflector arrays (except for actual GPS)

⇒ Around 70 satellites available to track

Tracking Data:
ILRS tracking list

As of Oct 31, 2018 from https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_missions/current_missions/index.html

GPS:

None of 32

GLONASS:

8 of 24 (others optional)

Galileo:

4 of 4 IOV

20 of 22 FOC

BeiDou/Compass:

9 of 17

BeiDou-3M2	1706902	2014	43002	9	300	21,500	55	2018-Aug-04
BeiDou-3M3	1801802	2015	43208	9	300	21,500	55	2018-Aug-10
BeiDou-3M9	1802901	2019	43245	9	300	21,500	55	2018-Aug-04
BeiDou-3M10	1802902	2020	43246	9	300	21,500	55	2018-Aug-03
COMPASS-G1	1000101	2002	36287	9	300	35,786	55.5	2012-Apr-28
COMPASS-I3	1101301	2003	37384	9	300	35,786	55.5	2012-Apr-27
COMPASS-I5	1107301	2005	37948	9	300	35,786	55.5	2012-Jul-06
COMPASS-I6B	1602101	2012	41434	9	300	35,677	55.5	2016-Mar-29
COMPASS-M3	1201801	2004	38250	9	300	21,528	55.0	2012-Jul-11
Cryosat-2	1001301	8006	36508	3	15	720	92	2010-Apr-20
Etalon-1	8900103	0525	19751	9	300	19,105	65	1989-Jan-26
Etalon-2	8903903	4146	20026	9	300	19,135	65	1989-Jul-13
Galileo-101	1106001	7101	37846	9	300	23,220	56	2011-Nov-29
Galileo-102	1106002	7102	37847	9	300	23,220	56	2011-Nov-29
Galileo-103	1205501	7103	38857	9	300	23,220	56	2012-Nov-07
Galileo-104	1205502	7104	38858	9	300	23,220	56	2012-Nov-07
Galileo-201	1405001	7201	40128	9	300	17,000 - 26,210	~ 50	2014-Dec-05
Galileo-202	1405002	7202	40129	9	300	17,000 - 26,210	~ 50	2015-Mar-17
Galileo-203	1501701	7203	40544	9	300	23,220	56 +/- 2 deg	2015-Mar-27
Galileo-204	1501702	7204	40545	9	300	23,220	56 +/- 2 deg	2015-Mar-27
Galileo-205	1504501	7205	40889	9	300	23,220	56 +/- 2 deg	2015-Sep-11
Galileo-206	1504502	7206	40890	9	300	23,220	56 +/- 2 deg	2015-Sep-11
Galileo-207	1606901	7207	41859	9	300	23,220	56 +/- 2 deg	2017-Feb-16
Galileo-208	1507902	7208	41175	9	300	23,220	56 +/- 2 deg	2015-Dec-17
Galileo-209	1507901	7209	41174	9	300	23,220	56 +/- 2 deg	2015-Dec-17
Galileo-210	1603002	7210	41550	9	300	23,220	56 +/- 2 deg	2016-Jun-12
Galileo-211	1603001	7211	41549	9	300	23,220	56 +/- 2 deg	2016-Jun-12
Galileo-212	1606902	7212	41860	9	300	23,220	56 +/- 2 deg	2017-Feb-20
Galileo-213	1606903	7213	41861	9	300	23,220	56 +/- 2 deg	2017-Feb-20
Galileo-214	1606904	7214	41862	9	300	23,220	56 +/- 2 deg	2017-Feb-20
Galileo-215	1707901	7215	43055	9	300	23,220	56 +/- 2 deg	2018-Apr-17
Galileo-216	1707902	7216	43056	9	300	23,220	56 +/- 2 deg	2018-Apr-18
Galileo-217	1707903	7217	43057	9	300	23,220	56 +/- 2 deg	2018-Apr-19
Galileo-218	1707904	7218	43058	9	300	23,220	56 +/- 2 deg	2018-Apr-19
Galileo-219	1806003	7219	43566	9	300	23,220	56 +/- 2 deg	2018-10-17
Galileo-220	1806004	7220	43567	9	300	23,220	56 +/- 2 deg	2018-10-16
Geo-IK-2	1603401	5561	41579	5	30	943.5 - 973.5	99.47	2017-Oct-18
GLONASS-128	1106401	9128	37867	9	300	19,140	65	2012-Jan-01
GLONASS-131	1301901	9131	39155	9	300	19,140	65	2013-May-23
GLONASS-132	1401201	9132	39620	9	300	19,140	65	2014-Apr-17
GLONASS-133	1403201	9133	40001	9	300	19,140	65	2014-Jun-14
GLONASS-134	1407501	9134	40315	9	300	19,140	65	2014-Dec-30
GLONASS-135	1600801	9135	41330	9	300	19,140	65	2016-Mar-01
GLONASS-136	1603201	9136	41554	9	300	19,140	65	2016-May-29
GLONASS-137	1705501	9137	42939	9	300	19,140	65	2017-Oct-16

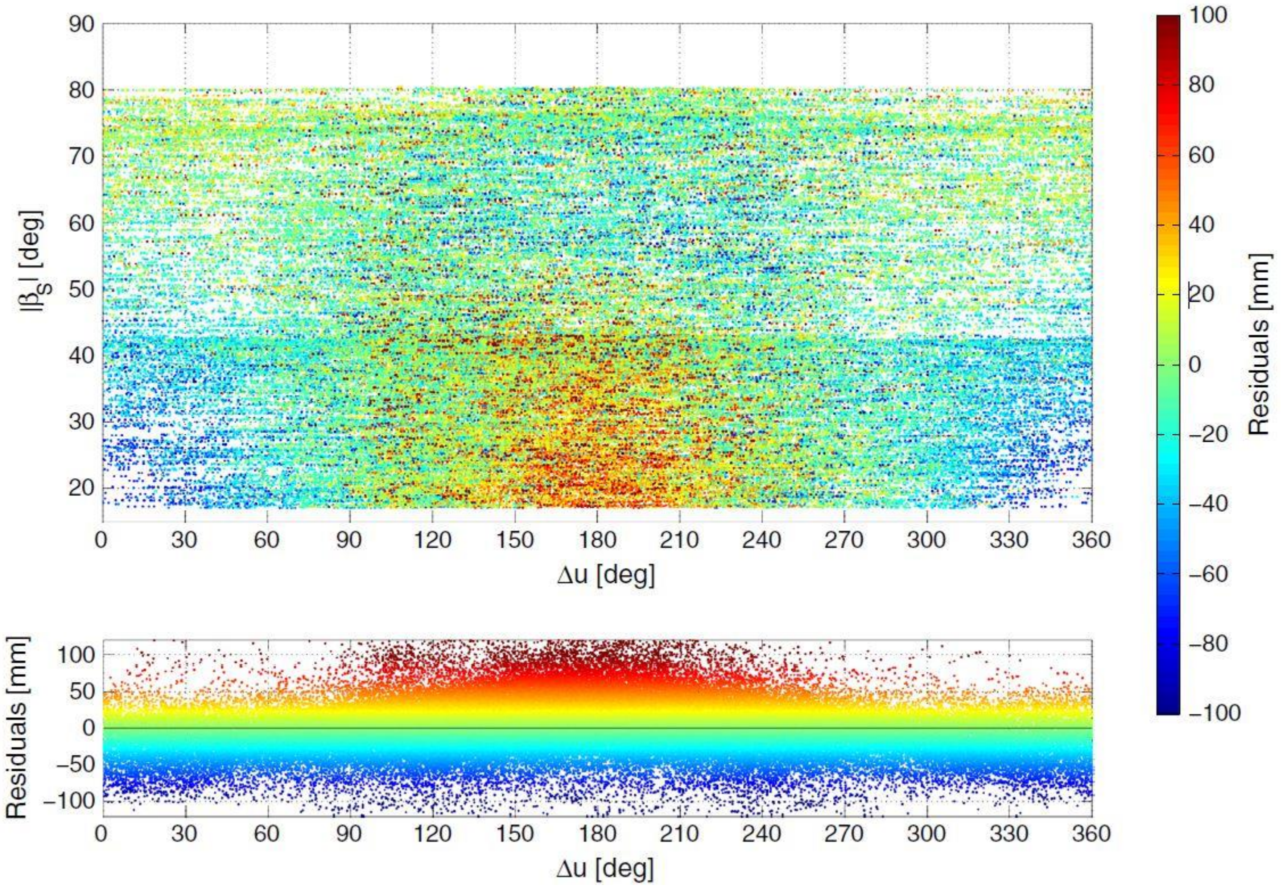
What applications do SLR tracking data to GNSS have?

- Validation of orbit modelling for GNSS
- Investigation of inconsistencies and biases between SLR and GNSS
- Validation of laser retro-reflector arrays
- Validation of microwave satellite antenna offsets
- Improvement of reference frame products

Others (not yet widely done; not shown hereafter):

- Estimation of GNSS orbits

Orbit model validation: GLONASS

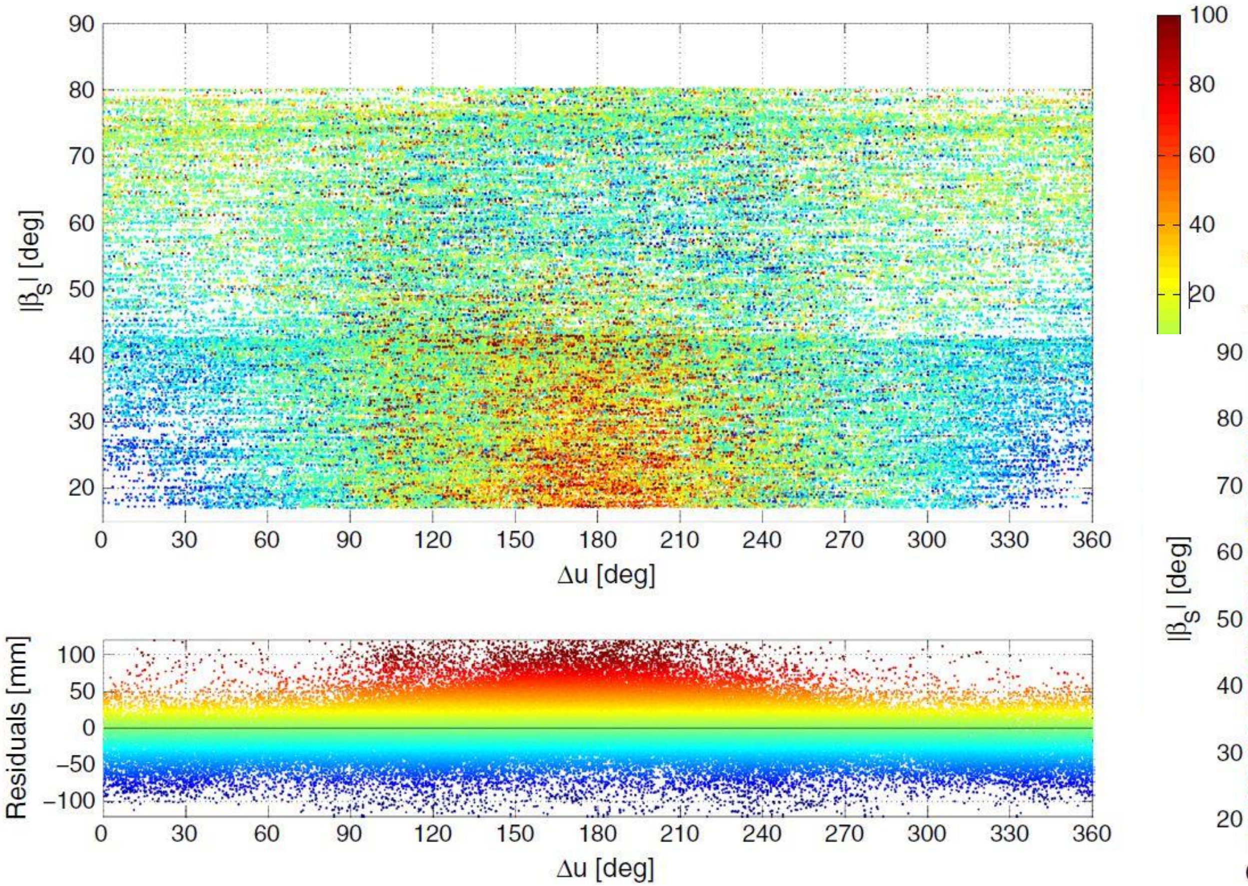


Old CODE orbit model

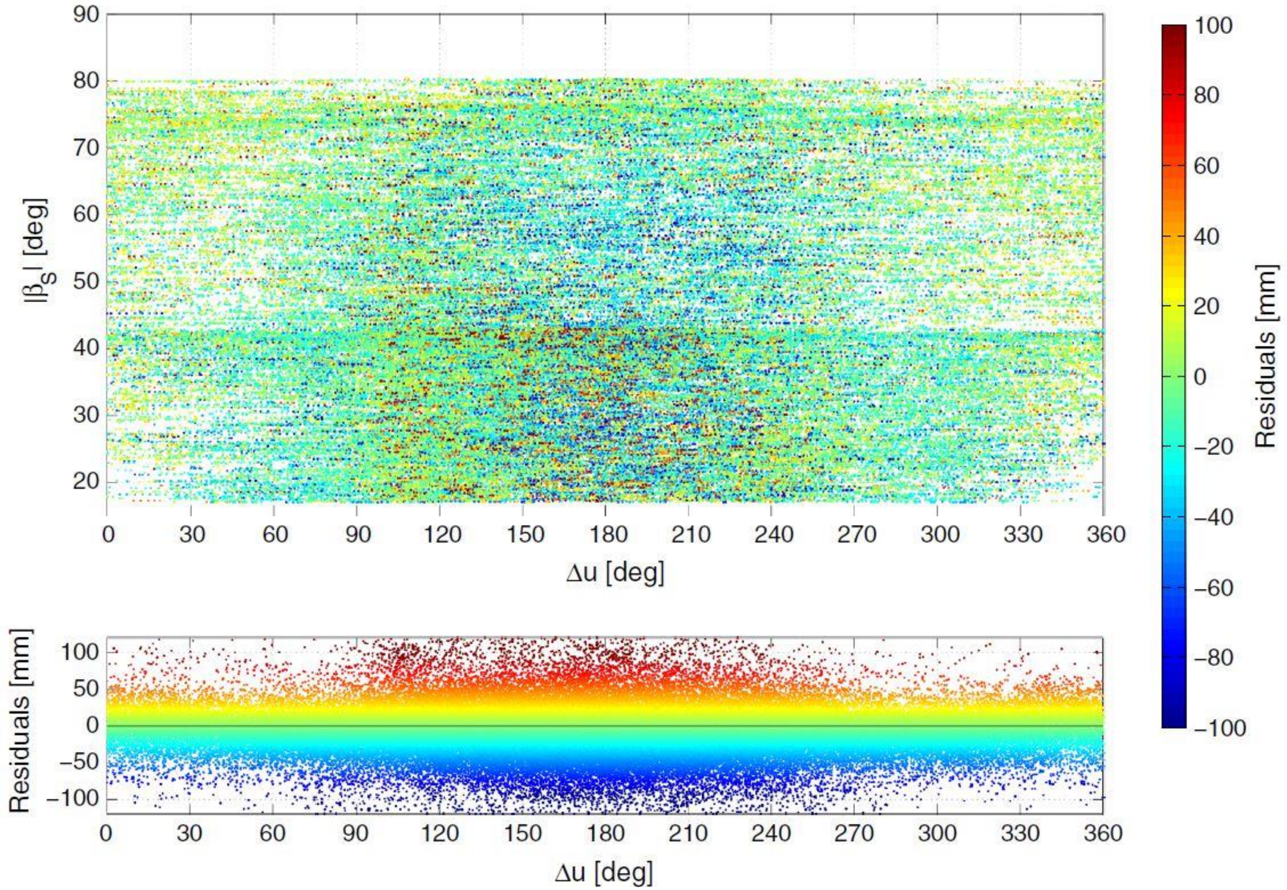
- Clear systematics due to deficiencies in modelling SRP (solar radiation pressure)

