SLR-Beobachtungen zu LAGEOS und GNSS-Satelliten und die gemeinsame Auswertung mit GNSS-Beobachtungen

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Gliederung

1. Prozessierung der **LAGEOS**-Daten am AIUB

2. Allgemeine Aspekte der **Kombination von GNSS und SLR**
   - Stationen als Kolokation
   - Satelliten als Kolokation

3. **SLR-Tracking der GNSS-Satelliten** (GPS und GLONASS)

4. **Resultate** der kombinierten GNSS-SLR-Auswertung
   - Stationskoordinaten / TRF
   - GNSS satellite antenna offsets
   - Biases zwischen GNSS und SLR

5. **Zusammenfassung** und **Ausblick**

Prozessierung von LAGEOS am AIUB

Bernese GPS Software (BSW) wurde erweitert:

→ Orbit-Modellierung für Kugelsatelliten

→ Handling von SLR-Beobachtungen

Zusammenarbeit mit ***Bundesamt für Kartographie und Geodäsie (BKG):***

→ **ILRS** Analysis Center

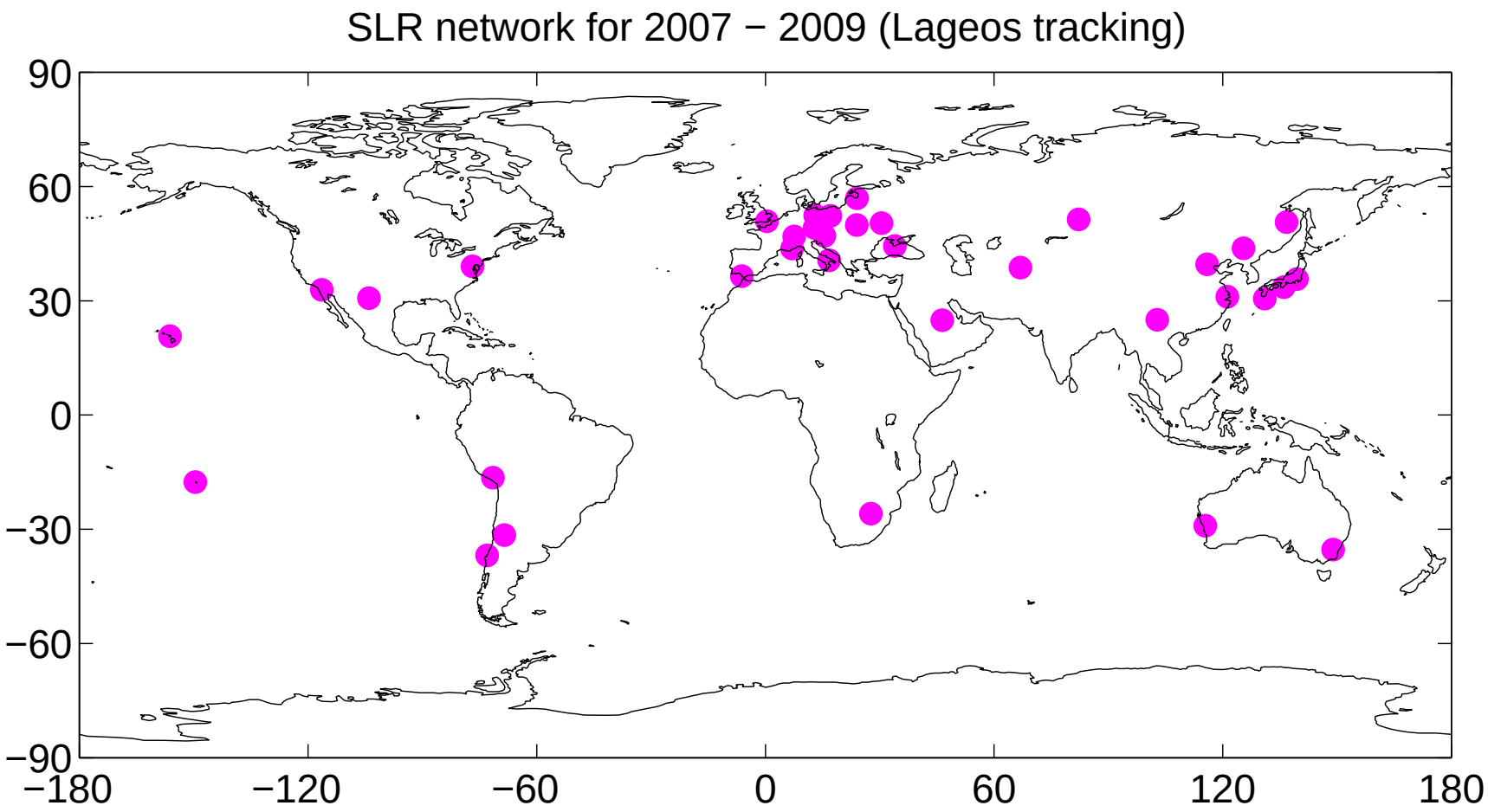
→ BKG-Beiträge basierend auf ***BSW*** seit **Juli 2010**

Analyse der LAGEOS-Daten am *AIUB*:

→ **2 Satelliten: LAGEOS-1 / -2**

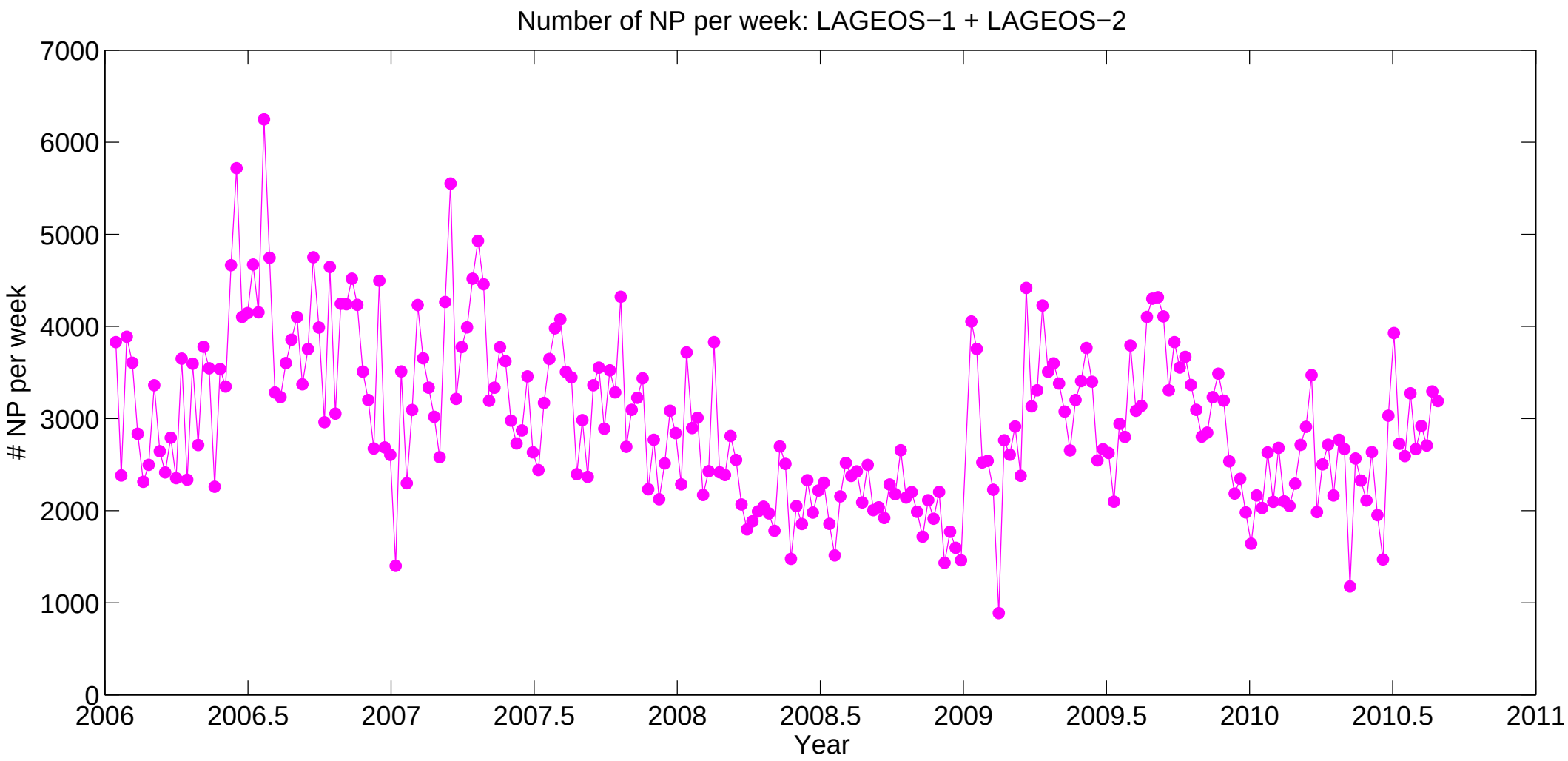
→ **Wochenlösungen für 2006 – 2010**

SLR tracking of LAGEOS



→ Geographical distribution is not ideal!
→ **Total** for 2006 – 2009: **35 stations**; 11 stations for datum definition
→ Number of stations **per week**: **12 – 26** (datum definition: 7 – 11)

SLR tracking of LAGEOS



Total number of observations (normal points) per week for both satellites: **~ 3000**

Weekly LAGEOS solutions

Estimated parameters for weekly ILRS solution:

→ **Station coordinates**

→ **Satellite orbits**: 1 arc per week
- → 6 osculating elements
- → Dynamic orbit parameters:
  - Constant acceleration in along-track
  - Once-per-rev in along-track
  - Once-per-rev in cross-track

→ **Earth rotation**:
- → Polar motion (constant per day)
- → Length of Day (LOD)

→ **Range biases** for selected sites (1 – 3 stations per week)

⇓

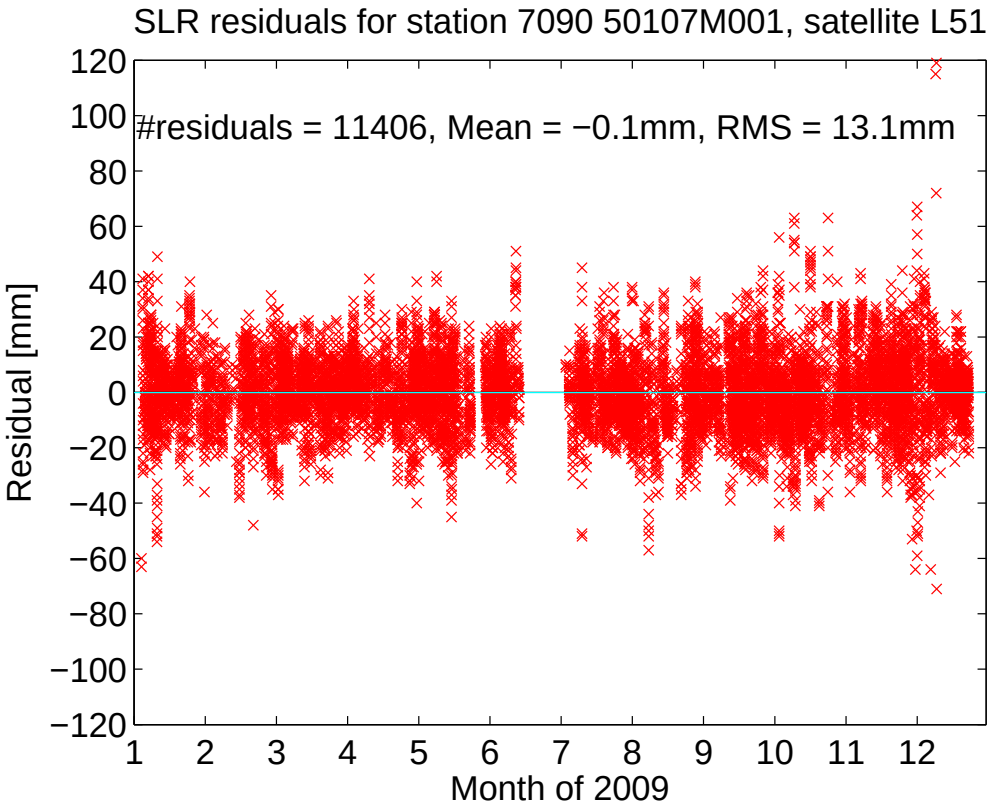
~ **120 – 140** parameters per week

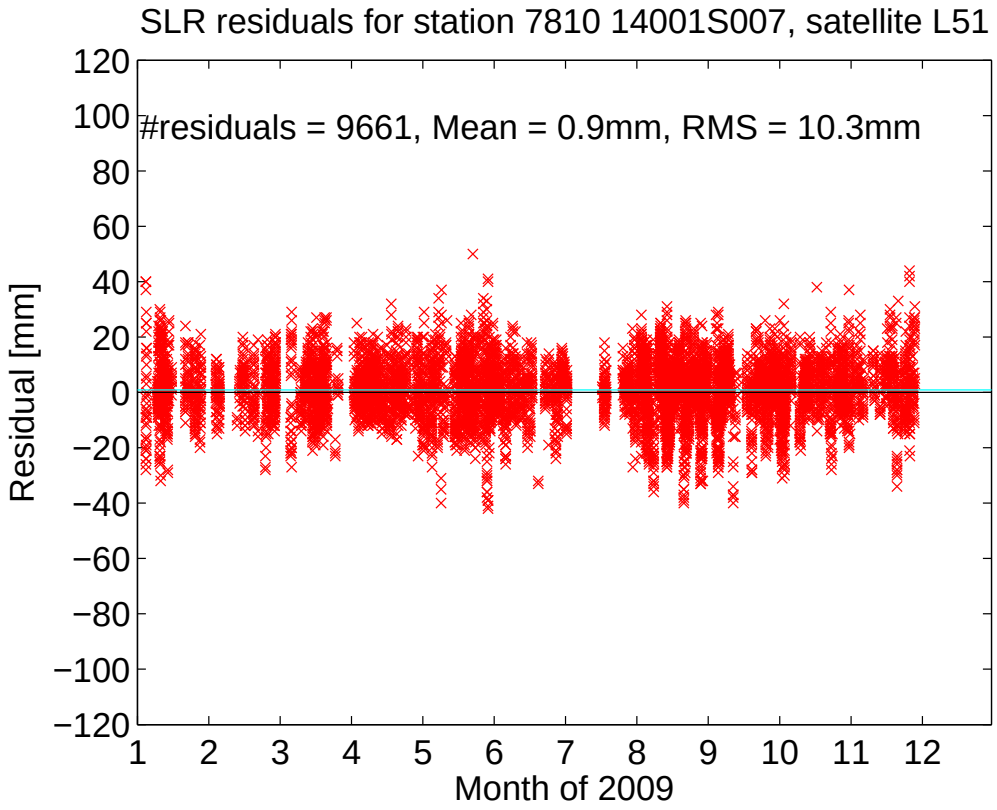
Weekly LAGEOS solutions

Residuals for LAGEOS-1after least squares adjustment:

