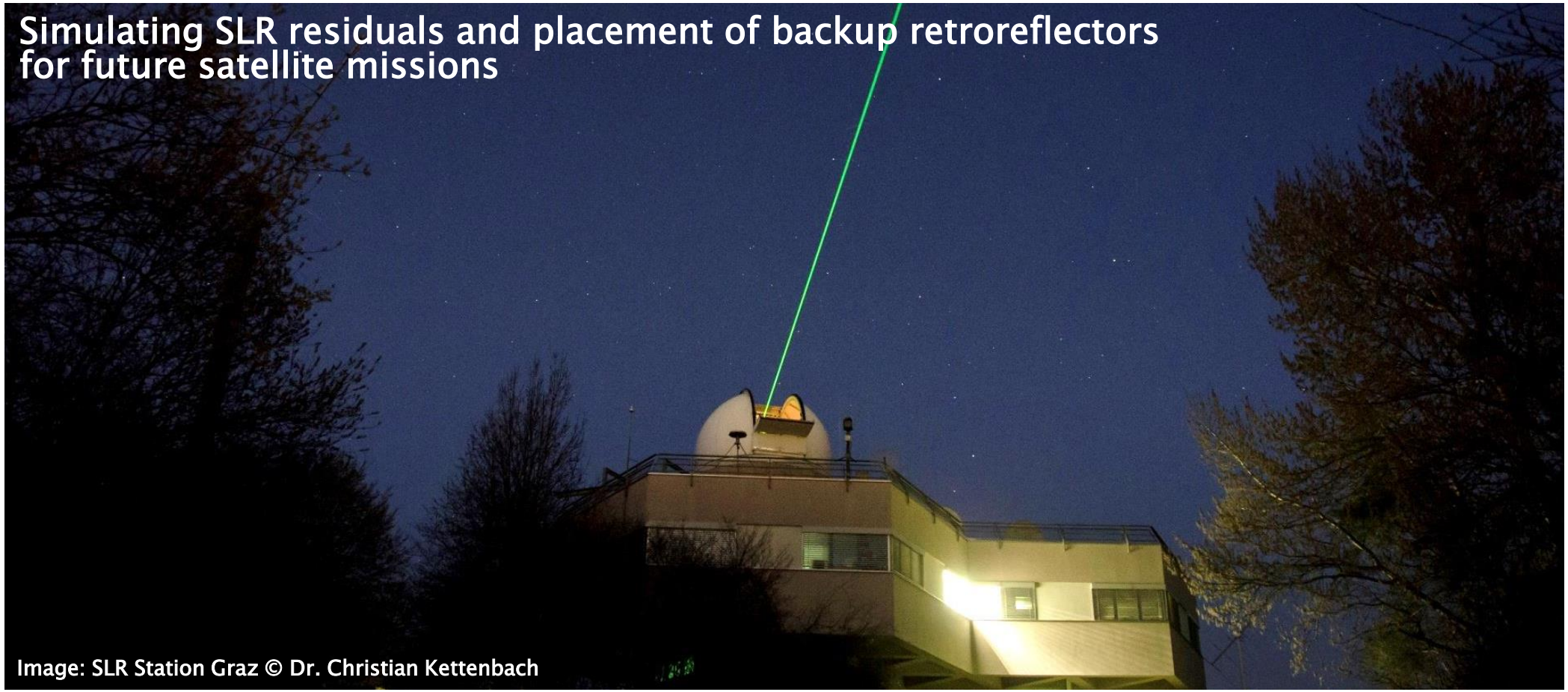
REFLECTOR-BASED ATTITUDE DETECTION SYSTEM – SLR RESIDUAL SIMULATION TOOL



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INTRODUCTION AND AIM OF THE PROJECT

Aim: Ease removal of future LEO satellites

Objective: Provide a tool to assess the positioning of backup-CCRs for optimal identification

End of lifetime: satellites can start to tumble

- Outgassing
- Solar radiation pressure
- Magnetic torque
- Collision
- …

Requirement for future removal:

- Knowledge of position/orbit
- Knowledge of attitude

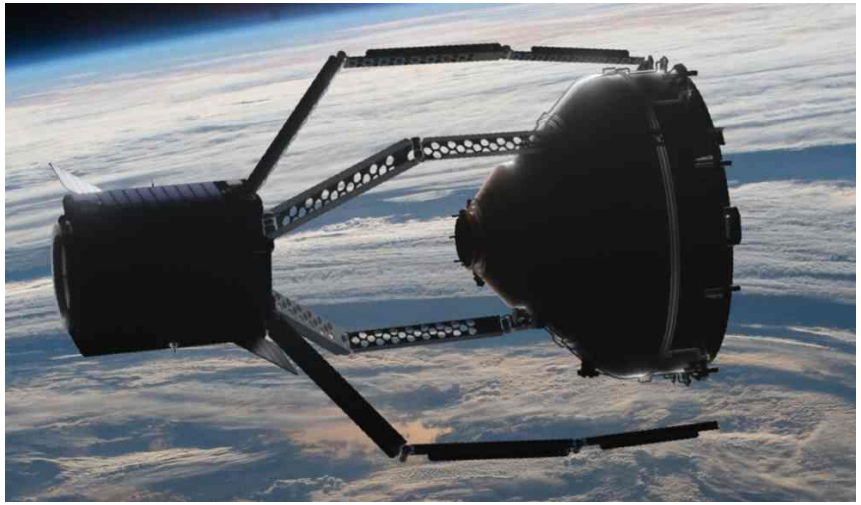


Image: Example of ClearSpace-1 ©ClearSpace-1, ESA, www.esa.int

- Investigated possible solution:

  Additional CCR on every face of the spacecraft could enable attitude determination from ground

SLR RESIDUAL SIMULATION TOOL

Basic structure of the tool:

1. Read of the input file (JSON)
   Satellite, Rotation/CCR parameters, reference coordinate frame (RCF)
2. Definition of pass time
   Start and stop of (realistic) pass … Elevation > 0°
3. Download TLE for prediction
4. Read in station coordinates
   Sinex files from CDDIS
5. Coordinate transformations (TEME, ITRS, GCRS …)
6. Lagrange interpolation (interval closable)
7. Read in CCR position, normal vector and FOV
8. Rotate CCR around fixed axis in RCF