From Arnold et al. (2015)

Orbit model validation: GLONASS

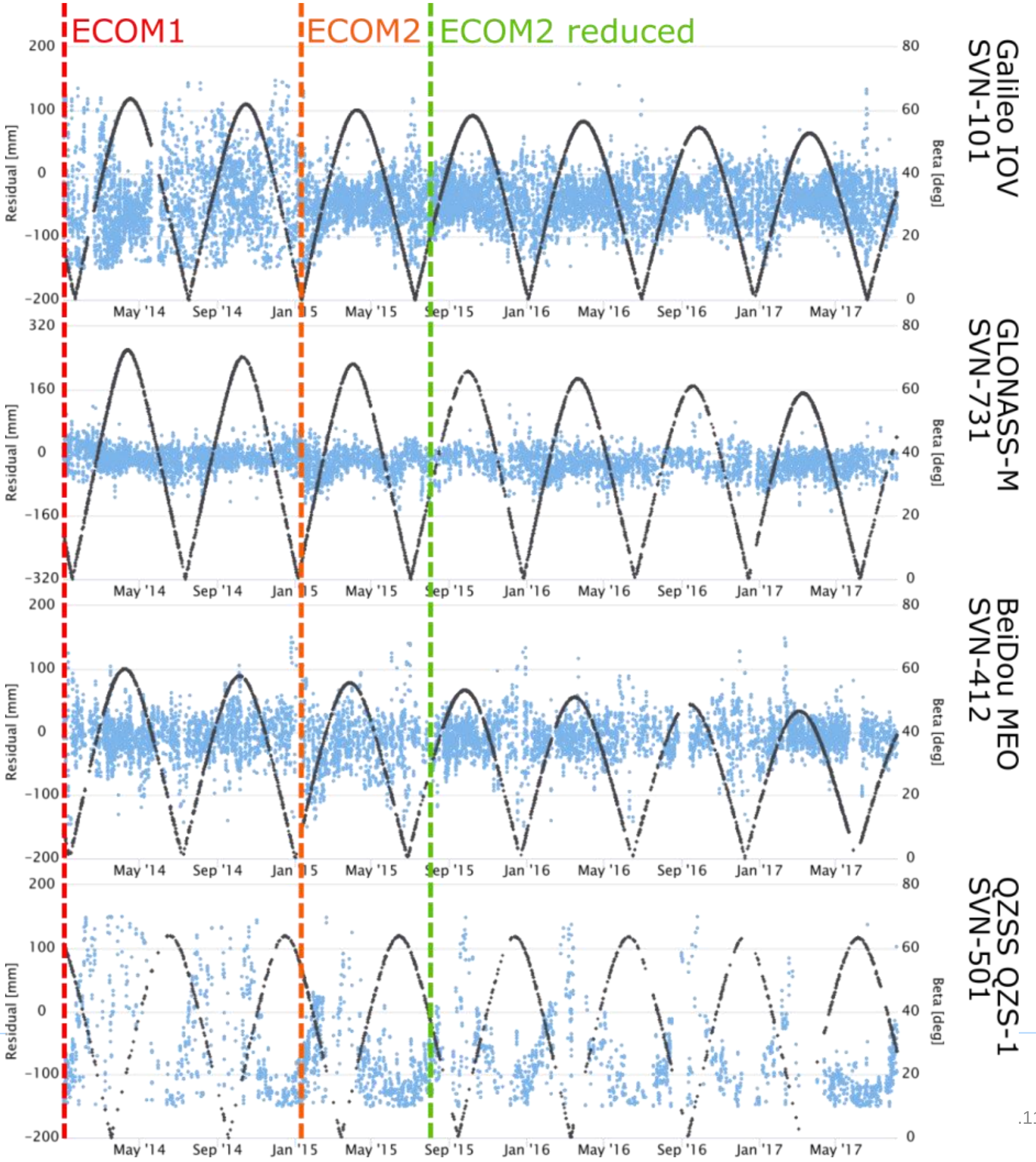


New CODE orbit model estimating twice-per-rev D terms



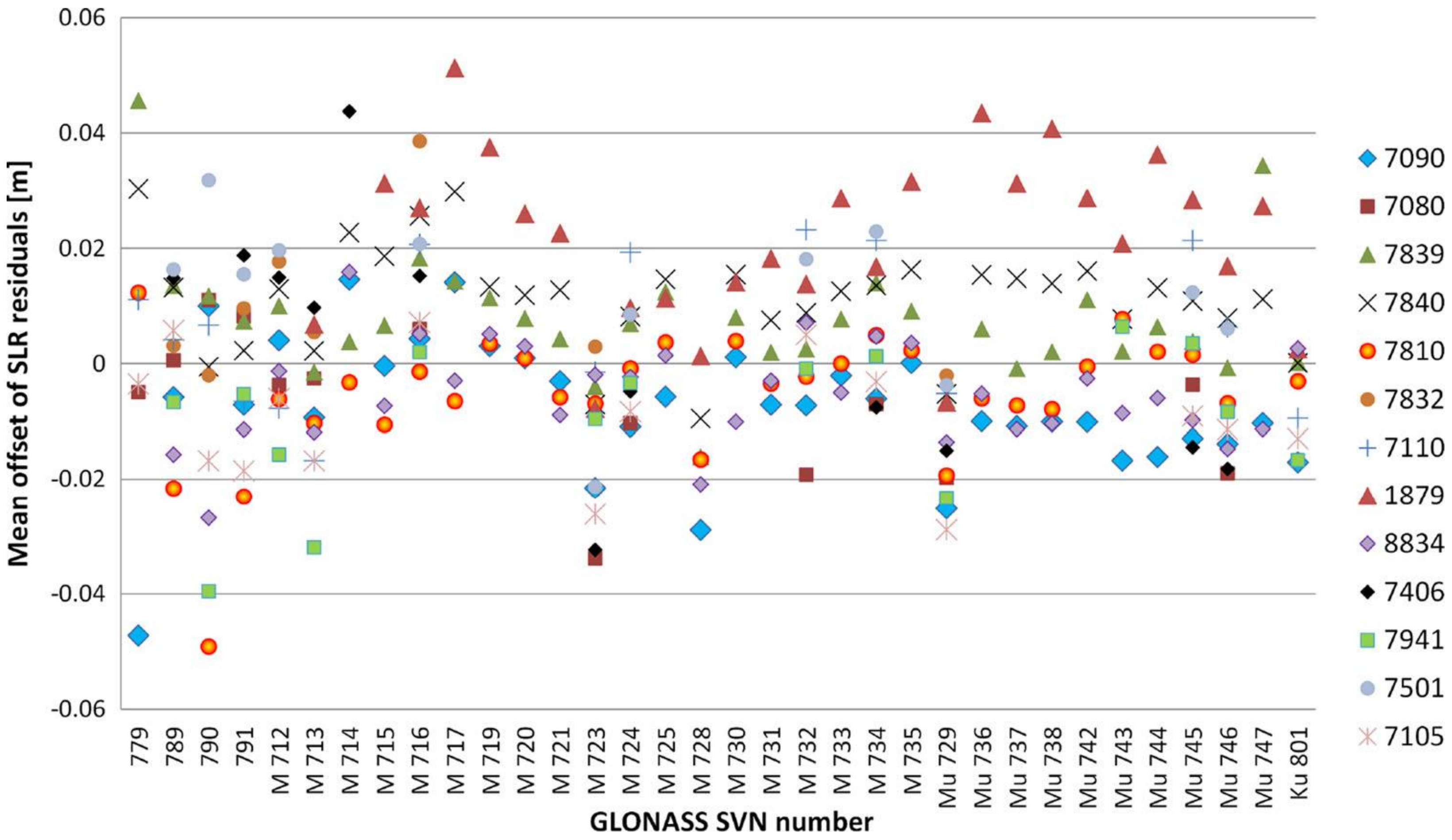
From Arnold et al. (2015)

Orbit model validation: All GNSS constellations



Provided by K. Sośnica: www.govus.pl

Inconsistencies and biases between SLR and GNSS



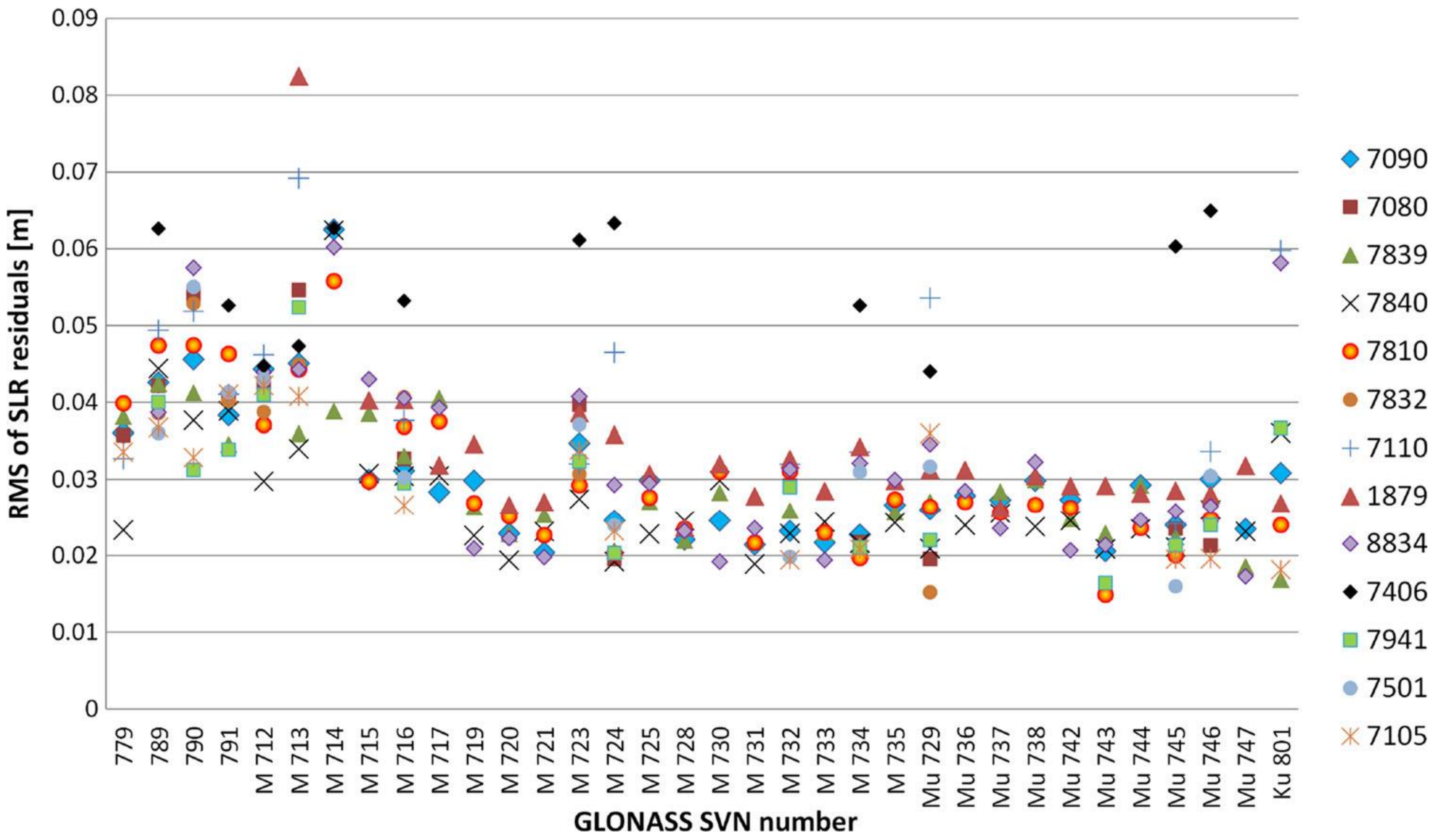
From Sośnica et al. (2015)

using GLONASS data from 2002 - 2013

- Mean values of SLR range residuals to GLONASS **vary between stations**
- Mean values are mostly within **+- 2 cm**

Federal Agency for Cartography and Geodesy

Inconsistencies and biases between SLR and GNSS



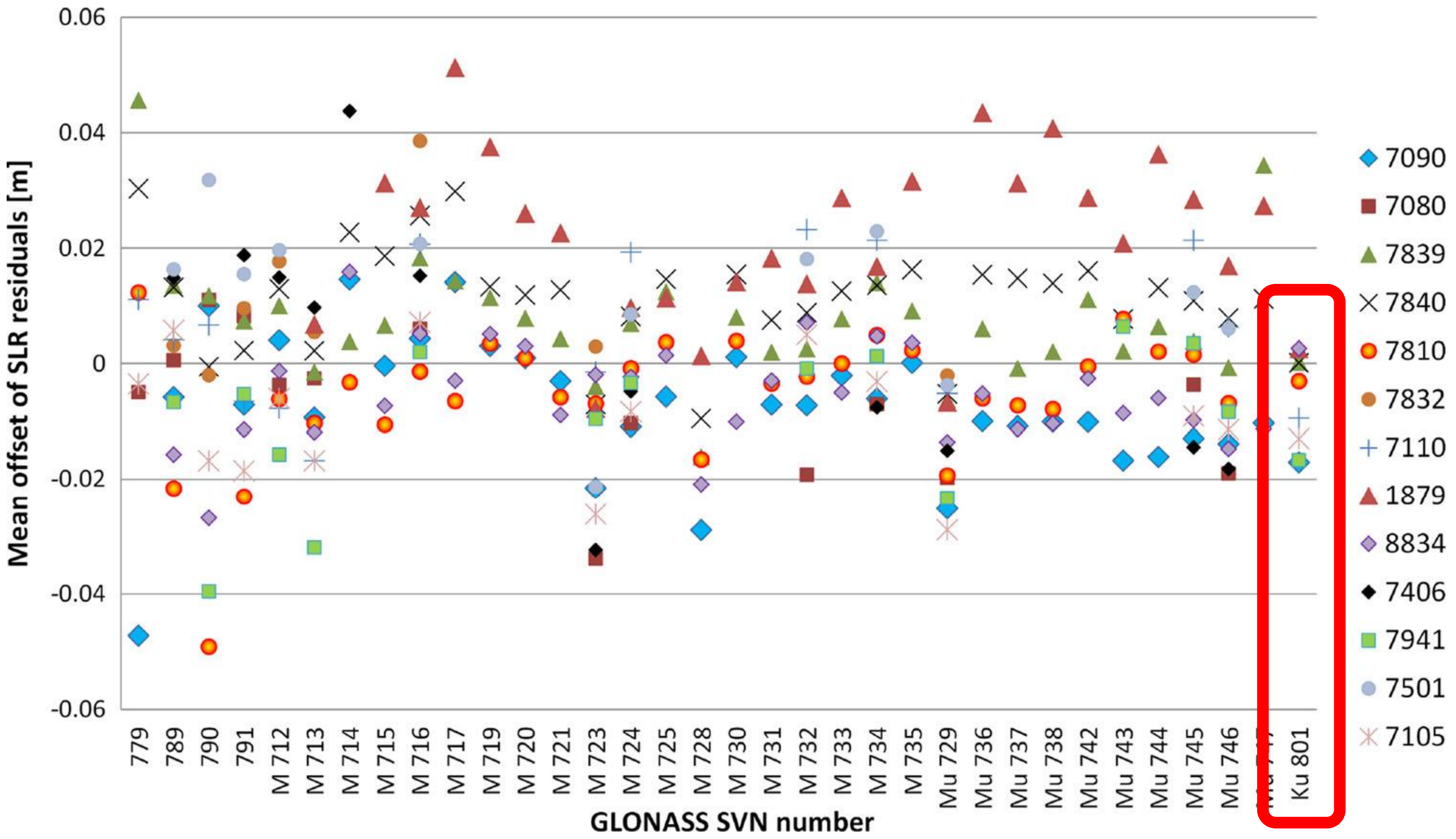
From Sośnica et al. (2015)

