Upgraded CoM modelling for geodetic SLR targets: accuracy, sources of uncertainty and errors

José Rodríguez

NSGF AC, UK

Intro/context

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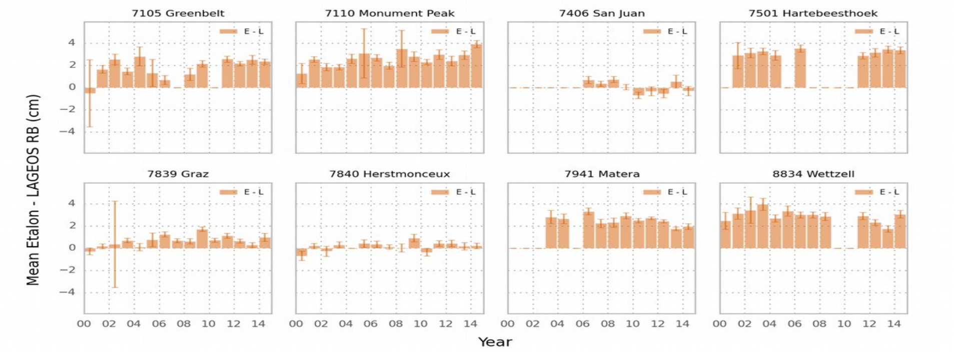
These estimates, with no clear correlation with biases from other targets, suggested the problem might not lie with the observations



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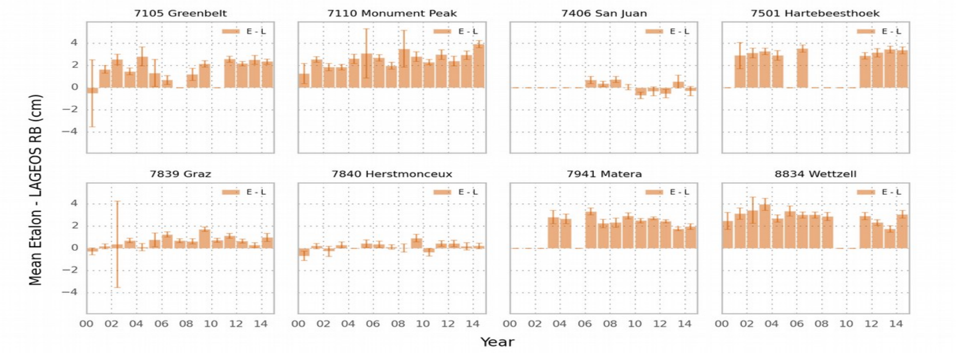
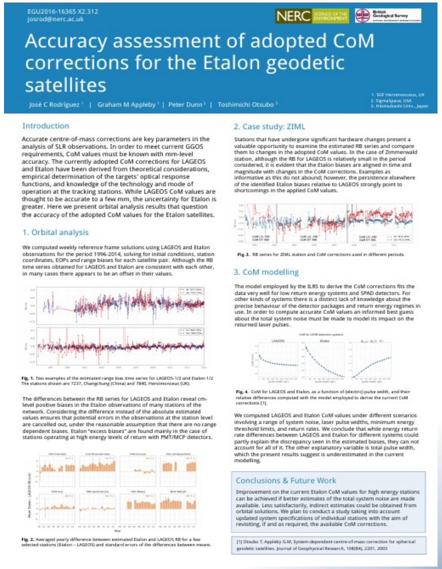
This prompted us to revisit the model employed to derive CoM corrections for all geodetic spherical satellites





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Accuracy assessment of adopted CoM corrections for the Etalon geodetic satellites

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1. SGF Herstmonceux, UK
2. SigmaSpace, USA
3. Hitotsubashi Univ., Japan

Introduction

Accurate centre-of-mass corrections are key parameters in the analysis of SLR observations. In order to meet current GGOS requirements, CoM values must be known with mm-level accuracy. The currently adopted CoM corrections for LAGEOS and Etalon have been derived from theoretical considerations, empirical determination of the targets' optical response functions, and knowledge of the technology and mode of operation at the tracking stations. While LAGEOS CoM values are thought to be accurate to a few mm, the uncertainty for Etalon is greater. Here we present orbital analysis results that question the accuracy of the adopted CoM values for the Etalon satellites.

1. Orbital analysis

We computed weekly reference frame solutions using LAGEOS and Etalon observations for the period 1996-2014, solving for initial conditions, station coordinates, EOPs and range biases for each satellite pair. Although the RB time series obtained for LAGEOS and Etalon are consistent with each other, in many cases there appears to be an offset in their values.

Fig. 1. Two examples of the estimated range bias time series for LAGEOS-1/2 and Etalon-1/2 The stations shown are 7237, Changchung (China) and 7840, Herstmonceux (UK).

The differences between the RB series for LAGEOS and Etalon reveal cm-level positive biases in the Etalon observations of many stations of the network. Considering the difference instead of the absolute estimated values ensures that potential errors in the observations at the station level are cancelled out, under the reasonable assumption that there are no range dependent biases. Etalon "excess biases" are found mainly in the case of stations operating at high energy levels of return with PMT/MCP detectors.

