Interoperability for satellite tracking aids: the Satellite Retroreflector Standards

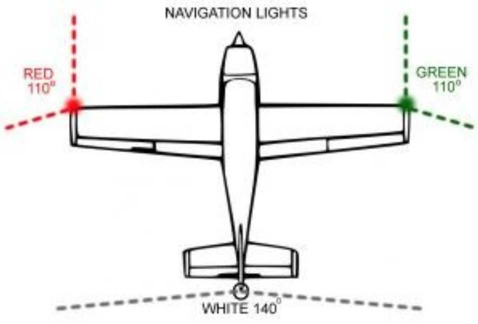
Standards for Dark & Quiet Skies - Lumi Space - CleanSpace Industry Days

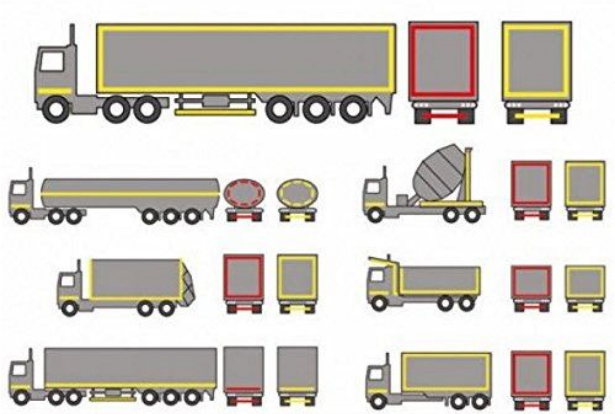
Hira Virdee, David Gooding, Ewan Schafer, Liam Pieters

09-10-2024

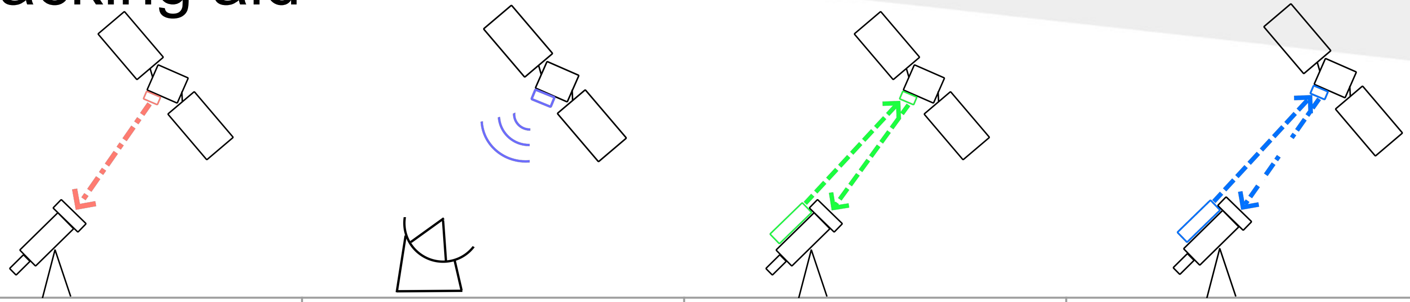
Why tracking aids?

Why standardise?