→ Yarragadee

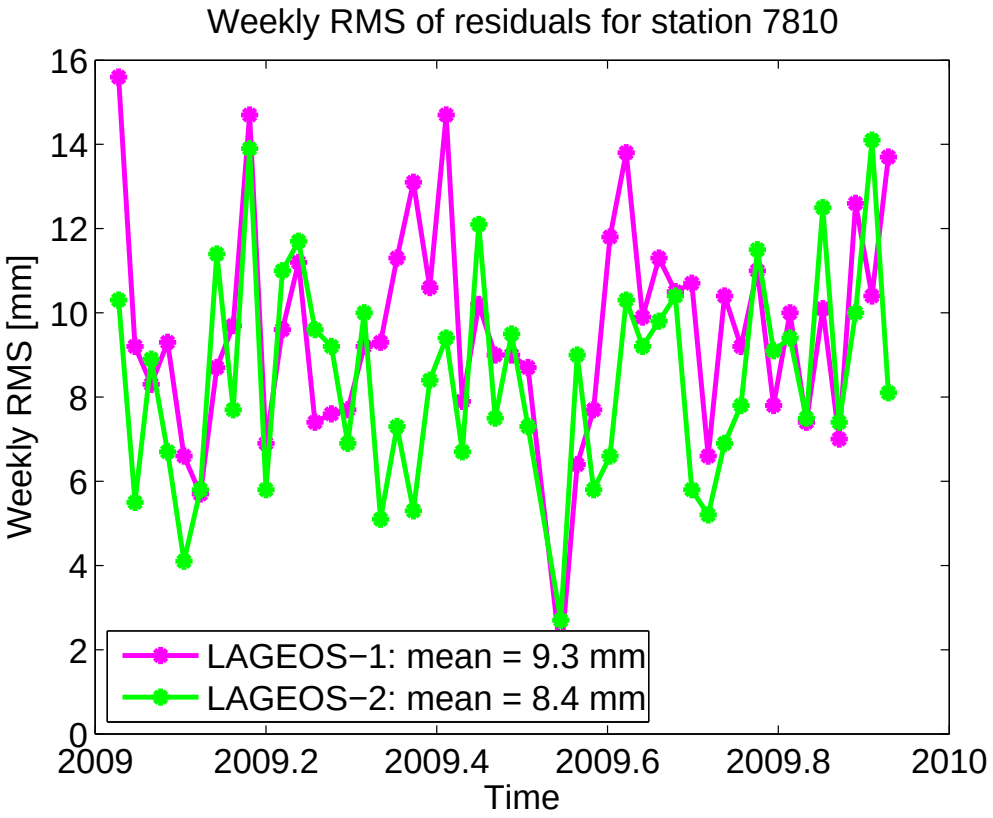
→ Zimmerwald

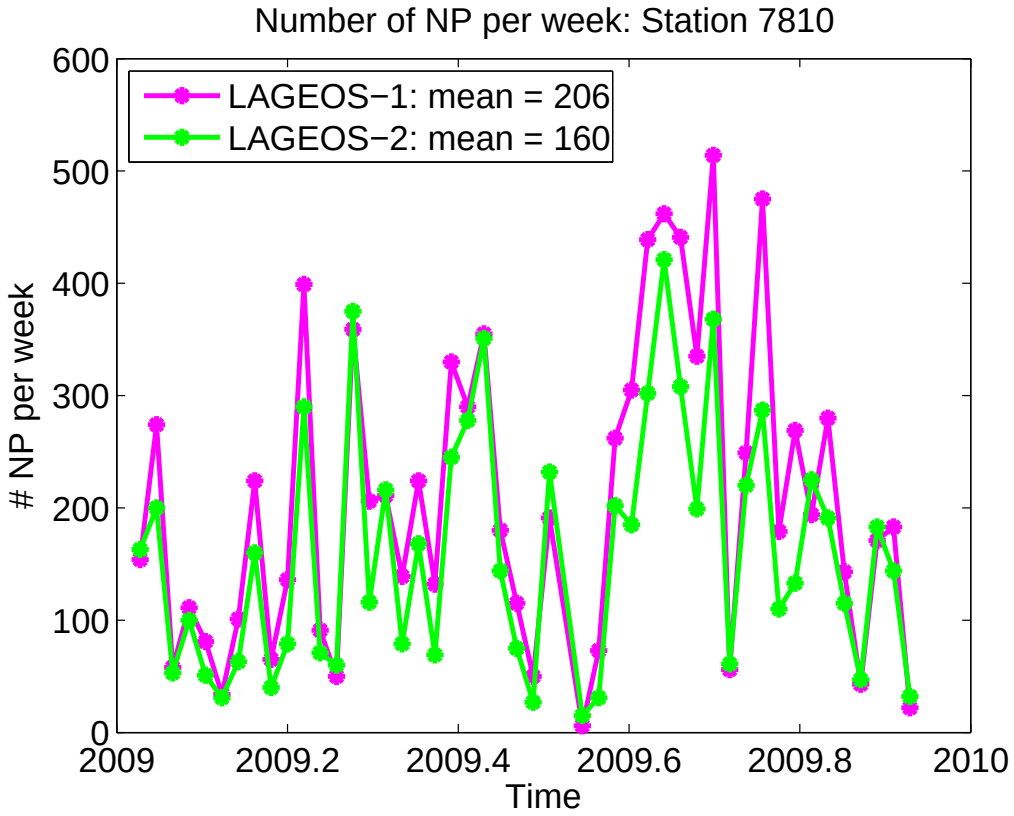




Weekly LAGEOS solutions

Weekly RMS after least squares adjustment for Zimmerwald

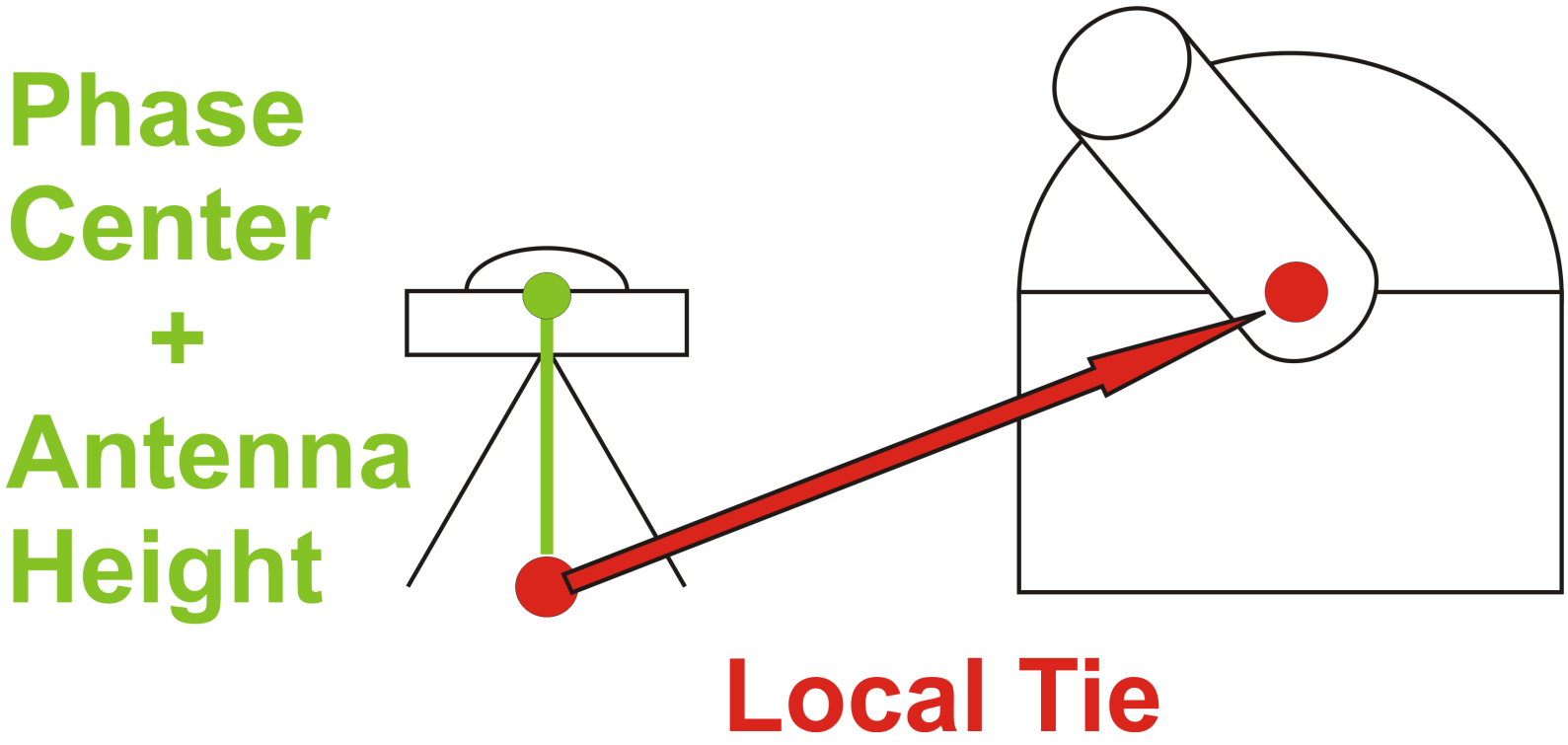




Co-locations for GNSS and SLR

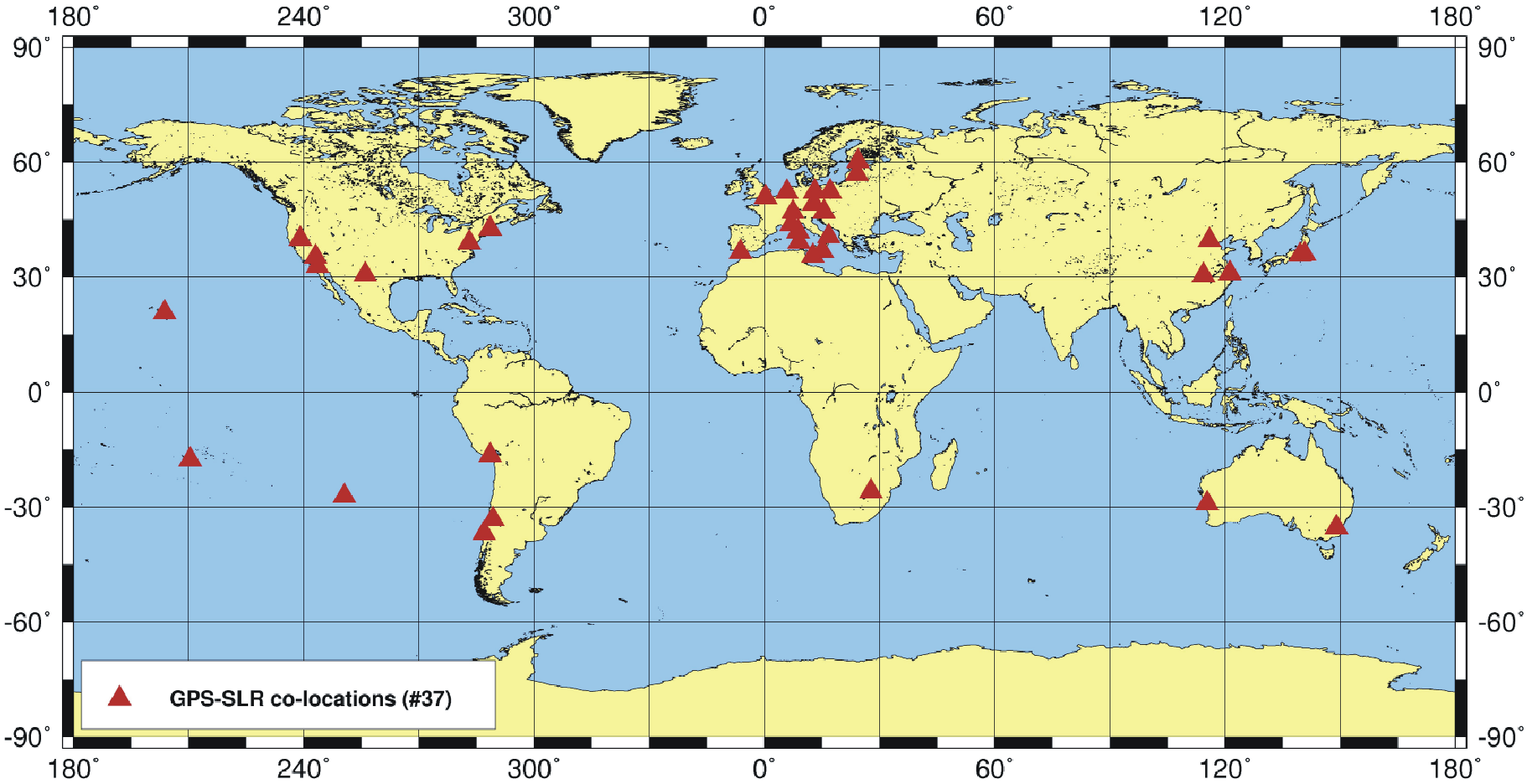
Co-location at stations (e.g., for actual ITRF computation):
→ Application of known **local tie** values
→ GNSS observations of ground network; SLR observations to Lageos etc.