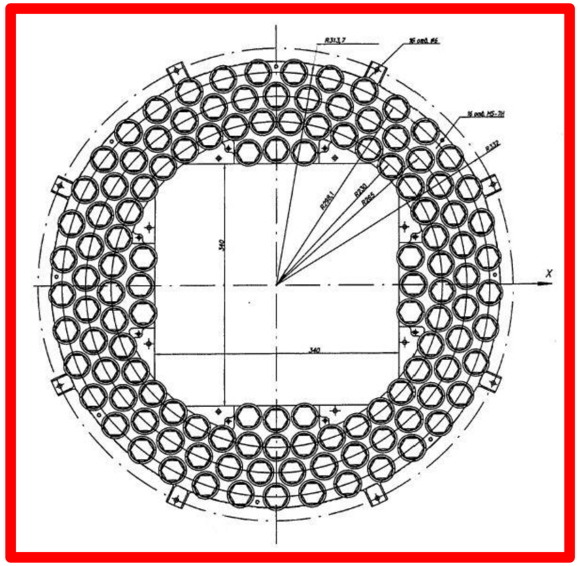
using GLONASS data from 2002 - 2013

- RMS of SLR range residuals to GLONASS are **similar for all stations**, but clearly **varies between satellites**
- RMS values are **2-3 cm** for best GLONASS, **3-5 cm** for older satellites

Federal Agency for Cartography and Geodesy

Laser retro-reflector array: Design

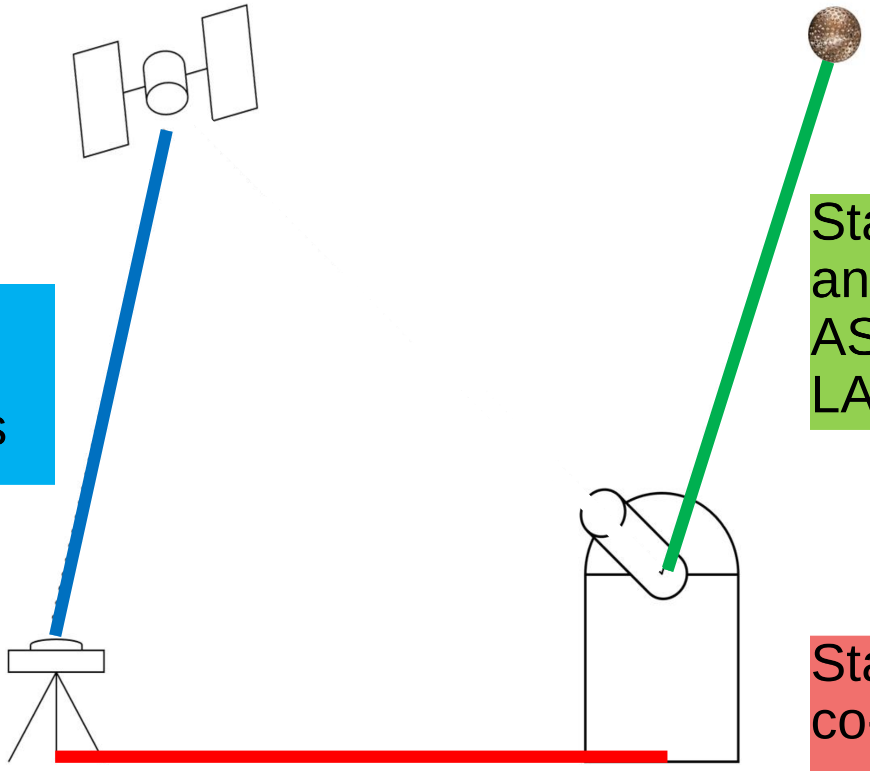




The design used for GLONASS K1 reduces the variability between stations

From Sośnica et al. (2015)

Current ITRF approach



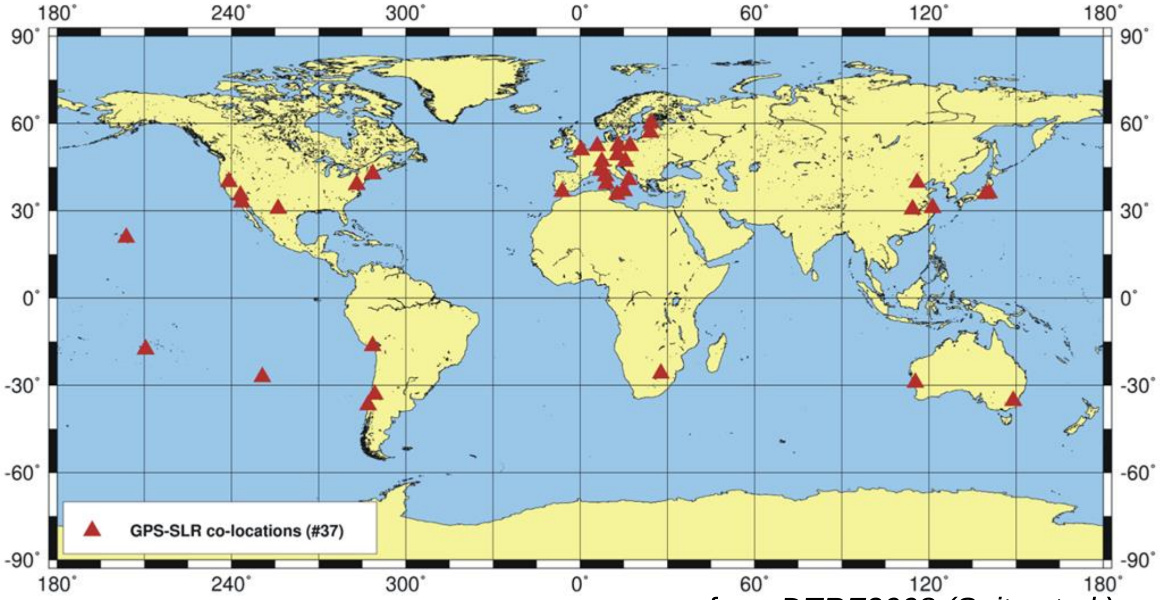
Standard GNSS analysis by IGS Analysis Centers

Standard SLR analysis by ILRS ASC based on LAGEOS / Etalon

Stations need to be co-located: Local ties

Current ITRF approach

Station co-locations are the major connection between GNSS and SLR



from DTRF2008 (Seitz et al.)

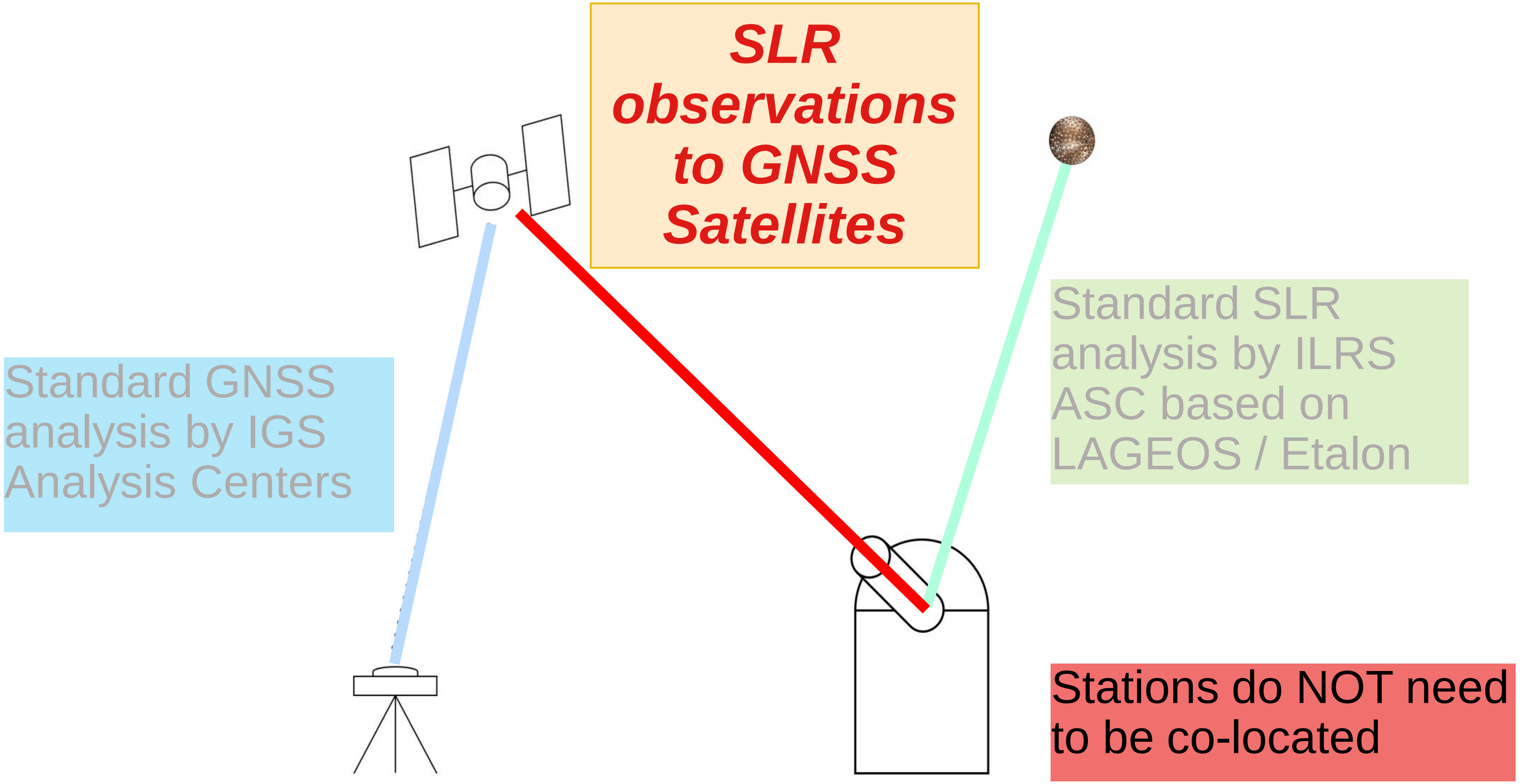
BUT:

- Only 37 co-locations
- Bad global distribution
- Issues with local ties

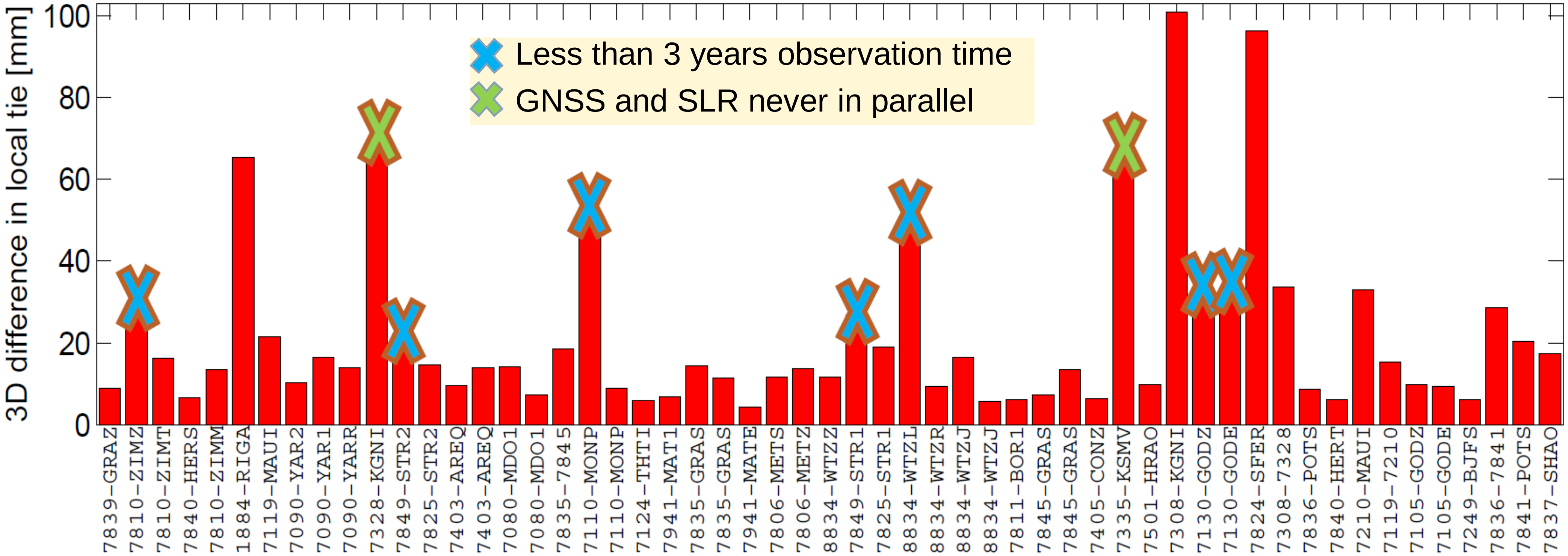
SLR observations to **other than LAGEOS/Etalon satellites** are ignored

Federal Agency for Cartography and Geodesy

Extended approach using satellite co-locations of SLR and GNSS at GNSS satellites



Validation of local ties within GNSS-SLR combined solutions

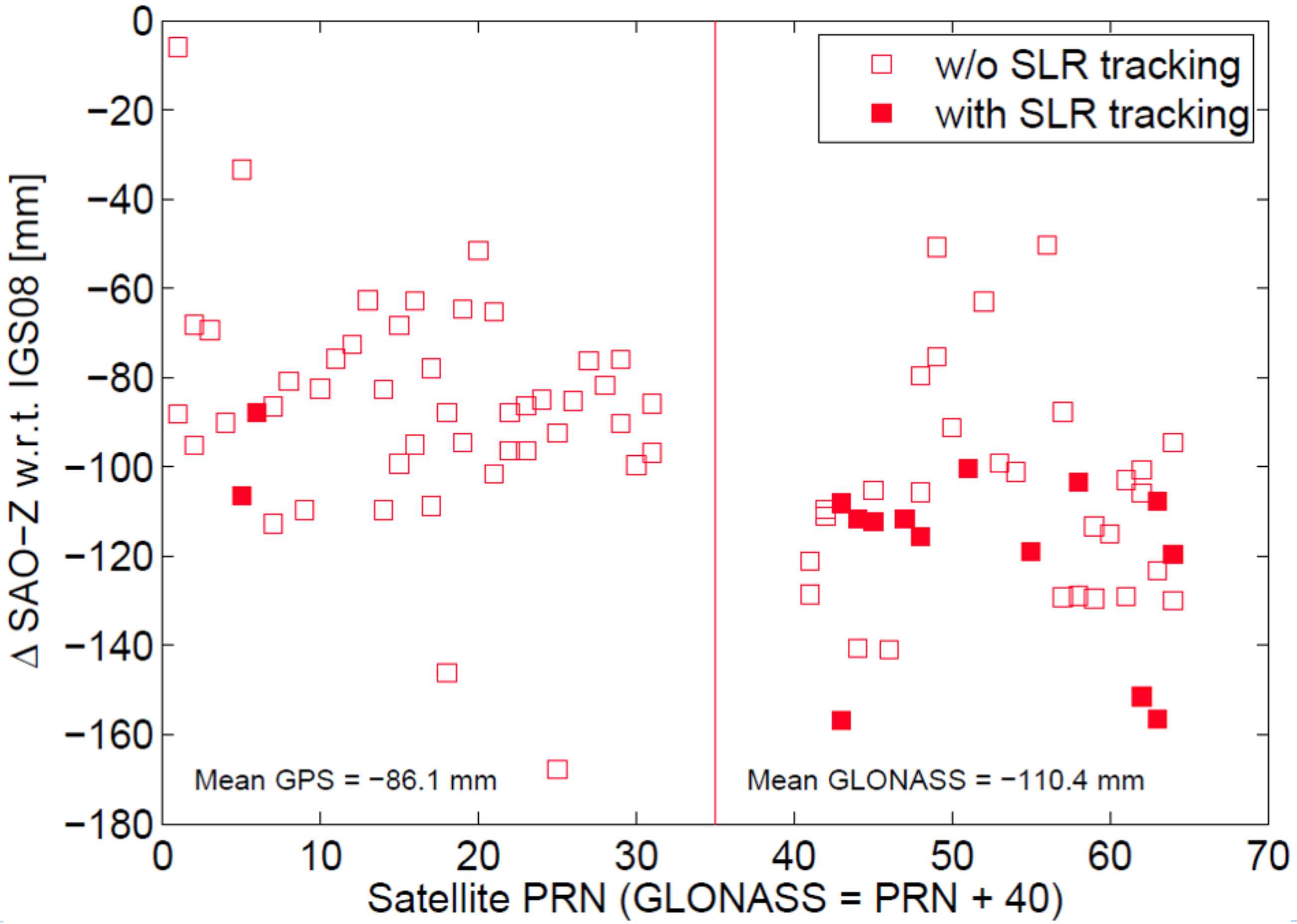


3-D agreement:

0 mm < Δ ≤ 10 mm	17 co-locations
10 mm < Δ ≤ 20 mm	13 co-locations
20 mm < Δ ≤ 30 mm	5 co-locations
30 mm < Δ	15 co-locations

From Thaller et al. (2015)

Microwave antenna offsets:
Estimation within combined SLR-GNSS solution



From Thaller et al. (2015)

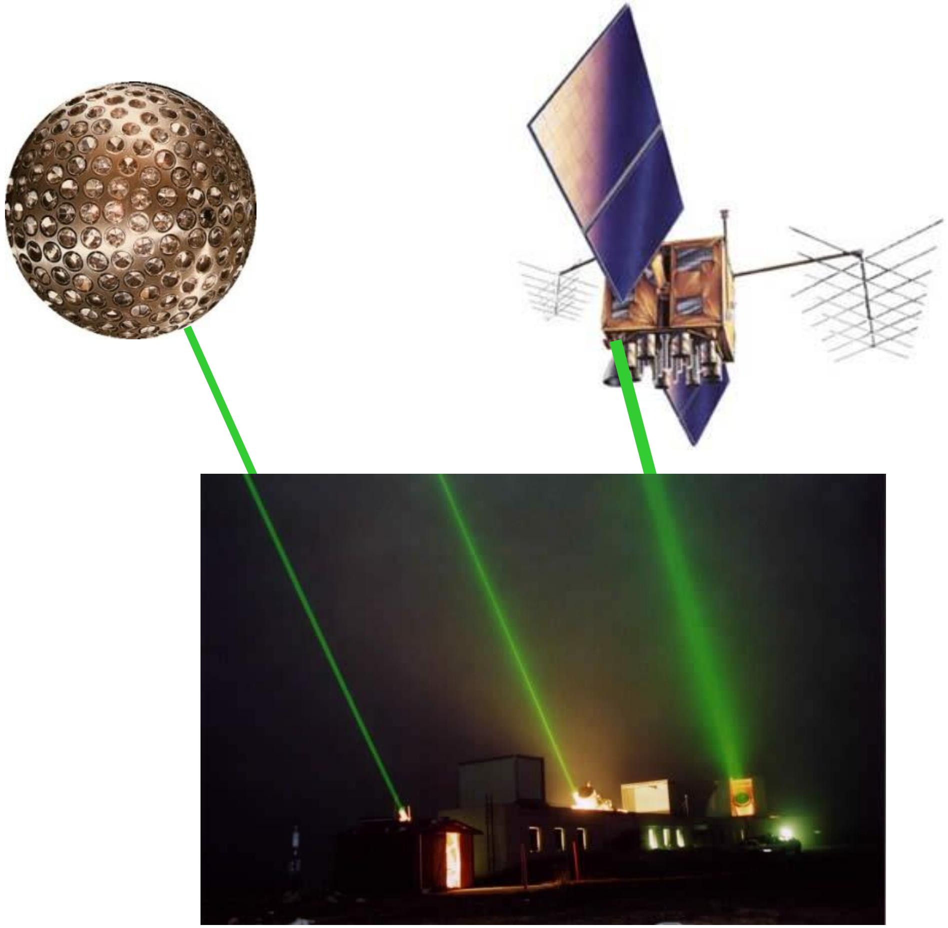
using GPS + GLONASS data for 2002.0 – 2014.0

Microwave antenna offsets can be estimated **consistently with the SLR scale**

Summary

- Many SLR tracking data of the GNSS constellations are available
- SLR tracking has proven to be valueable for orbit validation since many years
- Inconsistencies / biases between SLR and GNSS have to be determined and understood
- Satellite co-locations provide an additional connection to strengthen inter-technique combination
- More data from space-geodetic stations can be included in reference frame computation

Thank you for your kind attention!

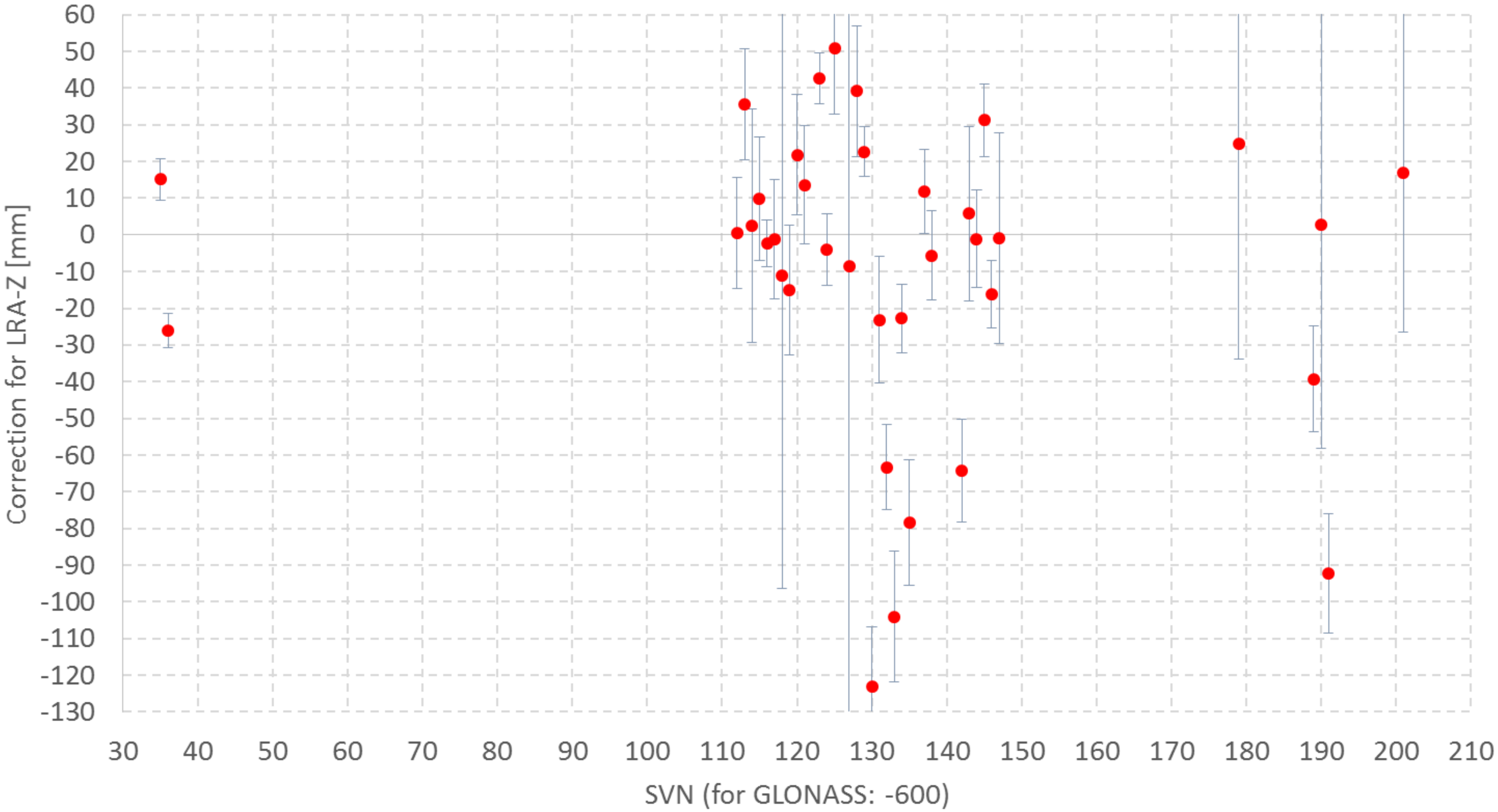


Contact:

Federal Agency for Cartography and Geodesy
Section G1
Richard-Strauss-Allee 11
60598 Frankfurt, Germany

contact person:
Daniela Thaller
daniela.thaller@bkg.bund.de
www.bkg.bund.de
Tel. +49 (0) 69 6333-273

Laser retro-reflector array offsets: Estimation within combined SLR-GNSS solution

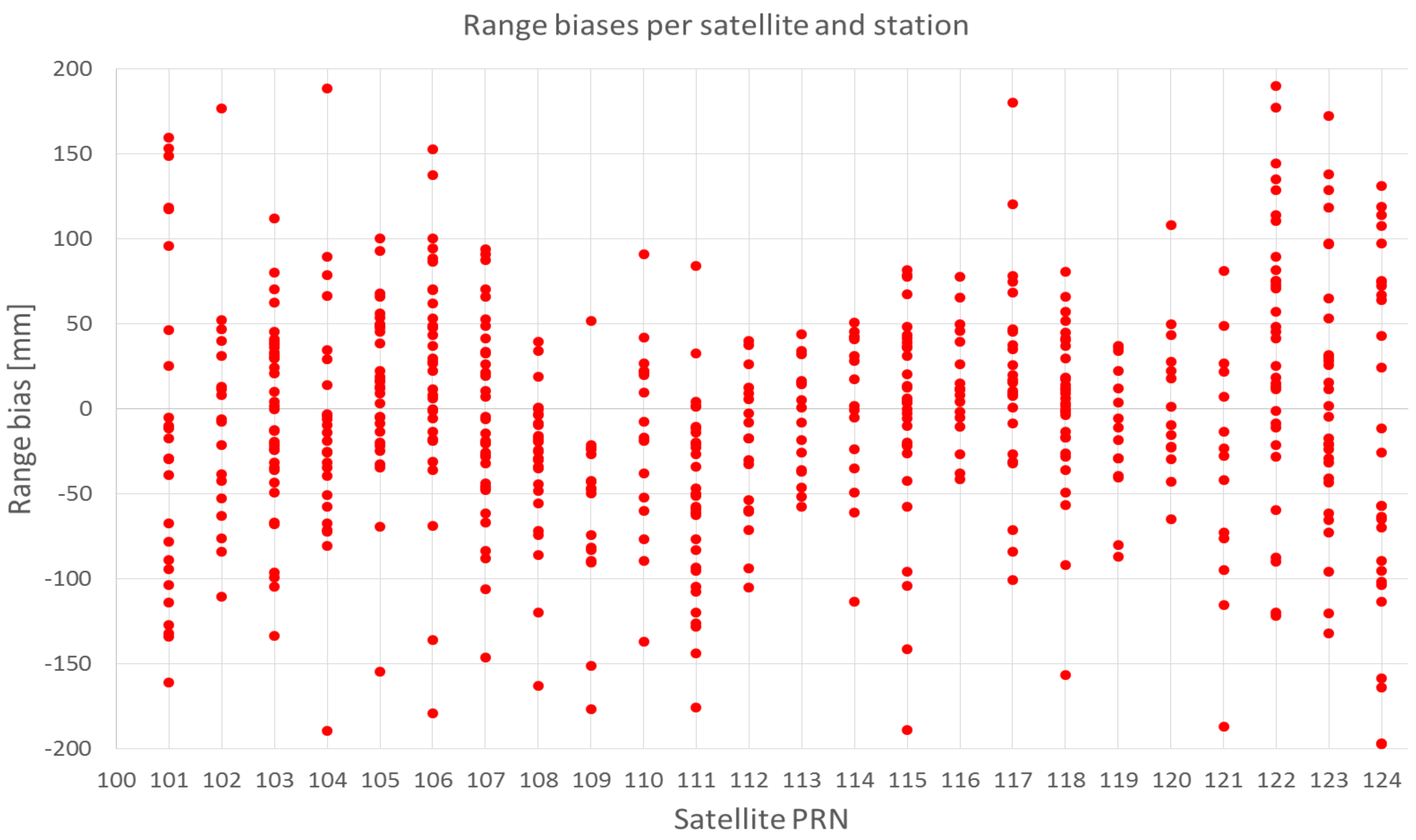


Mean GPS = -5.5 mm

Mean GLONASS = -6.6 mm

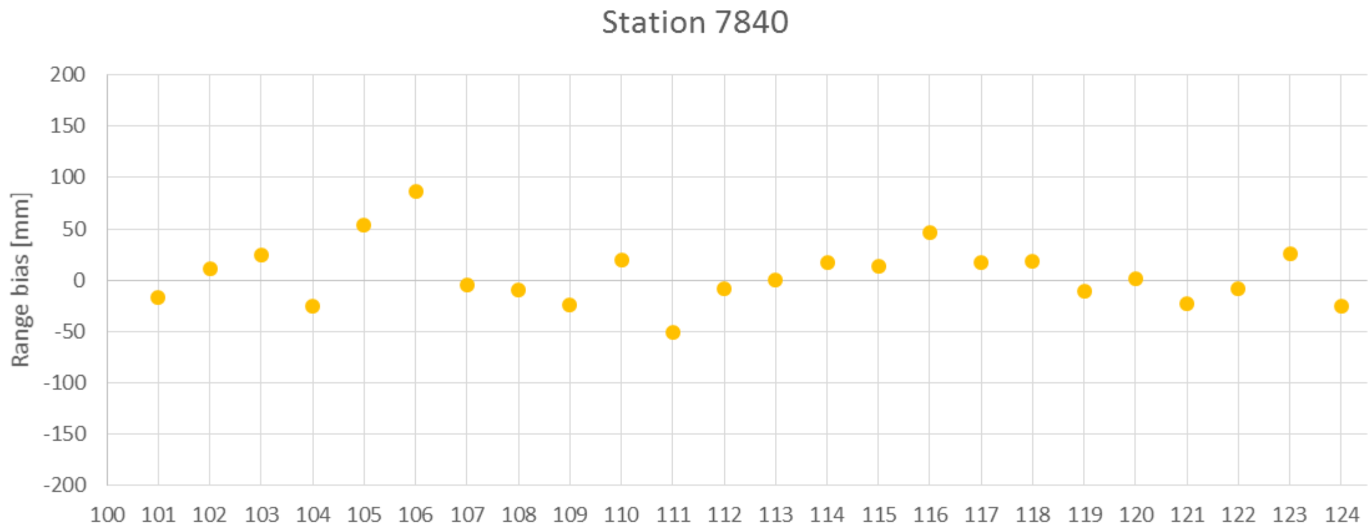
Federal Agency for Cartography and Geodesy

