British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Gateway to the Earth

Systematic errors in the SLR observations to the LAGEOS satellites and impact on the TRF scale

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Outline

1. A few words about SGF
2. SLR
   - technique
   - performance metrics
   - QC
3. Systematic errors
   - potential issues
   - bias estimation
   - a word of caution
4. Conclusions

Space Geodesy Facility at Herstmonceux

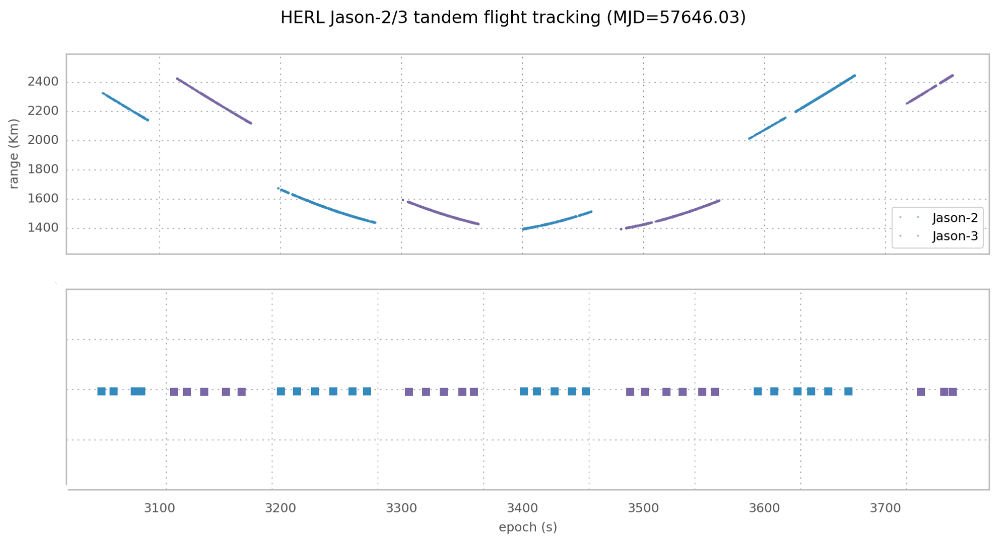
(7840)

Space Geodesy Facility at Herstmonceux

(7840)

- Geodetic observatory (originated within the Royal Greenwich Observatory) located in Herstmonceux, south of England
- SLR, 3 x AG, 3 x GNSS receivers plus supporting equipment (meteorological and atmospheric sensing)
- Official ILRS Analysis Centre (NSGF)
- Very active and long standing ILRS involvement (Analysis Standing Committe, Networks and Engineering Standing Committee, Quality Control Board, Governing Board...)
- Experience and expertise obtained through development of a very successful SLR station plus involvement in the data analysis activities puts us in a good position to investigate potential systematic effects

Altimetry mission support



Jason-2

4 pass segments
21 NPs
13,111 returns

Jason-3

4 pass segments
19 NPs
13,224 returns

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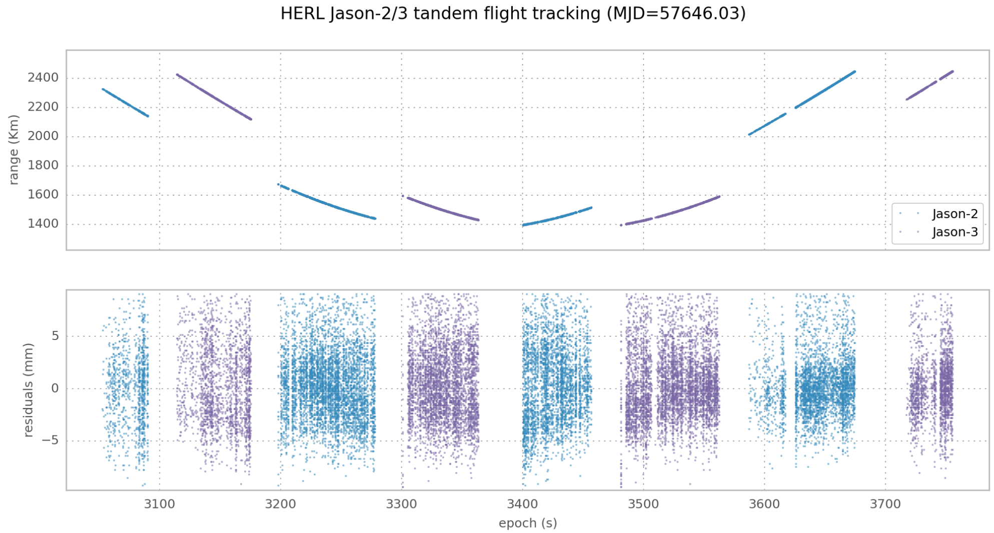

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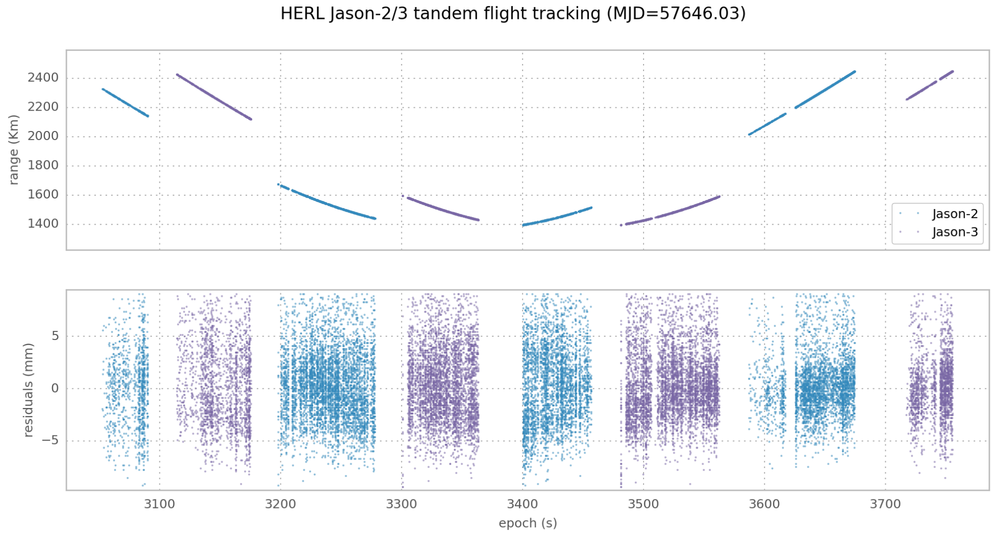