Fig. 2. Averaged yearly difference between estimated Etalon and LAGEOS RB for a few selected stations (Etalon – LAGEOS) and standard errors of the differences between means.

2. Case study: ZIML

Stations that have undergone significant hardware changes present a valuable opportunity to examine the estimated RB series and compare them to changes in the adopted CoM values. In the case of Zimmerwald station, although the RB for LAGEOS is relatively small in the period considered, it is evident that the Etalon biases are aligned in time and magnitude with changes in the CoM corrections. Examples as informative as this do not abound; however, the persistence elsewhere of the identified Etalon biases relative to LAGEOS strongly point to shortcomings in the applied CoM values.

Fig. 3. RB series for ZIML station and CoM corrections used in different periods.

3. CoM modelling

The model employed by the ILRS to derive the CoM corrections fits the data very well for low return energy systems and SPAD detectors. For other kinds of systems there is a distinct lack of knowledge about the precise behaviour of the detector packages and return energy regimes in use. In order to compute accurate CoM values an informed best guess about the total system noise must be made to model its impact on the returned laser pulses.

Fig. 4. CoM for LAGEOS and Etalon, as a function of (electric) pulse width, and their relative differences computed with the model employed to derive the current CoM corrections [1].

We computed LAGEOS and Etalon CoM values under different scenarios involving a range of system noise, laser pulse widths, minimum energy threshold limits, and return rates. We conclude that while energy return rate differences between LAGEOS and Etalon for different systems could partly explain the discrepancy seen in the estimated biases, they can not account for all of it. The other explanatory variable is total pulse width, which the present results suggest is underestimated in the current modelling.

Conclusions & Future Work

Improvement on the current Etalon CoM values for high energy stations can be achieved if better estimates of the total system noise are made available. Less satisfactorily, indirect estimates could be obtained from orbital solutions. We plan to conduct a study taking into account updated system specifications of individual stations with the aim of revisiting, if and as required, the available CoM corrections.

[1] Otsubo T, Appleby G.M, System-dependent centre-of-mass correction for spherical geodetic satellites. Journal of Geophysical Research, 108(B4), 2201, 2003

Intro/context

CoM values used until now:

- **Otsubo & Appleby** 2003 (LAGEOS, Etalon, Ajisai)
- **Otsubo et al** 2014 (LARES, Starlette, Stella)

We have revisited this model, improved some aspects of it, developed it further, and applied it to compute new CoM offsets for six “cannonball” satellites (**Rodríguez, Otsubo, Appleby** 2019)

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Some of the novelties:

New modelling approach for multi-photon stations
Recomputed optical response functions, now wavelength dependent
Return rate dependency now system specific
Thorough hardware and operation details gathered from several sources
High precision, full rate single-photon data

Intro/context

New values are sufficiently different to old ones to affect global parameters of interest

On average: ~2.5 mm change for small targets (LARES, Starlette, Stella)
~4.5 mm change for LAGEOS
~20 mm change for big targets (Etalon, Ajisai)

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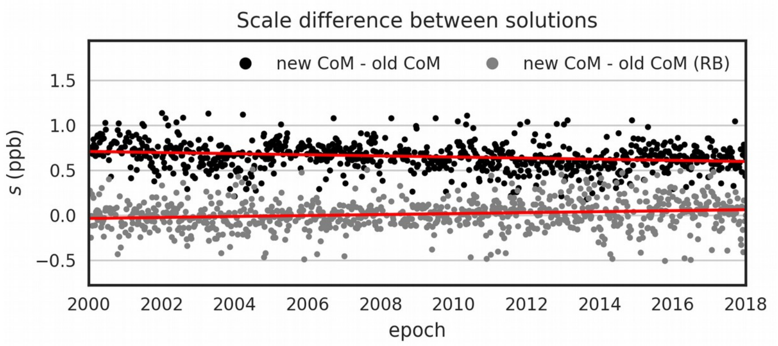
This, on its own, implies a change in SLR frame scale of ~0.65 ppb



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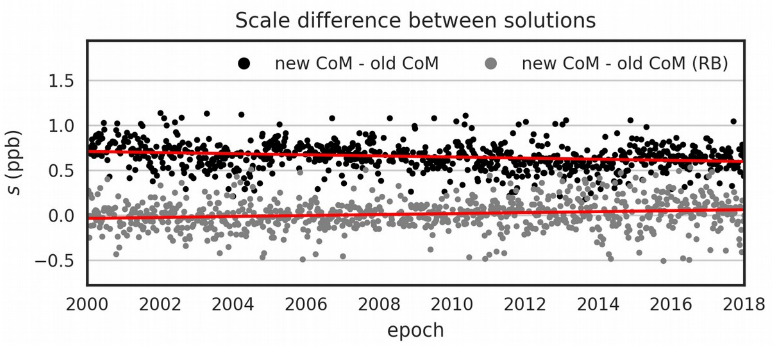
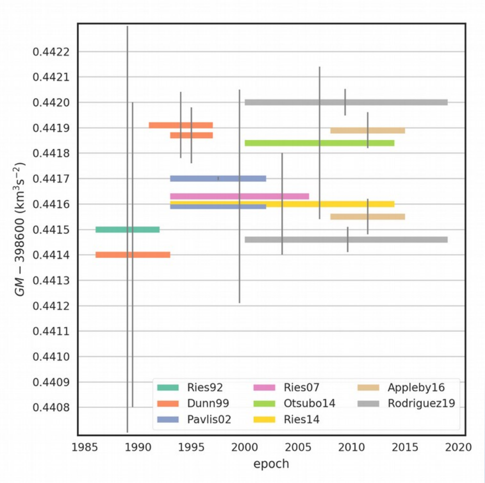
Also GM: current GM value confirmed when using new CoM values
(higher GM estimate obtained with old ones)



