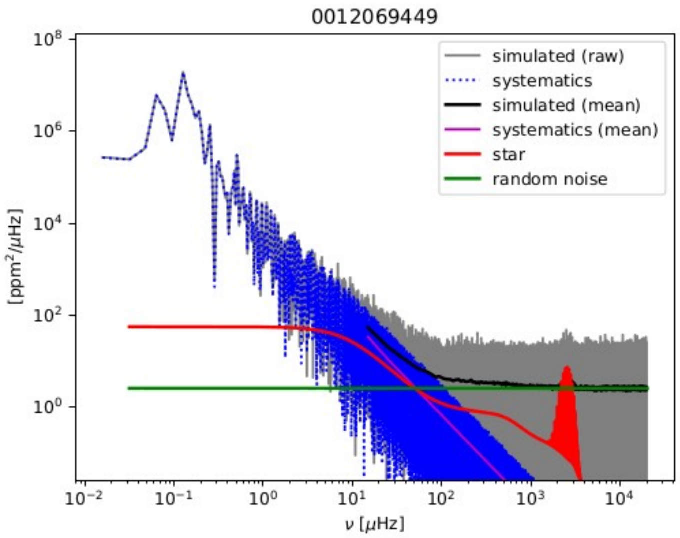


the PLATO Solar-like Light-curve Simulator (PSLS)

https://psls.lesia.obspm.fr

Réza Samadi
and the members of the DPA-WG

special dedications: Daniel, Alexis, Emmanuel

PSLS: fiche d’identité

- Generate **realistic PLATO L1 light-curves for solar-like pulsators** (including RG)
- Include: stochastically-excited oscillations ; rotational splitting, stellar granulation background, activity, planetary transit, white noise and **instrumental systematic errors**
- Applications:
  - Stellar science performance study and consolidation of the science case
  - Hare and Hounds exercises
  - PSM validation of the light-curve generation process (→ L1)
- Developed in Python (3.5 and higher)
- Paper: Samadi et al., 2019, A&A
- **Website**: https://psls.lesia.obspm.fr

Outline

- The stellar components
- The instrumental components

Outline

- **The stellar components**
- The instrumental components

General principle

Model of the expected PSD : $\bar{P}(\nu) = A(\nu) + G(\nu) + O(\nu)$

A: activity ; G : granulation ; O : Oscillation spectrum

Simulation of the stochastic nature of the simulated phenomenon (Anderson et al, 1990's approach):

$$F(\nu) = \sqrt{\bar{P}(\nu)}\ (U + iV)$$

U and V : two Normal distribution ; Hypothesis : uncorrelated phenomenon

Simulated ligth-curve : inverse Fourier transform of F(ν)

Simulated PSD : $P(\nu) = |F(\nu)|^2 = \bar{P}(\nu)\ (U^2 + V^2)$

Granulation spectrum

Two components (pseudo-lorentzian):

$$G(\nu) = \sum_{i=1,2} \frac{h_i}{1+(2\pi\tau_i\nu)^{\alpha_i}}$$

h_i : height(s)

τ_i : characteristic time(s)

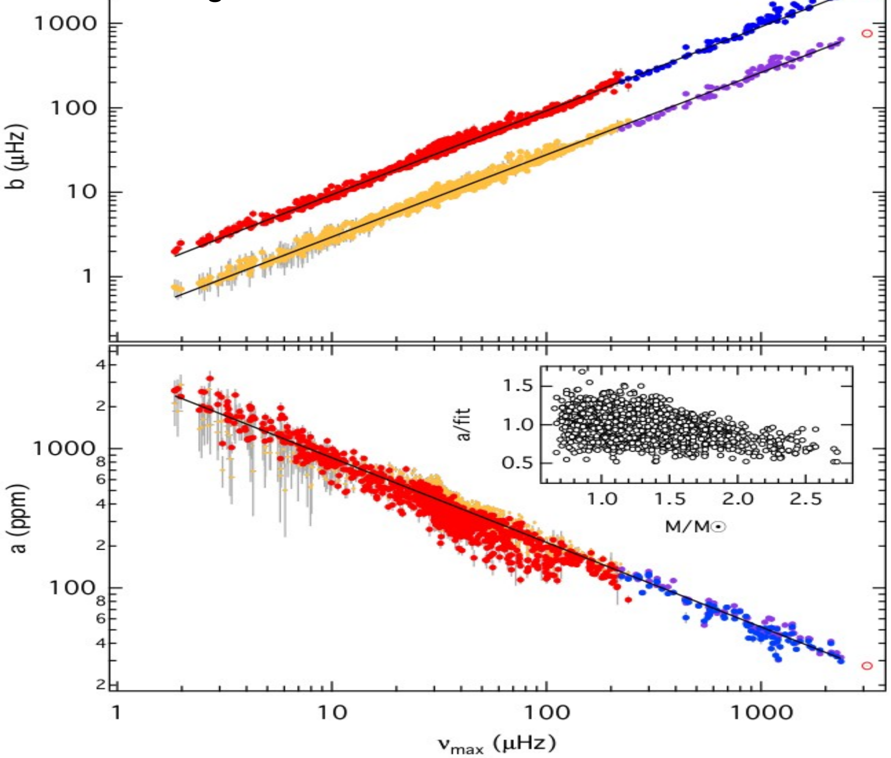
α_i : slope(s)

Origin of the two components not well established ….

Following Kallinger et al (2014) :

- Slopes fixed (=4)
- h_i and τ_i from scaling relations function of ν_{max}

Kallinger et al 2014



Oscillation spectrum

Two types of oscillation spectra:

- Universal Pattern (UP, Mosser et al 2010) with mixed-modes and splitting → for red-giant stars
- Set of theoretical oscillation frequencies derived from a pulsation code (ADIPLS) → for dwarf and sub-giant stars

---

$$O(\nu) = \sum_{i=1,N} L_i[\nu]$$

Resolved mode:

$$L_i(\nu) = \frac{H_i}{1 + (2(\nu - \nu_i)/\Gamma_i)^2}$$

Unresolved mode:

$$L_i(\nu) = \frac{\pi \Gamma_i H_i}{2 \delta \nu} sinc^2[\pi(\nu - \nu_i)]$$

h_i : mode height

ν_i : mode frequency

Γ_i : mode linewidth

Universal pattern

Following Mosser et al (2011)

$$\nu_{n,\ell} = n + \frac{\ell}{2} + \varepsilon(\Delta\nu) - d_{0\ell}(\Delta\nu) + \frac{\alpha_\ell}{2}\left(n - \frac{\nu_{\max}}{\Delta\nu}\right)^2 \Delta\nu + \delta_{n,\ell}$$

Additional term for dipole modes, asymptotic gravity-mode spacing (Mosser et al 2012)

$$\delta_{n,\ell} = \frac{\Delta\nu}{\pi} \arctan\left[q \tan\pi\left(\frac{1}{\Delta\Pi_1 \nu_{n,\ell}} - \epsilon_g\right)\right]$$

Mode amplitudes and line-widths:

Gaussian envelope

$$G(\nu) = H_{max} \exp\left[\frac{-(\nu-\nu_{max})^2}{\delta\nu_{env}^2/4\ln 2}\right]$$