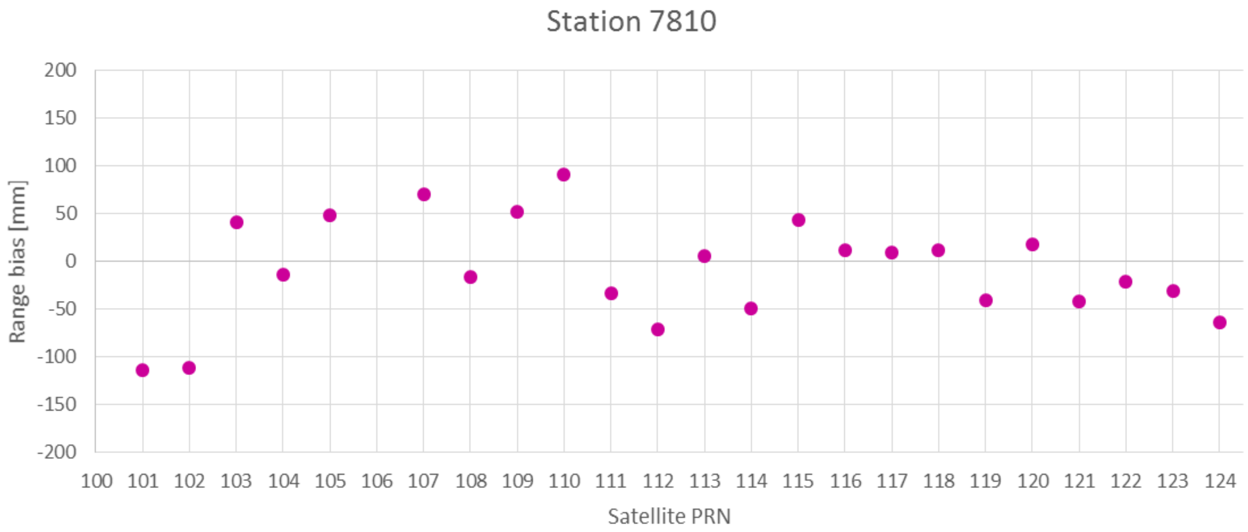
Range biases



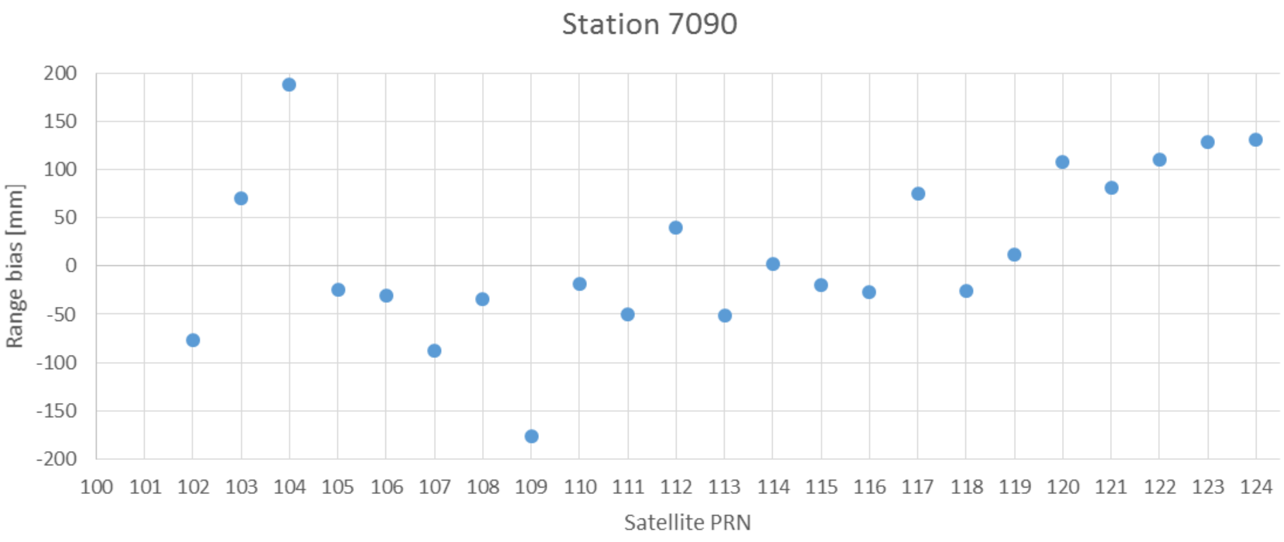
Federal Agency for Cartography and Geodesy

Range biases

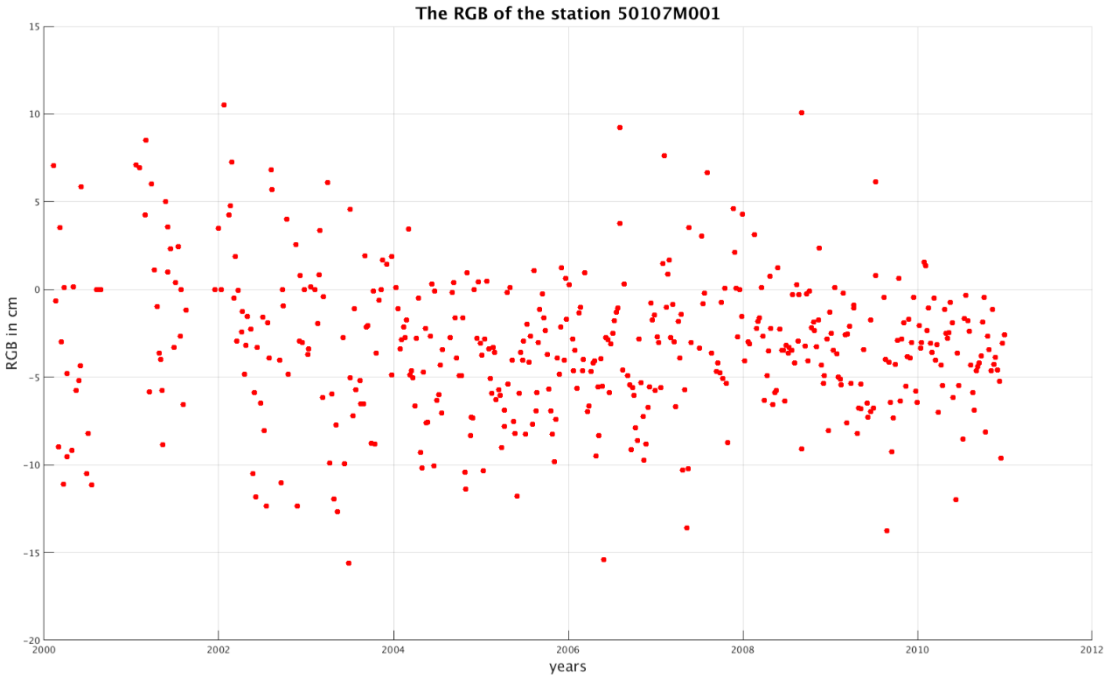




Range biases



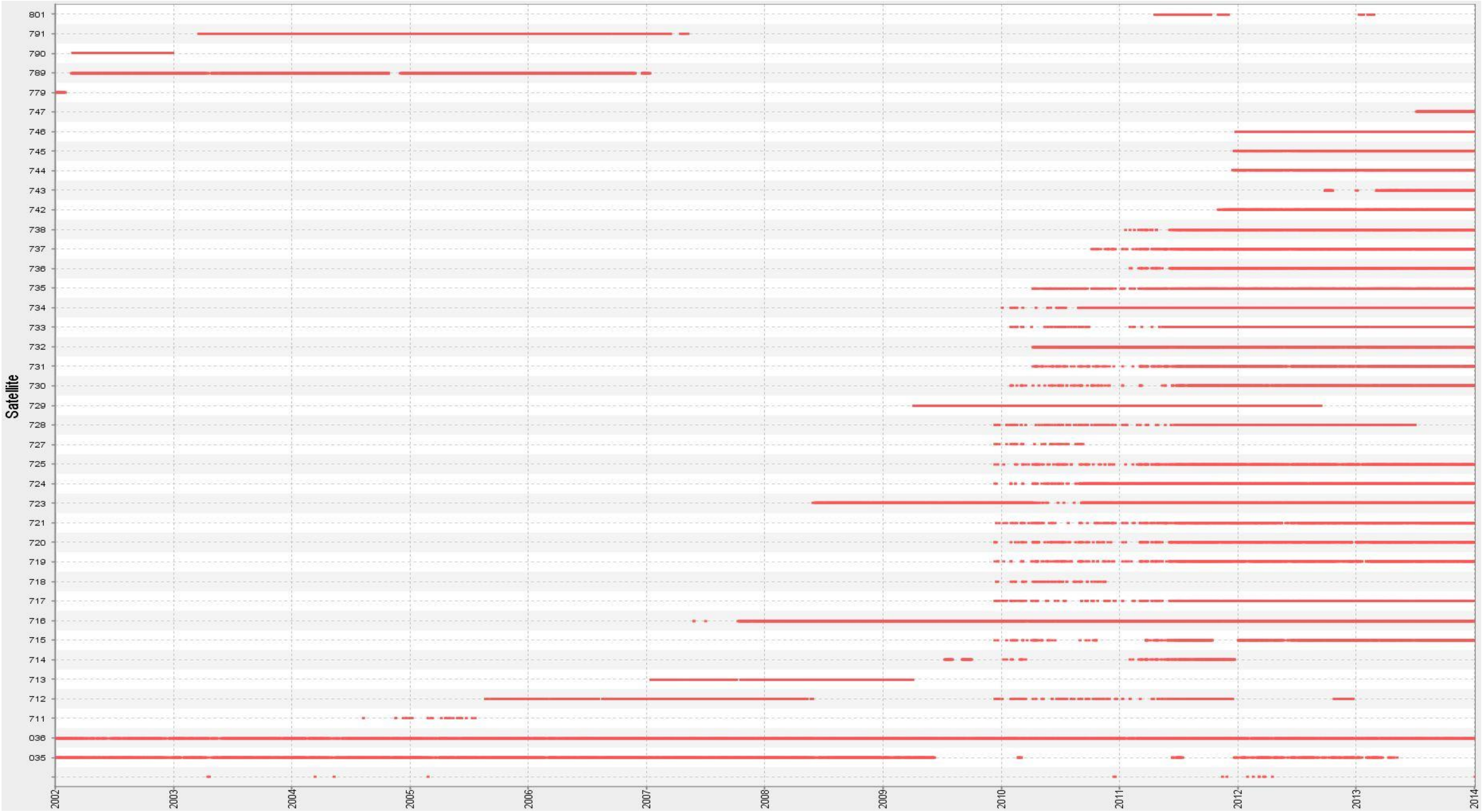
RGB Bestimmung der 7090 Station (Yarragadee, Australien) (Szenarium II)



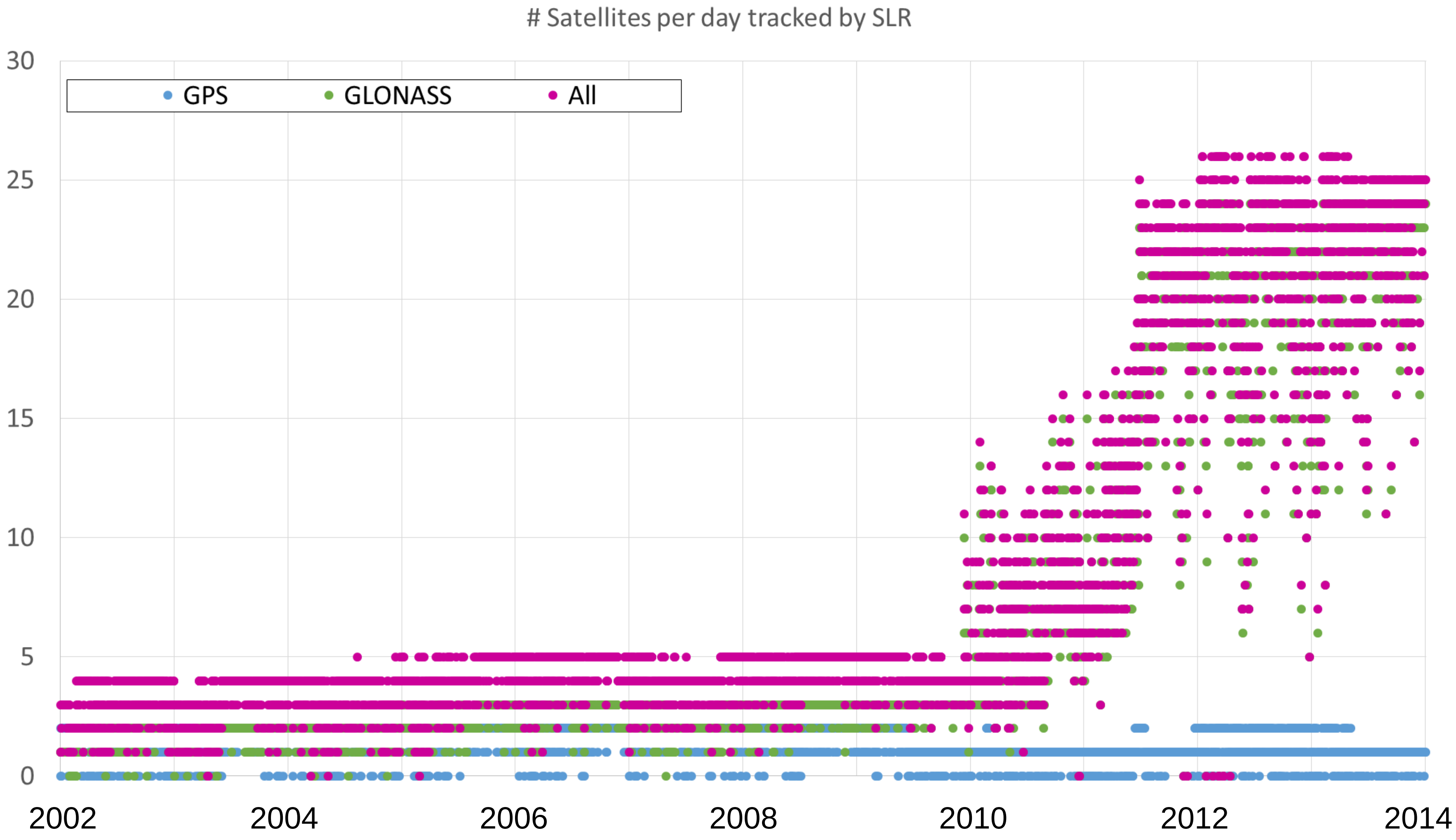
min	=	-151.1	mm
max	=	105.2	mm
mean	=	-32.4	mm
std	=	43.8	mm