→ Independent of **satellite** tracked
→ **Local ties** from terrestrial measurements



Co-locations for GNSS and SLR

→ bad **global distribution** of co-location sites
→ only **few** co-locations (37)
→ questions concerning **accuracy**, **transformation** local measurements → global

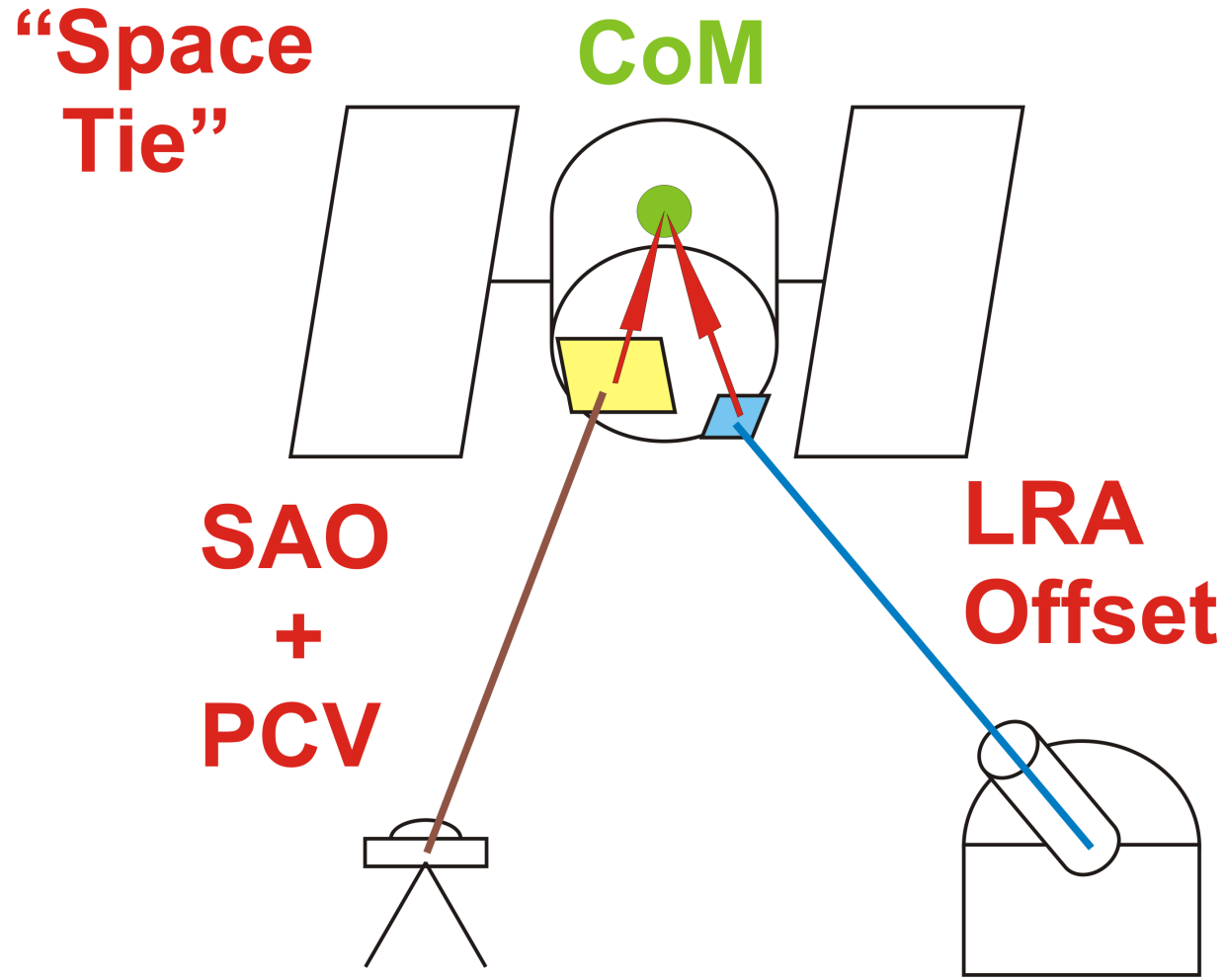


from ITRF2008-D solution (provided by M. Seitz, DGFI)

Co-locations for GNSS and 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



***Space Tie* =**

1. GNSS Satellite Antenna Offsets (**SAO**) w.r.t. CoM
2. GNSS Phase Center Variations (**PCV**)
3. Offsets for Laser Retroreflector Array (**LRA**) w.r.t. CoM

Expectation from combined analysis

	GNSS @GNSS	SLR @GNSS	SLR @Lageos
Radiation pressure ↔ **Geocenter**	Problems in RPR modelling	Problems in RPR modelling	RPR well modelled
GNSS satellite antenna phase center ↔ **Scale**	Problems in phase center modelling	independent	-
Range biases ↔ **Scale**	-	Decorrelated if different elevation angles	For a few sites only

SLR @GNSS:

⇒ **Geocenter** is affected as well ⇒ LAGEOS needed

⇒ **Scale** is transferred to GNSS ⇒ LAGEOS helps for decorrelation

SLR tracking of GNSS satellites

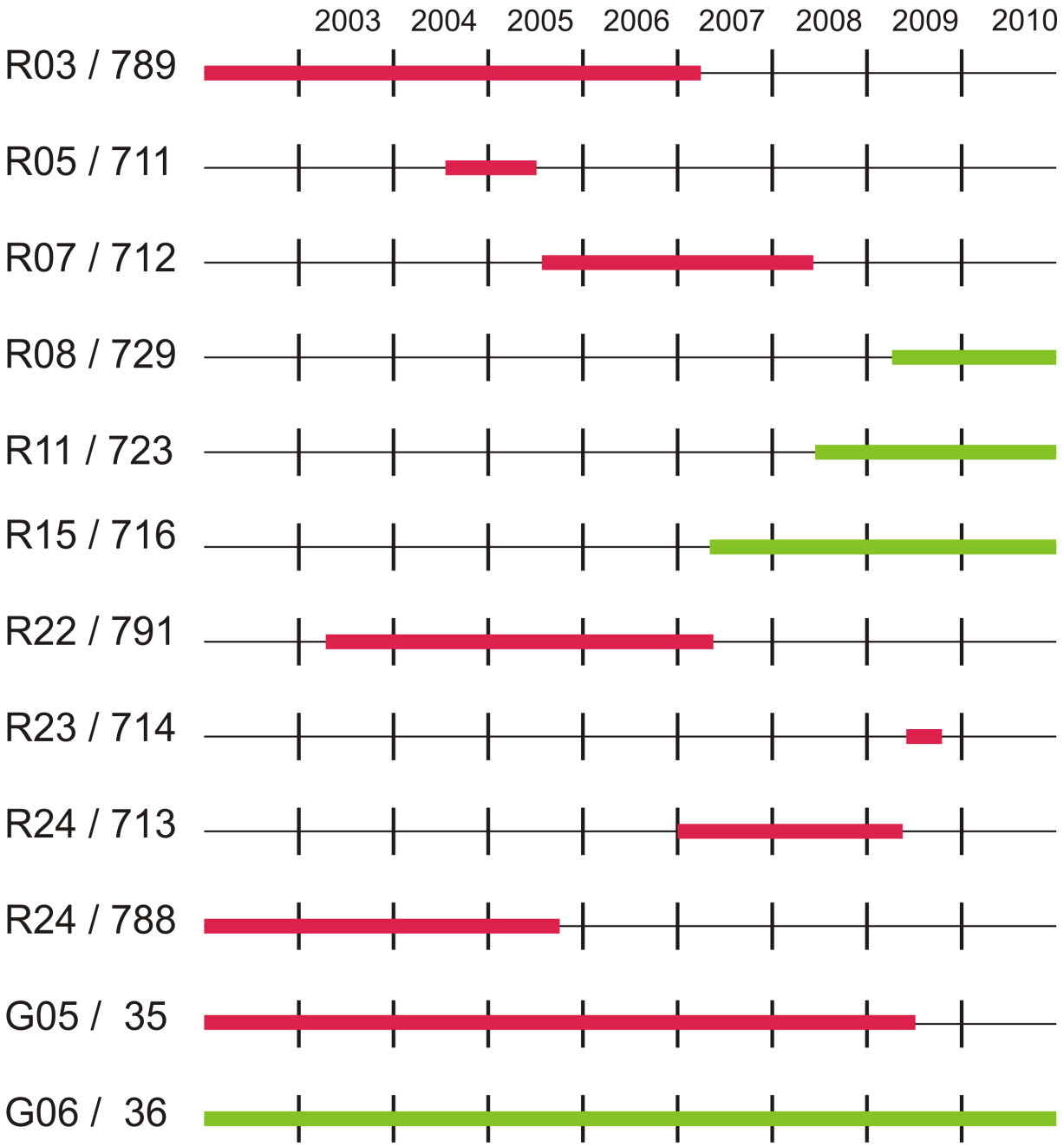
→ Only **2 GPS satellites** are equipped with retro-reflector arrays (G05, G06)

→ **All GLONASS satellites** are equipped with retro-reflector arrays

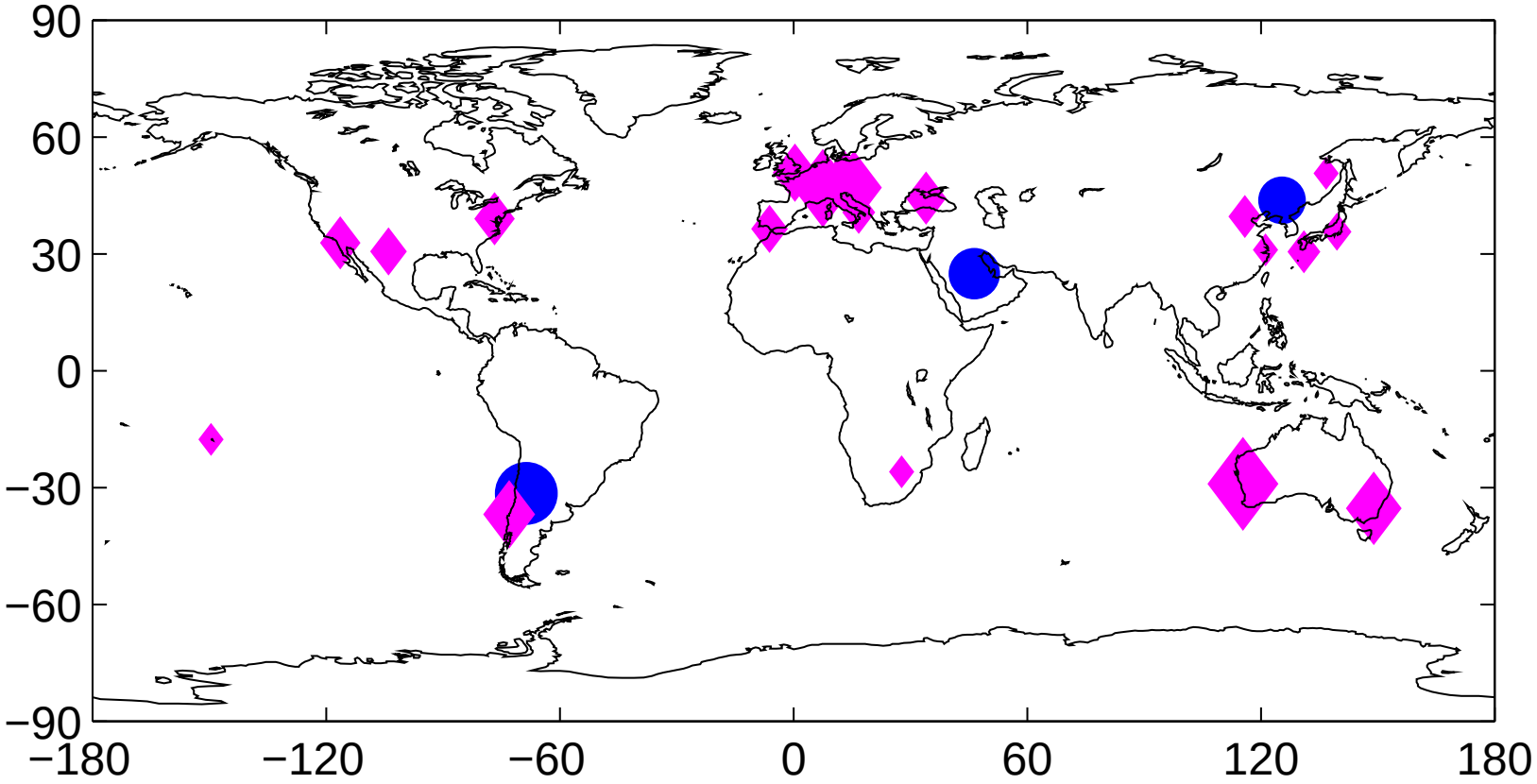
→ SLR tracking for selected GNSS satellites:

2 GPS → 2009: 1

3 GLONASS → 2010: 6



SLR tracking of GNSS satellites



Satellites tracked in 2008:

GPS: G05
G06

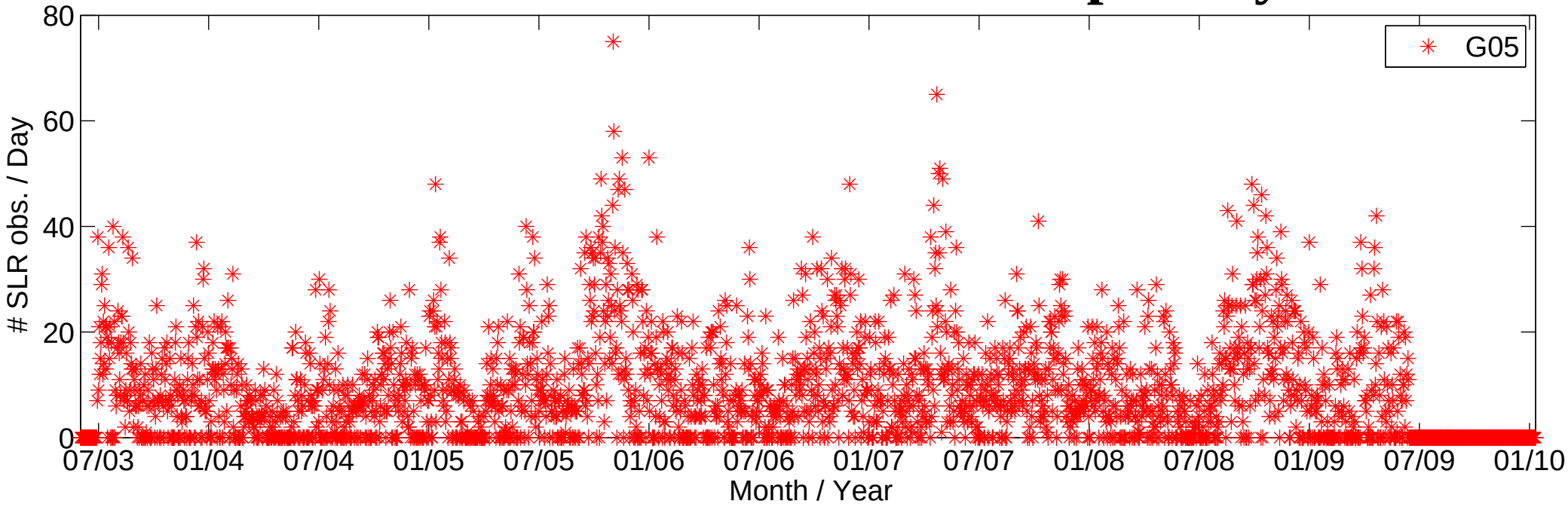
GLONASS:
R15
R24
R07
R11

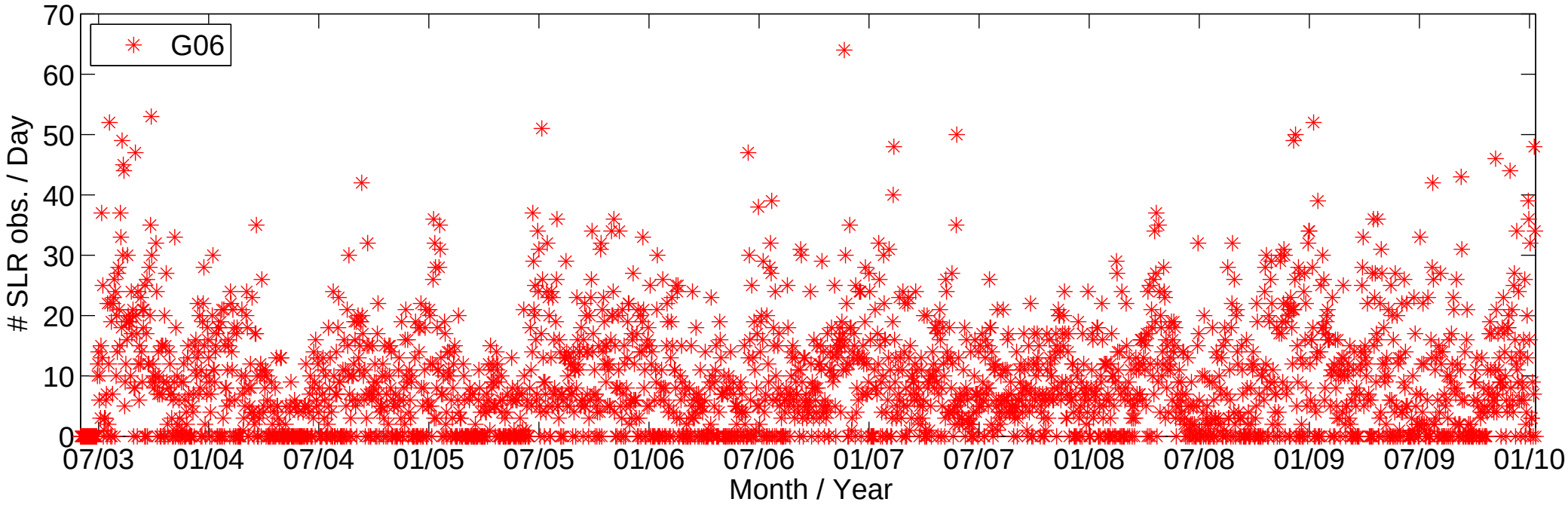
Altogether (2008):
25 SLR sites
31855 normal points (NP)