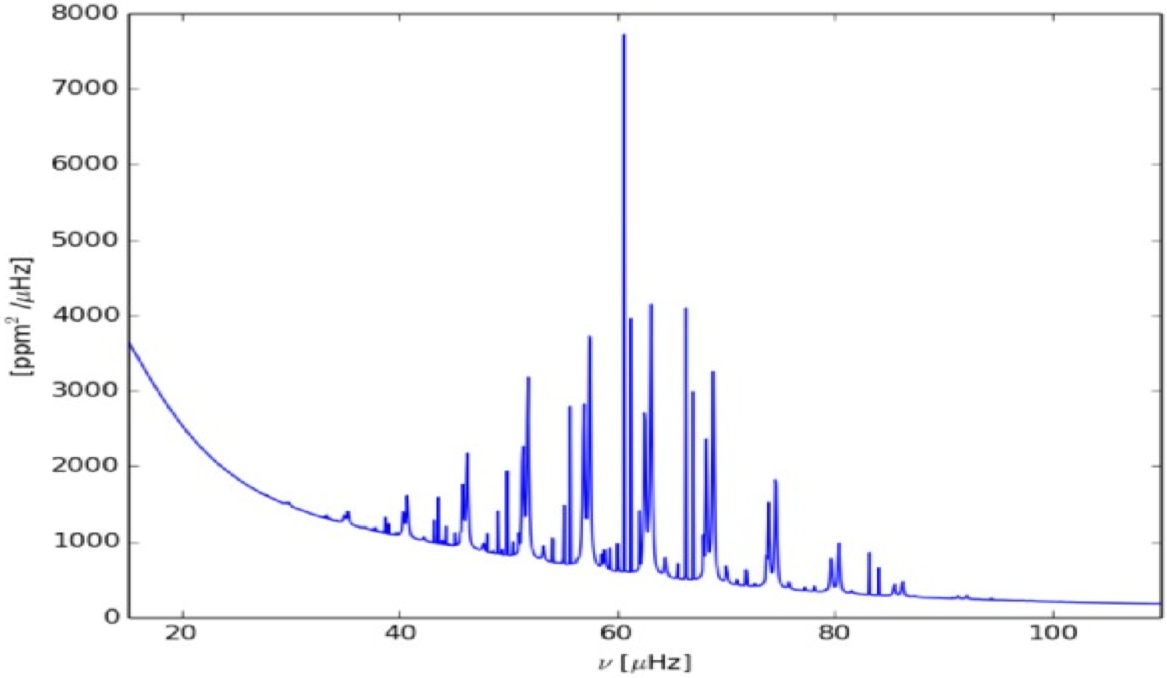
$$H_{max} = \alpha\,\nu_{max}^{-2.38}$$

(Mosser et al 2013, SF2A)

$$\Gamma_{max} = \Gamma_0 \left(\frac{T_{eff}}{4800\,K}\right)^{10.8}$$

(Belkacem 2012, SF2A)

Universal pattern



Theoretical spectrum ("expectation")

Input parameters:
- νmax

- Δν
- Teff

- q (coupling)
- ΔΠ (asymptotic period spacing)

Mode characteristics

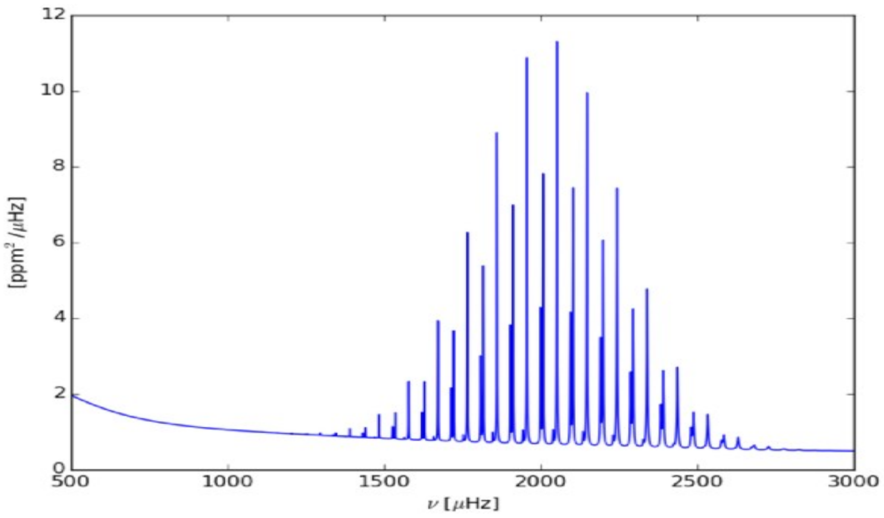
Theoretical adiabatic frequencies : as given by ADIPLS

Splitting : constant (Ledoux's constant from ADIPLS)

Surface effects :
Modified lorentzian component (Sonoi et al 2015), involved 2 free input parameters (a,b), derived as a function of T_{eff} and log g from corresponding scaling relation

Amplitudes : observationnal scaling relation from Corsaro et al (2013)

Line-widths : observationnal scaling relation from Appourchaux et al (2012)



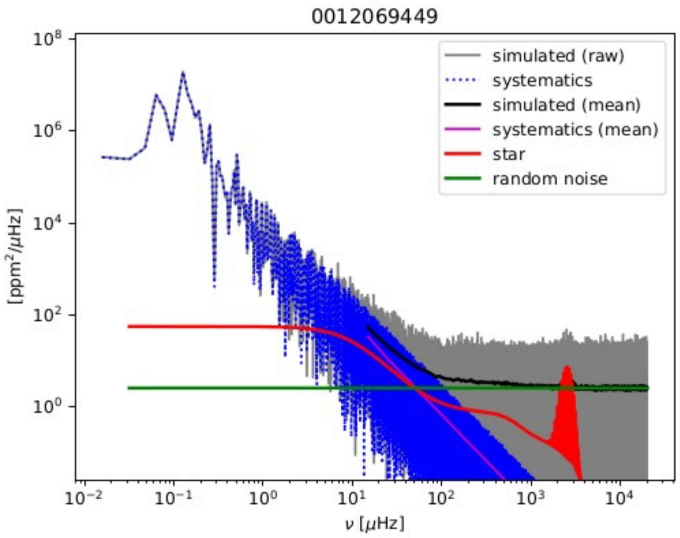
A typical PLATO target (here noise free...)

