British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Gateway to the Earth

SLR School - Session 3: Corrections and Error Sources

José Rodríguez [1] and Ivan Procházka [2] and Johann Eckl [3]

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Stuttgart, 20th October 2019

Session 3: Corrections and Error Sources

- What corrections do we add to our basic range data?
- Where do they come from?
- How do we calibrate and get the most accurate data products?
- What are the error sources to our ranging data?
- Accurate timing: how do we get it? How good is it? Improvements?
- The importance of ground surveys and how do we do them
- Spacecraft centre of mass: modelling considerations and operational issues

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Session 3: Corrections

What do I mean by “corrections” here?

correction (kəˈrɛkʃən)

n

1. the act or process of correcting

2. something offered or substituted for an error; an improvement

3. the act or process of punishing; reproof

4. (Mathematics) a number or quantity added to or subtracted from a scientific or mathematical calculation or observation to increase its accuracy

“CITE” Collins English Dictionary – Complete and Unabridged, 12th Edition 2014 © HarperCollins Publishers 1991, 1994, 1998, 2000, 2003, 2006, 2007, 2009, 2011, 2014

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The basic corrections we are going to discuss serve the purpose of achieving the required **accuracy** from the SLR **technique**…

They do **not** imply that the measurements themselves, at a technical level, are inaccurate

Session 3: Corrections

To recap:

- SLR observations (NPs) →
- Orbit propagation and parameter estimation

The SLR observable is TOF, **not** distance

Time-of-flight is not what we need in the analysis stage:

We need to convert TOF to ranges, multiplying by the speed of light + applying some corrections

Photo: M.Wilkinson

However accurate TOF measurements are, without corrections distances are off by metres

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Session 3: Corrections – tropospheric delay

Troposphere: lowest layer of Earth's atmosphere

Geometric path length != Optical path length

OPL = geometric length x refractive index

Depends on pressure, temperature and composition, which are heterogeneous and time variable

We compute appropriate corrections using models

Photo: NASA

Session 3: Corrections – tropospheric delay

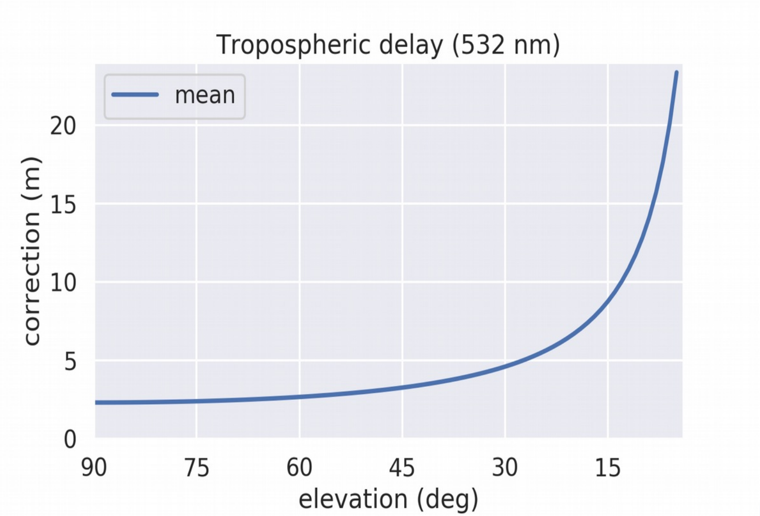
Normally the total delay at the zenith is computed, followed by a projection to the angle of interest

Currently we use the Mendes-Pavlis model (2004)

- Zenith delay accuracy: sub-mm
- Mapping function: sub-cm

Developed from ray-tracing computations, using satellite observations of the atmosphere

Assumption: spherically symmetric atmosphere



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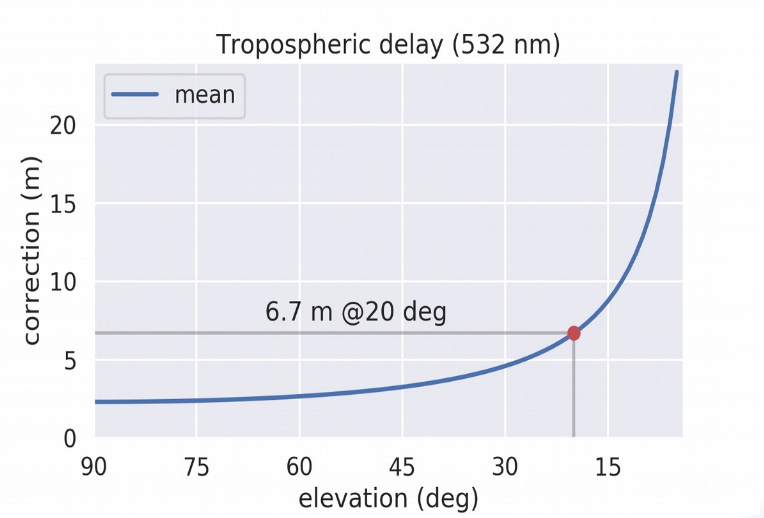

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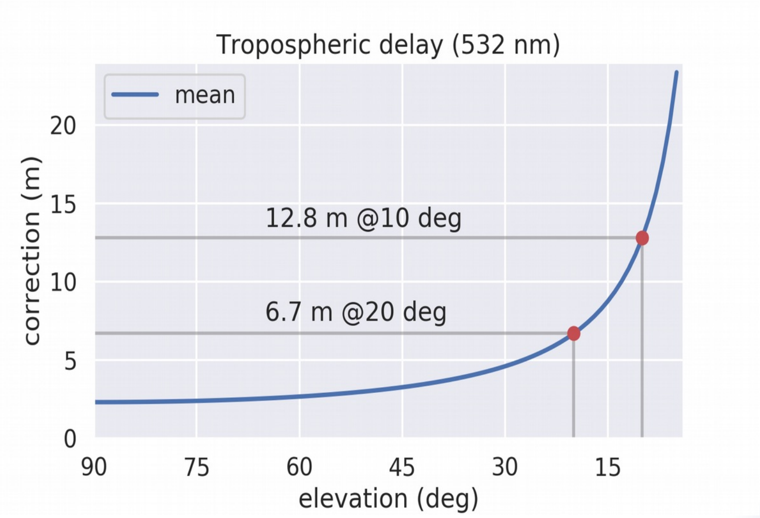


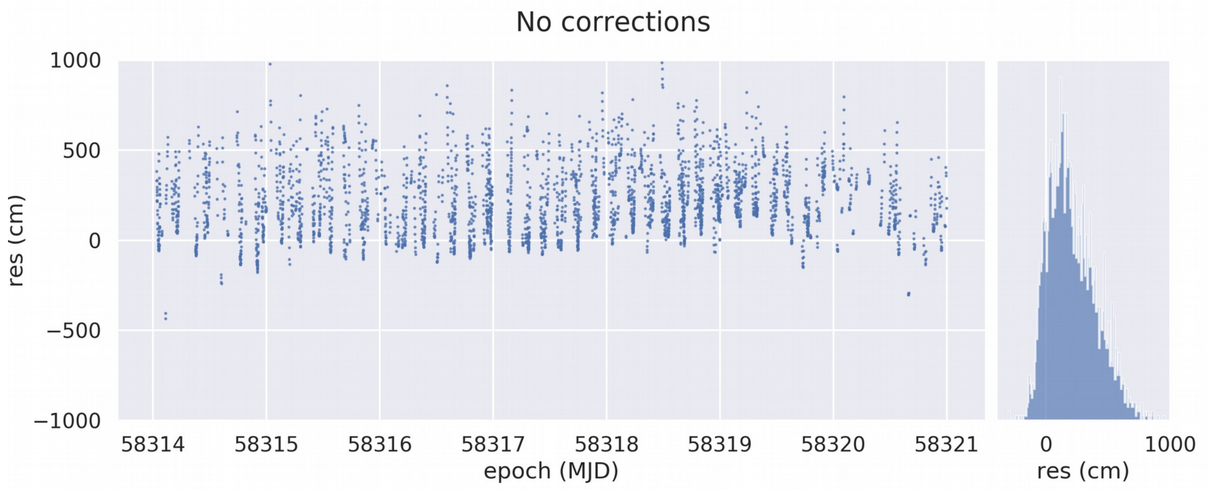
Session 3: Corrections – tropospheric delay

Test: orbit fit **without** applying any corrections

- Data: LAGEOS & LAGEOS-2 normal points from the global network (7 days)
- Only dynamic parameters estimated (satellite positions, force model)
- Quantity of interest: observed minus computed residuals

Session 3: Corrections – tropospheric delay

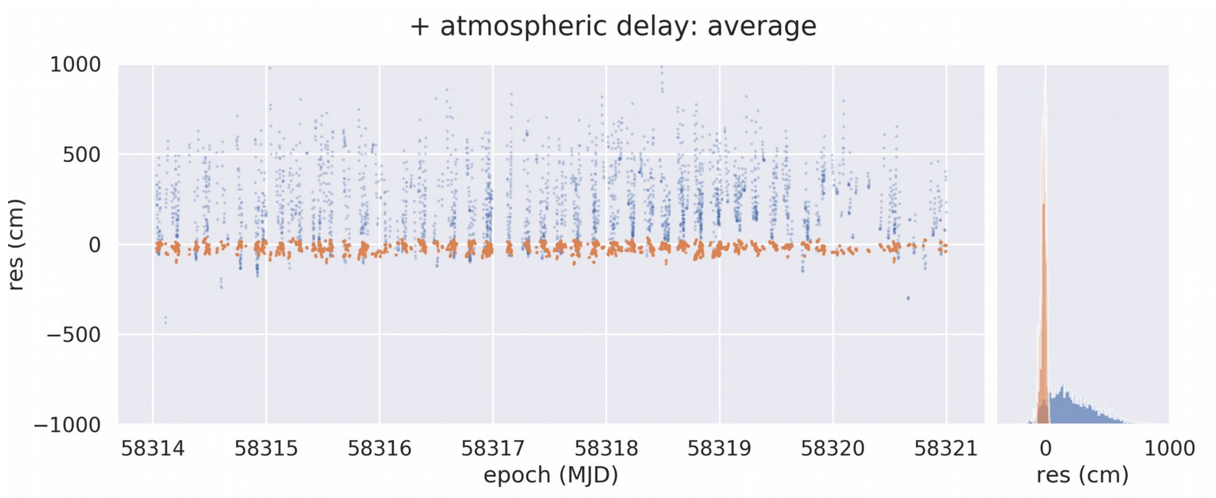
Test: orbit fit **without** applying any corrections



- Very poor orbital fit (no better than several metres)
- Evident systematic signatures in histogram of residuals
- Possibly only good for orbit predictions, if at all

Session 3: Corrections – tropospheric delay

Test: **mean** atmospheric delay



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- No meteorological data employed, simple average delay applied