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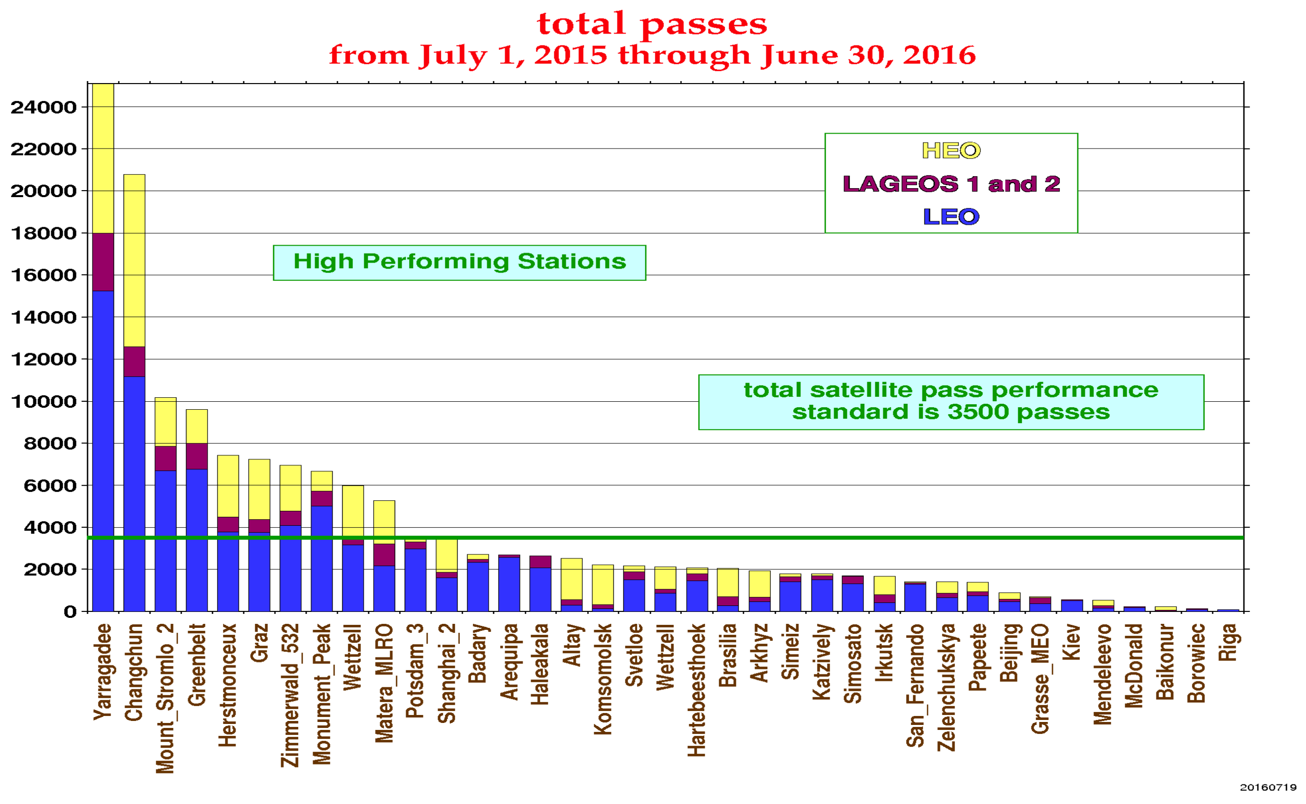
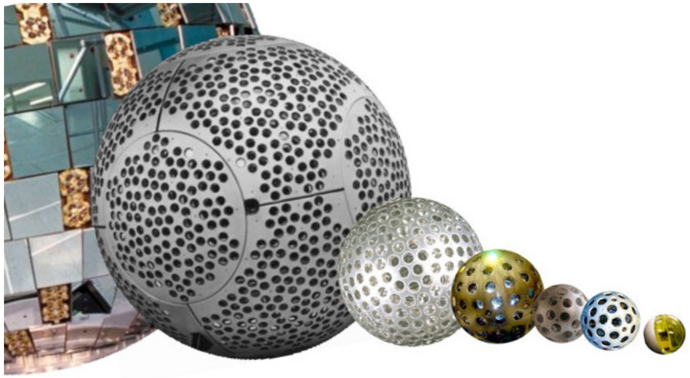
	Passes tracked 01-09/2016
Cryosat-2	173
HY2A	165
Jason-2	364
Jason-3	308
Saral	168
Sentinel-3a	146



http://ilrs.gsfc.nasa.gov/network/system_performance/global_report_cards/images/2016_06_tot_pas.html

SLR

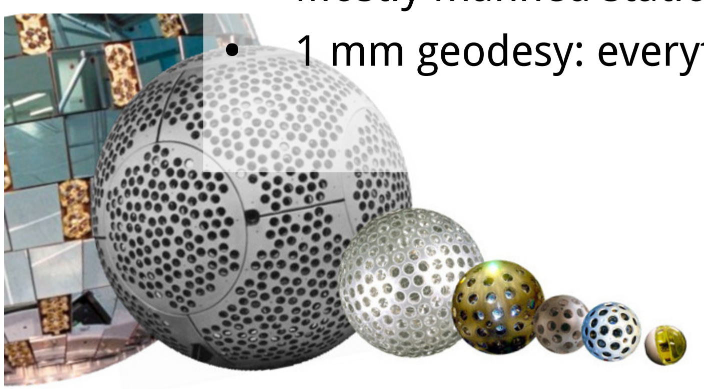
- Time of flight of laser pulses travelling to and from satellites and tracking stations: simple and elegant idea
- Accurate, unambiguous measurements
- Advantageous propagation channel
- Consolidated ground network being expanded and upgraded
- Fundamental role in ITRS realisation: origin & scale
- Low degree gravity coefficients
- Independent validation for altimetry and GNSS, SRP model testing
- If required, simple to make missions “SLR-worthy”: fit a LRA on board



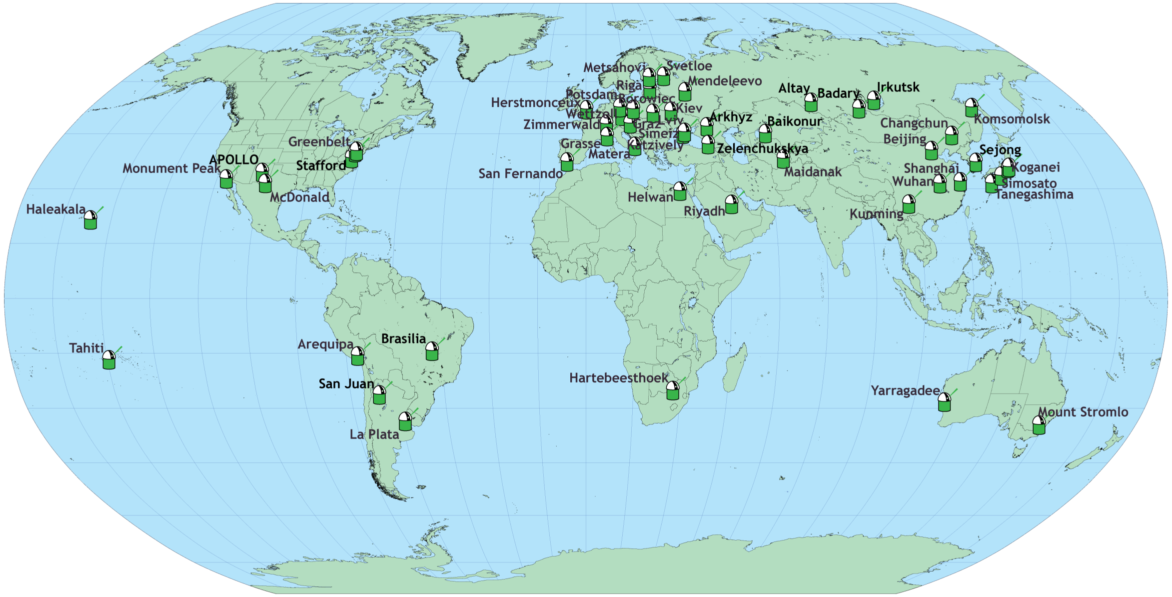
SLR

- Clean (e.g. no clock parameters, no ionospheric refraction, no wet component of tropospheric refraction, no satellite antenna offsets)
- Highly optimised geodetic space segment
- Simple calibration procedure (ranging to surveyed ground target)
- Mostly manned stations: personnel present to detect, report and correct equipment anomalies/malfunction

- Non-standard, heterogenous ground network (technology, mode of operation)
- Weather dependent
- Mostly manned stations: 24/7 operations rare
- 1 mm geodesy: everything becomes a challenge