8 sites with > 1000 NP
5 sites with > 500 NP
6 sites with > 100 NP
6 sites with < 100 NP

Northern hemisphere:
16804 NP
Southern hemisphere:
15051 NP

Number of SLR observations per day





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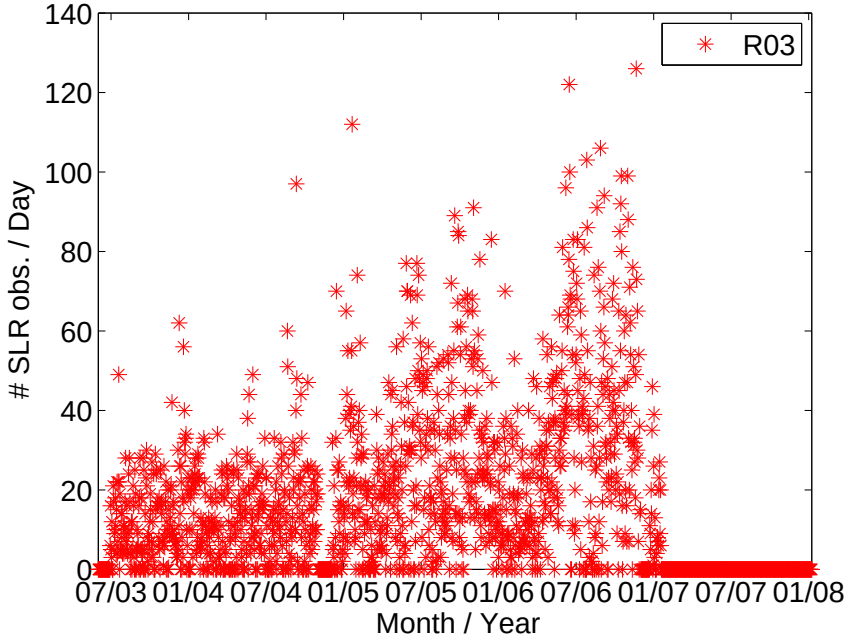
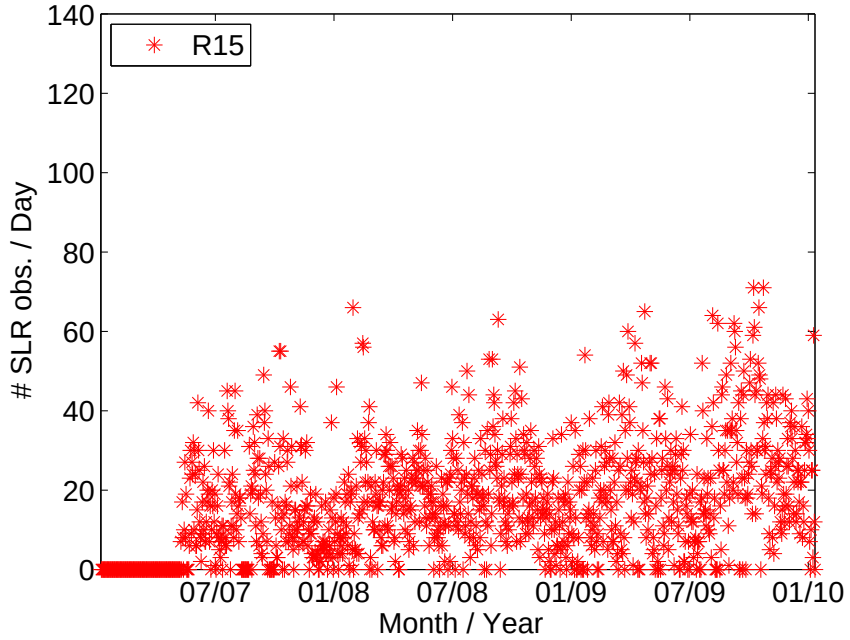
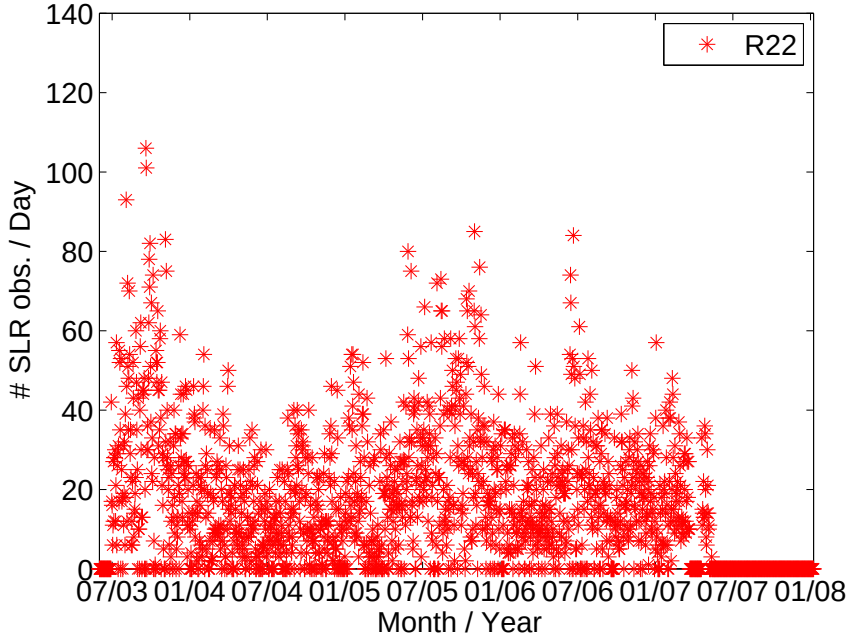
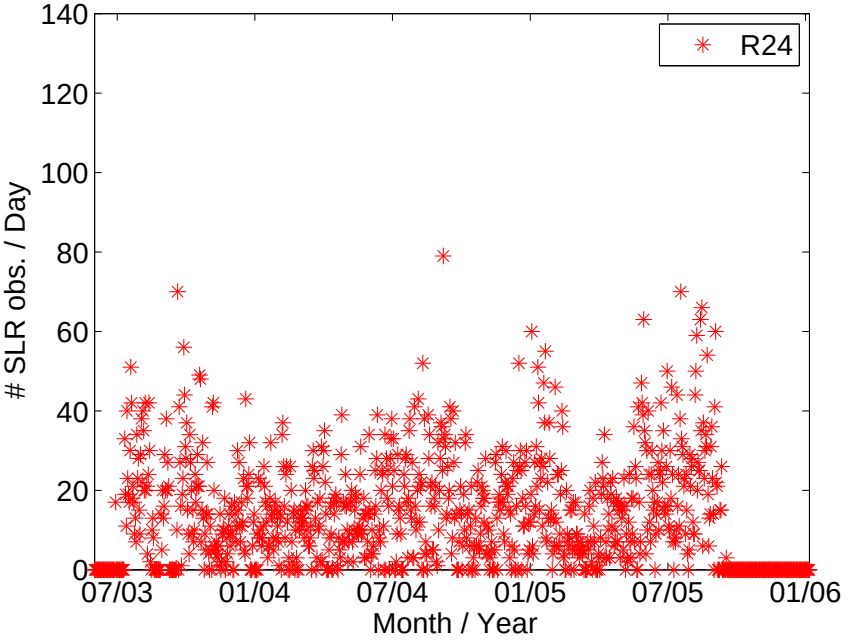
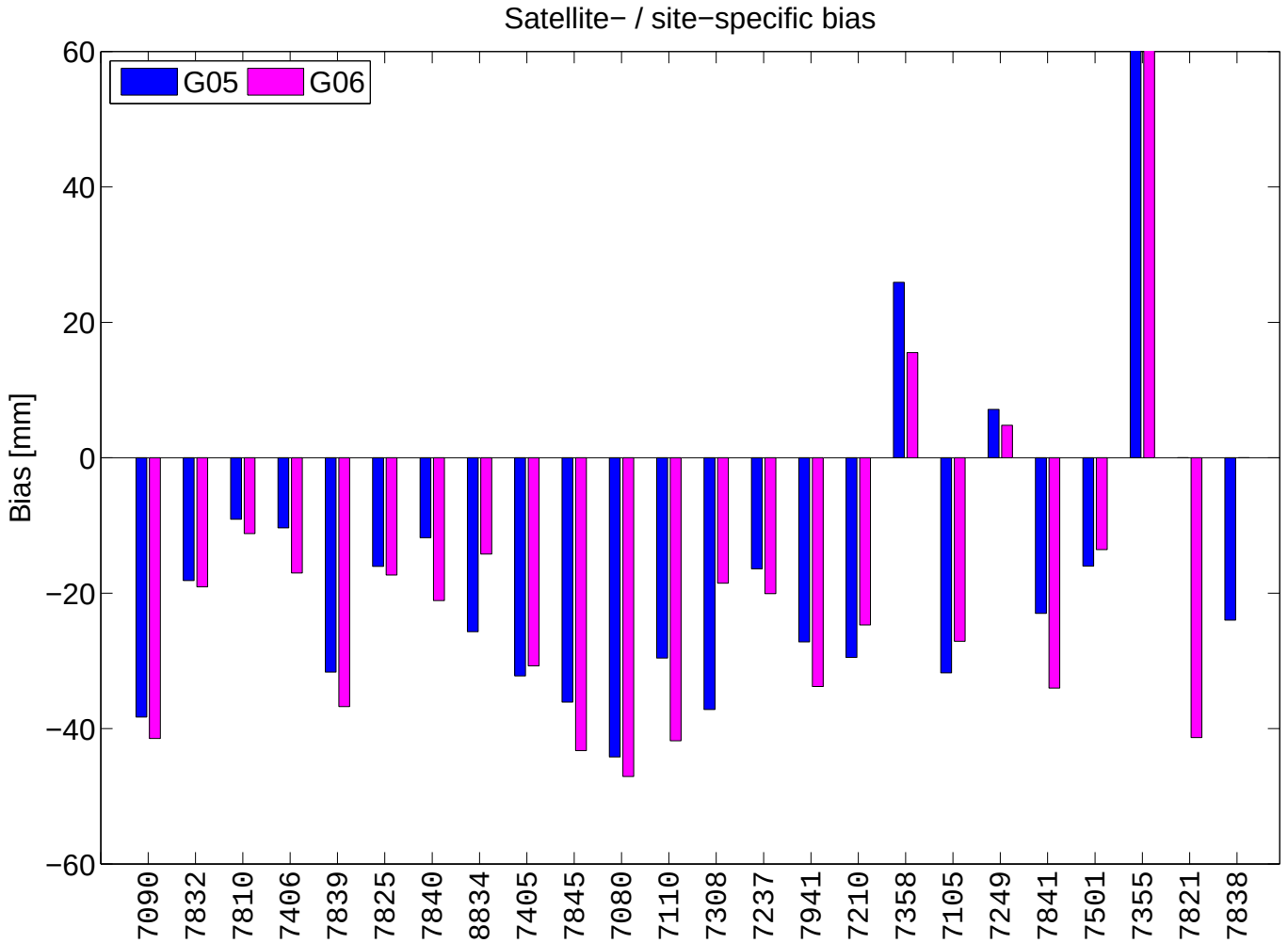








SLR residuals: Mean bias



Stations

Mean bias for all stations for 2003 – 2009 [mm]:

G05	G06
-24.0	-26.4

R03	R07	R11	R15	R22	R24a	R24b
-13.5	-8.6	-19.5	-2.6	-14.1	-17.9	-16.0

Combined analysis of GNSS and SLR

Problems and Questions:

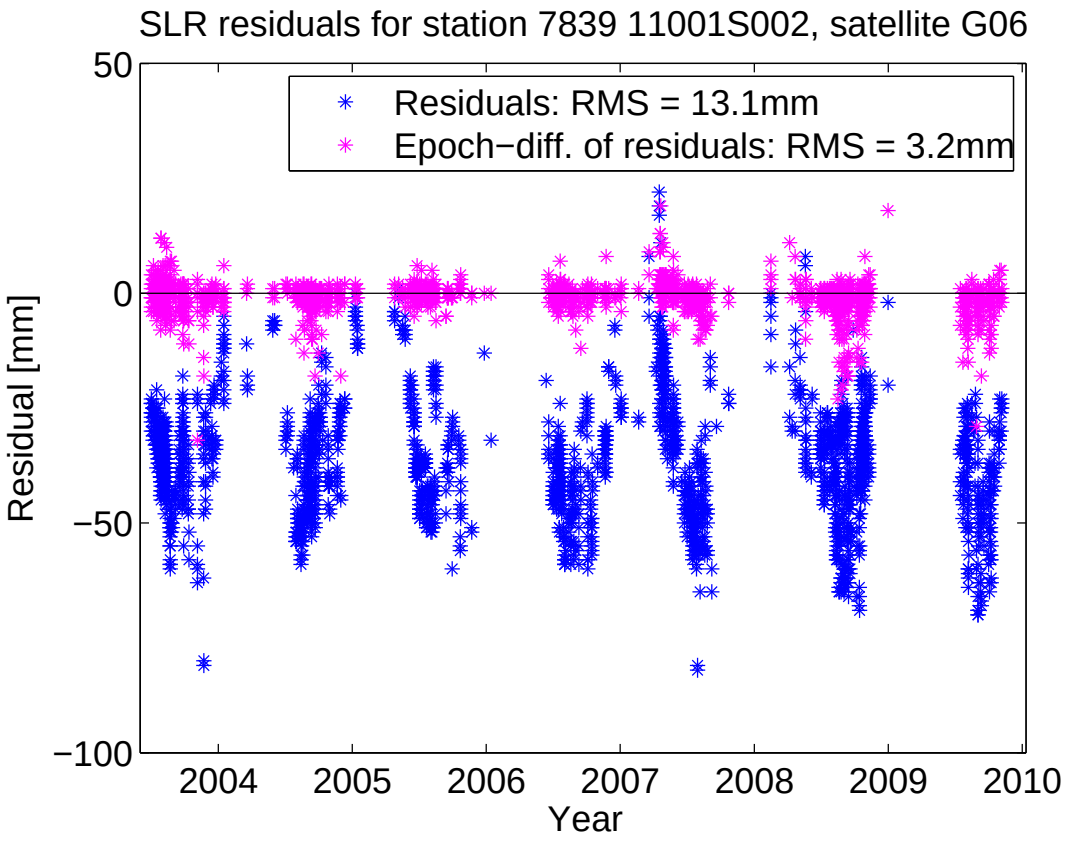
Only **few SLR observations** to GNSS satellites (10 – 20 per day)
→ Weak estimation of parameters
→ Daily solutions not possible