Session 3: Corrections – tropospheric delay

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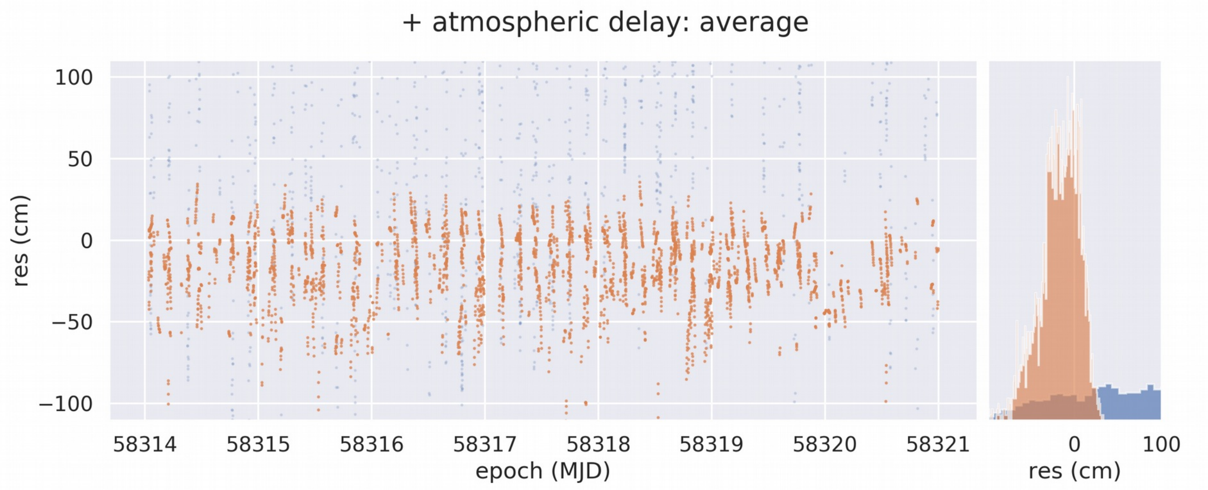
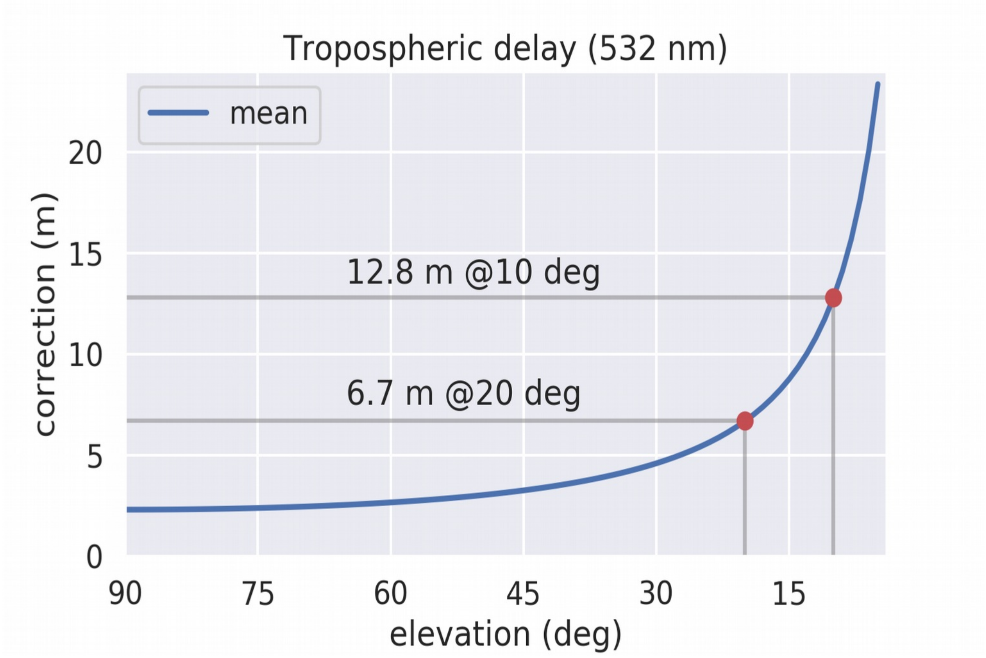
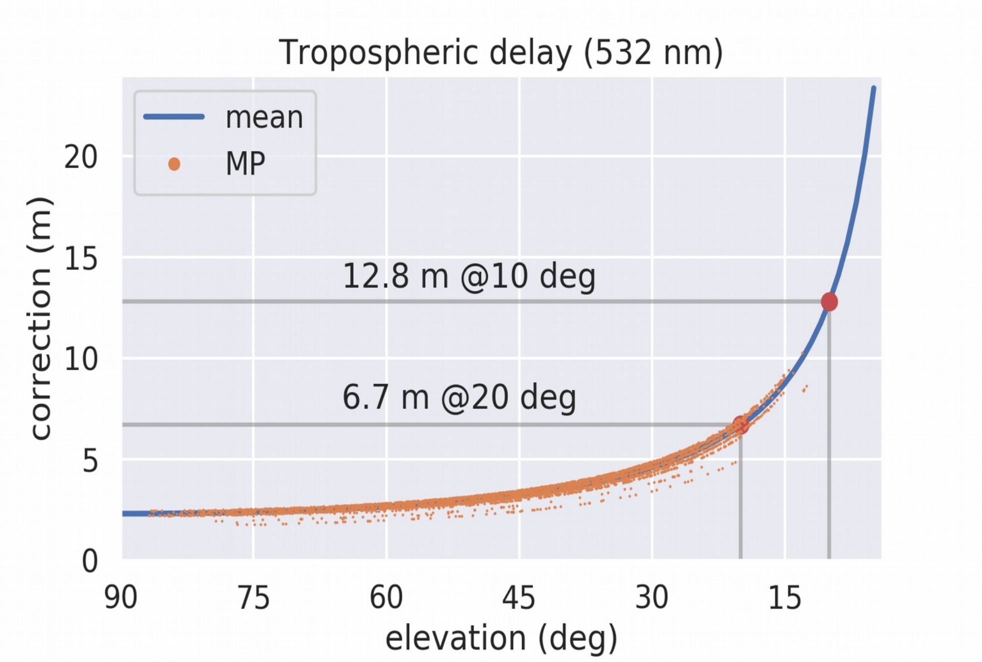


- Massive improvement in orbit fit (one order of magnitude)
- No meteorological data employed, simple average delay applied
- But clearly not good enough: RMS = 22.0 cm; mean residual offset = -16.5 cm
- Distribution of residuals evidently non-Gaussian

Session 3: Corrections – tropospheric delay



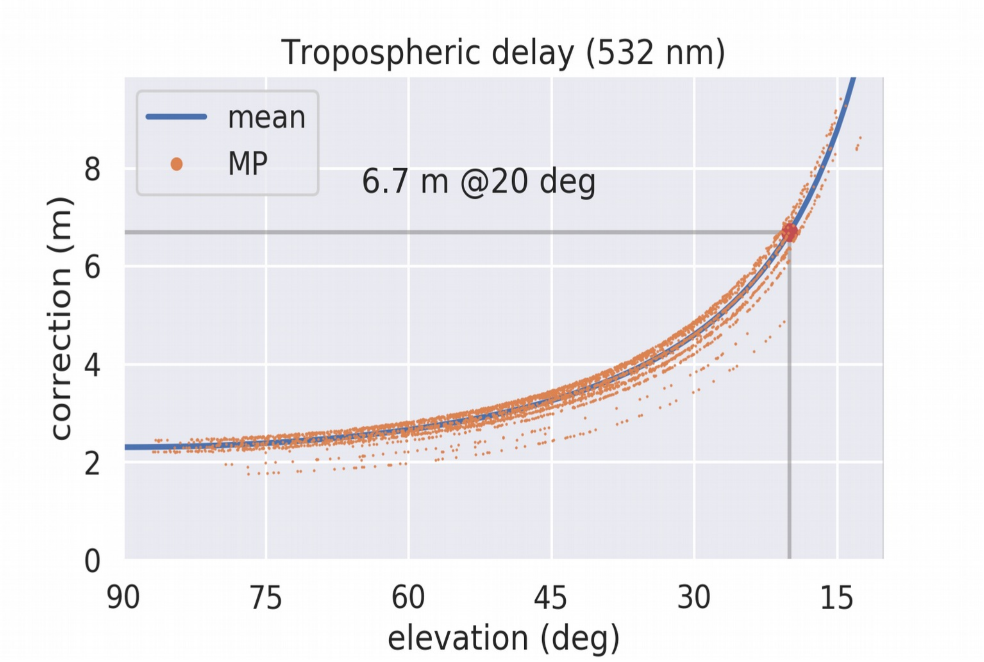
Session 3: Corrections – tropospheric delay



Model used to compute delay values

Variables: P, T, RH, elev., wavelength, latitude, height

Session 3: Corrections – tropospheric delay



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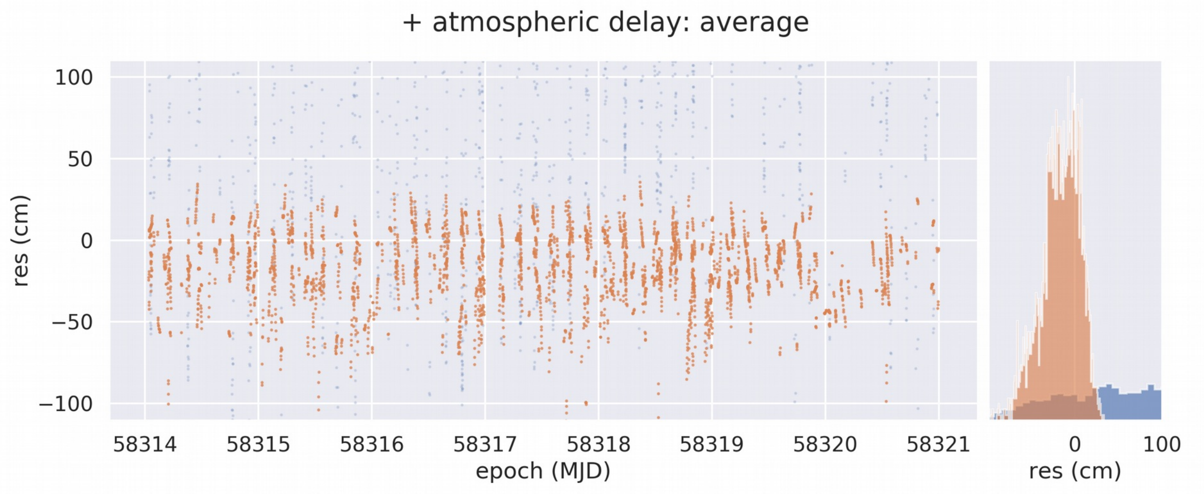
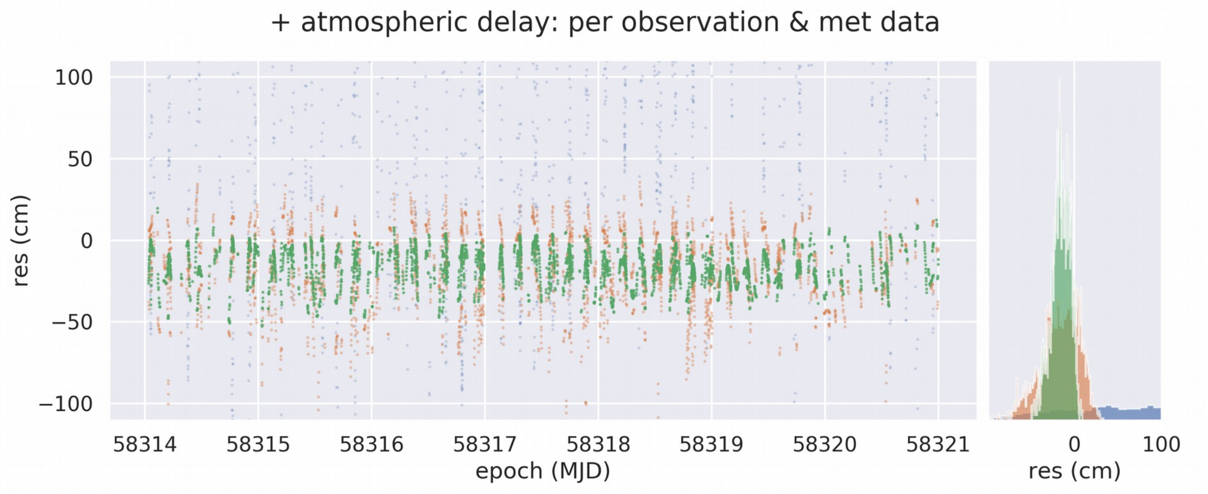
Session 3: Corrections – tropospheric delay

Test: full model atmospheric delay



Session 3: Corrections – tropospheric delay

Test: full model atmospheric delay



- Much better fit and distribution of residuals
- RMS = 11.0 cm; residuals mean offset = -15.7 cm

Session 3: Corrections – tropospheric delay

A curiosity?

