Satellite illumination for pointing and auto-tracking at Grasse station - France (ID7845)

D-H. Phung (1), J. Chabé (1), C. Courde (1), N. Maurice (1), H. Mariey (1), J. Scariot (1), N. Raymond (1), G. Martinot de Lagarde (1)

(1) Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Géoazur, 2130 Route de l'Observatoire 06460 CAUSSOLS, France

22nd ILRS Workshop. Nov.07-11.2022 Yebes, Spain

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Outline

1. Experiment purposes
2. Architecture of experiment
3. Filter & centroid detection
4. Preliminary results
5. Conclusion & Future works

Grasse station ILRS7845 - Sciences

- ❑ **Satellite Laser Ranging**
  (GNSS, Geodesy Satellites, Debris …)
- ❑ **Lunar Laser Ranging**
  (Moon Reflectors + LRO)
- ❑ **Time Transfer by Laser Link**
  (T2L2, Chomptt, **LRO**, **Hayabusa**…)
- ❑ **Satellite – OGS LaserCom**
  (SOTA, OPALS, **OSIRIS**, NorSatTD…)
- ❑ **QuantumCom demonstration**
- ❑ **Imaging / Astrometry**
  (Adaptive Optics, Intensity Interferometry)
- ❑ **T/F transfer by Fiber network**
  (**T-Refimeve** European fiber network)

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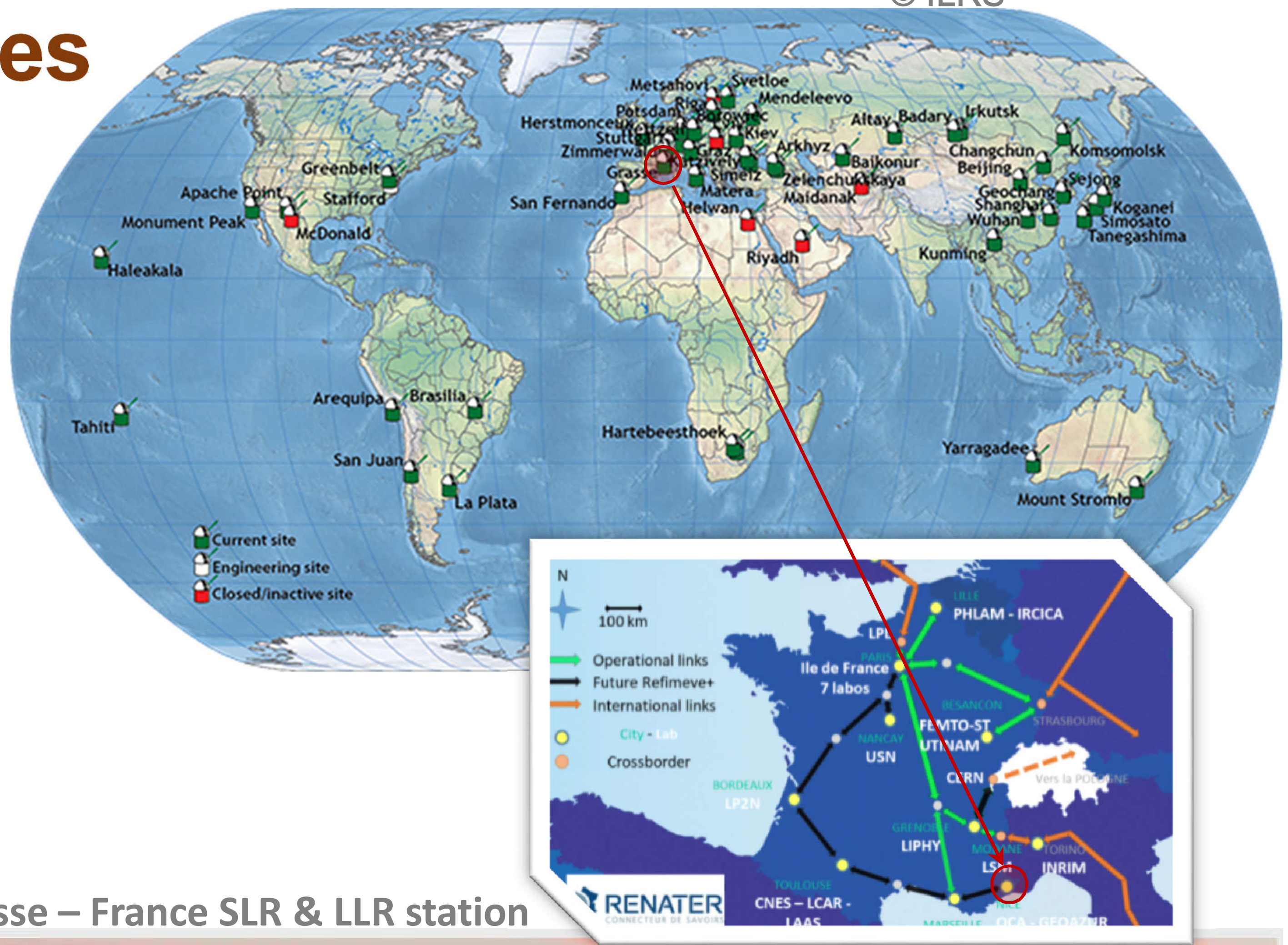


Grasse – France SLR & LLR station

1. Satellite illumination – Experiment purposes

- SLR Trends : High rate (up to 100 kHz – MHz), Two color technique

  ⇨ Smaller detector (25 – 80 µm APD or 50 µm SNSPD…)

- Grasse station – 1.5m F20 Telescope

  → Limited Field of View (FoV ~ 5 – 15 arcsec) on small-size detector

⇨ Needs: good pointing and fine-tracking of the telescope during satellite pass.

when satellite is not visible…
→ Difficulties to find the satellite
→ Large error pointing

⇨

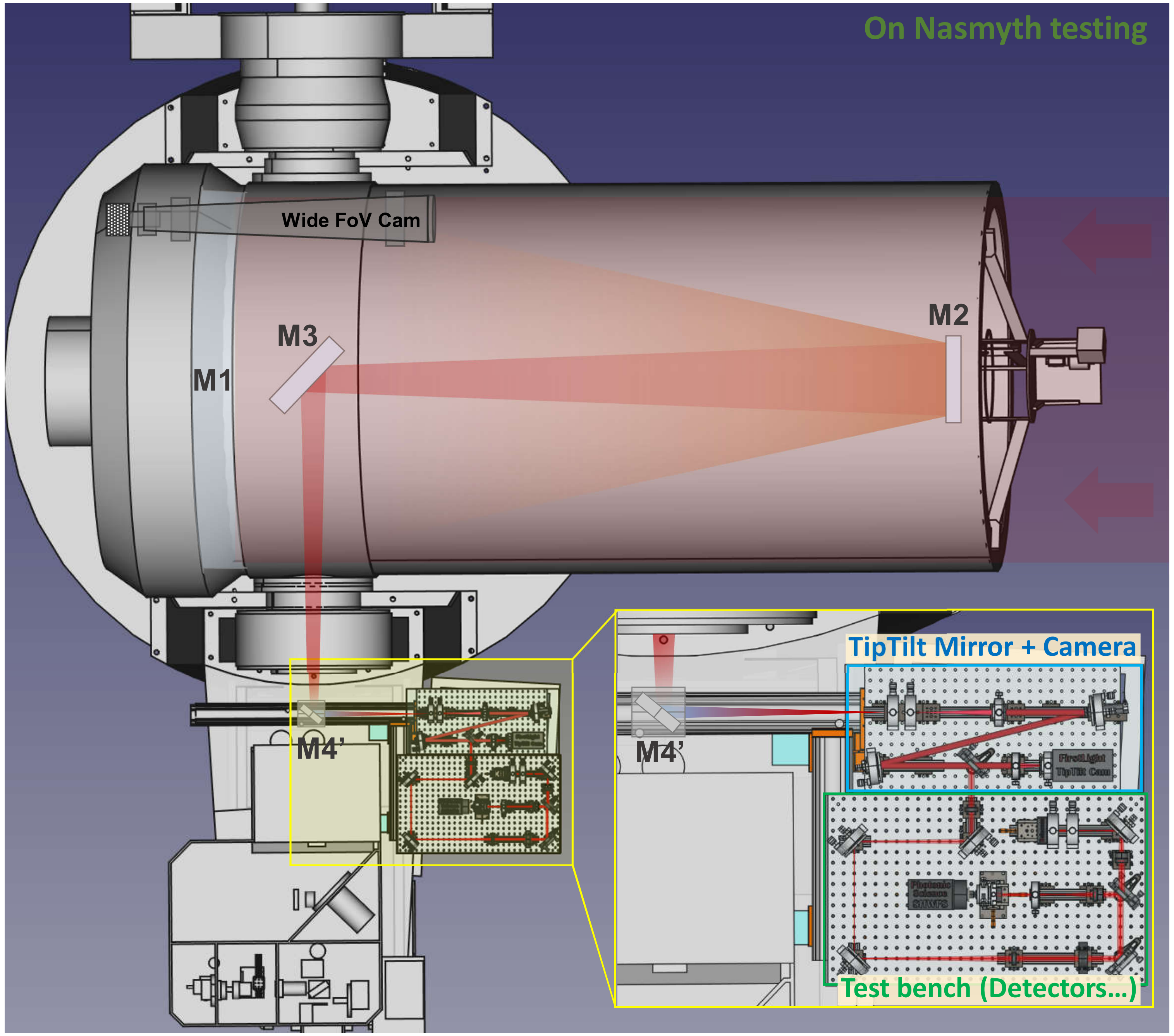
→ Discontinuities in the ranging data…
→ Errors in timing detection…
→ Difficult to activate 'autonomous operation'