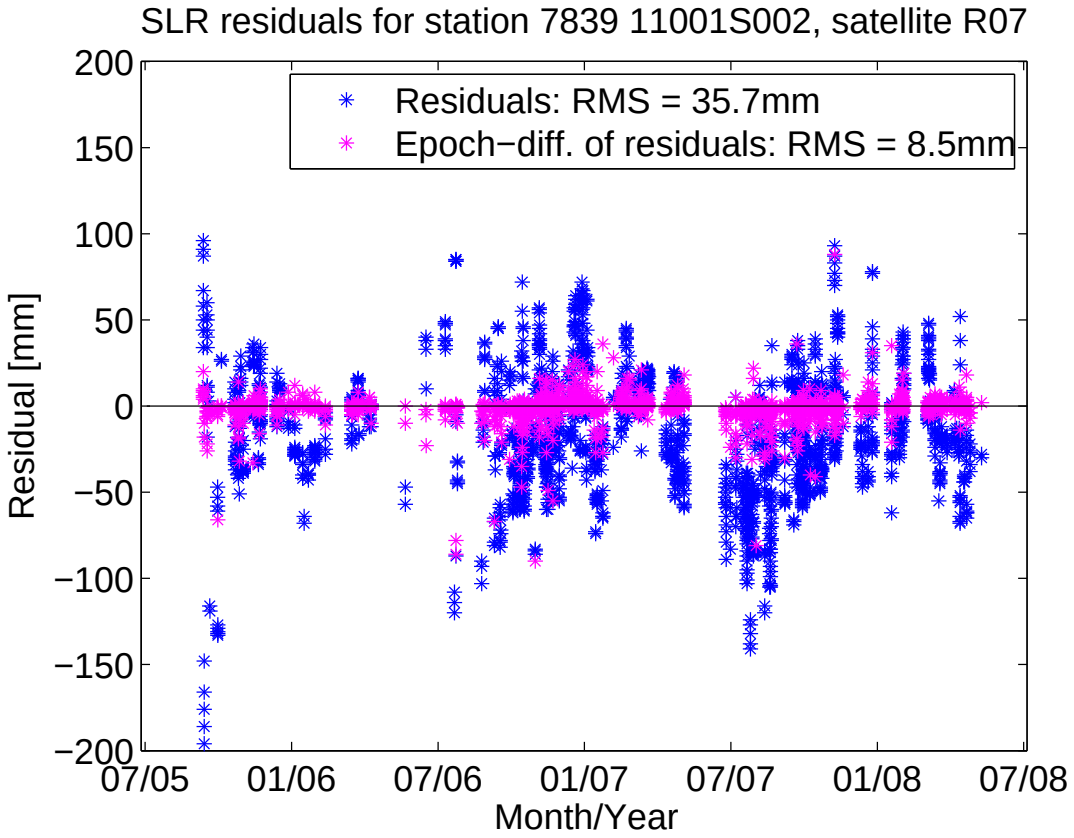
Correlations between parameters (offsets, range biases) and **scale**
→ Common estimation possible?

Are satellite co-locations (**space ties**) strong enough or are co-locations on ground (**local ties**) needed additionally?

Biases between GNSS and SLR are seen in SLR range residuals to given microwave-based orbits
→ Several possible error sources ...

Systematic effects between SLR and GNSS





1) Biases in SLR range residuals (cm-level)

2) Epoch-differences of SLR range residuals have a much smaller RMS

⇒ **systematic effects**

Systematic effects between SLR and GNSS

Possible reasons for systematic effects in SLR range residuals:

SLR station coordinates (fixed to SLRF2005)

TRF (scale, geocenter)

Offset for GNSS satellite antenna (SAO from igs05.atx)

Offset for laser reflector array (LRA from ILRS web site)

SLR range biases (unknown for GNSS satellites)

GNSS orbit modelling (solar radiation pressure)

⇒ **Must be handled in combined solution:**

- use known / better values
- **Estimation**

Combined analysis of GNSS and SLR

SLR station coordinates
→ **estimate + inclusion of LAGEOS**

TRF scale (and geocenter)
→ **use from SLR**

Offset for GNSS satellite antenna (SAO from igs05.atx)
→ **estimate**

GNSS has rank-deficiency w.r.t. scale if SAO are estimated

Offset for laser reflector array (LRA from ILRS web site)
→ **estimate**

SLR range biases (unknown for GNSS satellites)
→ **estimate + inclusion of LAGEOS**

Estimation of 1 bias parameter per station / per GNSS satellite

⇒ GNSS-microwave + SLR@GNSS + SLR@LAGEOS for 2006-2009

Combined analysis of GNSS and SLR

→ ***GNSS-only NEQs (daily):***

- Combined GPS+GLONASS analysis performed at CODE
- Re-analysis for 2003 – 2008, routine IGS analysis for 2009

→ ***SLR-only NEQs for SLR@GNSS (daily):***

- SLR data to GPS and GLONASS satellites
- Parameterization identical to GNSS analysis (orbits, ERP, geocenter)
- Range biases for all sites

→ ***Combination of daily NEQs***

→ ***SLR-NEQs for Lageos (weekly):***

- Range biases only for selected sites

→ ***Combination of NEQs and accumulation to long-term solution:***

- Use of "**Space ties**" only; Local ties are not applied!

SLR station coordinates

SLR station network

- Not included in the datum definition (no-net-rotation, no-net-translation)
- No local ties applied

→ Only appended via the „space ties“ (common orbit parameters)

Validation of SLR station coordinates: Helmert transformation

		SLRF2005	Lageos-only	
RMS	**Comb: SLR@GNSS**	**54.40**	54.22	[mm]
	Comb: + Lageos	**6.70**	2.95	[mm]
	Lageos-only	**7.49**		[mm]

→ Agreement is at the **cm-level** if only SLR@GNSS is used

→ **Inclusion of Lageos** improves the coordinate estimates

→ Connection by using space ties only is feasible

SLR station coordinates

SLR station network:
- Not included in the datum definition (no-net-rotation, no-net-translation)
- No local ties applied
→ Only appended via the „space ties“ (common orbit parameters)

Validation of SLR station coordinates: Helmert transformation

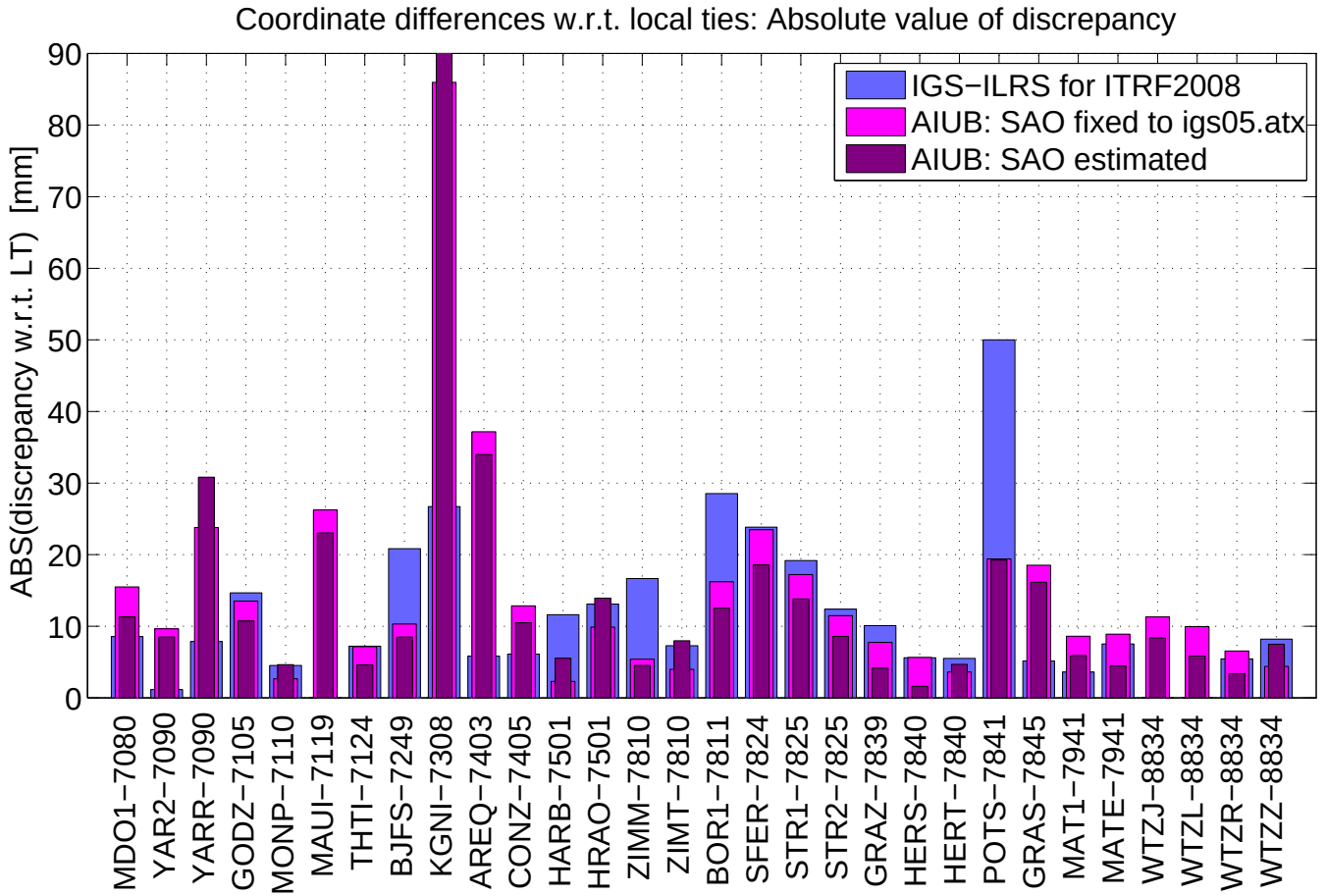
		SLRF2005	Lageos-only	
Scale	**Comb: SLR@GNSS**	**1.06 +- 2.76**	2.34 +- 2.75	[ppb]
	Comb: + Lageos	**1.02 +- 0.34**	0.25 +- 0.15	[ppb]
	Lageos-only	**1.28 +- 0.38**		[ppb]

→ Scale of SLR is defined well
→ **Inclusion of Lageos** improves the coordinate estimates

Comparison with co-located GNSS sites

1. Estimated SLR and GNSS station coordinates ⇒ **ΔCRD_estimate**
2. Local tie between SLR and GNSS reference points: **ΔCRD_LT**

⇒ **ΔCRD_estimate - ΔCRD_LT**



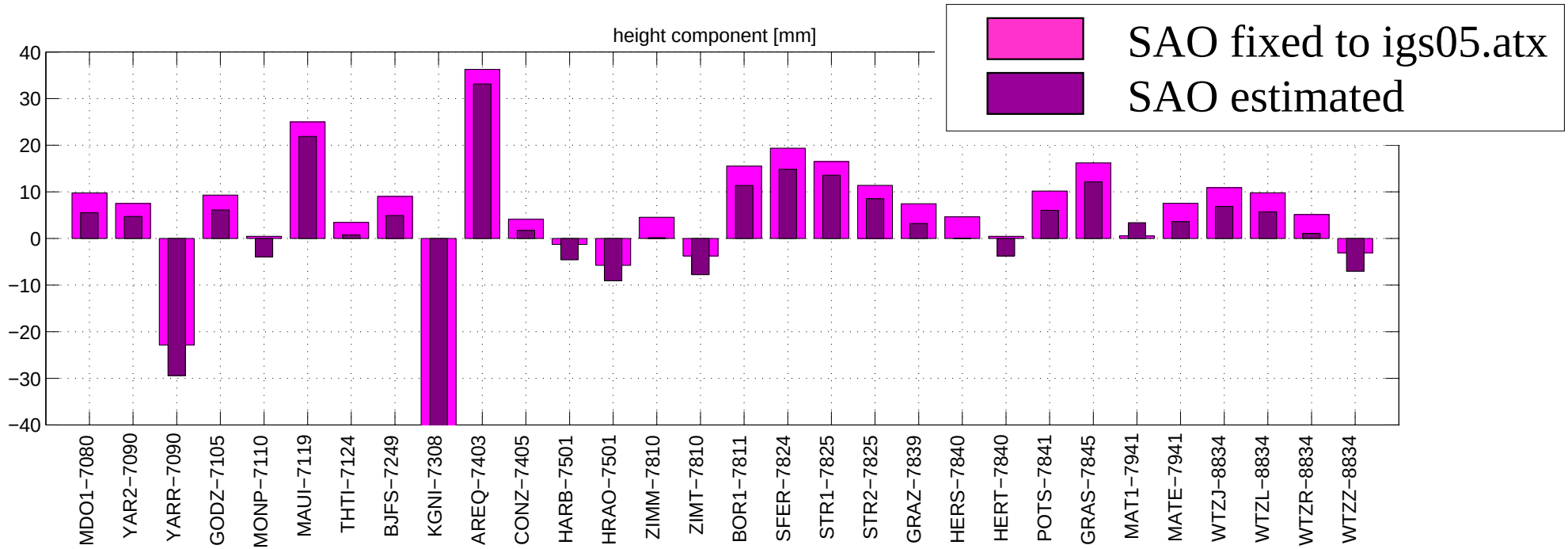
from ITRF2008-D solution (provided by M. Seitz, DGFI)