Note: Simulation tool creates observed-minus-calculated residuals

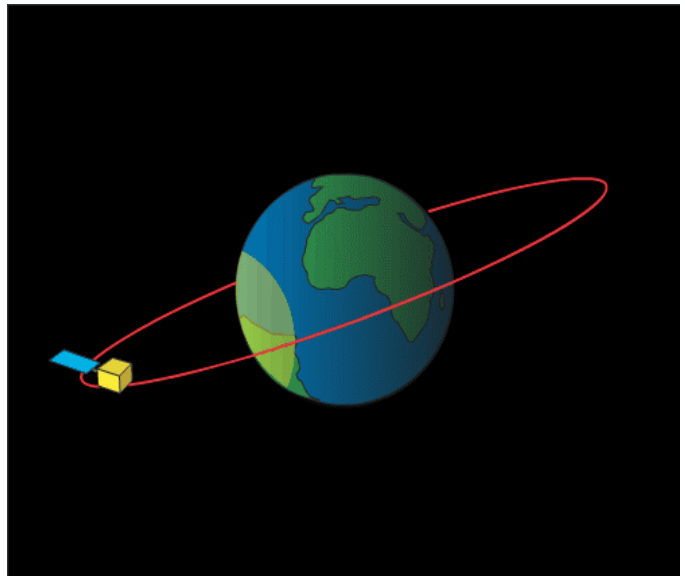


Image: Satellite Orbit ©NWS

EXAMPLE OUTPUT

Input source for orbit propagation

Pass time

Number Observing SLR station

Rotation parameters

FOV of CCRs

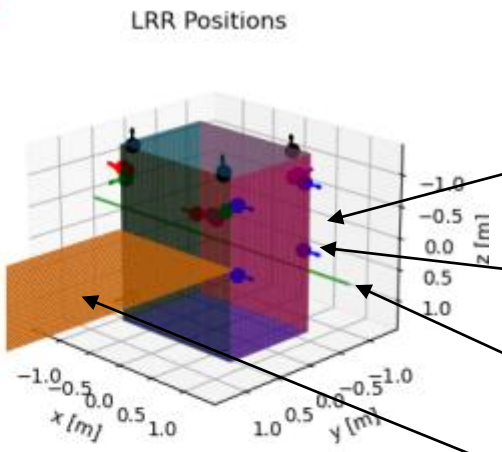
Faces of the S/C

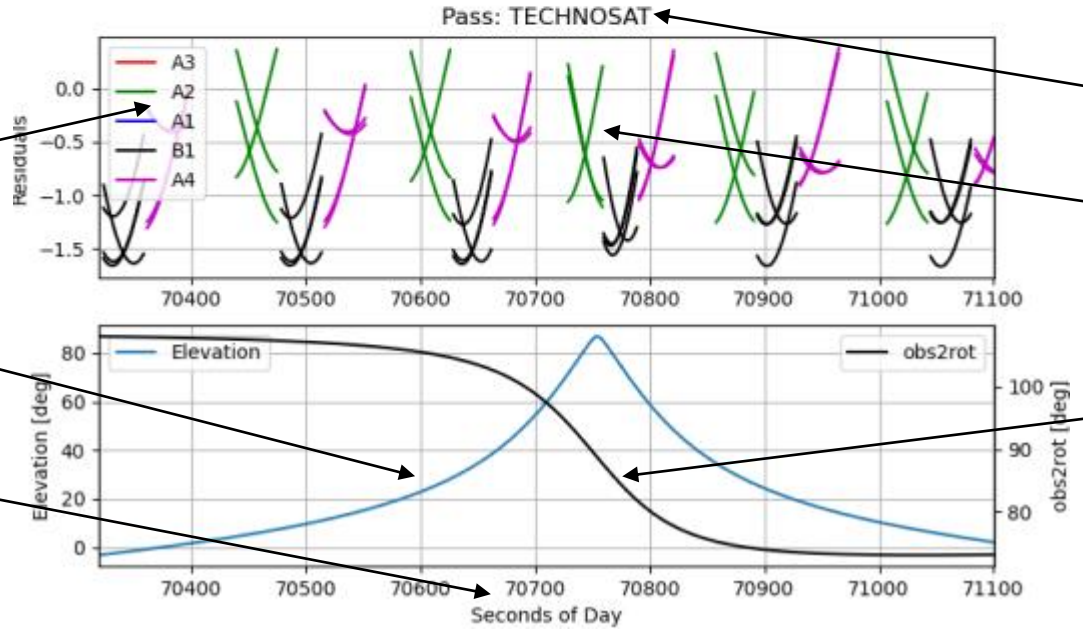
Elevation of observed S/C in degree

Seconds of day: time parameter

Simulation results RADS acticity

- TLE file from TECHNOSAT (42829)
  - Pass start: 2022-02-03 19:32:00
  - Pass end: 2022-02-03 19:45:00
  - Pass over SLR-Station: 7839
- Rotation Type: const_vec
  - Body fixed rotation axis: [1, 0, 0]
  - Init rotation axis gcrs: [1.0, 0.0, 0.0]
  - Rotation periode: 160 s
- Reference frame: gcrs
- Mode: Free tumbling
- Default FOV: 45.0 deg





Sketch of spacecraft

Dots and arrows: CCRs and corresponding normal vectors

Rotation axis

Possible appendage (shadowing)

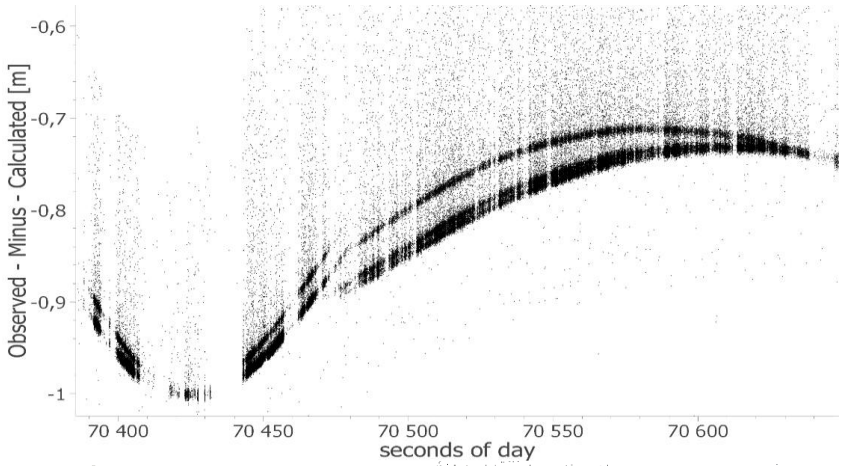
Orbit used

Observed-calculated residuals

obs2rot: angle between observation vector and rotation axis in degree

VALIDATION OF THEORY

Requirement: Single CCRs on one S/C face shall be distinguishable



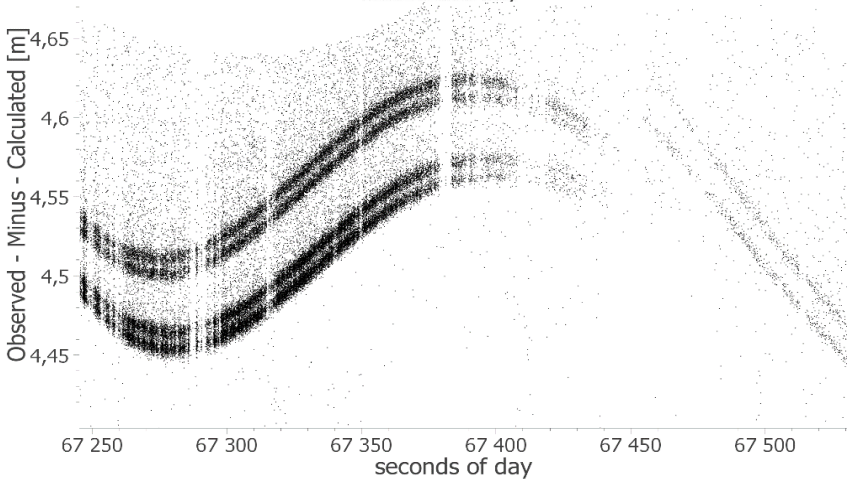


Image: Cleaned SLR measurements of TechnoSat done by SLR-Station Graz, Austria

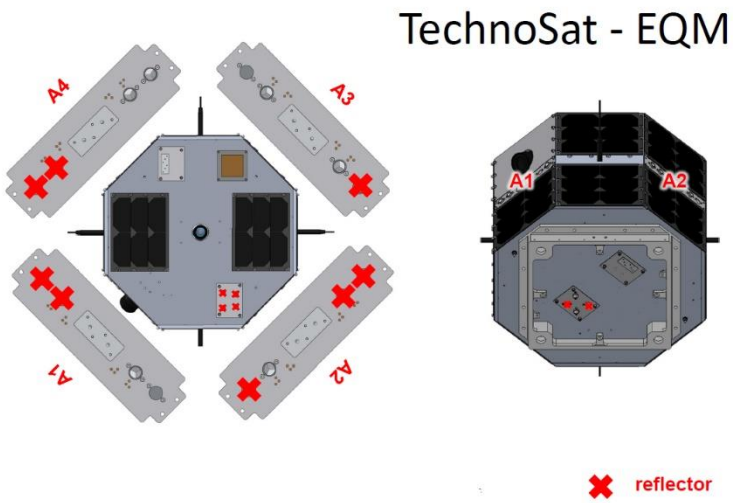


Image: TechnoSat retroreflector Array (RRA) Characteristics ©Technische Universität Berlin

Important:

Faces distinguished by CCR pattern
--> single CCRs have to be visible

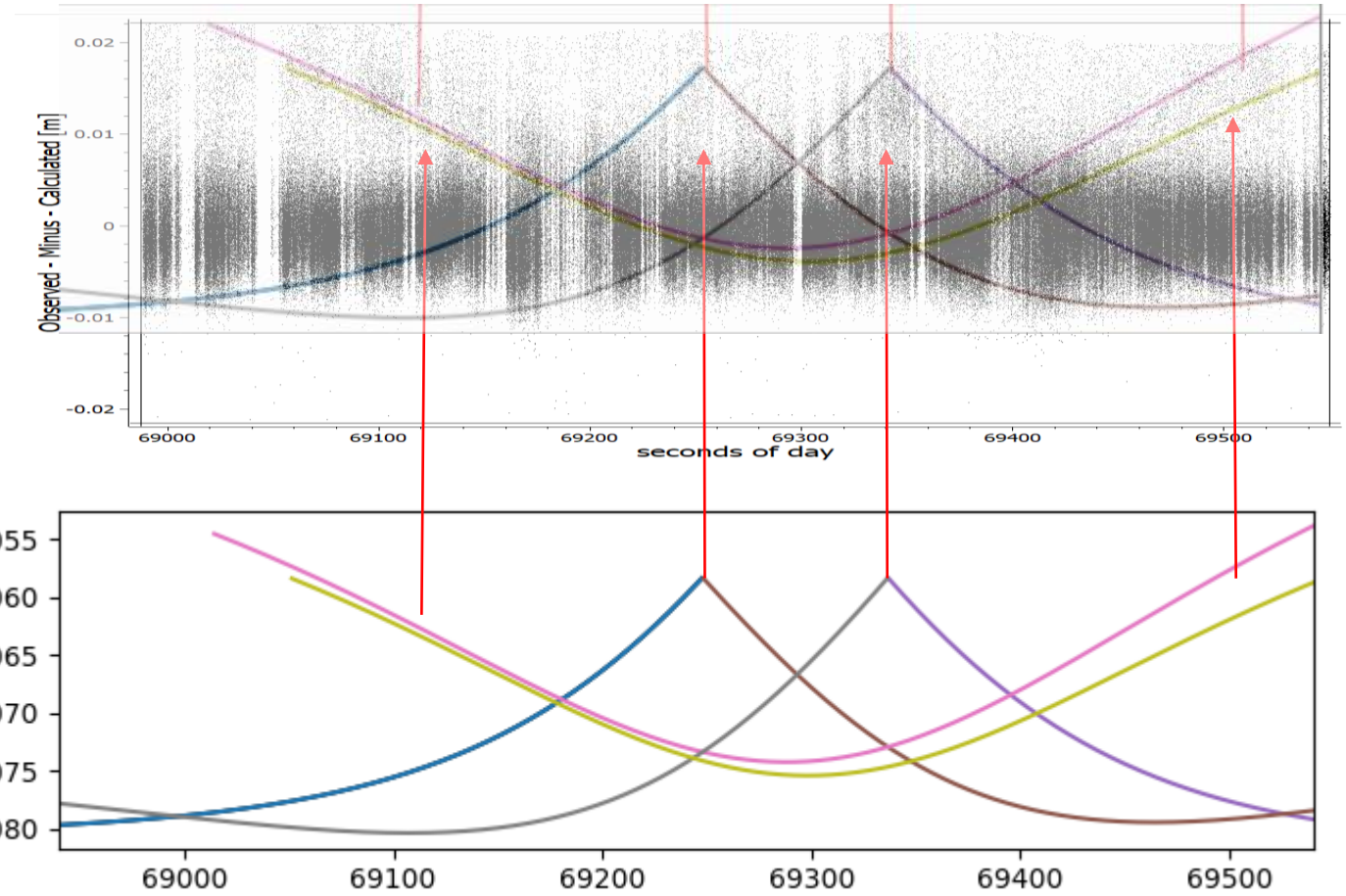
Example TechnoSat:
Max. distance between CCR: ~140 cm
Min. distance between CCR: ~30 cm

VALIDATION OF THE TOOL

Jason 3 (JA308219):

Nadir pointing, JA308219, Single CCR on pyramid visible

SLR residuals “orbit cleaned” in patches (baseline flat)



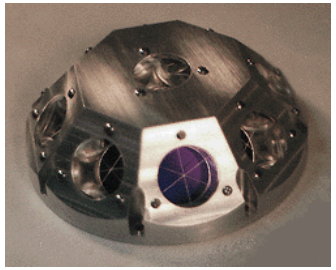


Image: Jason 3 POD pyramid © *https://ilrs.gsfc.nasa.gov/missions/satellite_missions*

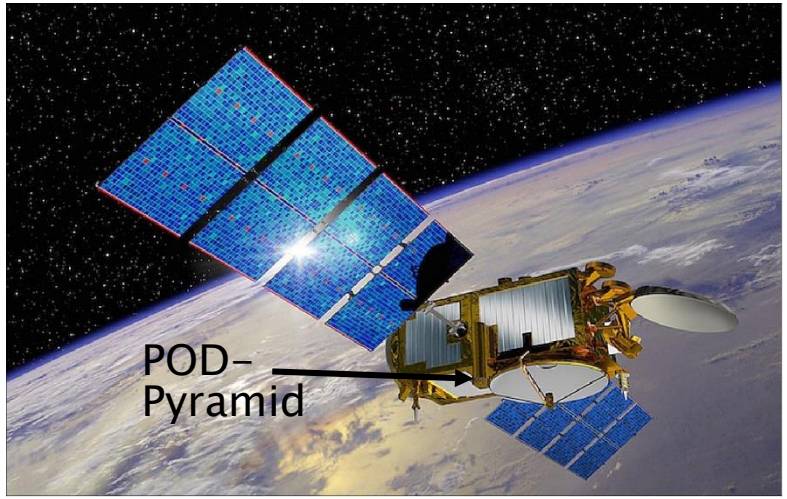
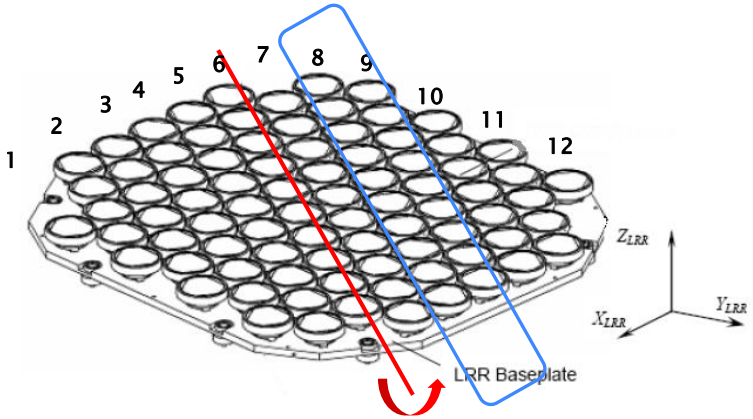


Image: Artist’s rendition of the deployed Jason-3 spacecraft ©CNES

VALIDATION OF TOOL: SLR MEASUREMENTS

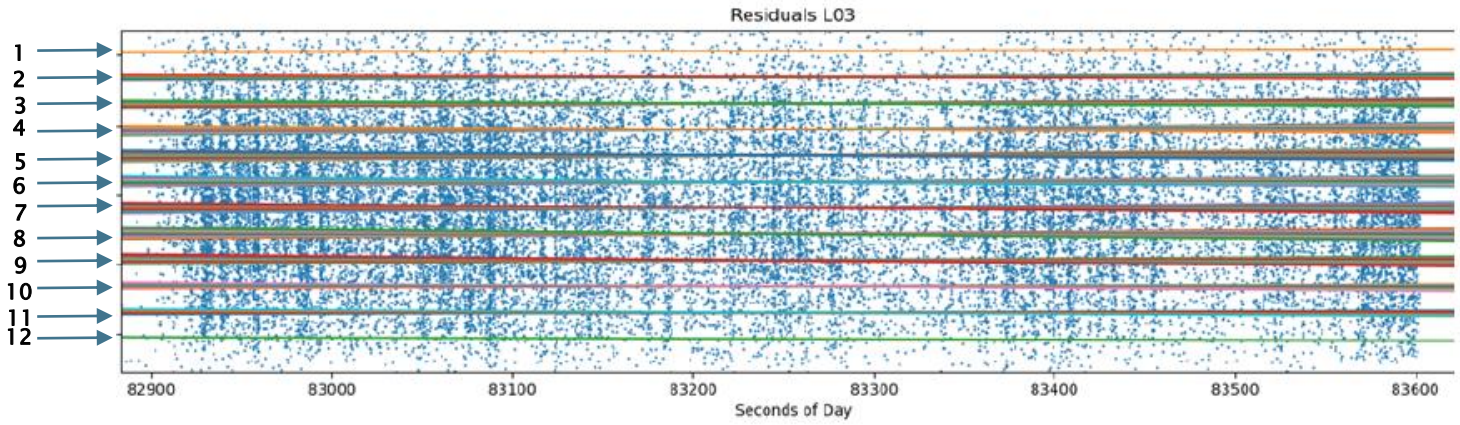
Galileo Yaw Steering: Galileo 101, L0116319