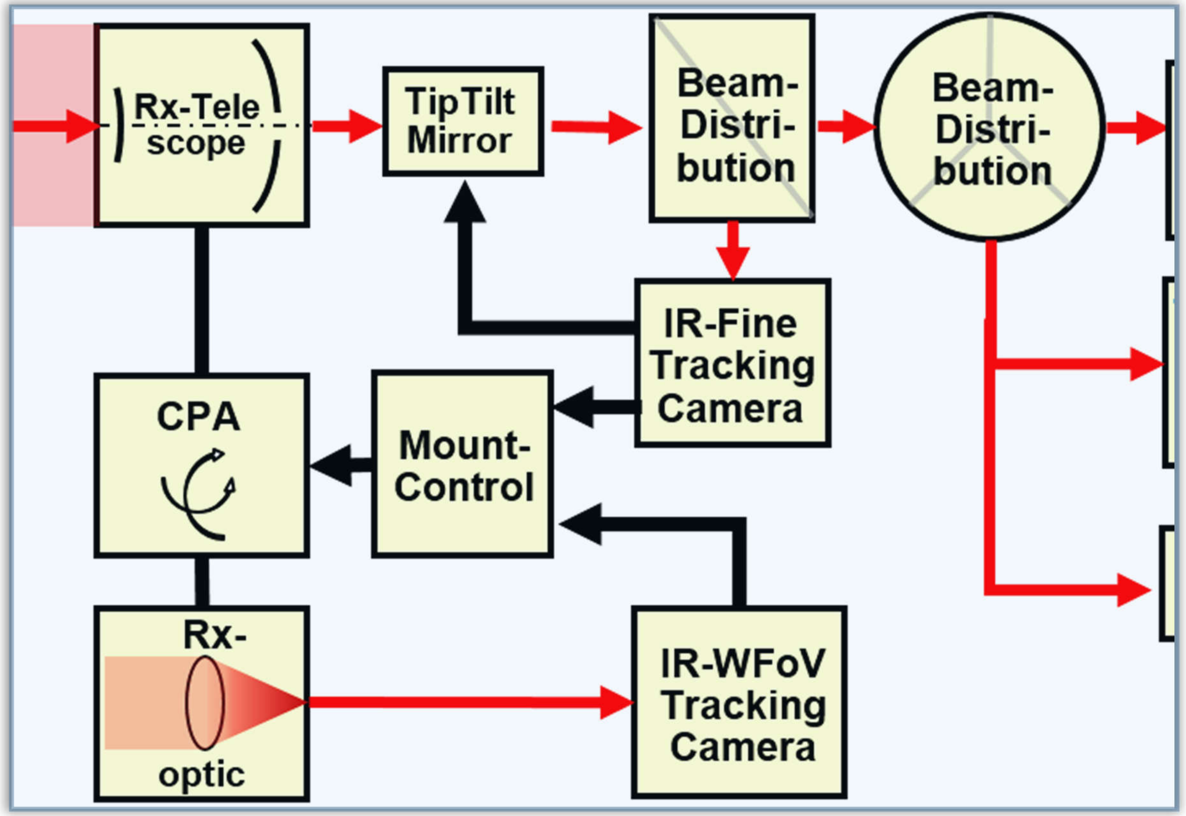
- Solution:

illuminate the satellite (by high-power laser) and using fine-tracking (TipTilt mirror) in order to maintain the returning signal from satellite in the center of detector.

2. Architecture of experiment – Fine-Tracking

Coarse-tracking (1.5m telescope controller) and Fine-tracking (TipTilt mirror + Camera)



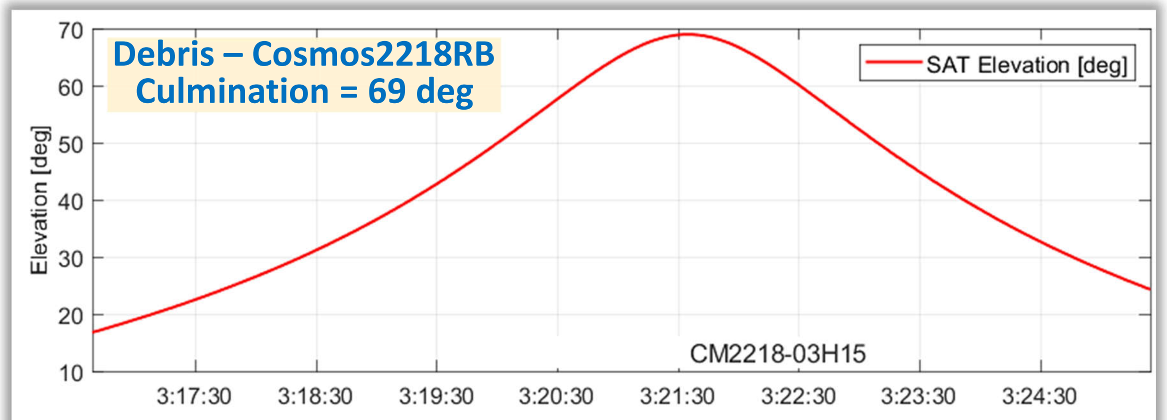


❑ Auto-tracking

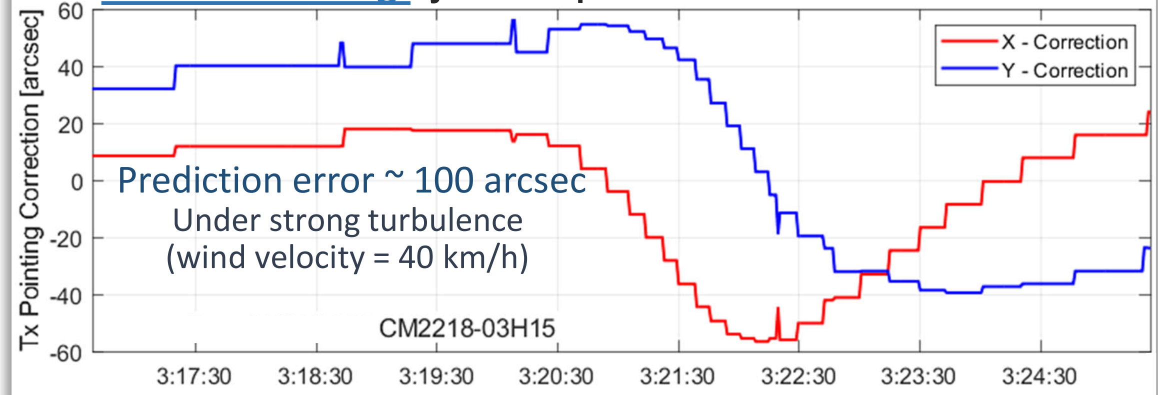
Fine-tracking discharges its correction by **Coarse-tracking** when the corrections approach the TipTilt saturation limit.