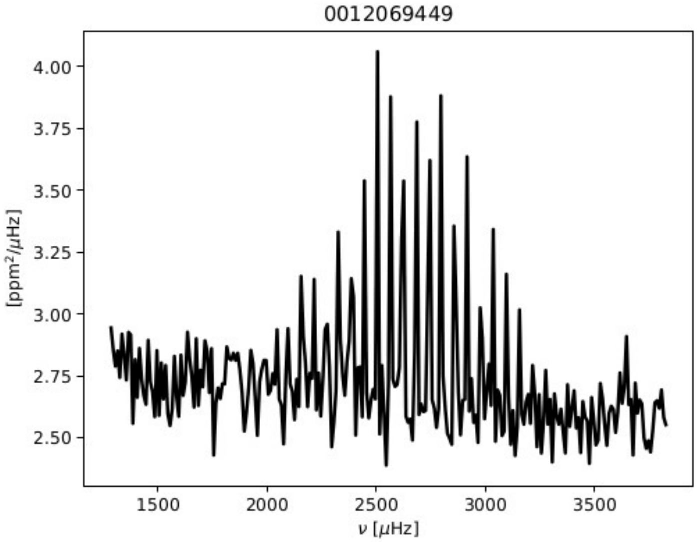
Other astrophysical components

- Activity component: Lorentzian function (α=2) ; users specify its characteristic time (τ) and amplitude (σ)
- Planetary transit: based on Mandel & Agol (2002) equations ; users specify typical transit parameters (radius, period, distance, and orbital angle)

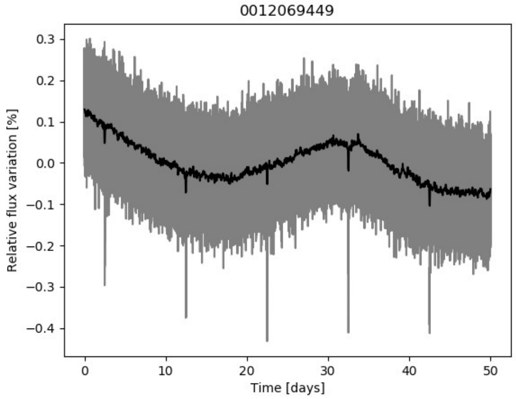
The PLATO Solar-like Light-curve Simulator (PSLS)

16 Cyb B (KIC 12069449): observed by PLATO at V = 10





With planetary transits



Samadi et al., 2019, A&A

Website: https://psls.lesia.obspm.fr

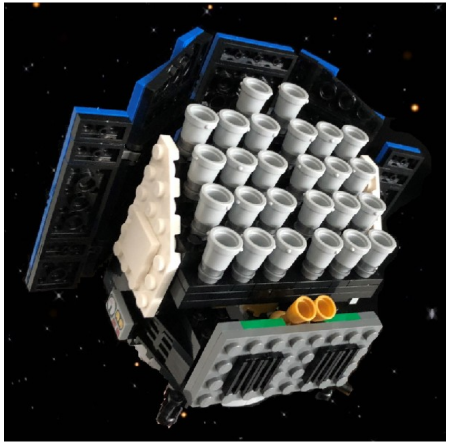
l'Observatoire de Paris LESIA

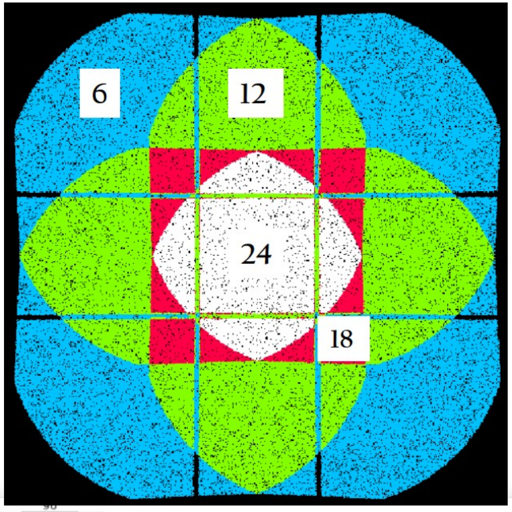
Outline

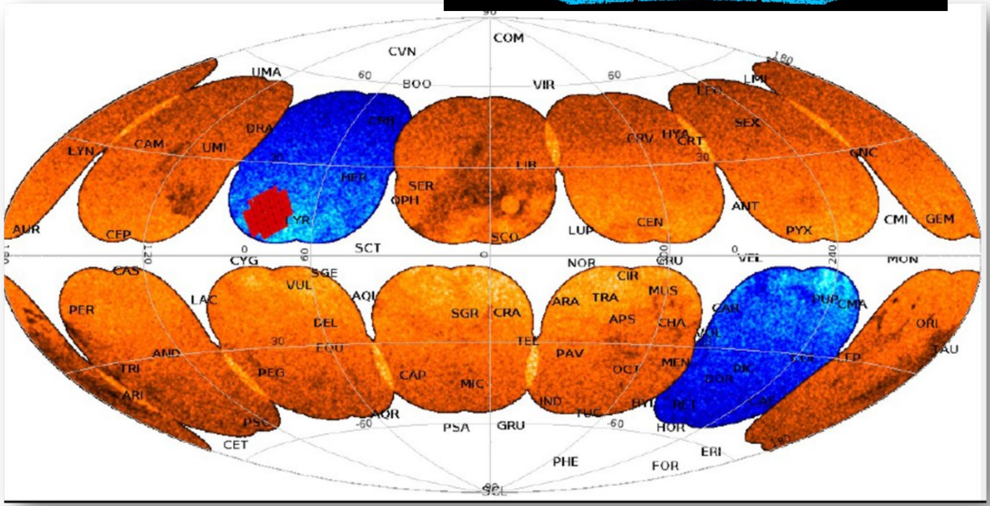
- The stellar components
- **The instrumental components**

The mission

- Multi-telescope concept
- 2 “fast” (2.5 seconds cadence) cameras used as star trackers by attitude and orbit control system
- 24 “normal” (25 seconds cadence) cameras for the core science
- Full field of view 2232 deg² (almost 20x that of Kepler)
- 2 long pointings of 2 years each
- Possible extension: step and stare phase → ~ 50 of the sky
- Instrument designed for 8 years

