Contributions of SLR for the Next Decade

Thomas Herring, Professor of Geophysics
Massachusetts Institute of Technology, Cambridge, MA, 02139.

Overview

- Contributions from different Geodetic techniques to achieve in scientific insights about the Earth.
- Issues to be addressed:
  - Impacts of range biases
  - Re-visit multi-color ranging and combination of methods
  - Geodetic monument stability
  - Scale between SLR and VLBI
  - Geo-center from SLR and GNSS (frame translation versus deformation signal)
  - Non-secular motions: Targets for geodetic studies.
- Science and SLR directions

Geodetic noise: Limits the possible science

- Noise in geodetic systems falls into 3 classes:
  - **Instrumentation noise** – With good engineering this noise source can be reduced (at a cost) to very small values. Failure to understand instrument noise can lead to un-diagnosed errors.
  - **Environmental noise** – In this category is propagation medium delays and satellite orbit perturbations. This class of noise can be modeled (atmospheric delay models), calibrated (e.g., dual frequency microwave systems), or estimated (atmospheric delay parameterization or empirical orbit model parameters).
  - **Earth noise** – The surface of the earth is not a deterministic system (e.g., loading effects, poro-elastic deformations, site instabilities)
- We will explore each of these topics

Addressing geodetic noise

- How to we address each of the noise sources?
  - **Instrumental noise**: Better engineering but it comes at a cost (dollars type) and how to handle mixed systems.
  - **Environmental noise**: Better models and sources of data for the models; better parameterizations of models. Better observing strategies (obvious for VLBI, more channels for GNSS, maybe satellite observation planning for SLR).
  - **Earth noise**: This is the scientifically interesting area. What can we learn from the non-secular motions of the Earth? Some examples:
    - Hydrology from surface deformations both loading and poro-elastic
    - Episodic tremor and slip (ETS) and implications about earthquake nucleation processes.

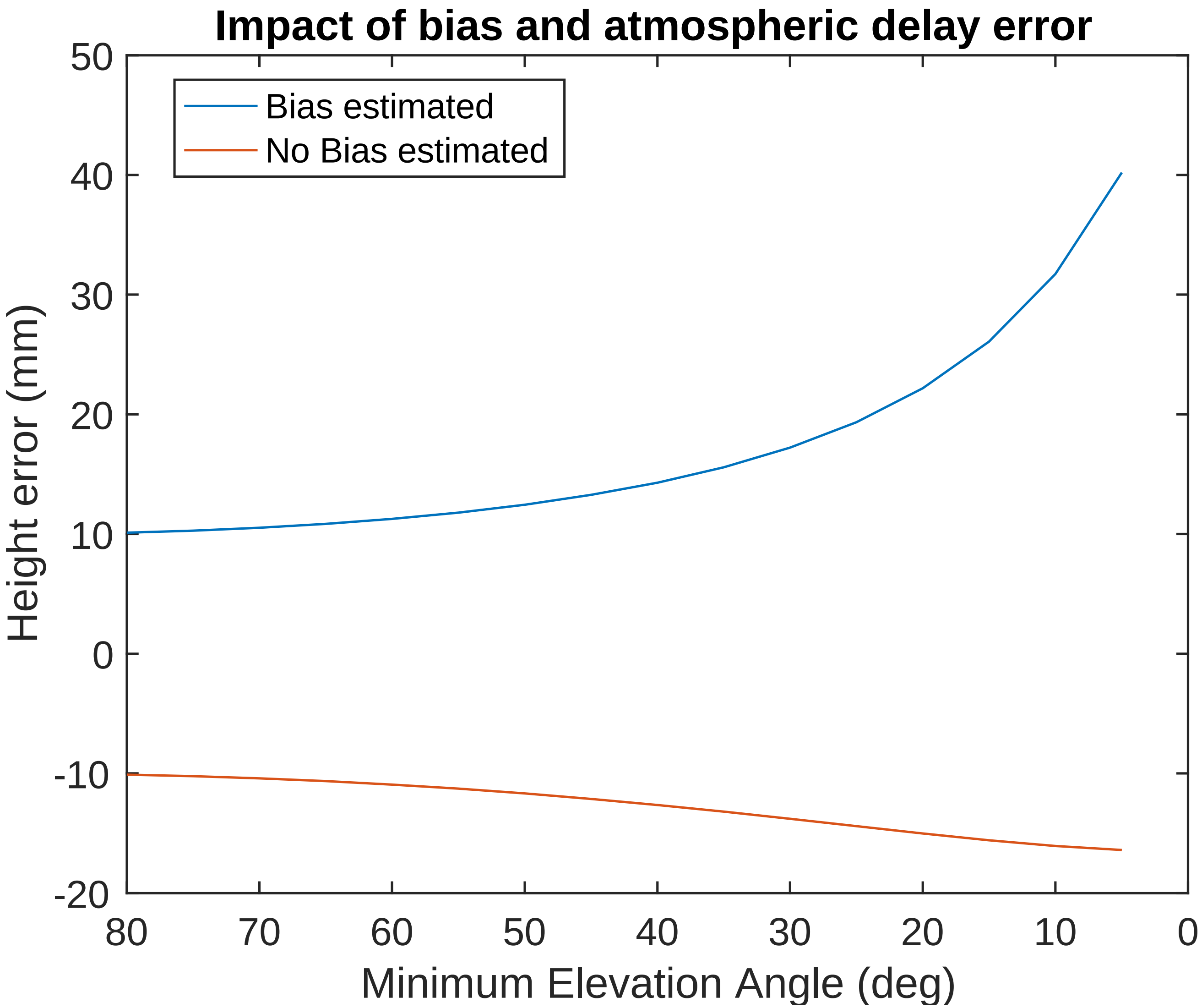
Instrumental and Environmental noise

Range bias impacts

- Problem arises from bias, height estimate ($-\sin \varepsilon$) and atmospheric delays ($\sim 1/\sin \varepsilon$) where ε is elevation angles, being correlated.
- For high elevation angles $\sim\pi /2$ all these partial derivatives are near unity and the deviation from 1 for the height and atmospheric delay goes as $(\pi /2-\varepsilon)^2$
- Approximate behavior of systems can be assessed with simple models of uniform elevation angle coverage between 90^o and a minimum elevation.
- **Example:** Atmospheric delay error impact with no atmospheric delay estimated with and without bias estimated which illustrates important characteristics.

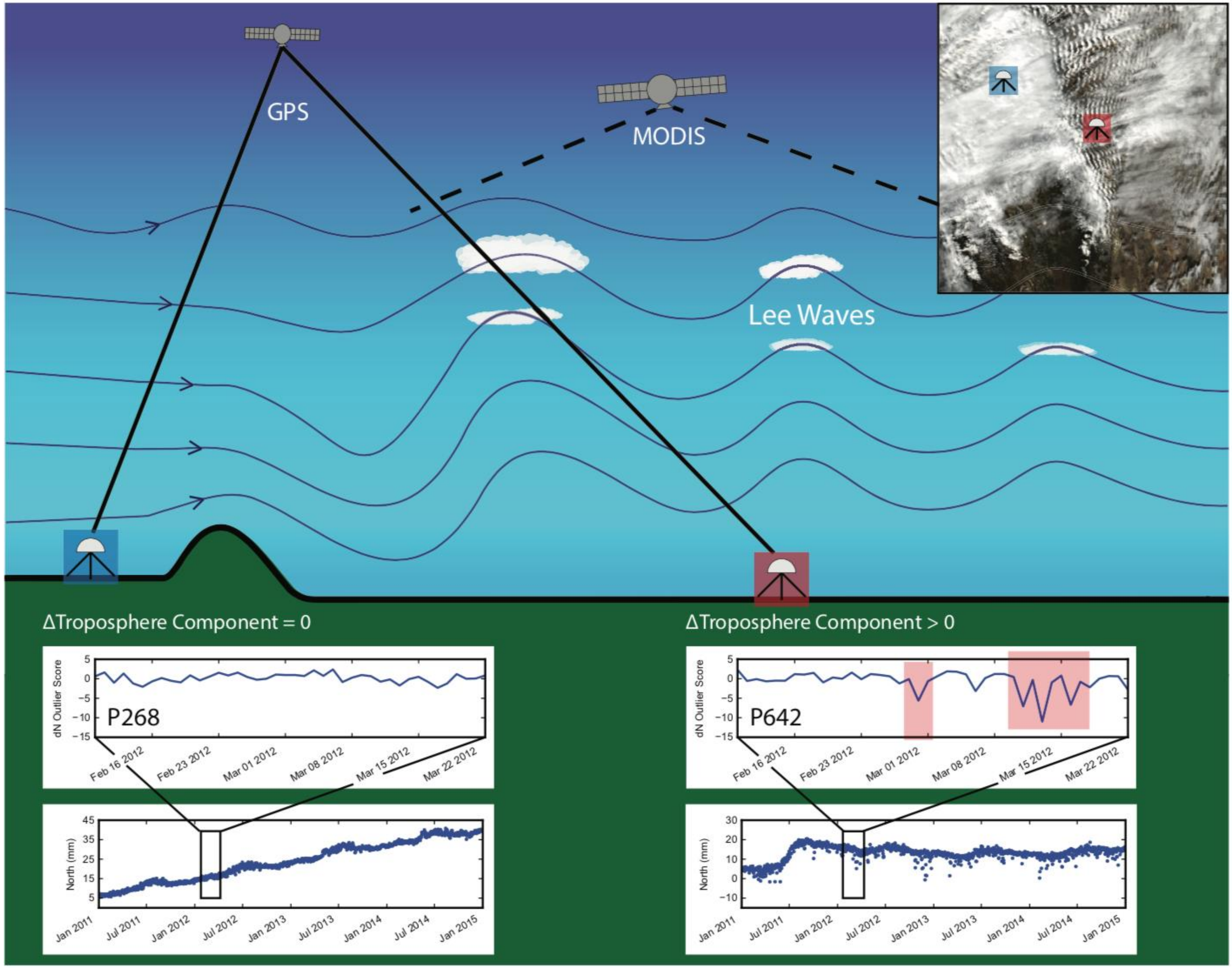
Bias estimation impact

- Figure shows impact of 10 mm zenith delay error when atmospheric delay corrections are not estimated and when a bias is or is not estimated.
- The change in sign for the atmospheric effect is a common feature.
- Implications for common atmospheric errors on microwave and SLR systems (opposite sign).



Problems with delay models

- Example of skewed position residuals
- In and near mountainous regions Lee waves can generate large position errors.
- (Originally studied for SLR applications).
- GPS example



Multi-color ranging and combination of methods

- Wavelength dependence (Owens, Optical refractive index of air, *Appl. Opt., 6*, 51-59, 1967).
- P_d, P_w are dry and wet pressures (hPa), T temperature (K), λ wavelength (μm).

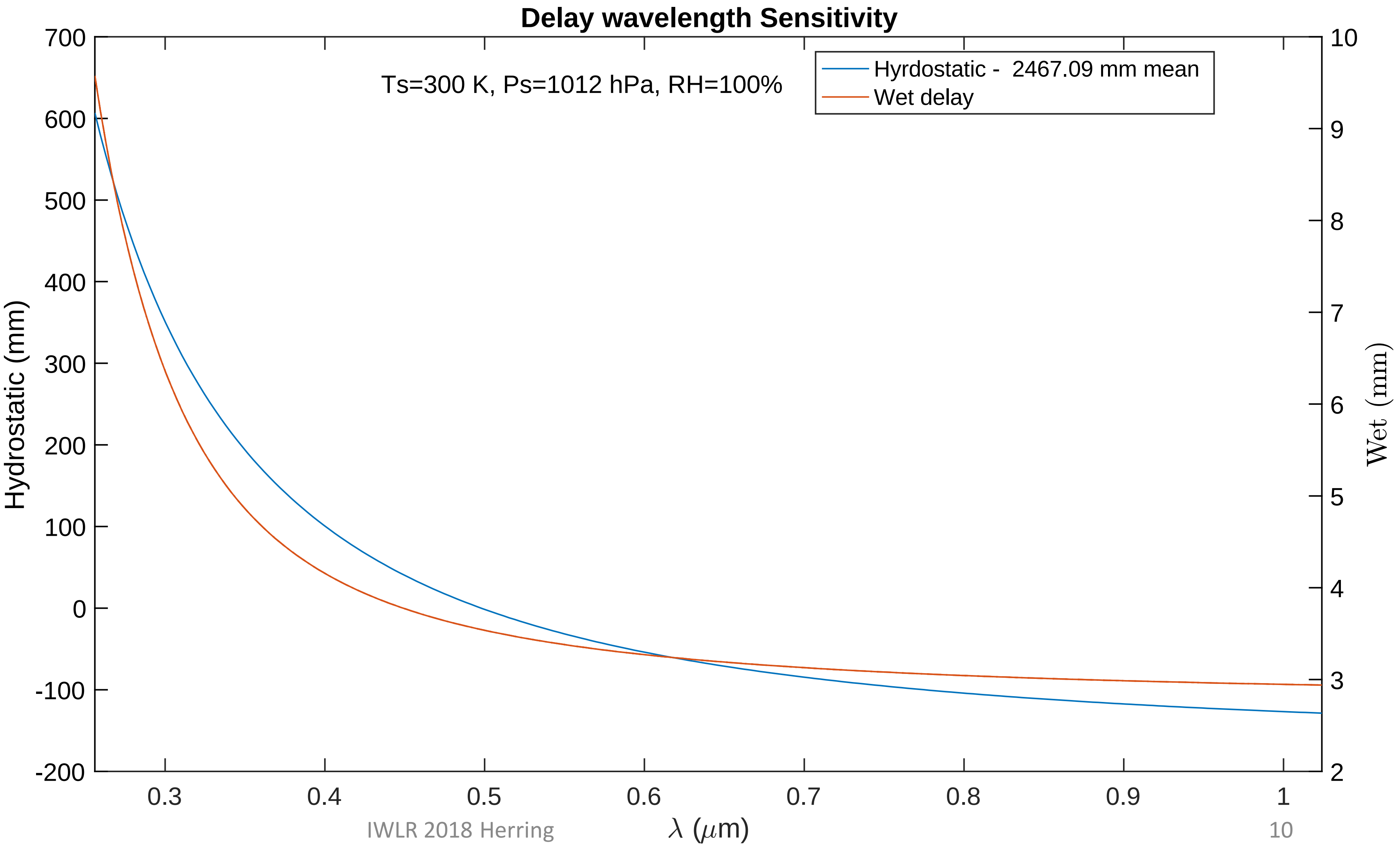
$$N = k_1(\lambda)\frac{P_d}{T}Z_d^{-1} + k_2(\lambda)\frac{P_w}{T}Z_w^{-1}$$

$$k_1(\lambda) = 164.63860\frac{(238.0185 + \lambda^{-2})}{(238.0185 - \lambda^{-2})^2} + 4.77299\frac{(57.362 + \lambda^{-2})}{(57.362 - \lambda^{-2})^2}$$

$$k_2(\lambda) = 0.648731 + 0.0174174\lambda^{-2} + 3.55750\times10^{-4}\lambda^{-4} + 6.1957\times10^{-5}\lambda^{-6}$$

Example 1.024/0.512/0.256 (μm)

- Delay at 300K, 1013 hPA, 100% Relative humidity
- Microwave wet delay: 213 mm.