- Tropospheric delay model contains a corrective factor dependent on the concentration of atmospheric CO_2
- Recommended value: 375 ppm

- Very small correction, will it ever matter?

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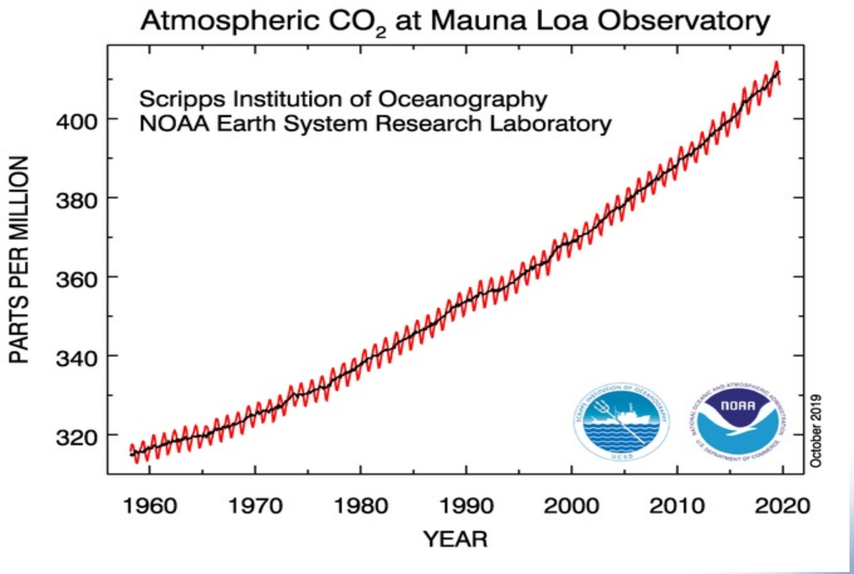
CO2 concentration in 1976 : 330 ppm
2019 : 410 ppm

Total zenith delay @330 ppm : 2.447487 m
Total zenith delay @410 ppm : 2.447592 m



Session 3: Corrections – tropospheric delay

A curiosity?

- Tropospheric delay model contains a corrective factor dependent on the concentration of atmospheric CO_2
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- Delay @330@10 deg : 13.5812 m
- Delay @410@10 deg : 13.5818 m (+ 0.6 mm)
- Delay @550@10 deg : 13.5828 m (+ 1.6 mm)

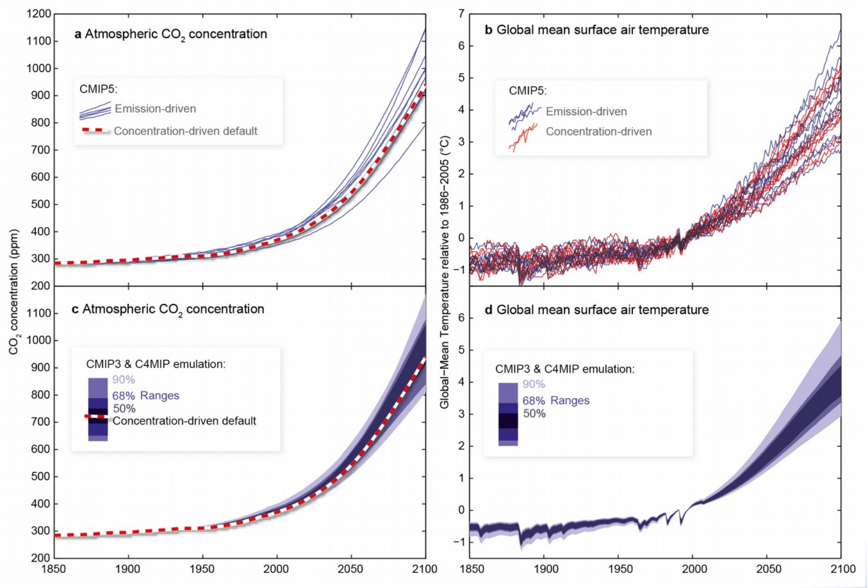
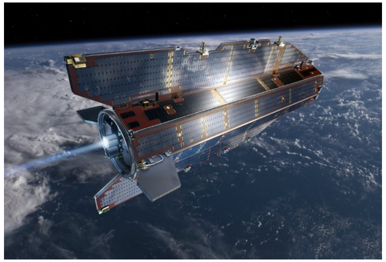


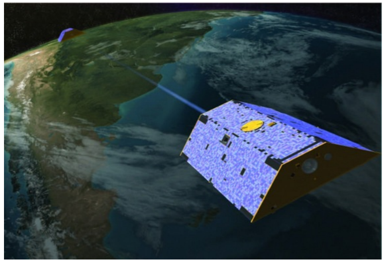
Figure 12.36 | Simulated changes in (a) atmospheric CO_2 concentration and (b) global averaged surface temperature (°C) as calculated by the CMIP5 Earth System Models (ESMs) for the RCP8.5 scenario when CO_2 emissions are prescribed to the ESMs as external forcing (blue). Also shown (b, in red) is the simulated warming from the same ESMs when directly forced by atmospheric CO_2 concentration (a, red white line). Panels (c) and (d) show the range of CO_2 concentrations and global average surface temperature change simulated by the Model for the Assessment of Greenhouse Gas-Induced Climate Change 6 (MAGICC6) simple climate model when emulating the CMIP3 models climate sensitivity range and the Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP) models carbon cycle feedbacks. The default line in (c) is identical to the one in (a).