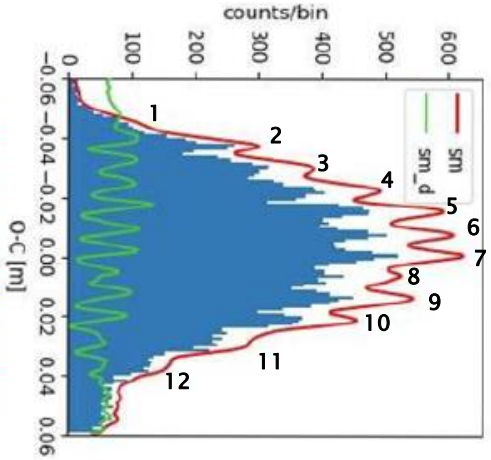
- Orientation follows sun: Yaw steering reference frame
- Symmetry conditions: panel tilted
- CCRs align at equal ranges -> e.g. 12 rows
- Peak distance -> incidence angle can be calculated



Galileo IOV panel arrangement

Measured SLR residuals vs. Simulated residuals





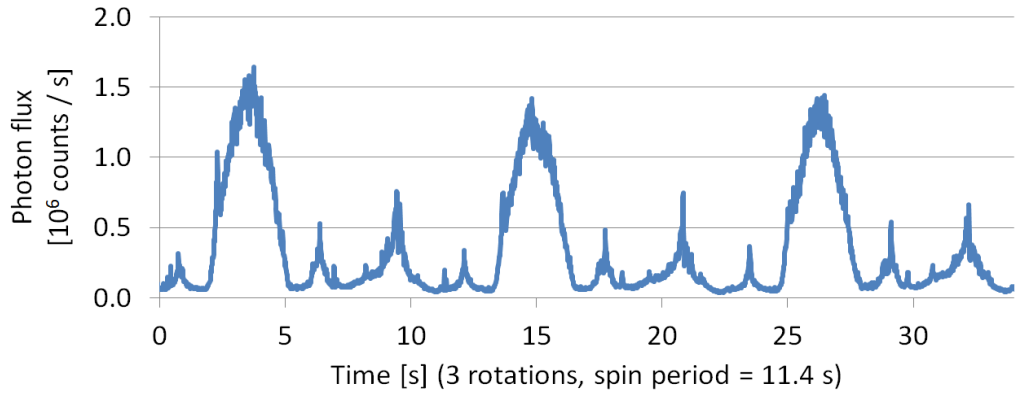
CCR image: https://ilrs.gsfc.nasa.gov/missions/satellite_missions/

HOW TO IMPROVE FUTURE SATELLITE MISSIONS

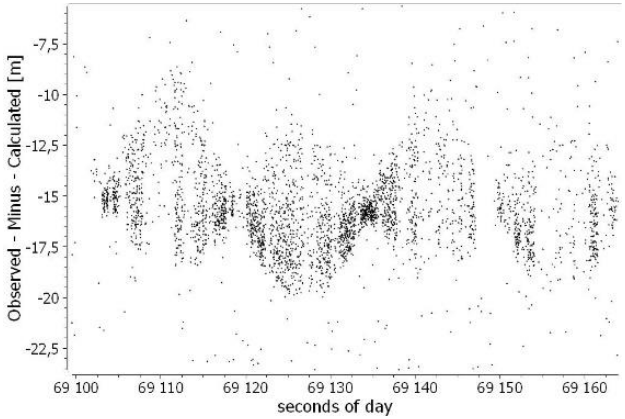
Tumbling behavior more difficult to monitor if no CCRs or just pyramid is on satellite

- Combination of multiple techniques: Light curves, space debris laser ranging, satellite laser ranging

Graz data: single photon light curve (Topex)



Graz data: space debris laser ranging (SL16 R/B)



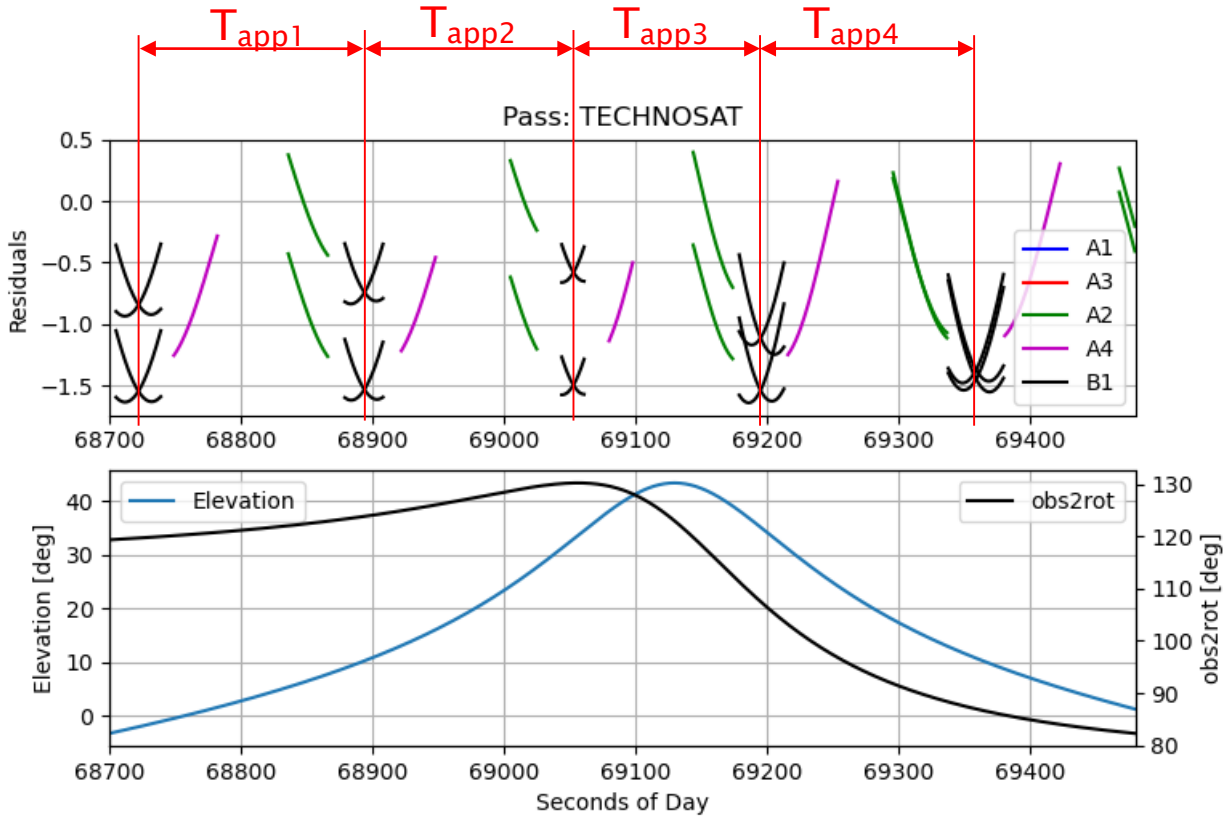
How allow more stations collect attitude determination data?