Impact of water vapor

- Dual color approach (Nd:YAG, double/triple/quad)

Wavelengths (μm)	$F\lambda_1$	$F\lambda_2$	Wet Delay (mm)	Wet Error (mm)
1.024/0.512	20.7	-19.7	2.9	-7.9
0.512/0.256	5.0	-4.0	3.5	-20.8

- Tri-color approach

Wavelengths (μm)	$F\lambda_1$	$F\lambda_2$	$F\lambda_3$
1.024/0.512/0.256	33.43	-34.89	2.47
1.024/0.512/0.341	46.56	-59.72	14.16

Water vapor is 100% humidity for 2-km layer with 300K surface temperature (213 mm microwave delay)

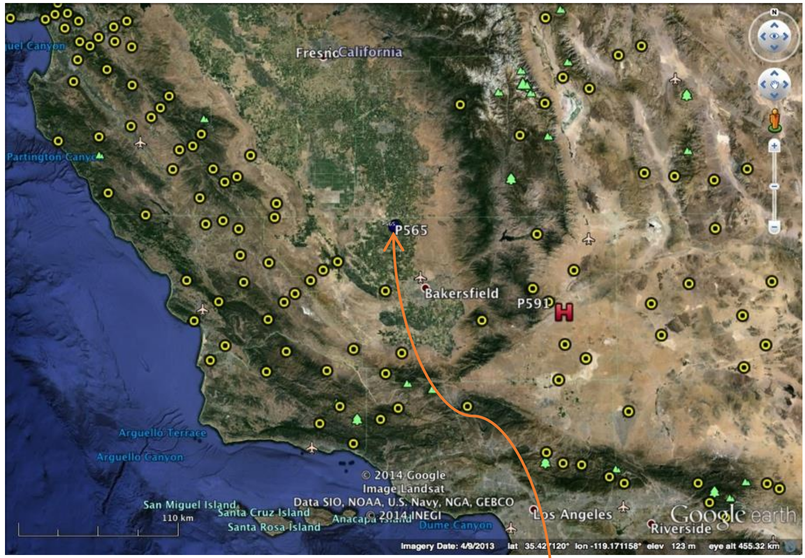
Geodetic monument stability: Analysis Methods

- The analyses here will concentrate on short-baseline processing. Site separations are less than 50 m.
- For these lengths compare L1+L2 phase solution with ionospheric free phase (LC):
  - For GPS: PC = 2.5 P1 – 1.5 P2 Range equation
  - LC = 2.5 L1 – 2.0 L2 Phase equation (result in L1 cycles, 190 mm wavelength)
- Noise amplification of ionosphere observable makes it useful for seeing electrical effects at site (multipath and other frequency dependent errors).
- LC is observable used standard processing.
- In these analyses, atmospheric delays are not estimated.

Environment: Local ground motions

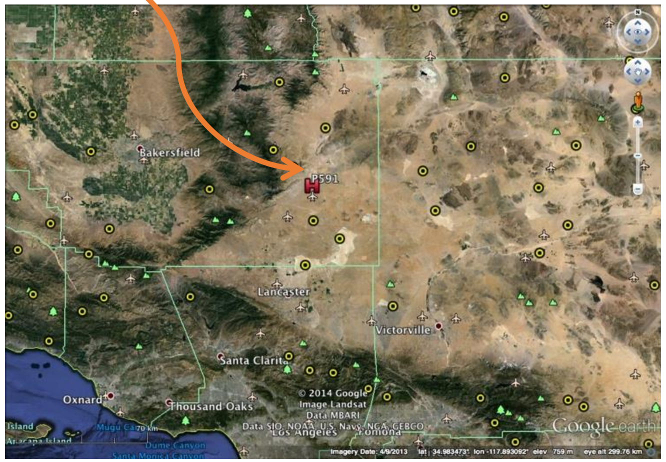
P591+P811+P812 GPS sites

- These sites are part of the UNAVCO GAGE/PBO monument stability test that has been running for about 1 year so.
- P591: Deep drilled braced monument; P811: Pillar design; P812 short drilled braced monument.

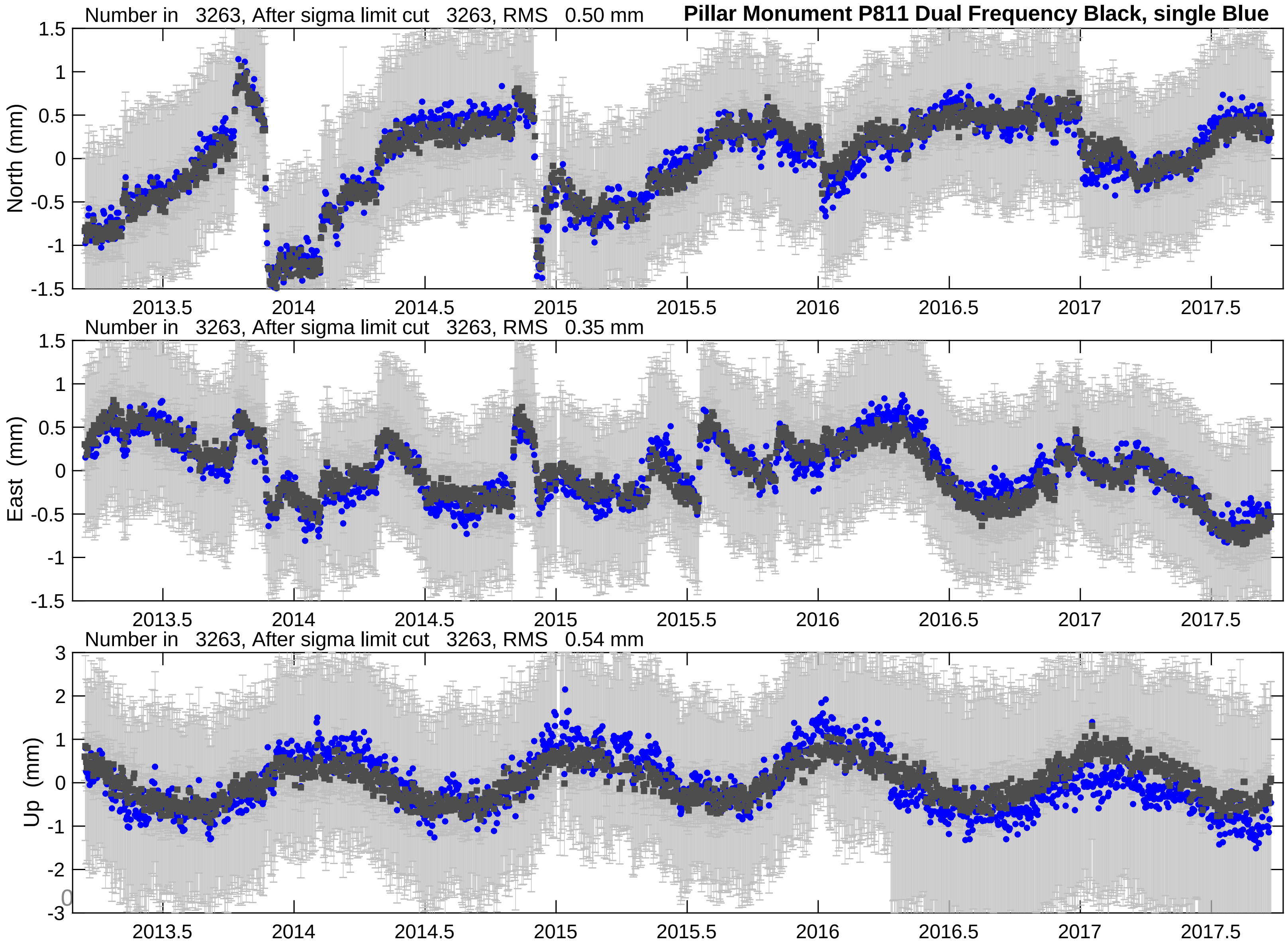


P565 (Central California)

P591/P811/P812 (Southern California)



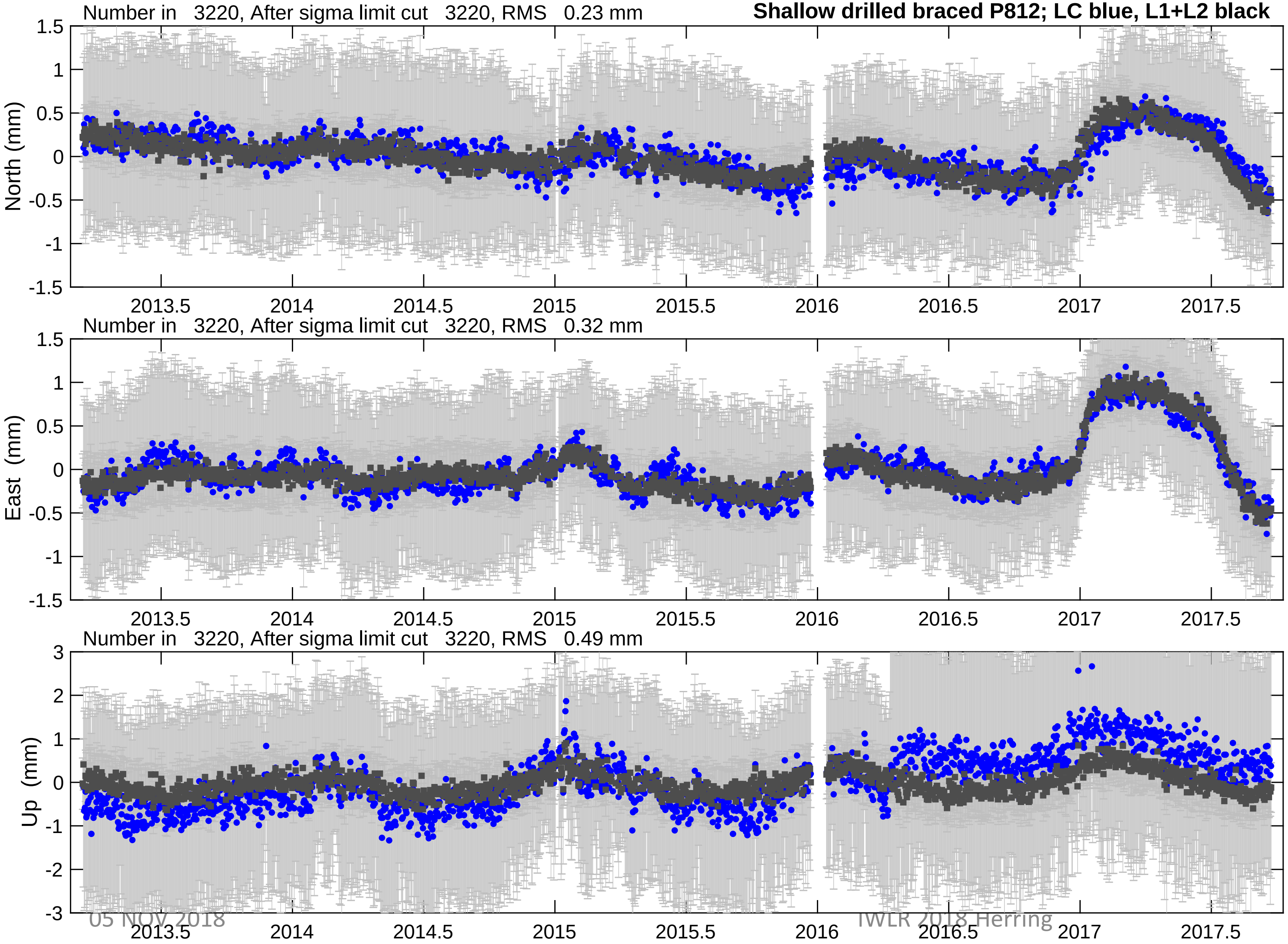
P811 Pillar wrt P591 deep drilled braced monument



Pillar is unstable at 1 mm level; physical motion implied similar L1+L2 and LC changes. Rapid change at times of rain.