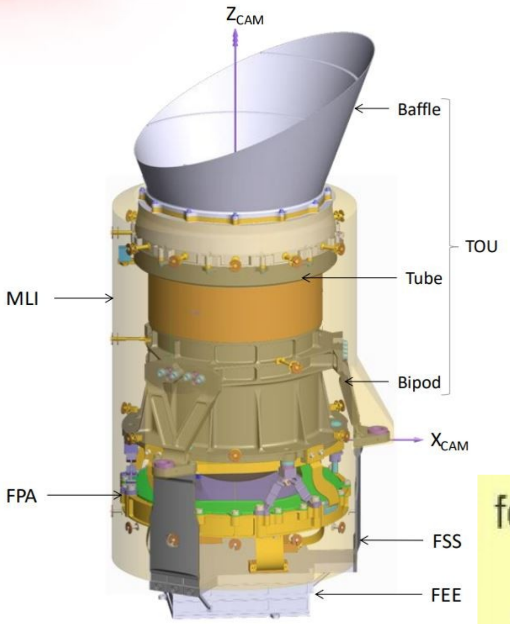


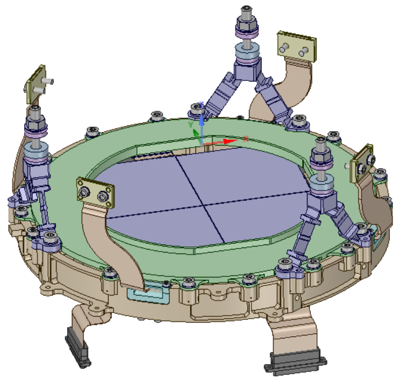


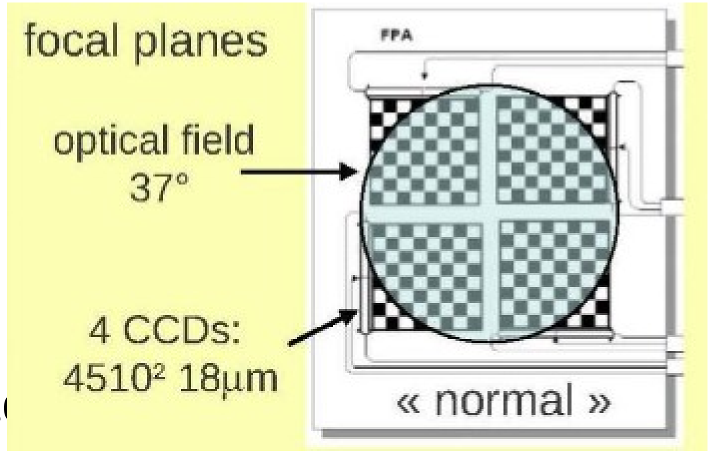


The instrument

- Each camera has:
  - 12 cm diameter pupil
  - 1037 deg² field-of-view
  - 4 CCDs (45104510 18 pixels each)
  - Plate scale: 15 arcsec/pixel
  - 500-1000 nm spectral range
  - 80 cm height, 30 cm diameter, 20 kg







High SNR, low stellar contamination and stability !!

Star samples

Telemetry must be shared between the 26 cameras !

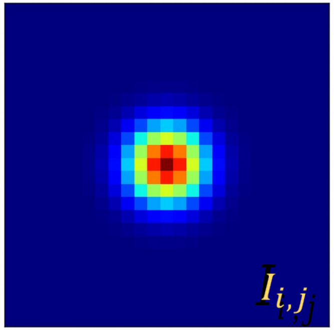
→ Limited number of imagettes
→ for most of the targets: **photometry** must be extracted **on-board**
→ **~ 250k stars**
→ **sample P5 + guest program** (about 40k light-curves)

		Sample 1 (P1)	Sample 2 (P2)	Sample 4 (P4)	Sample 5 (P5)
Stars		≥ 15 000 (goal 20 000)	≥ 1000	≥ 5000	≥ 245 000
Spectral type		Dwarf and subgiants	Dwarf and subgiants	M dwarfs	Dwarf and subgiants
Limit *V*		11	8.2	16	13
Random noise (ppm in 1 hour)		34	34	800	
Observation phase		LOP	LOP	LOP	LOP
Sampling time	Initial measurement	-	-	-	≤ 600
	Centroid measurements	-	-	-	≤ 50 for 5% of targets
	Transit oversampling			-	≤ 50 for 10% of targets
	Imagettes	25	2.5	25	25 for > 9000 targets
Wavelength		500–1000 nm	500–1000 nm	500–1000 nm	500–1000 nm

Photometry extraction methods

PSF fitting photometry

STAR IMAGE

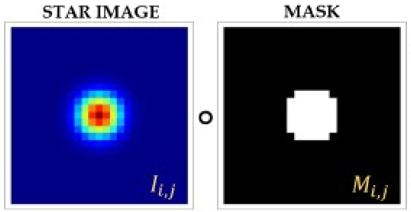


MODELLED IMAGE: $\hat{I}_{i,j} = a.P_{i,j}(x_c, y_c) + b$

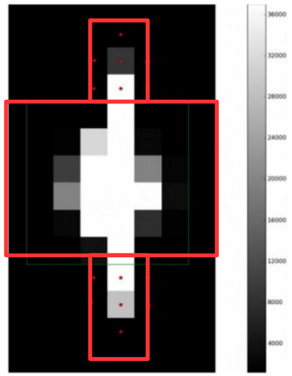
$$\chi^2 = \sum_{i,j} \frac{\left(I_{i,j} - \hat{I}_{i,j}\right)^2}{\sigma_{i,j}^2}$$

Aperture (mask) photometry (on-board)

$$f(k) = \sum_{i,j}\left(\int_{t_1}^{t_2}\left(I_{i,j} \circ M_{i,j}\right)dt\right)$$



Saturated stars photometry



“Extended” window: only useful pixels outside the standard 6x6 imagette are downloaded together with the 6x6 imagette

Aperture photometry methods

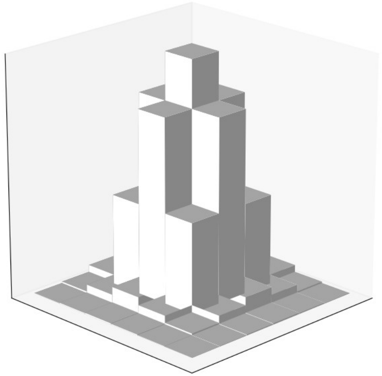
NOISE-TO-SIGNAL RATIO (NSR)

$$\mathbf{NSR}=\frac{\sqrt{\sum_{i,j}\left(\left(F_{T_{i,j}}+\left(\sum_{k}F_{C_{k,i,j}}\right)+B_{i,j}+R_{i,j}^{2}+D_{i,j}\right)\times w_{i,j}^{2}\right)+J^{2}}}{\sum_{i,j}\left(F_{T_{i,j}}\times w_{i,j}\right)}$$

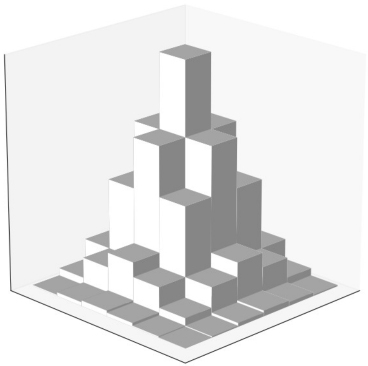
STELLAR POLLUTION RATIO (SPR)

$$\mathbf{SPR}=\frac{\sum_{i,j}\left(\left(\sum_{k}F_{C_{k,i,j}}\right)\times w_{i,j}\right)}{\sum_{i,j}\left[\left(F_{T_{i,j}}+\left(\sum_{k}F_{C_{k,i,j}}\right)\right)\times w_{i,j}\right]}$$

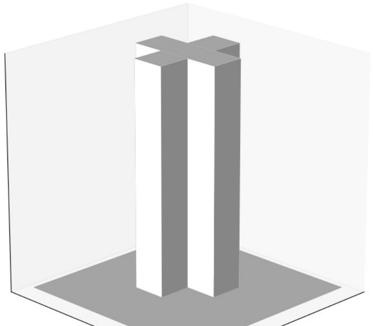
Weighted Gradient Mask (global optimal NSR)



Weighted Gaussian Mask (sub-optimal NSR)

