Further Improvements in Understanding Subtle Systematic Effects in Laser Ranging Observations

Graham Appleby [1], **Toshi Otsubo** [2] and **Philip Gibbs** [1]

1: Space Geodesy Facility, Herstmonceux, UK;

2: Hitotsubashi University, Tokyo, Japan

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Outline of work

- SLR technique is capable of making extremely *precise* range measurements to retro-reflector clusters on geodetic satellites
  - Short-pulse lasers, high-precision counters=>
  - mm-level ‘Normal point’ precision, 0.2ppb in range to LAGEOS
- To realise same accuracy, three key features:
  - Linearity of range measuring devices;
  - Correct ranges for ‘size’ of satellite, CoM value;
  - Accurate tropospheric refraction model.

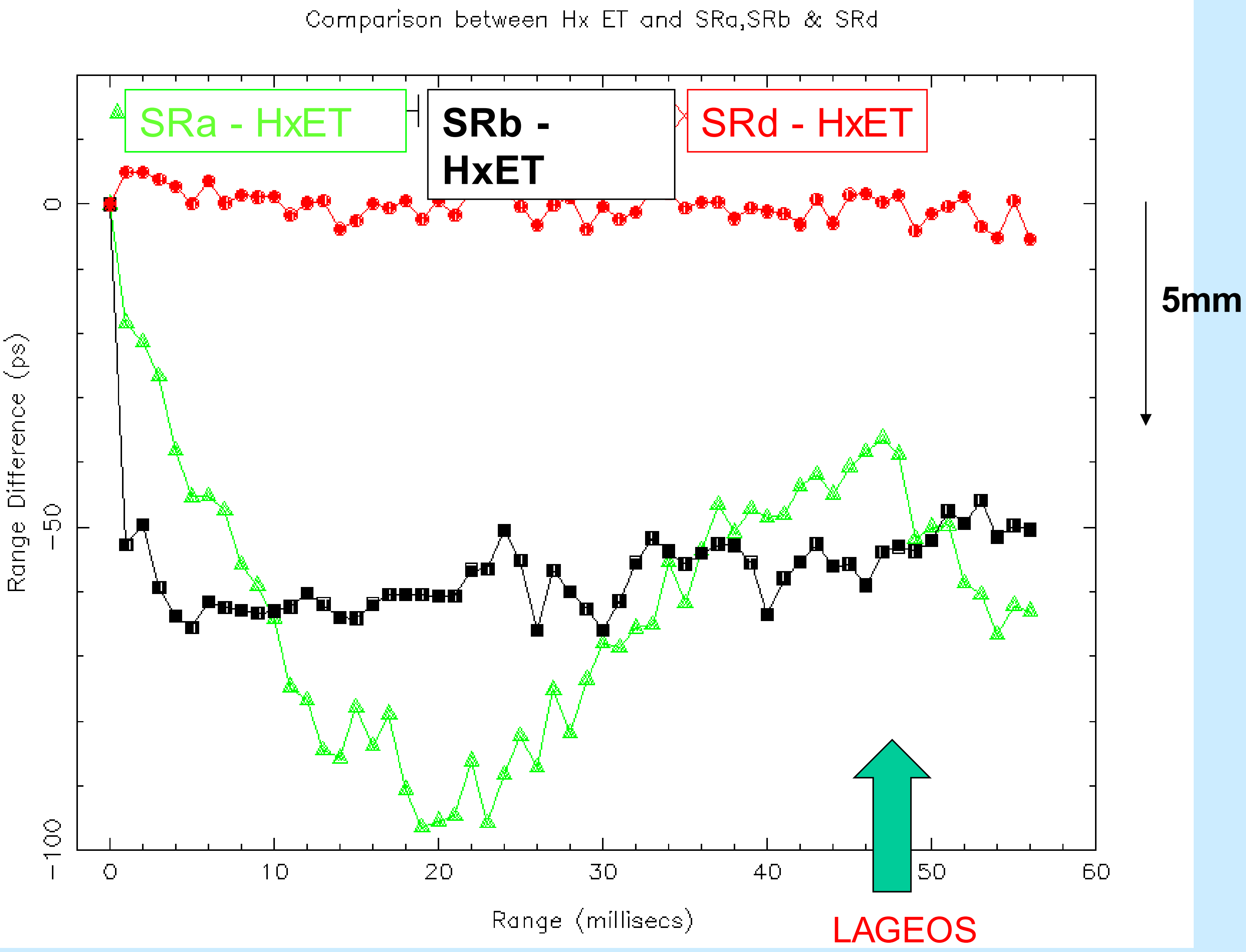
Tests on counter linearity

- Relative to a ‘perfect’ time-of-flight counter, what are the characteristics of the counters in common use over the last 15+ years?
- Work was started by a careful examination of *Stanford* counters in use at Herstmonceux, UK, relative to a high-spec, ps-level event timer.
- Studied effects at LAGEOS and at local calibration target distances.

Herstmonceux counters

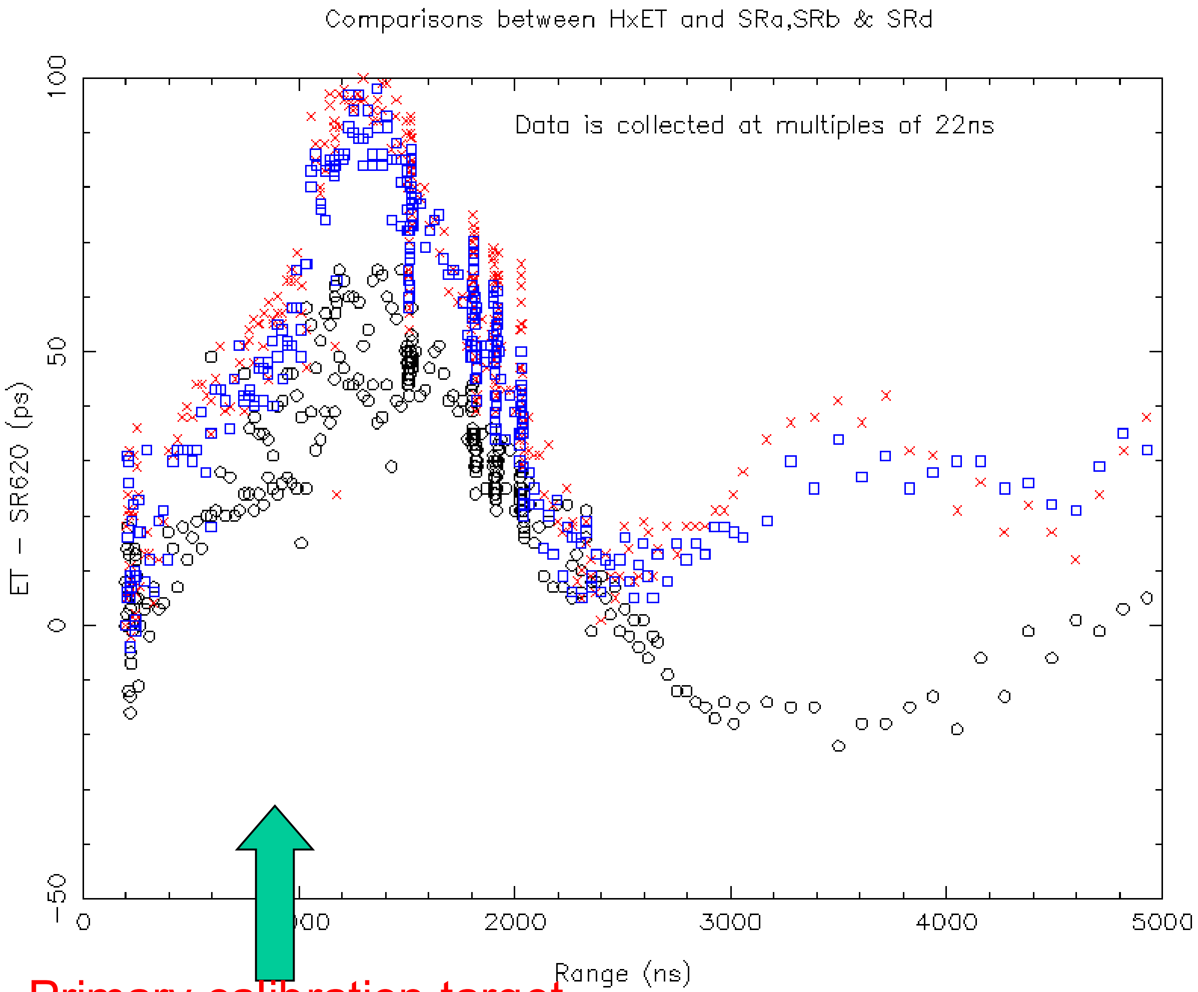
- A ps-level event timer (HET) has been built in-house from *Thales* clock units;
- A prerequisite for the upcoming kHz operations.