GM



Intro/context

What is the accuracy of the new model?

What are the possible sources of errors and uncertainty?

When and what for does it even matter anyway?

CoM model

1. Computation of satellite optical transfer functions
2. Computation of CoM values
    a. Single-photon, single-stop stations
    b. Multi-photon stations

CoM model

1. Computation of satellite optical transfer functions

2. Computation of CoM values

   a. Single-photon, single-stop stations
   b. Multi-photon stations

Single-photon operation: intensity of detected laser pulses is limited, statistically only one photon reaches the detector

Achieved by limiting detection rate below ~10%, so that probability of multi-photon events is very low (Poisson statistics)

CoM model. Optical transfer functions

Characterisation of target **optical response**

Function of:

- physical characteristics of retroreflectors
- geometry of arrays
- laser wavelength
- target orientation

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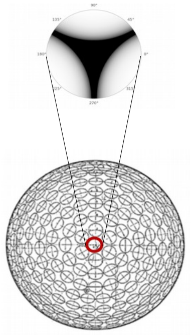
Physical data → ray tracing individual retro

Reflectivity map



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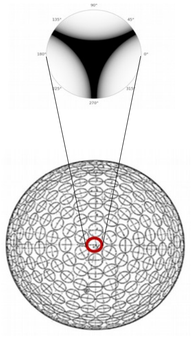
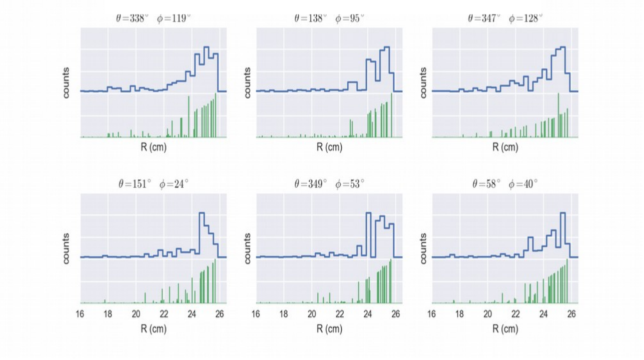


Response at arbitrary orientations



CoM model. Optical transfer functions

Characterisation of target **optical response**

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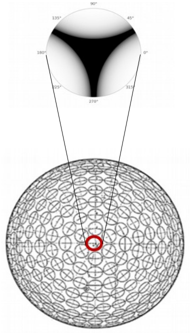
Physical data → ray tracing individual retro → average over array → **empirical fit** to single-photon data

Reflectivity map



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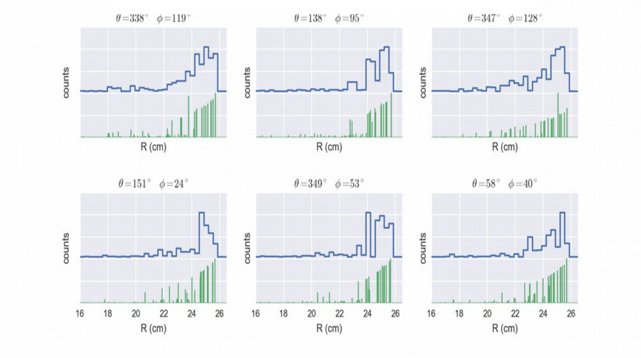
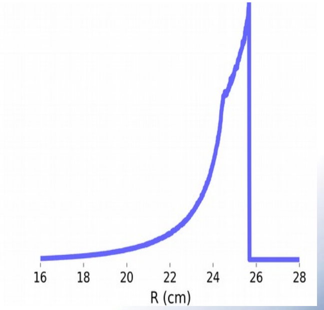