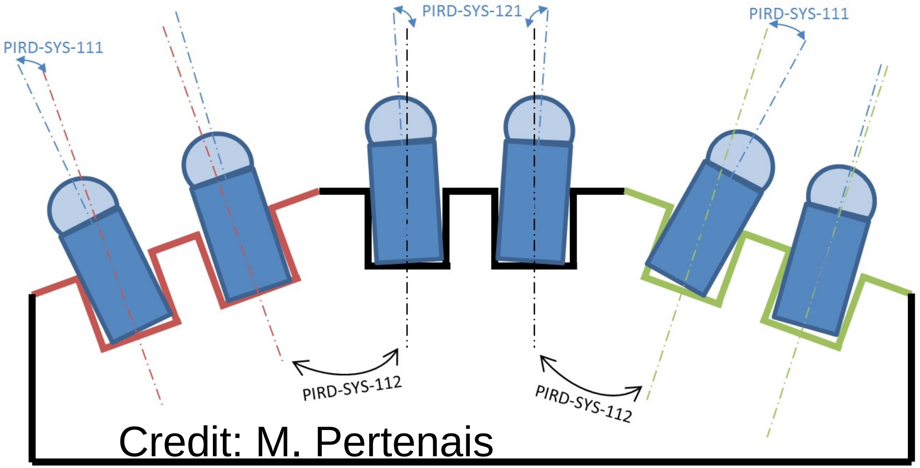


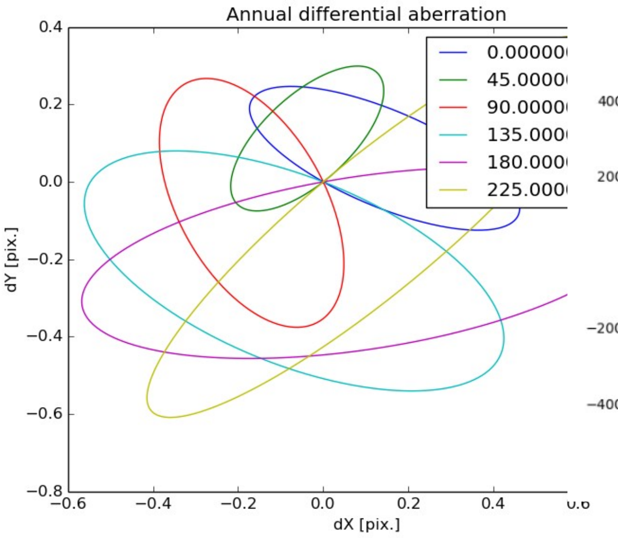
Binary Mask (narrower)

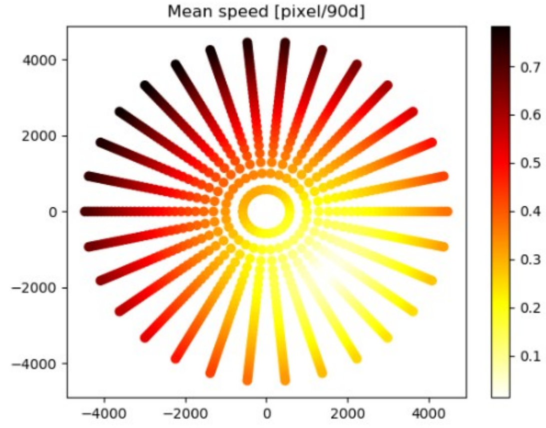


Marchiori et al (2019, A&A)

Undesirable disturbances



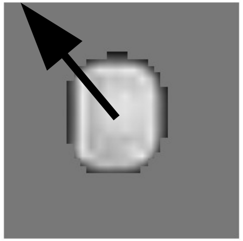


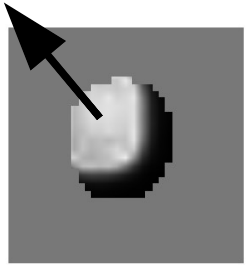


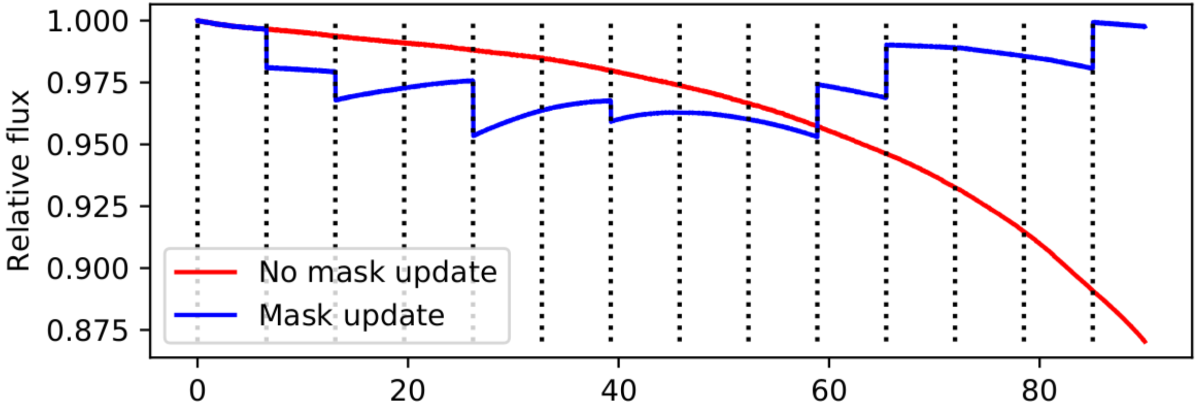
Thermo-elastic distortion
- Up to 0.4 pixel/3 months

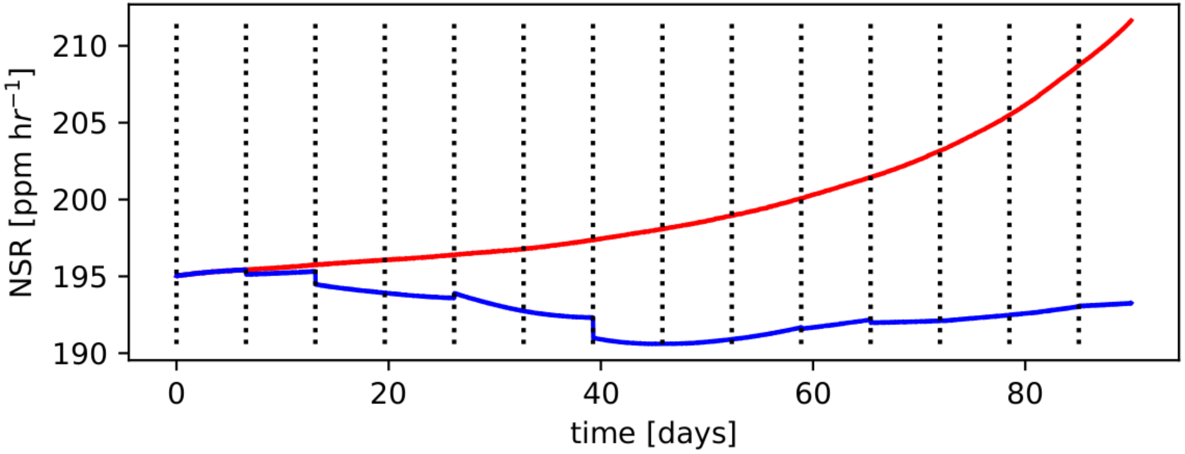
Differential aberration
- Unavoidable relativistic effect
- Up to 0.9 pixel/3 months