- Extensive use of HET to calibrate existing cluster of *Stanford* counters prior to routine use of HET;
- In particular we wish to **back-calibrate** Hx data 1994-present.
- Look at effect on range accuracy and station height in ITRF2000/05.


Comparison between Hx ET and SRa,SRb & SRd
SRa - HxET
SRb - HxET
SRd - HxET
Range Difference (ps)
0
−50
−100
Range (millisecs)
0
10
20
30
40
50
60

5mm

LAGEOS



Primary calibration target

Comparisons between HxET and the Stanford counters for calibration boards’ distances;

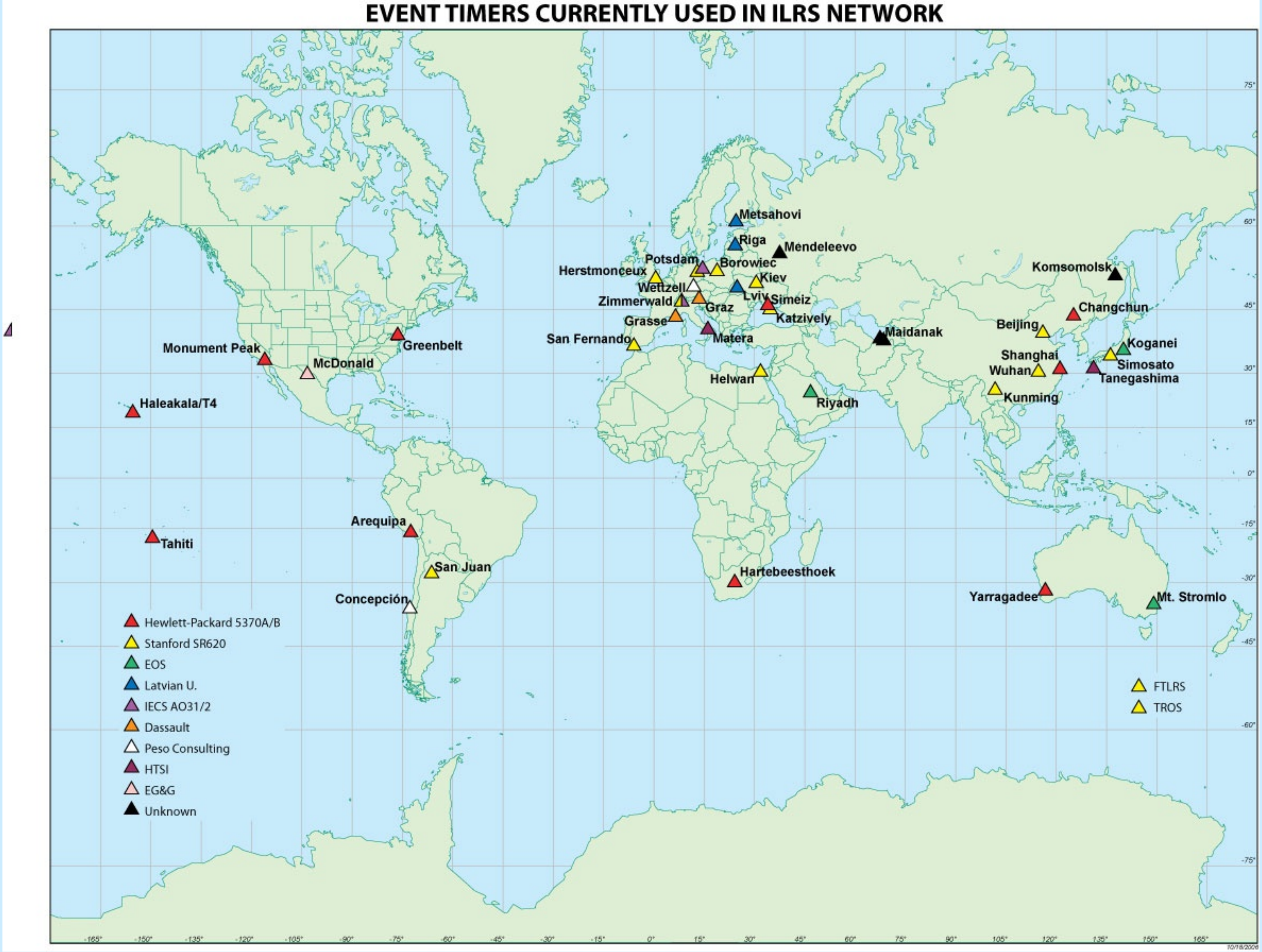
Behaviour very similar to spec;