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

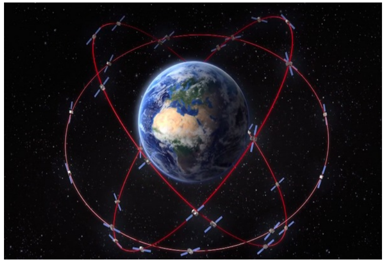
SLR space segment

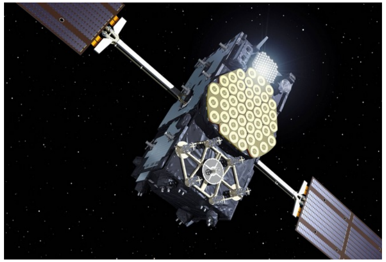
Earth observation



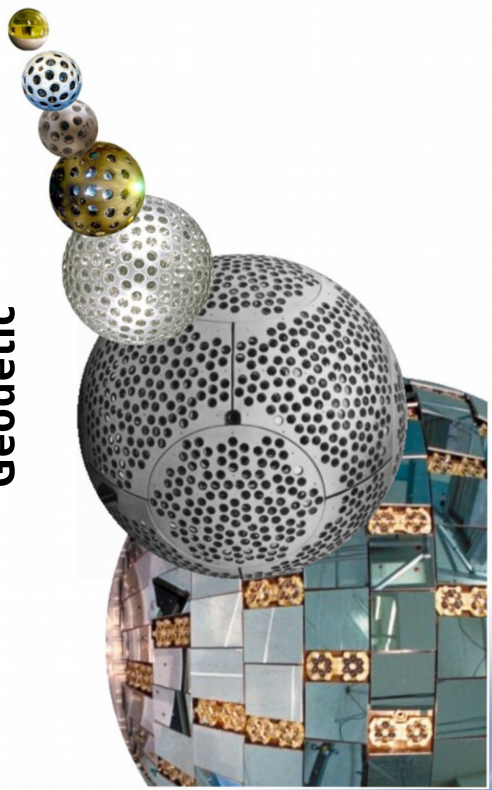


GNSS constellations

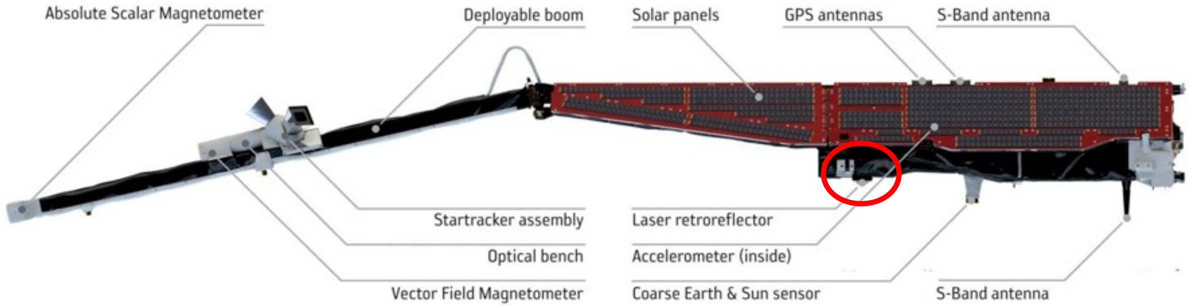




Geodetic



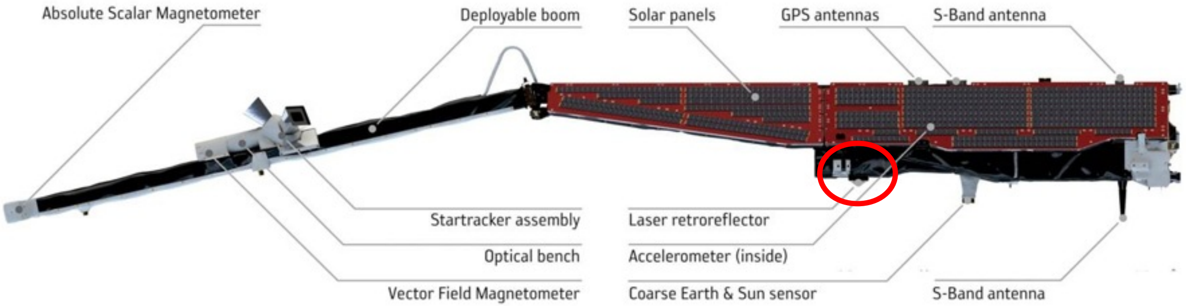
Session 3: Corrections – centre of mass



Side view of instrumentation on the Swarm satellites

Image: ESA

Session 3: Corrections – centre of mass



Side view of instrumentation on the Swarm satellites

Image: ESA

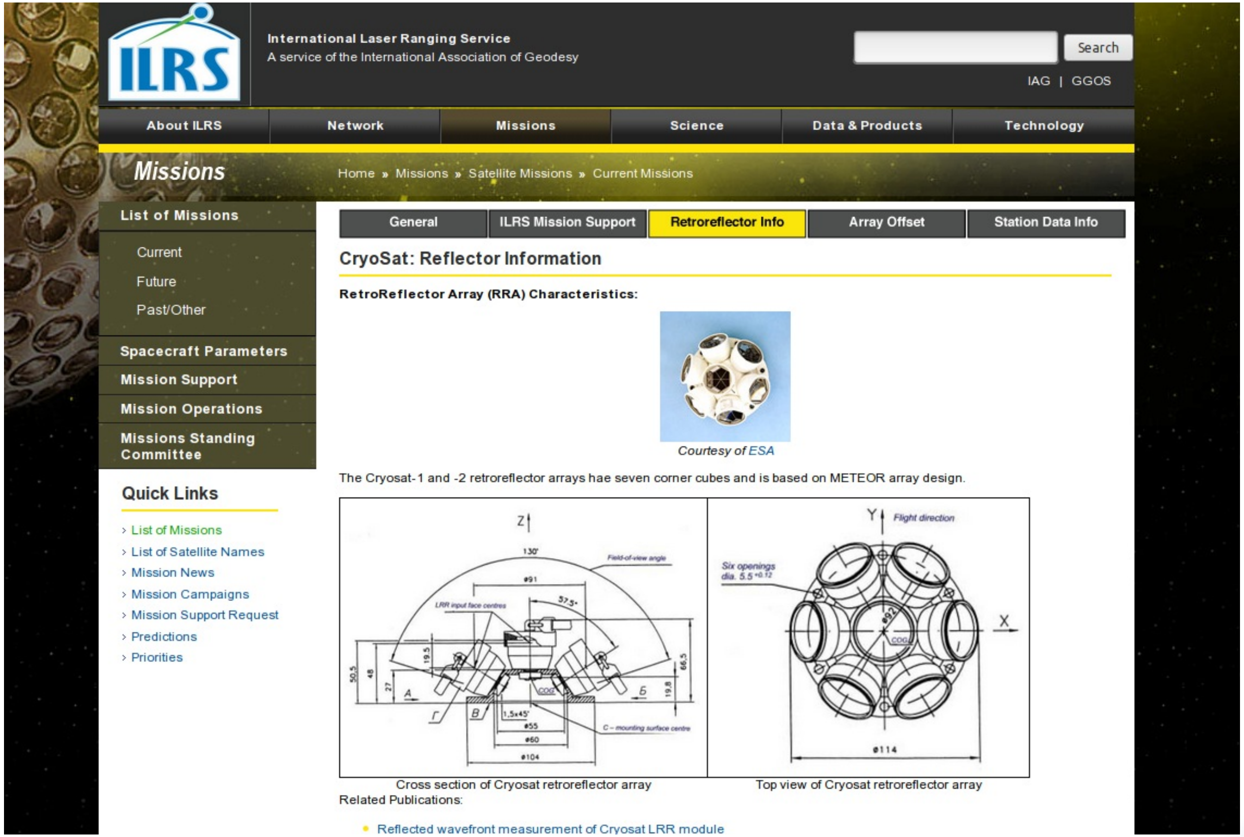
Time of flight measurements are made to the internal surfaces of the cube corner retroreflectors

We want the distance to the centre of mass of the orbiting object

We need information relating the position of the retroreflector array to the centre of mass

Retroreflector array information and its location on the satellite must be provided by missions when requesting laser tracking to the ILRS

Session 3: Corrections – centre of mass



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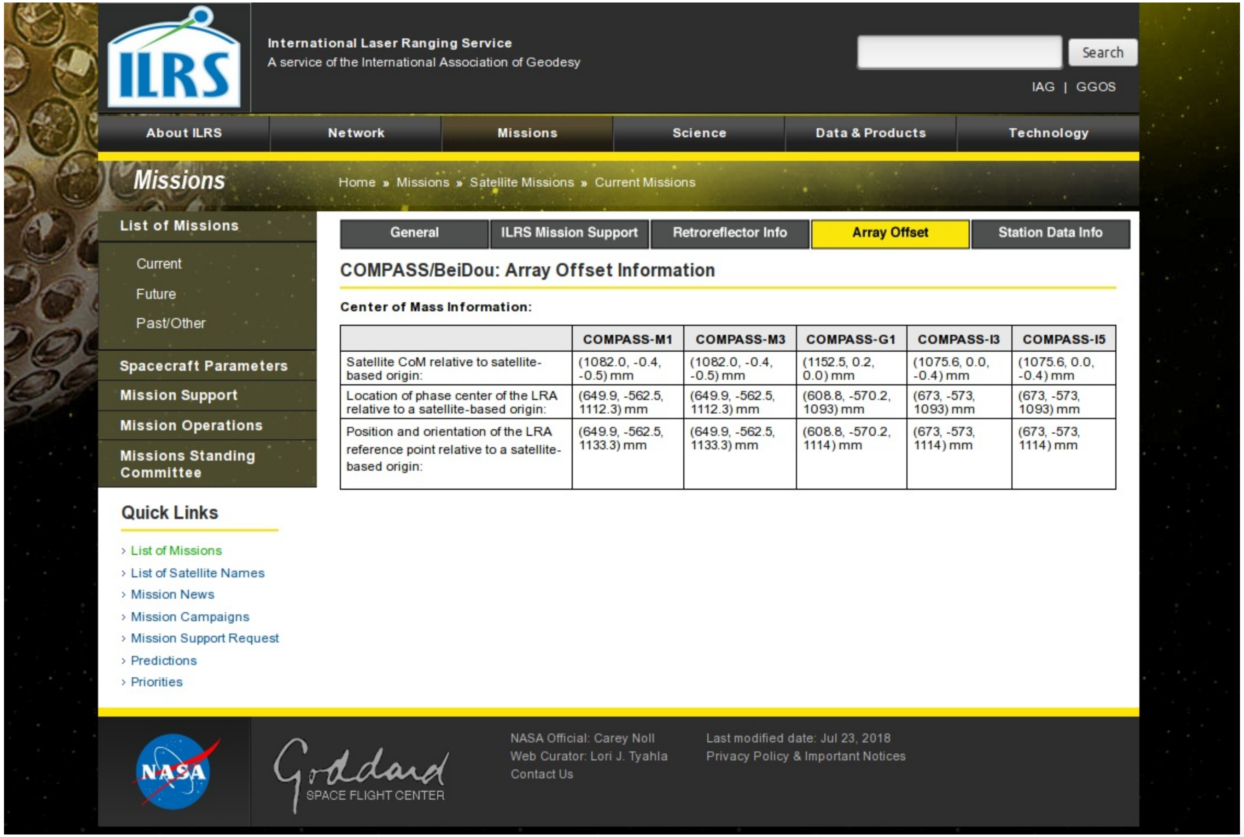

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Mission Operations
Missions Standing Committee

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COMPASS/BeiDou: Array Offset Information

Center of Mass Information:

	COMPASS-M1	COMPASS-M3	COMPASS-G1	COMPASS-I3	COMPASS-I5
Satellite CoM relative to satellite-based origin:	(1082.0, -0.4, -0.5) mm	(1082.0, -0.4, -0.5) mm	(1152.5, 0.2, 0.0) mm	(1075.6, 0.0, -0.4) mm	(1075.6, 0.0, -0.4) mm
Location of phase center of the LRA relative to a satellite-based origin:	(649.9, -562.5, 1112.3) mm	(649.9, -562.5, 1112.3) mm	(608.8, -570.2, 1093) mm	(673, -573, 1093) mm	(673, -573, 1093) mm
Position and orientation of the LRA reference point relative to a satellite-based origin:	(649.9, -562.5, 1133.3) mm	(649.9, -562.5, 1133.3) mm	(608.8, -570.2, 1114) mm	(673, -573, 1114) mm	(673, -573, 1114) mm

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NASA Official: Carey Noll
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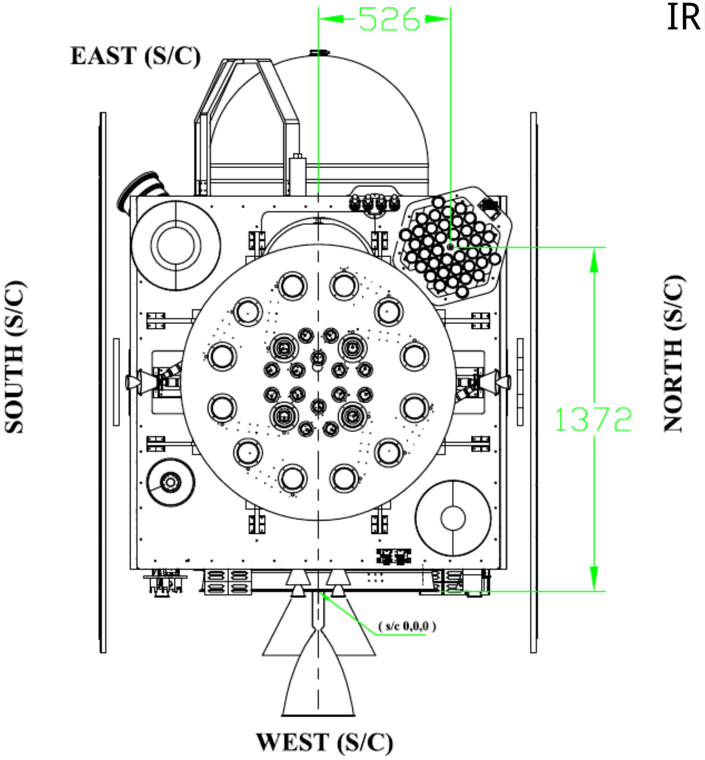
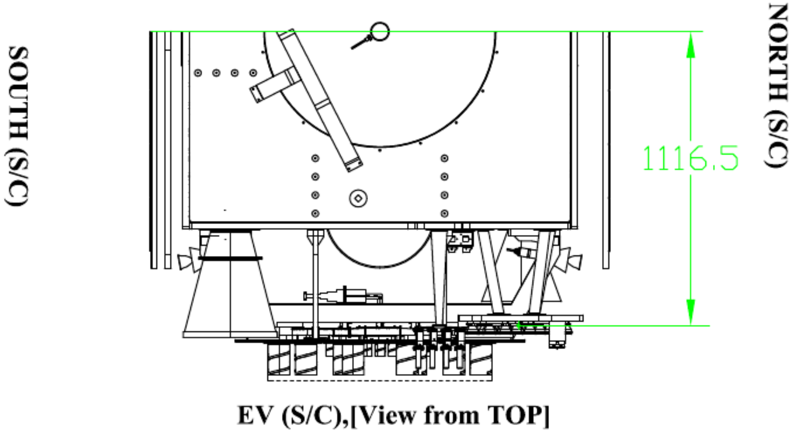
Session 3: Corrections – centre of mass

