SLR School - Session 3:
Corrections and Error Sources

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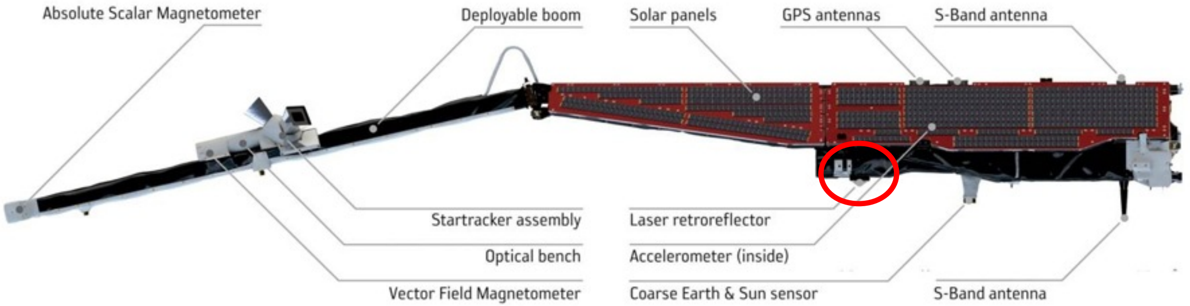
Session 3: Corrections – centre of mass



Side view of instrumentation on the Swarm satellites

Image: ESA

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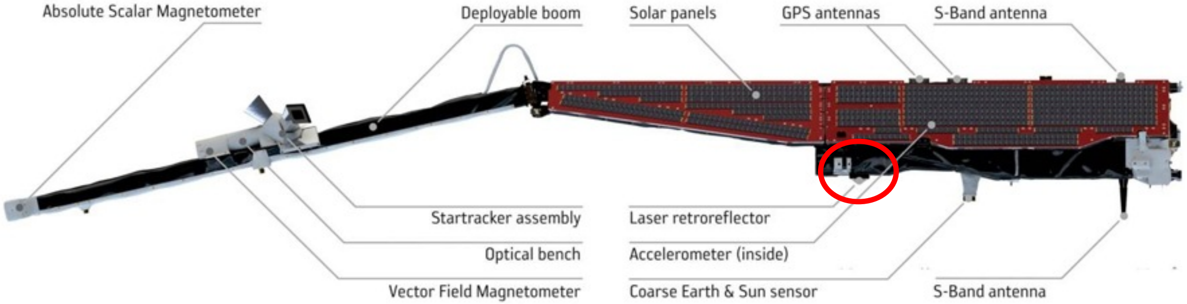

Side view of instrumentation on the Swarm satellites

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

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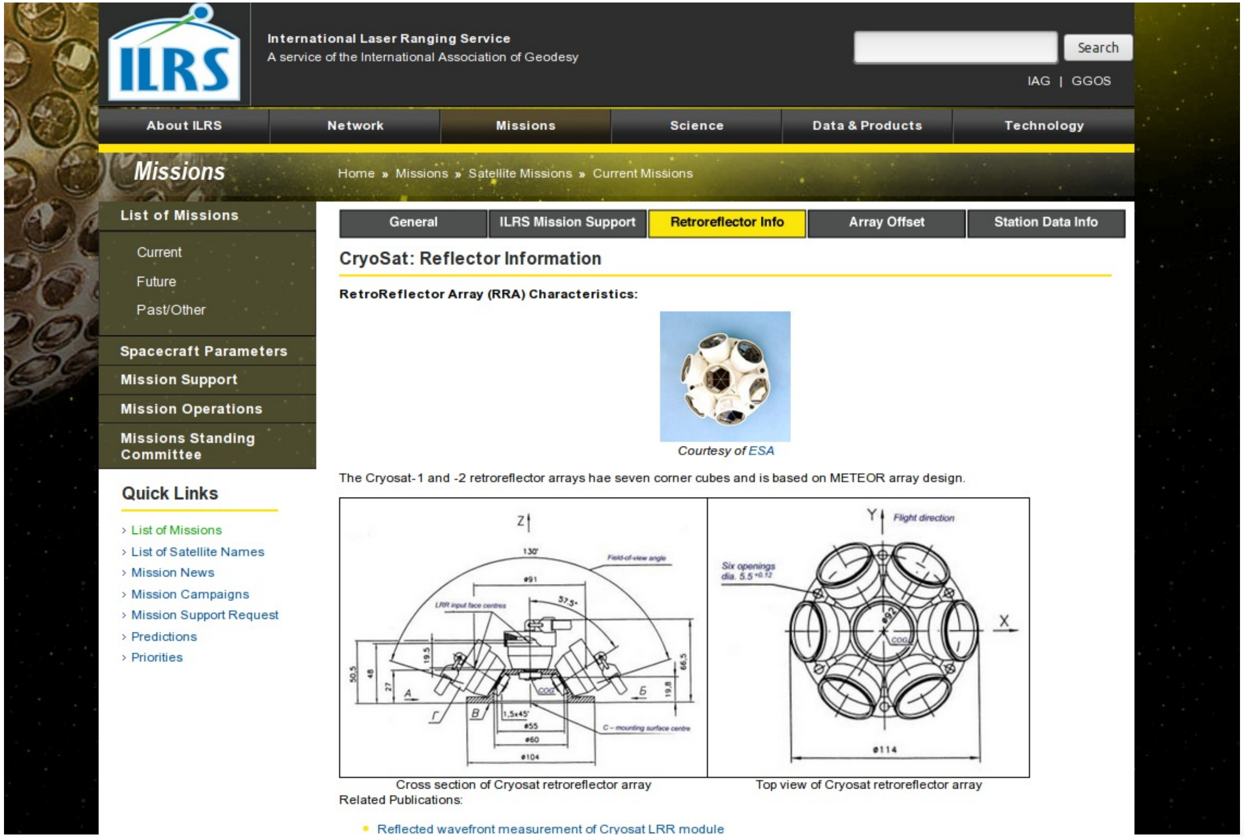

CryoSat: Reflector Information

RetroReflector Array (RRA) Characteristics:

Courtesy of ESA

The Cryosat-1 and -2 retroreflector arrays hae seven corner cubes and is based on METEOR array design.