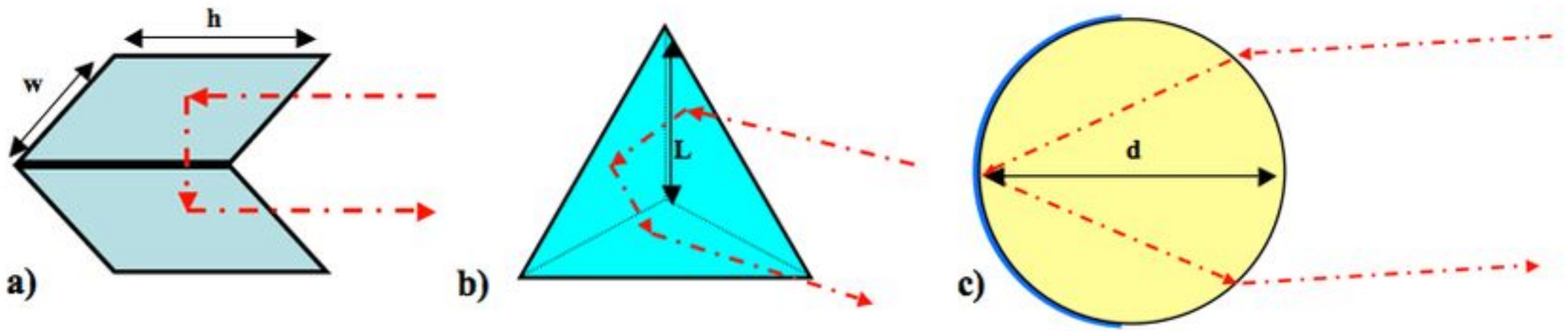
Types of tracking aid



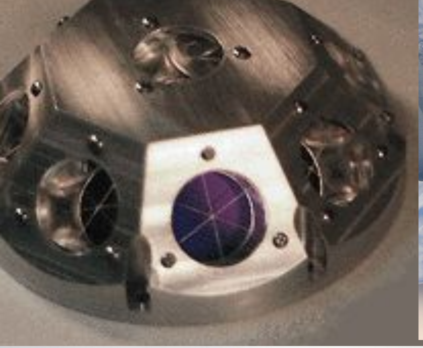
	LED beacon	Radio transmitter	Retroreflector	Modulated retroreflector
Integration + regulatory hurdle	Medium 😐	High 😟	Low 😊	Medium 😐
Accuracy	Low 😟	Medium/high 😊	High 😊	High 😊
Power need	Low/medium 😊	Medium 😐	Zero 😊	Low 😊
Resilience	Medium 😐	Low 😟	High 😊	Medium 😐
Dark/quiet skies	Poor 😟	Poor 😟	Good 😊	Good 😊

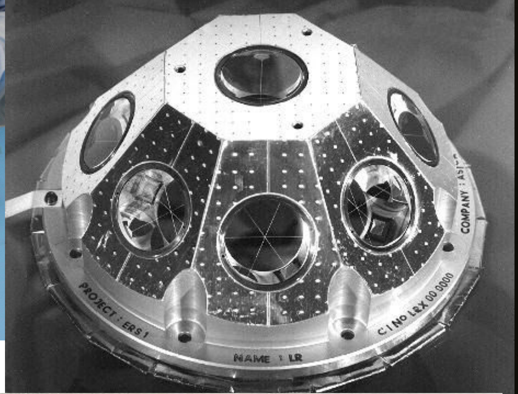
Lumi

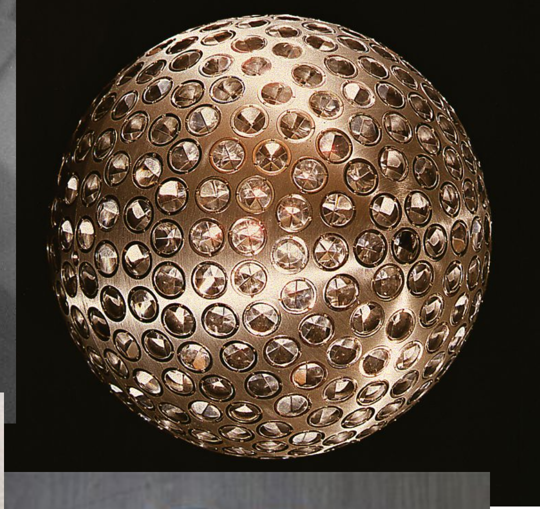
Retroreflectors

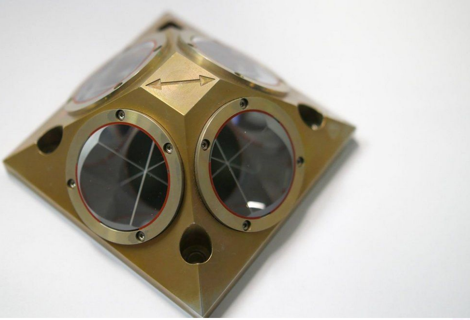


Williams, Gateman, Goyette and Giles, “Radar cross section measurements of frequency selective terahertz retroreflectors”