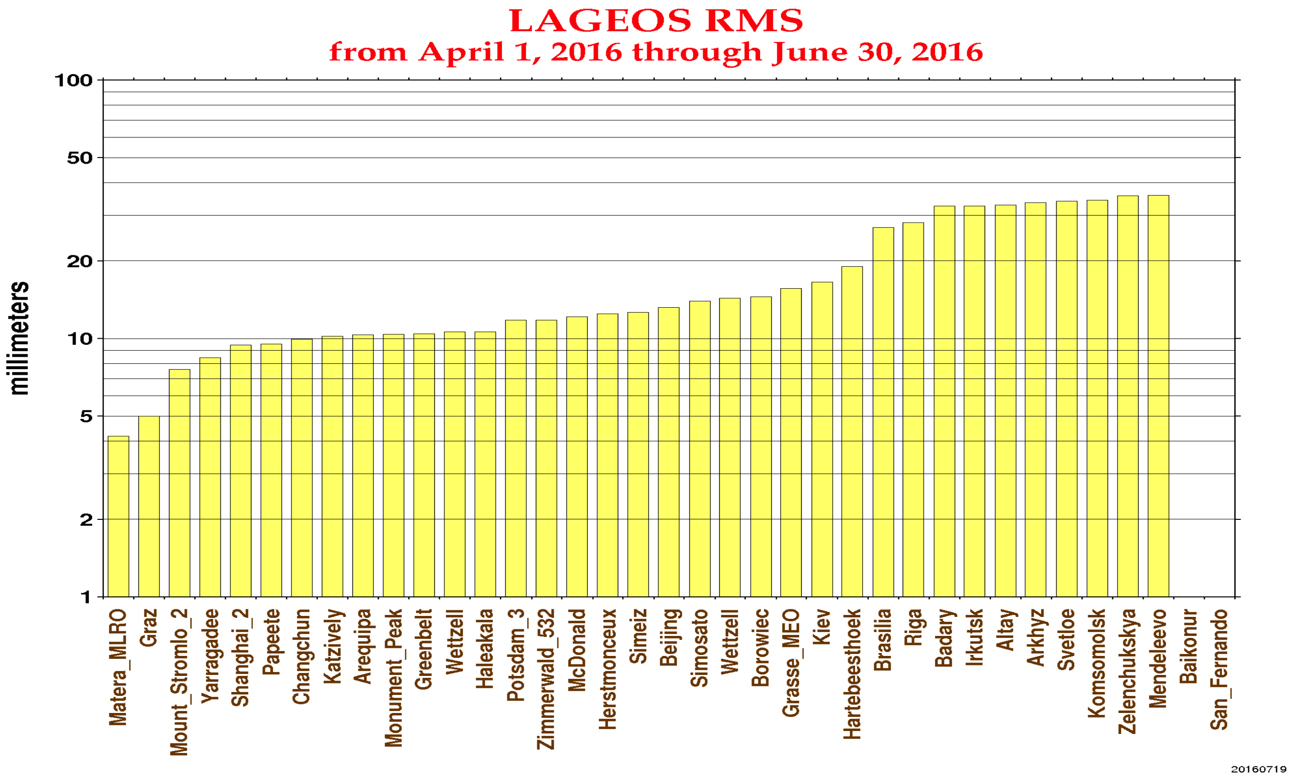


ILRS network



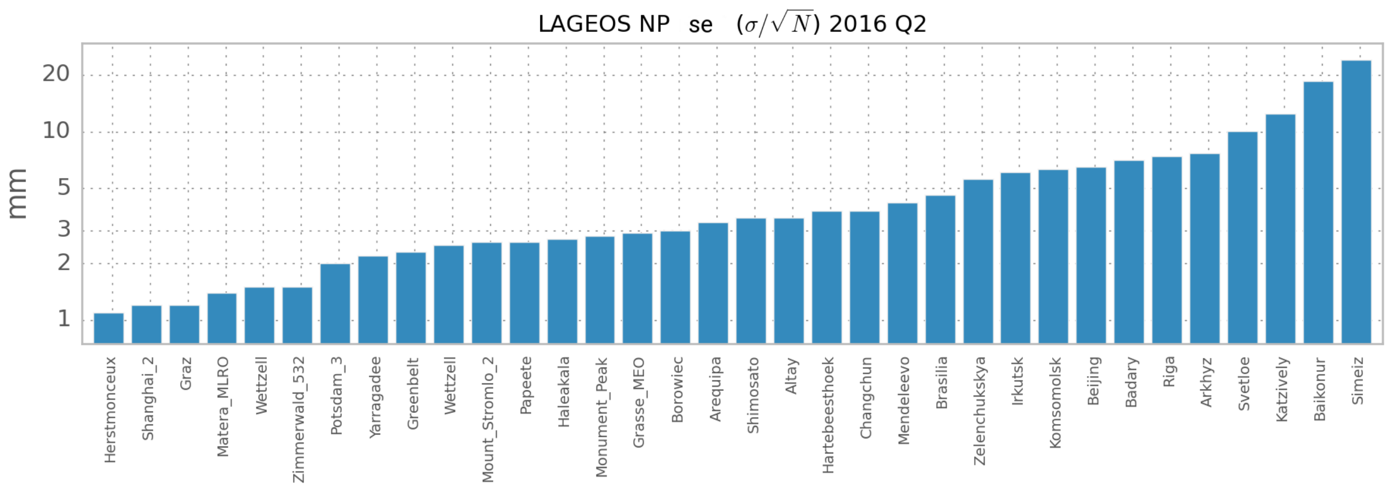
- Improving geographical distribution
- Mixture of modern and legacy systems

Single shot precision

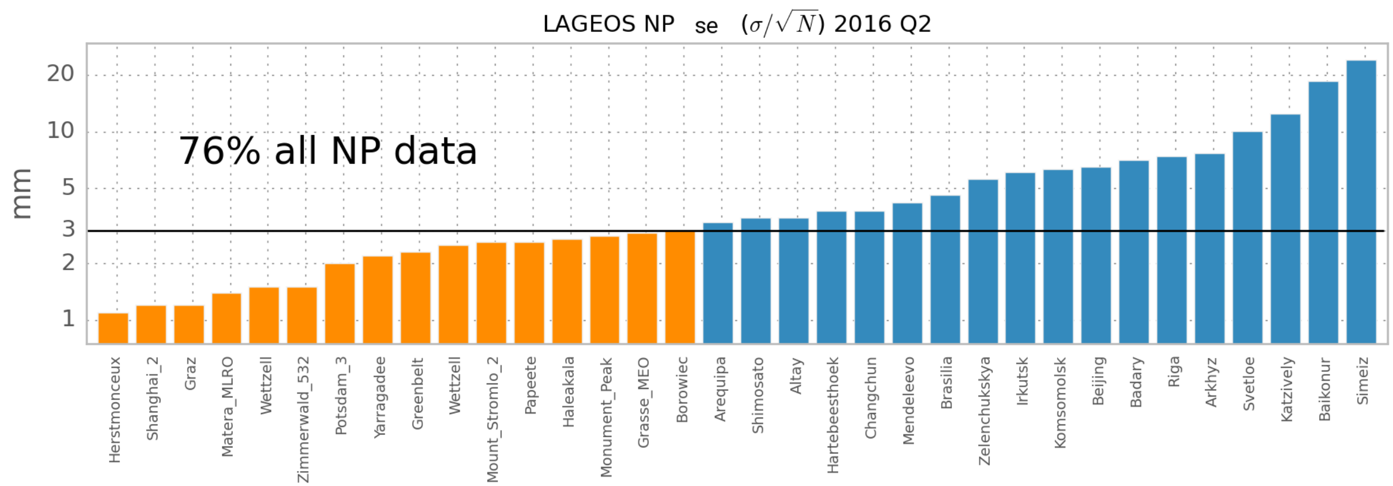


This means different things for different systems; not an actual measurement of precision (e.g. single-photon ranging samples depth of retroreflector array)

NP precision (Hitotsubashi University analysis 2016 Q2)