Federal Agency for Cartography and Geodesy

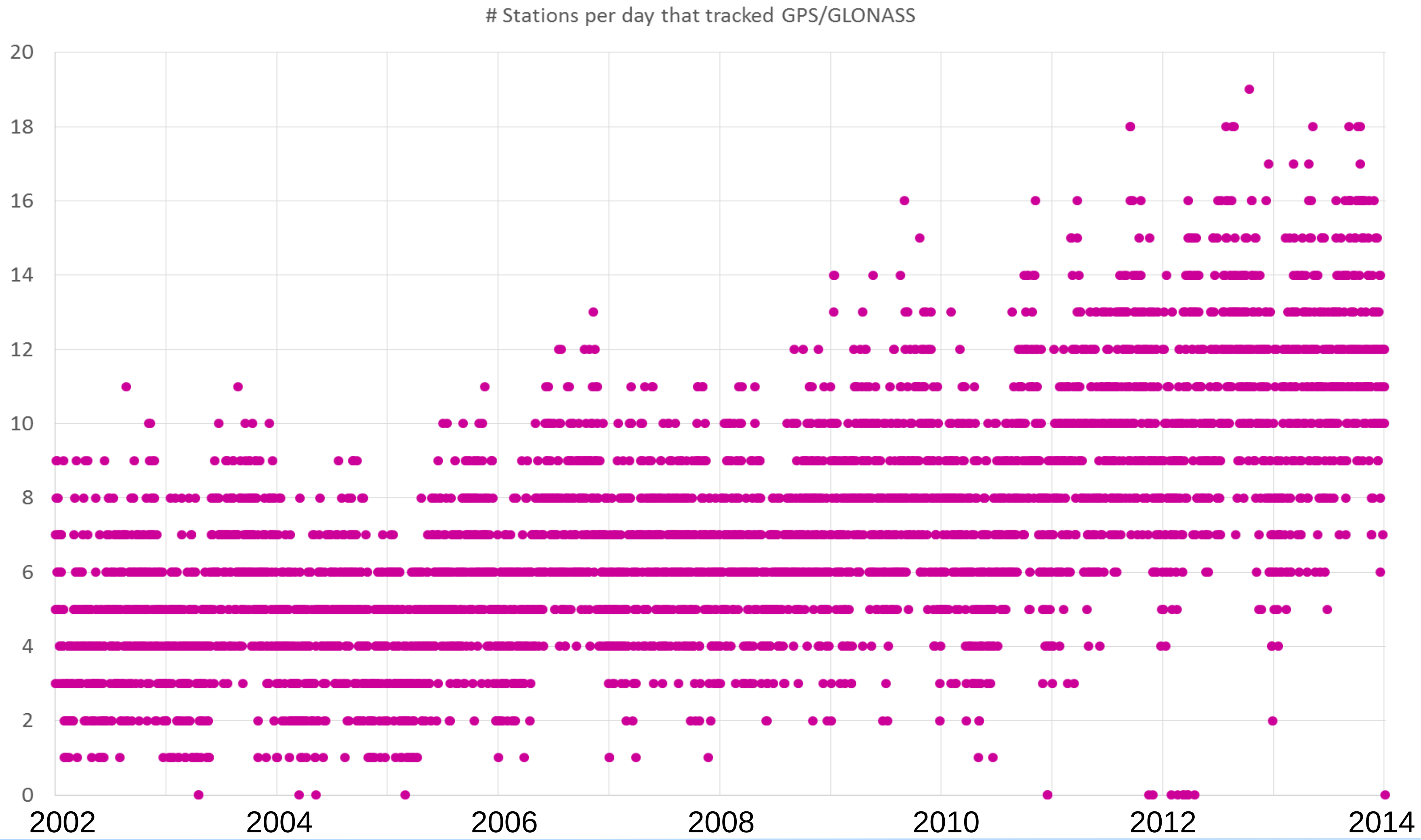
SLR tracking of GNSS



GNSS satellite co-locations

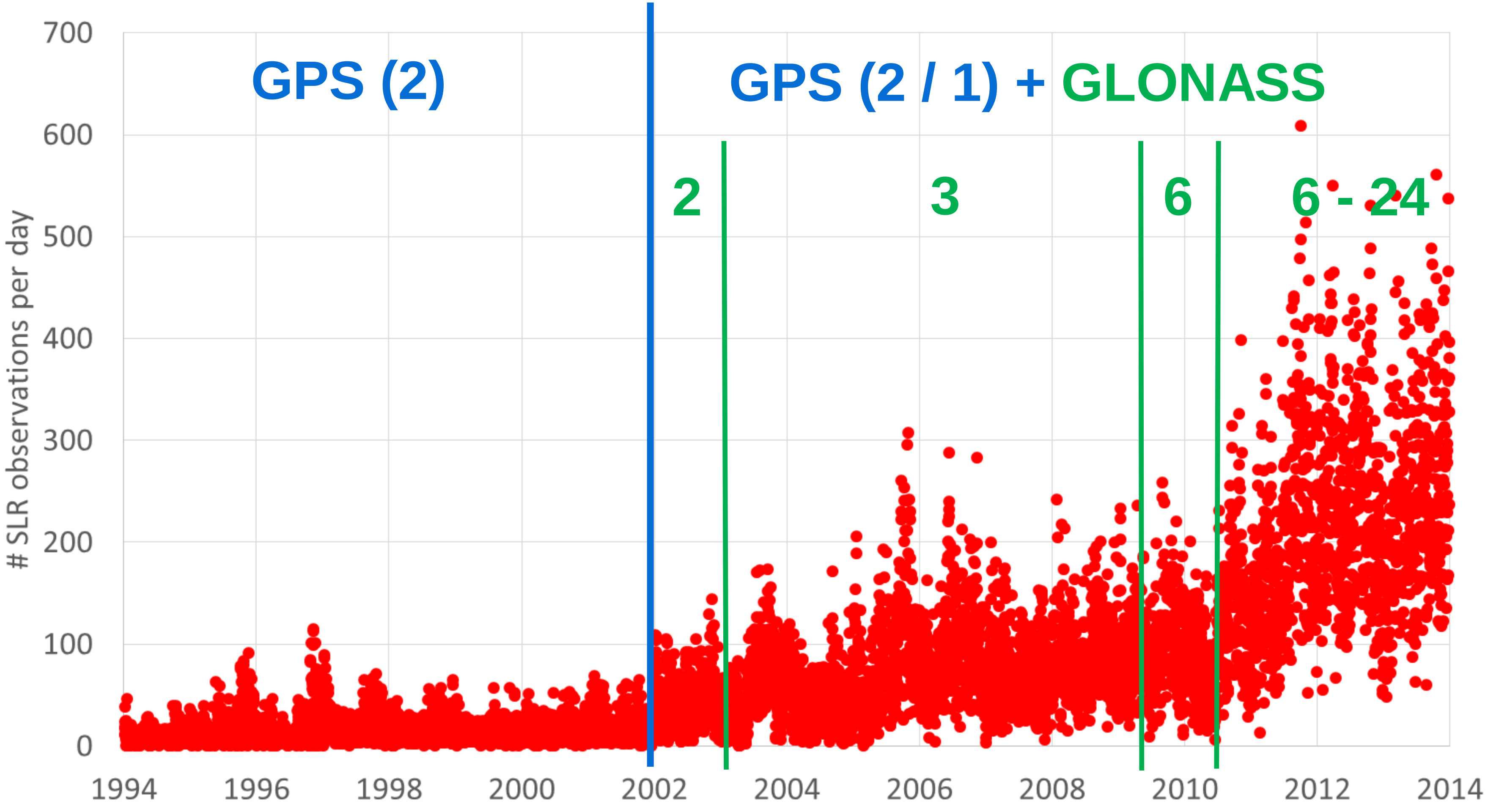


GNSS satellite co-locations

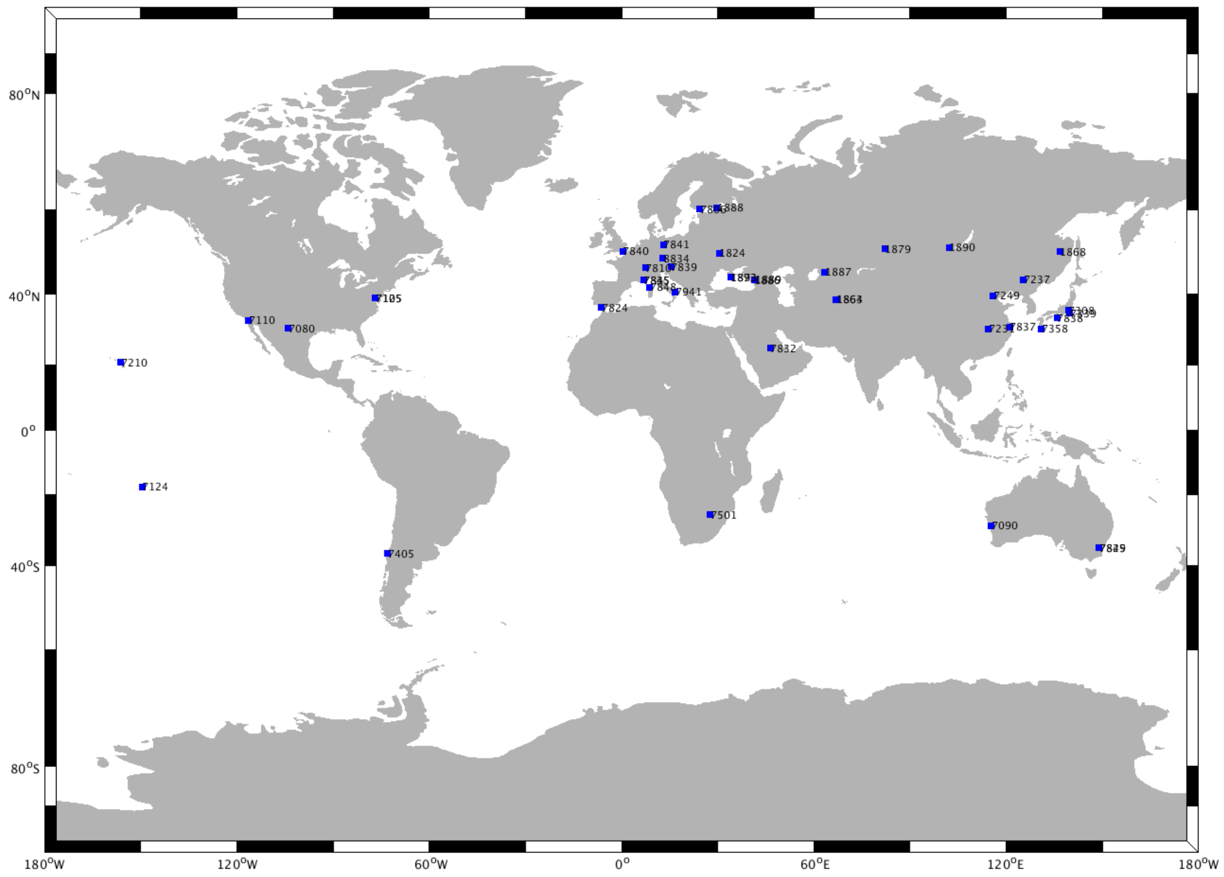


Federal Agency for Cartography and Geodesy

GNSS satellite co-locations

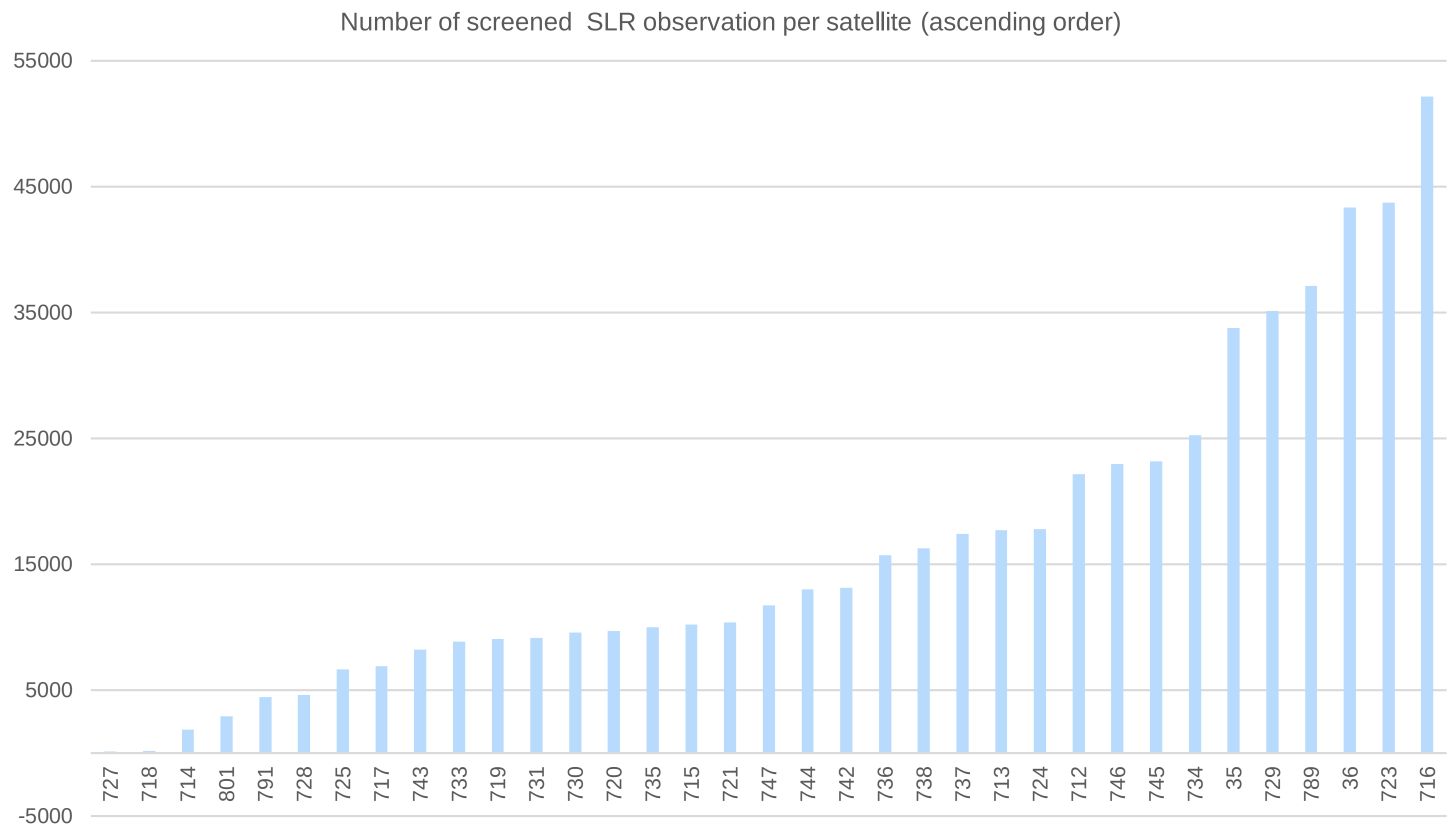


SLR@GNSS globales Netzwerk



Federal Agency for
Cartography and Geodesy

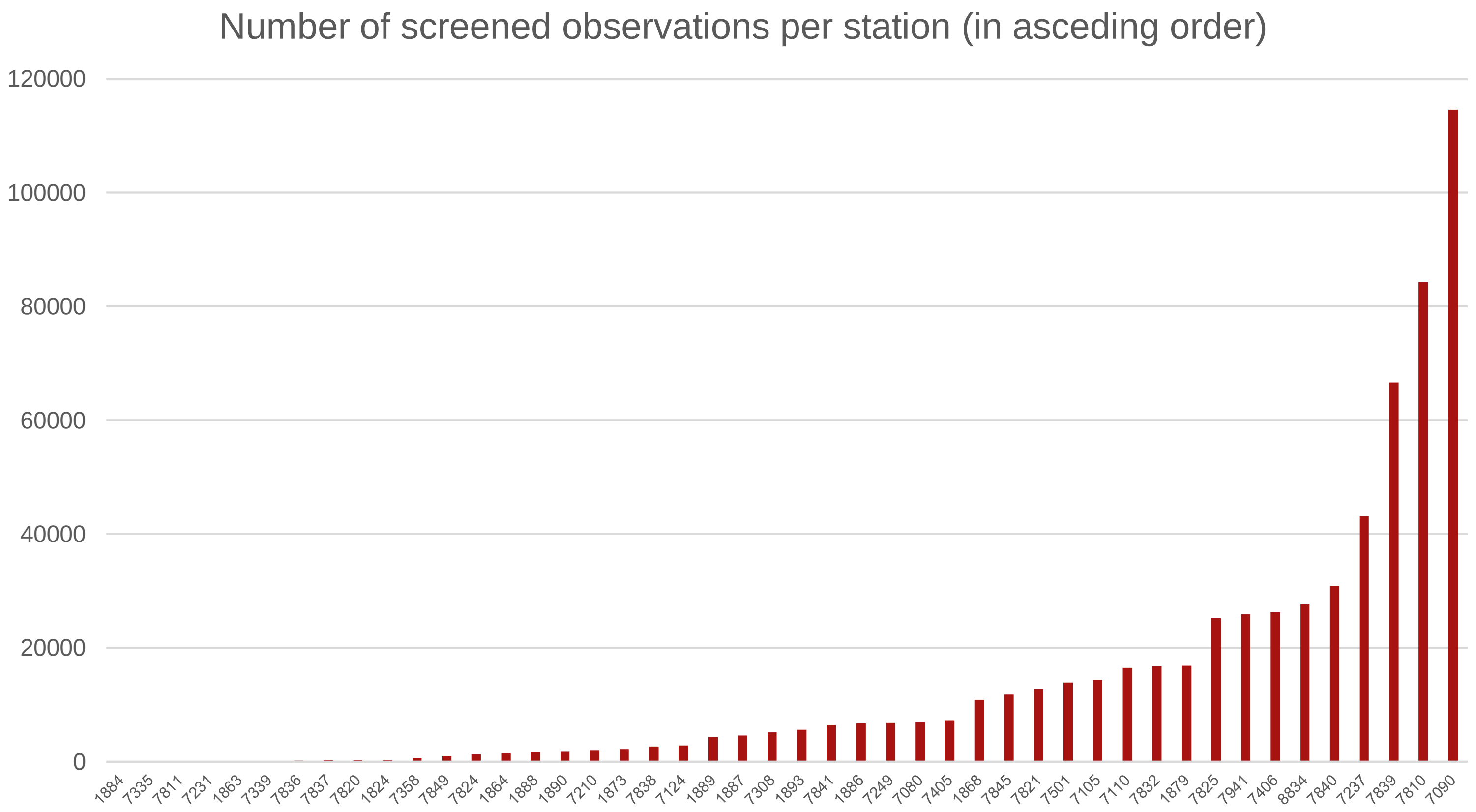
SLR@GNSS (1)