Long-term star drift









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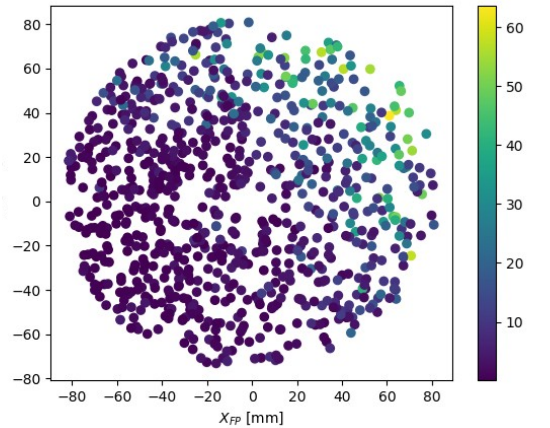
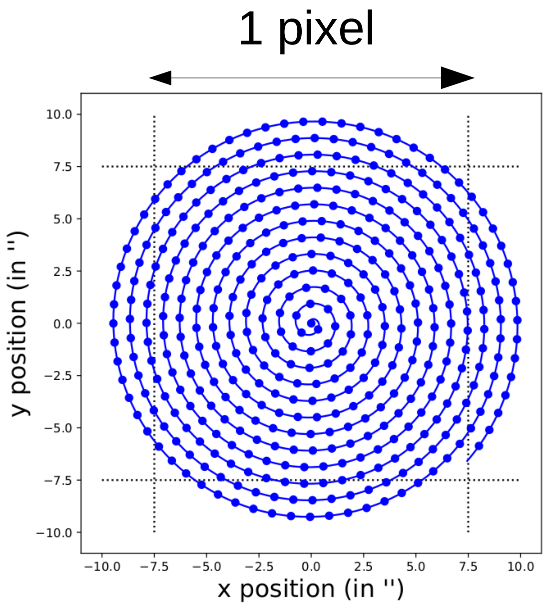
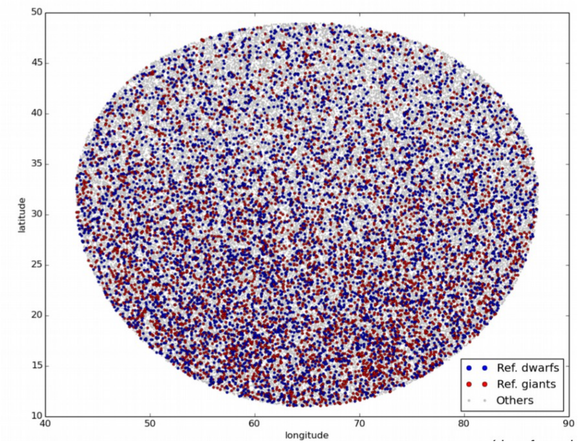


→ up to 60% reduction in the star intensity (in 3 months) !

Microscanning and PSF





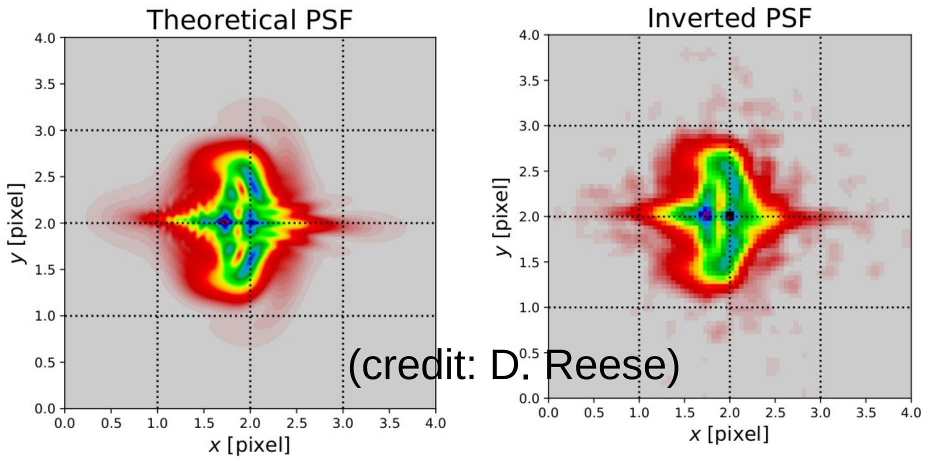
(credit: D. Reese)

”Microscanning” technique:

- Series of imagettes acquired during a imposed slow motion of the satellite (pure translation → variations of the transverse angles only)
- Coupled with an **inverse technique**: reconstruction of the PSF at different positions across the field of view

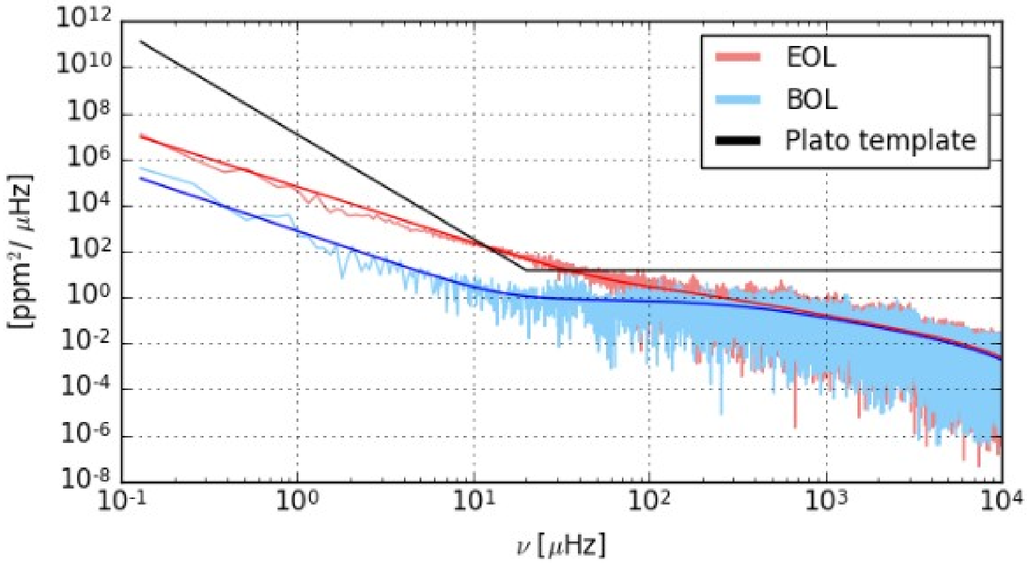
Leader: Daniel Reese (WP 321)