Cross section of Cryosat retroreflector array

Top view of Cryosat retroreflector array

Related Publications:

- Reflected wavefront measurement of Cryosat LRR module

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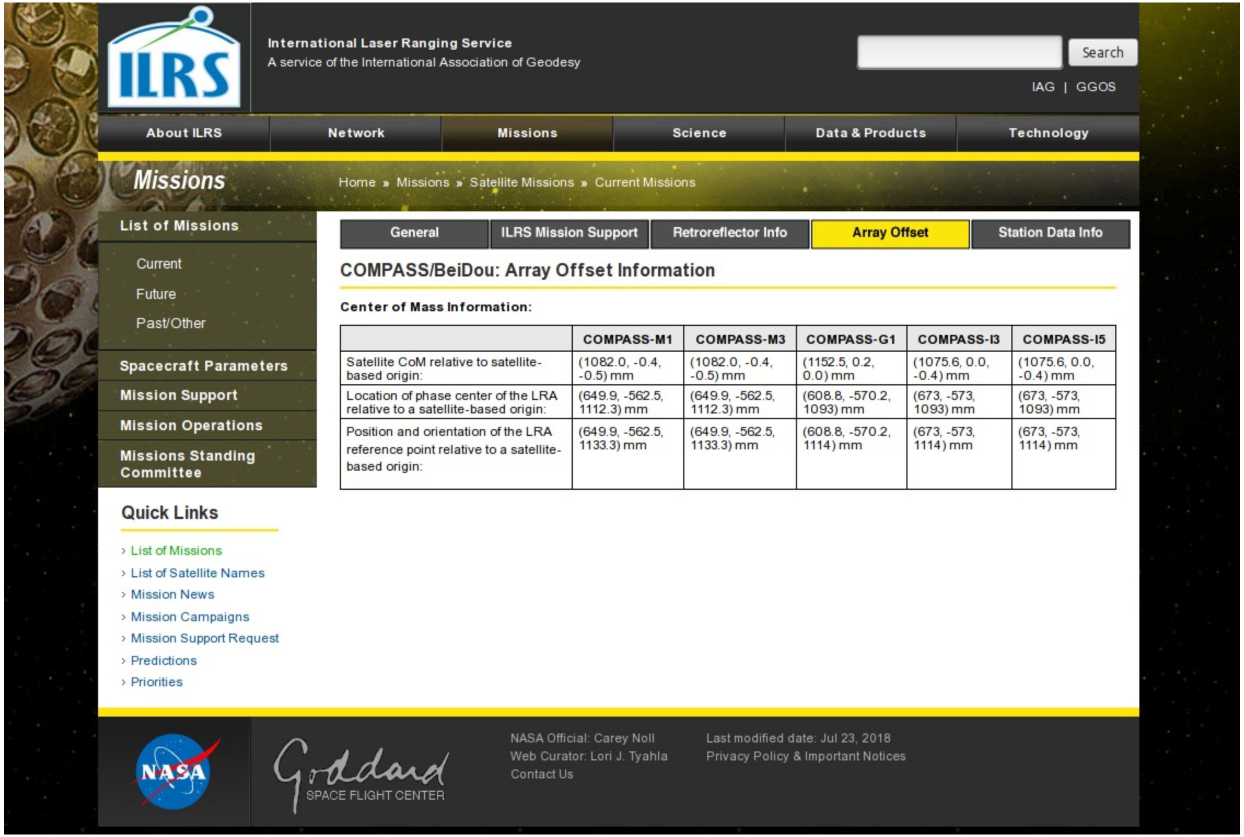

COMPASS/BeiDou: Array Offset Information

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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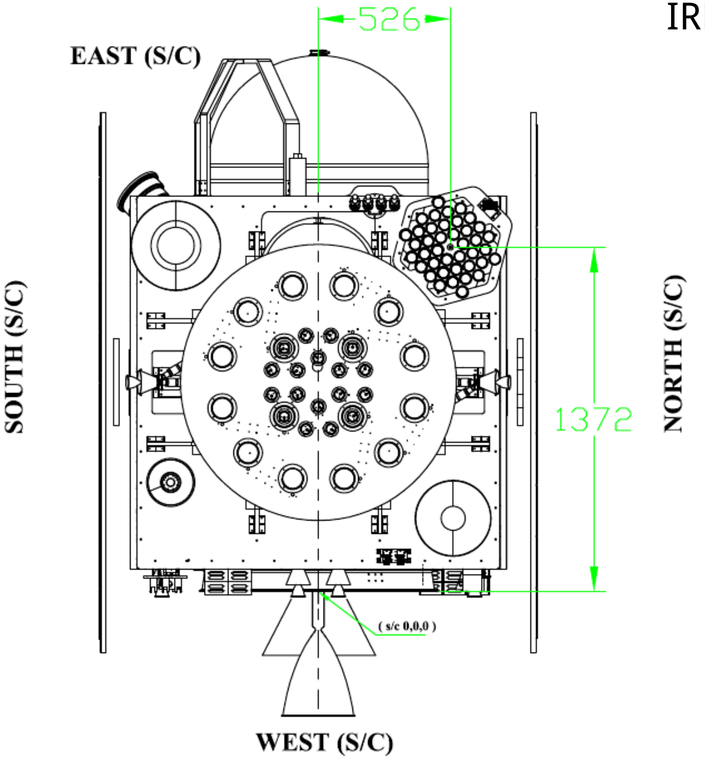
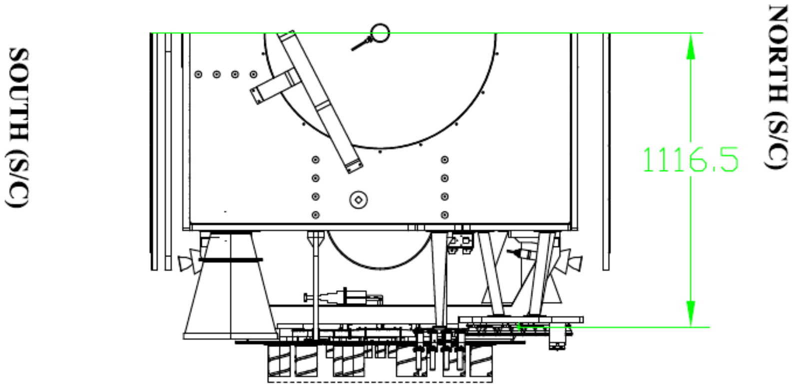
IRNSS LRA diagram (ISRO)