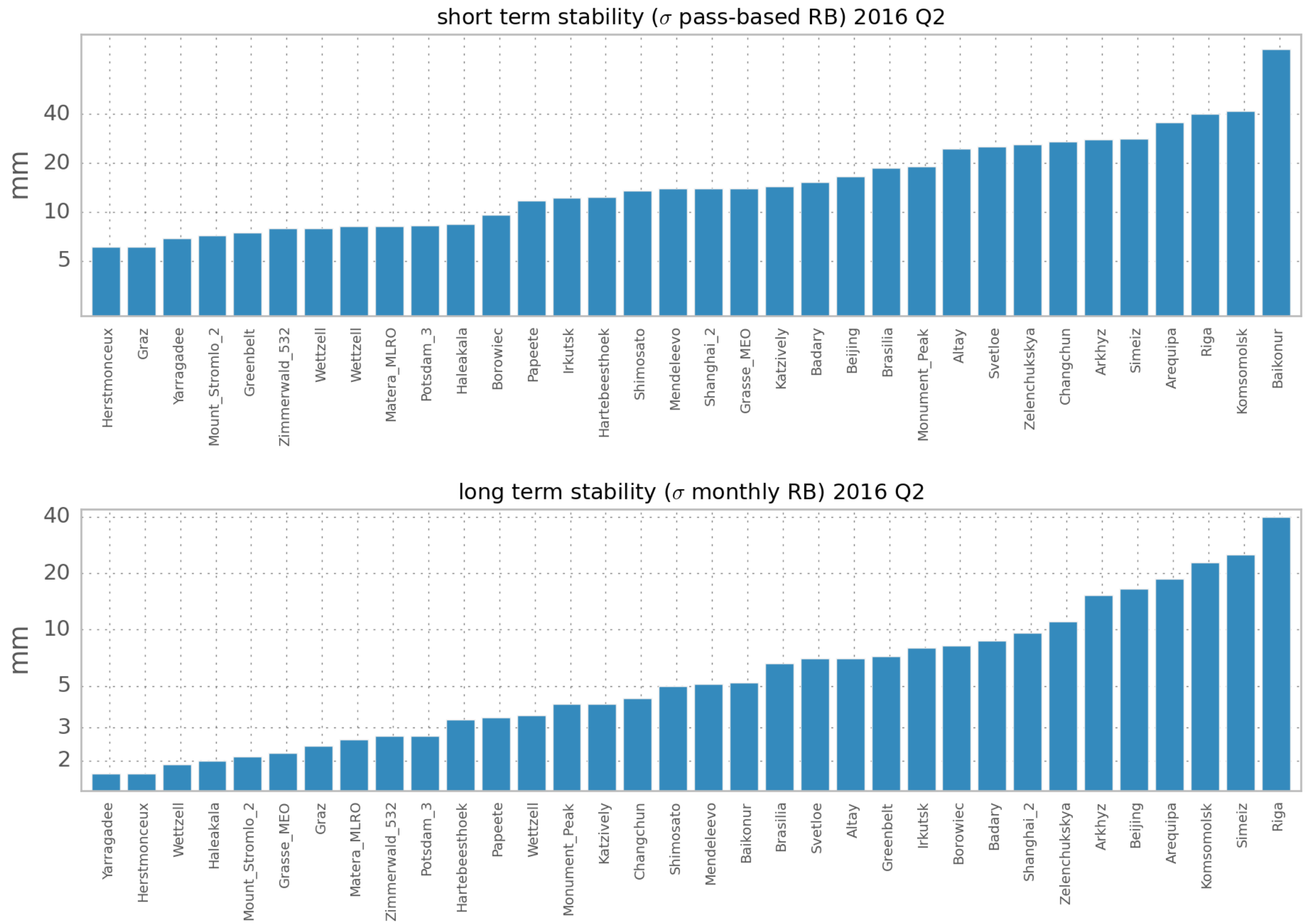


NP precision (Hitotsubashi University analysis 2016 Q2)



Almost 50% stations (¾ of all data) achieve NP se < 3 mm for LAGEOS

Stability: short- and long-term (Hitotsubashi University analysis 2016 Q2)



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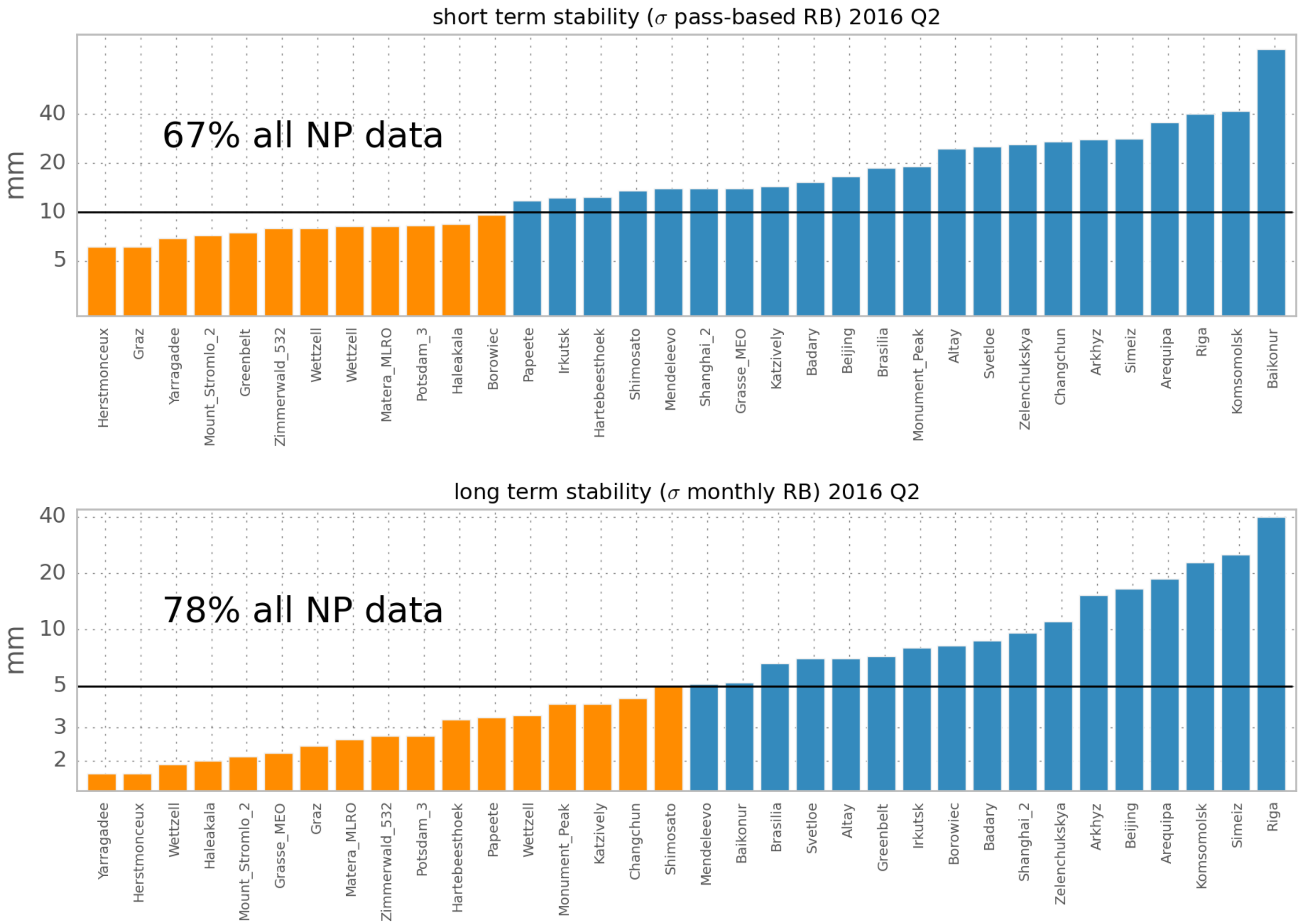


Almost 50% stations (¾ + all data) achieve long-term stability < 5 mm

Quality Control

- Continuous ILRS-coordinated effort (through Analysis Standing Committee) to monitor network and detect potential issues
- Several Analysis Centres provide QC results/tools:

DGFI: http://ilrs.dgfi.tum.de/quality/weekly_biases/

Hitotsubashi University: ftp://cddis.gsfc.nasa.gov/pub/reports/slrhitu/

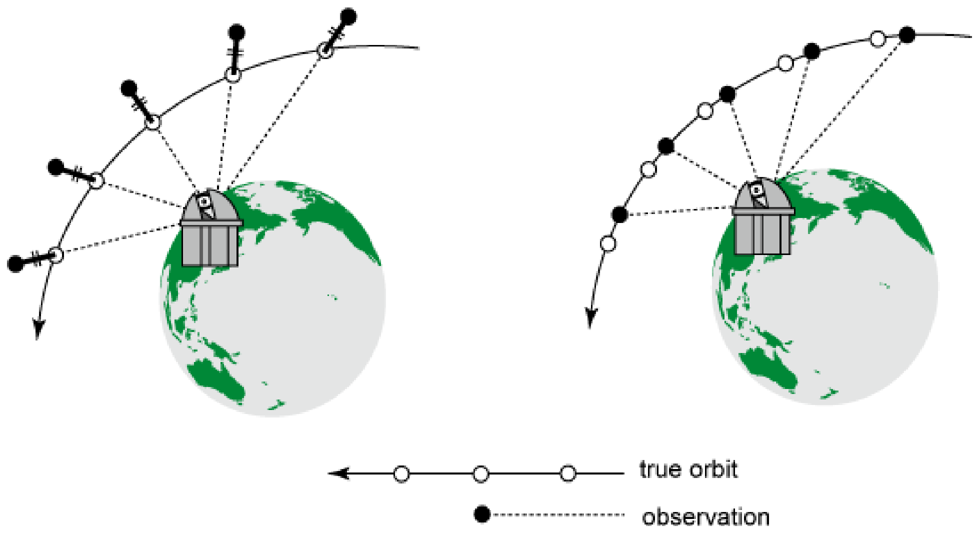
JCET: ftp://cddis.gsfc.nasa.gov/pub/reports/slrjcet