2. Architecture of experiment – Fine-Tracking

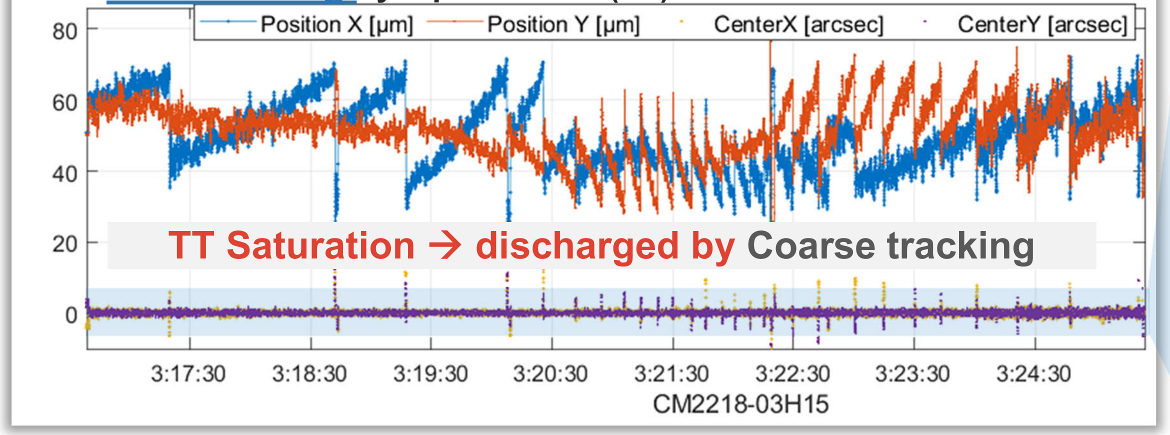
Coarse-tracking (1.5m telescope controller) and Fine-tracking (TipTilt mirror + Camera)

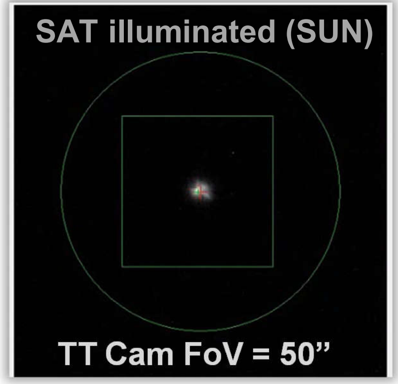


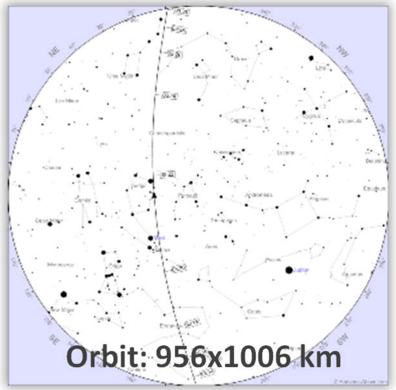
Coarse Tracking by Telescope controller 10 Hz

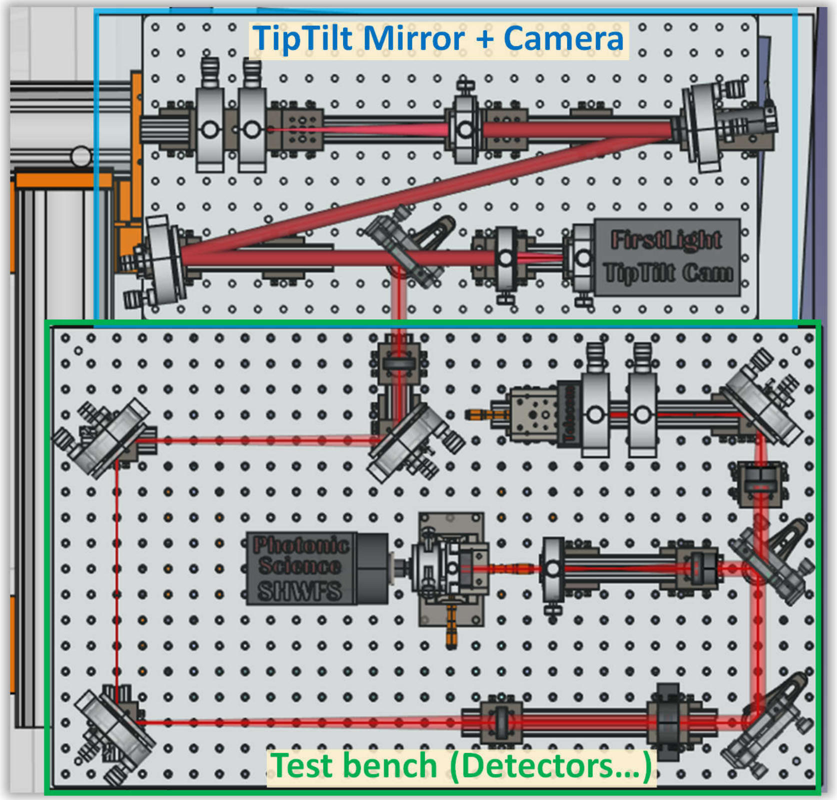


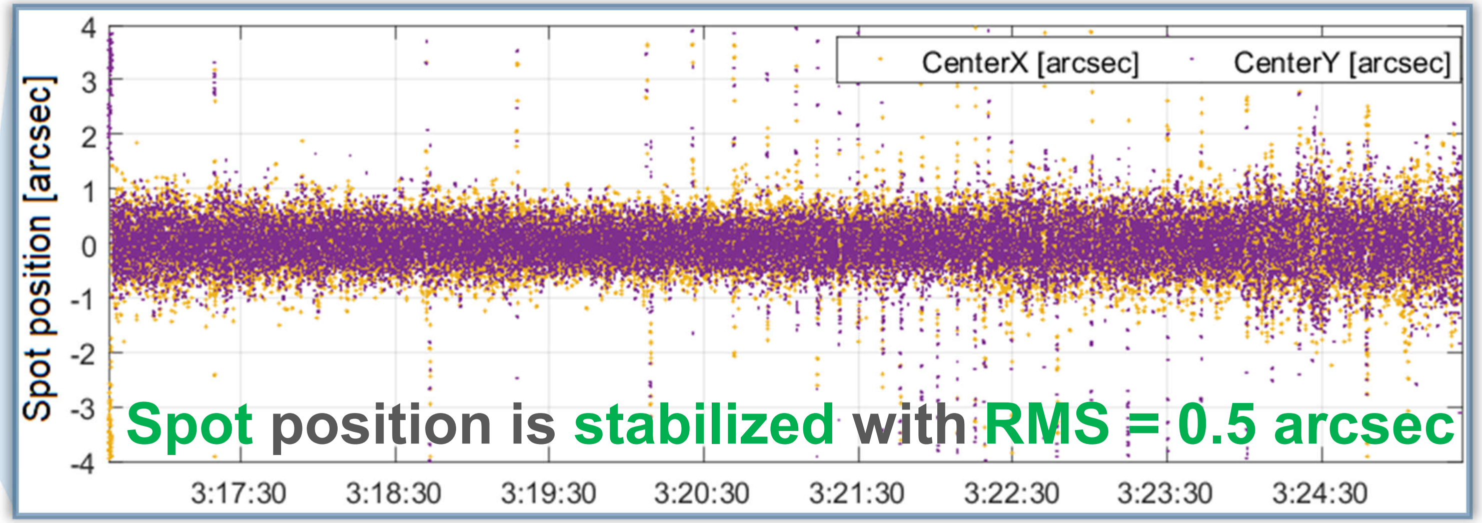
Fine tracking by TipTilt Mirror (TT) + Camera --- 10 – 400 Hz