Offset between L1+L2 and LC have been removed suggesting antenna element centering problem. ΔNEU 2.7, -1.5, -2.1 mm

P812 short drilled braced wrt P591

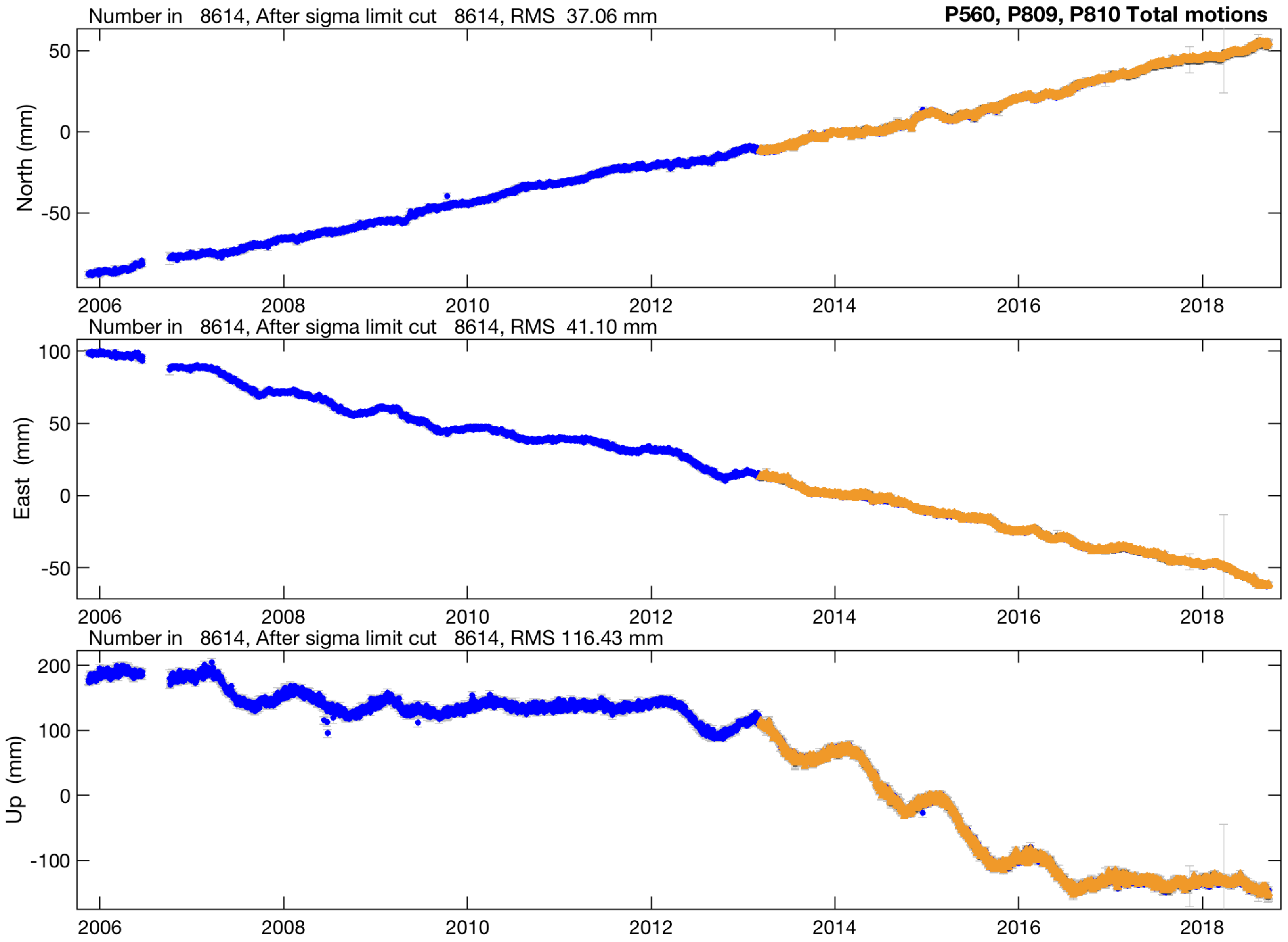


Short drilled braced is more stable until early 2017.

Annual signals in height between shallow and deep monuments is commonly seen (thermal expansion of upper layers).

Offsets between LC and L1+L2
ΔNEU -1.1, -0.4, -1.8 mm

P565 Central Valley: Standard processing



Results for standard UNAVCO GAGE project processing. These are available on web. Large motions are due to tectonics and ground water removal

Relative monument motion is small at this scale

VLBI/SLR comparisons

VLBI/SLR comparison

- Colocation sites for time series and scale comparison
- There are 25 VLBI/SLR sites within 10 km of each other. 17 pairs of these halve VLBI and SLR velocities standard deviations < 1 mm/yr (3 of these are 1 VLBI with 2 SLR stations).
- Only 6 pairs have survey ties between the VLBI and SLR sites in the ITRF2014 site tie files.
- Processing here:
  - ILRS SLRa ITRF2014 sinex files (ends 2015.0)
  - IVS on-going files in ITRF2014 systems (ends September 2018).
  - Start 1996 to be consistent with GPS and avoid low quality early solutions

Analysis approach

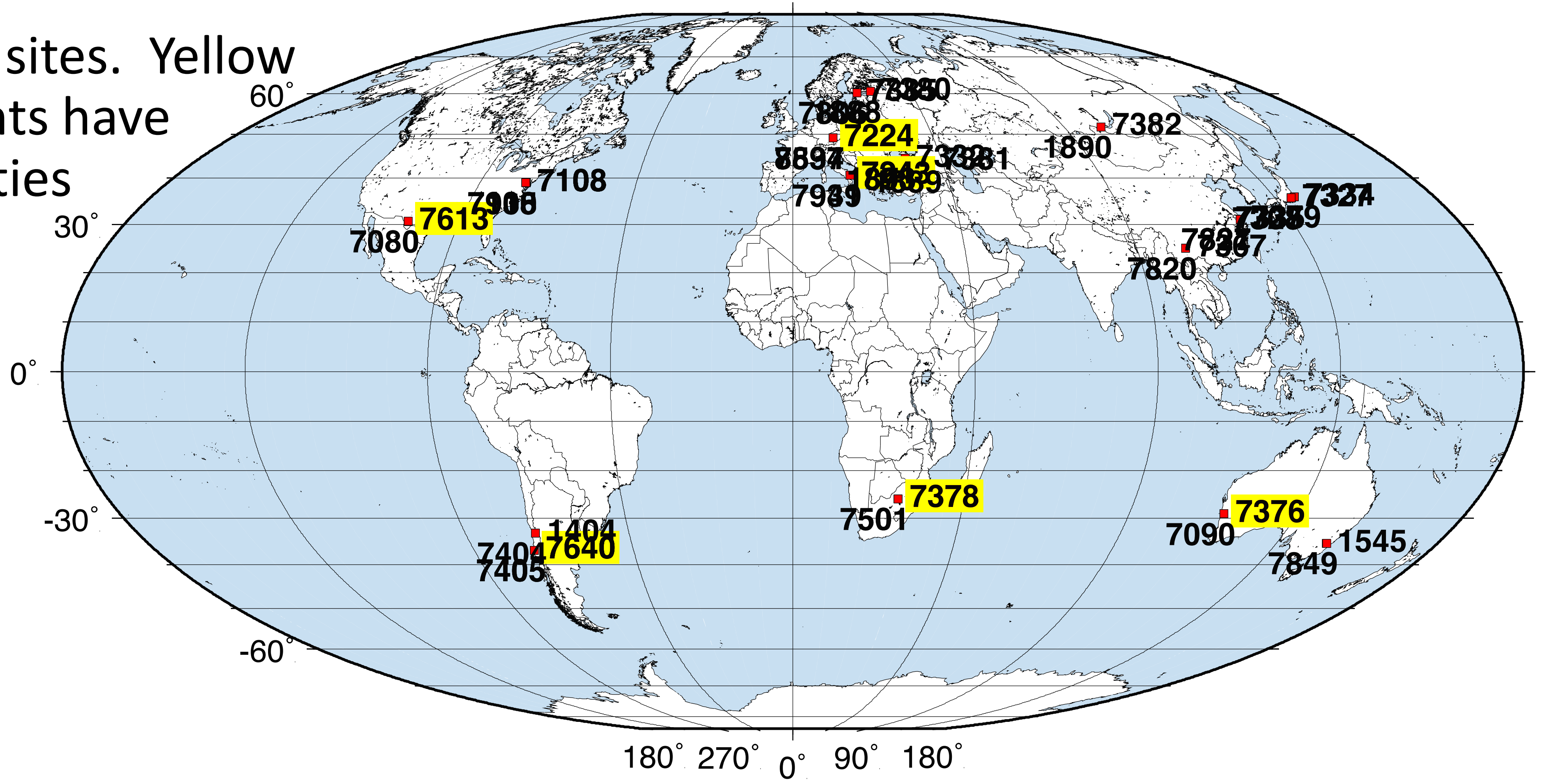
- **Two types of solutions:**
- "Mean" position differences
  - Velocity estimates VLBI and SLR separately
  - Apply survey ties to VLBI solution to generate SLR coordinates
  - Compare VLBI $\rightarrow$SLR with SLR direct estimate
  - NOTE: Velocities not forced to be equal and because additional ~3 years of VLBI data, velocity differences affect results.
- Time series analyses
  - Process each session/week separately and align to ITRF2014 with rotation and translation. Heights down weighted in transformation estimation.
  - Use mean height difference as scale difference estimate

Basics of Analysis Approach

- Kalman filter processing
- Variance factors of 50 need to be applied for both SLR and VLBI processing
- Reference frame resolved by rotation and translation with heights down weighted (variance factor of 10) in the computation of transformation parameters.
    - This approach is different to ITRF2014 methods

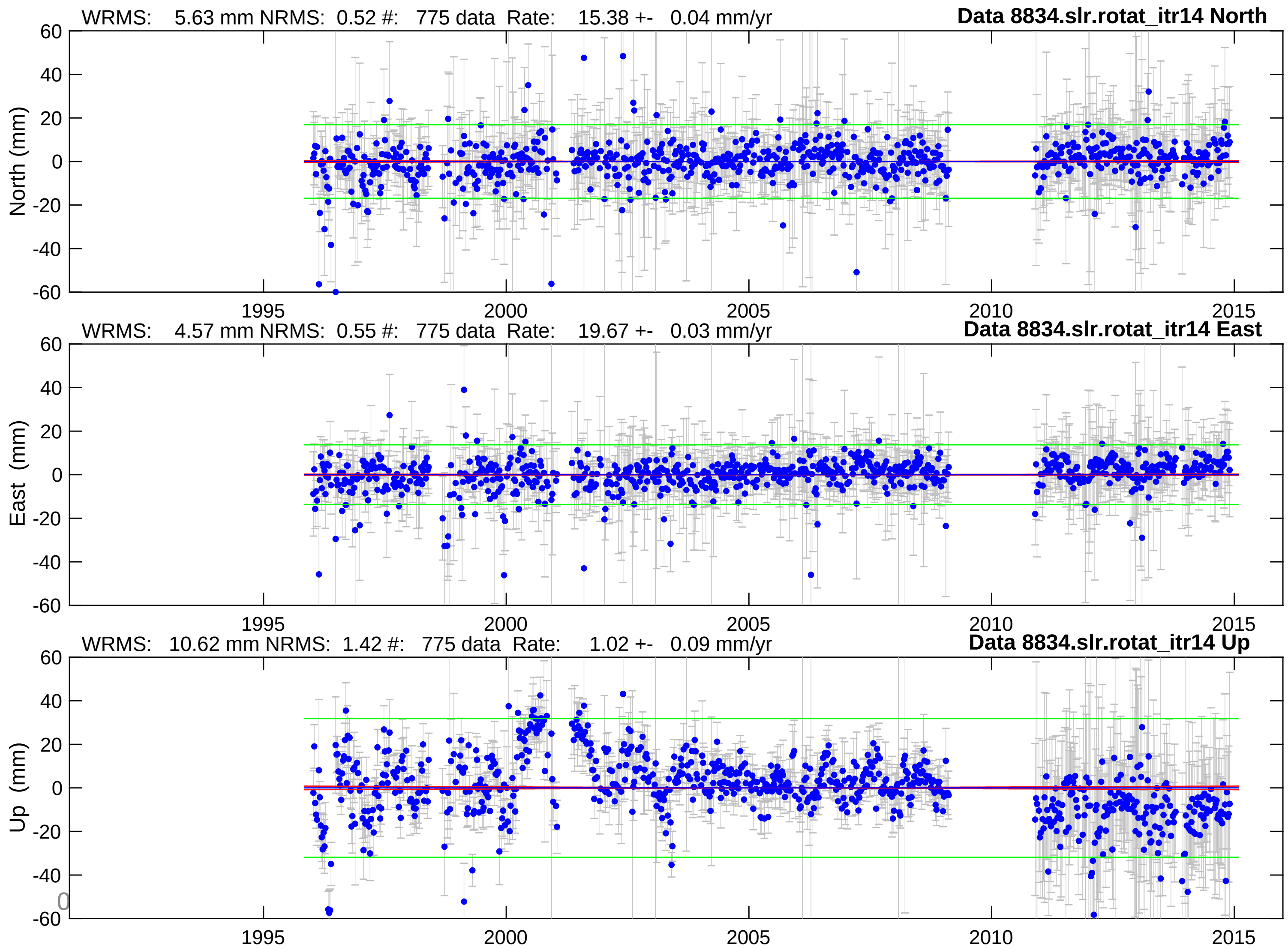
Locations of VLBI/SLR sites <10 km apart