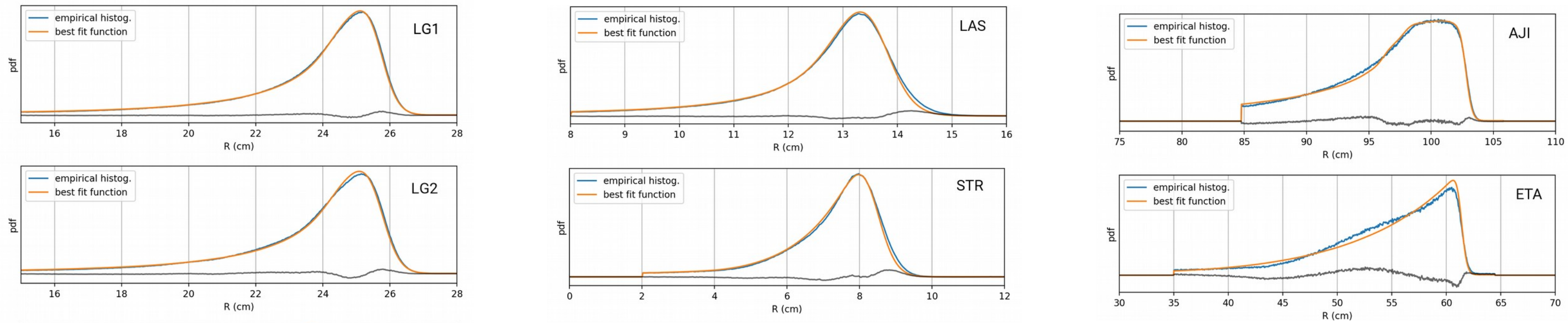
Average over 250K orientations



CoM model. 1) Optical transfer functions

Obtained high quality fits using data from Herstmonceux station

A **single** parameter is optimised here, describing the shape of the response functions



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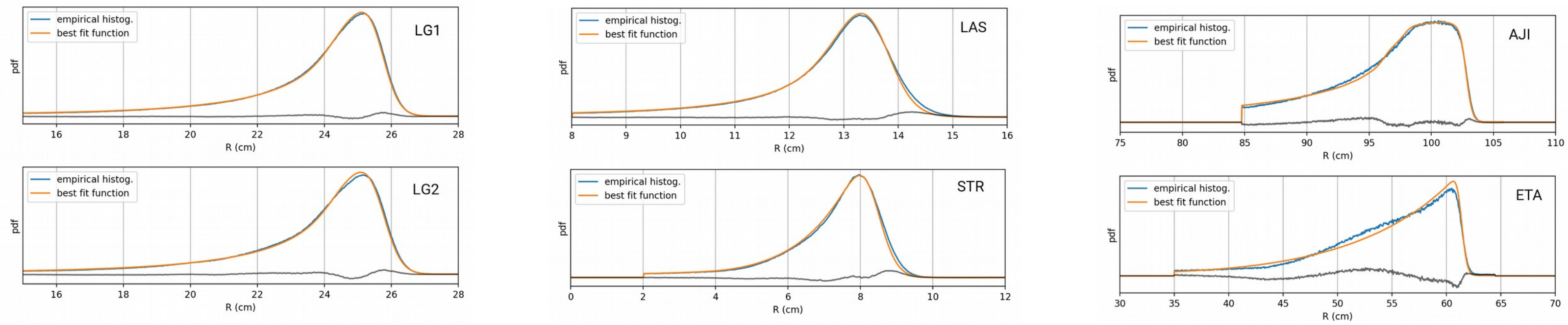

Uncertainties/issues:

- fit parameter inaccuracies
- orientation effects
- wavelength dependency (fit to 532 nm)
- clipping of distribution

CoM model. 2) Computation of values

Taking into account specifics of hardware/operation, use transfer functions to compute CoM offsets

a. Single photon systems

Distribution of detections = convolution system noise with target response

Use station details to compute expected distribution of detections (laser pulse width, detector jitter, timer precision...)

Use reduction algorithm employed at station to compute reference point

CoM = difference between calibration and satellite

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Uncertainties/issues:

- Is hardware data accurate?
- Accuracy of average return rate?
- Impact of noise?
- Calibration return rate?
- Detector effects at high return rates

CoM model. 2) Computation of values

Taking into account specifics of hardware/operation, use transfer functions to compute CoM offsets

b. Multi photon systems

Distribution of detections != simple convolution

Using station details perform Monte Carlo simulation of detection process

Use reduction algorithm employed at the station to compute reference point

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b. Multi photon systems

Distribution of detections != simple convolution

Using station details perform Monte Carlo simulation of detection process

Use reduction algorithm employed at the station to compute reference point

CoM = difference between calibration and satellite

Uncertainties/issues:

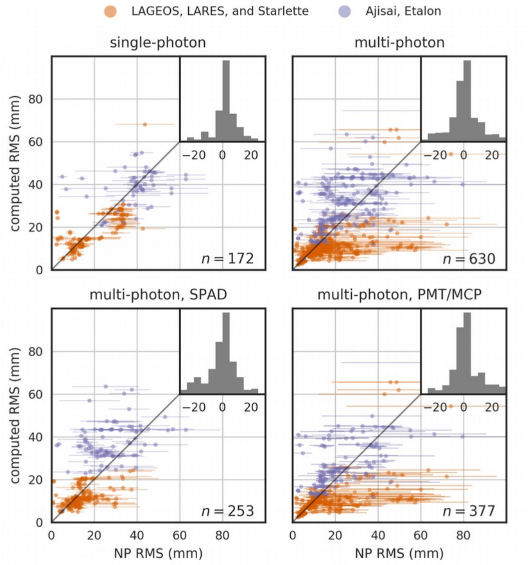
- Is hardware data accurate?
- Simplifications in Monte Carlo simulation:
  - systems are simplified, idealised, and possibly missing components that could impact the result (amplifiers, discriminators, cabling?)
- Accuracy of return rates (cal and sat)
- Non-linearities of detection components