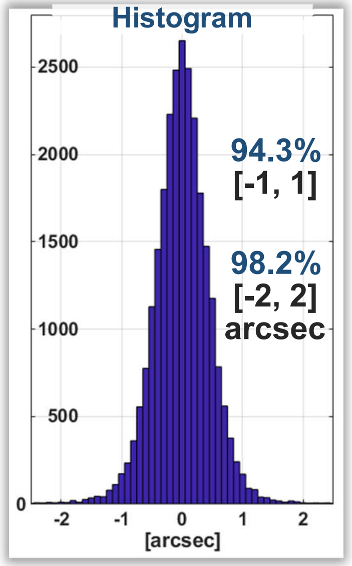






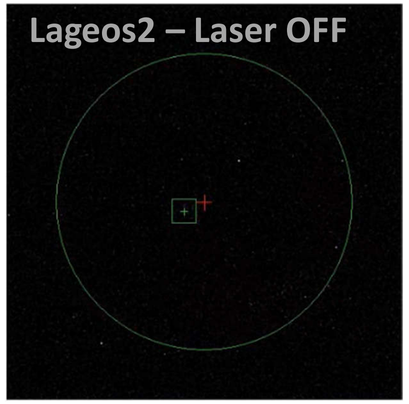


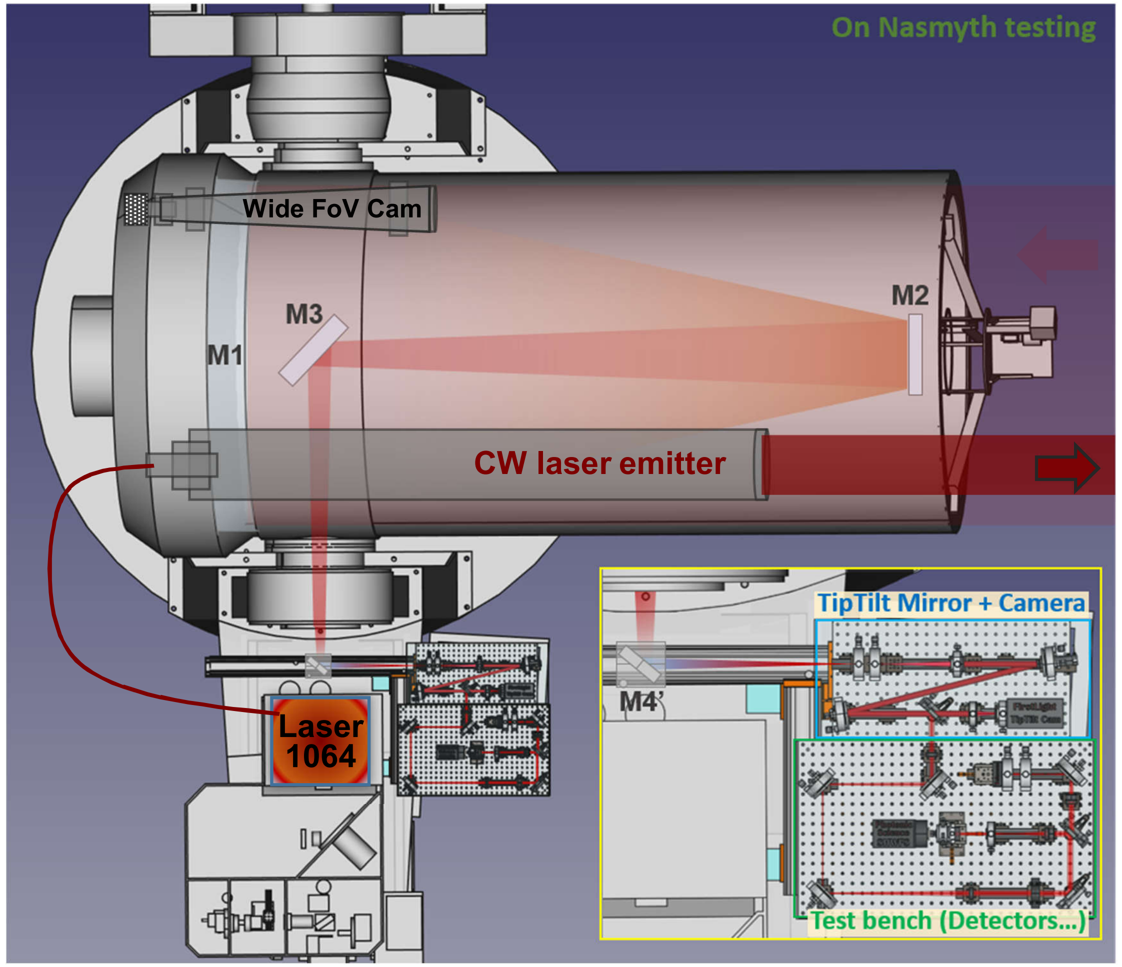




2. Architecture of experiment – Fine-Tracking

When satellite is not illuminated (by the SUN), we use a high-power (30W), continuous laser 1064 nm
Full Divergence = 100 – 200 µrad





High power cw laser (30W)

- 195 mm telescope
  - Aperture: 195 mm, F/9
  - Material: Carbon
  - Lens: Apochromatic
  - Limited Diffraction
- **1064 nm laser ML30-CW**
  - Power: 3 – 30 W
  - Output: Monomode fiber
  - FWHM: < 3 nm
  - Beam quality: M² < 1.1
- Tuning
  - Optical Power (Software)
  - Divergence (20 – 200 µrad)
  - Orientation (manual)

High-speed IR Camera

- FirstLight C-RED 2
  - Resolution: 640×512 pixel²
  - Pixel size: 15 µm
  - Quantization: 14 bits
  - Frame rate: 400 Hz
  - Noise: 30e- at 400 fps

TipTilt Mirror - Motorized

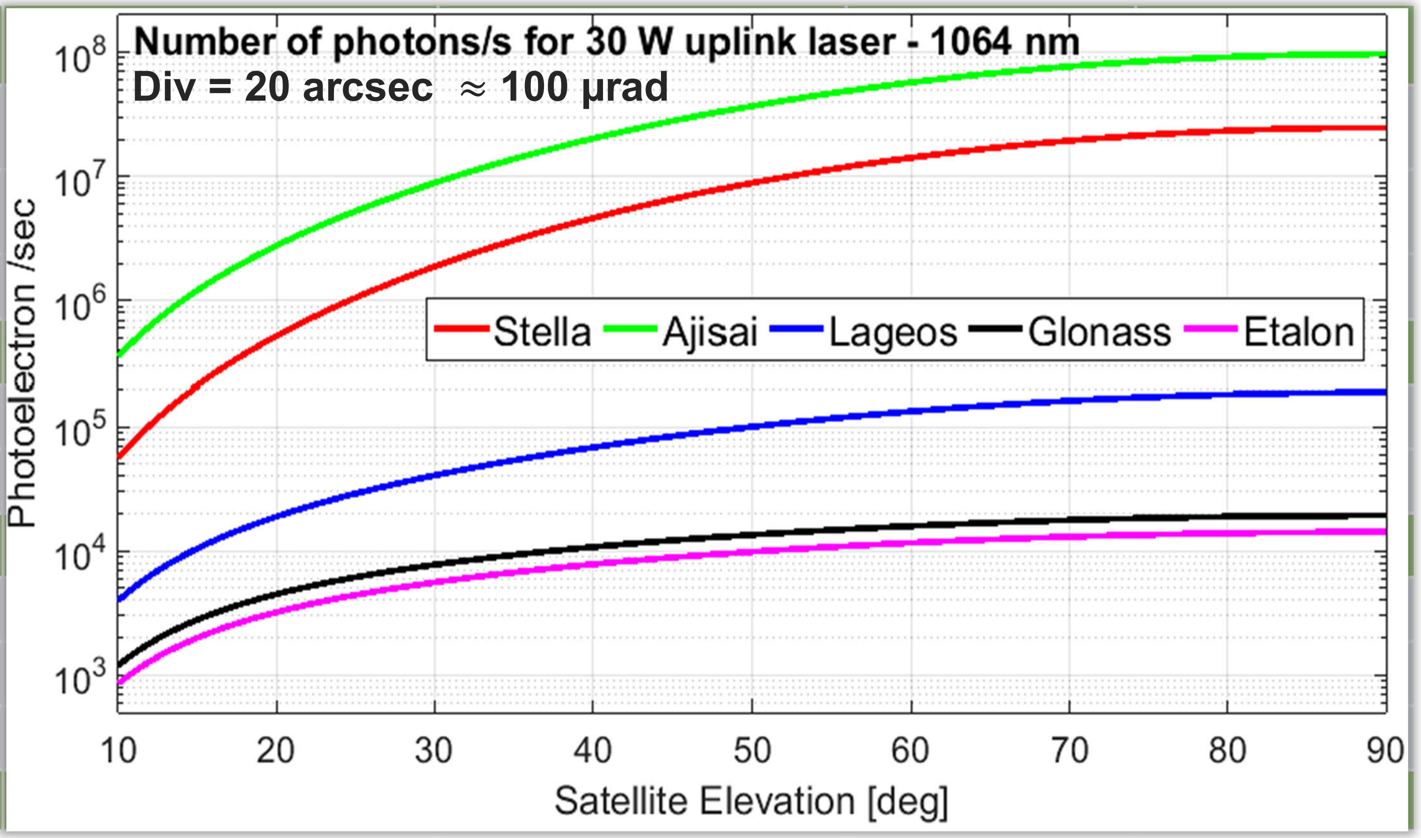
- PI S-330.8SL + E.505/E.509
  - Dynamic Range: 10 mrad
    → 50 arcsec Correction
  - Jitter: <0.2 µrad, 1.5 kHz
  - Mirror Diameter: 25 mm

2. Architecture of experiment – Link budget

Link budget -- high-power (30 W), continuous laser 1064 nm

$$n_{pe1s} = \eta_q . \left(P_0 \frac{\lambda}{hc}\right) . \eta_t . \frac{G_t}{4\pi R^2} . \frac{\varrho \sigma_0 k_\sigma}{4\pi R^2} . A_r . \eta_r . T_a^2 . T_c^2$$

Parameter	unit	Stella	Ajisai	Lageos	Etalon
P_0	$30\ W$				
η_q	0.75				
η_t	0.86				
G_t	$1/rad^2$				
σ_0	m^2				
ϱ	0.80				
k_σ	0.50				
R	km				
A_r	$1.68\ m^2$				
η_r	0.52				
T_a	0.78				
T_c	0.50				
n_{pe}	pe/sec	1.4×10^7	5.7×10^7	1.3×10^5	1.2×10^4



Spot size in the tracking cam: 5×5 pixels (0.32”/pixel)

Camera noise of 30e-/pixel, we need at least 100 pe/pixel in order to achieve a good spot movement measurement for auto tracking process.