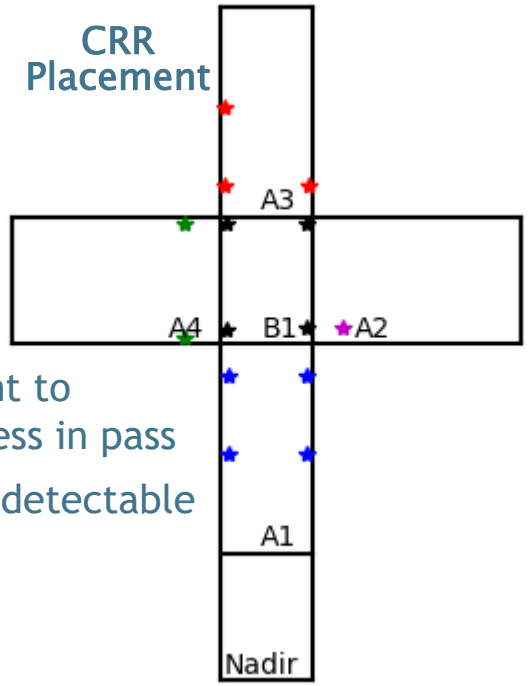
- Placement of „backup“ CCRs on side faces
- Select CCRs and design placement of CCRs for better detectability and attitude determination

FIRST EXAMPLE: NOTABLE FINDINGS

Basic simulation parameters:

- Cuboid satellite, 1-4 LLRs on each side, no CCRs on nadir, Pass Technosat: el_max ~43°
- $T_{rot\_inertial}$ = 180 s, rotation axis = [1, 0, 0], through A1 and A3





Apparent rotation effect

- Satellite: more / less than one rotation to point to observer -> due to progress in pass
- Changed rotation period detectable from dataset (T = 180 s)
  - T_{app1} = 171 s
  - T_{app2} = 159 s
  - T_{app3} = 142 s (greater deviation with higher EL)
  - T_{app4} = 164 s

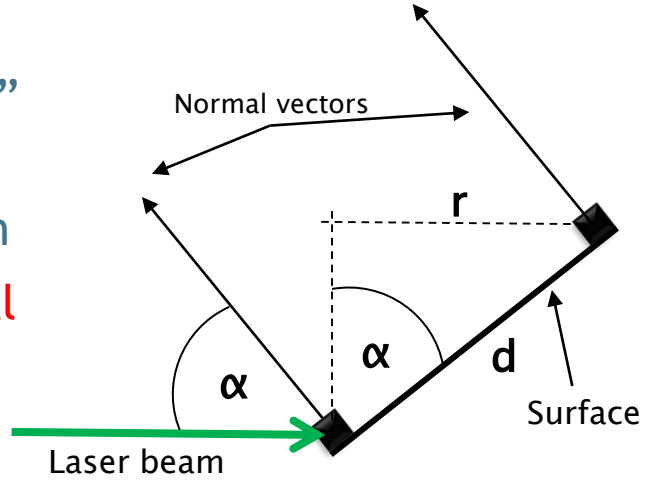
Obs2rot angle:

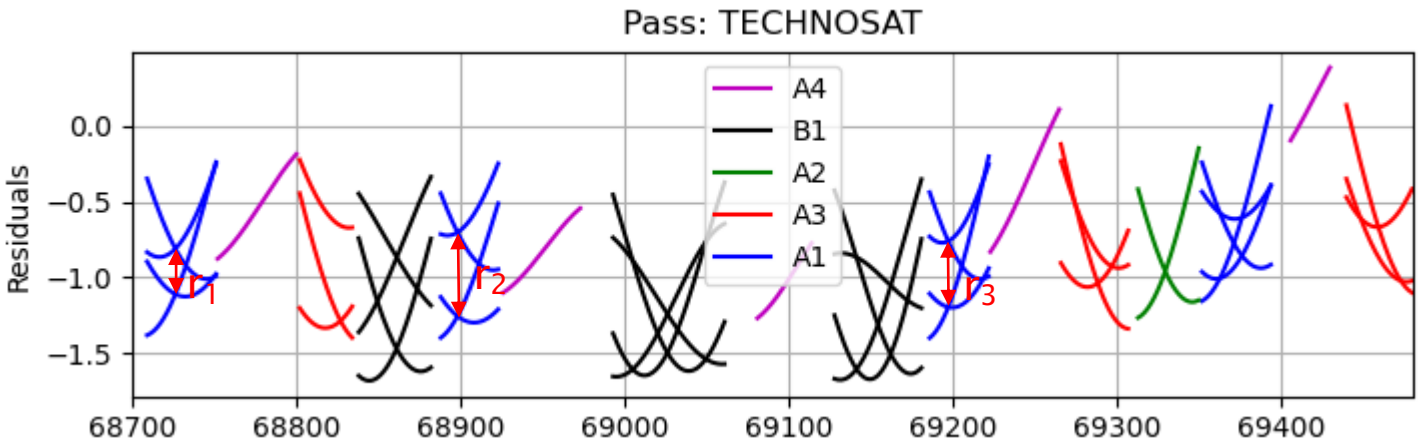
- Describes the angle between observation vector and rotation axis

FIRST EXAMPLE: NOTABLE FINDINGS

Calculation of incidence angle:

- Angle in which laser beam "hits" the surface
- CCR positioning has to be known
- Calculation with central residual distance of intersection of two crossing CCR residuals





Calculation (simple trigonometry):

$$\alpha = \arcsin\left(\frac{r}{d}\right)$$

α … incident angle

r … central residual distance

d … side length of the square created by the CCRs (e.g.: 1 m)

Example with r1, r2 and r3:

$$\boldsymbol{r} = [0.30, 0.55, 0.43]\ m$$

Results:

$$\boldsymbol{\alpha} = [17.46, 33.37, 25.48]\ deg$$

Note: max α would be the FOV of the CRR

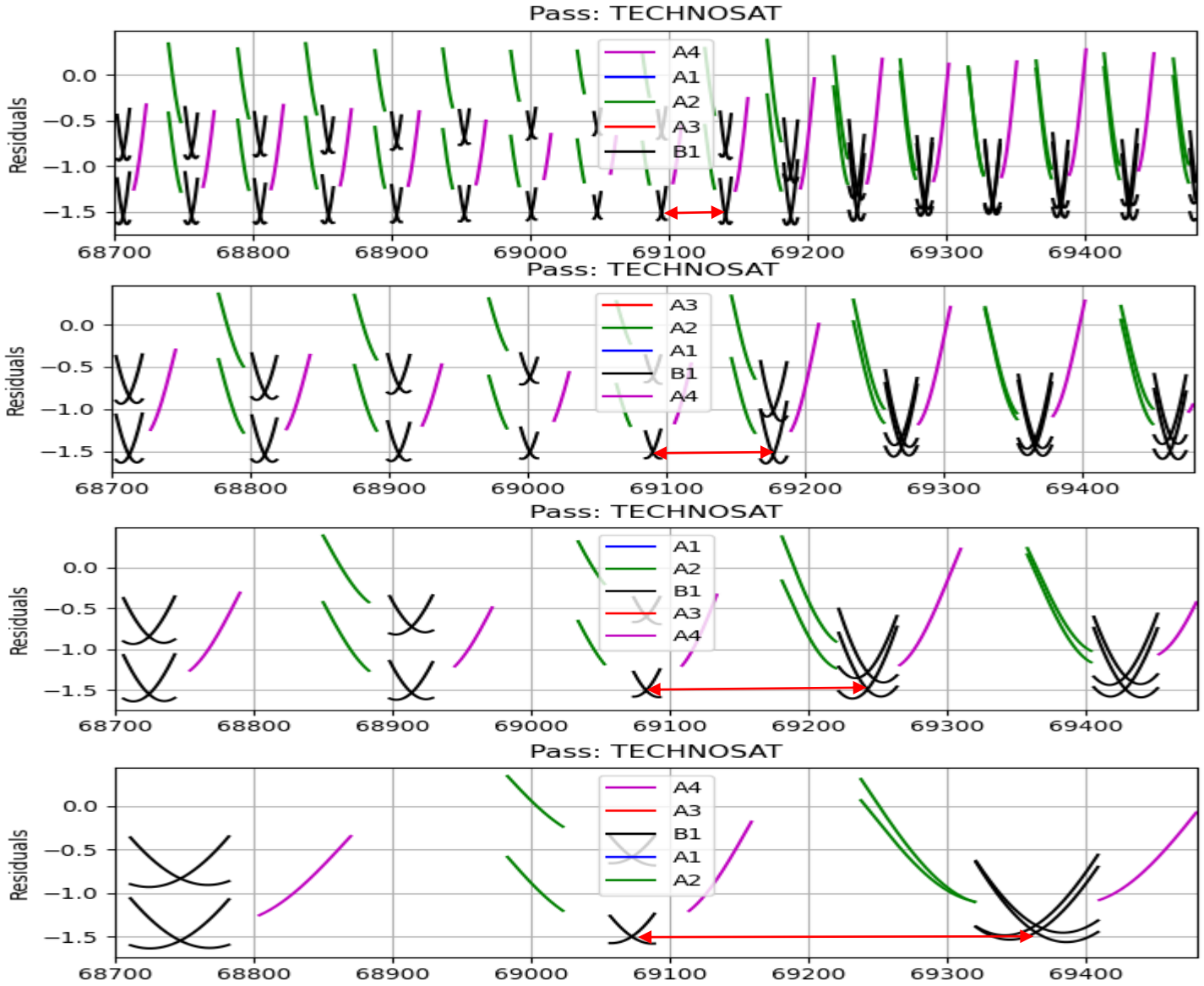
ROTATION PERIOD VARIATION

Rotation period variation

- axis = [1,0,0] (same as before)
- T = 50 s, 100 s, 200 s, 400s
- Stretching pattern, influence on apparent period

Rotation period	Measured apparent period	Deviation in %
50 s	47 s	6 %
100 s	87 s	13 %
200 s	159 s	20.5 %
400 s	292 s	27 %

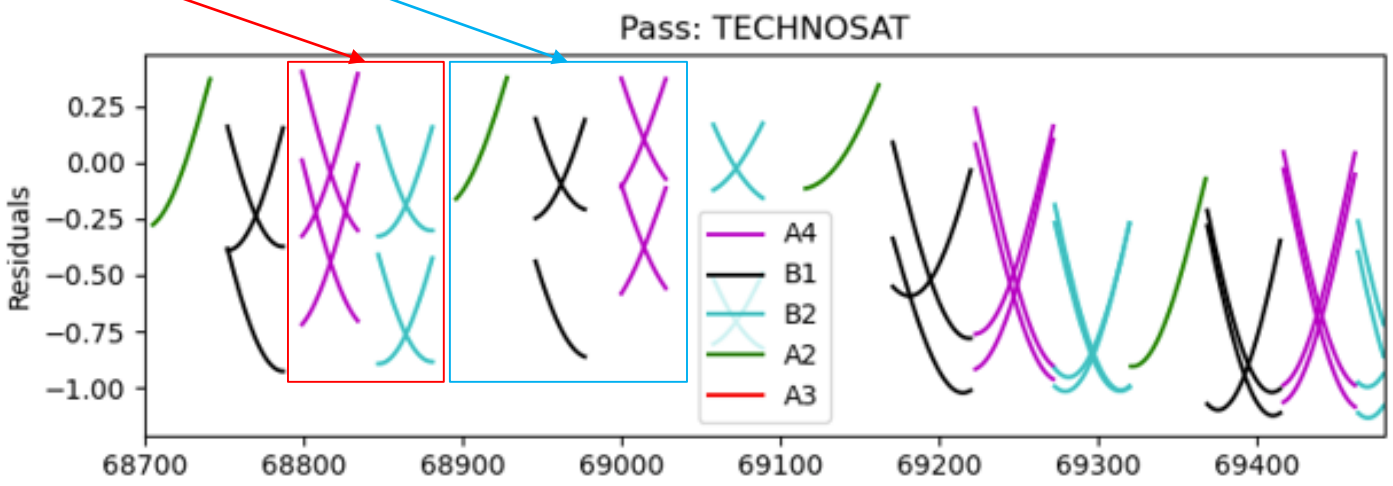
Conclusion: The higher the rotation period the higher the deviation

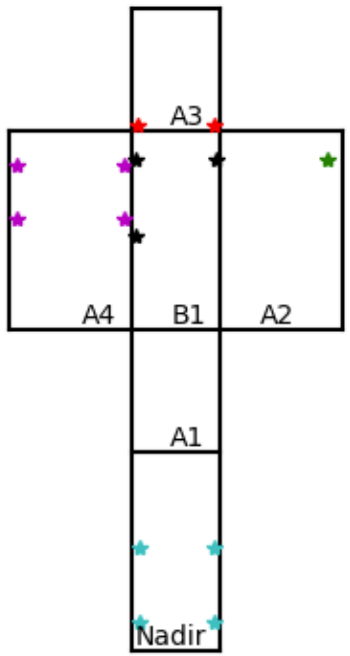


DISTINGUISH SURFACES

Distinguishability of surfaces

- Case A: Easy if any number of CCRs can be chosen -> number of tracks in SLR residuals
- Case B: Equal number of CCRs can lead to similar pattern: A4 (purple), Nadir (cyan)





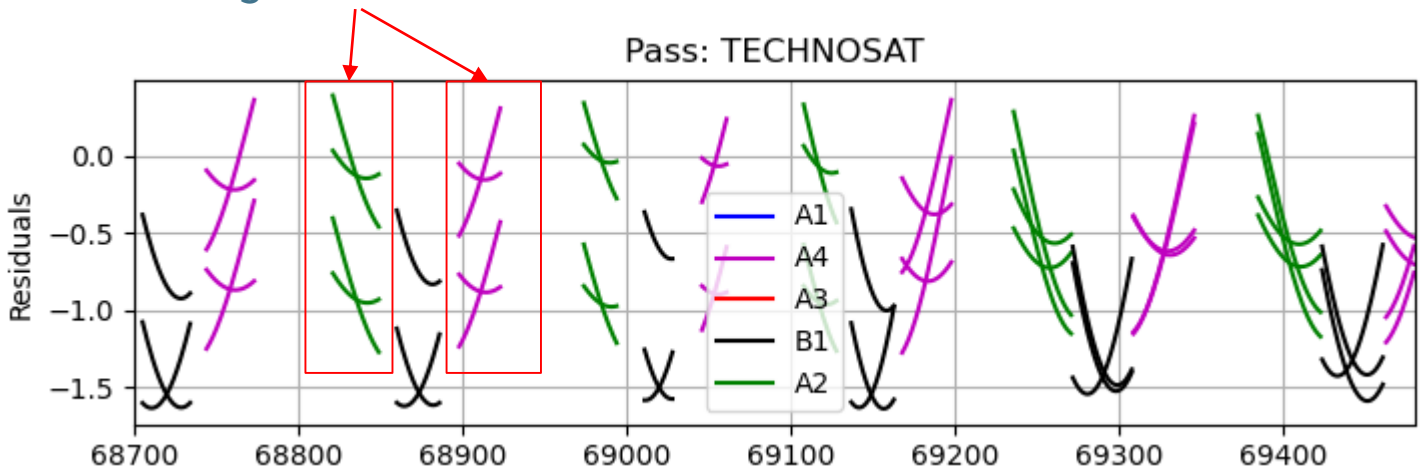
- With 1-4 CCR on ervery face two faces remains with same number of CRR

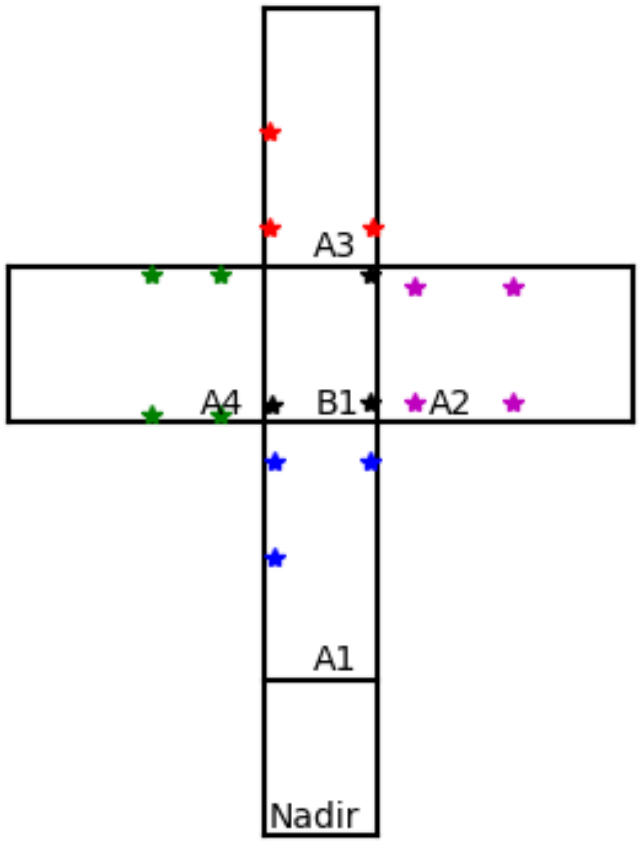
Problem: At least three corner cube reflectors per face, would facilitate a possible attitude reconstruction.