CoM model validation

No direct means of validation available

Range bias estimates are NOT useful, on an individual basis, to validate CoM values

Indirect: comparison of RMS of expected distributions and the empirical ones



Reasonable agreement found for all modes of operation
No systematic effects

ALL: 54% within 5 mm RMS; 75% within 10 mm
TOP 25: 59% within 5 mm RMS; 78% within 10 mm

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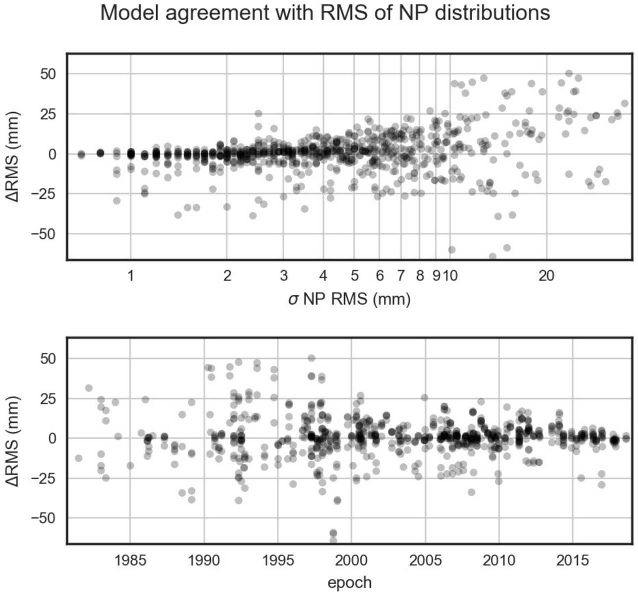

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ALL: 54% within 5 mm RMS; 75% within 10 mm
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Variability in empirical data is a limiting factor
Higher agreement for modern data

σ(RMS) < 5 mm: 71% within 5 mm; 89% within 10 mm

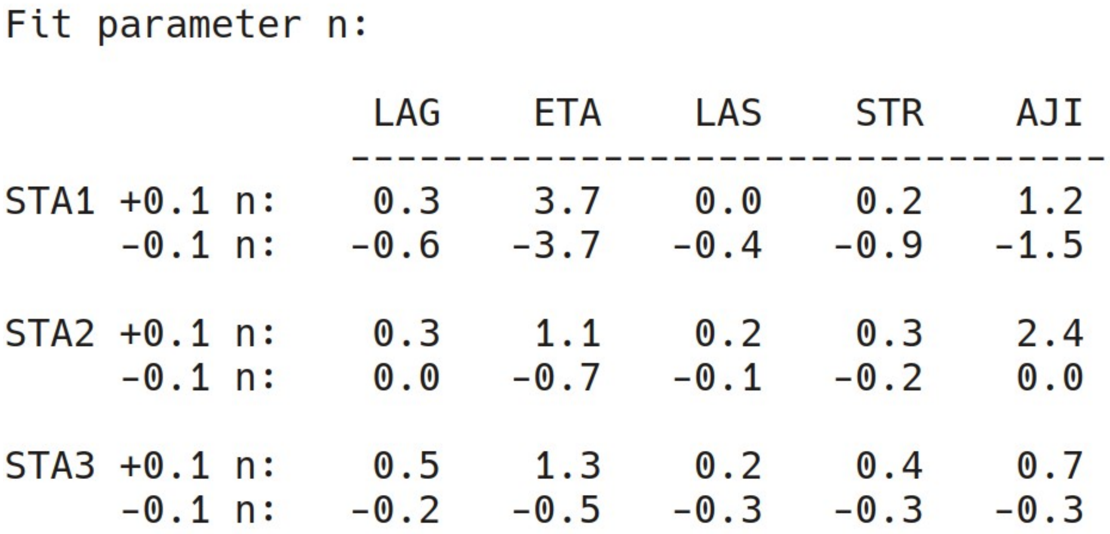
Sensitivity analysis

Explored some factors in a simple one-at-a-time approach:

- **Fit parameter n**. Dictates shape of optical transfer function, encapsulates complex optical effects
- **Return rate**. Changes the shape of the probability distribution of detections
- Inaccurate system details: **doubling detector jitter**
- Inaccurate system details: **doubling detector rise time**

