Further improvements in understanding systematic errors in laser ranging observations

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outline

* Laser ranging technique is capable in principle of very precise two-way range measurements to satellites at heights of from LEO to the Moon
* Unique among the geodetic Services for definition of origin of the ITRF and, with VLBI, its scale
* Existing technology can support sub-mm range *accuracy*:
  * very short laser pulses, time-linear event timers, fast detectors

outline

* However, in practice among the inhomogeneous technology sets in use within the worldwide ILRS network, many are sub-optimal for this demanding mm-level work:
* Long pulse-lengths, non-linearity in time-of-flight counters, variable return energy levels

outline

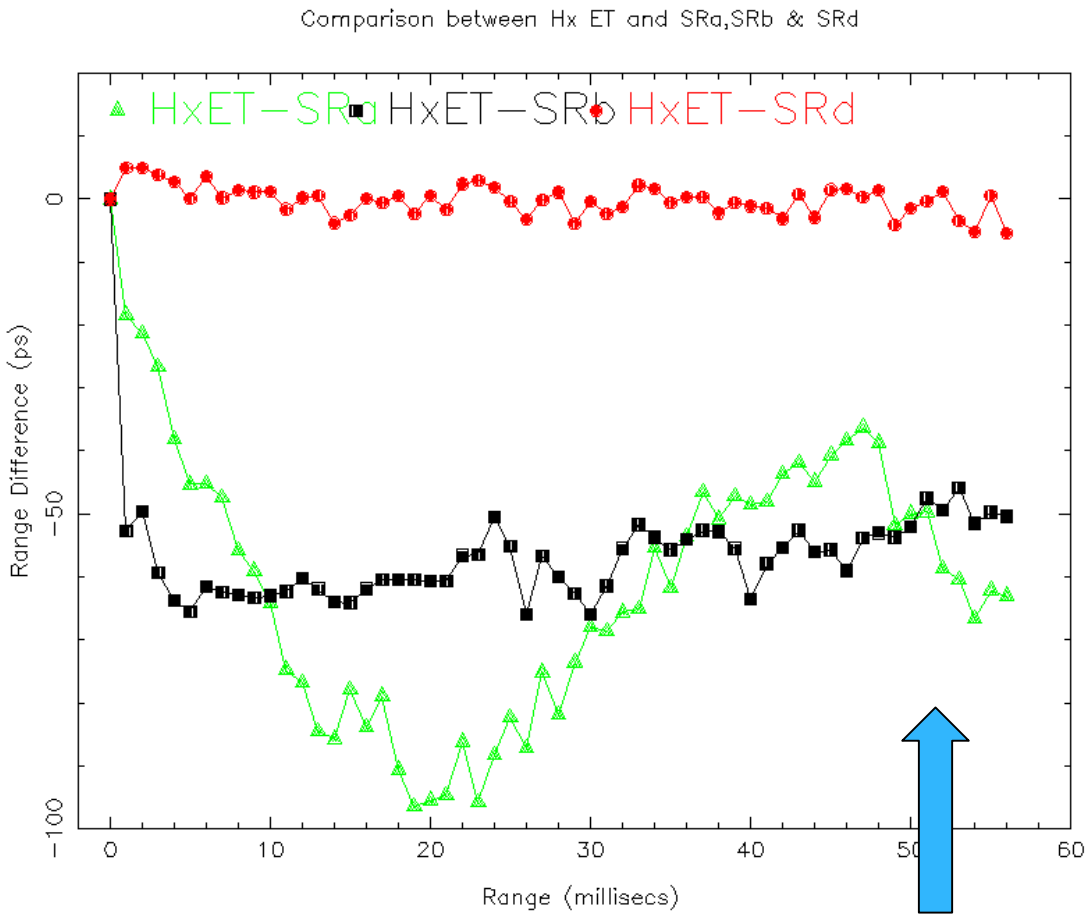
* In this work, we report on mainly successful attempts to mitigate two of the main causes of inaccuracy in LR observations:
  * Non-linear time-of-flight counters
  * Effect on range of ‘large’ geodetic satellites

* Other important effects not discussed here include potential for erroneous ground-survey measurements to calibration targets
* Also not discussed is current excellent model for tropospheric delay – Mendes-Pavlis model at mm-level of accuracy for most observations.

Range error context

* Range-error strongly correlated to error in deduced station height – and therefore in scale of TRF
* Therefore must be modeled or removed.
* But the two effects *are* separable:
  * Range partial wrt range error = 1, wrt station height ≈ sin(elevation)
  * Separable given good geometry & 2 satellites (LAGEOS)
* A major cause of range error was identified previously:

Non-linearity in time-of-flight counters



Error approaches 10mm at LAGEOS distance

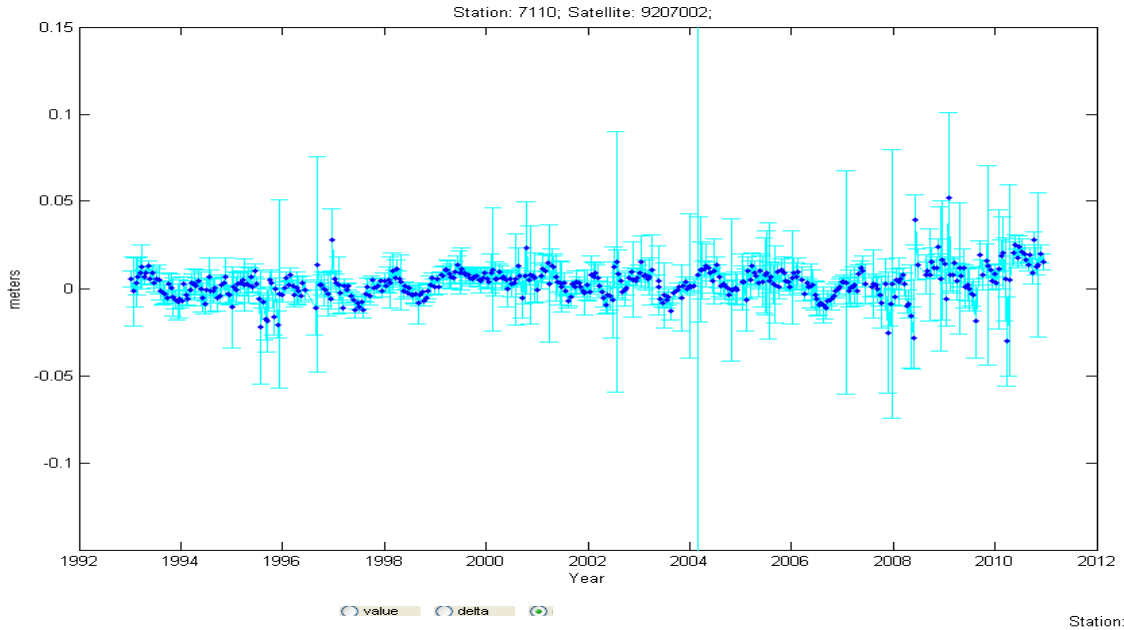
LAGEOS

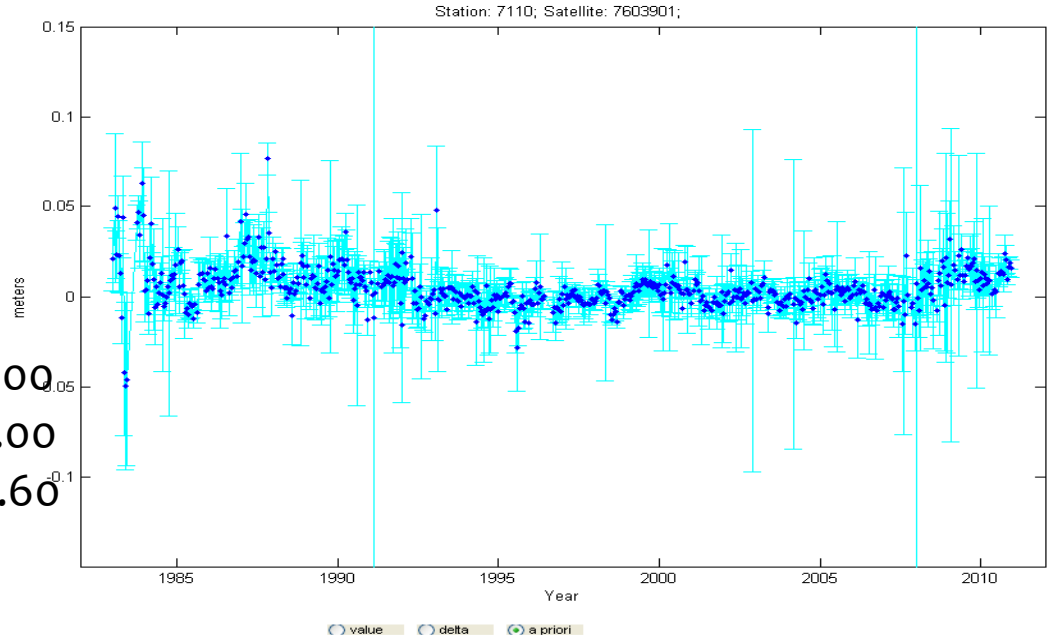
Mitigation of non-linearity effects

* So, to exploit the strength of long-term SLR measurements in determination of geocentre and scale of ITRF, must handle range errors in existing data
* Previous work suggested that the observed 'signatures' of individual time-of-flight counters could be modeled and removed from the range observations;
* Combined effects of calibration and satellite-ranging errors can exceed 15mm.
* But counter-errors are very sensitive to electronic setup;
  * Errors are altered by attempting to view them using additional electronics!

Mitigation of non-linearity effects

* Solution: use the epochs of potential problems as given by station engineers
* Solve for piecewise-continuous range bias for selected stations;
  * Ideally simultaneously with all geodetic parameters and satellite orbits, given robust set of observations
  * But also useful using say ITRF2005 as a fixed a-priori:
  * Following are examples derived relative to ITRF2005 when forming ILRS contribution to ITRF2008