PSF and light-curve correction



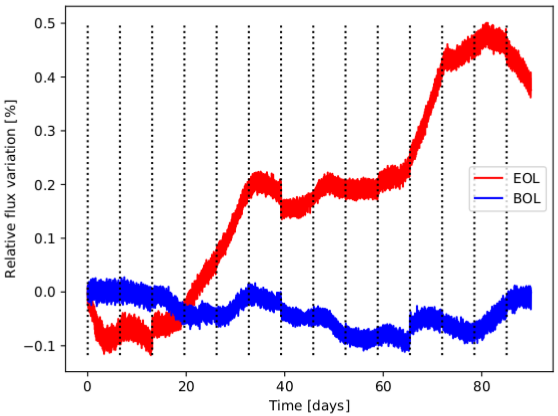
(credit: D. Reese)

Working resolution: 1/20 pixel (interpolated at 1/128 pixel)

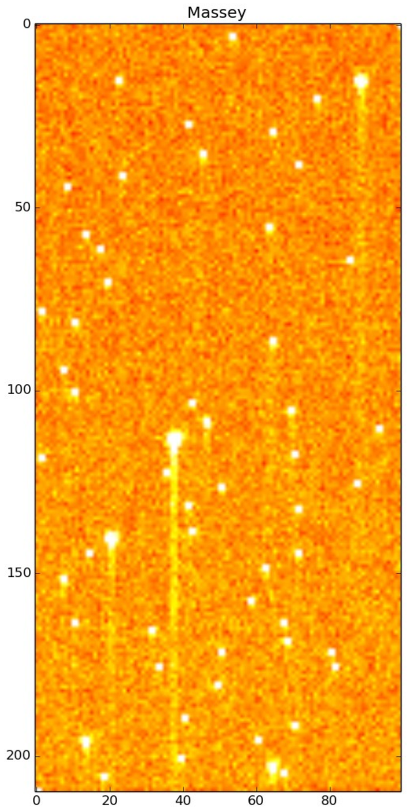


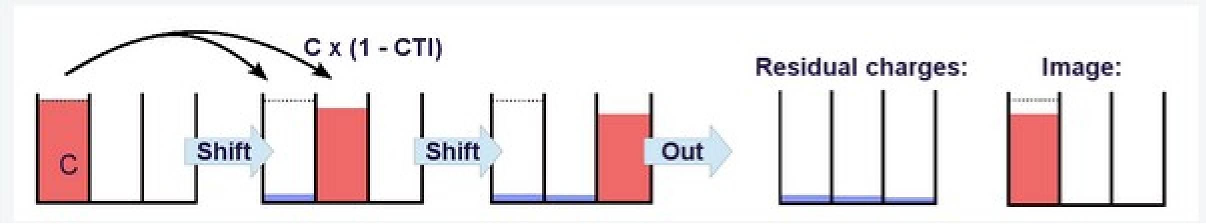
(see Samadi et al., 2019, A&A)

Corrected light-curve:



Charge transfer inefficiency



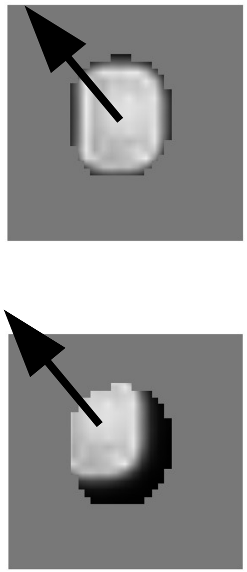


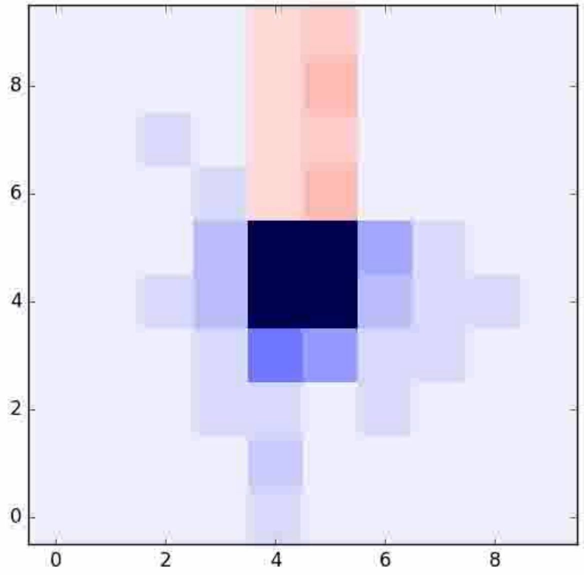
Electrons captured by traps (during the charge transfers) and released after a while:

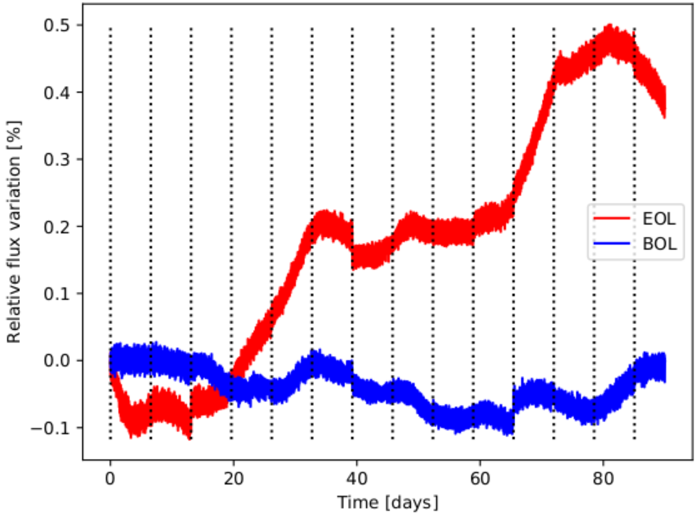
- Photon-electrons are **lost** (released outside the mask)
- Image are distorted by the **trailing**