Comparison with local ties

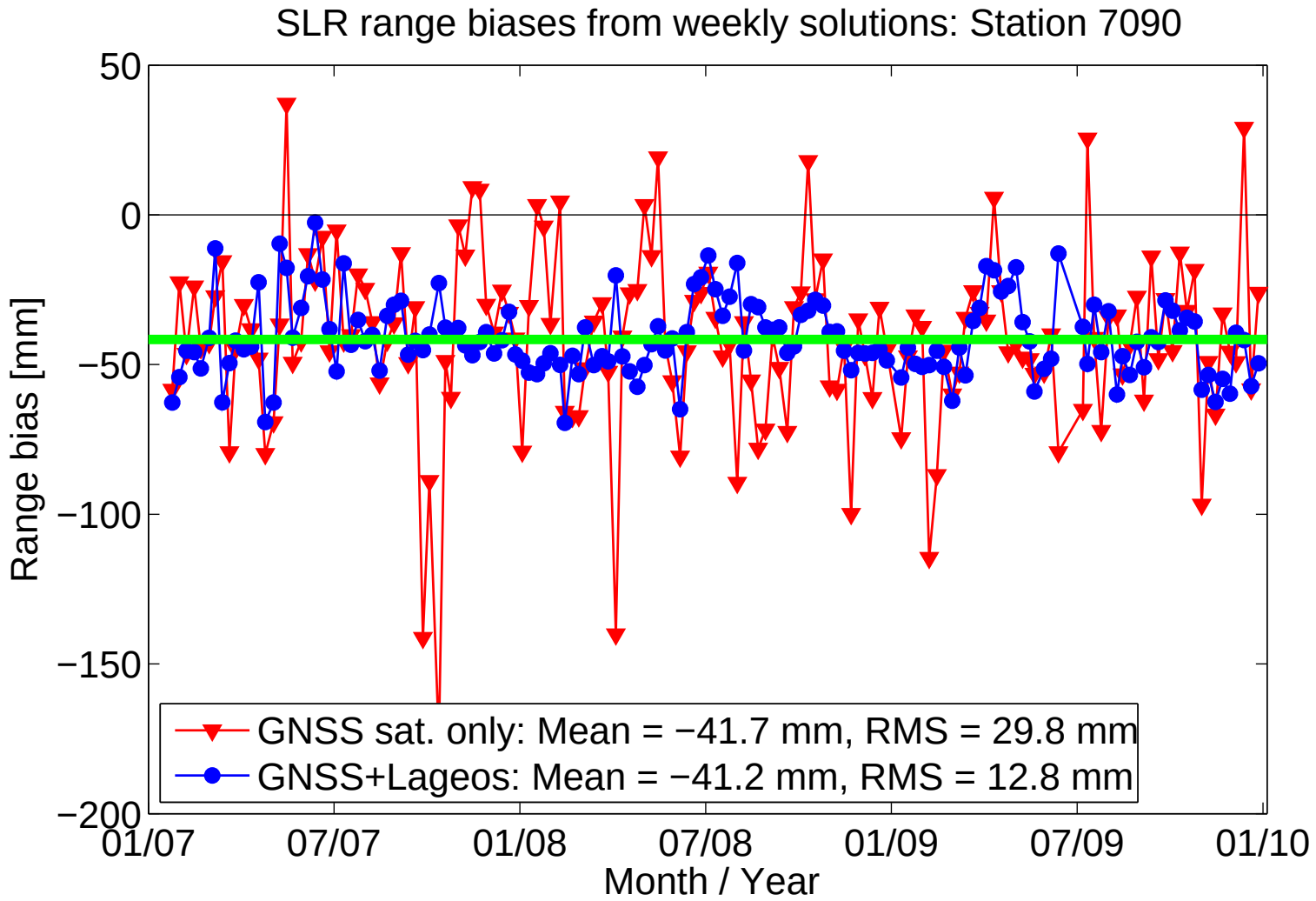
1. Estimated SLR and GNSS station coordinates ⇒ **ΔCRD_estimate**
2. Local tie between SLR and GNSS reference points: **ΔCRD_LT**

⇒ **ΔCRD_estimate - ΔCRD_LT: Height component**

⇒ Agreement between GNSS and SLR sites better if GNSS SAO are estimated (i.e. using the SLR scale)



SLR-GNSS biases



→ **Weekly** estimation from **SLR@GNSS** data only: not possible

→ Inclusion of **Lageos** data improves weekly solutions

→ **Yearly (or multi-year)** solutions needed for reliable values

SLR-GNSS biases and GNSS SAO

Effect of **range bias**:

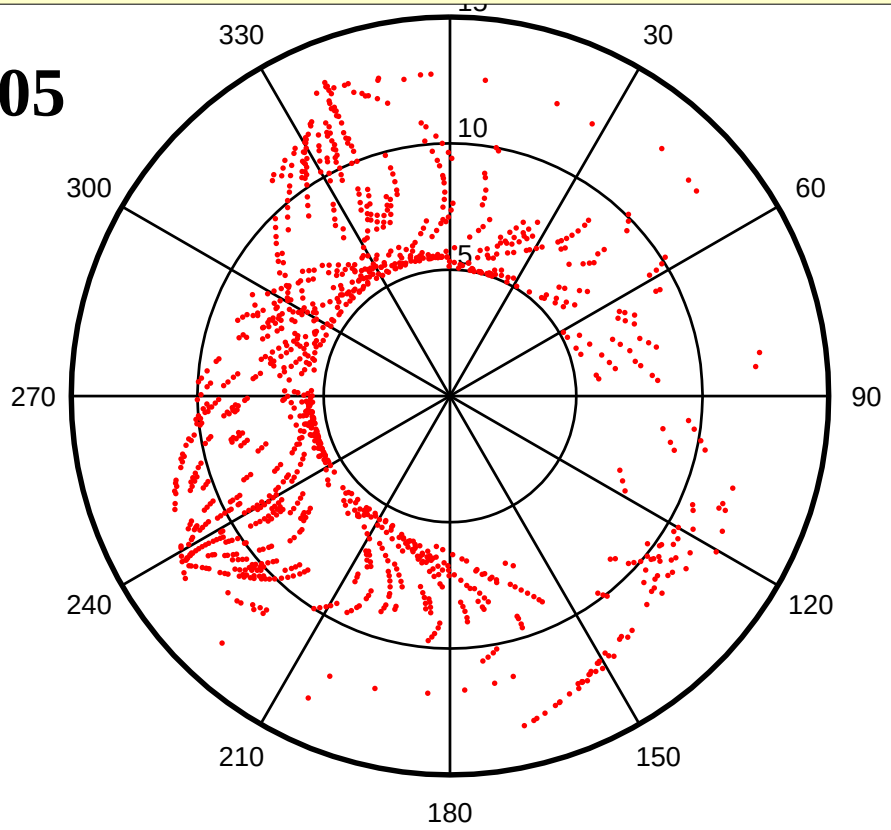
identical effect for **all directions** of the observation

Effect of **SAO**:

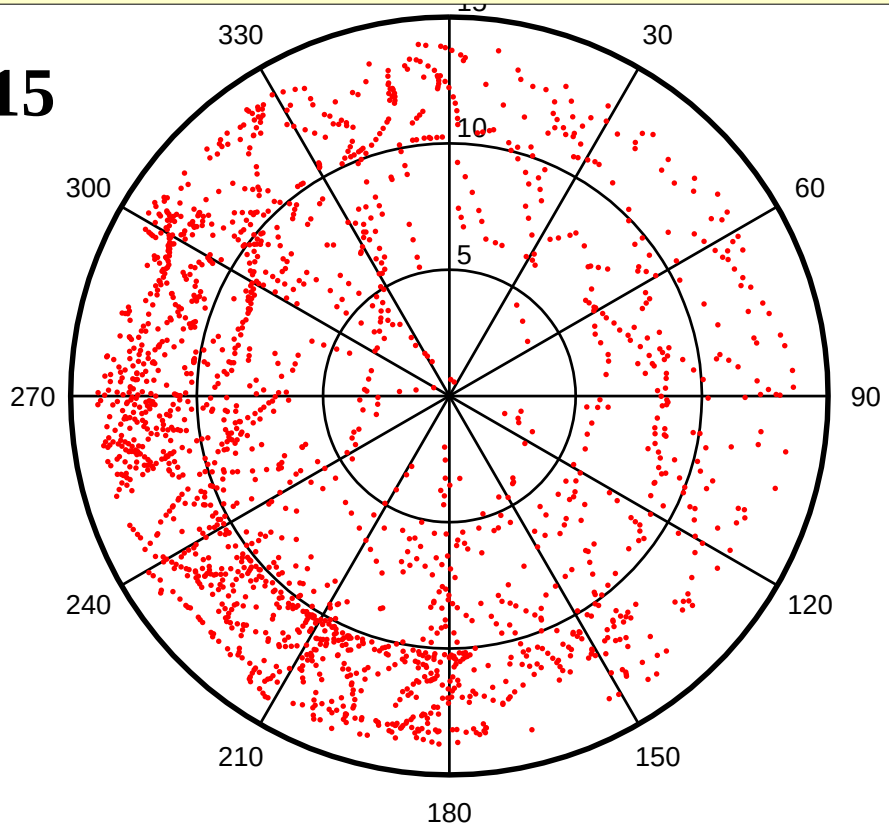
different size for **different directions** of the observation

⇒ Correlation can be reduced by **homogeneous distribution** of observations (regarding nadir / azimuth angle at the satellite)