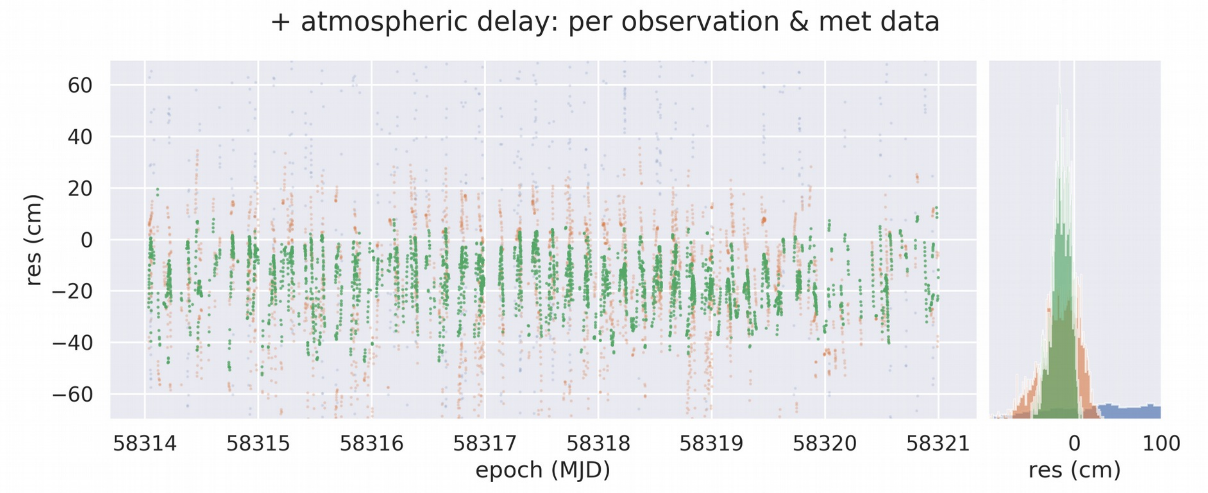


EV (S/C),[View from TOP]

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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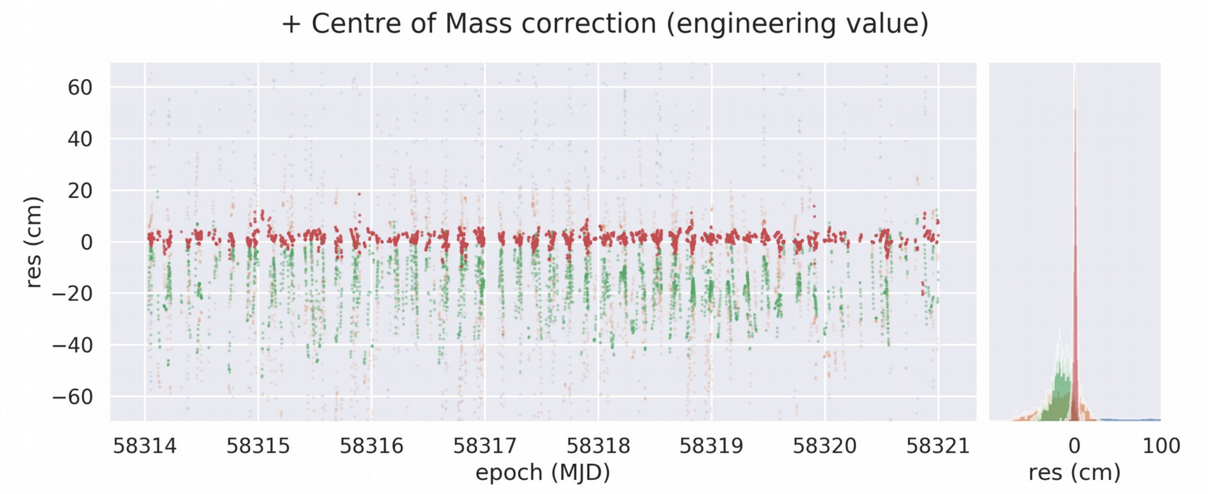