MCC: ftp://cddis.gsfc.nasa.gov/pub/reports/slrmcc/

SAO: ftp://cddis.gsfc.nasa.gov/pub/reports/slrsao/

- All this on top of ground stations internal QC procedures

Quality Control



- Example: Hitotsubashi University Quick Quality Check
- 6-hourly reports
- Pass-based range and time bias estimation
- Powerful tool for instant detection of large biases

http://geo.science.hit-u.ac.jp/slr/bias

Quality Control

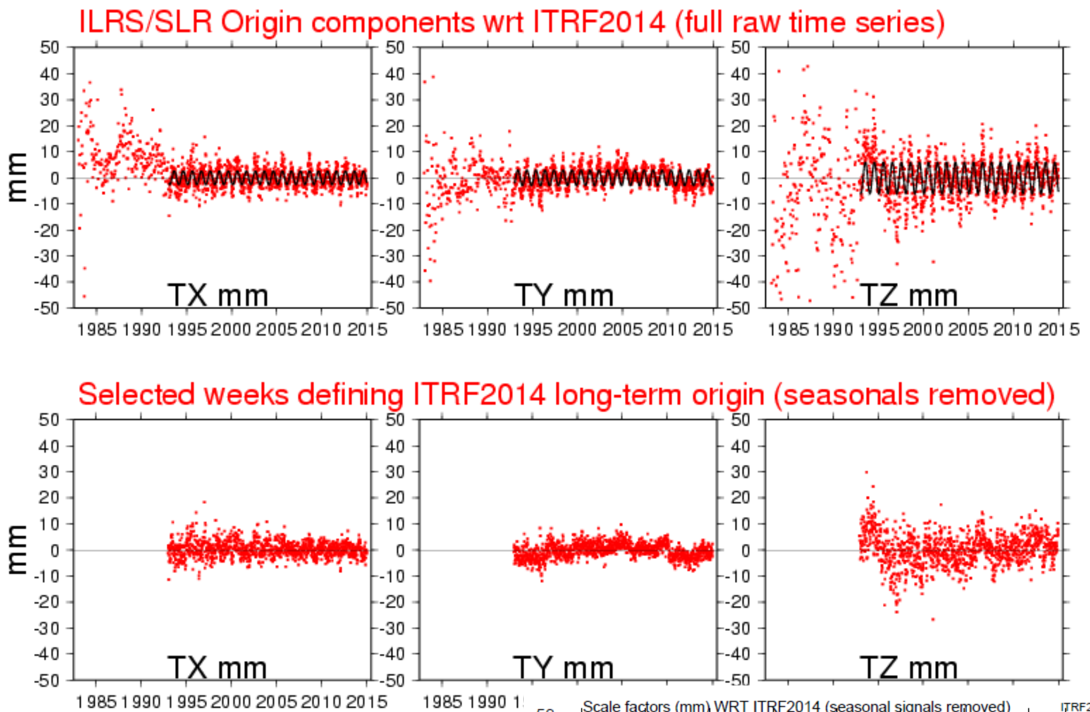
Data handling file

- maintained by the ILRS ASC, contains information on pressure, range and time biases from SLR stations, plus information on observations to be deleted
- Corrections accumulated throughout many years of monitoring and engineering feedback
- http://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx

Quarantine procedure

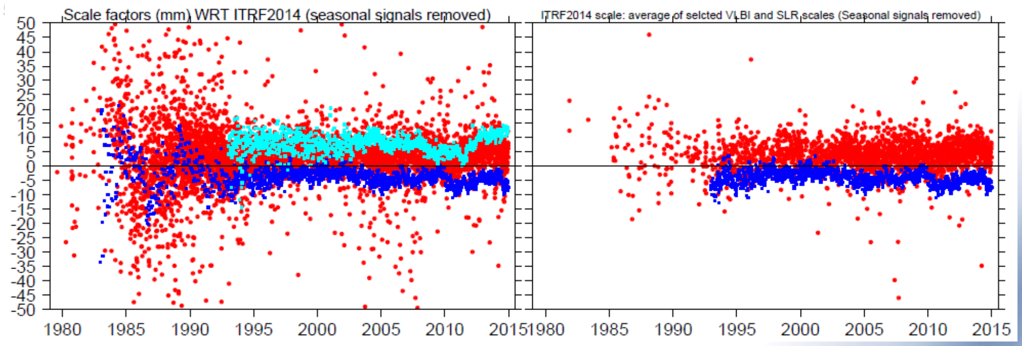
- to avoid transmission of questionable data (e.g. station upgrades or outage) until it is verified by the ASC
- stations automatically quarantined if no data received for 90 days
- stations can declare themselves in quarantine (e.g. planned system changes)

Result of these efforts:



Comparatively few discontinuities

Stable long term series



(plots courtesy of Z. Altamimi)

So what can possibly go wrong?

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- On paper, not much; in practise, quite a few things:

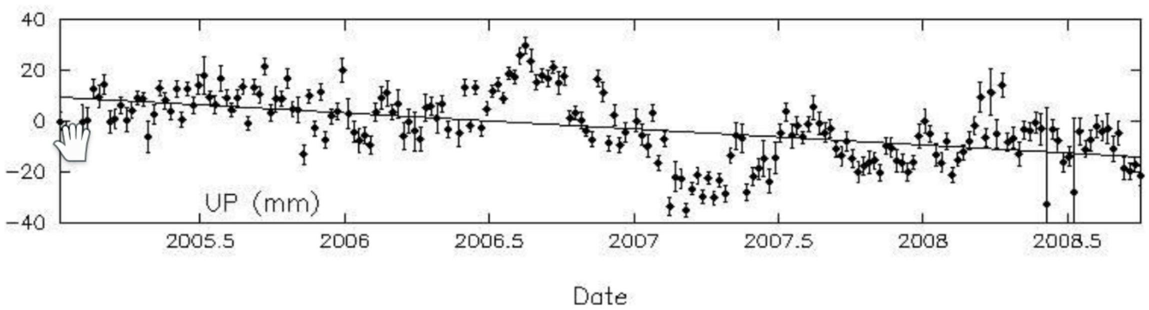
  timing devices (non linearities, undetected faults)
  unreported/unmodelled hardware changes
  local survey inaccuracies
  centre of mass uncertainties/mismodelling
  return intensity dependent effects
  inconsistent calibration/tracking
  inconsistent operation
  other hardware instabilities

- Some of these issues, at the few mm level, may be very difficult to detect by engineers/operators and regular QC analyses

So what can possibly go wrong?

An example:

7840 height (SLR weekly estimates)



- Herstmonceux: 2007 upgrade from Stanford counters to event timer uncovered a years-long range bias of ~11 mm (>_<)
- Initially unnoticed, problem was detected by analysis of estimated range bias time series
- What is there to assure us that similar issues did not affect other stations?

Accuracy: network-wide RB estimation

- Abandoned idea of untouchable “core sites”: errors could be anywhere
- Computed weekly solutions, compatible with regular ASC product, estimating RBs for all stations at all epochs
- Extensive testing performed:

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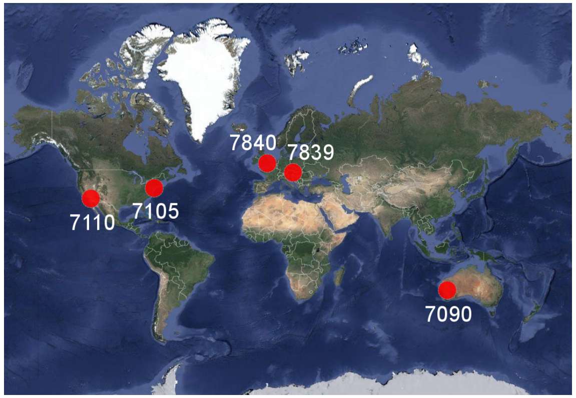