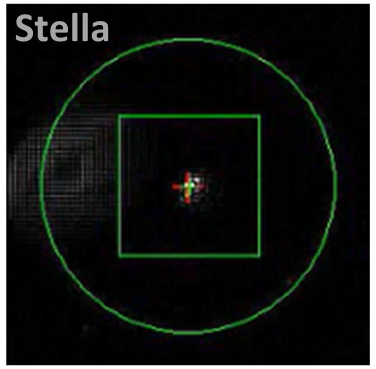
Lageos: 60 deg Elevation

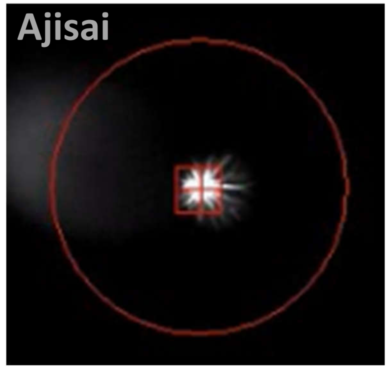
by TipTilt Mirror + Camera --- 10 – 400 Hz

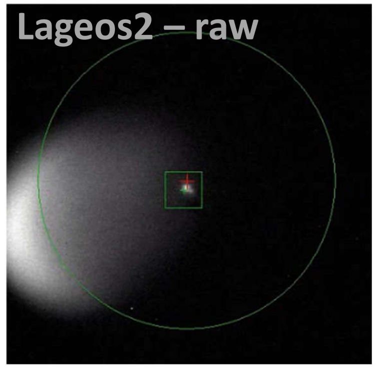
At 10 Hz, we expect to have: 400 pe/pixel → good SNR → activate fine-tracking

Link budget estimation OK

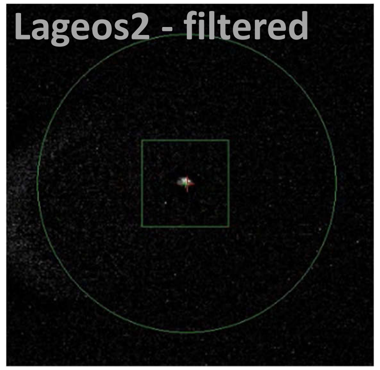
Laser 1064 nm - ON







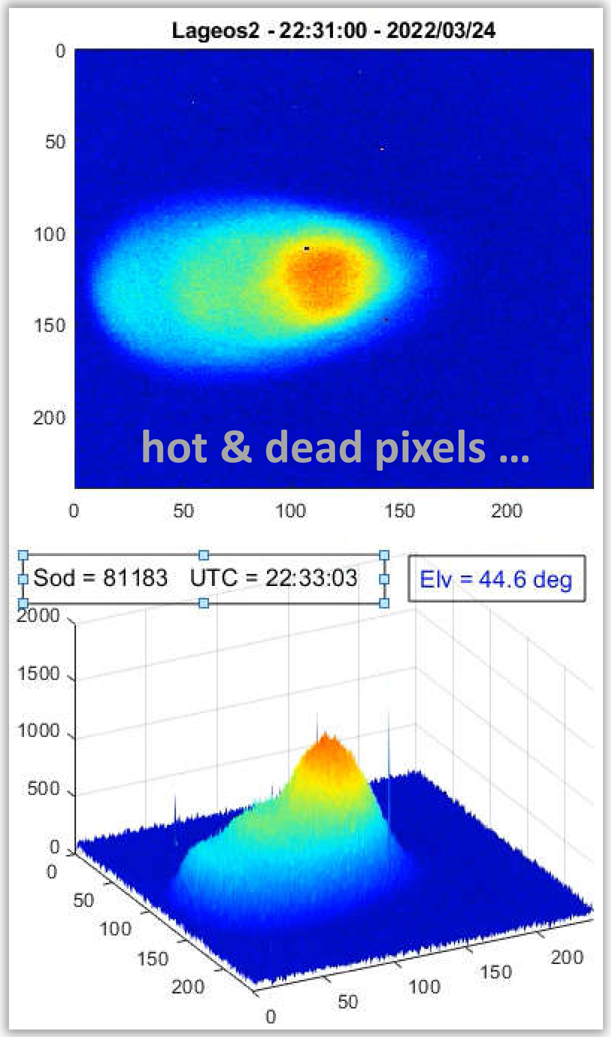
Lageos2
~400pe/pixel
Diffusion issue…
Image Filtering



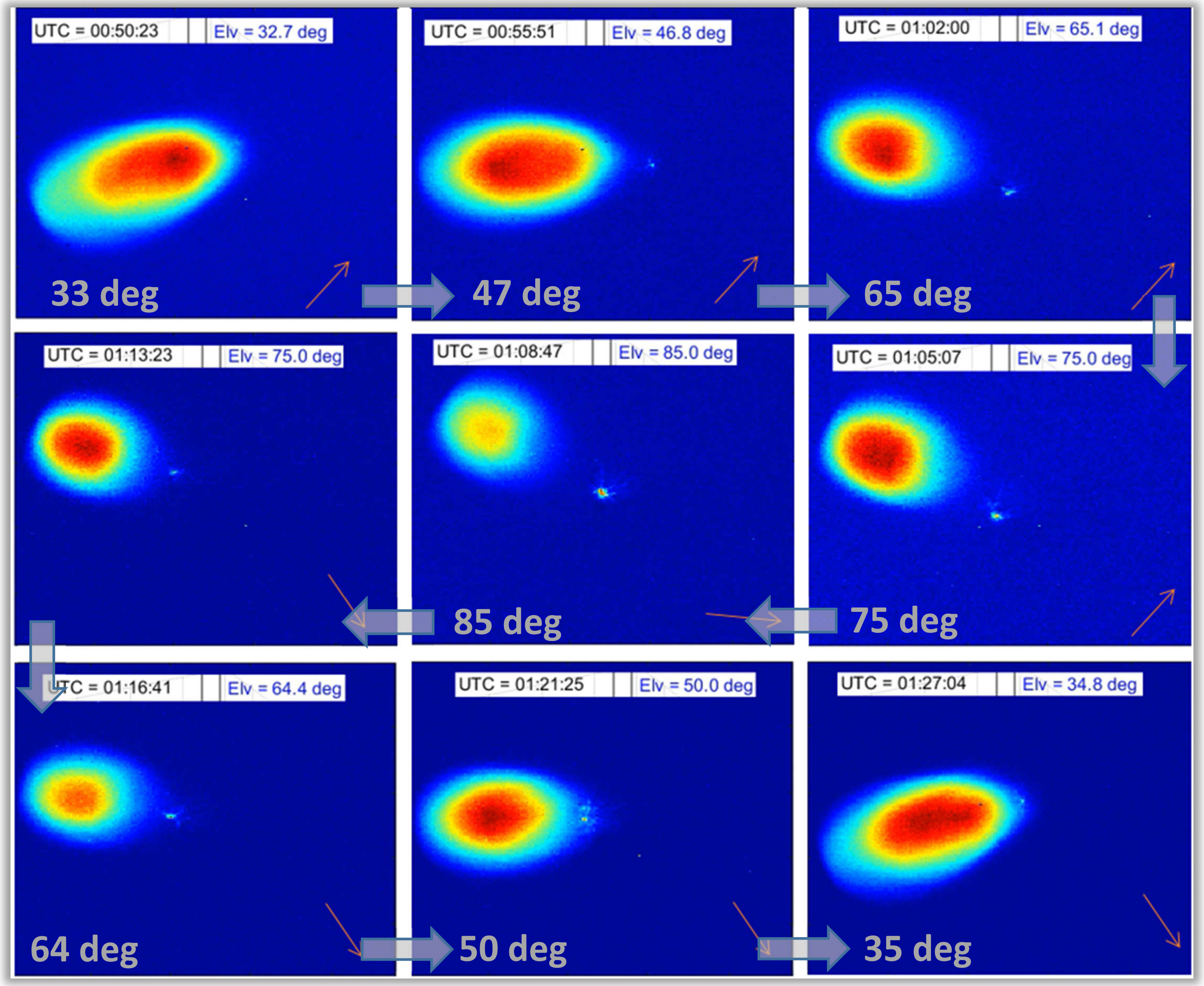
3. Filter & centroid detection – SNR optimization