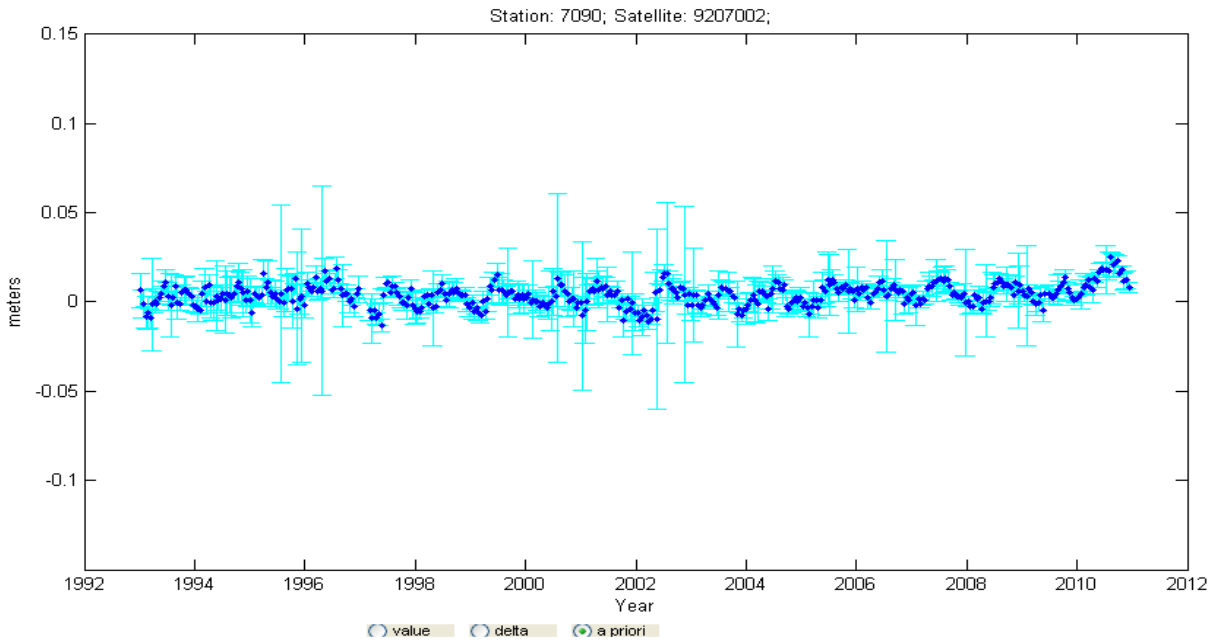
AWG Corrections (mm)