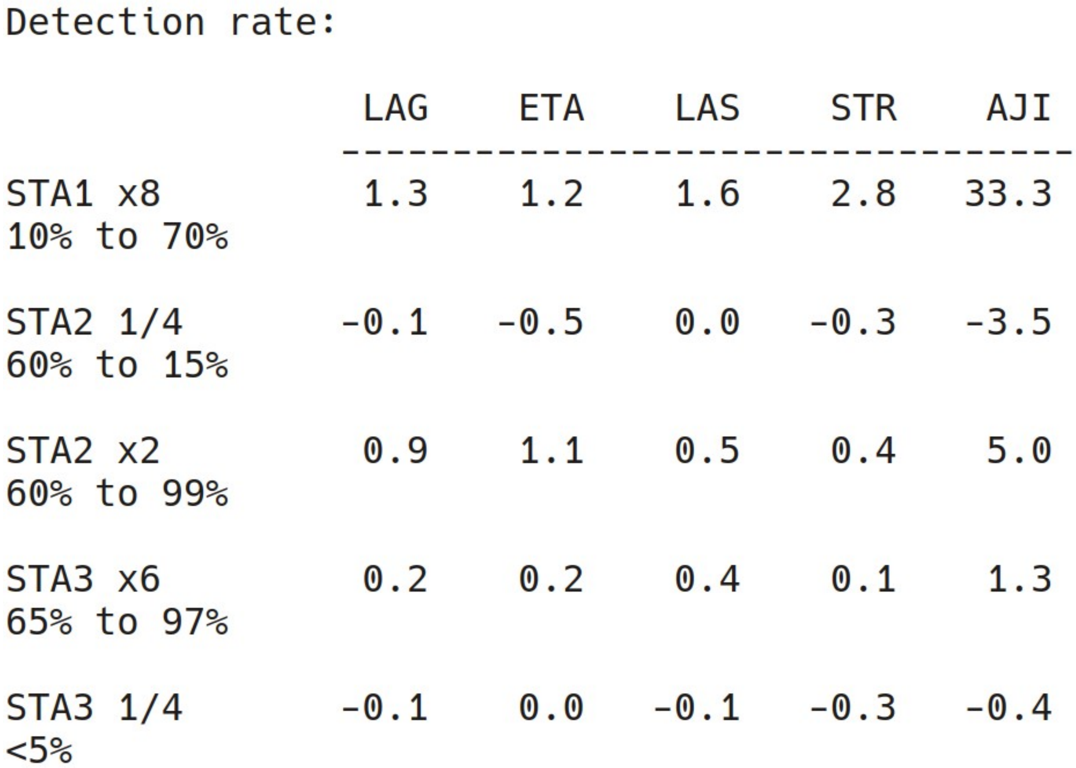
Three stations used as starting points: HERL 7840, MATL 7941, YARL 7090

Sensitivity analysis



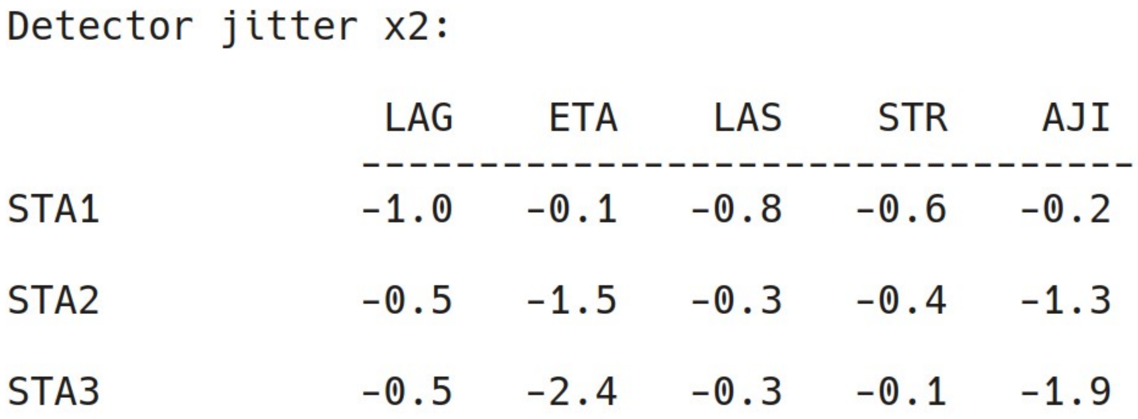
```
Fit parameter n:

                  LAG    ETA    LAS    STR    AJI
                 ------------------------------------
STA1 +0.1 n:      0.3    3.7    0.0    0.2    1.2
     -0.1 n:     -0.6   -3.7   -0.4   -0.9   -1.5

STA2 +0.1 n:      0.3    1.1    0.2    0.3    2.4
     -0.1 n:      0.0   -0.7   -0.1   -0.2    0.0

STA3 +0.1 n:      0.5    1.3    0.2    0.4    0.7
     -0.1 n:     -0.2   -0.5   -0.3   -0.3   -0.3
```