- Order of magnitude improvement
- RMS = 1.87 cm; mean of residuals = 9.97 mm

Session 3: Corrections – centre of mass

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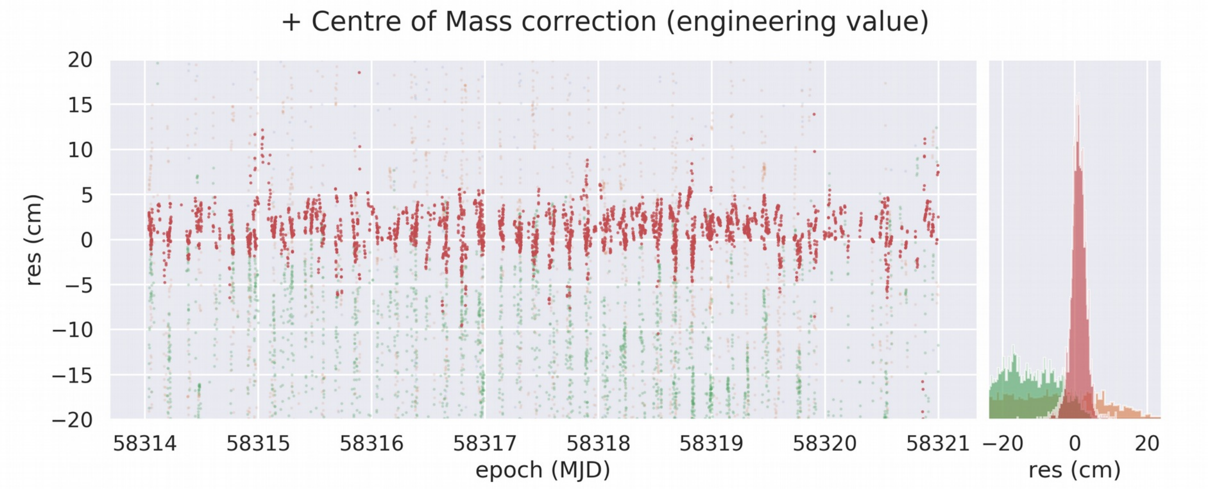
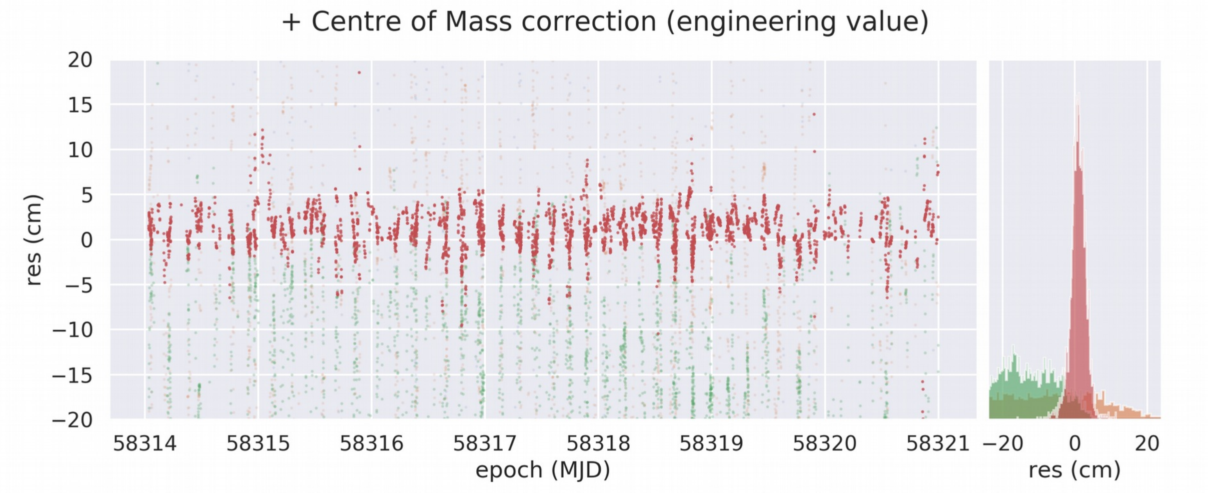


- Order of magnitude improvement
- RMS = 1.87 cm; mean of residuals = 9.97 mm
- Good residuals distribution (just slightly skewed)

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

Test: geometric centre of mass from engineering drawings



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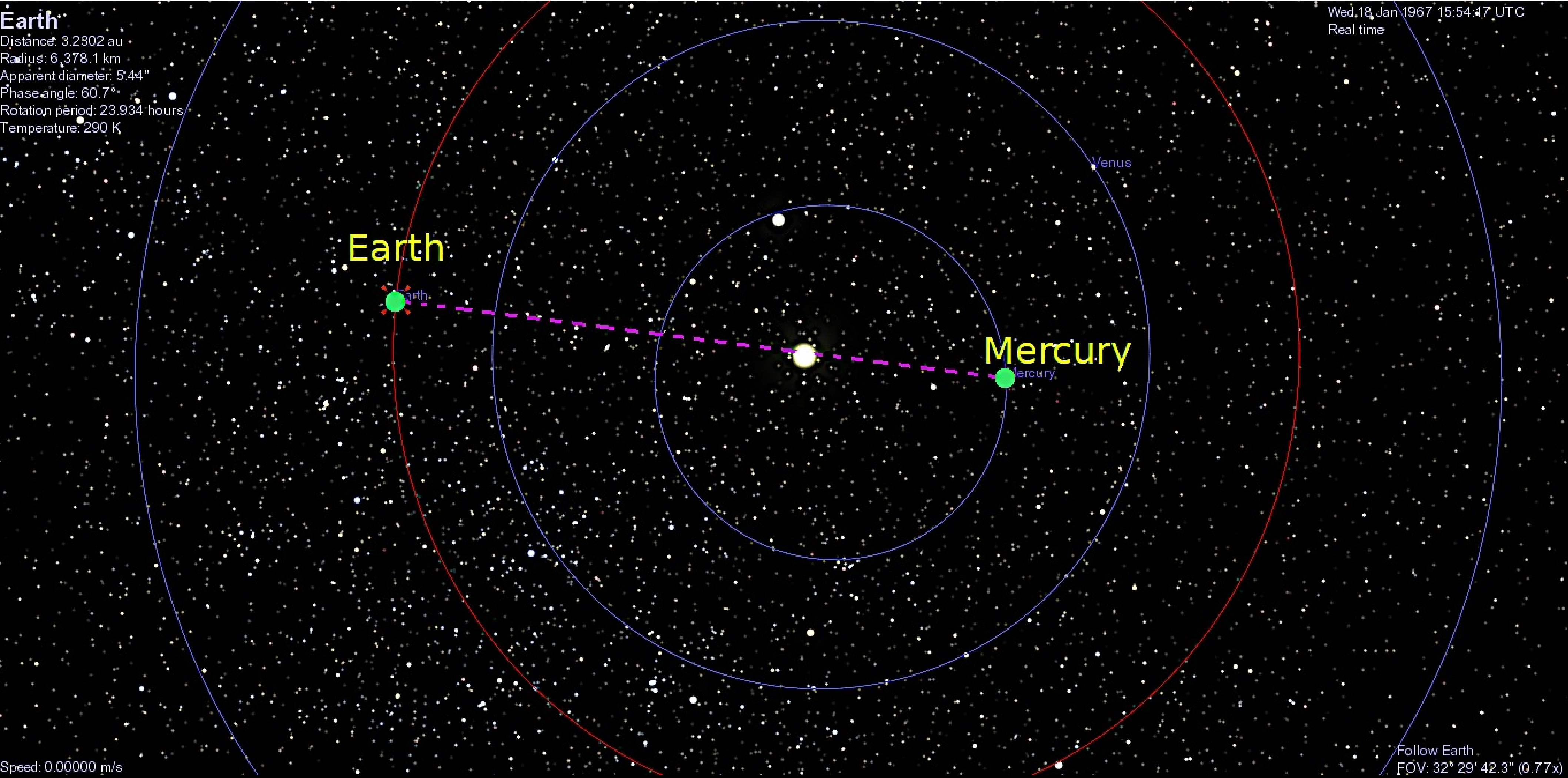