IRNSS LRA diagram (ISRO)

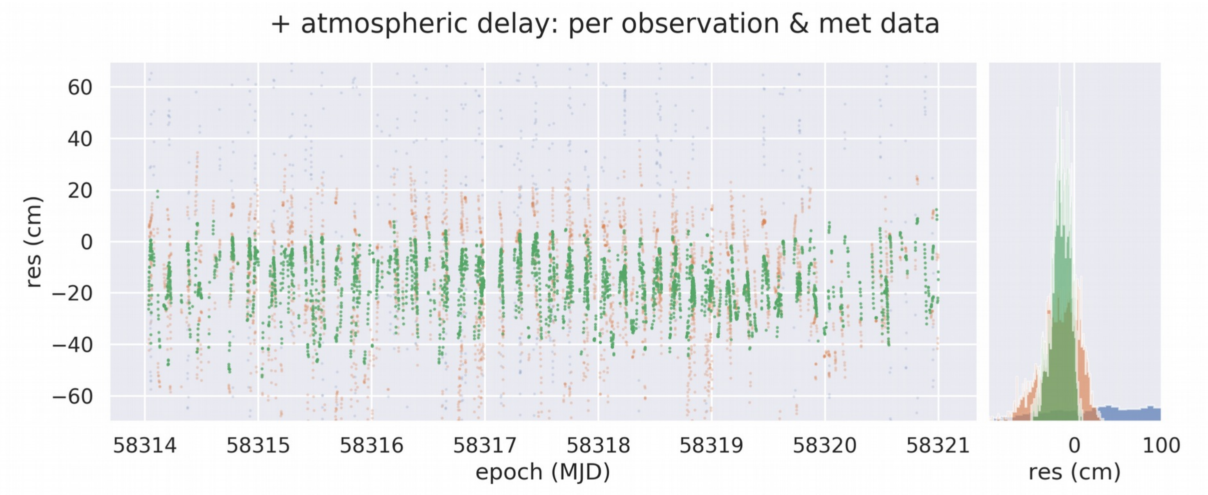




https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_missions/current_missions/irnb_com.html

Session 3: Corrections – centre of mass

Test: geometric centre of mass from engineering drawings



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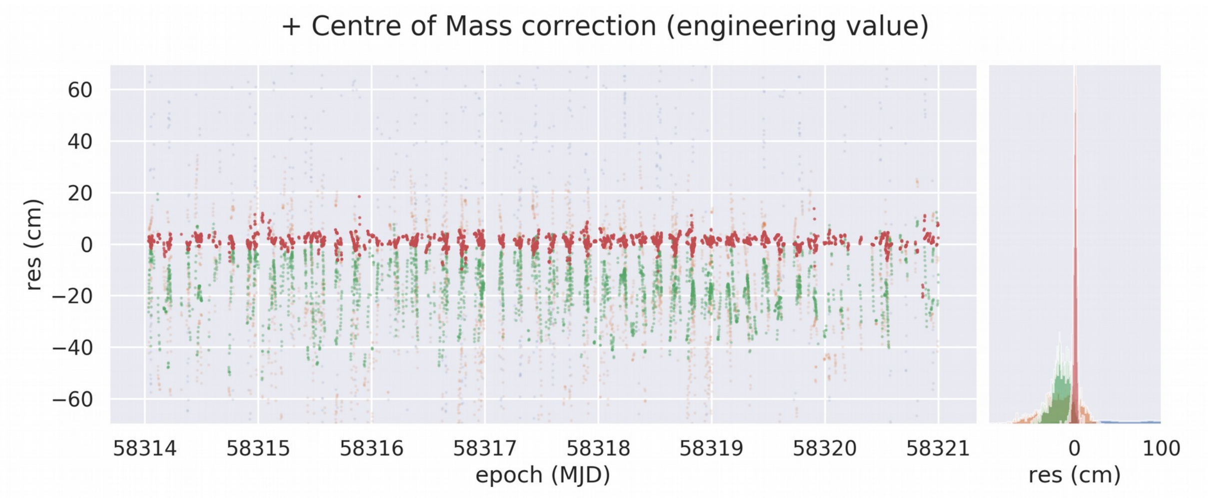

- Order of magnitude improvement
- RMS = 1.87 cm; mean of residuals = 9.97 mm

Session 3: Corrections – centre of mass

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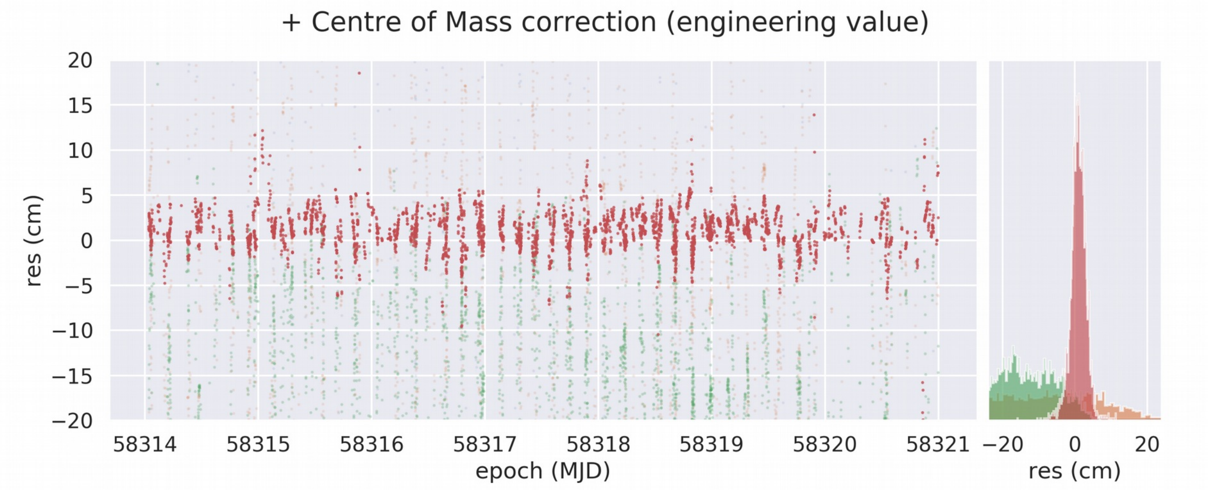
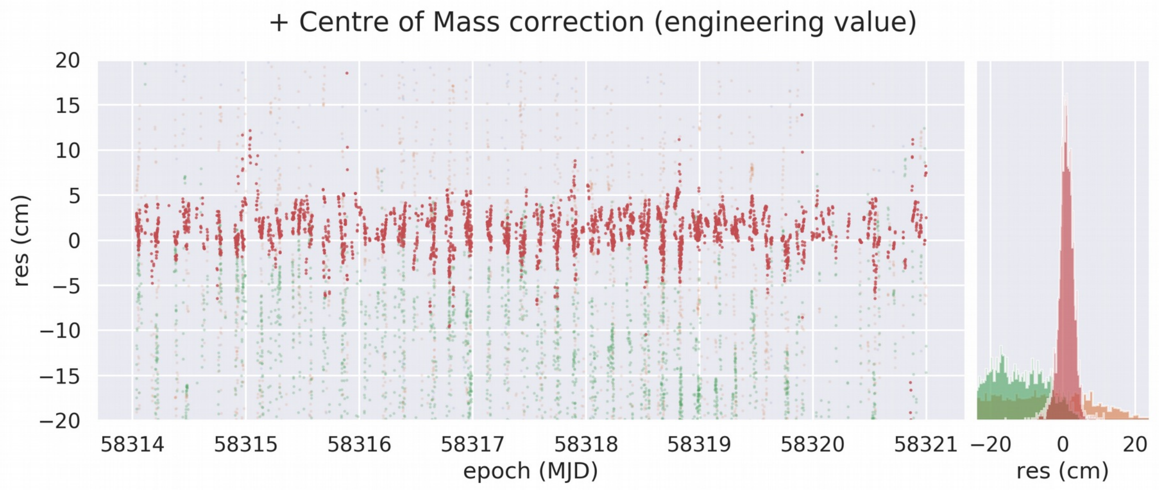


- Order of magnitude improvement
- RMS = 1.87 cm; mean of residuals = 9.97 mm
- Good residuals distribution (just slightly skewed)

Session 3: Corrections – centre of mass (to be continued)

Test: geometric centre of mass from engineering drawings



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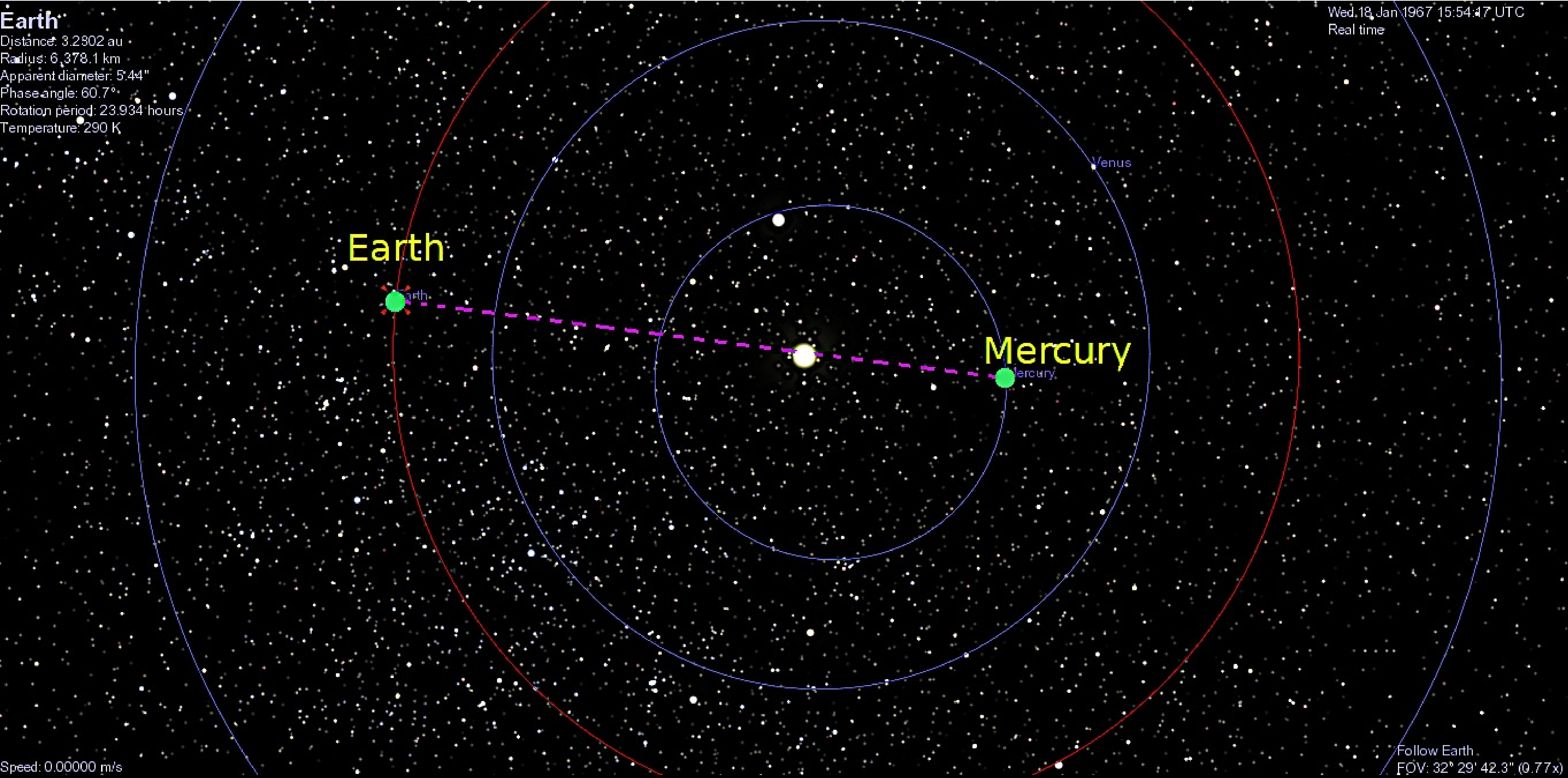