Jahre: 01/2000 – 05/2015

Nach Anwendung des 3-σ Kriteriums

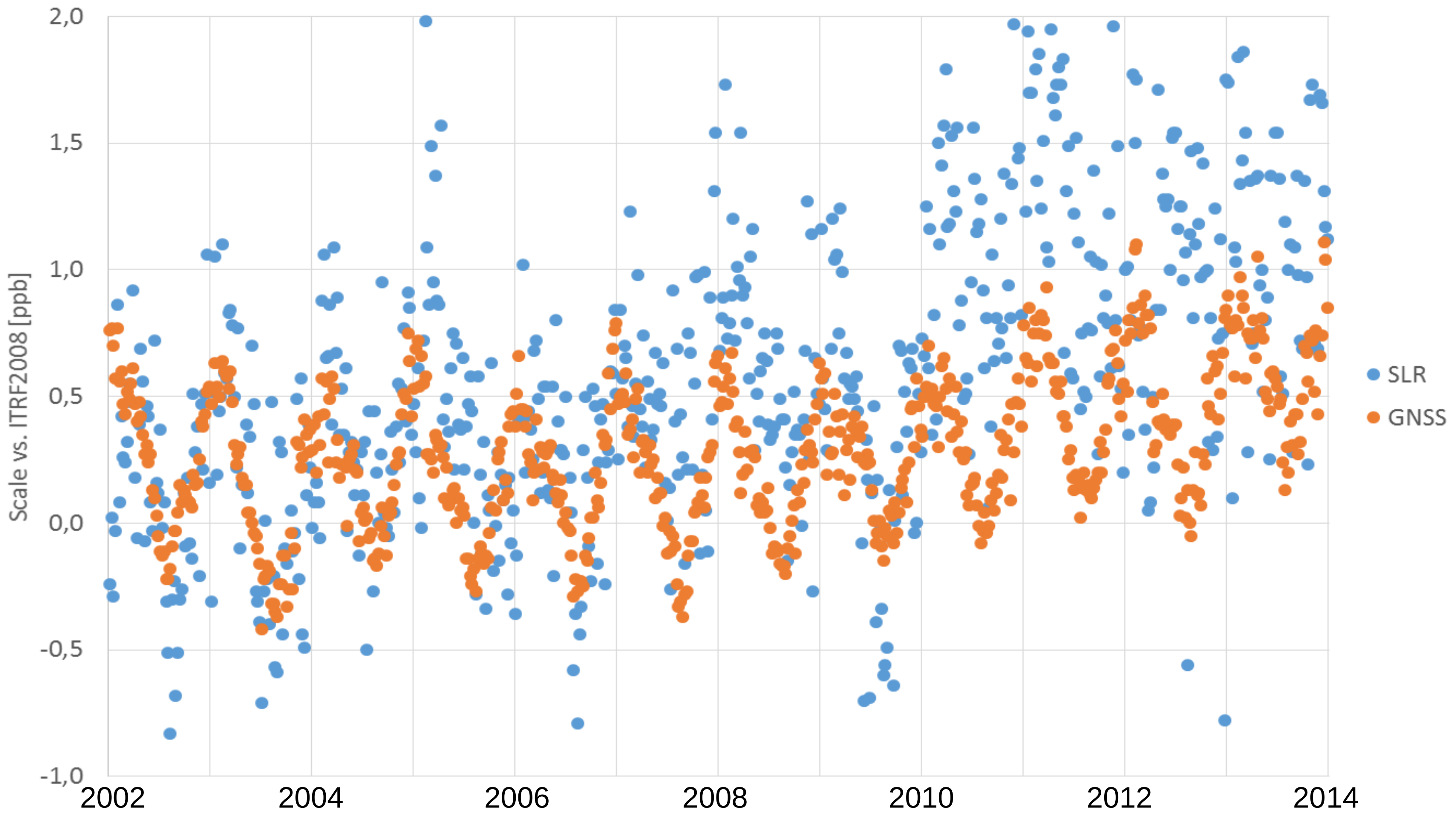
SLR@GNSS (2)



Jahre: 01/2000 – 05/2015

Nach Anwendung des 3-σ Kriteriums

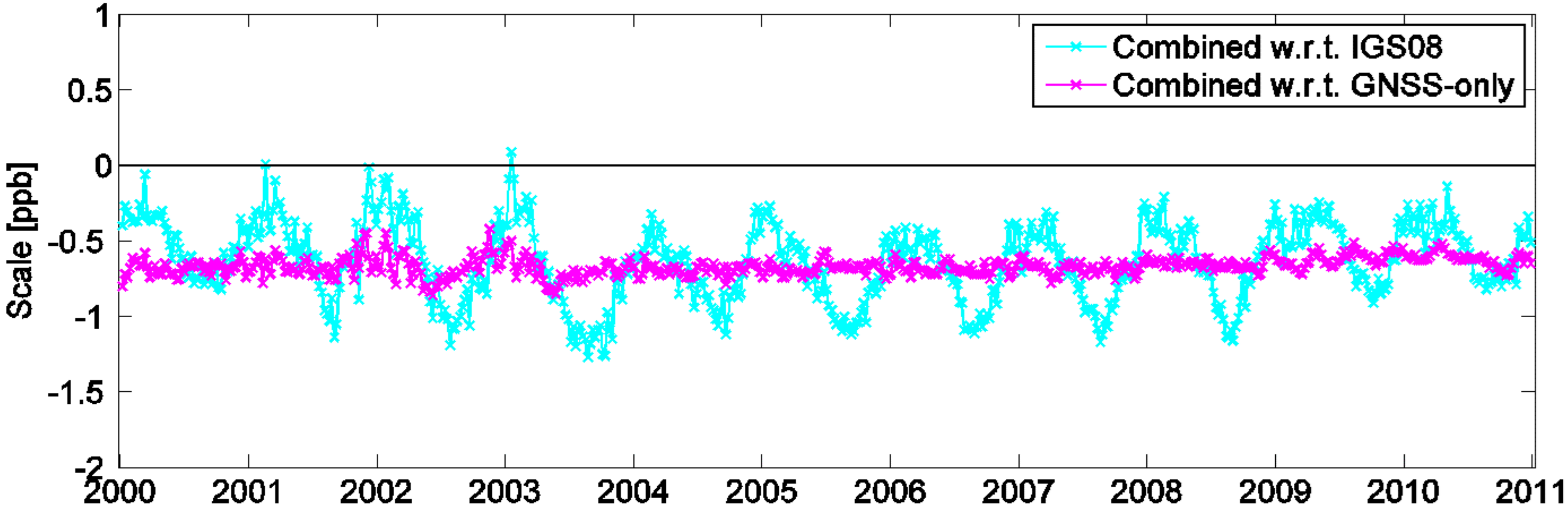
Scale w.r.t. ITRF2008



Mean SLR = 0.57 ppb   Mean GNSS = 0.28 ppb

Federal Agency for Cartography and Geodesy

Scale



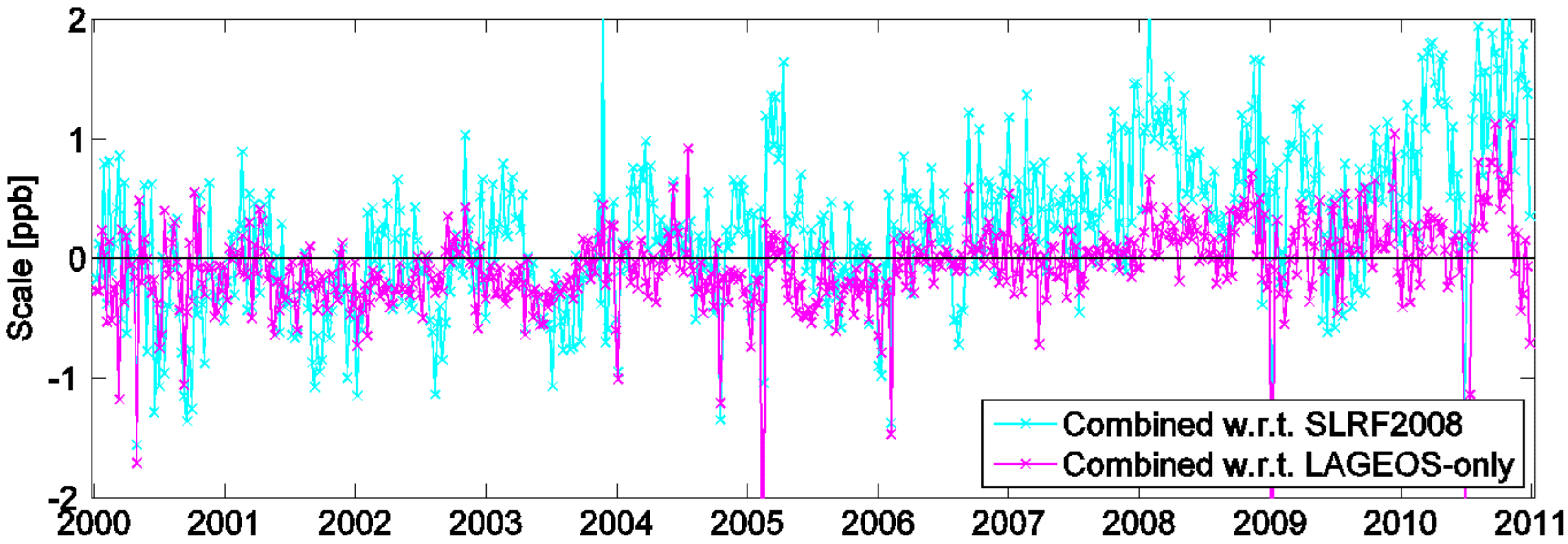
SAO-Z is correlated with scale: ΔScale [ppb] = -7.8 · ΔSAOz [m]

ΔSAOz (GPS) = -86.1 mm $\Rightarrow$ Δscale = 0.67 ppb

ΔSAOz (GLONASS)= -110.4 mm $\Rightarrow$ Δscale = 0.86 ppb

SAO corrections are absorbed by the GNSS network scale

Scale



- No systematic scale difference for the SLR network
- Scale from SLR is transferred to the combined solution

SAO corrections are fully consistent to the SLR scale

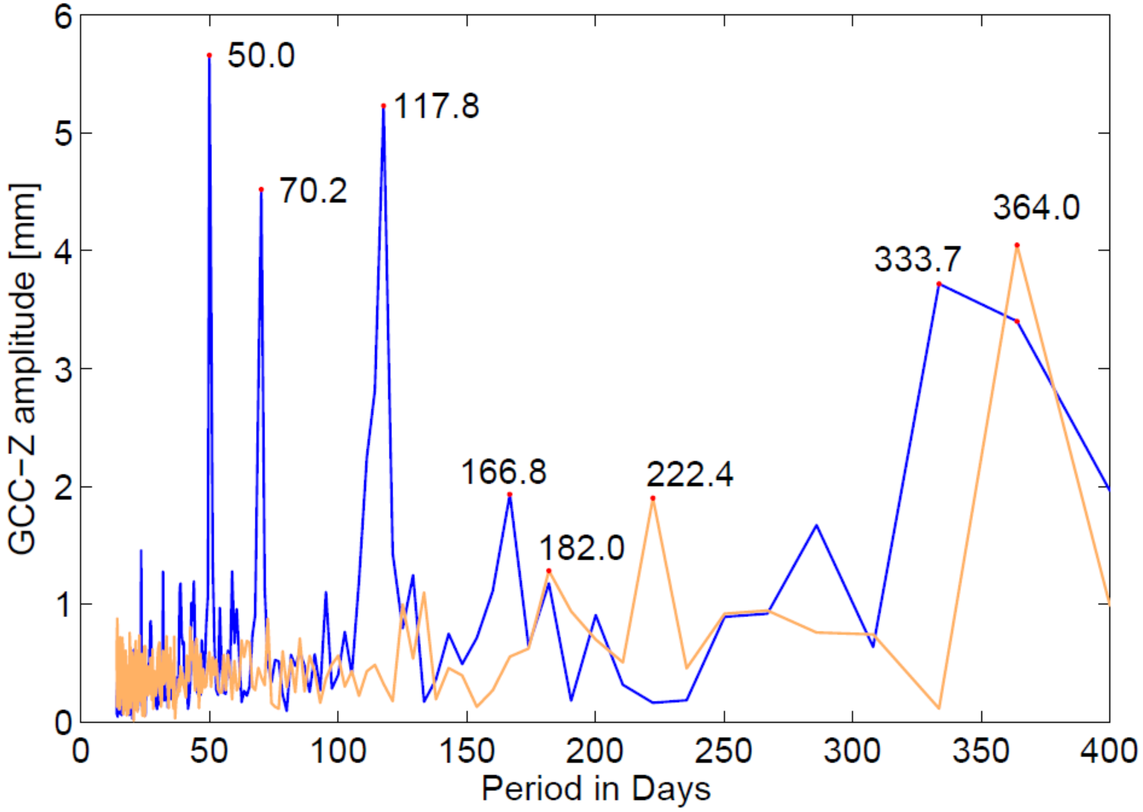
Geocenter: Single techniques

Draconitic year is visible: GNSS = 352d, LAG-2 = 222d

+ Harmonics for GNSS

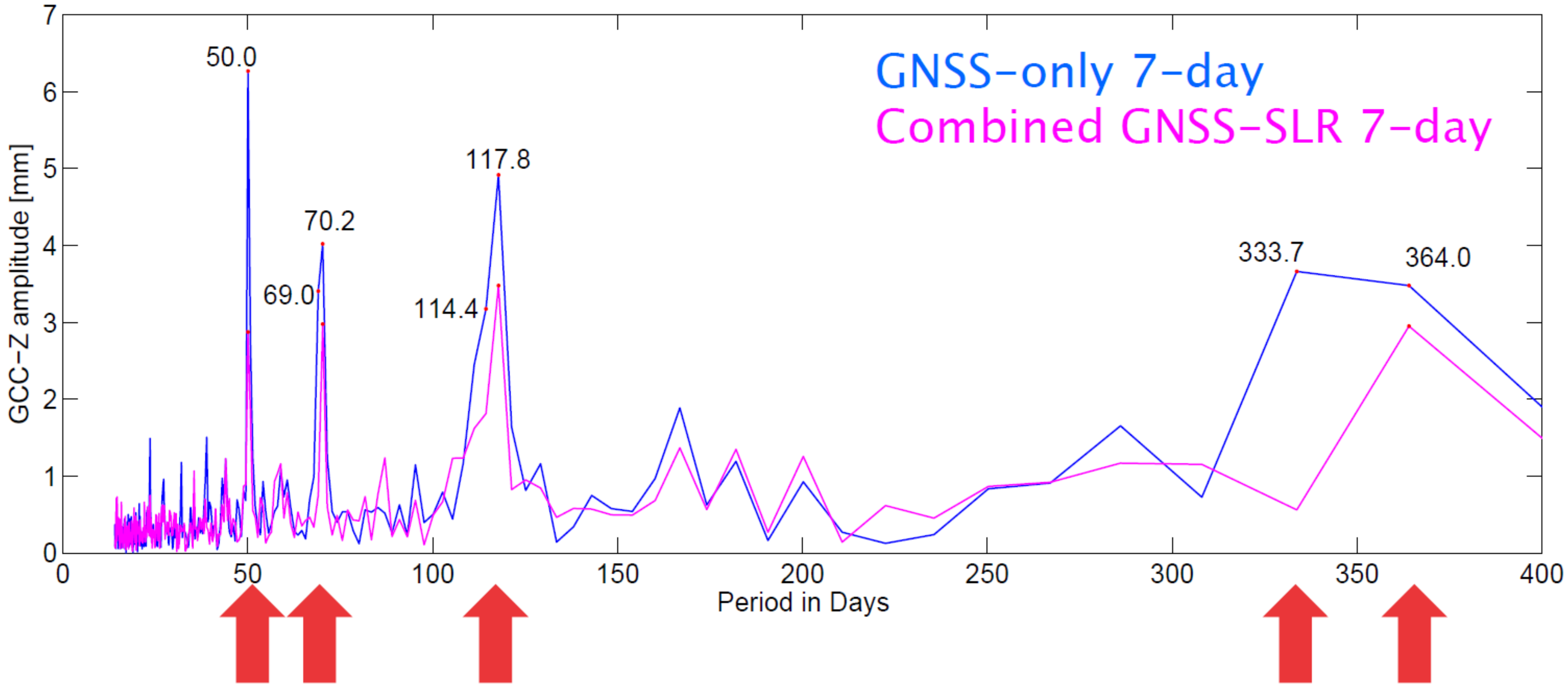
GNSS-only

SLR-only



Federal Agency for Cartography and Geodesy

Geocenter: Combined solutions



- Annual signal remains; draconitic signals disappear
- Harmonics of draconitic GNSS year are reduced, but not eliminated