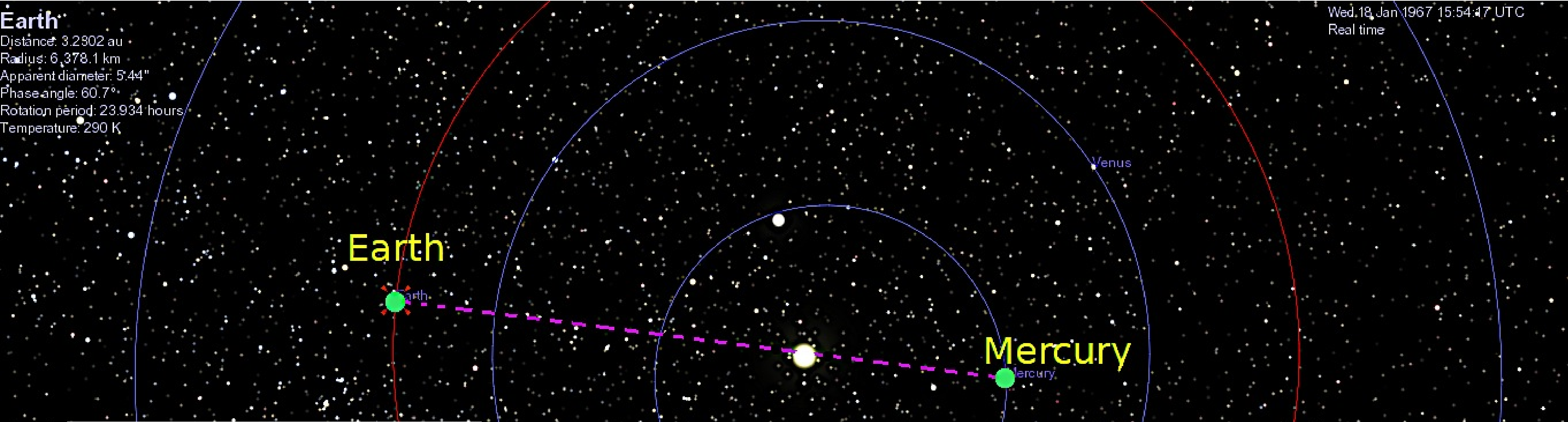
Earth
Distance: 3.2802 au
Radius: 6,378.1 km
Apparent diameter: 5.44"
Phase angle: 60.7°
Rotation period: 23.934 hours
Temperature: 290 K

Wed.18 Jan 1967 15:54:17 UTC
Real time

Speed: 0.00000 m/s

Follow Earth
FOV: 32° 29' 42.3" (0.77x)

Wed.18 January 1967



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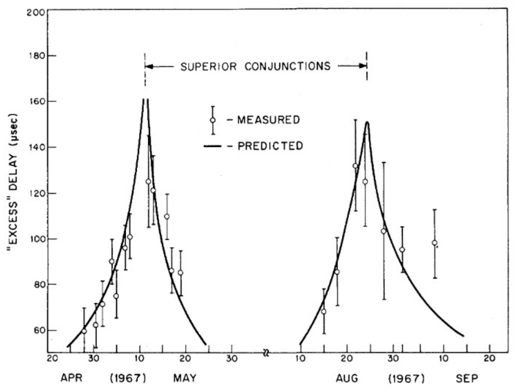


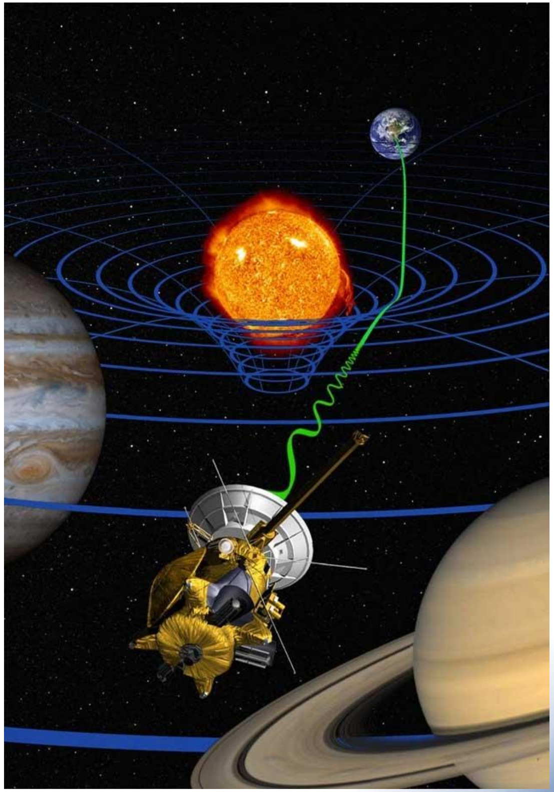
FIG. 3. Comparison of measured and predicted effects of general relativity on Earth-Mercury time delays. Predictions are based on orbits determined from other data.