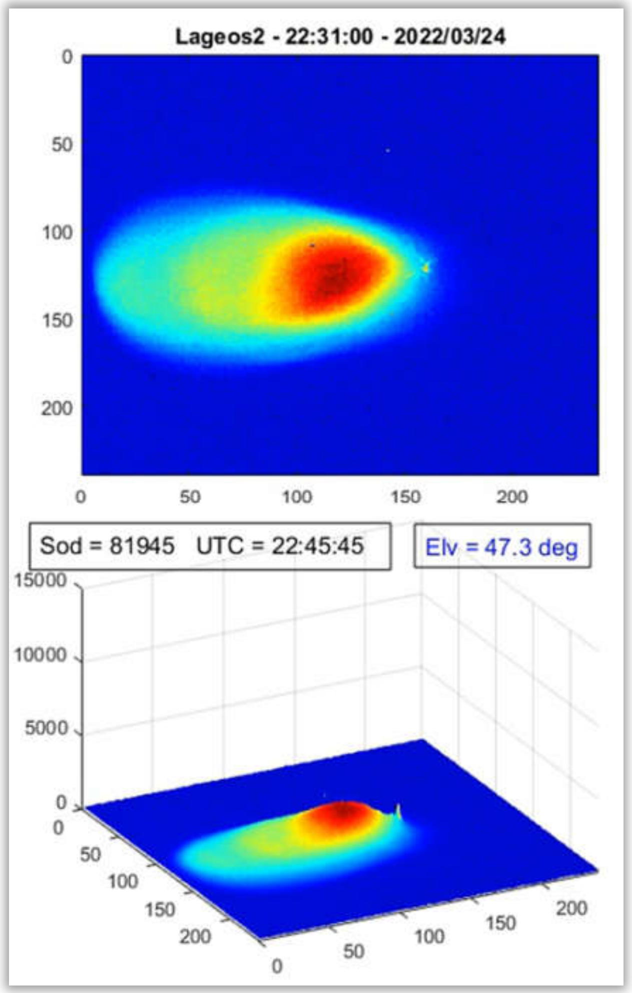
Image Filter – SNR optimization on centroid detection – Lageos (limited link budget)

- hot & dead pixels
- offset noise



- **Diffusion…**(size and position change following telescope elevation)



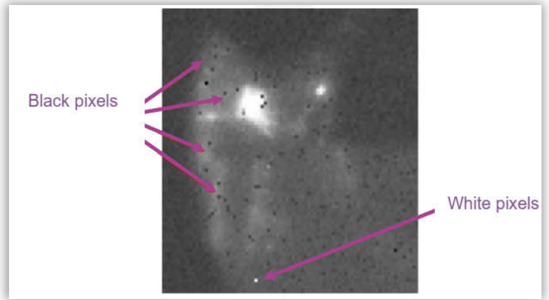


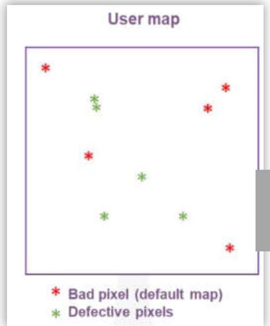
Spot detection???

3. Filter & centroid detection – for Lageos fine tracking

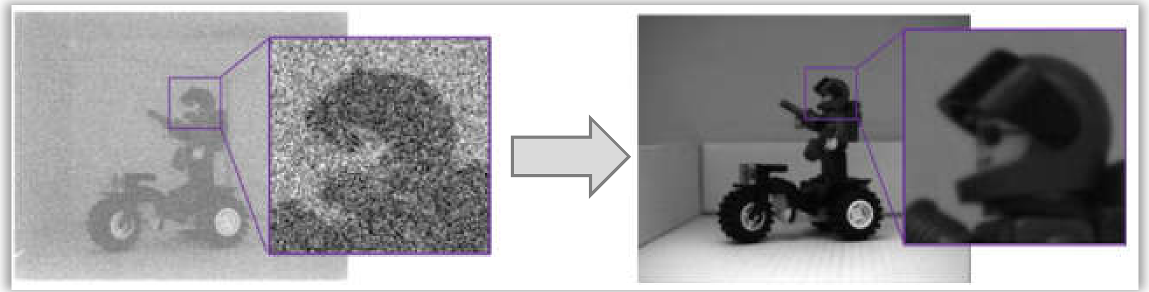
Image Filter – SNR optimization on centroid detection

- Cooling (noise ↘) + Dark suppression (offset + uniformity ↘),
- + Correction map FirstLight CRED-2 Camera (hot & dead pixels 0.28% correction) --- Camera Build-in Tools

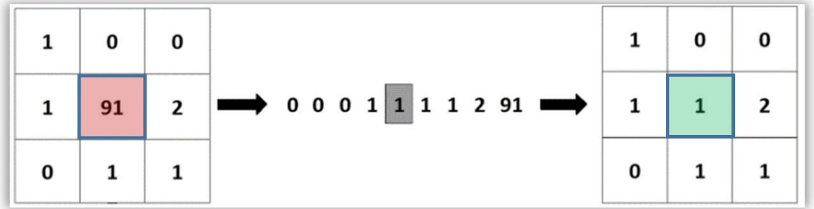


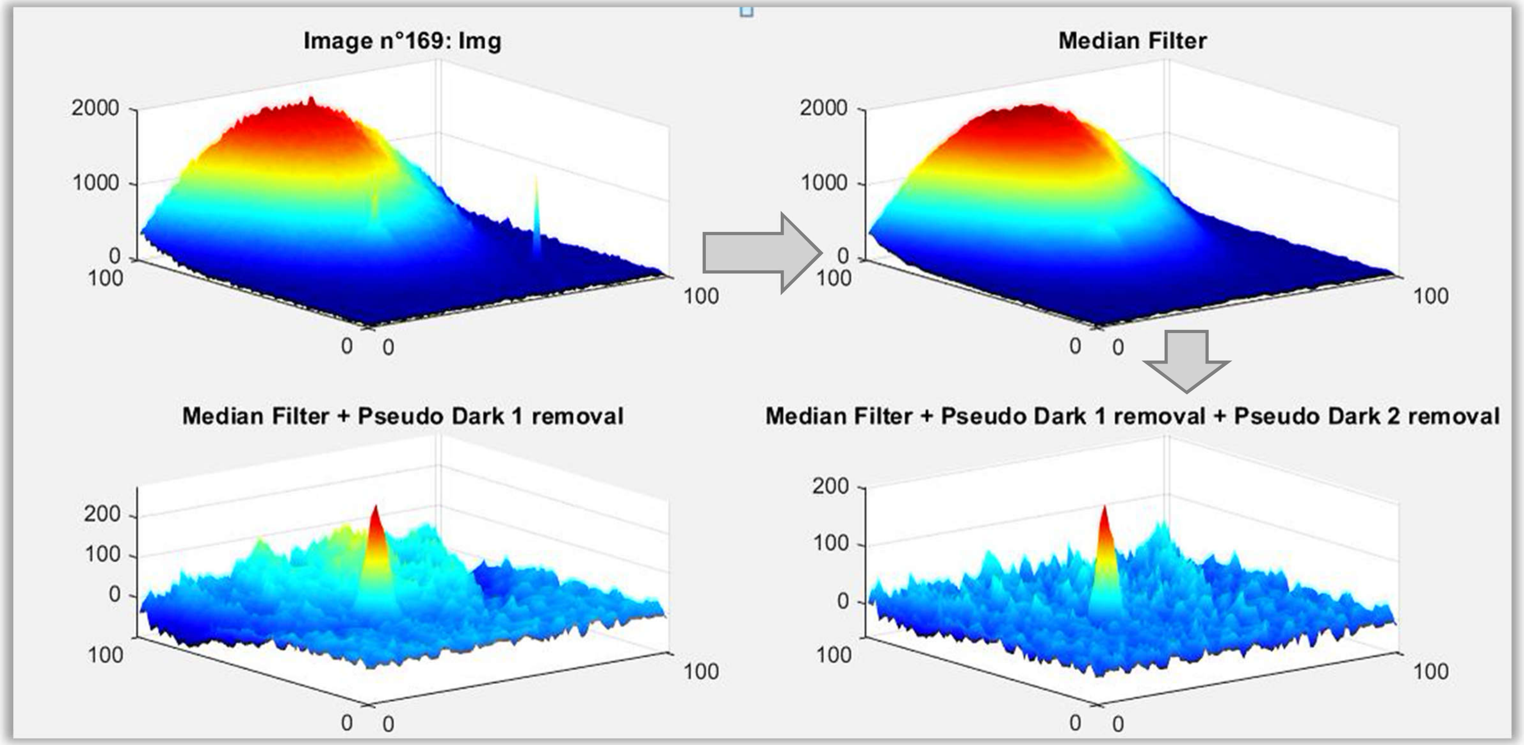


Built-in Correction

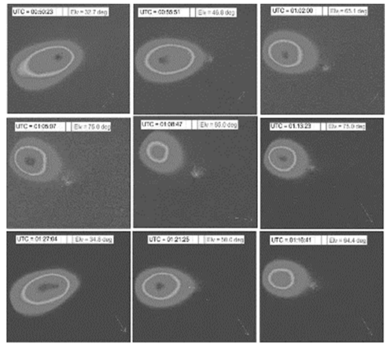


- Median filter (filter hot pixels), on 3×3 or 5×5 pixels





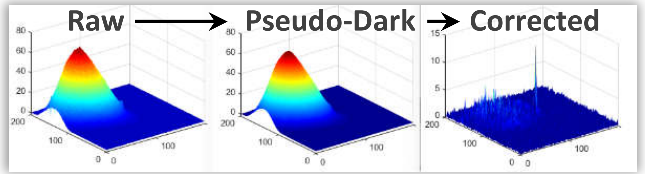
- Box blur or low-pass filter (Diffusion Suppression)