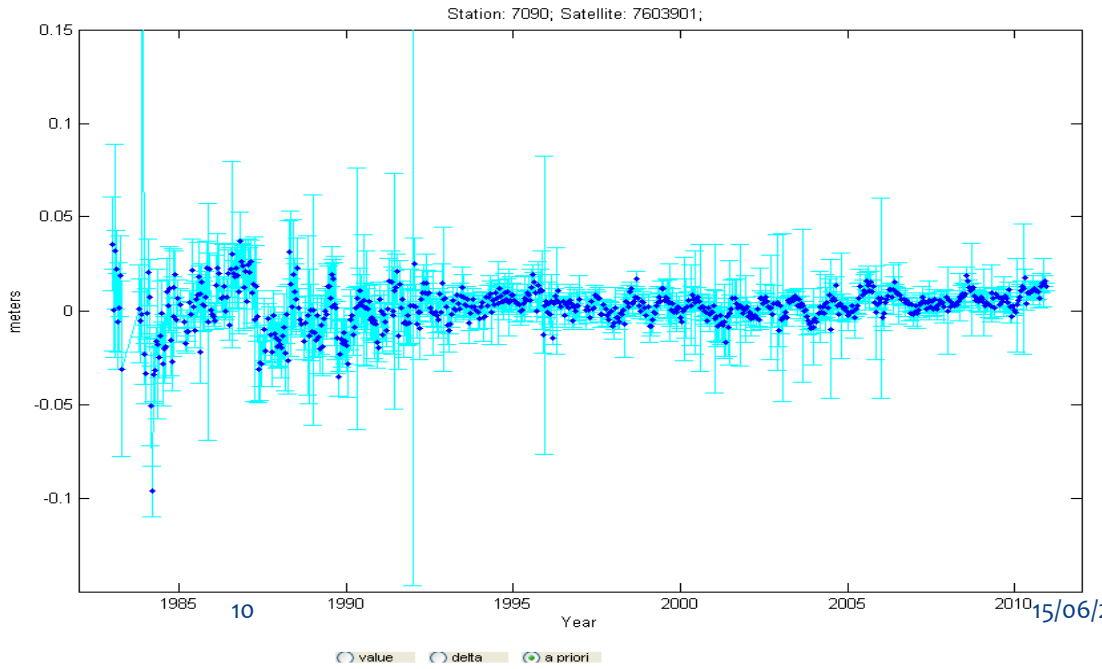
7110 A 84:001:00 84:136:00 R 30.00

7110 A 87:300:00 88:025:00R 30.00

7110 A 96:240:00 96:277:00 R 163.60

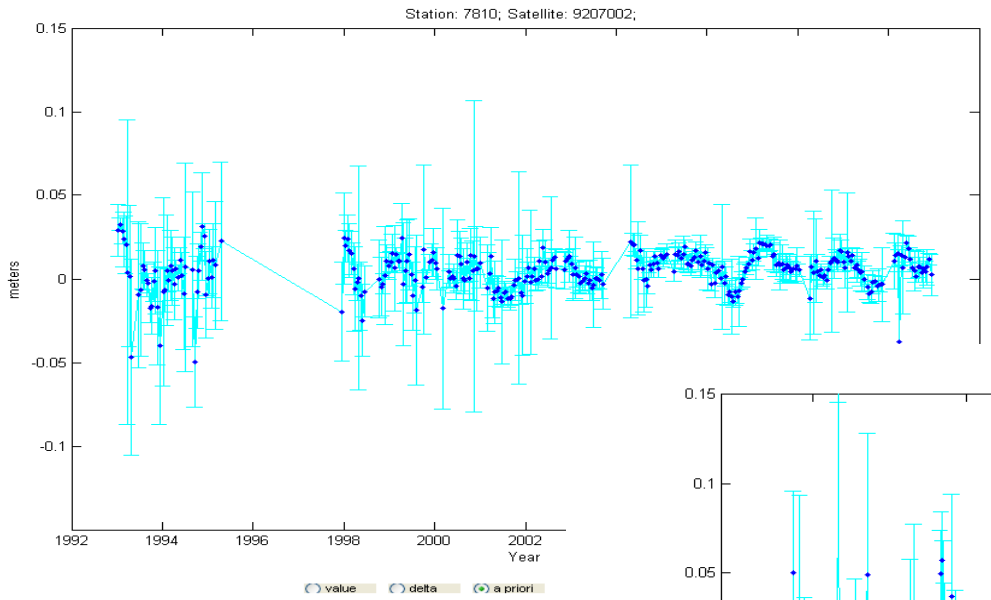
7090

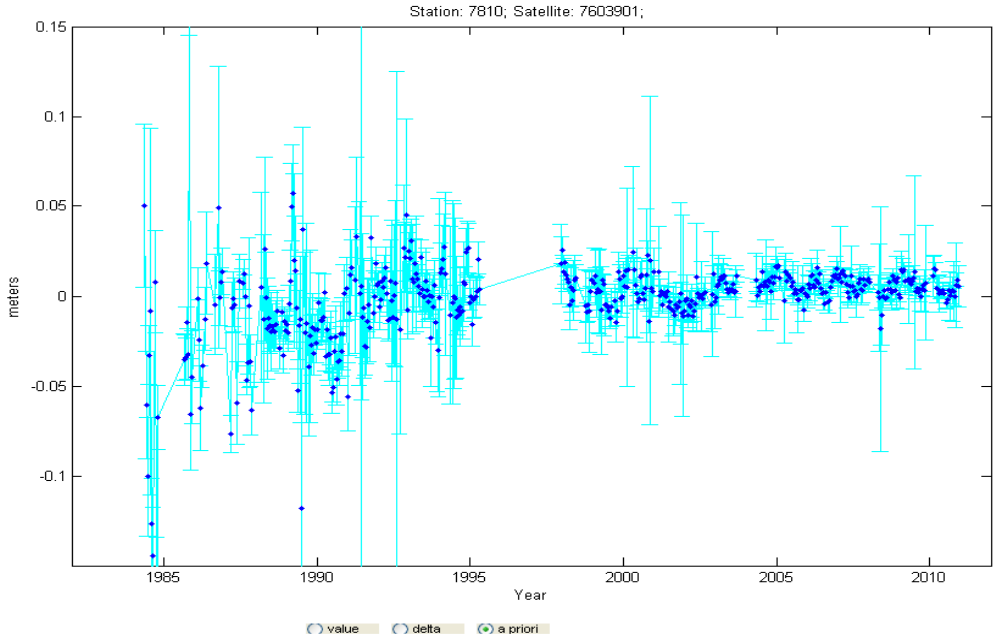




No AWG corrections

7810





Bias to be estimated

7810 B 00:000:00 00:000:00 IR

Applied biases (mm)