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*

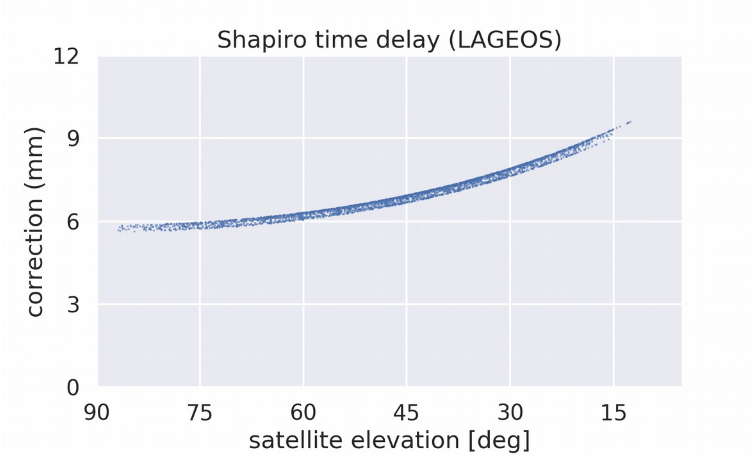
Session 3: Corrections – Shapiro delay

In near Earth environment small effect neglected for low accuracy applications

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

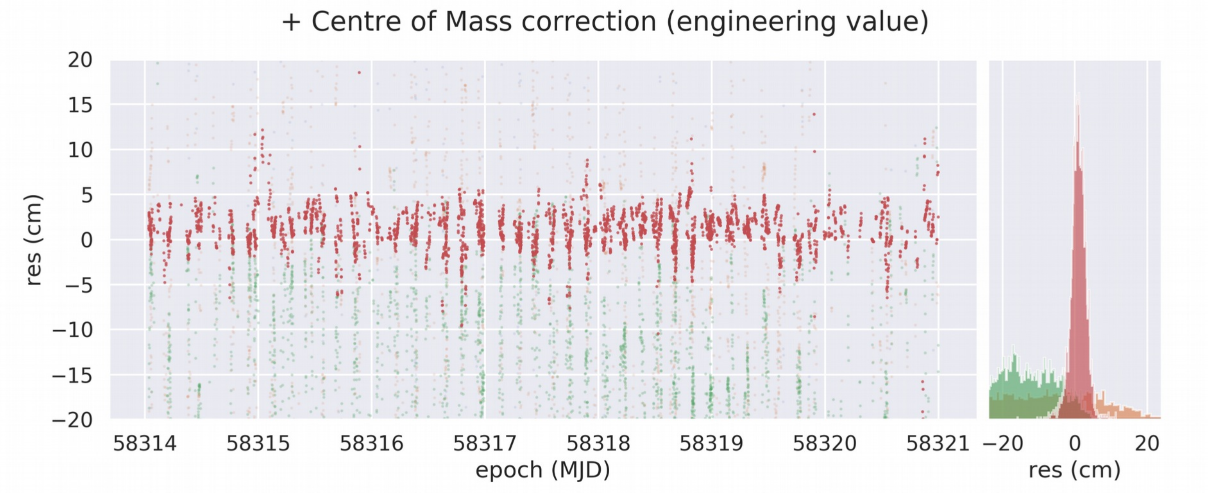
- 6 – 9 mm for LAGEOS
- 13 – 19 mm for GNSS

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



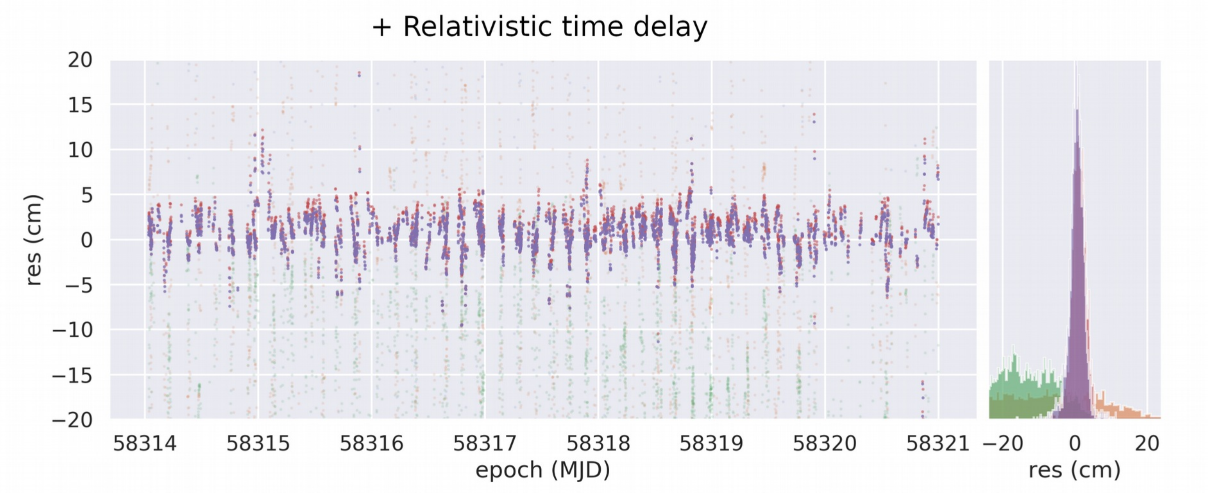
Session 3: Corrections – Shapiro delay

Test: relativistic Shapiro time delay



Session 3: Corrections – Shapiro delay

Test: relativistic Shapiro time delay



- 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

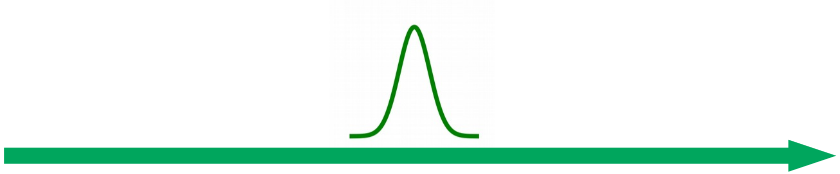
In the early 1990s it became clear that SLR data from different satellites presented different **signatures**