Wed.18 January 1967

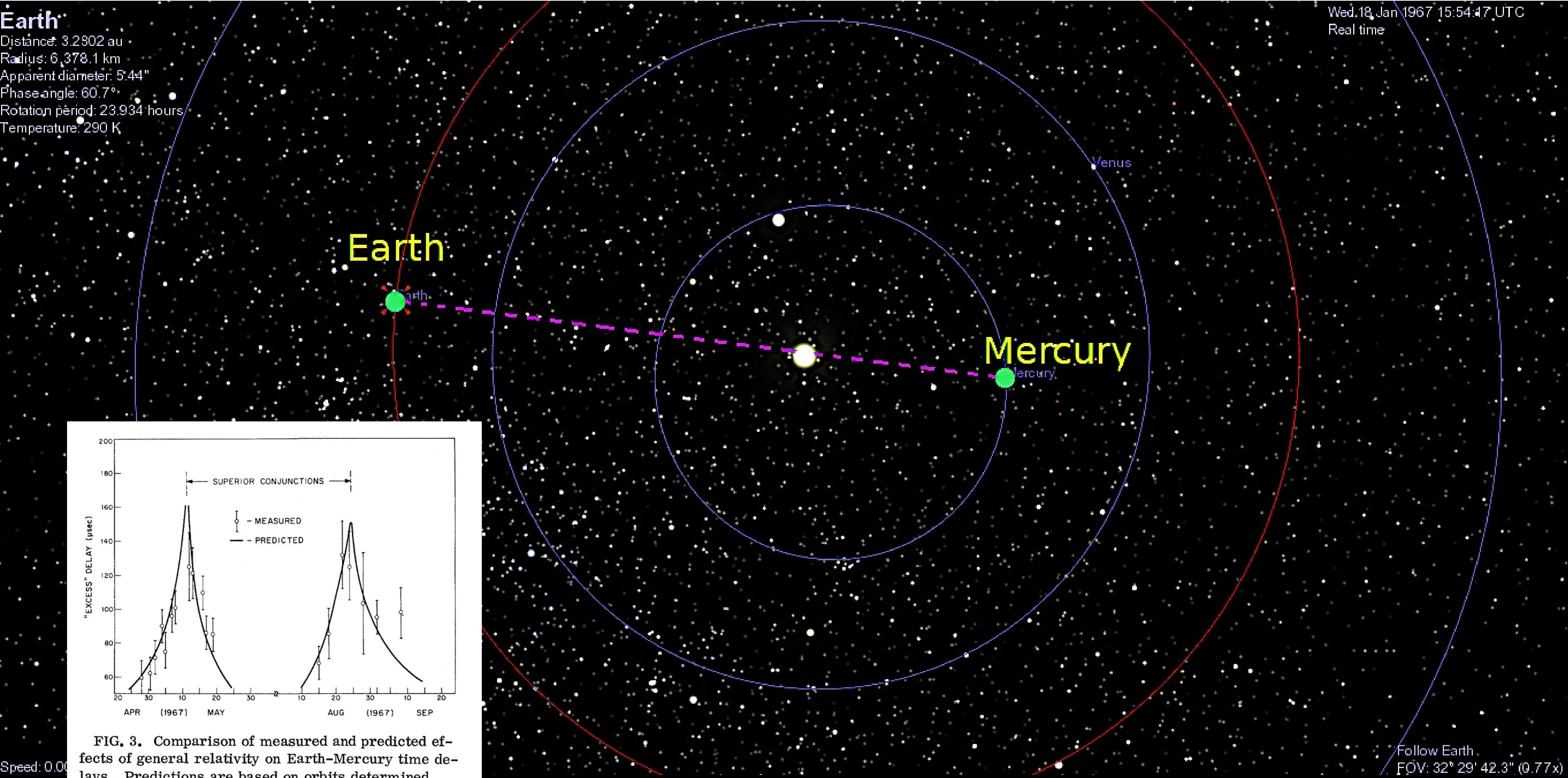


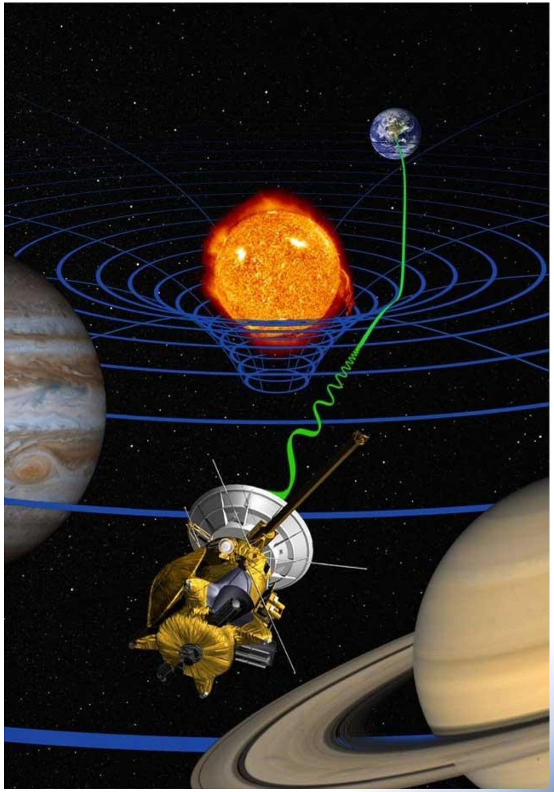
FIG. 3. Comparison of measured and predicted effects of general relativity on Earth-Mercury time delays. Predictions are based on orbits determined from other data.

Wed.18 January 1967

Session 3: Corrections – Shapiro delay

Relativistic time delay

- Electromagnetic waves propagate slower in the presence of a strong gravitational field
- Irwin Shapiro noted in 1964 that measuring this delay was technically feasible (expected ~200 us to/from Mercury)
- Experiment successfully performed in 1967 of the round-trip delay between Earth – Mercury and Earth – Venus
- Refinements would follow repeating the experiment with the Viking Landers and Orbiters



Cassini spacecraft. *NASA*

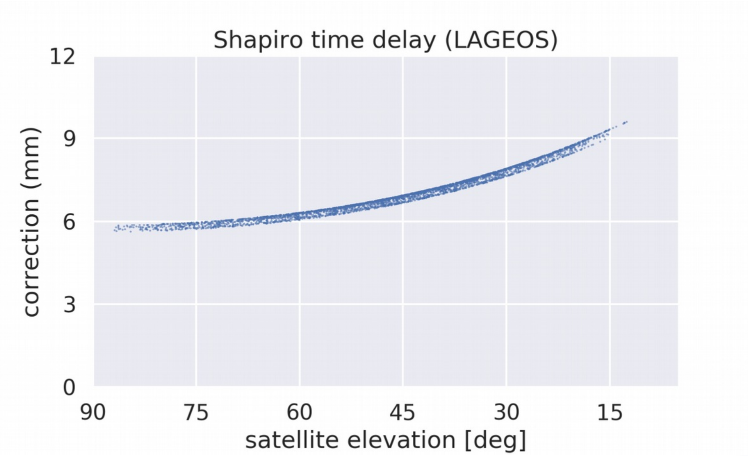
Session 3: Corrections – Shapiro delay

In near Earth environment small effect neglected for low accuracy applications

Depends on the relative positions of the ground stations and the satellites

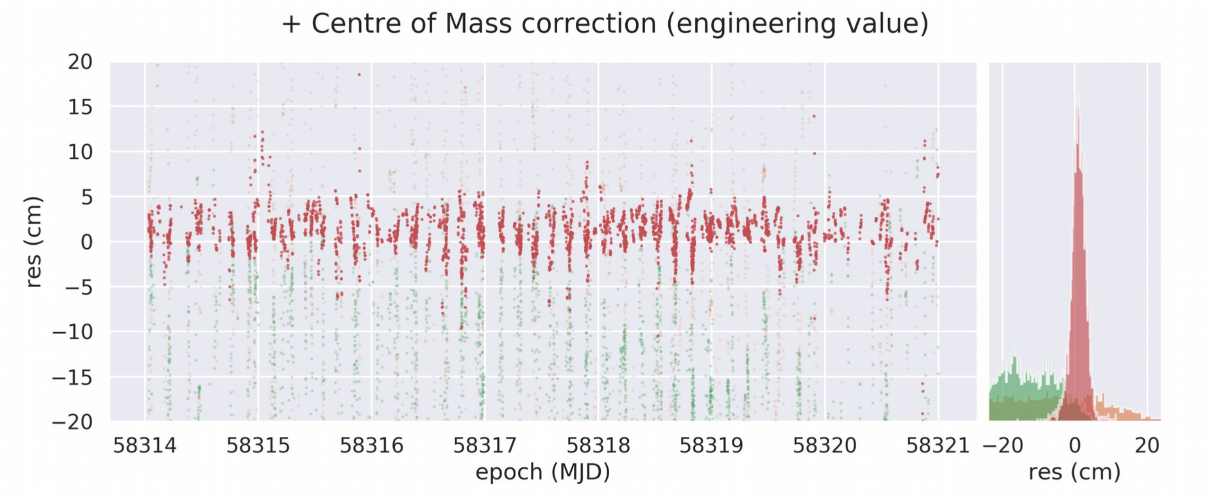
- 6 – 9 mm for LAGEOS
- 13 – 19 mm for GNSS

With accuracy goals of 1 mm, geodetic analyses must include this relativistic effect