Errors up to 100ps (15mm), with some systematic detailed structure

Summary of effect on range measurements at Herstmonceux (1992-2006)

- The non-linearity of the Stanfords:
- imparts an average of ~-7±2mm error onto the observed calibration range;
  - Hence calibrated satellite ranges are too long.
- Value is dependent on the target range and on the particular Stanford;
- At distance of LAGEOS, range error is between zero and ~-8±2mm;
  - Hence observed LAGEOS ranges are too short
- **So total range error was up to 8mm**
- **Currently error is ~zero, with new event timer**

Effect present in other ILRS stations?



EVENT TIMERS CURRENTLY USED IN ILRS NETWORK

Effect present in other ILRS stations?

- At this stage, we confine our investigation to Stanford counters;
  - Our limited experience with *e.g*. HP timers suggests they do not have problem – used by NASA network
- We have made ‘worst case’ **estimates** of calibration error and total range error at LAGEOS for all ‘Stanford stations’

- Error span is -10 to +11mm, frequent error +10mm
- Uncertainty in these **estimates** is ~5mm

Worse-case error estimates (mm)

Station		ID	Calibration error	LAGEOS error	Total error
BEIL	**Beijing**	**7249**	**-12**	**10**	**- 2**
BORL	**Borowiecz**	**7811**	**- 9**	**0 meas**	**- 9**
BREF	**Brest**	**7604**	**-10**	**10**	**0**
GLSV	**Kiev**	**1824**	**- 6**	**10**	**+ 4**
HELW	**Helwan**	**7831**	**0**	**10**	**+10**
HERL	**Herstmonceux**	**7840**	**- 8 meas**	**0 meas**	**- 8**
KTZL	**Katzively, Ukraine**	**1893**	**0**	**10**	**+10**
KUNL	**Kunming, China**	**7820**	**- 9**	**10**	**+ 1**
POT3	**Potsdam**	**7841**	**0**	**10**	**+10**
POTL	**Potsdam**	**7836**	**0**	**5 meas**	**+ 5**
SFEL	**San Fernando**	**7824**	**0**	**8 meas**	**+ 8**
SISL	**Simosato, Japan**	**7838**	**+1**	**10**	**+11**
SJUL	**San Juan**	**7406**	**0**	**10**	**+10**
WUHL	**Wuhan**	**7231**	**0**	**10**	**+10**
ZIML	**Zimmerwald**	**7810**	**-3**	**8 appl**	**- 3**
Closed sites					
GRSL	**Grasse**	**7835**	**- 1**	**10**	**11**

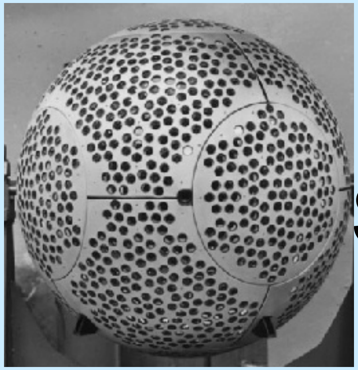
meas = measured on particular Stanford counters; appl = applied at station

Comments

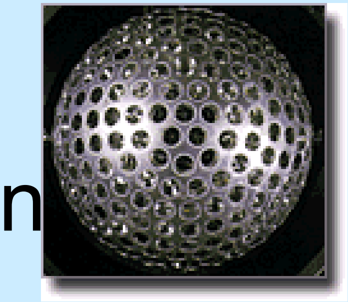
- We emphasise the preliminary nature of this table;
  - The plots of the 3 Herstmonceux Stanford counters show large inter-counter differences;
- Calibration of each stations’ counter(s) is essential.