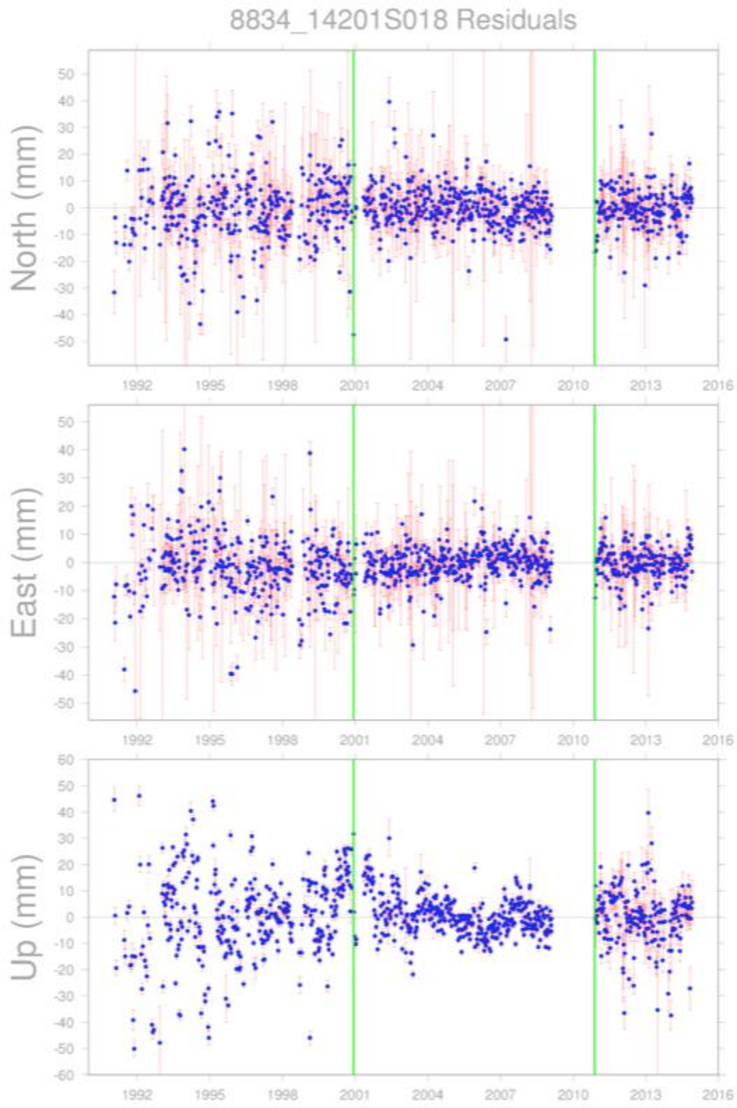
- Map of sites. Yellow highlights have survey ties



Comparison: ITRF2014 Residual vs MIT

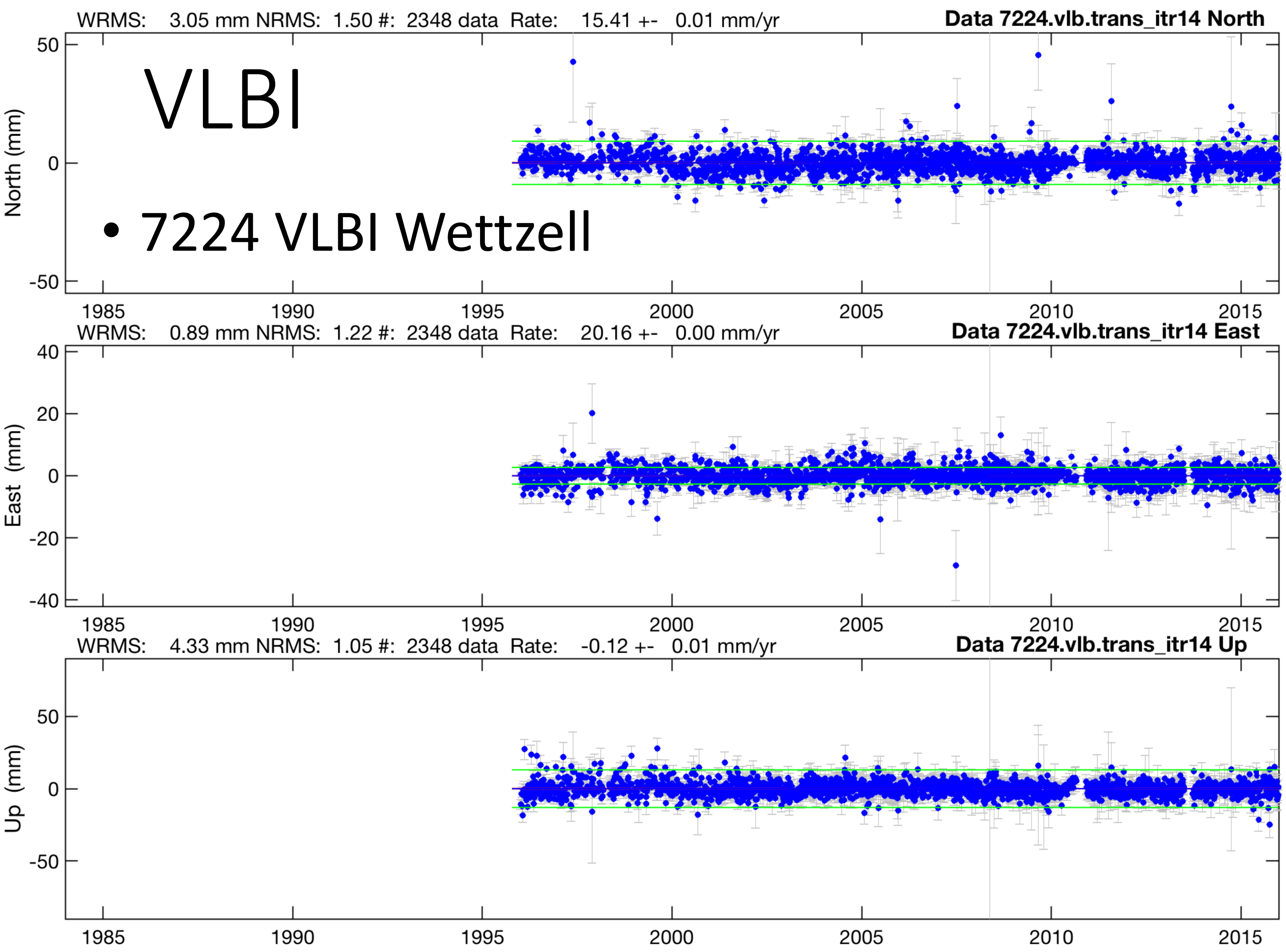
- Residuals for Wettzell SLR 8834

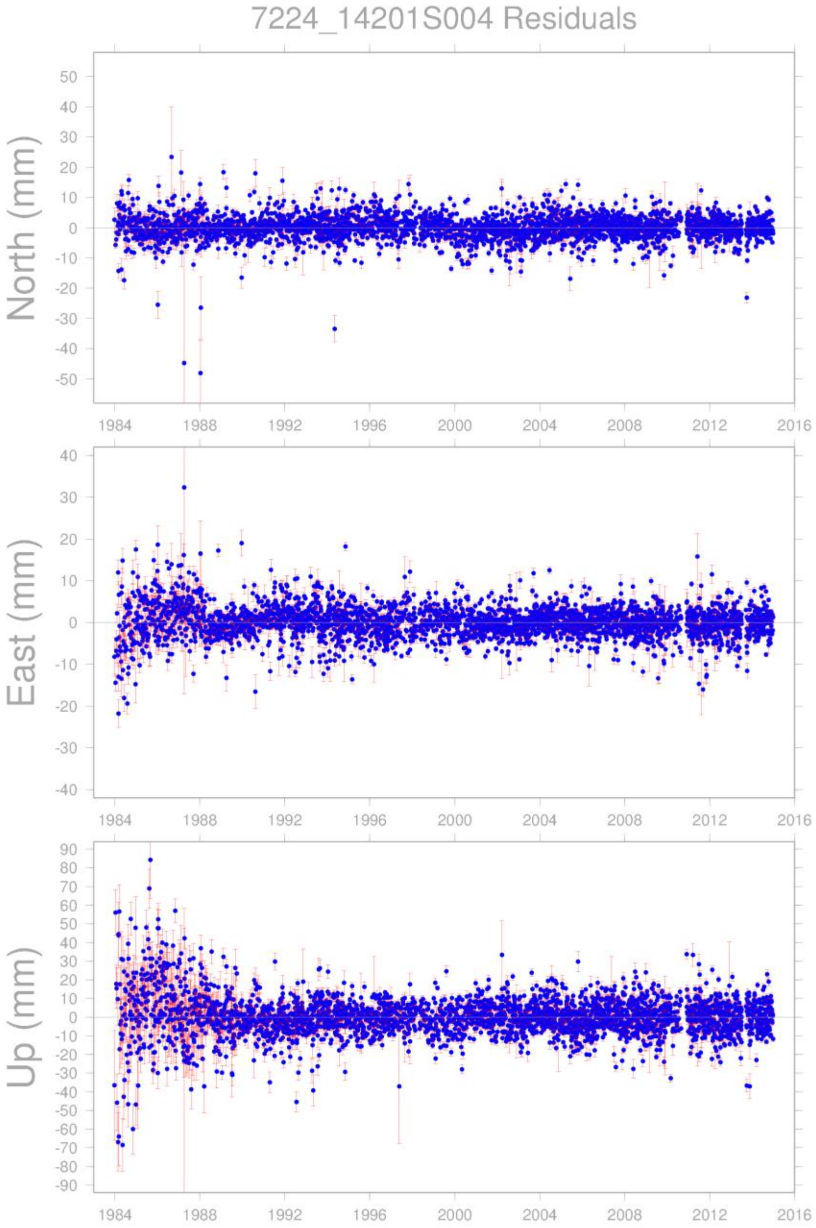




VLBI

- 7224 VLBI Wettzell





Wettzell (7224/8834/WTZR)

Height of interest for scale between VLBI and SLR

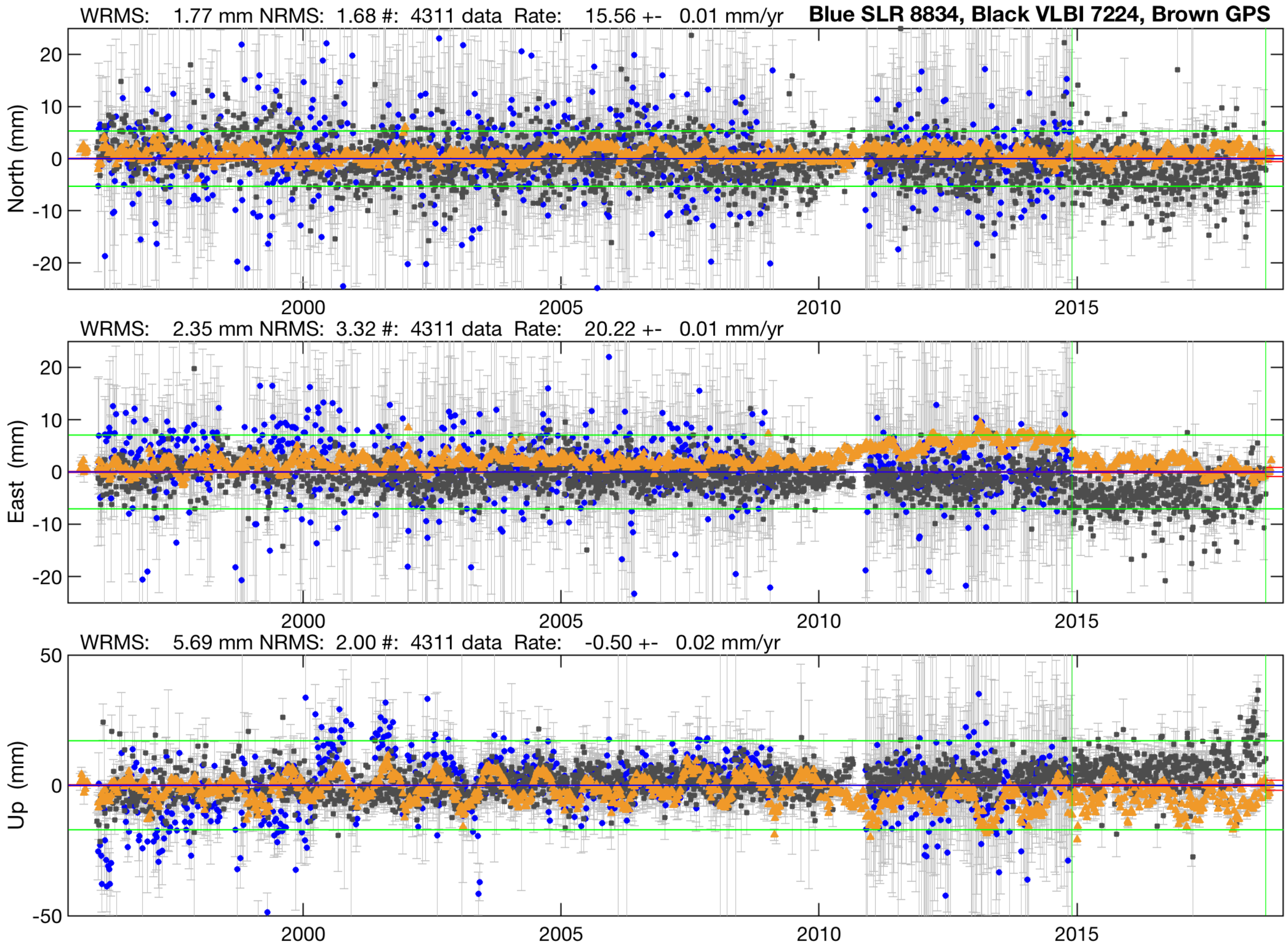
- Difference from ITRF2014

System	ΔN (mm)	ΔE (mm)	ΔU (mm)
VLBI	-5.6±0.4	-2.4±0.3	-11.9±0.5
SLR	-0.0±1.2	1.2±1.0	-13.0±1.9
ΔU			+1.1 (mm)
	ΔVn (mm/yr)	ΔVe (mm/yr)	ΔVu (mm/yr)
VLBI	-0.6	0.0	-0.1
SLR	-1.3	-0.3	-0.1

Two other SLR 8834 locations: ΔU -16.8±2.3 and -20.2± 1.4 (mm)

Overlay of SLR, VLBI, and GPS: Wettzell

- Comparison: Height difference VLBI-SLR 1.1 mm
- Offsets between the time series have been removed.
- SLR quality degrades after 2011



Matera (7941/7243/MATE)