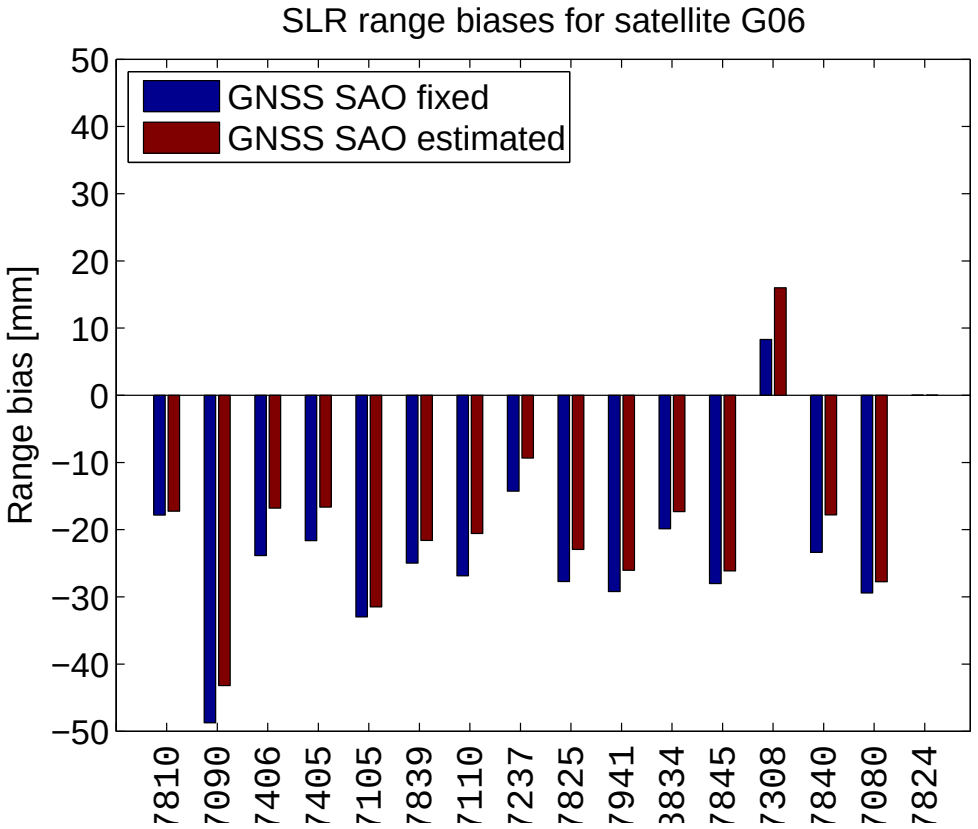
G05



R15

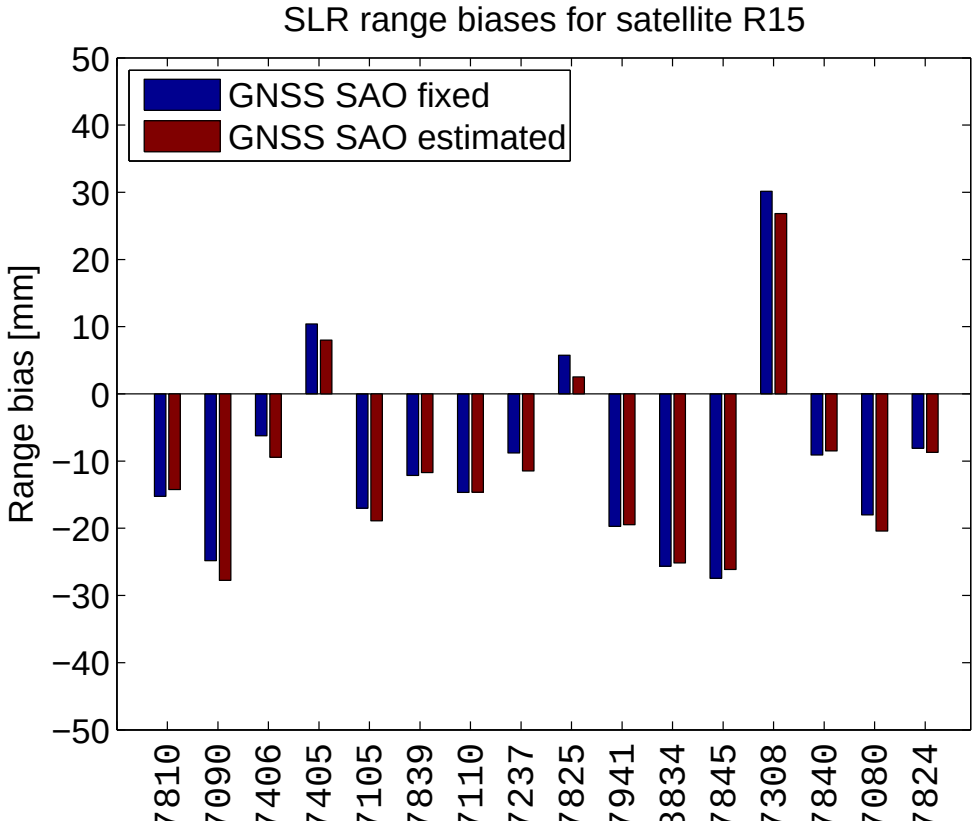


SLR-GNSS biases and GNSS SAO

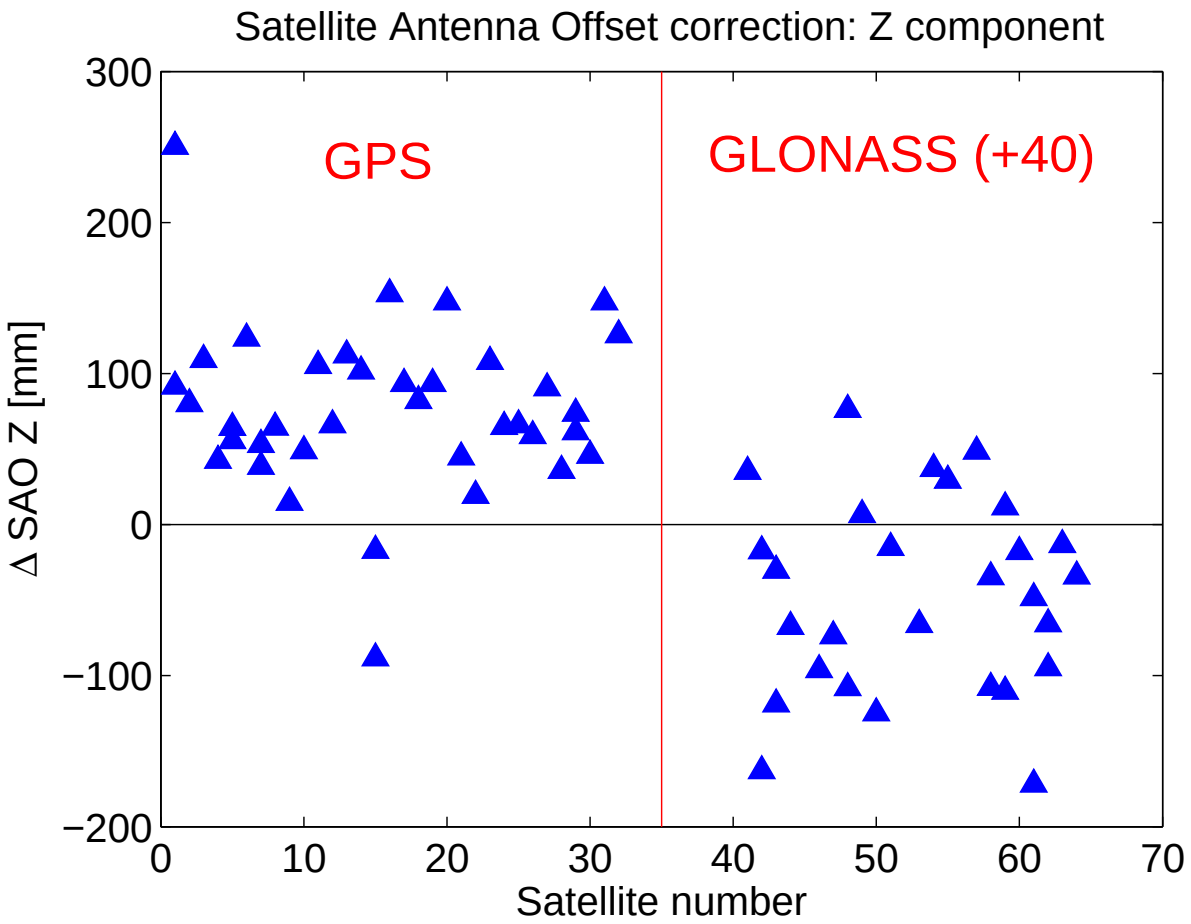


Impact of GNSS-SAO estimation on SLR-GNSS „range“ biases:

< 5 mm



SLR-GNSS biases and GNSS SAO

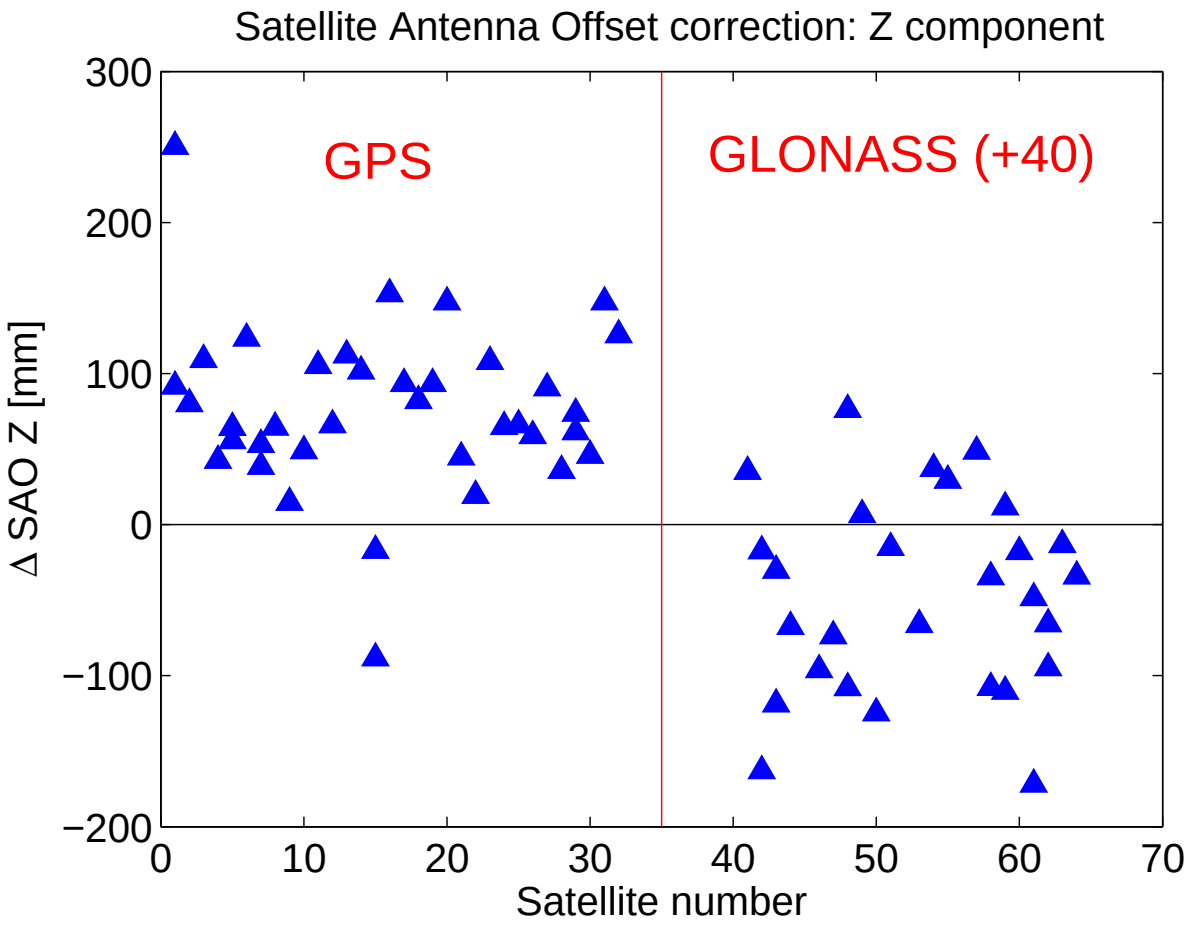


Mean **ΔZ** for GPS:
76.4 mm

Mean **ΔZ** for GLONASS:
-47.7 mm

No general shift of SAO estimates
⇒ Scale of SLR is transferred properly to GNSS

SLR-GNSS biases and GNSS SAO



Mean **ΔZ** for GPS:
76.4 mm
≈ 0.59 ppb

Mean **ΔZ** for GLONASS:
-47.7 mm

$$\Delta scale_{[ppb]} \approx -7.8 \bullet \Delta SAO_{[m]}$$

No general shift of SAO estimates
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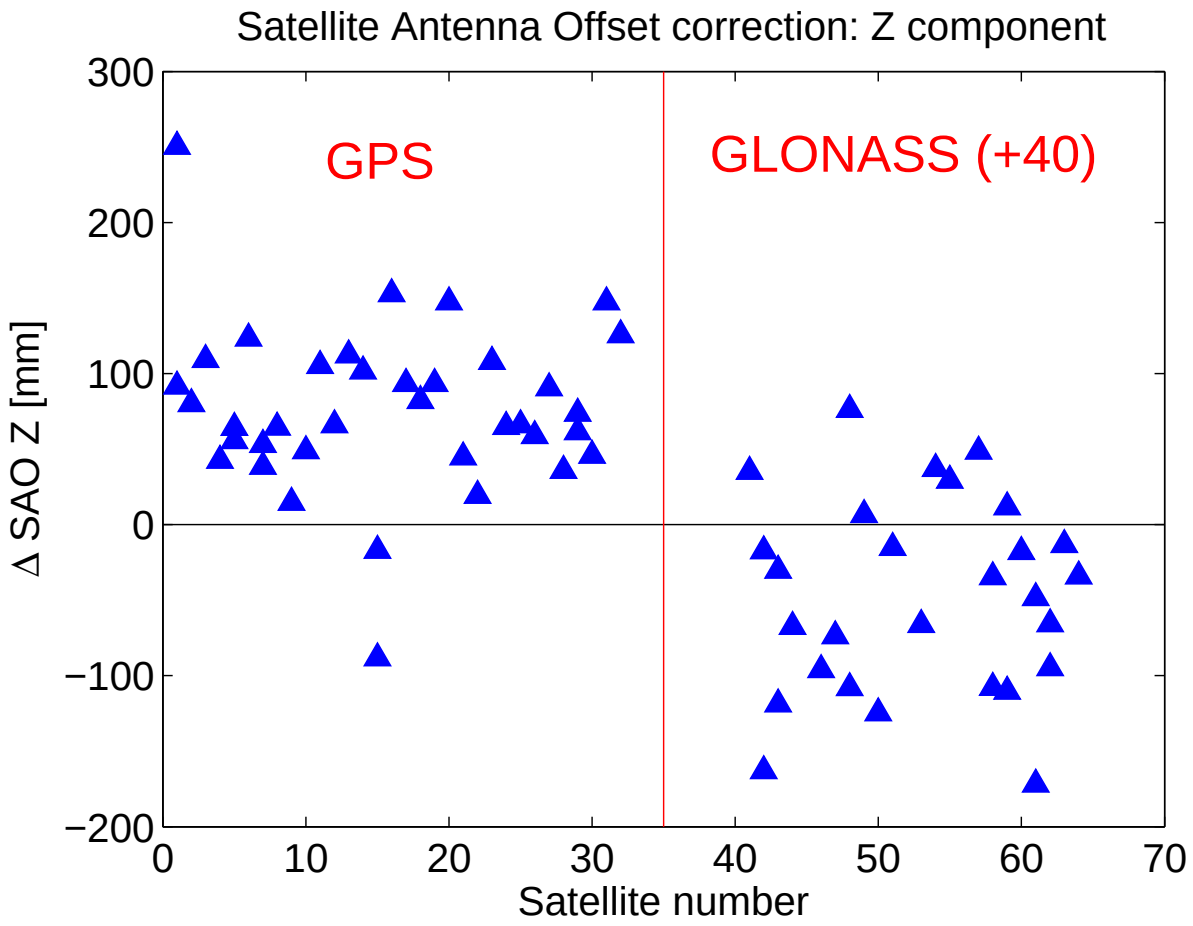
SLR-GNSS biases and GNSS SAO



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ΔScale for GNSS network:
0.59 ppb

ΔScale for SLR network:
0.00 ppb

Zusammenfassung und Ausblick -1-

- **LAGEOS**-Prozessierung mit BSW ist auf einem guten Stand

- In Zusammenarbeit mit **BKG** werden täglich Lösungen an den **ILRS** geliefert (seit Juli 2010)

- **Re-Prozessierung** am AIUB bisher für **2006 – 2010**

- Weitergehende Re-Prozessierung im Rahmen eines gemeinsamen Projektes zusammen mit ETH Zürich, TU München und TU Dresden

- Erweiterung für **ETALON** ist momentan in der Testphase

- Verbesserung der **Orbitmodellierung** (Albedo-Modell)

- Weitere Parameter, z.B. **Schwerefeld**

Zusammenfassung und Ausblick -2-

- Gemeinsame Auswertung von **SLR**- und **Mikrowellen**-Beobachtungen zu **GNSS-Satelliten** erfolgreich

- **LAGEOS** Beobachtungen stabilisieren die kombinierte Lösung

- **SLR-Massstab** wird über Satelliten-Kolokationen direkt ins GNSS-Netz übertragen
  → ermöglicht Schätzung der **GNSS SAO** ohne Fixieren des apriori Massstabs

- GNSS SAO aus ***igs05.atx*** und **SLR Massstab** sind inkonsistent (0.59 ppb)

- SLR-GNSS-Kombination via „***Space Ties***“ ist möglich (ohne Local Ties)
  → **Genaue Ties** als Voraussetzung (Stationen und Satelliten)