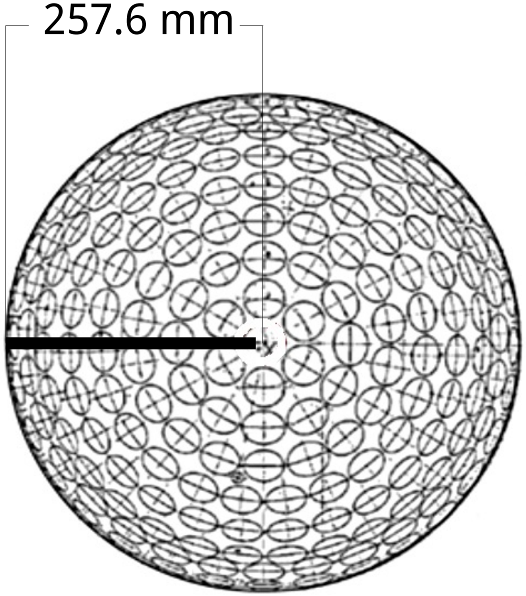
Moreover, the specific shape of these signatures depended on the detection **equipment** in use, as well as on the way they were **operated**

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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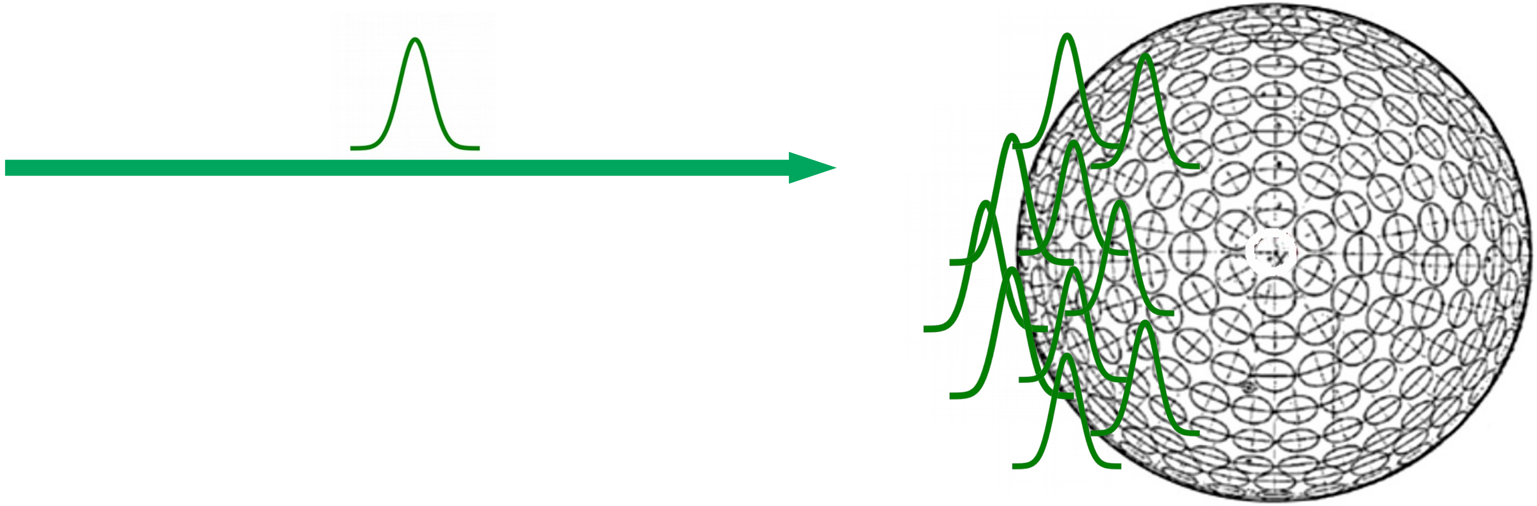