Session 3: Corrections – Shapiro delay

Test: relativistic Shapiro time delay



Session 3: Corrections – Shapiro delay

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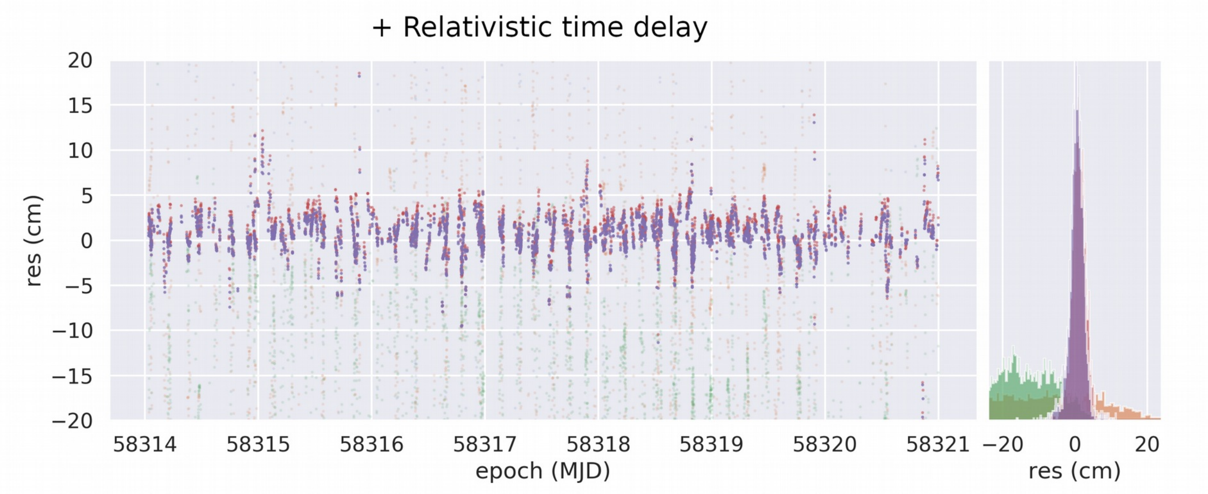


- Orbital fit improvement; modest RMS gains, 50% reduction of residual offset
- RMS = 1.68 cm; mean of residuals = 5.38 mm

Session 3: Corrections – centre of mass II

So far we only considered a naive approach to correct for the offset between CoM and reflection point

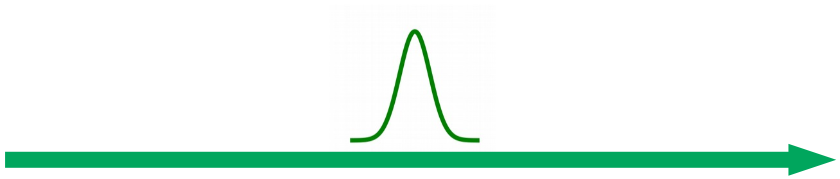
In the early 1990s it became clear that SLR data from different satellites presented different **signatures**

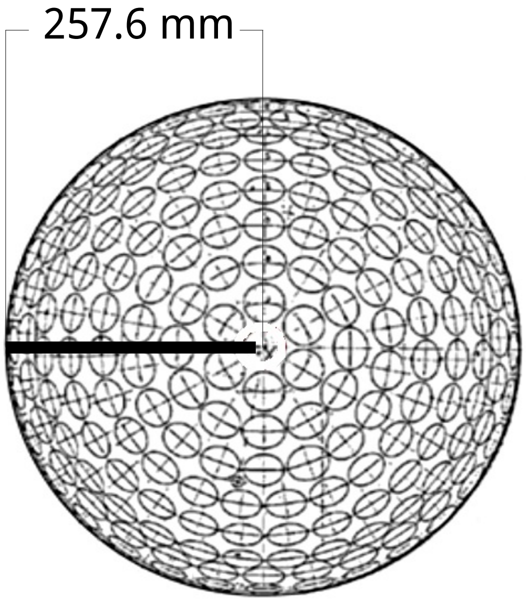
Moreover, the specific shape of these signatures depended on the detection **equipment** in use, as well as on the way they were **operated**

The use of a single CoM value for each satellite applicable to all stations was no longer considered valid

Ground tests in the laboratory are of limited use to solve this problem

Question: Why don't you just read the technical drawings?





LAGEOS

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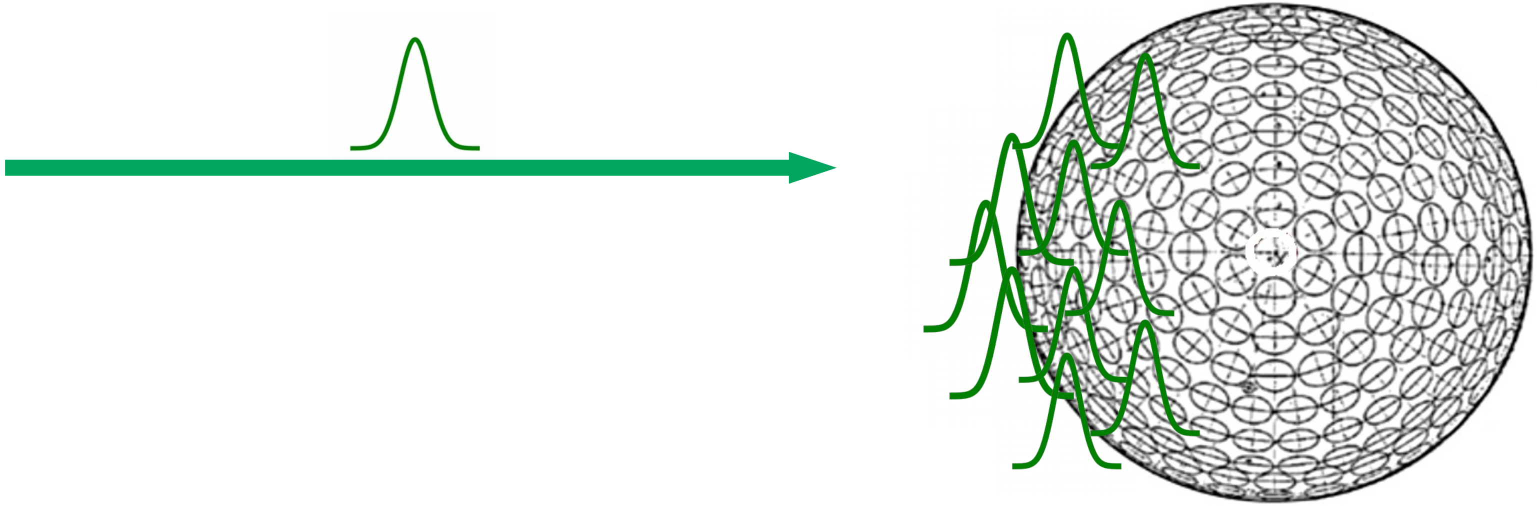

LAGEOS

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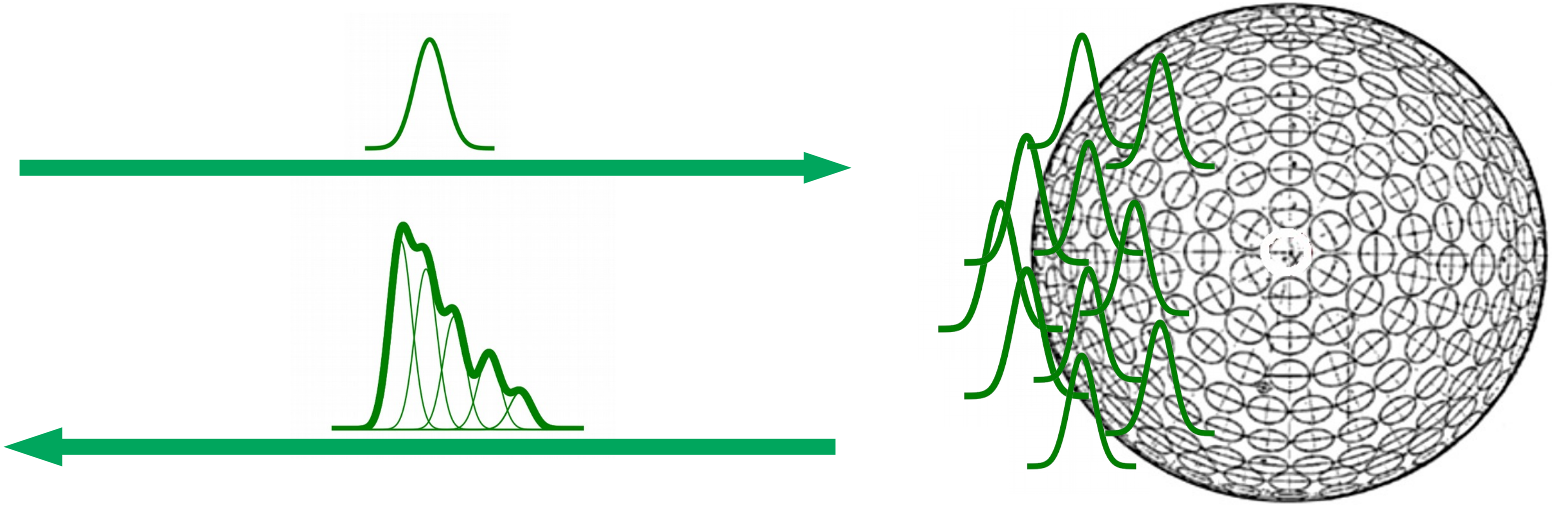
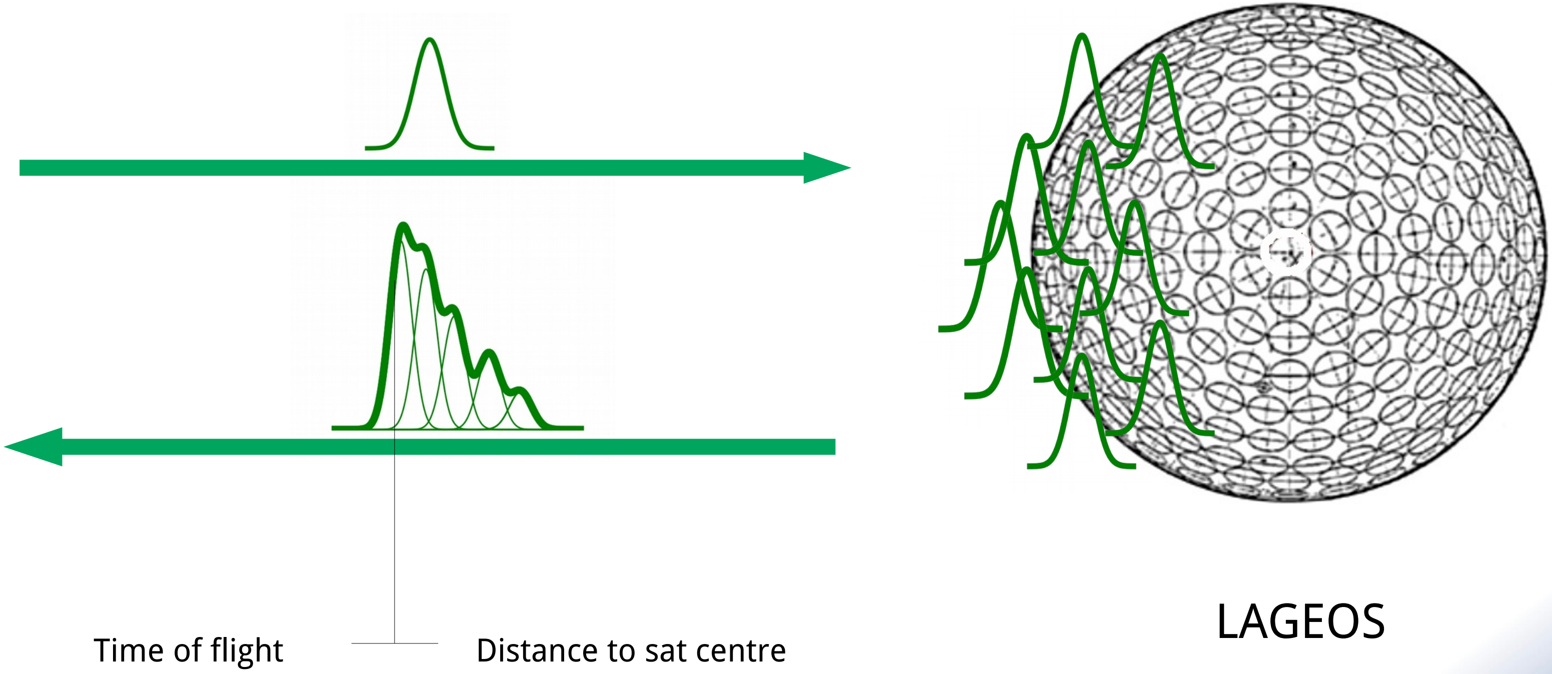


LAGEOS

Question: Why don't you just read the technical drawings?