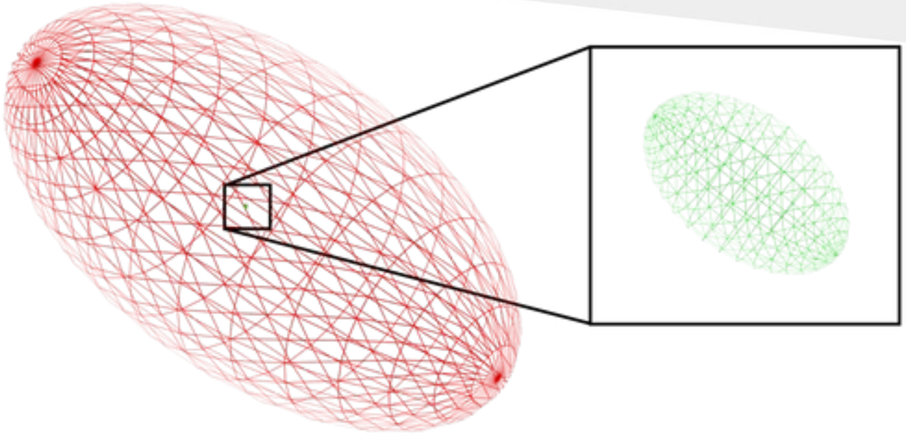


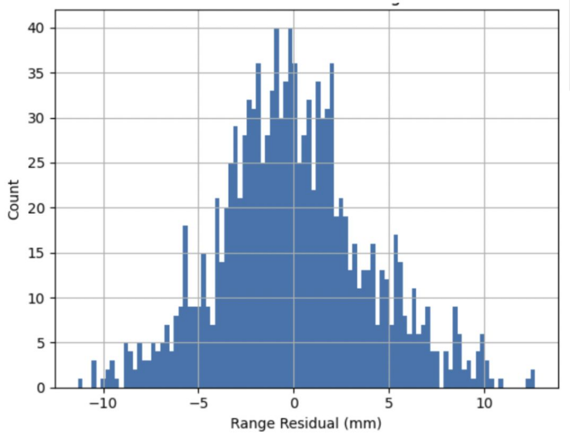




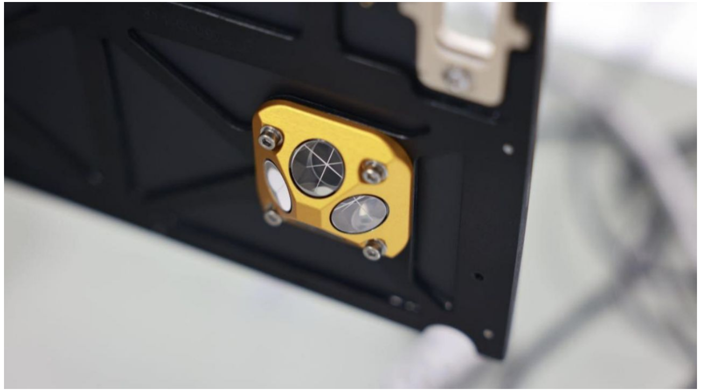


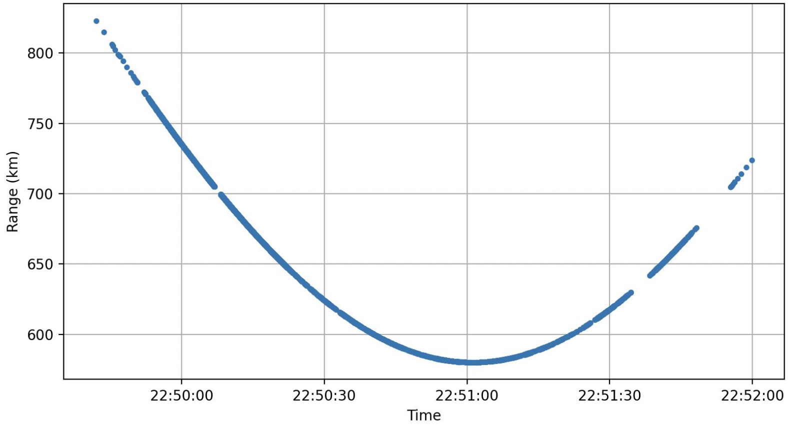
Lumi





Count
Range Residual (mm)
0
5
10
15
20
25
30
35
40
−10
−5
0
5
10





Range (km)
Time
600
650
700
750
800
22:50:00
22:50:30
22:51:00
22:51:30
22:52:00

Retroreflector standards and dependencies

Dependencies for standards:

- Space segment
  - Altitude/orbit
  - Placement
  - Corner cubes
    - Quantity
    - Size
    - Arrangement
    - Quality
    - Mass

Not dependencies:

- Bus size/mass
- Power availability
- Communications

Not for these standards

- Ground segment
  - Laser power
  - Pulse width
  - Wavelength
  - Location

Types that exist today

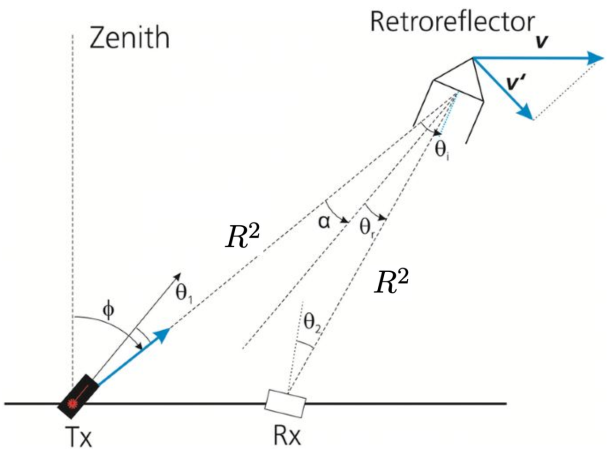
- Geodesy-grade:
    - mm-level accuracy
    - Minimise target signature effect
        - Coincident optical centres of the cubes
        - Spherically symmetrical satellites
        - Recessed / narrow acceptance angle
- SSA-grade:
    - cm-level
    - Increase detectability
    - Improve trackability
    - Increase
    - 10x cheaper
    - 5x lighter

Satellite Retroreflector Standards

Optimal cross-section by altitude

$$N_{pe} = N_t \cdot G_t \cdot \left(\frac{1}{4 \cdot \pi \cdot R^2}\right)^2 \cdot \sigma \cdot A_r \cdot \tau_r \cdot \tau_t \cdot \eta_q \cdot \tau_{filter} \cdot \tau_{atm}^2 \cdot \tau_c^2 .$$

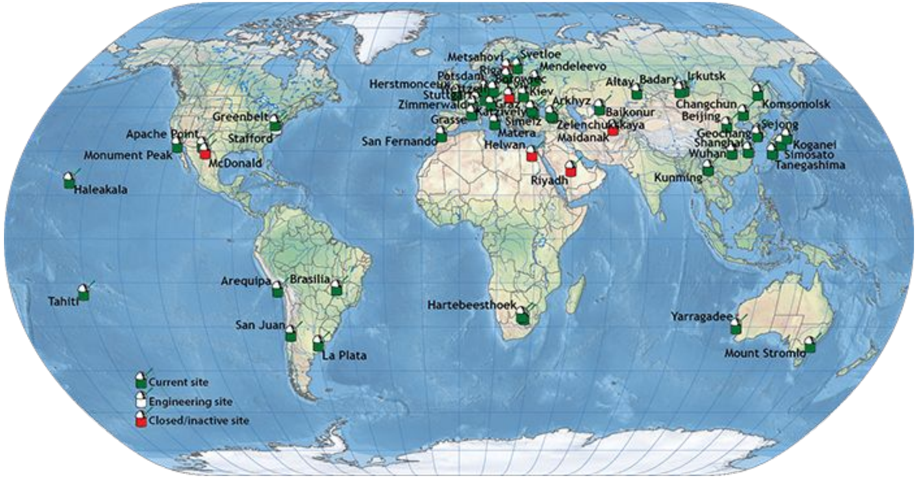
- Quartic dependence
  - R^2 on beam divergence out
  - R^2 on beam divergence back from satellite
- Retroreflector increases the “optical size” of the target
- Higher altitude -> Larger cross-section needed