3-4 CRR PER FACE

Problems:

- Indication of rotation direction
- Assignment of residuals to faces



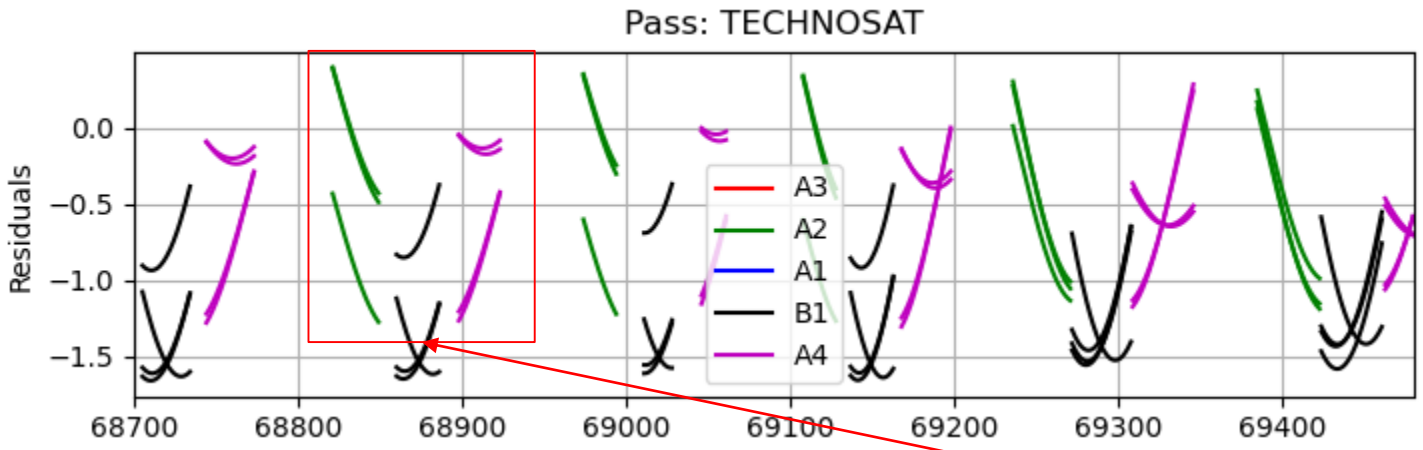


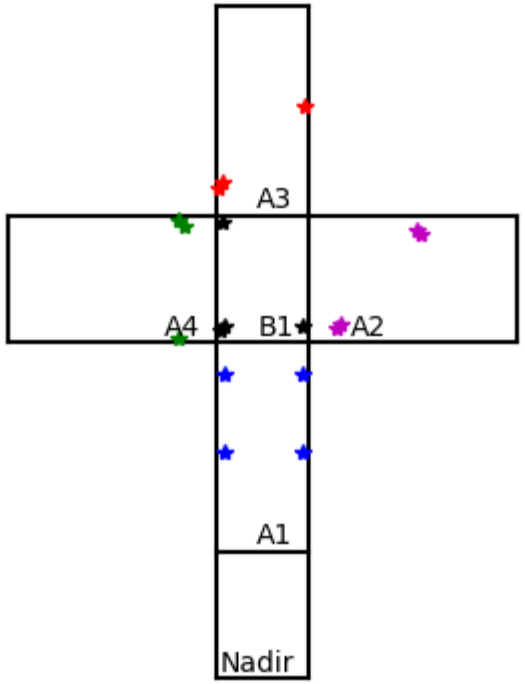
- A2 and A4 have a similar pattern as well as A1, A3 and B1
- Possible solution: Place two CCR close together

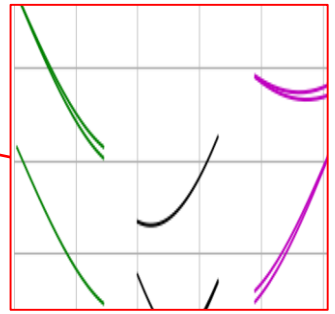
DISTINGUISHABILITY: EQUAL NUMBER OF CCRS

Distinguishability: patterns with equal number of CCRs

- Group e.g. two CCRs together (in the example distance 8.5 cm)
- Maximal residual distance: 6 cm (with FOV = 45 deg)



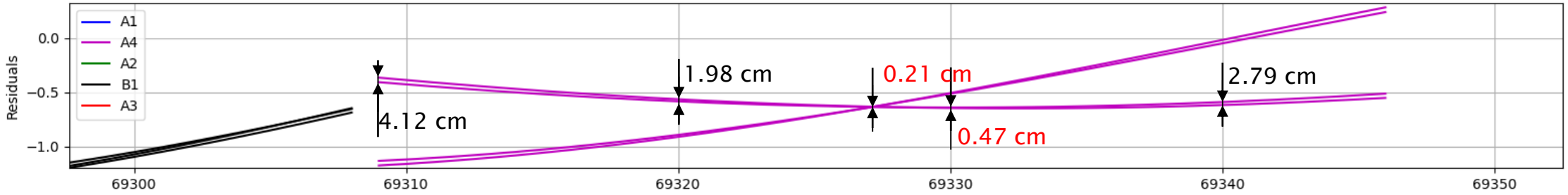




- Now, the two faces can be clearly distinguished
- Important: Other CRR not too close!

PAIR OF 2 CCR: CAN THEY ALWAYS BE DISTINGUISHED?

- Accuracy of SLR measurements between 0.3 cm and 1.0 cm
- → Residual distance > than accuracy