LAGEOS

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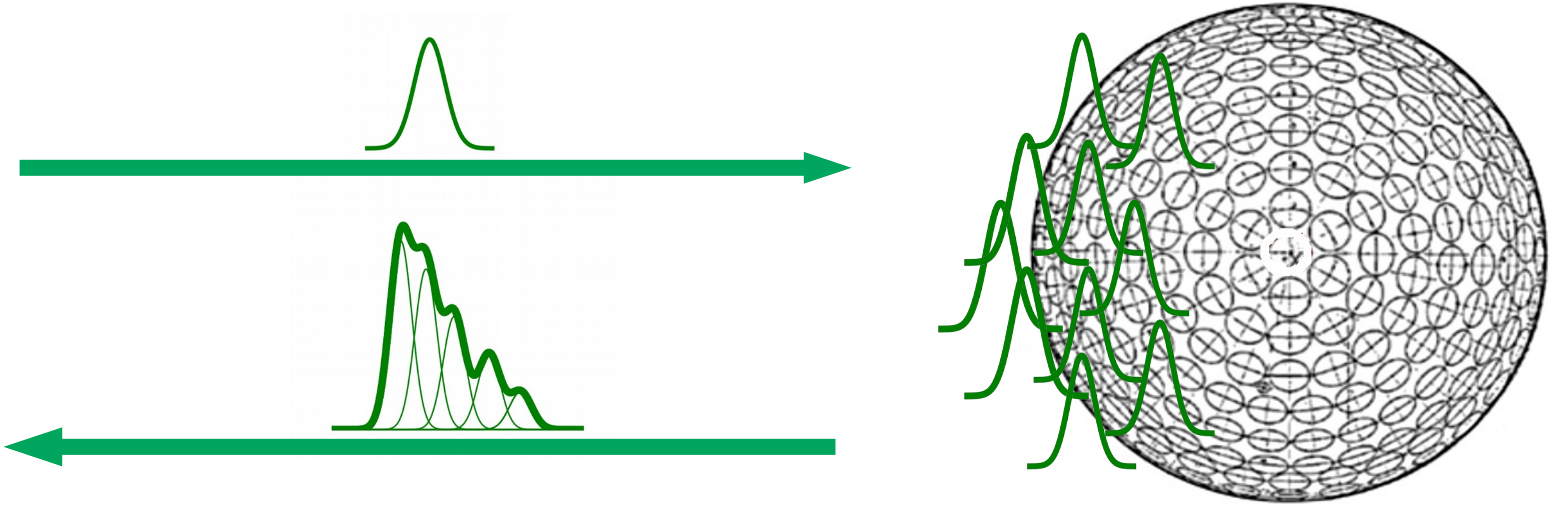
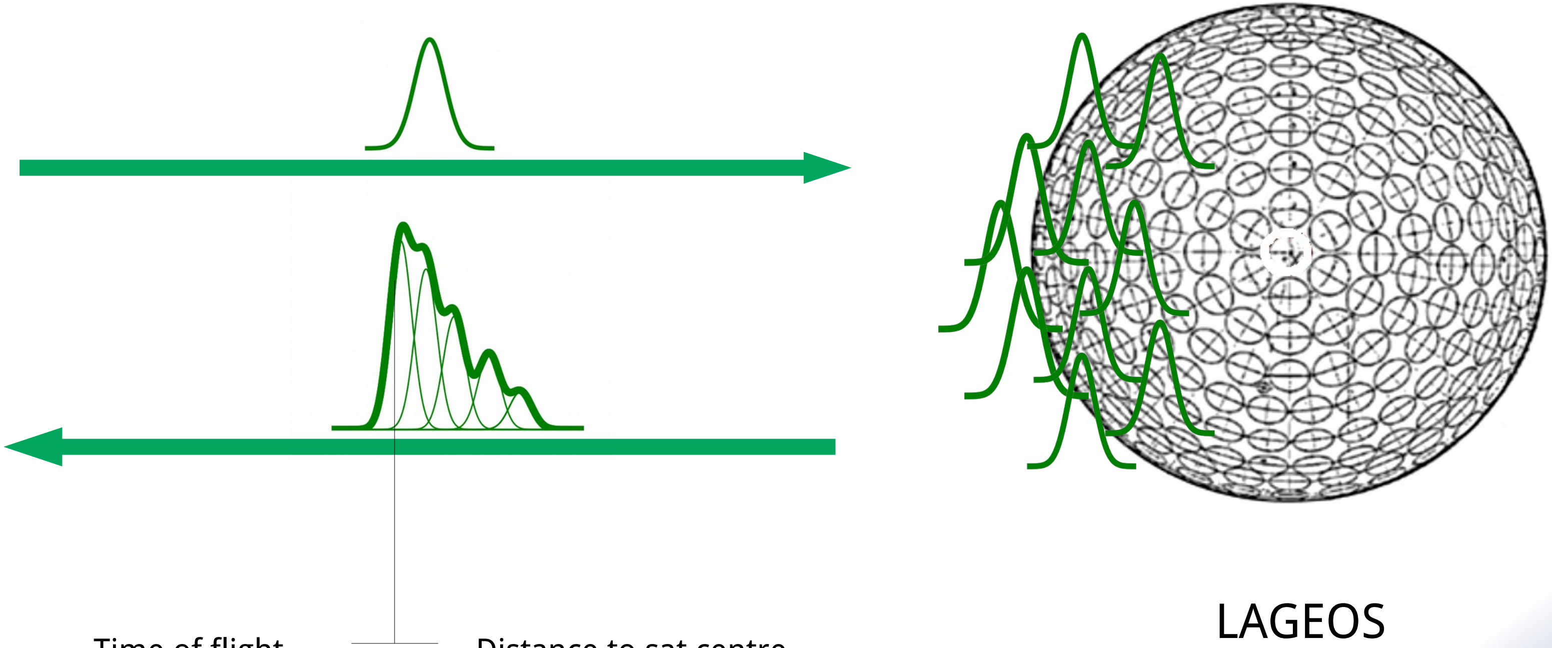


LAGEOS

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

Answer: Target signature effects



Time of flight

Distance to sat centre

LAGEOS

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)

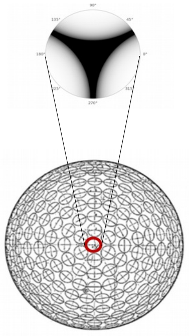
Session 3: Corrections – centre of mass II

Characterisation of target **optical response**

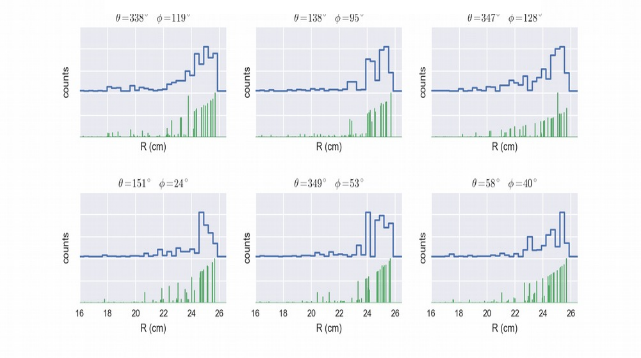
Function of:
physical characteristics of retroreflectors
geometry of arrays
laser wavelength
target orientation

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

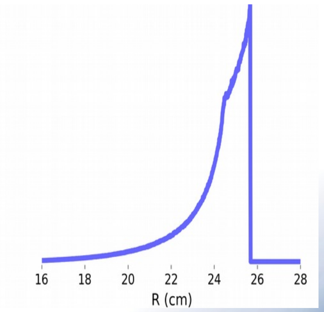
Reflectivity map



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

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