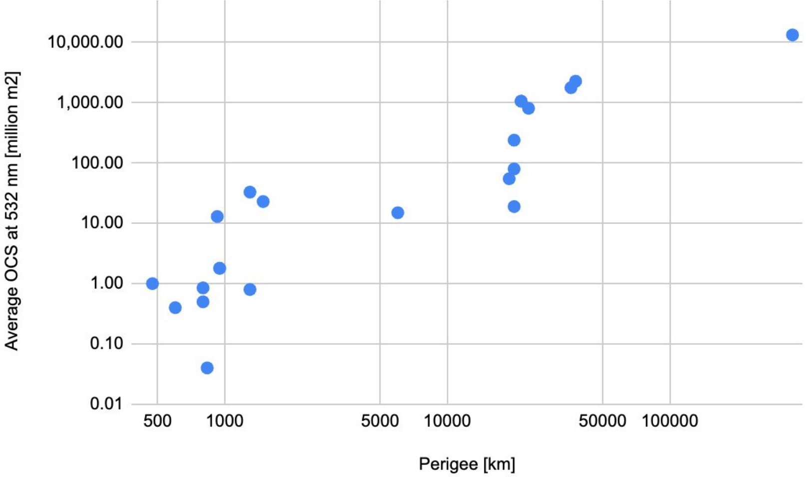


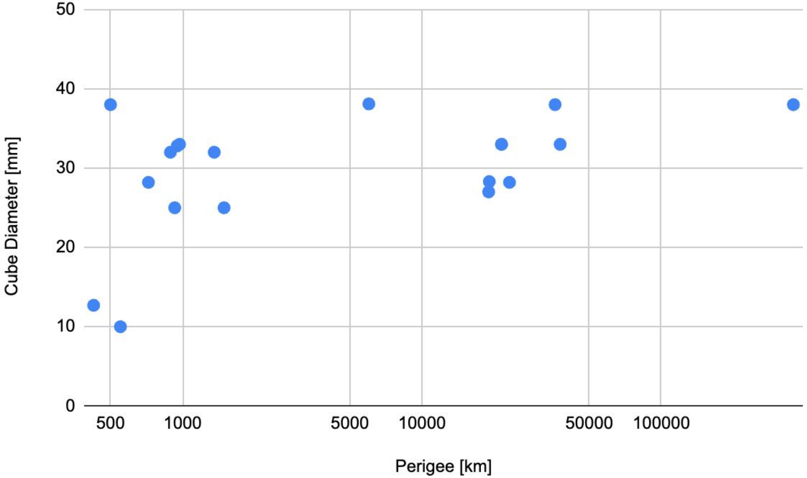
False positive alert

Covariance matrix with	
$20m \times 150m \times 30m$ at TCA	$10m \times 10m \times 10m$ at TCA
An action threshold of 10^{-4} would have to be applied to reduce the collision risk by $>$ 90%	For the same risk reduction of $>$ 90% an action threshold of 10^{-2} will be sufficient
This leads to about 2 annual manoeuvres per spacecraft on average	This leads to 0.025 annual manoeuvres per spacecraft on average
The false alert rate is at 99.9%	The false alert rate is at 10%

Setty, Flohrer & Krag,
SLR FOR SPACE DEBRIS MONITORING: AN ANALYSIS ON REQUIREMENTS AND ACHIEVABLE ORBIT IMPROVEMENT


Metsahovi
Svetloe
Mendeleevo
Herstmonceux
Potsdam
Riga
Borowiec
Kiev
Zimmerwald
Grasse
Katzively
Simeiz
Matera
Arkhyz
Zelenchukskaya
Maidanak
Baikonur
Altay
Badary
Irkutsk
Changchun
Beijing
Komsomolsk
Sejong
Geochang
Shanghai
Wuhan
Koganei
Simosato
Tanegashima
Kunming
San Fernando
Helwan
Riyadh
Greenbelt
Apache Point
Stafford
Monument Peak
McDonald
Haleakala
Tahiti
Arequipa
Brasilia
San Juan
La Plata
Hartebeesthoek
Yarragadee
Mount Stromlo
Current site
Engineering site
Closed/inactive site


Average OCS at 532 nm [million m2]
10,000.00
1,000.00
100.00
10.00
1.00
0.10
0.01
500
1000
5000
10000
50000
100000
Perigee [km]


Cube Diameter [mm]
50
40
30
20
10
0
500
1000
5000
10000
50000
100000
Perigee [km]