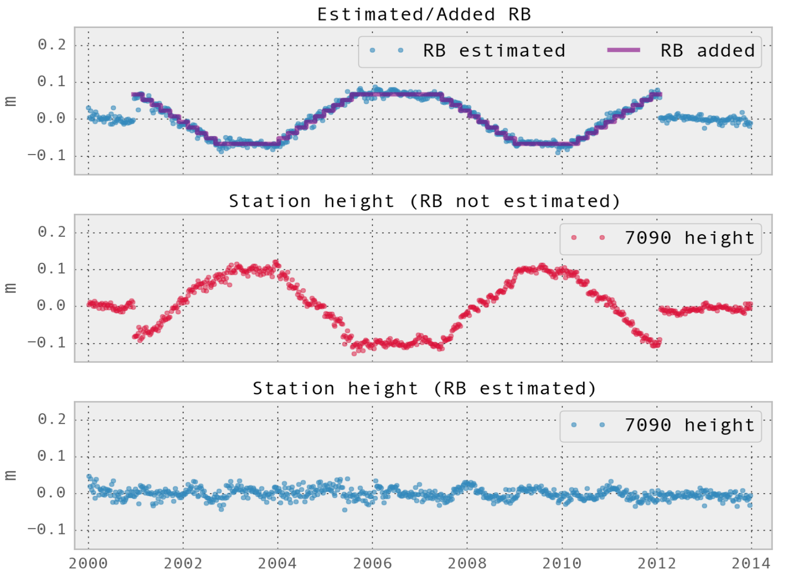

Addition and recovery (simultaneously) of synthetic biases to/from a group of stations

Accuracy: network-wide RB estimation

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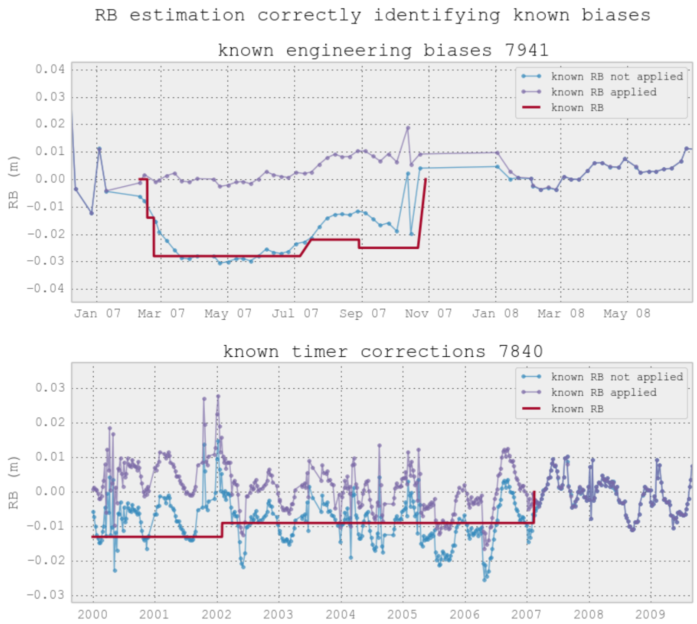
- Computed weekly solutions, compatible with regular ASC product, estimating RBs for all stations at all epochs
- Extensive testing performed: identification of known issues



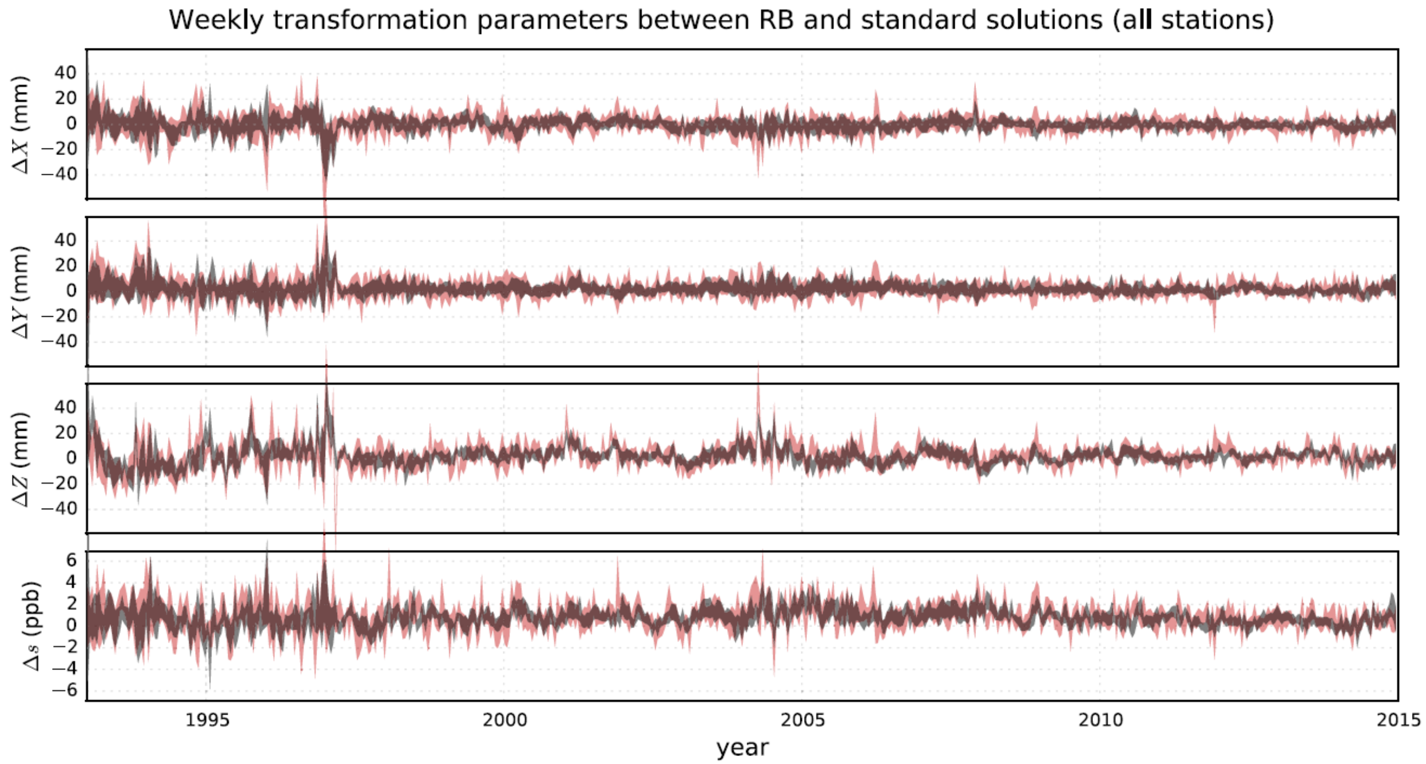
Identification of known issues included in data handling file (e.g. events at 7840, 7941)