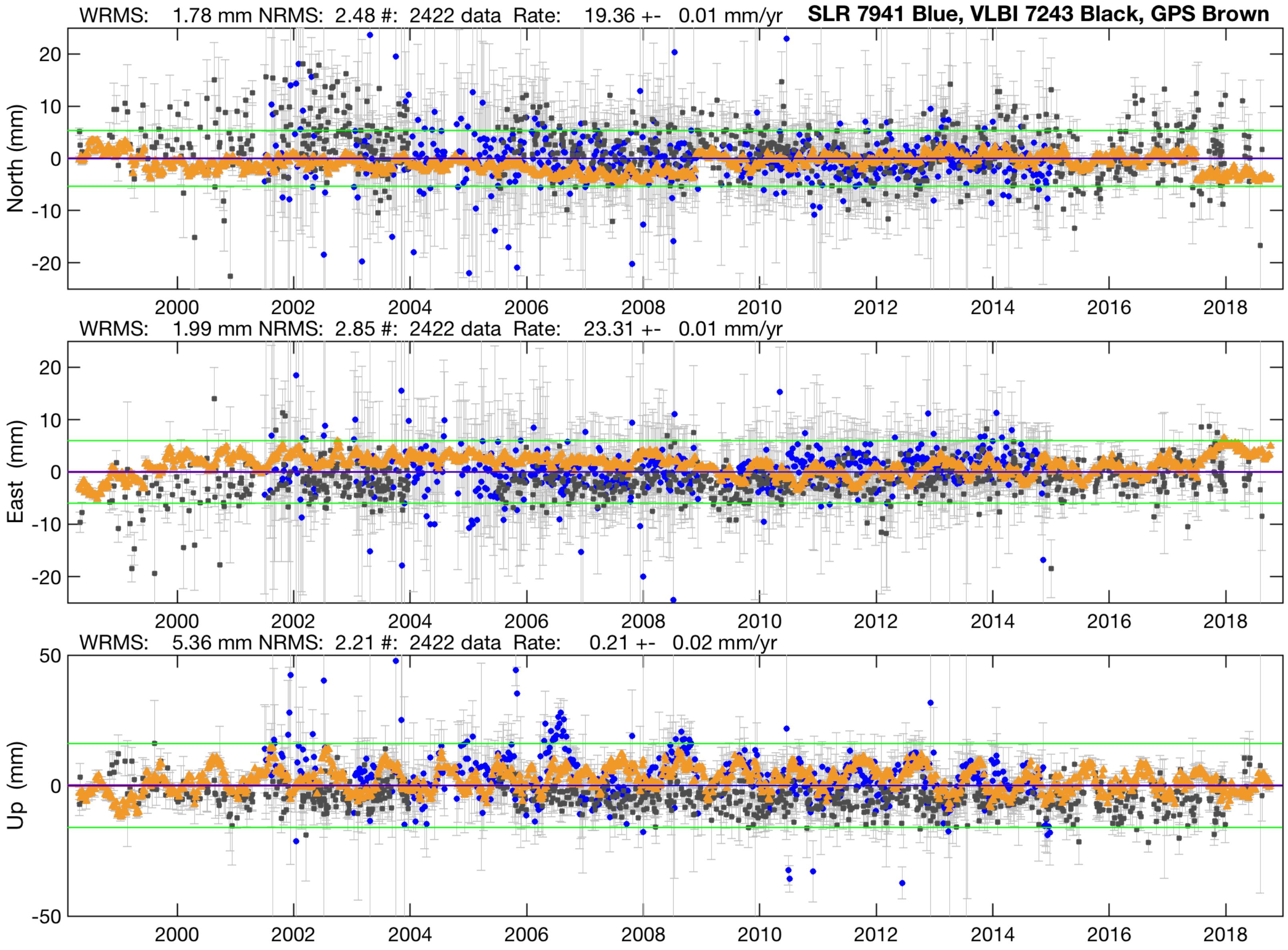
Again focus on height difference

- Difference from ITRF2014

System	ΔN (mm)	ΔE (mm)	ΔU (mm)
VLBI	-5.3 ±2.1	-5.6 ±0.5	-1.2 ±0.6
SLR	2.2 ±0.9	3.1± 0.8	-10.7± 0.8
ΔU			+9.5 (mm)
	ΔVn (mm/yr)	ΔVe (mm/yr)	ΔVu (mm/yr)
VLBI	-0.1	-0.2	0.2
SLR	0.1	0.3	-0.8

Overlay of SLR/VLBI and GPS

- Comparison: Mean height difference VLBI-SLR +9.5 mm
- Offsets between the time series have been removed
- SLR have large annual in 2006 and 2008.



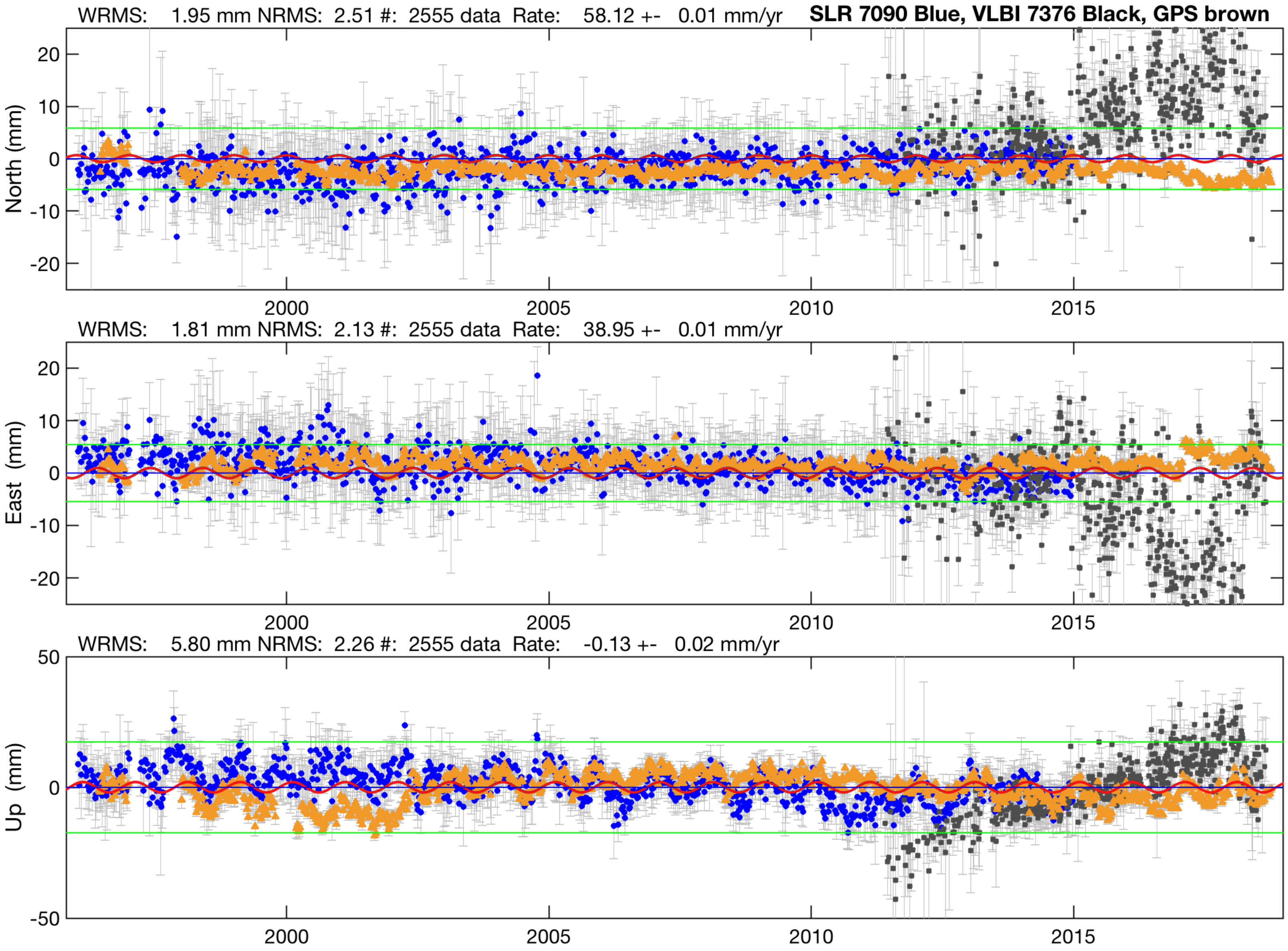
Yarragadee (7090/7376/YAR2)

- Difference from ITRF2014

System	ΔN (mm)	ΔE (mm)	ΔU (mm)
VLBI	3.5±0.7	-13.5±0.7	8.0±0.6
SLR	-1.2±1.0	9.8±0.9	0.8±0.7
ΔU			+7.2 (mm)
	ΔVn (mm/yr)	ΔVe (mm/yr)	ΔVu (mm/yr)
VLBI	2.4	-3.1	5.7
SLR	0.1	1.3	0.8

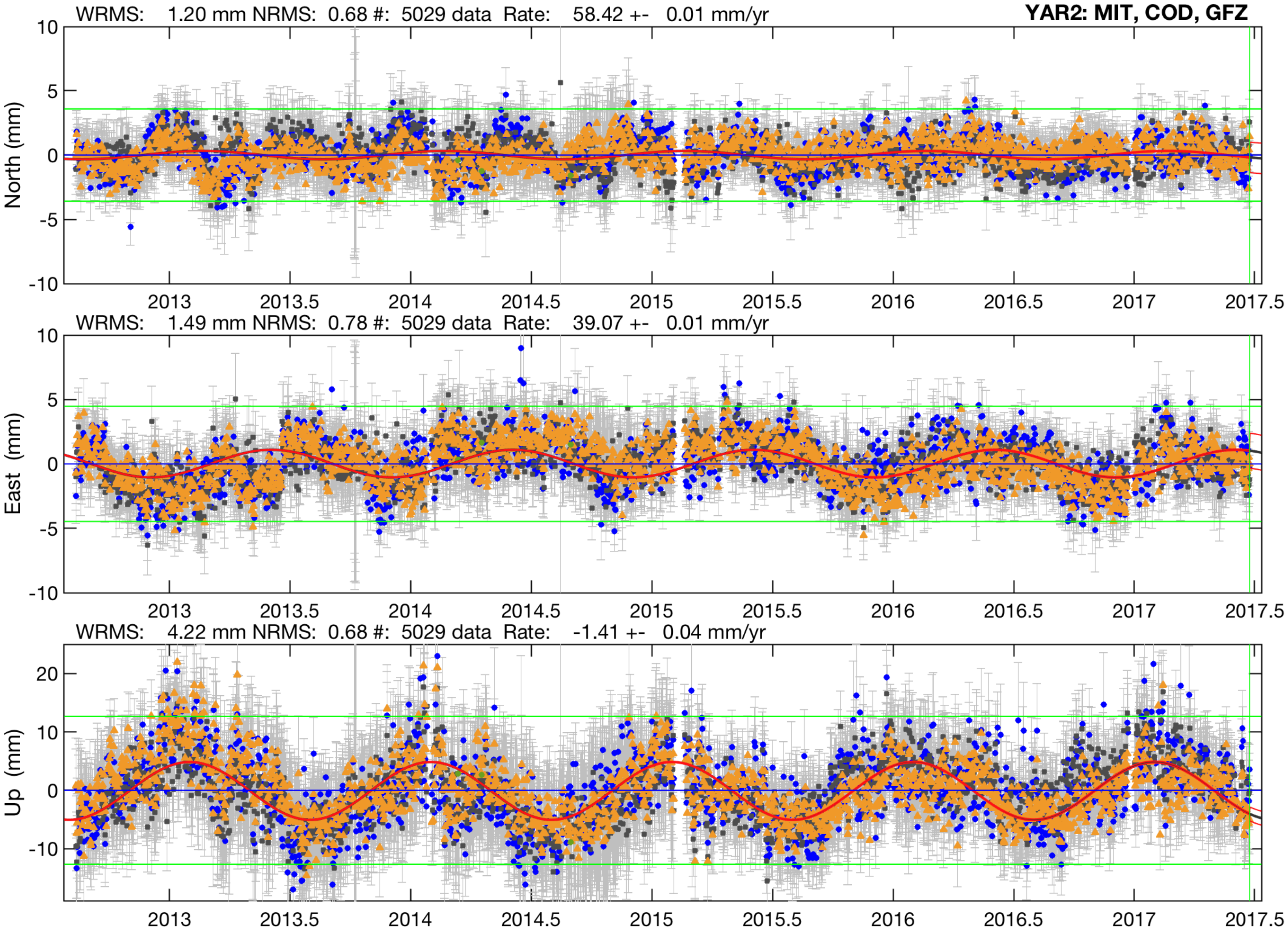
Yarragadee

- Comparison: Mean height difference VLBI-SLR +7.2 mm
- There is something odd in the VLBI data. Is the antenna “popping” up out of the ground
- Annual signals in GPS



YAR2 GPS

- The GPS results show annual signals and plot here shows that these annuals, while not identical, are very similar between different GPS analyses.
- Daily GPS for 3 IGS ACs.