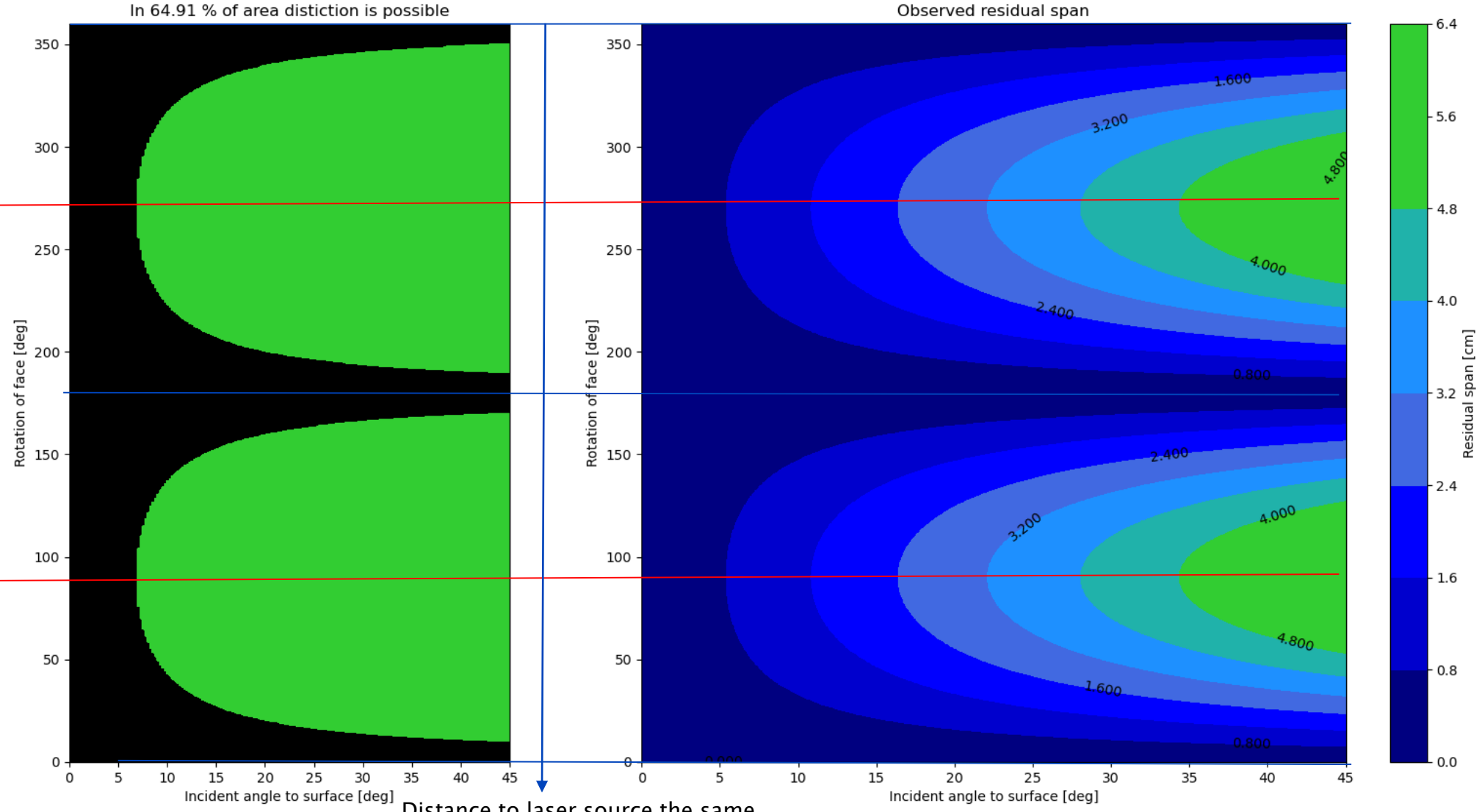
- Answer: No it is not always possible
- But: It is only necessary once per revolution to assign the residual to a face

- Remember: Pair of CCRs are mounted a distance of 8.5 cm

PROBABILITY OF A PAIR TO BE DISTINCT

Criteria: residual distance > 10 mm

Both CRRs are "behind" each other



Distance to laser source the same for every CRR

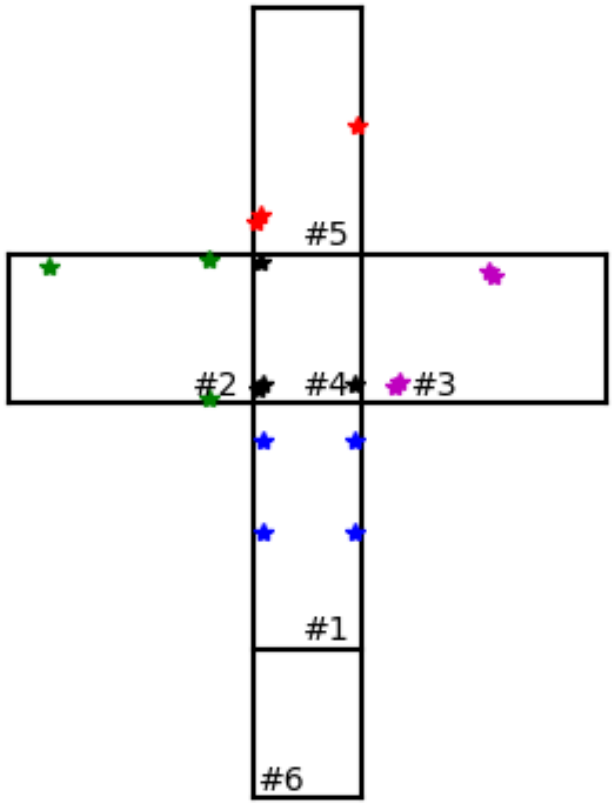
HOW MANY CCRS ARE NEEDED?

For a unique pattern at least 18 CCRs are needed

Assuming:

- At least three CCRs per face
- One face with no CCRs

Face	Single CCR	Pair of two CCRs	Total number of CCR per face
#1	4	0	4
#2	3	0	3
#3	0	2	4
#4	2	1	4
#5	1	1	3
#6	0	0	0
Total	10	4	18



OUTLOOK / SUMMARY

Summary / outlook

- Tool to simulate SLR residuals
- Modular setup, simple to iterate through different setups
- Verified with measured SLR residuals to different satellites

Potential applications

- Test various CCR setups in different rotation conditions
- Validate different attitude determination techniques on simulated data
- Data cleaning for outlier identification (leading edge, pattern recognition)

Acknowledgement

The work has been conducted within the framework of the ESA project „Reflector-based attitude detection system“

!!! THANK YOU !!!


SLR station Graz
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Alcantara
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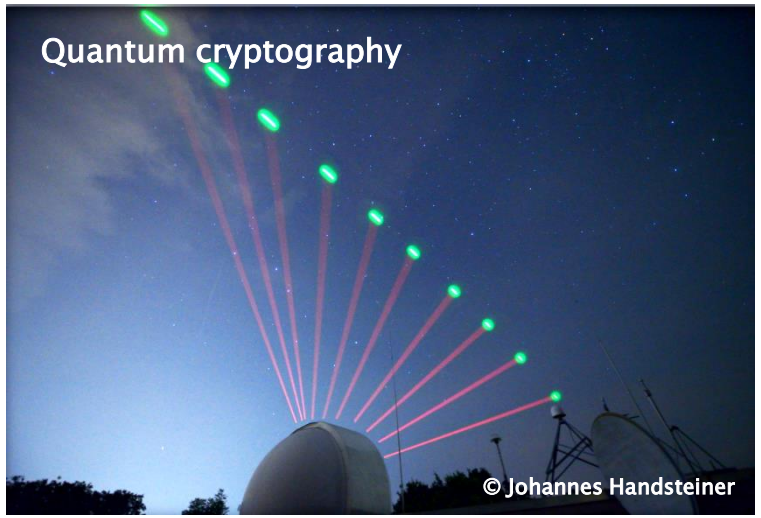
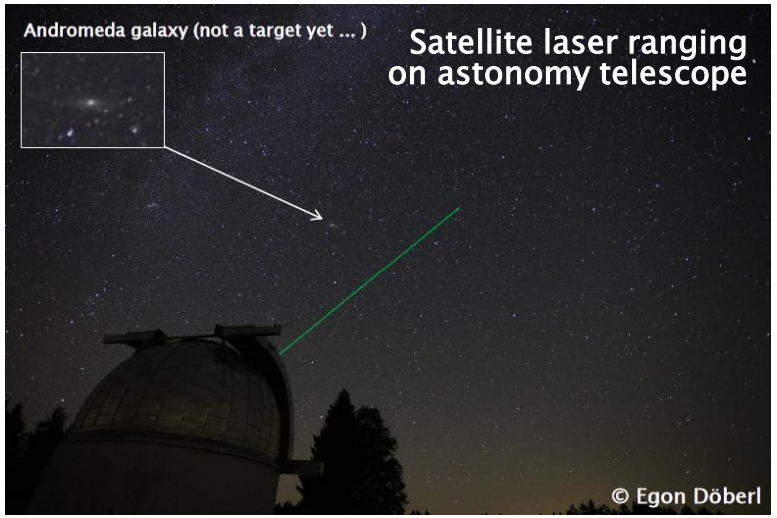

Quantum cryptography
© Johannes Handsteiner


Andromeda galaxy (not a target yet ...)
Satellite laser ranging
on astonomy telescope
© Egon Döberl

CCR FIELD OF VIEW

CCR Field of view

- 40° / 50° / 60° -> overlap of residuals from different surfaces