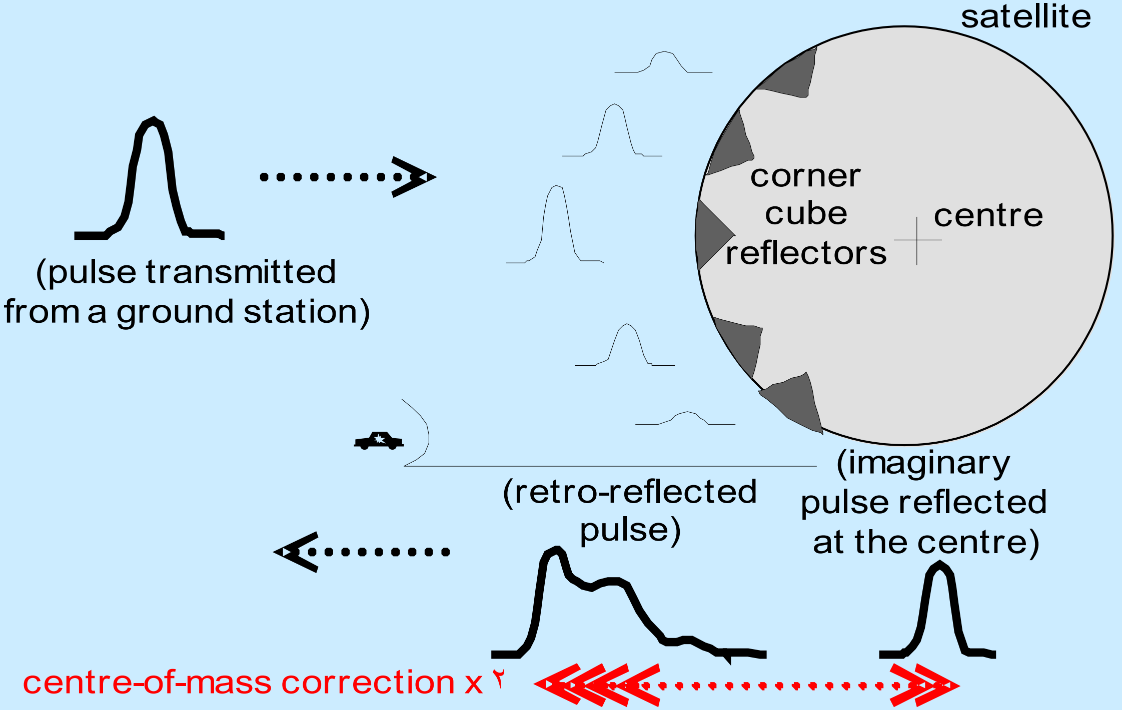
Summary/outlook

- We also note that:
- The stations are a subset of the full ILRS network, but do contain some core sites;
- The counters can be calibrated (ongoing) and data reprocessed;
  - Counter characteristics remain static over time;
- Several of the stations have already upgraded to higher-quality counters.



Satellite ‘signature’ contribution





satellite

corner
cube
reflectors

centre

(pulse transmitted
from a ground station)

(retro-reflected
pulse)

(imaginary
pulse reflected
at the centre)

centre-of-mass correction x ٢

On average, over many shots, returning pulse-shape can be modelled as a convolution of laser pulse-shape with the satellite response function.