7810 B 88:145:00 89:273:00 R 50.00

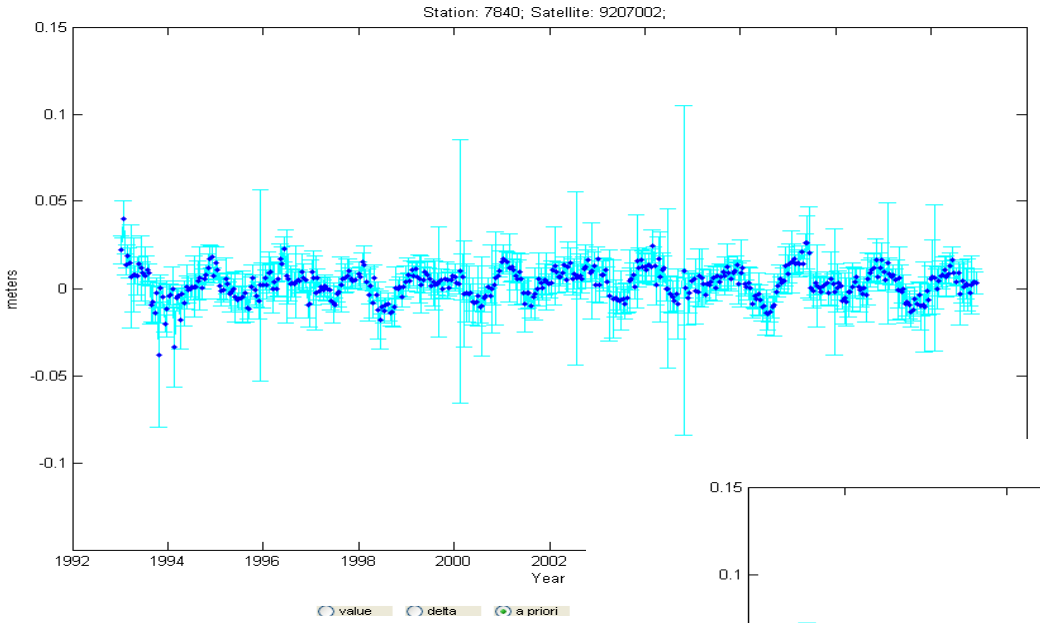
7810 B 98:001:00 02:149:00 R -26.00

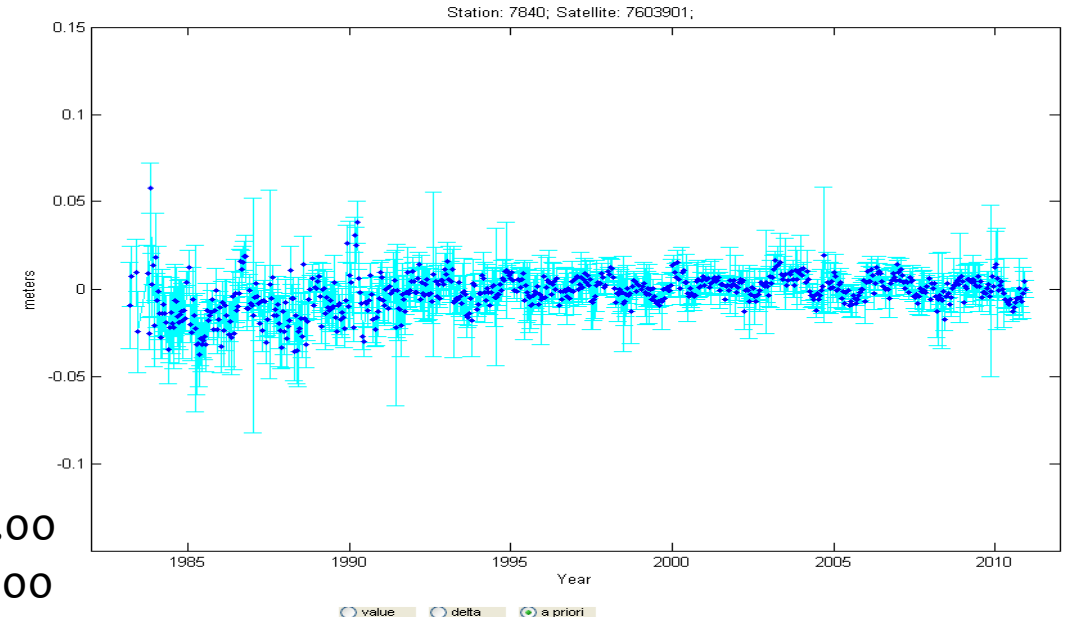
7810 B 02:149:00 03:070:00 R -15.00

7810 B 03:070:00 04:363:00 R -22.00

7810 B 04:363:00 06:037:00 R -26.00

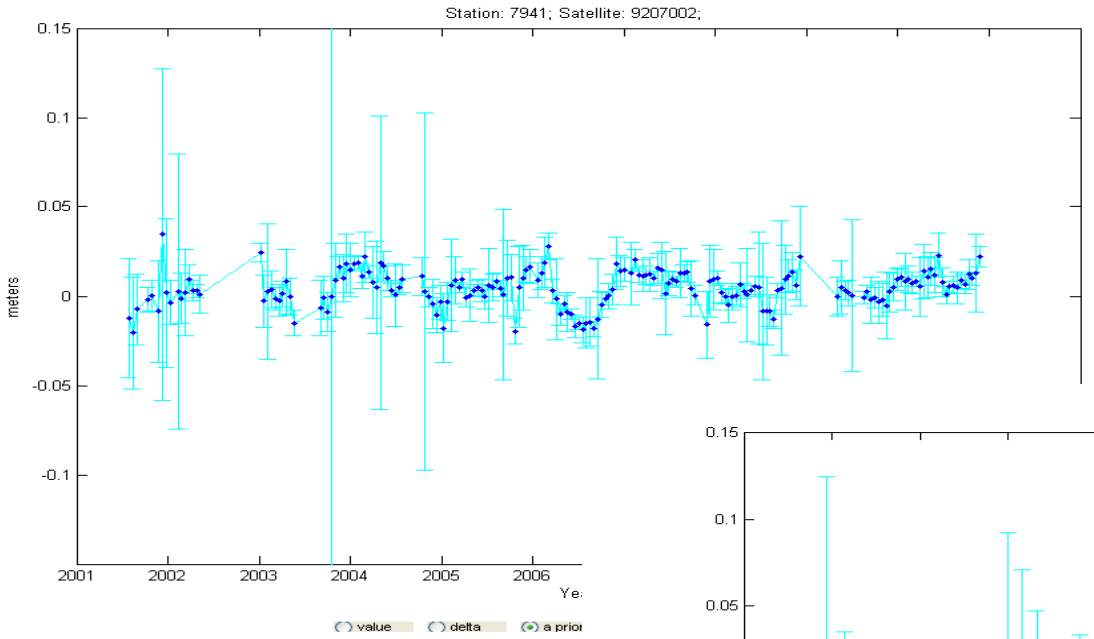
7840

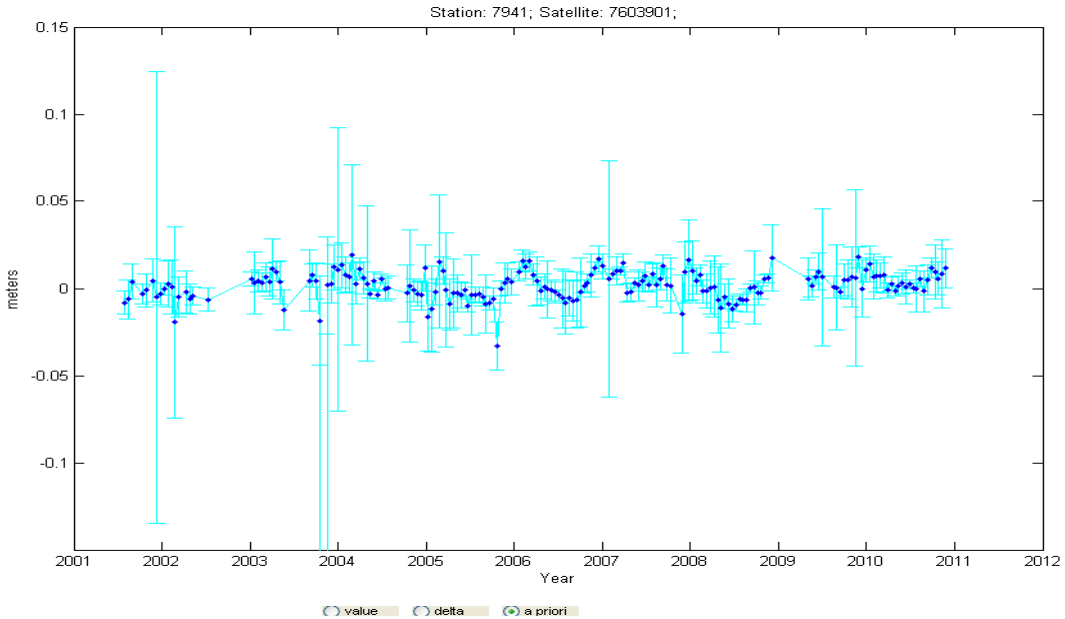




7840 A 83:244:00 84:136:00 R 40.00
7840 A 84:136:00 85:001:00 R 20.00
Linear bias from 88:254:00 to 93:302:00, from 40 mm to -15 mm
7840 A 94:013:00 99:210:00 R -9.00
7840 A 99:210:00 02:032:00 R -13.00
7840 A 02:032:00 07:042:00 R -9.00

7941





7941 --- mm A 07:047:00000 07:053:00000 R -14.00 engineering bias
7941 --- mm A 07:053:00000 07:187:39600 R -28.00 engineering bias
7941 --- mm A 07:187:39600 07:241:28800 R -22.00 engineering bias