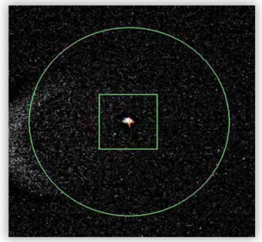


Aim to recalculate the Pseudo Dark

Kernel size = 7×7 (larger than spot size)

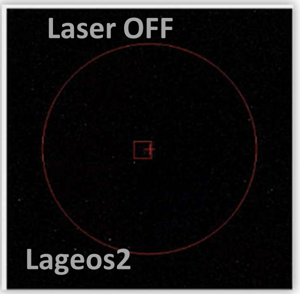
After suppression of Pseudo Dark

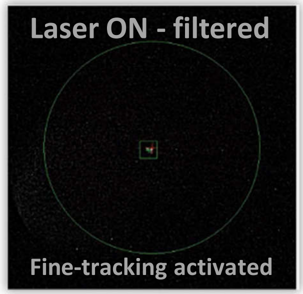




4. Preliminary results – Lageos fine tracking

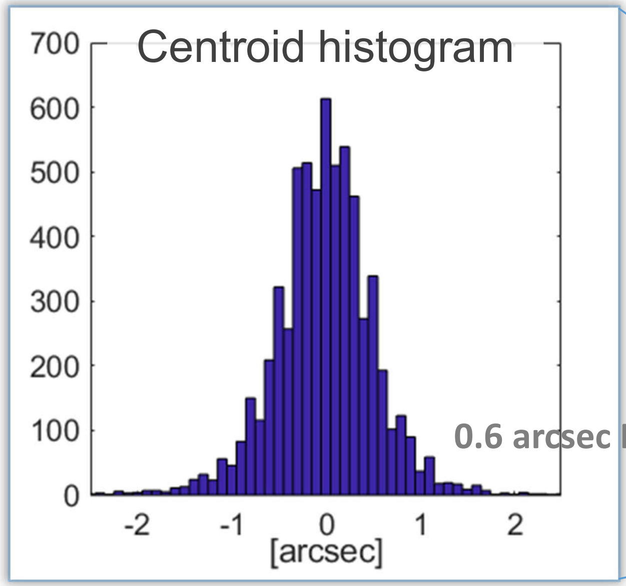
After optimize the spot detection by using some filters, we can activate the fine-tracking on Lageos illuminated by the high power laser.

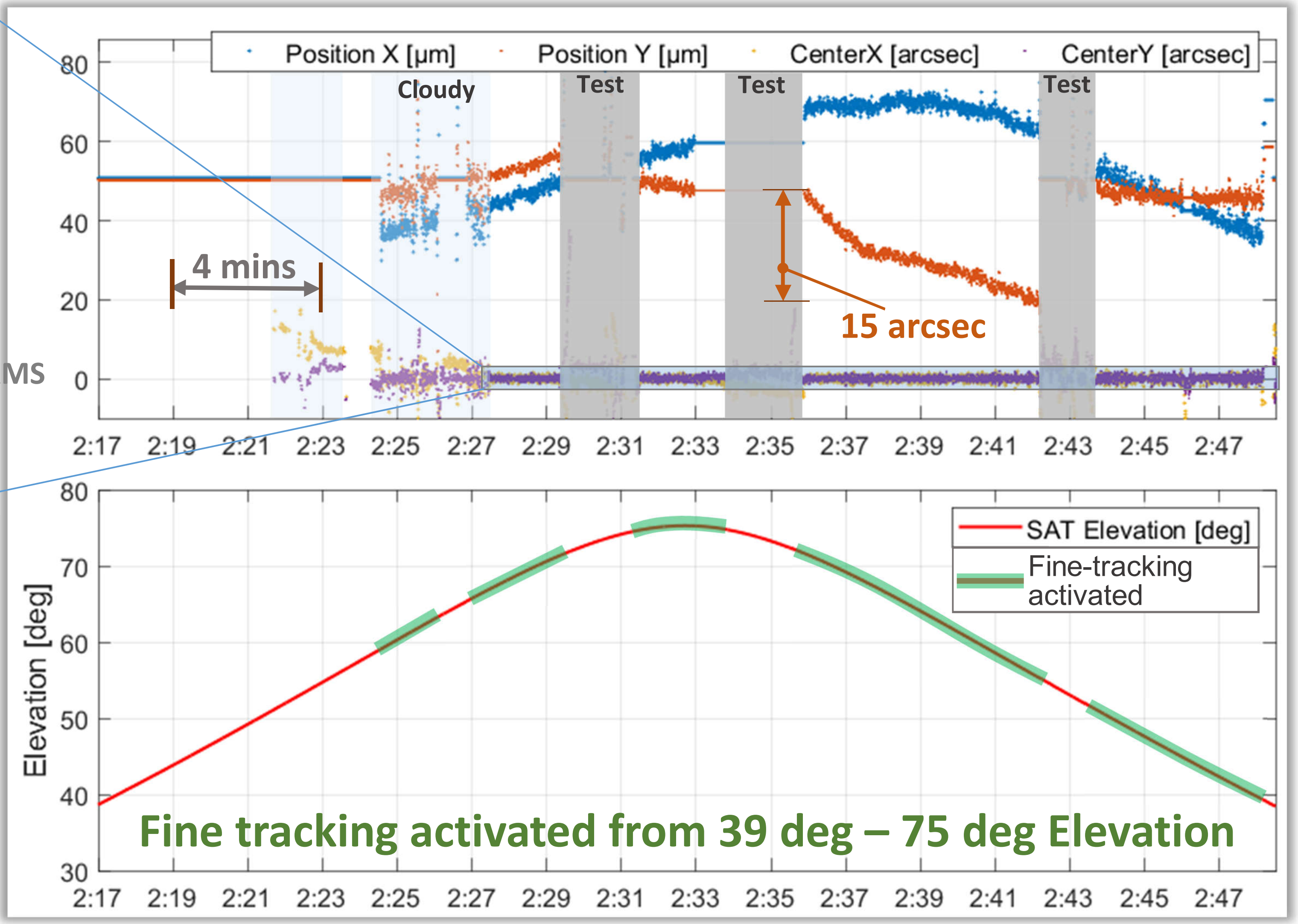




TipTilt correction
~21 arcsec on X – axis
~18 arcsec on Y – axis

Telescope Jitter
Telescope error pointing
Prediction error
Aberration velocity





0.6 arcsec RMS

With Image Filter + optimization on centroid detection

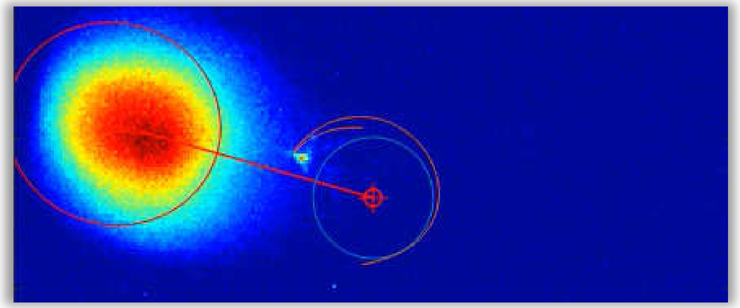
Auto- Fine tracking on Lageos can be activated from elv > 39 deg under strong turbulence condition (seeing > 2 arcsec)

Spot motion RMS = 0.6 arcsec (spot size ~2 arcsec FWHM) during 20 minutes (~ 50 % of Lageos tracking time)

5. Conclusion & Prospective applications

- **Preliminary results on satellite illumination with Imaging Filter – SNR optimization**
  Ajisai, Stella ---- OK during daylight, Lageos ---- OK during night-time.
  Lageos during daylight → to be optimized… (1550 nm + filter)

- **Satellite velocity (6 – 10 arcsec) may be modeled and corrected by TipTilt mirror**
  also the misalignment between transmitter & receiver to increase the link budget
  → better SNR to activate fine tracking and higher signal for detection



- **Integration the Fine-Tracking (TipTilt mirror) into actual SLR schema**

- **SLR measurement test with fine tracking → Estimate the improvement on SLR performance**
  (Sat illuminated by the SUN or by a high-power laser)