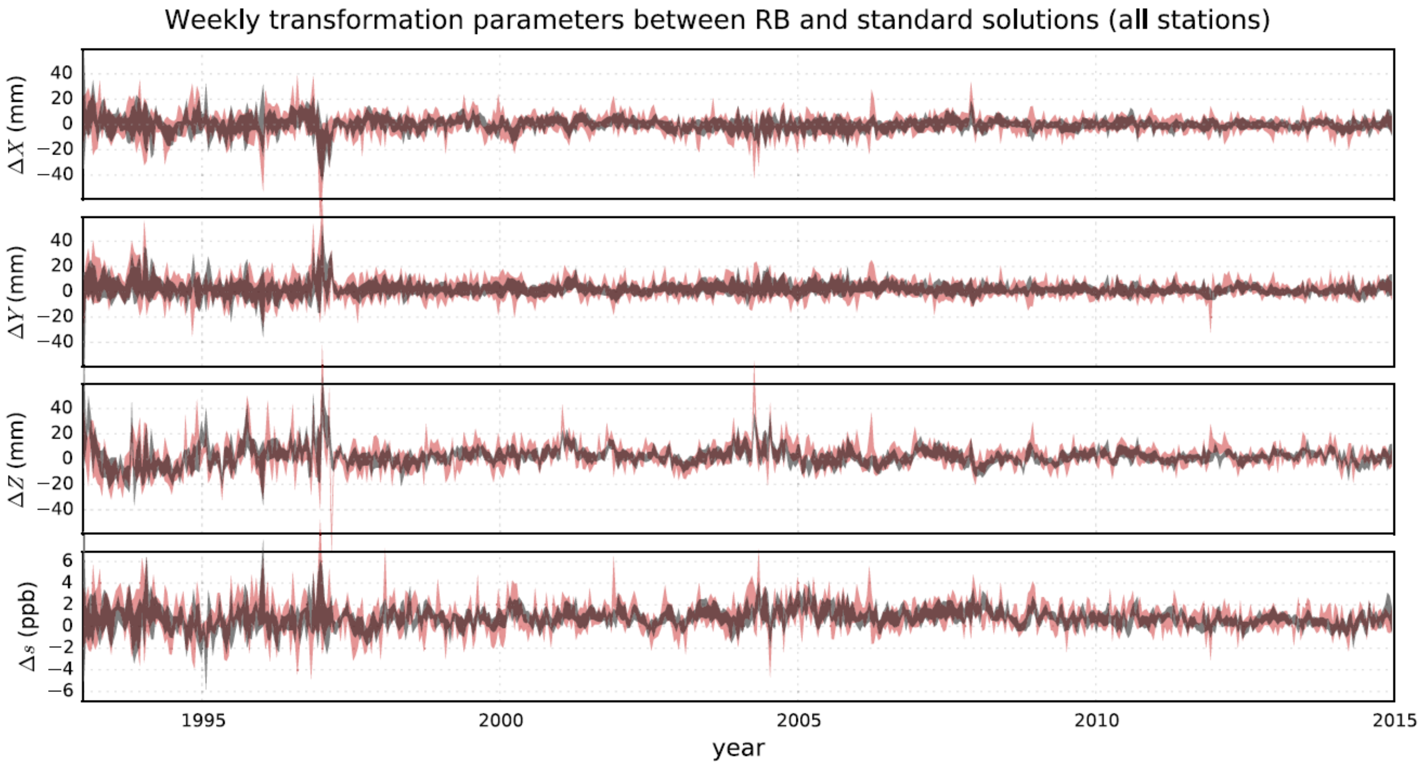
Accuracy: network-wide RB estimation

- Abandoned idea of untouchable "core sites": errors could be anywhere
- Computed weekly solutions, compatible with regular ASC product, estimating RBs for all stations at all epochs
- Extensive testing performed: recovery of added RBs, identification of known issues, testing a priori coordinates
- Studied mitigation of increased solution noise
- Indirect test on GM and scale factors between orbits, TRF, GM

Details in:

Appleby G., Rodriguez J., Altamimi Z.: *Assessment of the accuracy of the global geodetic SLR observations and estimated impact on ITRF scale: estimation of systematic errors in LAGEOS observations 1993-2014;* J Geod, 2016


Weekly transformation parameters between RB and standard solutions (all stations)
ΔX (mm)
ΔY (mm)
ΔZ (mm)
Δs (ppb)
40
20
0
−20
−40
6
4
2
−2
−4
−6
1995
2000
2005
2010
2015
year

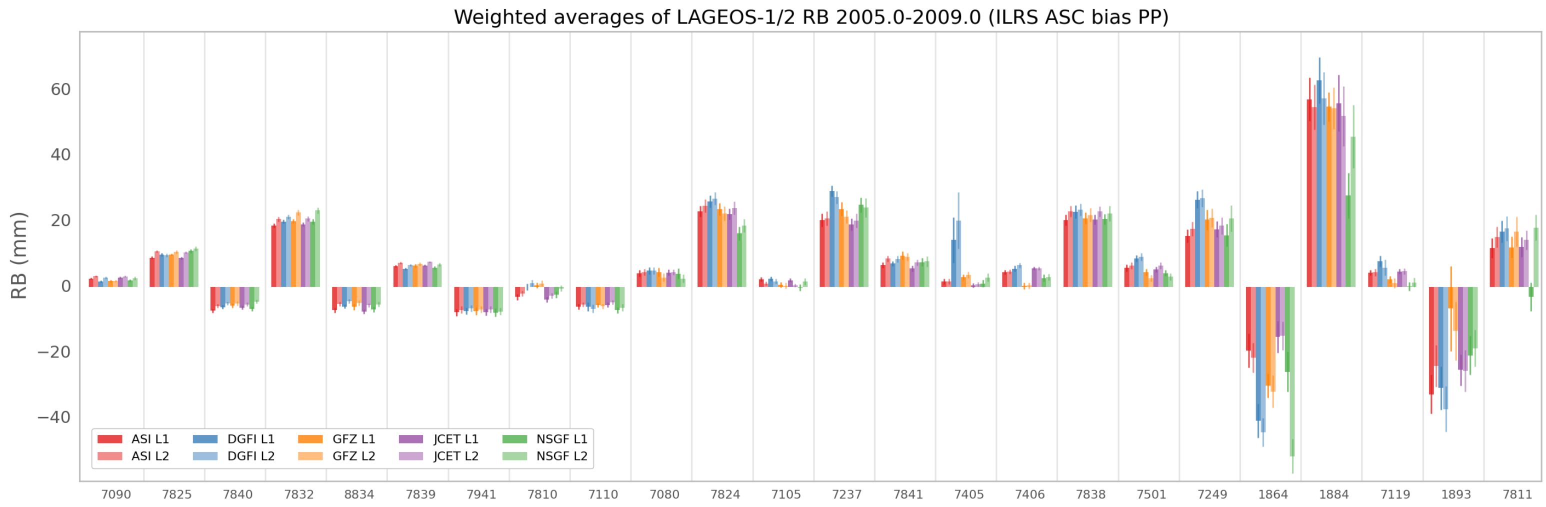


Transformation parameters between regular and RB solutions

	ΔX (mm)	ΔY (mm)	ΔZ (mm)	Δs (ppb)	Epoch (y)
RE	0.3	1.1	2.2	0.72	3:362
	0.7	0.7	1.6	0.13	
Rates	0.0	−0.2	−0.1	−0.01	
	0.1	0.1	0.3	0.02	

~0.7 ppb scale change towards VLBI

ILRS ASC pilot project on systematics



- Aimed to establish operational solution incorporating RB estimation
- Initial results available: excellent inter-AC agreement (and with external studies [1])
- Scale changes corroborated independently
- Satisfactory combination of RB solutions (ASI Combination Centre)
- Official product in the future, as combined solution of all ILRS ACs

[1]**Reinquin F., Couhert A., Bruinsma S**: *Ranging error determination using geodetic satellites in support of altimeter missions POD;* 20th ILRS Workshop on SLR, Potsdam, 2016

Some pitfalls to be aware of

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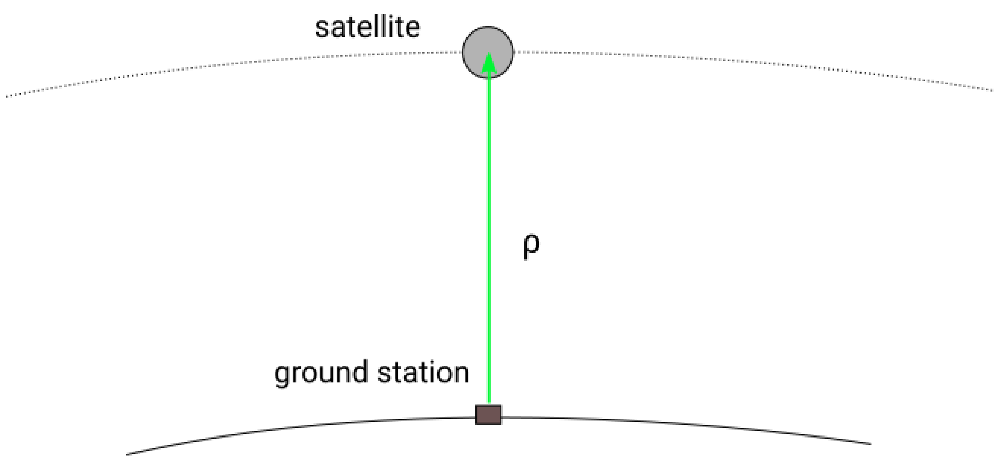
   Can’t “correct” observations with new error estimates while fixing coordinates to current frame (must wait for ITRF2014+)