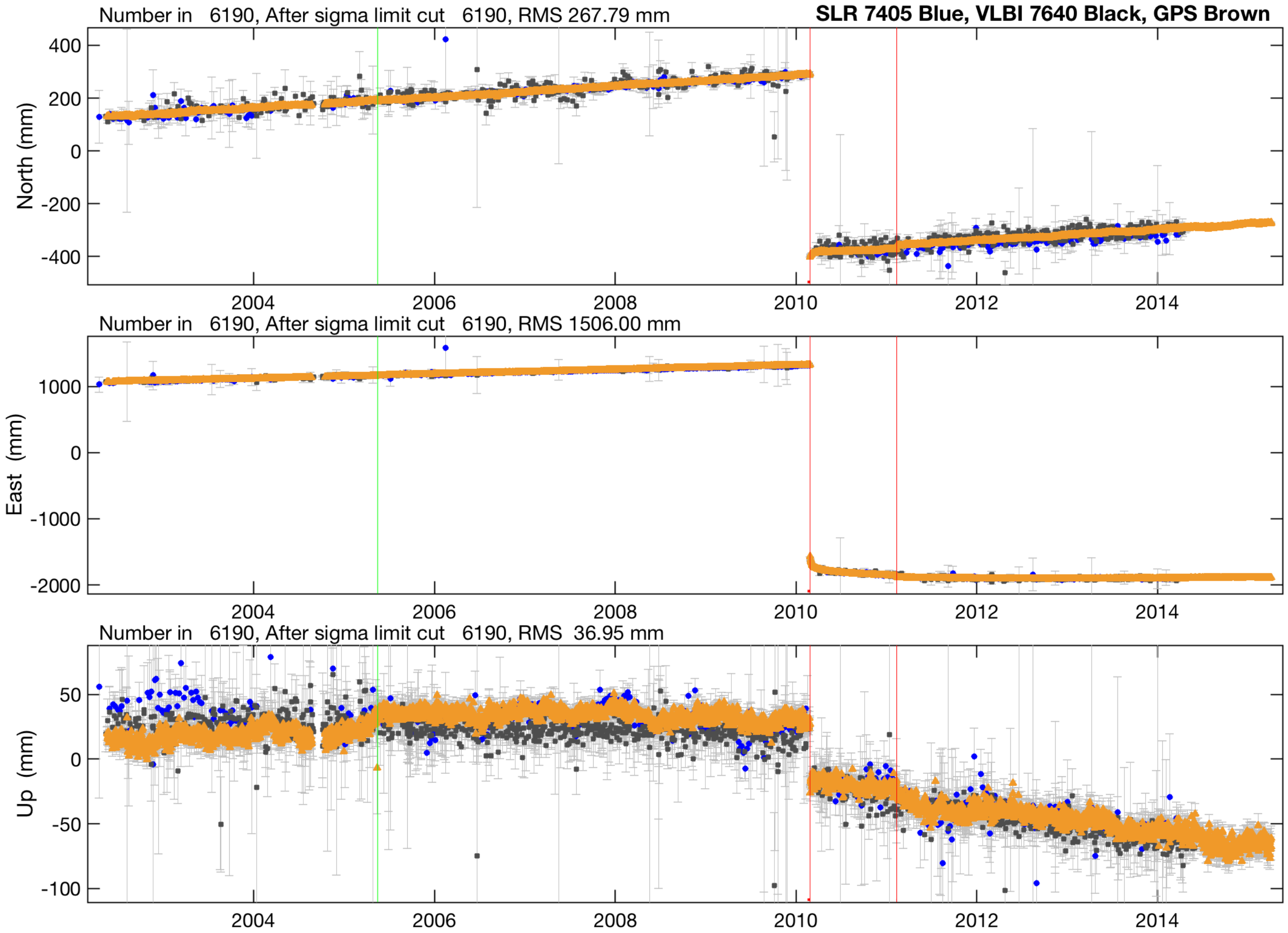
All Height differences

- Mean height difference excluding TIGO/CONZ is 3.9 mm which is equivalent to **0.6 ppb**. This is about half the ITRF2014 value.
- TIGO/CONZ is outlier (next slide)

Station	ΔU VLBI (mm)	ΔU SLR (mm)	VLBI-SLR (mm)
Wettzell	-11.9±0.5	-13.0±1.9	+1.1
Matera	-1.2±0.6	-10.7±0.8	+9.5
Yarragadee	8.0±0.6	0.8±0.7	+7.2
Hartebeesthoek	-2.9±0.8	-3.2±1.3	+0.3
McDonald, TX	-0.5±0.8	-2.0±0.9	+1.5
TIGO/CONZ	-11.5±2.7	1.6±2.1	-13.1

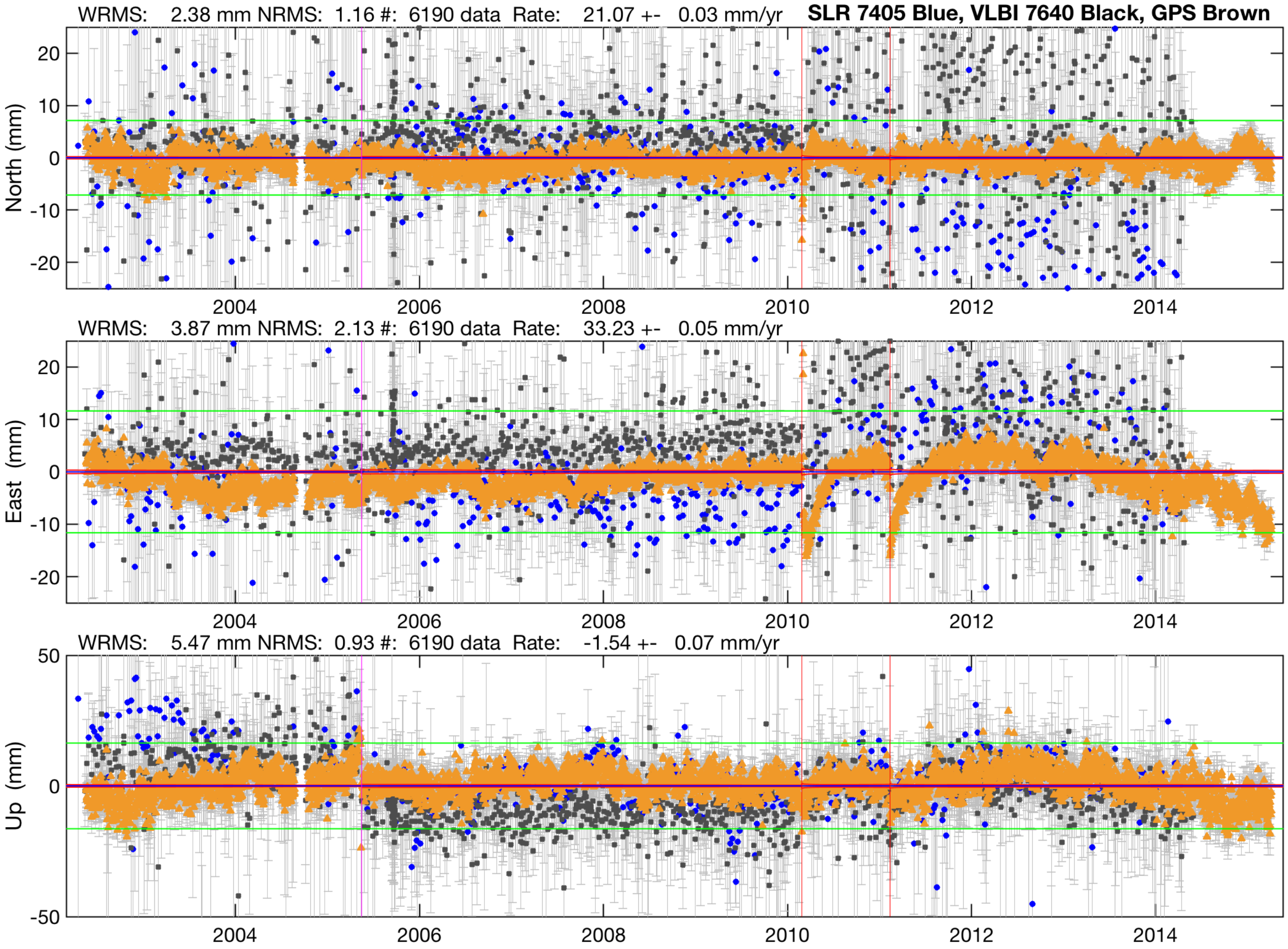
TIGO/CONZ case

- Time series shows complexity of interpreting this offset
- Large earthquake and aftershock both with post-seismic deformation when examined in detail (red vertical lines)



Residuals

- Complexity of motions
- Note: Noise levels as well.



Network parameters: Scale and translation

Scale between SLR and VLBI

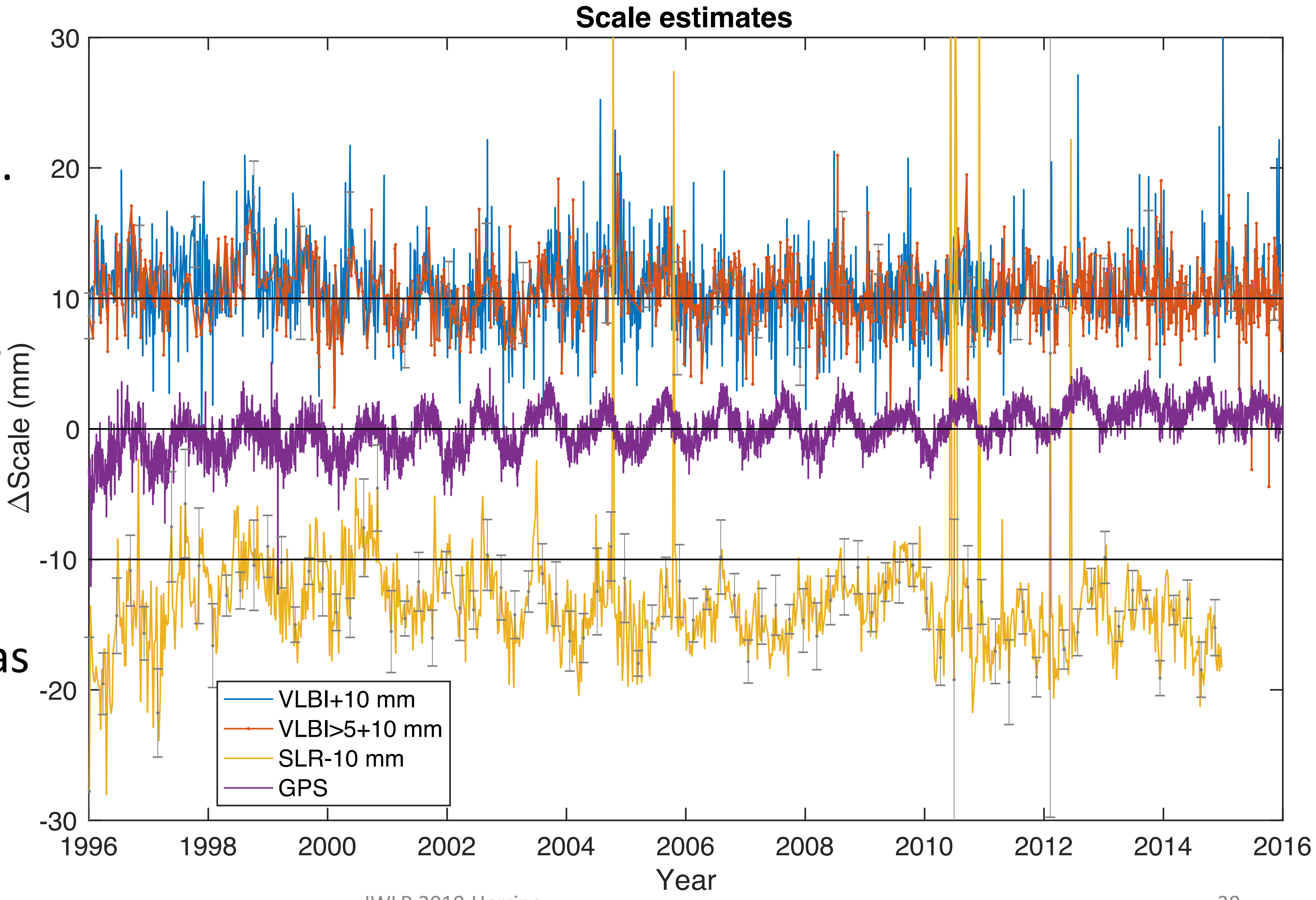
- **Scale Comparison**

Values with σ<5 mm.
Mean σ ~2.5 mm

VLBI Mean 0.5 mm
RMS 2.8 mm # 2603

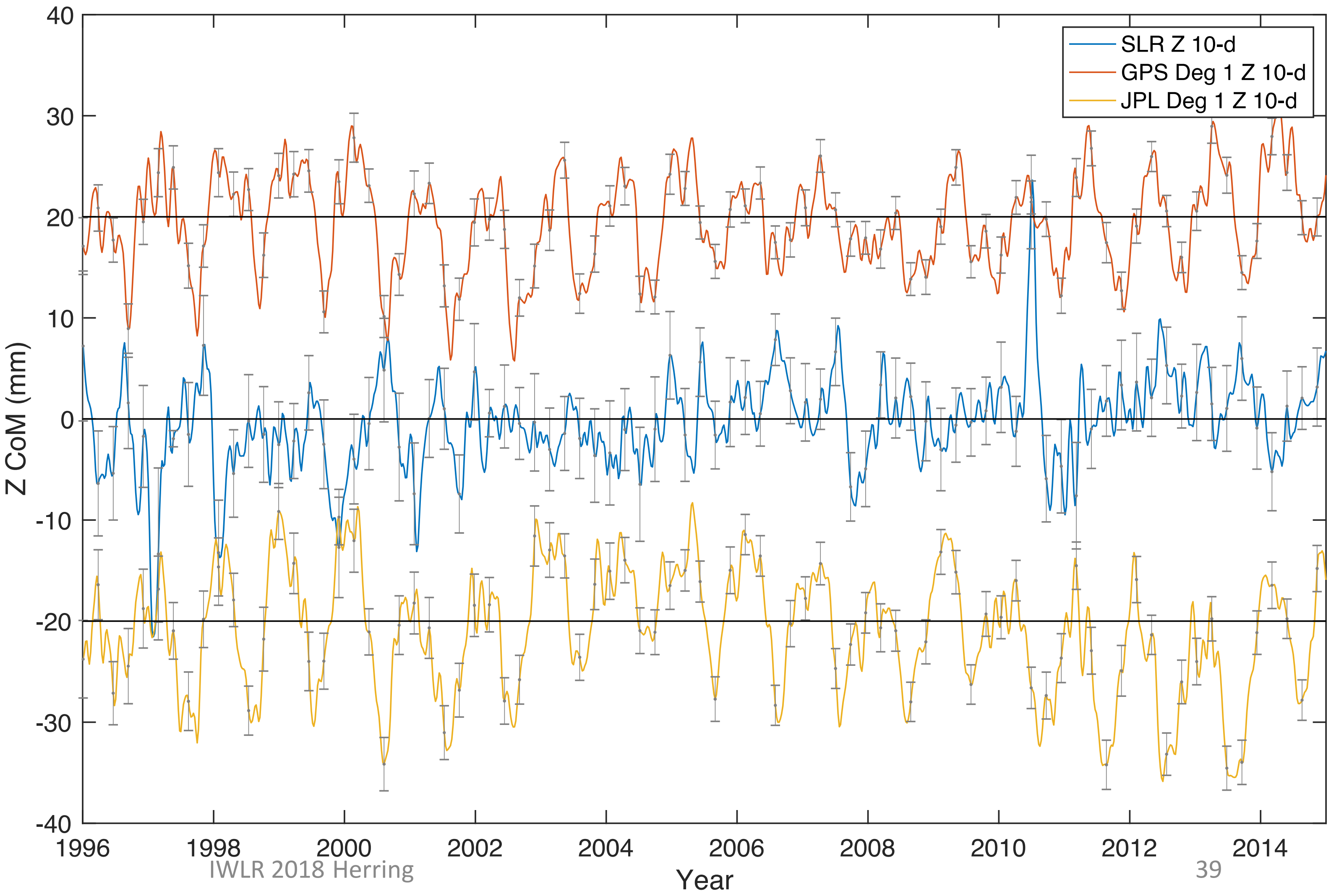
SLR Mean -3.6 mm
RMS 3.0 mm # 969

- There is a drift in the IGS scale for ITRF2014 which was not present for ITRF2008