Answer: Target signature effects



Session 3: Corrections – centre of mass II

Detailed modelling to compute CoM offsets for specific system specifications and mode of operation were developed by Otsubo & Appleby (2003), later applied to several satellites

Recently 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)

The most significant novelties include a new modelling approach for certain kinds of stations and the use of more detailed hardware specifications, operational and processing details

Session 3: Corrections – centre of mass II

How do we compute CoM offsets?

1. Characterisation of satellite optical response

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)

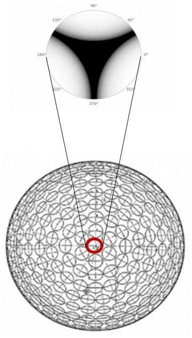
Session 3: Corrections – centre of mass II

Characterisation of target **optical response**

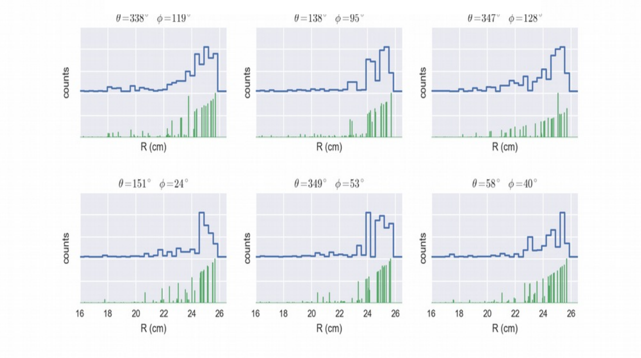
Function of: physical characteristics of retroreflectors
geometry of arrays
laser wavelength
target orientation

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

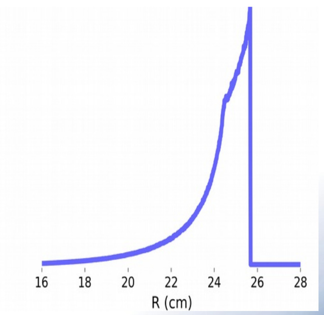
Reflectivity map



Response at arbitrary orientations



Average over 250K orientations



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Taking into account specifics of hardware/operation, use optical responses to compute CoM

a. Single photon systems
Simple mathematical relation between optical response and probability distribution of detections (Neubert 1994)

a. Multiple photon systems
More complex detection process and some practical operational pitfalls

We have modelled systems of both kinds with reasonable success

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Exploratory **sensitivity** analysis: play with the model to get a feeling of the inputs/outputs

Total range: (mm)

	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

Agreement between predicted and empirical data indicates situation is better than this

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

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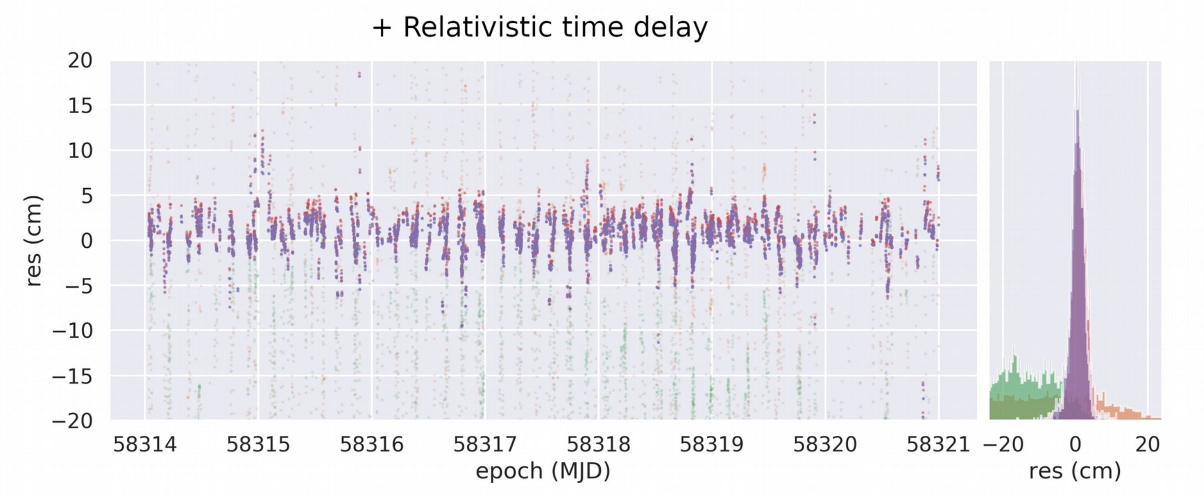
Test: detailed CoM (satellite, system, and operation specific)



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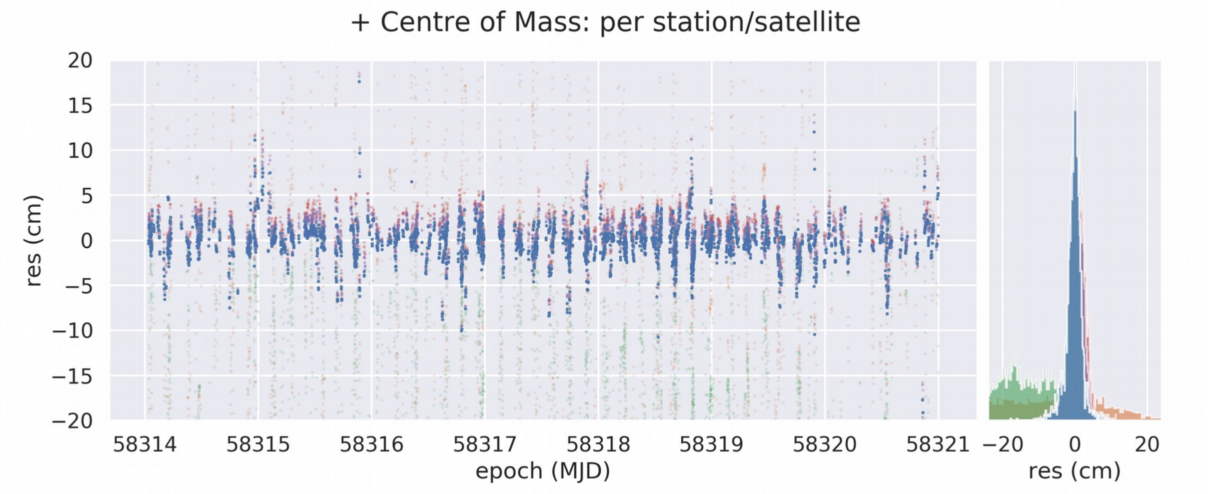
Test: detailed CoM (satellite, system, and operation specific)



- Orbital fit improvement; modest RMS gains, 50% reduction of residual offset
- RMS = 1.51 cm; mean of residuals = -2.27 mm

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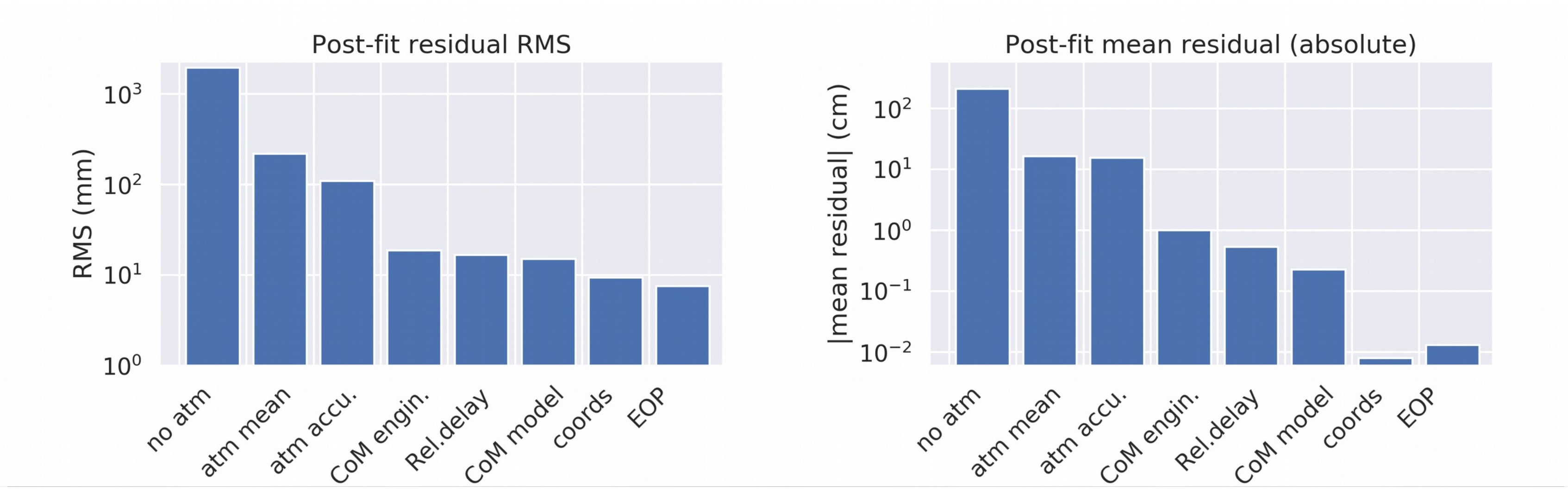

Session 3: Corrections and Error Sources

Summary

- SLR measures round trip time of flight between stations and optical reflection points of retroreflector arrays in orbit, using light pulses that propagate through the atmosphere in the near Earth environment

- Thus, we need to apply corrections to accurately derive distances from the measured TOF

- Tropospheric delays, centre of mass offsets, and relativistic delays are essential corrections applied to SLR data to achieve mm-level accuracies

- CoM offsets are system-specific, and dependent on how they operate → ideally stations should acquire data in a consistent way


Thank you