- Existing station compatibility / qualification
- Retros designed to have optical cross-sections far larger than necessary: Large, heavy & expensive.
- Few stations validate link performance
- Comprehensive ground-station performance validation by Tristan Meyer, at DLR Institute of Technical Physics in Stuttgart.
- Network-wide effort needed
- Critical for next-generation SLR stations

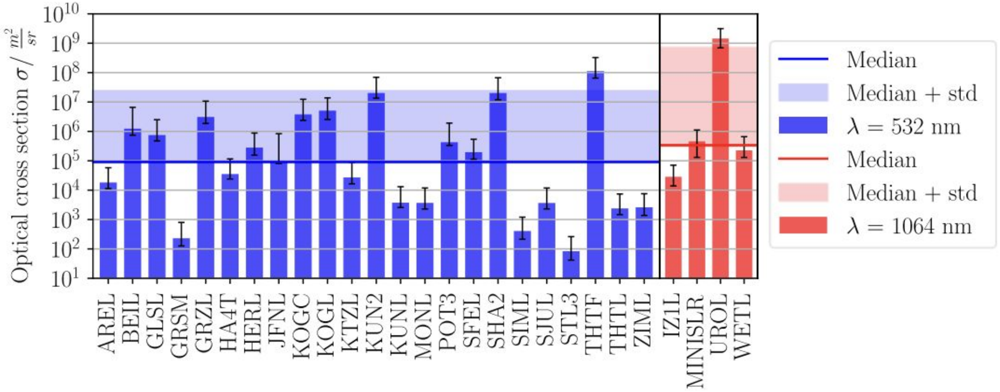
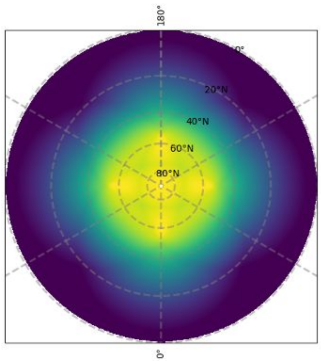


Figure from Meyer, Tristan, et al. "SLR link budget and retroreflector optical cross section evaluation." (2022).

Scoring

- Scoring outline (Issue 1):
  - Optical Cross Section
  - Far-Field Diffraction
  - Visibility / placement
  - Spectral Compatibility
- Attitude Determination and other applications:
  - Planned for issue 2
- Identification:
  - Planned for issue 3



Visibility score

- Total solid angle of acceptance where the OCS above threshold
  - Does the spacecraft operate in a fixed attitude mode?
  - Fraction of earth disk visible to the CCR
- Shouldn’t only consider operational attitude - End of Life
- Lumi policy:
  - We do not track missions with a visibility score < 0.25
  - Or it’s going to cost more due to incompatible passes

Velocity Aberration

The returning beam is dragged in the direction of relative velocity by a small angle.

$$\alpha \approx 2\ v/c$$

Depends on the component of the relative velocity tangential to the line-of-sight.

E.g. for circular orbits: greatest at zenith, lowest at the horizon.

Most significant in LEO where orbital velocities are highest.

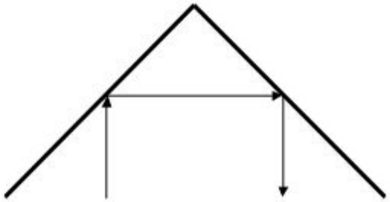


Figure 1a. Ray entering the left half.

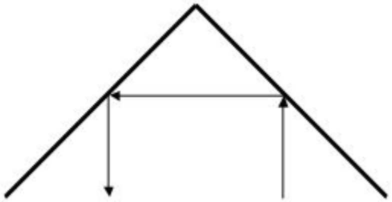


Figure 1b. Ray entering the right half.

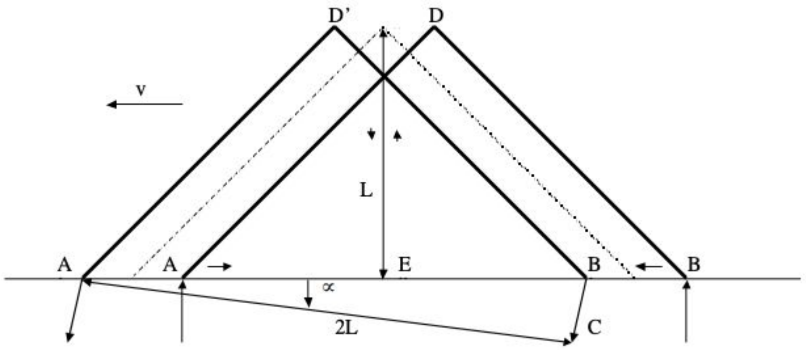


Figure 4. Moving retroreflector

Figures from David A. Arnold "Velocity Aberration"