7941 --- mm A 07:242:00000 07:295:50400 R -25.00 engineering bias
7941 --- ms A 10:221:61200 10:223:43200 U 100.00 uncorrected time bias

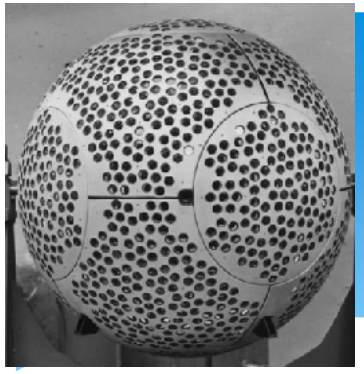
Application

* As a result of this work, a range-correction file has been prepared;
* Corrections by date and by tracking station, for 1983 onwards
* Should be applied to range data for all uses, applicable when using ITRF2008 for coordinates.

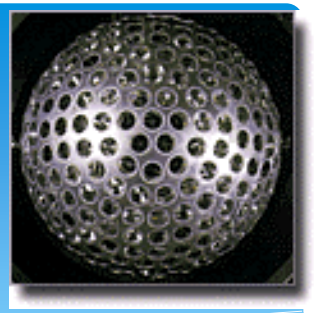
Non-linearity in time-of-flight counters

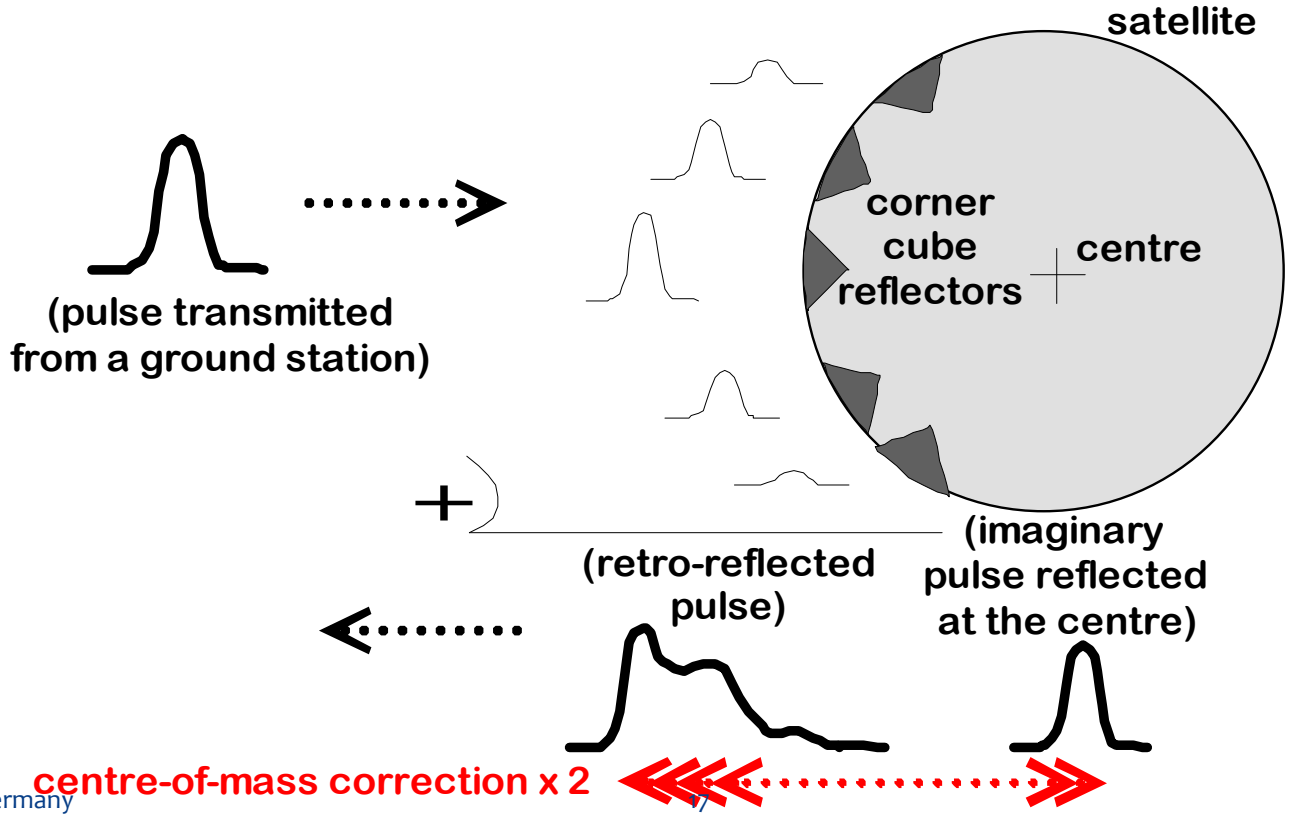
* Good news for the future is that some of the lower-quality counters are gradually being replaced:
* Stations upgrading to high-precision event timers:
  * Often to support high-repetition-rate (kHz) ranging
* such timers are linear at few ps (7ps = 1mm in range)