Local ties: Validation

„Local Tie":

3D vector between reference points of space geodetic instruments (GNSS antenna or SLR telescope or …) at co-located sites

From terrestrial measurements

↕

Discrepancies have to be evaluated

Station coordinates from space techniques:

3D position of reference points of space geodetic instruments

From combined GNSS-SLR solutions using satellite co-locations, **without using Local Ties !!!**

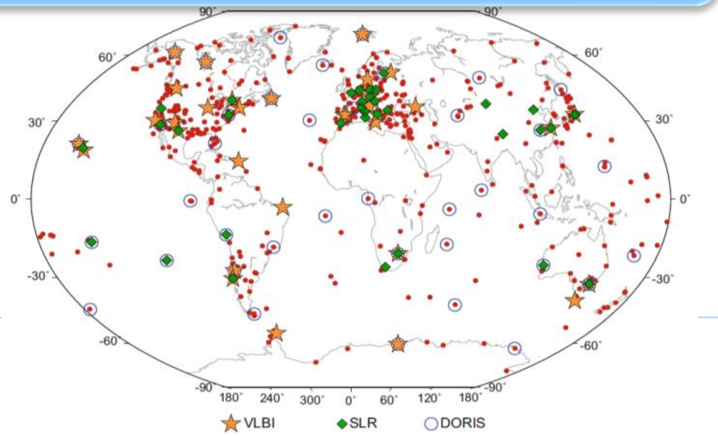
Current ITRF approach

Combined SINEX DORIS	Combined SINEX GNSS	Combined SINEX SLR	Combined SINEX VLBI

↓

Inter-technique Combination
DORIS + GNSS + SLR + VLBI

- IGN, Paris
- DGFI, München
- JPL, Pasadena



Call for ITRF2013: pre-combined solutions

IDS — Combined SINEX DORIS

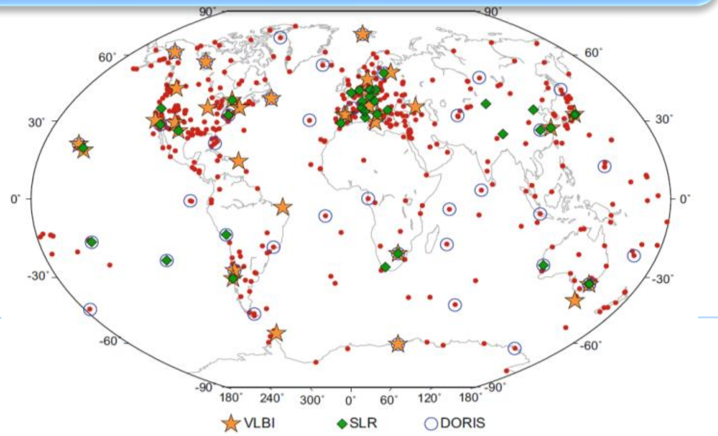
IGS INTERNATIONAL GNSS SERVICE — Combined SINEX GNSS

International Laser Ranging Service — Combined SINEX SLR

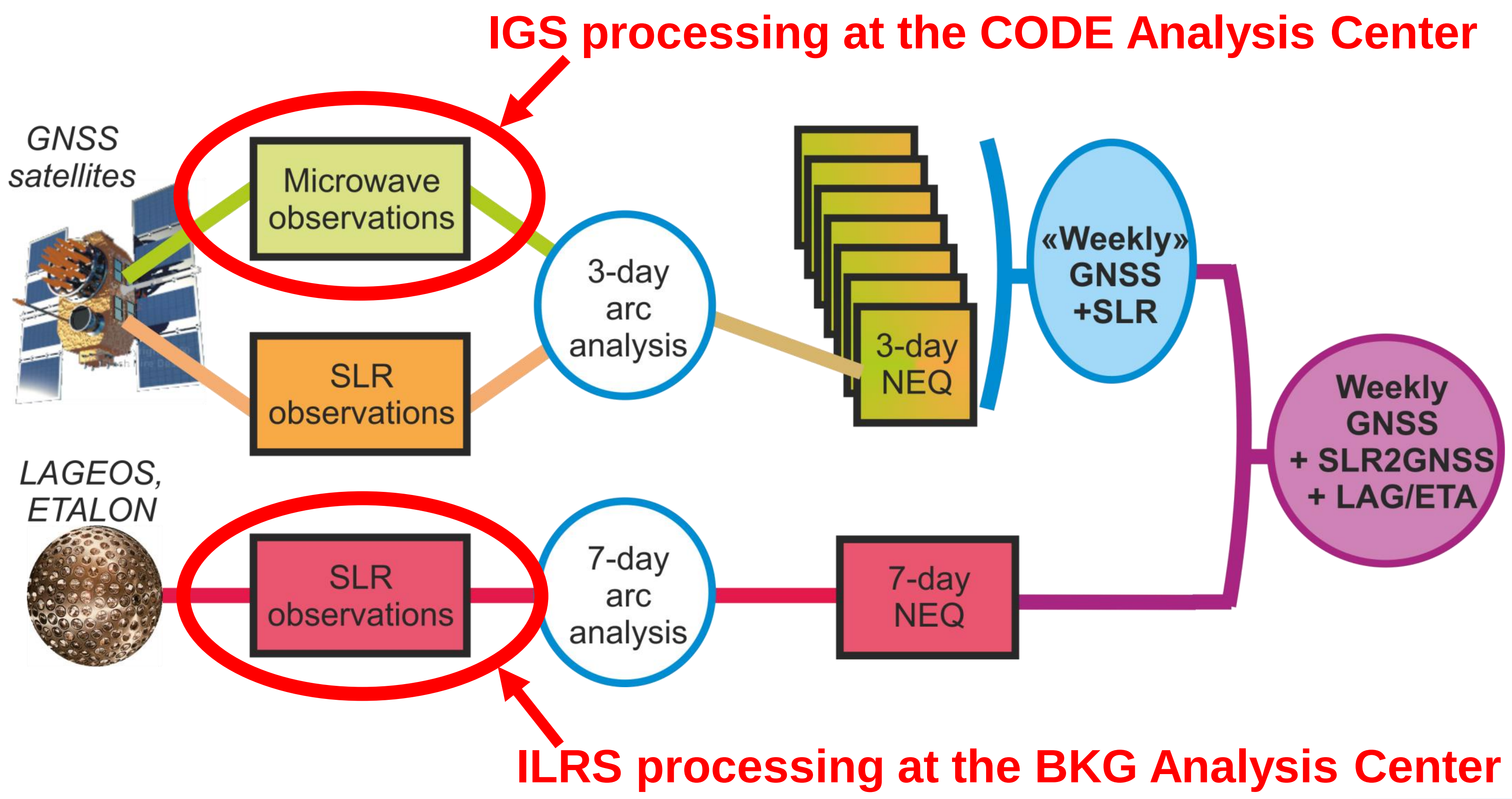
IVS — Combined SINEX VLBI

Inter-technique Combination
DORIS + GNSS + SLR + VLBI

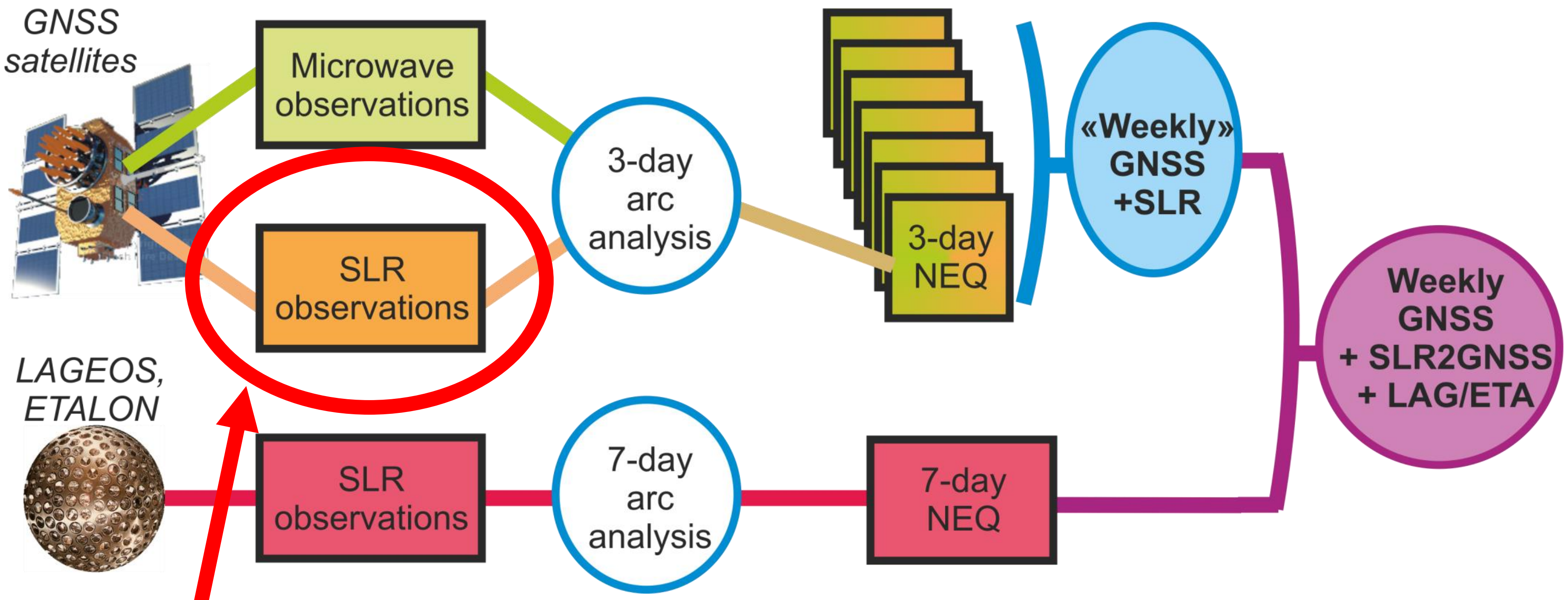
- IGN, Paris
- DGFI, München
- JPL, Pasadena



Pre-combined GNSS-SLR solutions from CODE



Pre-combined GNSS-SLR solutions from CODE



Using **co-locations at GNSS satellites** for connecting both techniques

Federal Agency for Cartography and Geodesy

Extended approach using satellite co-locations: Common parameters

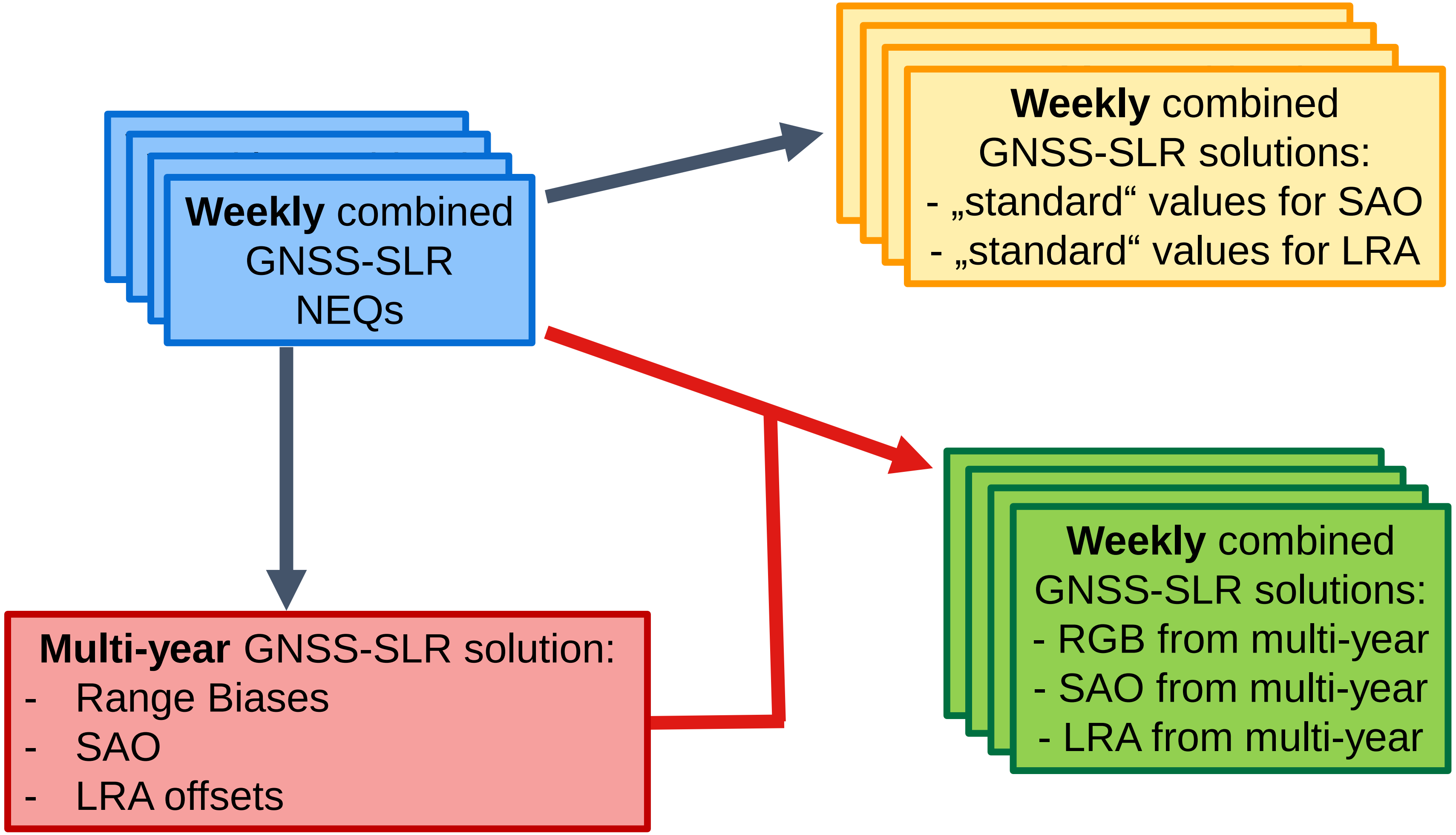
Direct combination

(**Indirect** combination by applying **correction terms**)

	GNSS microwave	SLR @ GNSS	SLR spherical satellites
Station coordinates	GNSS	SLR	SLR
ERP	X	X	X
Geocenter	X	X	X
Orbits GNSS satellites	X	X	
Microwave Sat. antenna offsets	X		
Laser Reflector Array offsets		X	
Range Biases		X	(X)
Orbits spherical satellites			X

Federal Agency for Cartography and Geodesy

Strategy for pre-combined solutions



Satellite co-locations
GNSS-SLR

Co-location at GNSS satellites

=

Common orbit parameters from GNSS microwave and SLR range data

→ **Vectors** of GNSS and SLR reference points **w.r.t. satellite CoM** needed:

- Satellite Antenna Offsets (SAO)
- Offset of Laser Retro-reflector Array (LRA)