- **Image SNR optimization process (adapting blurs size) can be applied for other camera to filter diffusions from cloud/dome/telescope during daylight. It can improve 1 or 2 star-magnitude on star detection (day-light).**

- **Latency from Imaging filter → Applying physical filter… instead of Blurs box (numerical) filter.**
  Ultra high-pass Fourier filtering – small pin-block in '4-f' spatial filtering system

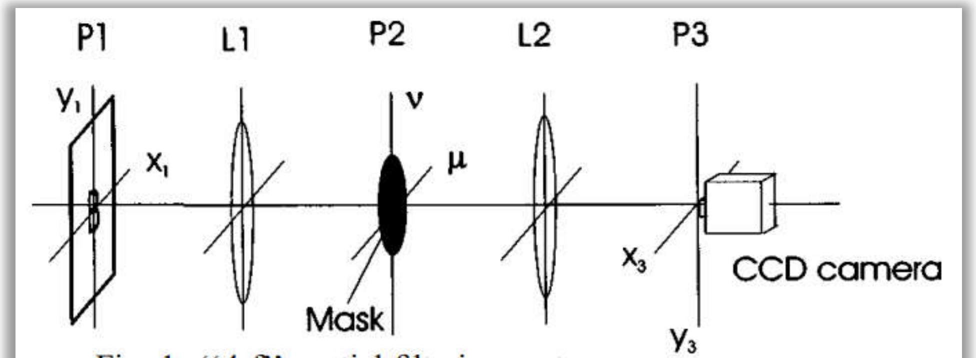
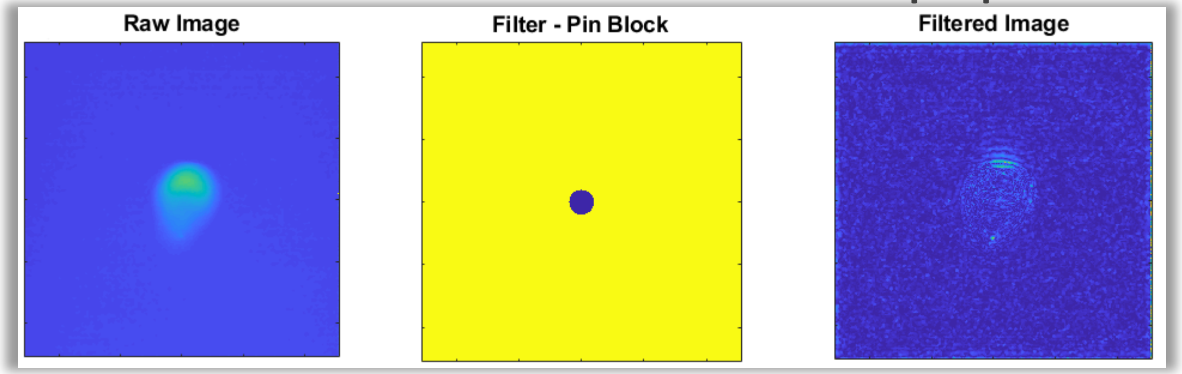


Fig. 1. "4-f" spatial filtering system.

Am. J. Phys. 69 (5), May2001

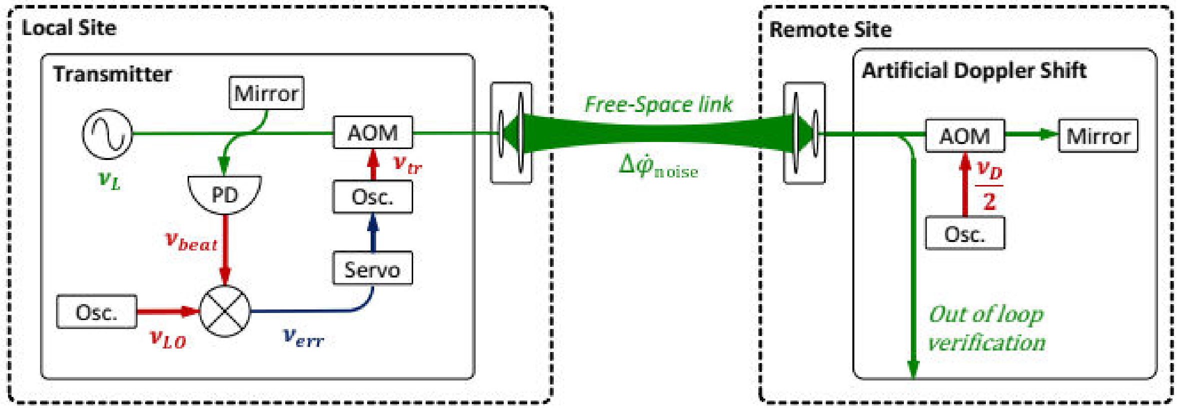
Simulation for our case… 120 µm pinblock



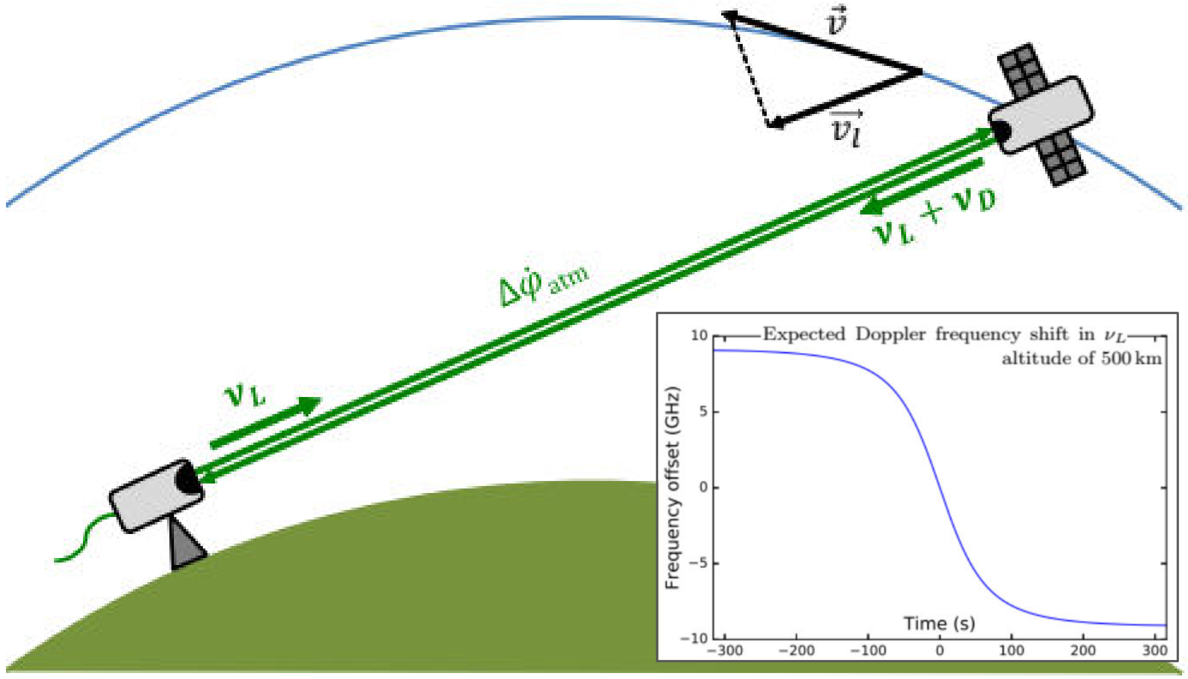
To be continued…

Modulation & Detection of high-power laser

First-step for 'Methods for **coherent optical Doppler orbitography**'



[Dix-Matthews 2020]



Dix-Matthews, B.P., Schediwy, S.W., Gozzard, D.R. et al. Methods for coherent optical Doppler orbitography. https://doi.org/10.1007/s00190-020-01380-w

Promising performance on **2.2 km** free-space:
estimated range rate precision of **9.0 nm/s at 1 s** of integration,

Atmospheric phase-noise (imprinted on Doppler measurement, ν_D) can be suppressed using the predicted Doppler shift, $\hat{\nu}_D$.

$$\nu_{err} = 2\Delta\nu_{tr} + 2\Delta\dot{\varphi}_{atm} + (\nu_D - \hat{\nu}_D)$$

The stabilized **Doppler measurement** may be obtained from this **component of $\Delta\nu_{tr}$**

The most significant obstacle: optical power losses during a long-distance **ground to space transmission**
1 W transmitted → receive ~nW (-60dBm) with high-speed photodiode…
→ Fiber coupling & amplification may be inevitable!

→ Experiment with our 1550 nm 42 dBm (15W) amplifier (MHz - GHz modulation) for the transmitter and measure the returning signal (fiber coupling & amplified → detection).

Thank you for your attention!