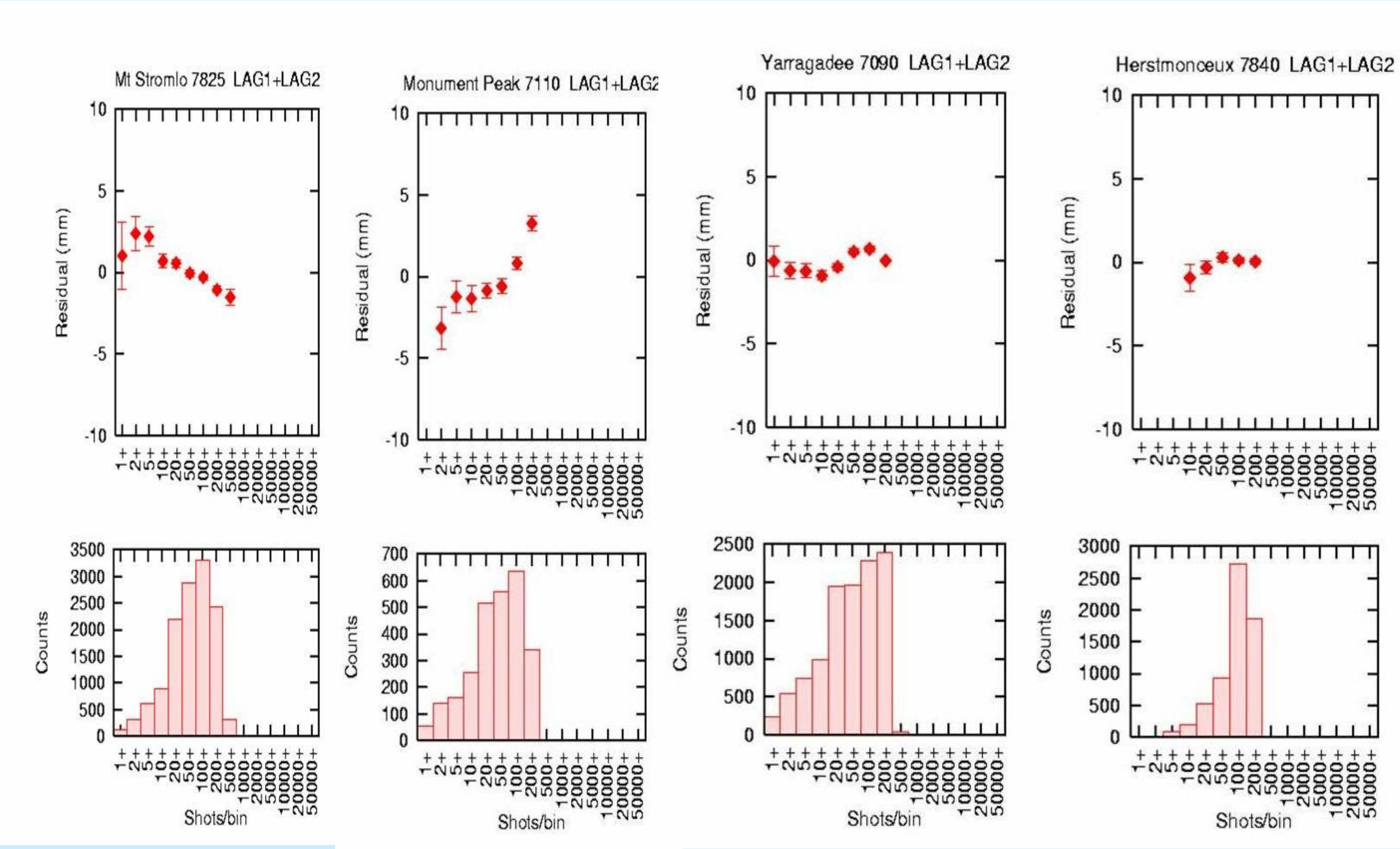
Magnitude of effect

- Depending upon the stations' technology:

  - there is a range of appropriate CoM values;
  - for LAGEOS the total range is ~8mm

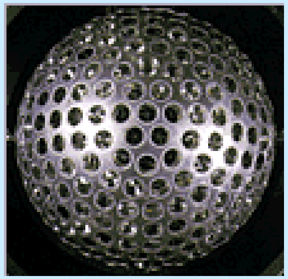
- Station technology:
  - multi-photon returns:
    - photomultiplier or first-photon detection
  - single photon return

- For a **given station**, there is a return-energy dependence too:



Multi photon **Multi photon** **Multi photon** **Single photon**

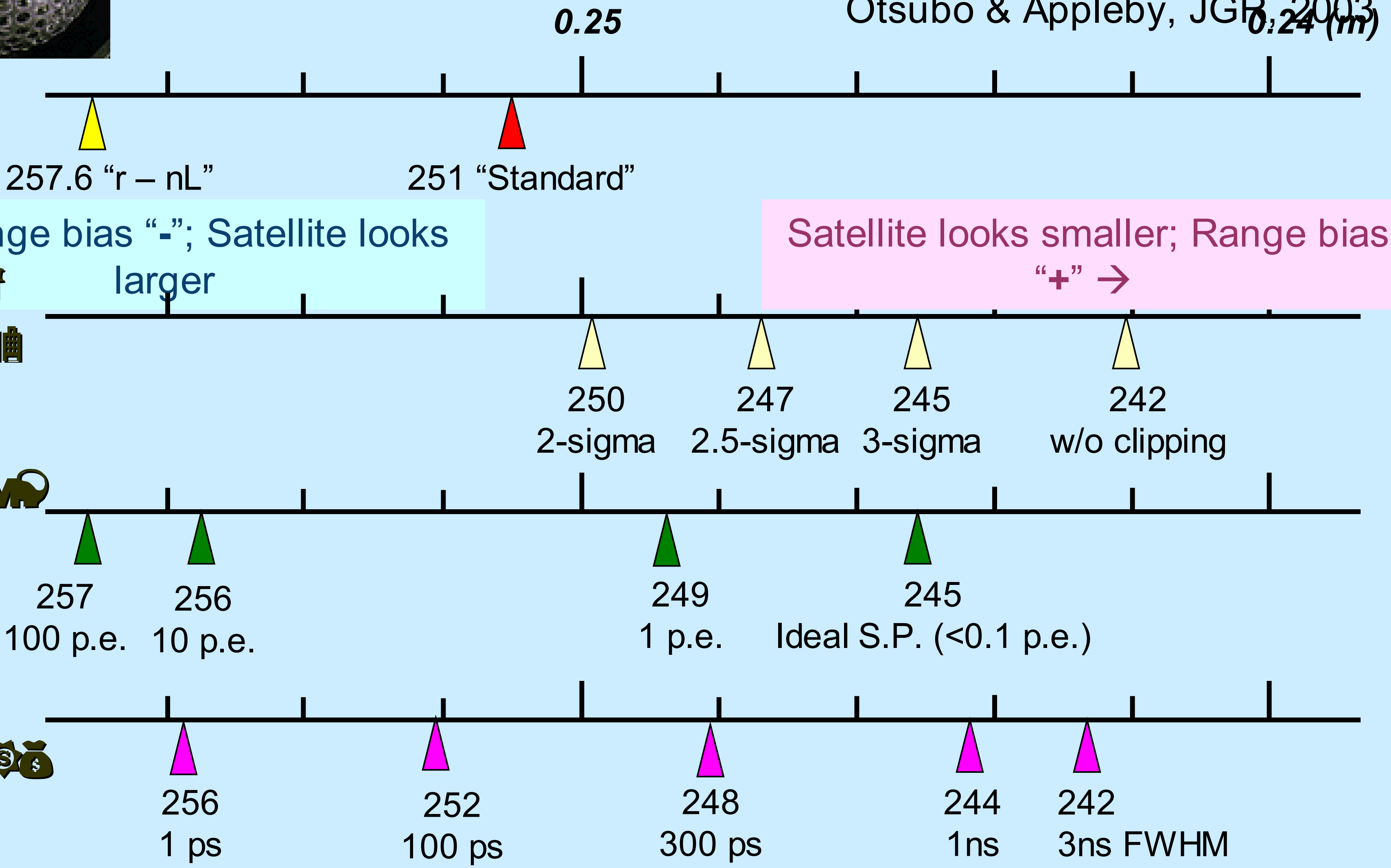
Example post-fit range residuals as a function of returns per normal point (a proxy for return energy variation). Jan 2004 - Jul 2005



LAGEOS

Diameter 600 mm

Otsubo & Appleby, JGR, 2003



0.25

0.24 (m)

257.6 “r – nL”

251 “Standard”

← Range bias “-”; Satellite looks larger

Satellite looks smaller; Range bias “+” →

250
2-sigma

247
2.5-sigma

245
3-sigma

242
w/o clipping

257
100 p.e.