Geo-center from SLR and GNSS

- Comparison of Z-CoM from SLR translation (blue) with GPS results from degree-1 deformation model (offset ±20 mm) from two different IGS analyses.
- Refined radiation pressure models in GNSS analyses will improve GNSS translation estimates

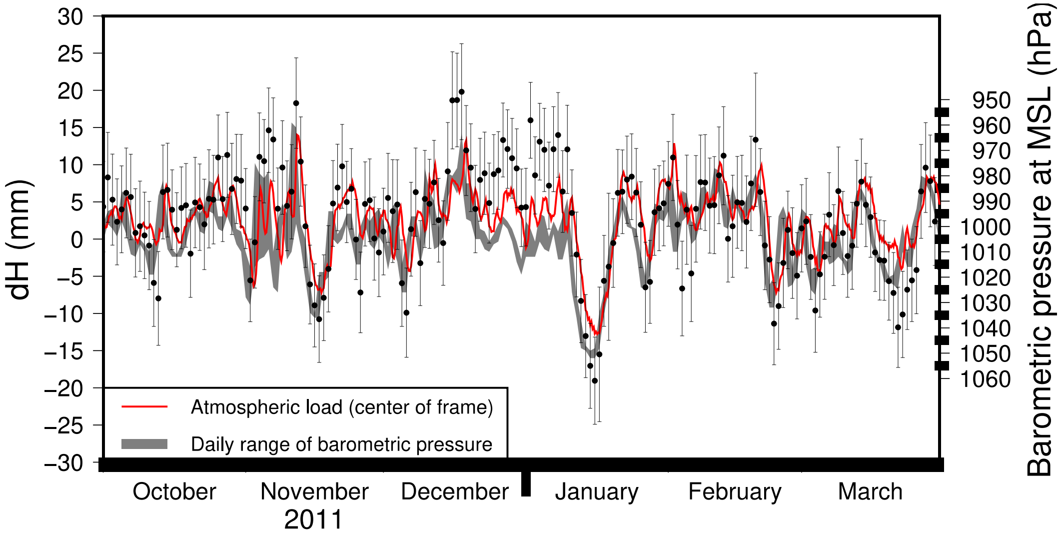


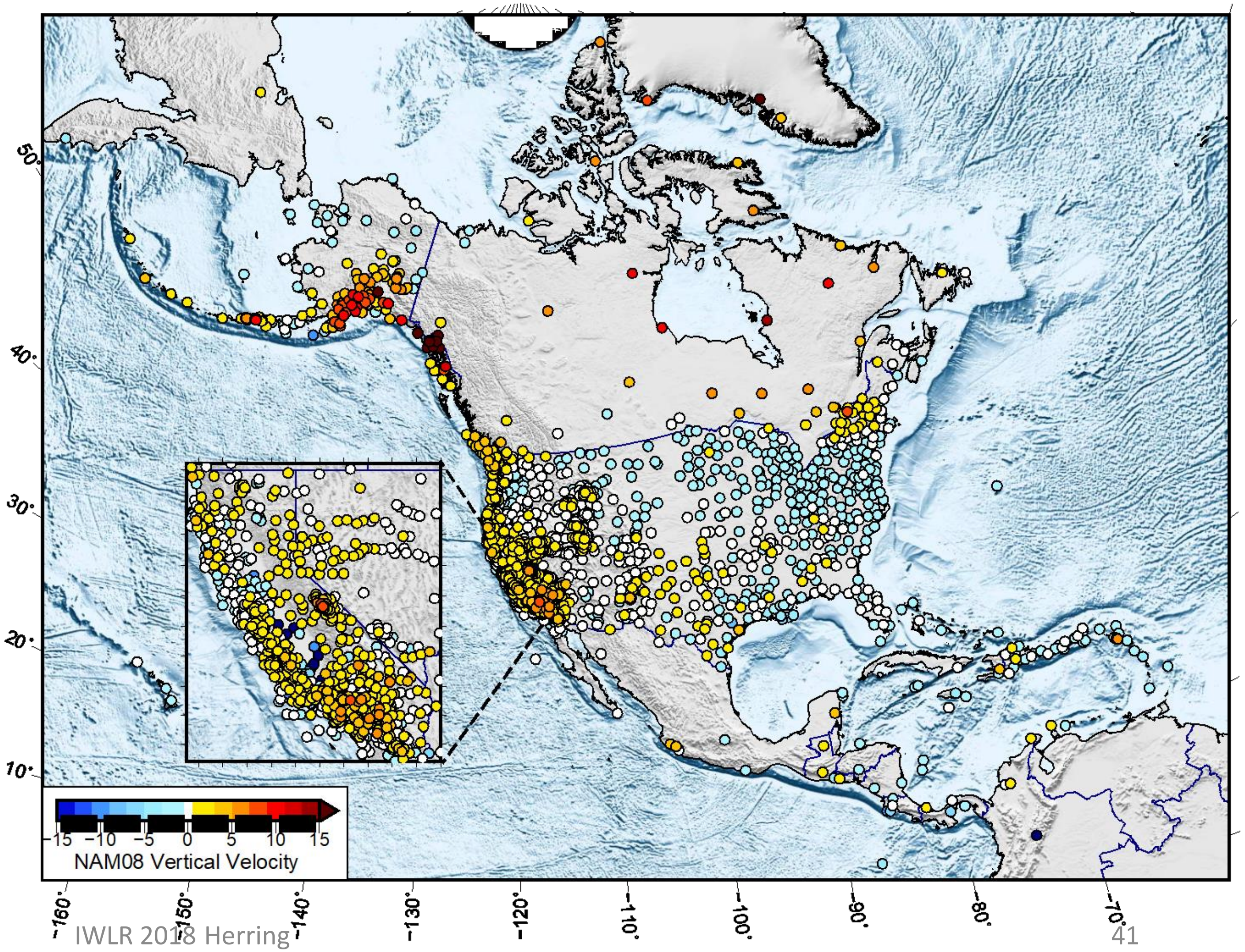
Earth motions: Non-secular components

- Just two examples
  - Vertical load signal
  - Episodic tremor and slip: Northern California horizontal and vertical signals

Vertical motions: Plate Boundary Observatory

- Example secular and non-secular vertical motions from GPS

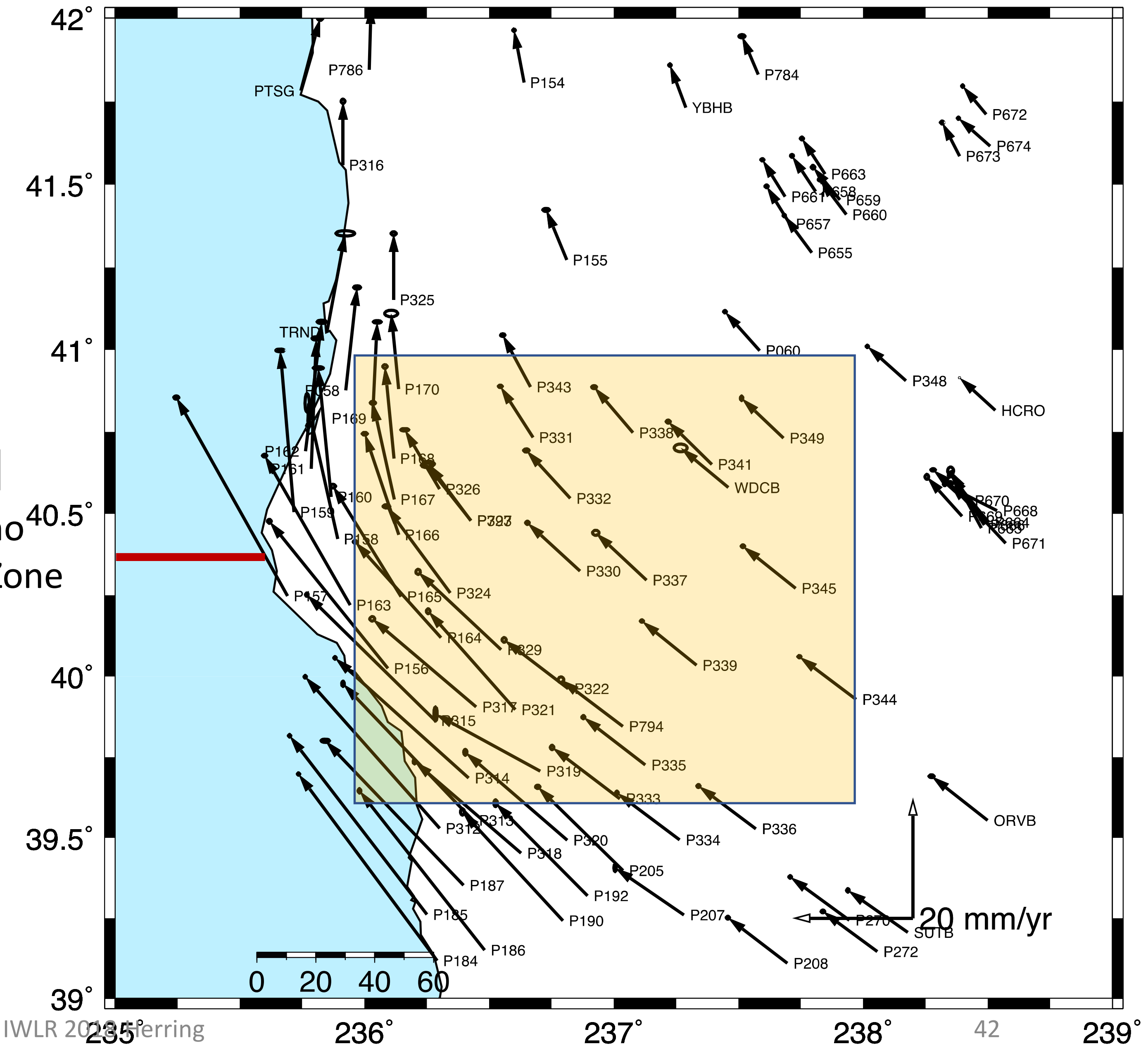




From Herring et al., 2018 *Review of Geophysics*

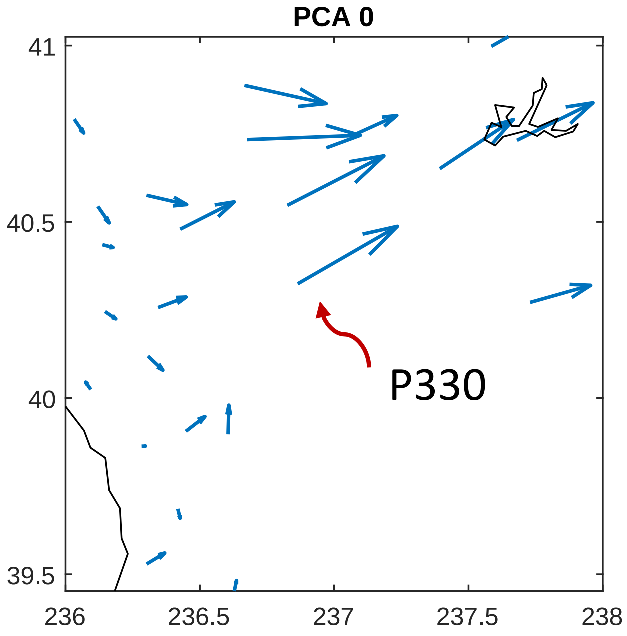
Northern California

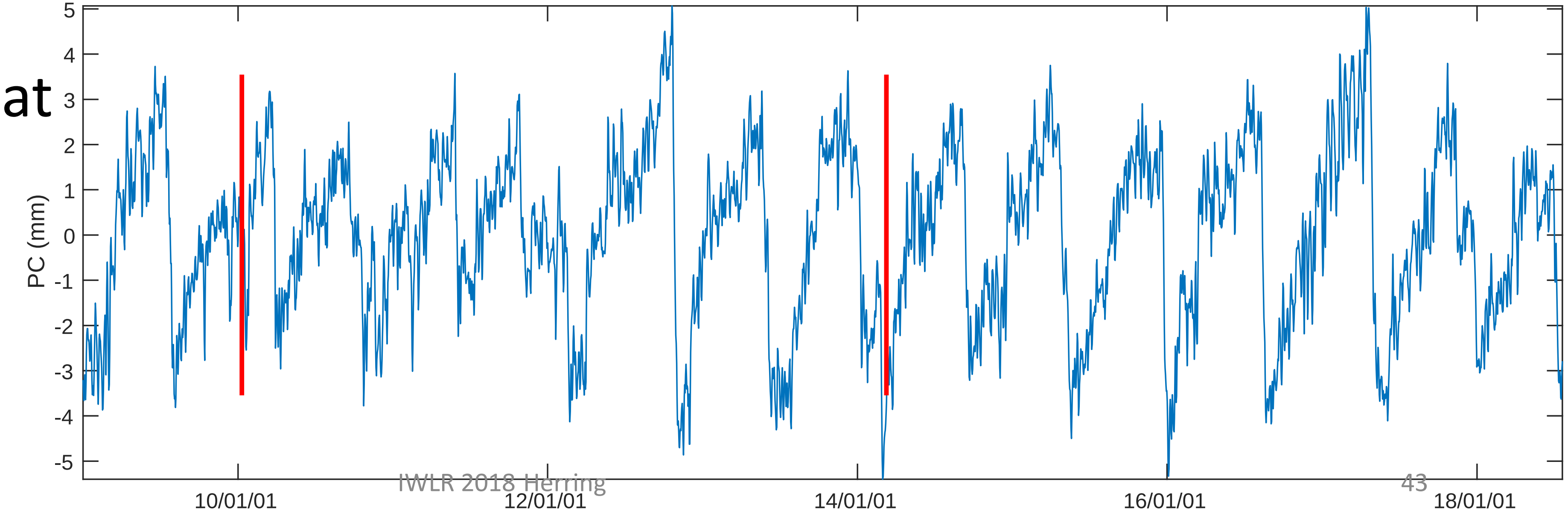
- Velocity field based on >10 years of GPS data
- There have been offshore earthquakes that are detected in the GPS data.
  2005/06/15 Mw 7.2
  2010/01/10 Mw 6.5
  2014/03/10 Mw 6.8
- Look at what happens in marked region