Sensitivity analysis



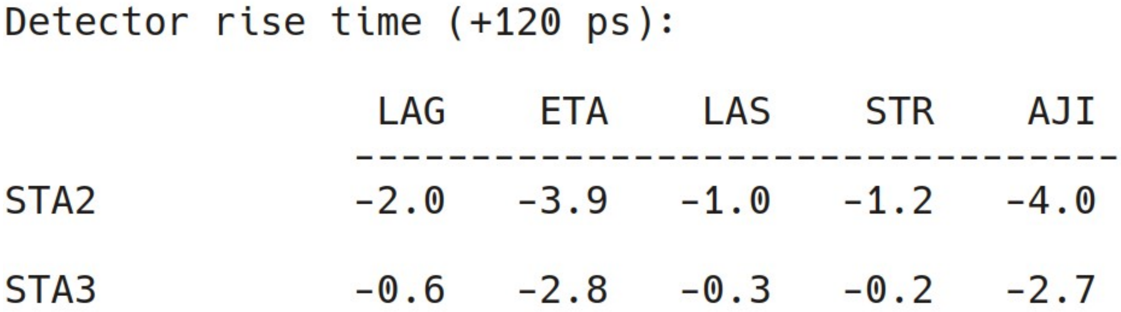
```
Detection rate:

                LAG    ETA    LAS    STR    AJI
               ---------------------------------
STA1 x8         1.3    1.2    1.6    2.8   33.3
10% to 70%

STA2 1/4       -0.1   -0.5    0.0   -0.3   -3.5
60% to 15%

STA2 x2         0.9    1.1    0.5    0.4    5.0
60% to 99%

STA3 x6         0.2    0.2    0.4    0.1    1.3
65% to 97%

STA3 1/4       -0.1    0.0   -0.1   -0.3   -0.4
<5%
```

Sensitivity analysis



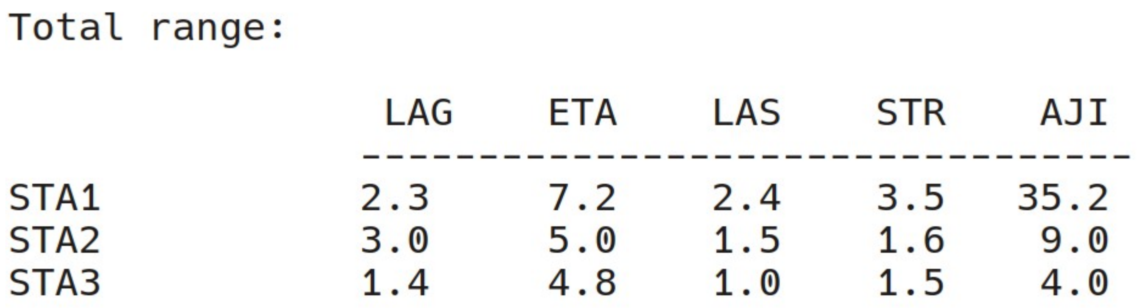
```
Detector jitter x2:

                     LAG    ETA    LAS    STR    AJI
                    ---------------------------------
STA1                -1.0   -0.1   -0.8   -0.6   -0.2

STA2                -0.5   -1.5   -0.3   -0.4   -1.3

STA3                -0.5   -2.4   -0.3   -0.1   -1.9
```

Sensitivity analysis



```
Detector rise time (+120 ps):

                  LAG    ETA    LAS    STR    AJI
                 -----------------------------------
STA2             -2.0   -3.9   -1.0   -1.2   -4.0

STA3             -0.6   -2.8   -0.3   -0.2   -2.7
```

Sensitivity analysis



```
Total range:

                    LAG    ETA    LAS    STR    AJI
                   ----------------------------------
STA1               2.3    7.2    2.4    3.5   35.2
STA2               3.0    5.0    1.5    1.6    9.0
STA3               1.4    4.8    1.0    1.5    4.0
```

Max error pessimistic case: 1-3 mm small targets and LAGEOS
                                         5-10 mm Etalon
                                         10-30 mm Ajisai

Comparison of computed and empirical distributions indicates situation is much better

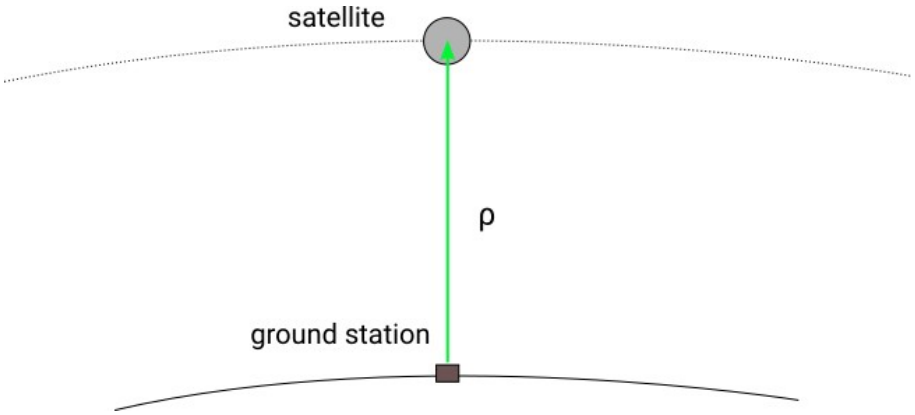
None of this informs us about whether models are fundamentally flawed somewhere

Consequences

If range biases are estimated inaccuracies in the CoM values have **no** impact on station coords.

How about users of TRF and SLR data?