256
10 p.e.

249
1 p.e.

245
Ideal S.P. (<0.1 p.e.)

256
1 ps

252
100 ps

248
300 ps

244
1ns

242
3ns FWHM

Theoretical LAGEOS CoM values based on stations' characteristics

Stn pad ID	Name	Pulse (ps)	Detector	Regime (single, few, multi)	Processing level	LAGEOS CoM (mm)
1873	Simeiz	350	PMT	No Control	2.0 sigma	244-248
1884	Riga	130	PMT	Controlled s->m	2.0 sigma	248-252
7080	Mc Donald	200	MCP	Controlled s->m	3.0 sigma	244-250
7090	Yaragadee	200	MCP	Controlled f->m	3.0 sigma	244-250
7105	Greenbelt	200	MCP	Controlled f->m	3.0 sigma	244-250
7110	Monument Peak	200	MCP	Controlled f->m	3.0 sigma	244-250
7124	Tahiti	200	MCP	Controlled f->m	3.0 sigma	244-250
7237	Changchung	200	CSPAD	Controlled s->m	2.5 sigma	245-250
7249	Beijing	200	CSPAD	No Control, m	2.5 sigma	248-250
7355	Urumqui	30	CSPAD	No Control	2.5 sigma	247-255
7405	Conception	200	CSPAD	Controlled s	2.5 sigma	245-246
7501	Harteb.	200	PMT	Controlled f->m	3.0 sigma	244-250
7806	Metsahovi	50	PMT	?	2.5 sigma	248-254
7810	Zimmerwald	300	CSPAD	Controlled s->f	2.5 sigma	244-250
7811	Borowiec	40	PMT	No Control f	2.5 sigma	250-256
7824	San Fernando	100	CSPAD	No Control s->m	2.5 sigma	246-252
7825	Stromlo	10	CSPAD	Controlled s->m	2.5 sigma	247-257
7832	Riyadh	100	CSPAD	Controlled s->m	2.5 sigma	246-252
7835	Grasse	50	CSPAD	Controlled s->m	2.5 sigma	246-255
7836	Potsdam	35	PMT	Controlled s->m	2.5 sigma	252-256
7838	Simosato	100	MCP	Controlled s->m	3.0 sigma	248-252
7839	Graz	35	CSPAD	No Control m	2.2 sigma	250-255
7839	Graz kHz	10	CSPAD	No Control s->f	2.2 sigma	?
7840	Herstmonceux	100	CSPAD	Controlled s	3.0 sigma	244-246
7841	Potsdam 3	50	PMT	Controlled s->f	2.5 sigma	248-254
7941	Matera	40	MCP	Controlled m	3.0 sigma	250-254
8834	Wettzell	80	MCP	No Control f->m	2.5 sigma	248-252

In close-up, for the example stations

Stn pad ID	**Name**	Pulse (ps)	Detector	Regime (single, few, multi)	Processing level	**LAGEOS CoM (mm)**
7825	**Stromlo**	10	CSPAD	**Controlled s->m**	2.5 sigma	**247-257**
7110	**Monument Peak**	200	MCP	**Controlled f->m**	3.0 sigma	**244-250**
7090	**Yaragadee**	200	MCP	**Controlled f->m**	3.0 sigma	**244-250**
7840	**Herstmonceux**	100	CSPAD	**Controlled s**	3.0 sigma	**244-246**

There exists a band of CoM values, the size of which is dependent on the stations' technology.

- Single photon systems have tightest band;
- MCP systems' results in some cases appear counter-intuitive in terms of bias wrt energy regime and do not agree in sign with the theoretical band:
  - more investigation required into the technology for these cases.
- Answer is strictly to maintain a particular regime during ranging.

Conclusion

- With improved
  - calibration of counters in the sub-network;
  - knowledge of band of appropriate CoM values throughout the network:
- Should include these effects in future re-analyses efforts towards:
  - TRF;
  - GM;
  - Constrained RB for stations based on informed CoM band and counter characteristics.