Short period signal

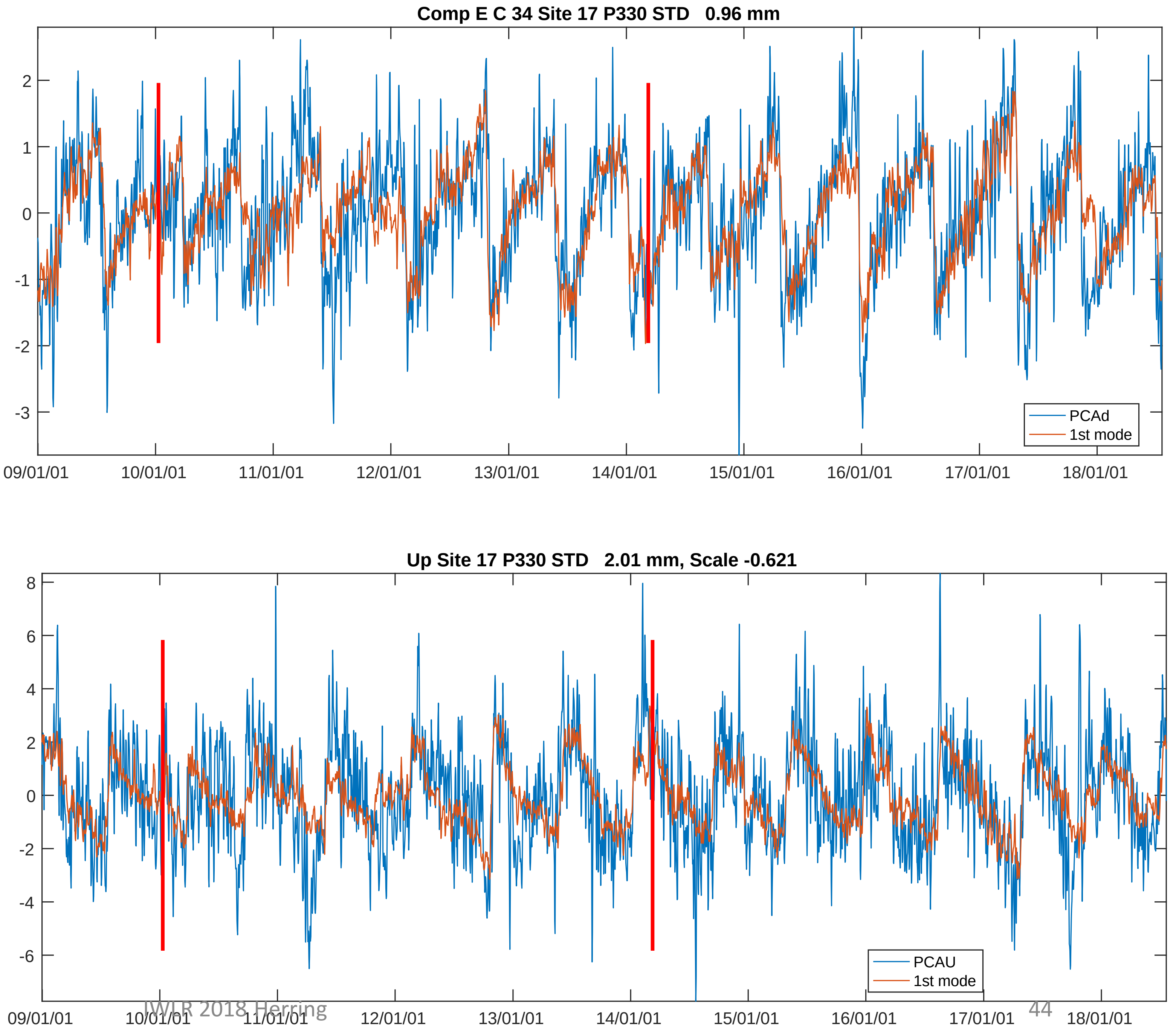
- Spatial pattern and time series
- Units of displacement are mm and vectors are proportions at each site.
- Red lines are off shore earthquakes
- ~7 month repeat period.





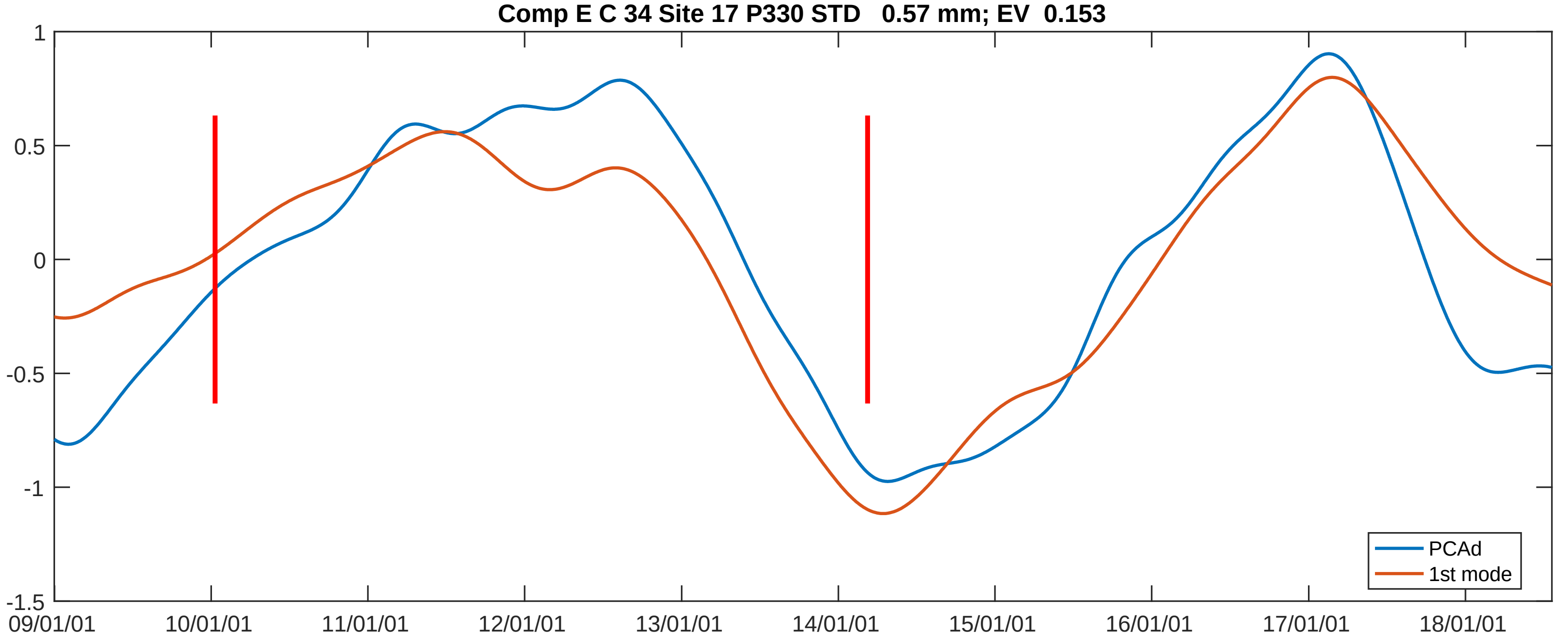
Fit to data: Short period

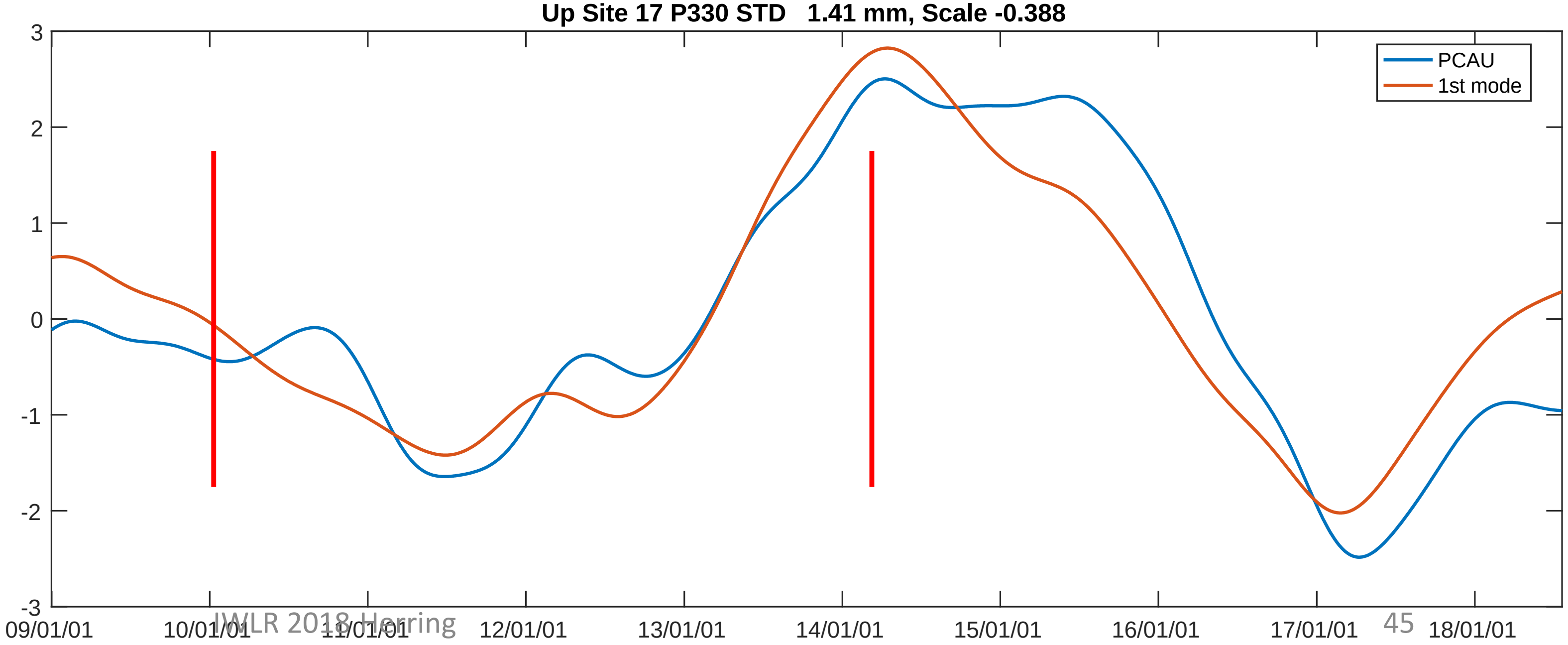
- Short period: East and "predicted" vertical motion
- Blue is data time series in mm, brown is first principal component.
- The magnitude of the Up mode is estimated from the data.



Fit to data: Long period

- Long period: East and “predicted” vertical motion
- Blue is data time series in mm, brown is first principal component.
- The magnitude of the Up mode is estimated from the data.





Science with SLR

- *The definition of the International Terrestrial Reference Frame (ITRF) by being the only space geodetic technique which defines the Earth's center of mass. In addition, provides scale and the core network for the ITRF*
- Monitoring Earth rotation and polar motion to provide the relationship with The International Celestial Reference Frame (CRF)
- *Modelling the temporal and spatial variation of the Earth's gravity field*
- Determination of the Ocean and Earth tides
- Monitoring tectonic plates and horizontal and vertical crustal deformation
- *Orbit determination for spaceborne altimeters and radar measurements for studies in global ocean circulation and changes in ice masses.*

Conclusion: Science for the next decade: Challengers

- GNSS developments:
  - Scale from calibrated satellite antennas (Galileo most importantly. Initial results suggest agreement with VLBI scale)
  - Center of Mass: New radiation force models and satellite meta-data (again Galileo)
  - *Soon GNSS is likely to provide accurate and precise scale and Center of Mass to Center of Network (large) independent of SLR.*
- However: optical, un-biased range measurements are capable of much higher accuracies than GNSS phase measurements. The ILRS needs to exploit this.
- The role of tracking satellites is critical and the ILRS community needs to balance the “service role” with achieving its own science directly.

Conclusion: Science for the next decade: Opportunities

- Bias between optical and microwave methods: Does this reflect differences in the wavelength dependence of refractive index? Did the original measurements consider the accuracy requirements of the year 2020?
- Exploit the difference in water vapor contributions to microwave and optical systems.
- Center of Mass motions from frame translation compared with inferred motion from degree 1 loading? Other low order mass movements that do not result in surface loading (e.g., poro-elastic). Green's functions for low degree loading?
- Impact of mass market laser ranging systems (autonomous vehicles. LIDAR) the way GNSS benefits from economy of scale
- *Higher level products must be available (with realistic uncertainties) if the larger community is to participate (e.g., position time series, CoM, scale: Combined and individual AC so users can explore).*

Many studies in GNSS arise from users "seeing" things in higher level products.