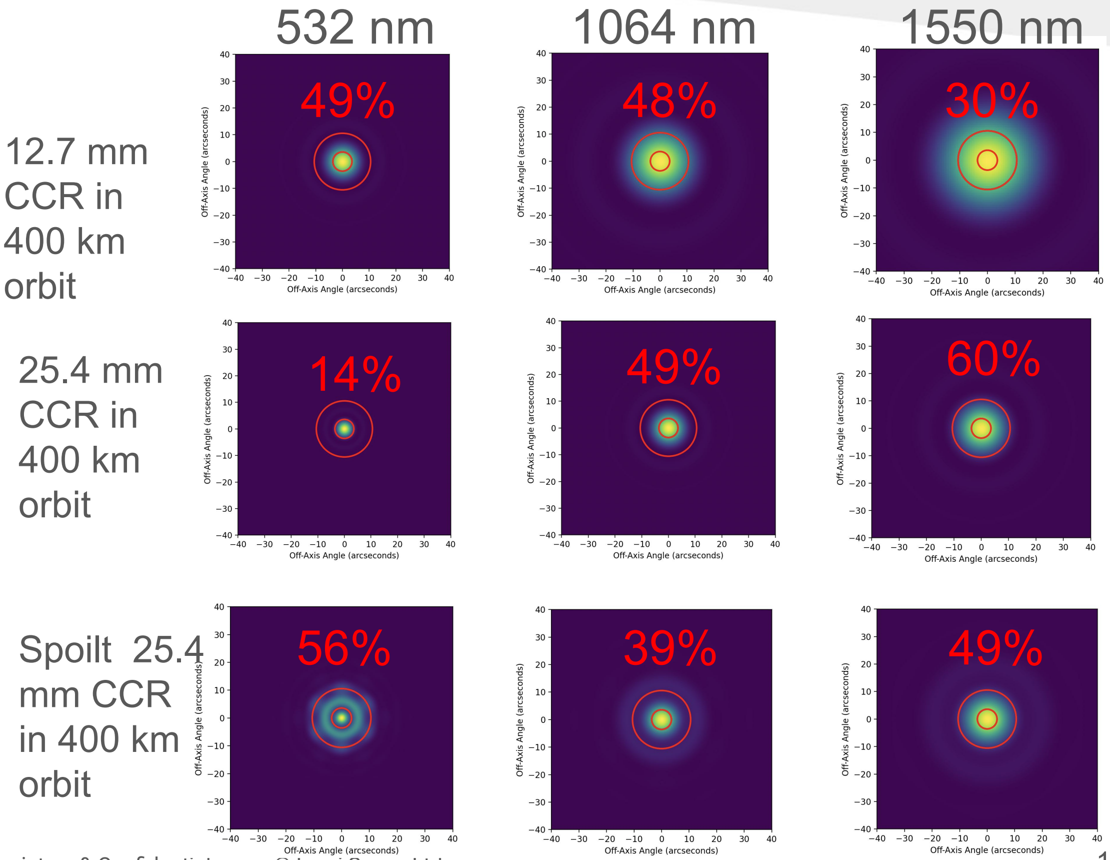
FFDP Score:

Min / max velocity aberration defines an annulus of possible observation geometries

Assign a score based on the fraction of the energy in the diffraction pattern that falls in this annulus.

Encourages use of smaller diameter cubes at lower altitude.

Spoiling large diameter cubes is a good strategy if the ranging wavelength is known, but can adversely affect stations that are not in the designed wavelength range.



Spectral Compatibility Score

Some LLRs use anti-reflection coatings e.g. Galileo-2XX

For the sake of improving the performance by a few % in the design wavelength, you make it much worse in others.

Discourage use of front-side AR coatings.

Conclusion

- Tracking aids are needed
- Retroreflectors are easiest
- Standards are important
- Reach out!

- hira@lumi.space

Lumi