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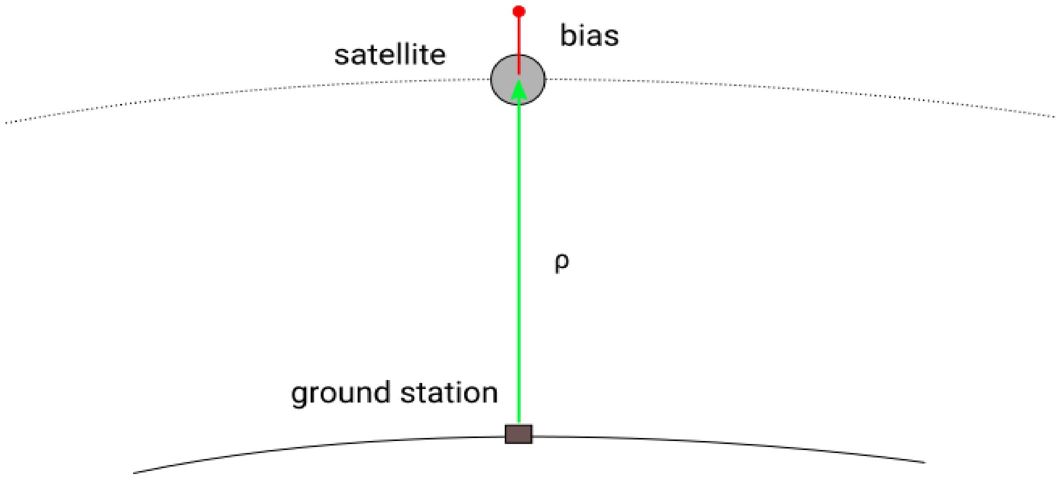

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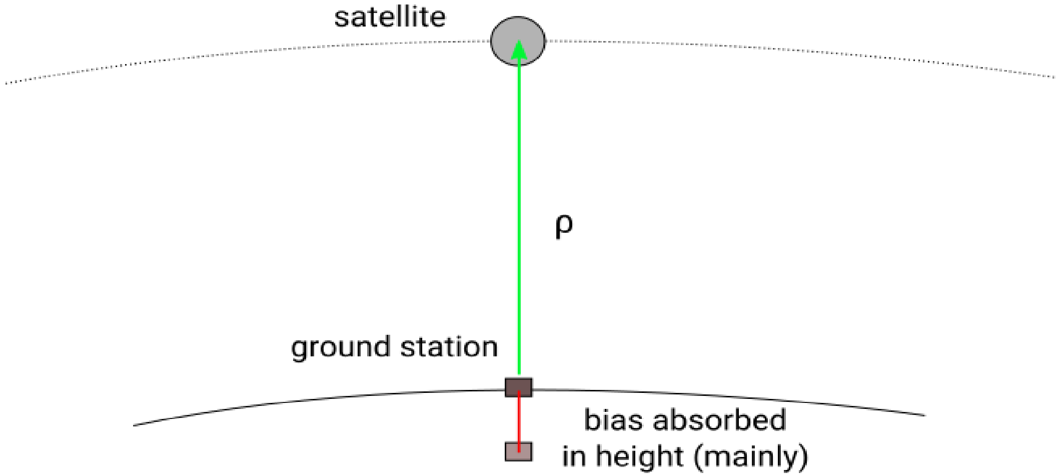

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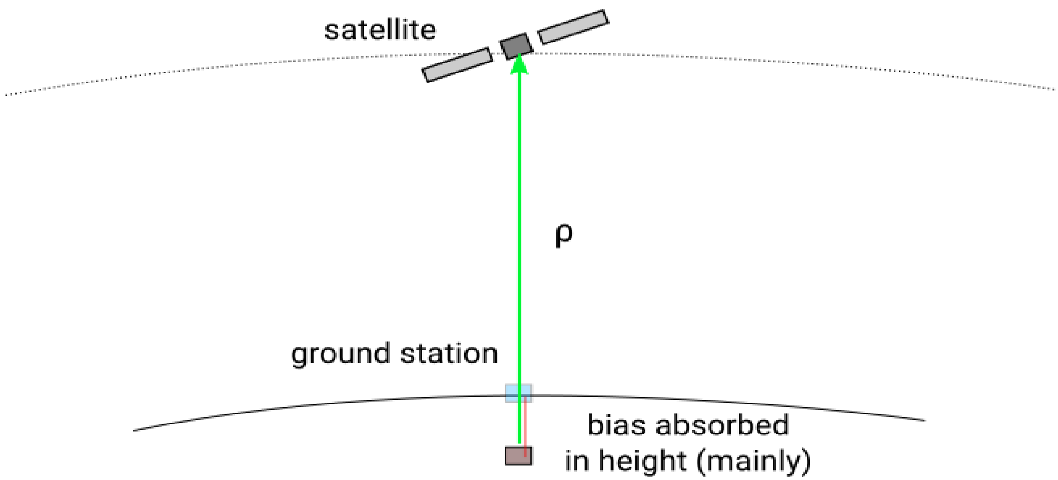

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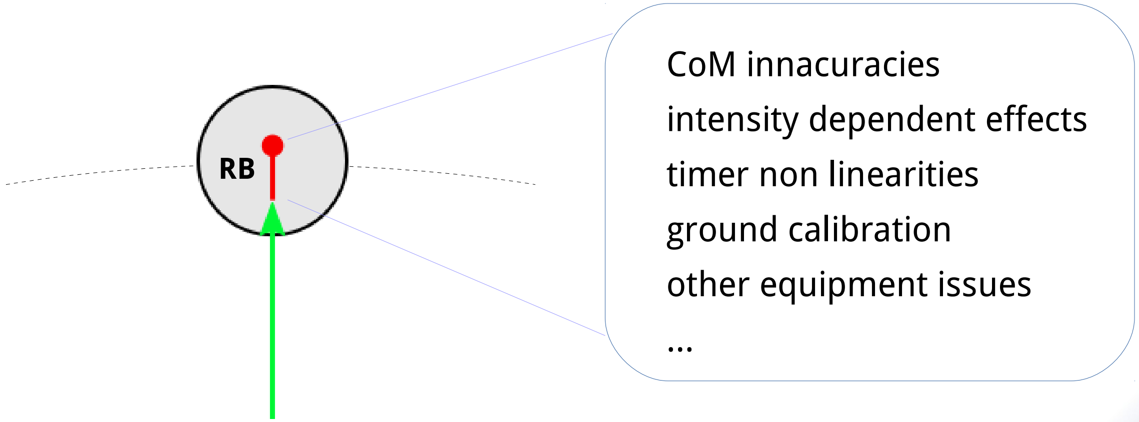

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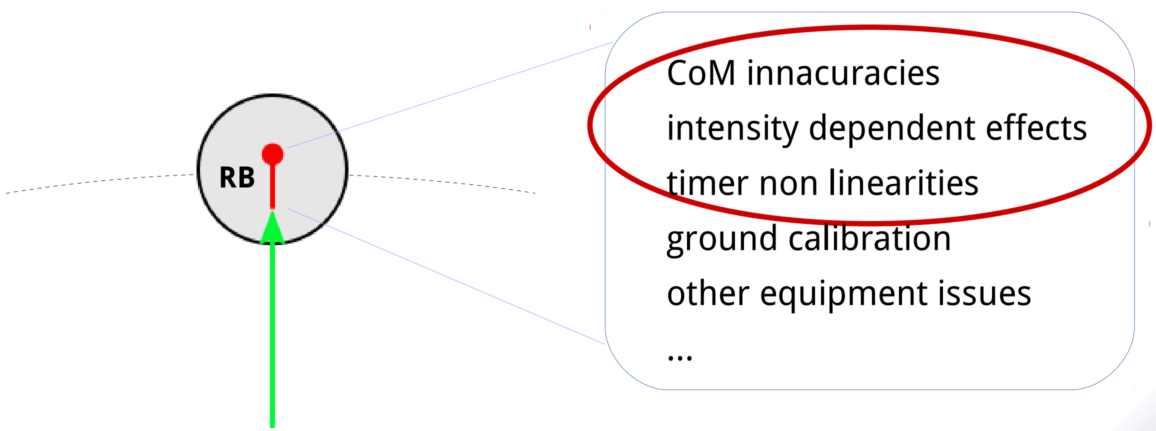

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   ILRS ASC job to assess, identify and minimise this possibility (multi-satellite combinations/comparisons, improved CoM modelling, knowledge of system behaviour and mode of operation)

Take home message

- ILRS performs extensive QC at various levels to ensure maximum product quality
- Taken significant steps forward to identificate, estimate and mitigate systematic errors and their effect on SLR observations: *absolute accuracy*
- Official error estimates product planned (and future reanalysis)
- More than 50% scale difference between SLR and VLBI explained
- Network improvements forthcoming (e.g. deployment of new NASA network) and system upgrades (towards high-repetition, low-energy, single-photon operation systems)


Thank you