Perfect observation. Height perfectly estimated



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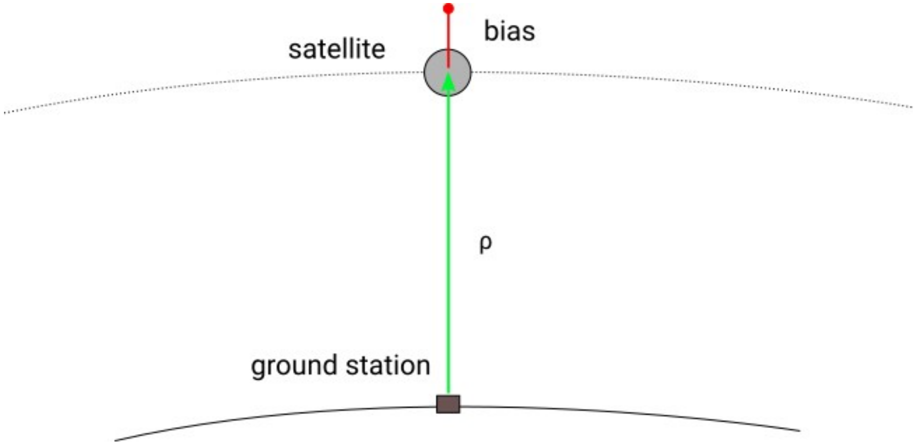
Biased observation. Positive residual



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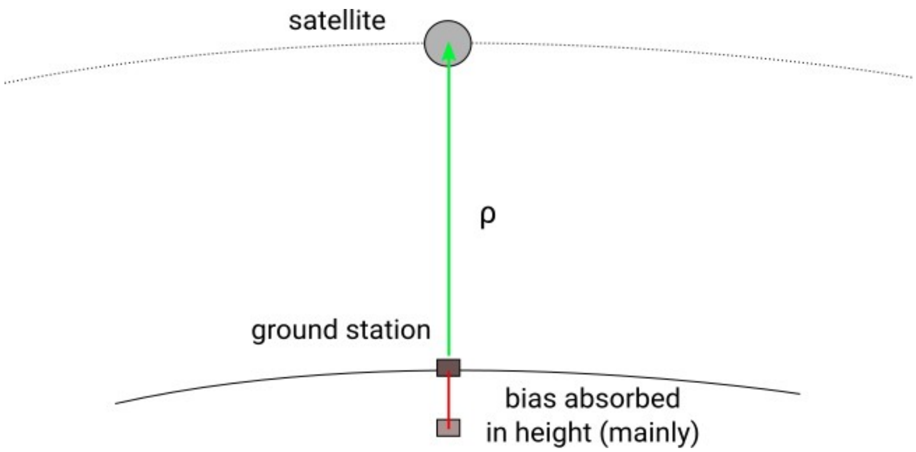
Biased observation. Height wrongly estimated



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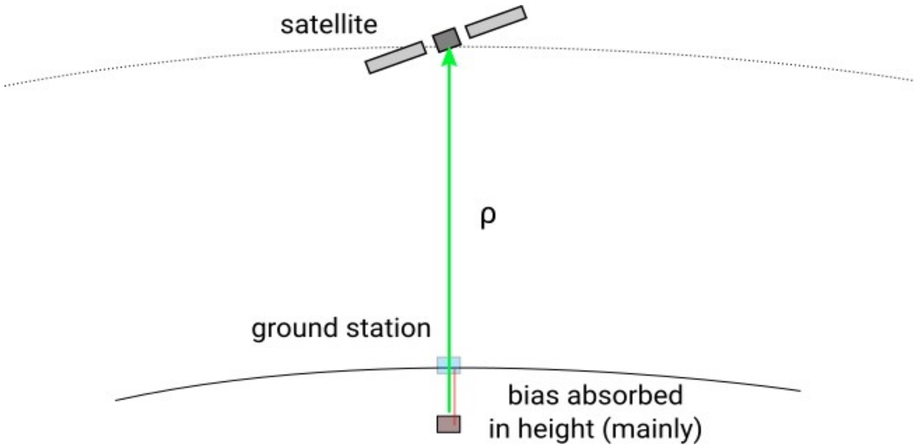
Biased observation. Residual?



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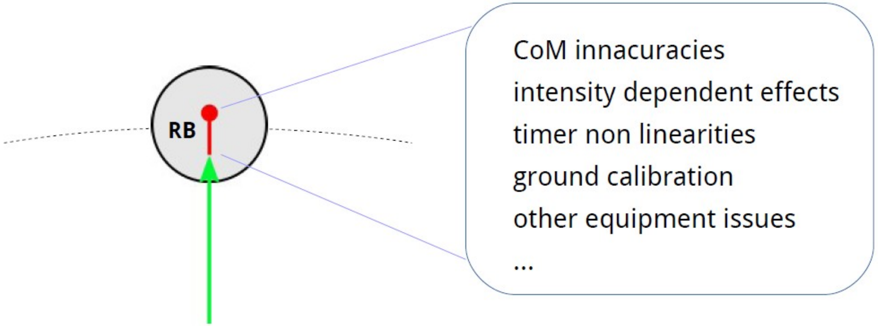
How about users of TRF and SLR data?

CoM mismodelling behind some of the previously estimated biases

Knowledge of error budget improved → transfer of biases to other targets



CoM innacuracies
intensity dependent effects
timer non linearities
ground calibration
other equipment issues
...

Thank you


Thank you