Event timers and counters in use in ILRS Network



Satellite ‘signature’ contribution





Satellite signature effects

* It is well known that the satellite signature effect needs careful station-dependent treatment in order to refer range measurements to the centres-of-mass of the geodetic satellites
* Up to 10mm station-dependent differences for LAGEOS, 30mm for Etalon (Otsubo & Appleby, 2003)

Satellite signature effects

* For ITRF work, as discussed, great strength of laser ranging technique is long time-span of observations:
  * LAGEOS 1976 onwards, Etalons from 1989, LAGEOS-2 from 1992.
* During that time, stations' technology changes:
  * Different centres-of-mass values appropriate

Satellite signature effects

* ILRS stations' site logs are a valuable source of relevant information:
* Detectors, laser pulse-length, operational practices (return-energy regimes), etc.
* Used to derive time-series of CoM corrections and their uncertainties for each station for LAGEOS and for Etalon
  * - using the published models
* Results currently under evaluation; suggesting overall mean CoM change of ~1 mm, but for individual stations ~±5 mm change from 'standard' values

Detail from CoM table for LAGEOS

Station	Time-span					detector info	CoM min, max, adopted (mm)				
7838	01 04 2008	31 12 2050	20	MCP CSM	3.0	6	15	252	248	**250**
7838	01 07 1990	01 04 2008	100	MCP CSM	3.0	20	40	252	248	**250**
7839	01 01 1983	31 12 2000	300	PMT NC	3.0	120	150	245	241	**243**
7839	01 11 1981	08 10 2003	35	CSP NCM	2.2	3	9	255	250	**252**
7839	09 10 2003	31 12 2050	10	CSP NSF	2.2	3	9	255	250	**252**
7840	01 02 2007	31 12 2050	10	CSP CS	2.5	3	9	245	245	**245**
7840	31 03 1983	31 03 1992	100	PMT NCF	3.0	35	45	252	244	**248**
7840	31 03 1992	31 12 2050	100	CSP CS	3.0	6	15	246	244	**245**
7841	20 07 2001	31 12 2050	50	PMT CSF	2.5	10	18	254	248	**251**