- **Trennung** von SLR Range Biases und **LRA Offsets** noch nötig

AIUB

Rolf Dach, Krzysztof Sosnica, Gerhard Beutler

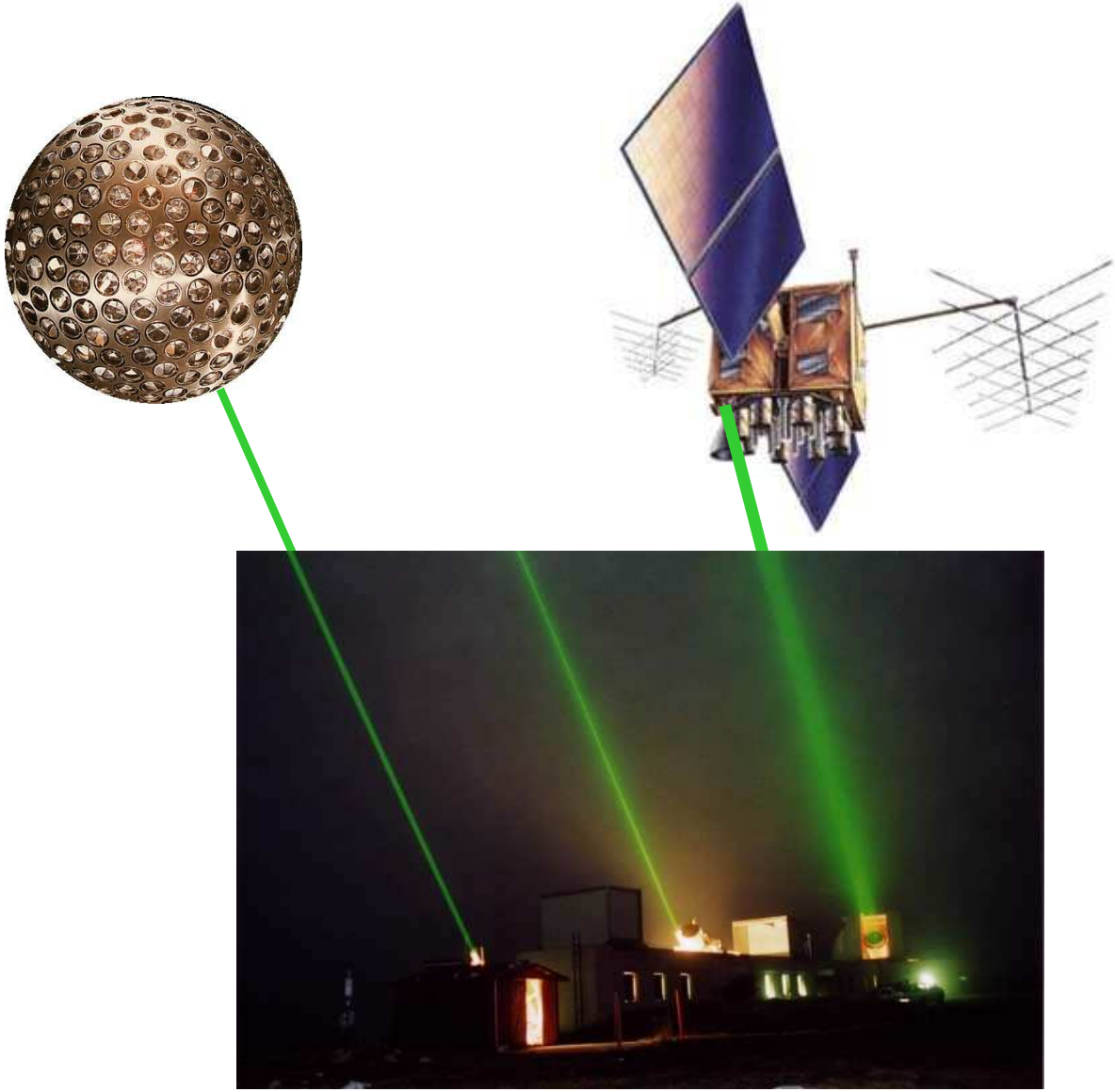
BKG

Maria Mareyen, Bernd Richter

DGFI

Manuela Seitz

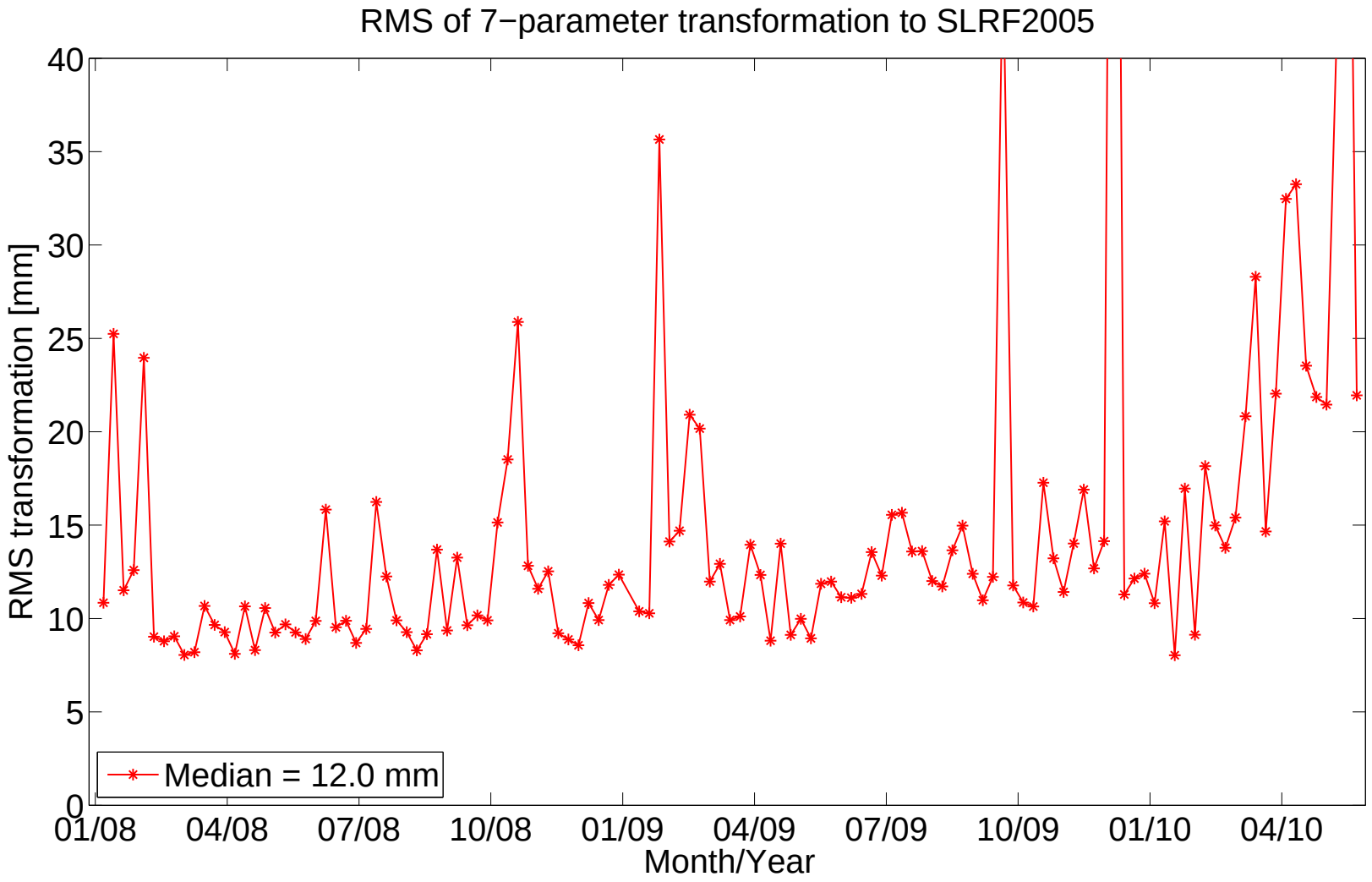
Danke für die Aufmerksamkeit !



Weekly LAGEOS solutions

Station coordinates: 7-parameter **Helmert transformation** w.r.t. SLRF2005

RMS of transformation (weighting not considered!)



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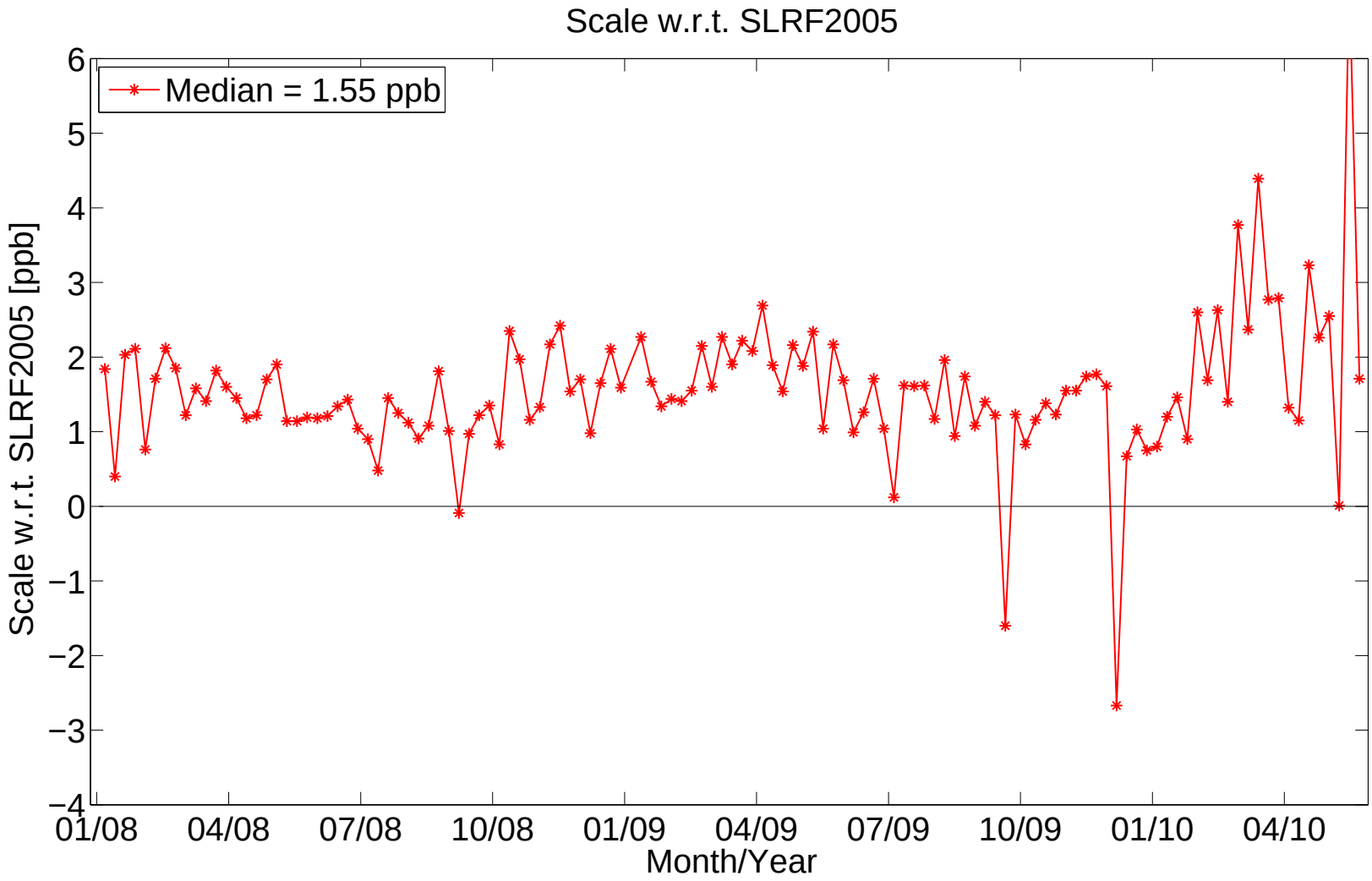
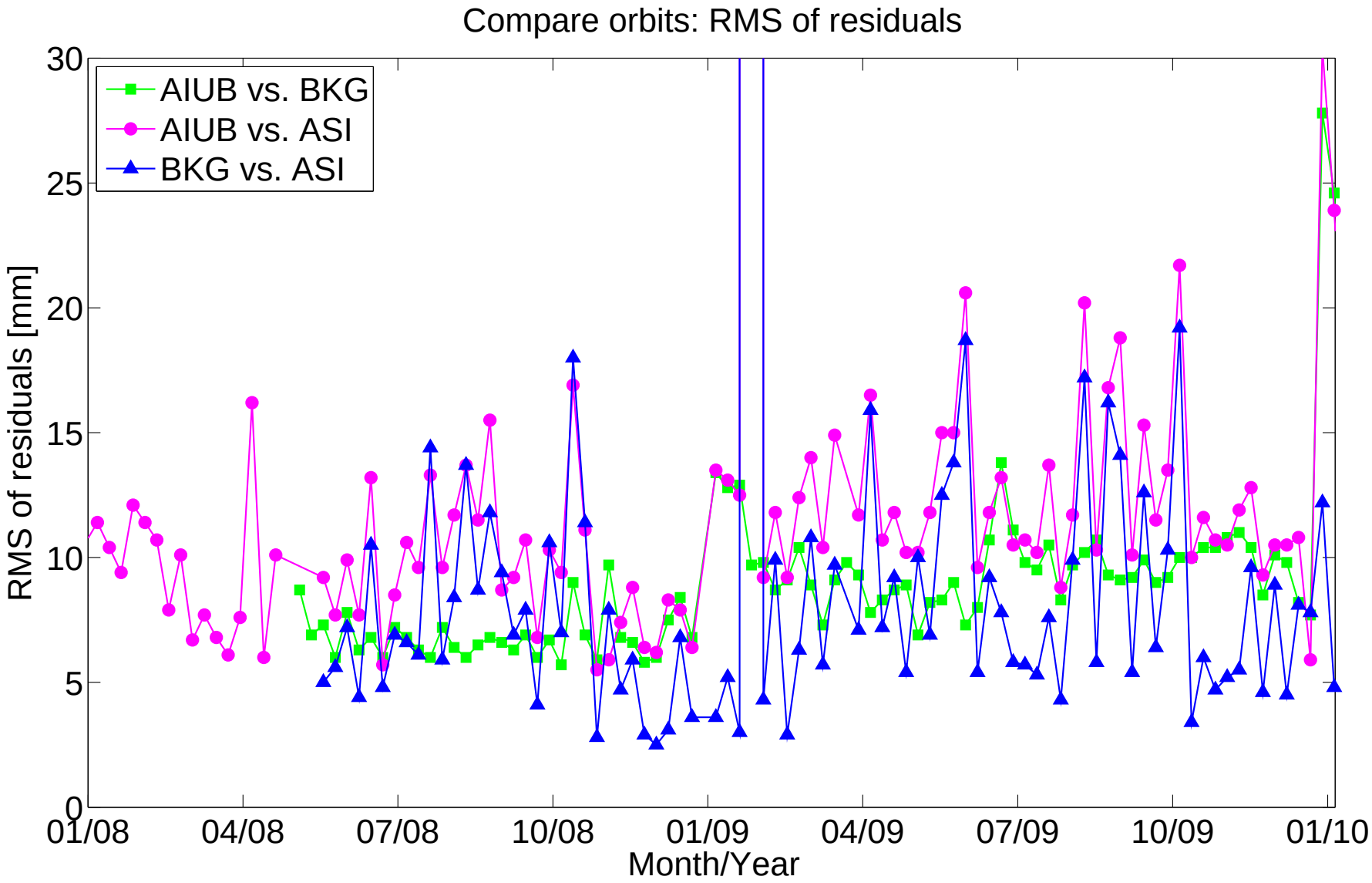


Weekly LAGEOS solutions

Orbit comparison with other ILRS analysis centers



Kombination von GNSS und SLR

GNSS

$$L_A^S = \left| \quad \mathbf{R_{EOP}} \cdot \quad \mathbf{r_A}(t_A) \qquad -\mathbf{r^S}(t_A - \tau_A^S) \right| + \delta\rho_{trop(MW),A} + \delta\rho_{ion,A} + c \cdot \delta t_A + \delta\rho_{rel} - c \cdot \delta t^S \quad + \lambda \cdot N_A^S + \delta\rho_{phas} + \delta\rho_{mult} + \varepsilon_A^S$$

SLR

$$\frac{1}{2} \cdot c \cdot \tau_A^S = \left| \quad \mathbf{R_{EOP}} \cdot \quad \mathbf{r_A}(t^S) \qquad -\mathbf{r^S}(t^S) \right| \qquad + \delta\rho_{trop(opt)} \qquad + \delta\rho_{rel} + \delta\rho_{bias} + \delta\rho_{CoM} + \varepsilon_A^S$$

Kombination von GNSS und SLR

GNSS

$$L_A^S = \left| \mathbf{R}_{\mathbf{EOP}} \cdot \mathbf{r}_{\mathbf{A}}(t_A) - \mathbf{r}^{\mathbf{S}}(t_A - \tau_A^S) \right| + \delta\rho_{trop(MW),A} + \delta\rho_{ion,A} + c \cdot \delta t_A + \delta\rho_{rel} - c \cdot \delta t^S + \lambda \cdot N_A^S + \delta\rho_{phas} + \delta\rho_{mult} + \varepsilon_A^S$$

SLR

$$\frac{1}{2} \cdot c \cdot \tau_A^S = \left| \mathbf{R}_{\mathbf{EOP}} \cdot \mathbf{r}_{\mathbf{A}}(t^S) - \mathbf{r}^{\mathbf{S}}(t^S) \right| + \delta\rho_{trop(opt)} + \delta\rho_{rel} + \delta\rho_{bias} + \delta\rho_{CoM} + \varepsilon_A^S$$

EOP:
Pol, UT, Nutation

TRF

Satellite orbit