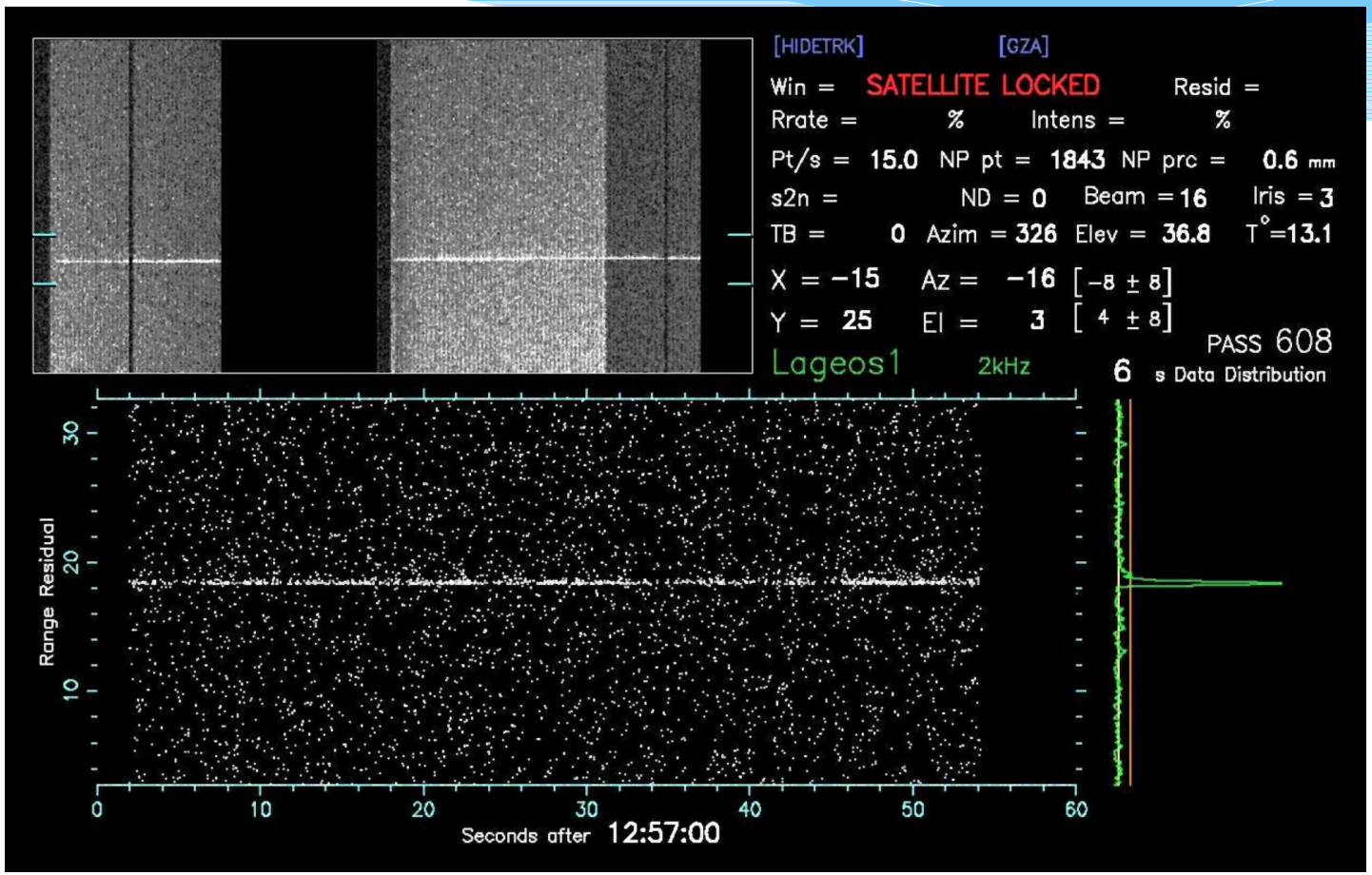
CoM corrections, outlook

* For some stations, range of possible CoM corrections is large (4 to 8mm)
* But ideal system for mm-level accuracy is:
* kHz rate, short-pulse laser;
* Very high-precision event timer;
* Working at single photon level of return:
* NASA's NGSLR, the current ILRS kHz plus some other stations do comply:

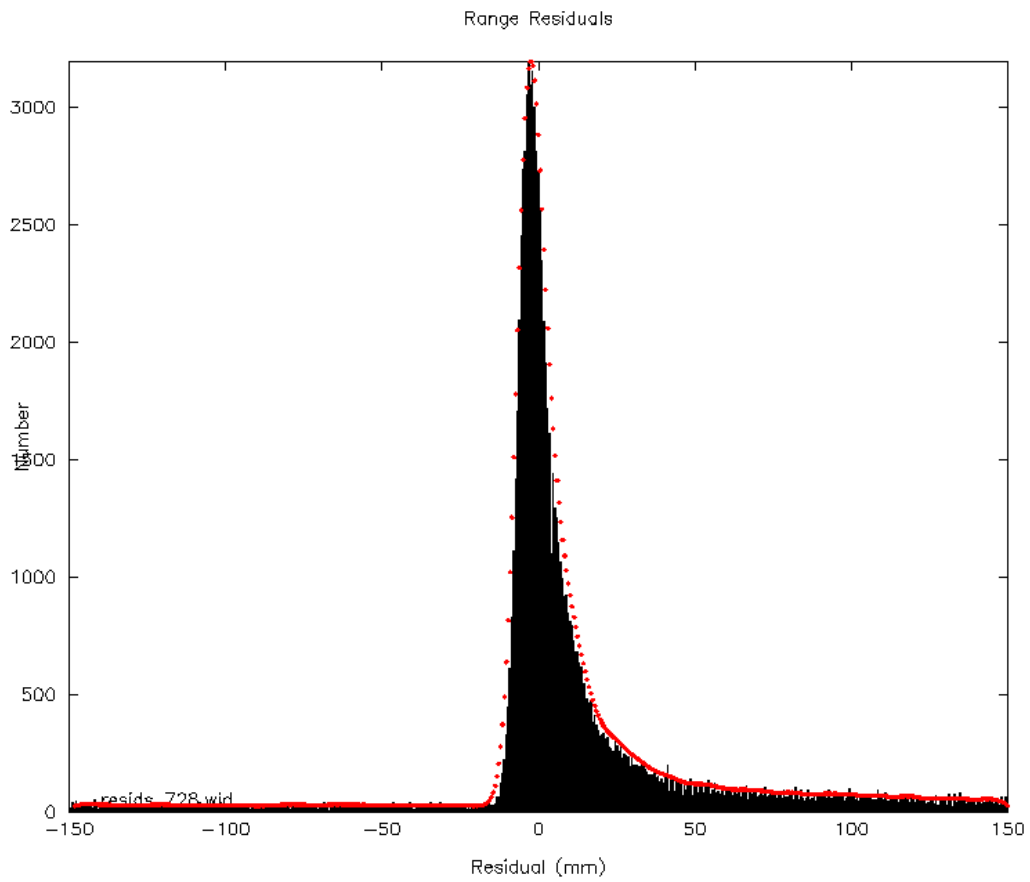
outlook

* For such stations, it is possible to build a response-model that allows extraction of very accurate CoM values, at **1 or 2 mm**-level of accuracy,
* Model built from a convolution of system response with satellite-response function
* Example for LAGEOS – Herstmonceux 2kHz, single-photon system:

Realtime range-gate display: LAGEOS during daytime



High-precision and accuracy from LAGEOS



Real O-C data from a kHz pass. Model (red) fits very well. Implied CoM value is 245 ± 1 mm

conclusions

* Much work done to estimate and remove known range errors in the LR data records 1980-present;
* Many of the problems are due to limitations of 'old' counters, some of which have been replaced in the last few years
  * Data correction file is available on ILRS web
* Progress with system & time-dependent CoM corrections:
  * CoM values for LAGEOS and Etalon being evaluated
  * Starlette/Stella to come next