Traps generated by proton impacts ; their number increased during mission life

CTI and long-term drift: differential CTI effect

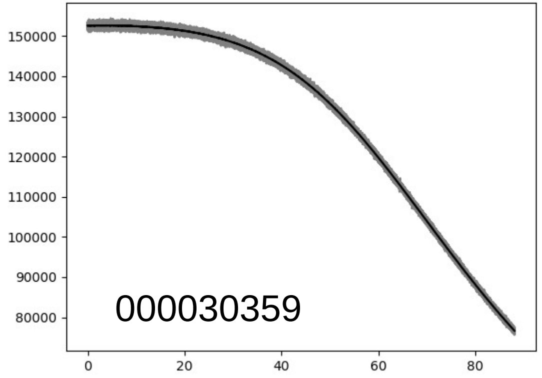




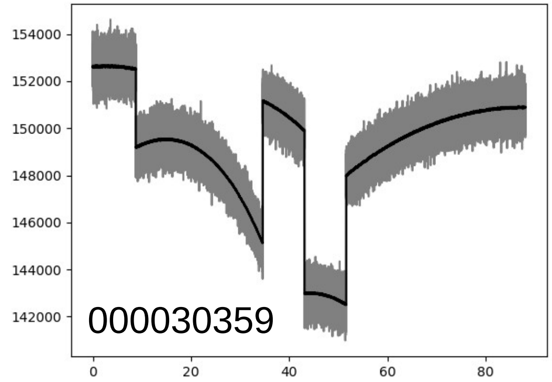


Some simulated light-curves

Raw LC

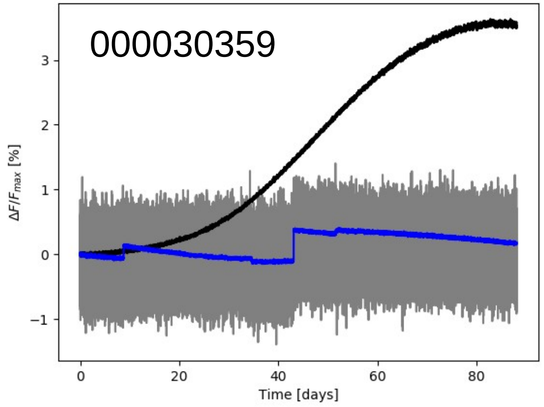


Fixed mask

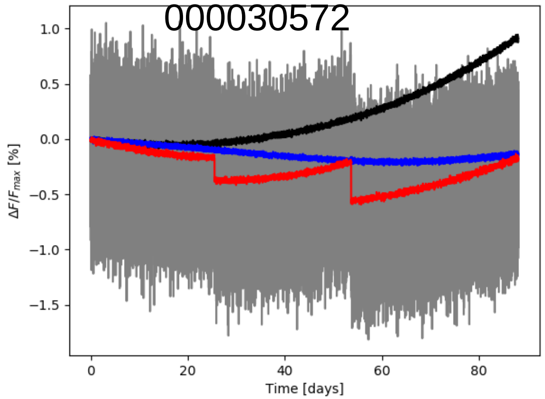


Mask update

Corrected LC



BOL

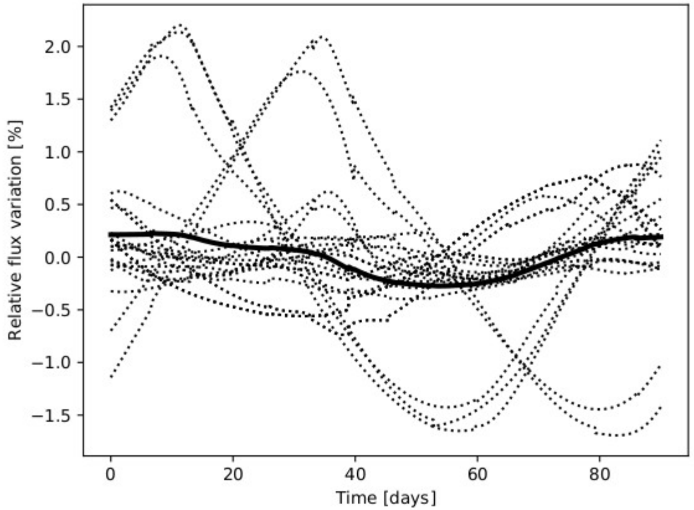


EOL / BOL

The PLATO Solar-like Light-curve Simulator (PSLS)

PSLS simulations include:

- Solar-like oscillations
- Granulation background
- Activity
- White noise
- **Instrument systematic errors**



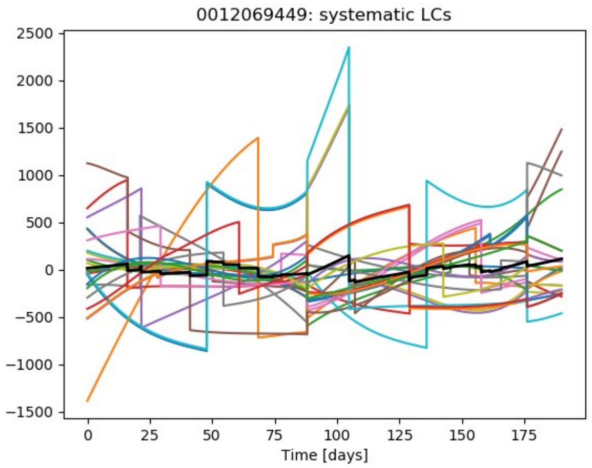
Systematic errors (individual camera and averaged over 24 cameras)

Updated simulations

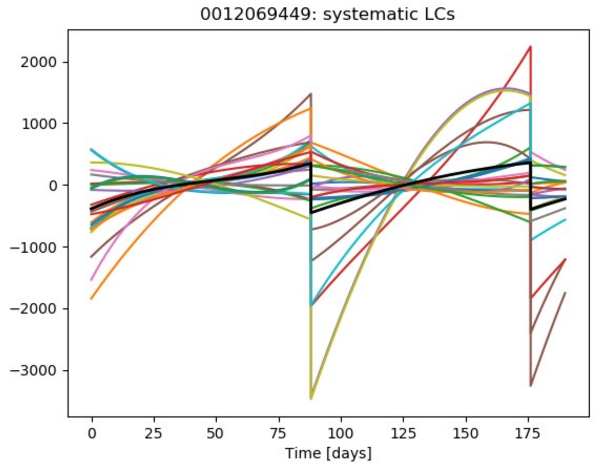
- Based on Gaia field (I.e with relastic contaminations)
- Include charge diffusion, more realistic inverted PSF, centroid errors, ...

P5 sample
(aperture mask method)

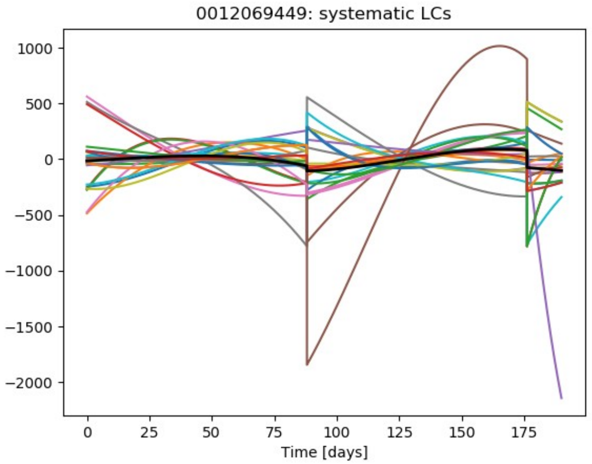
With mask updates



No mask updates



P1 sample
(PSF fitting method)



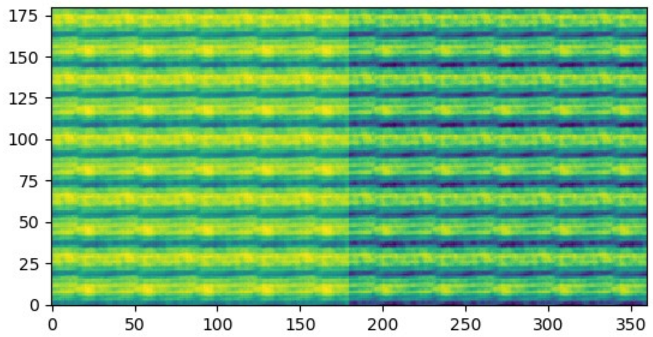
IPRNU = Intra Pixel Non-Uniformity

Wavelength (nm)	Peak-to-peak IPRNU (%)	Weight (%)
500	1.4	20.0
633	1.2	26.7
700	2.1	25.9
800	6.1	18.3
900	16.6	7.8
1000	36.1	1.4

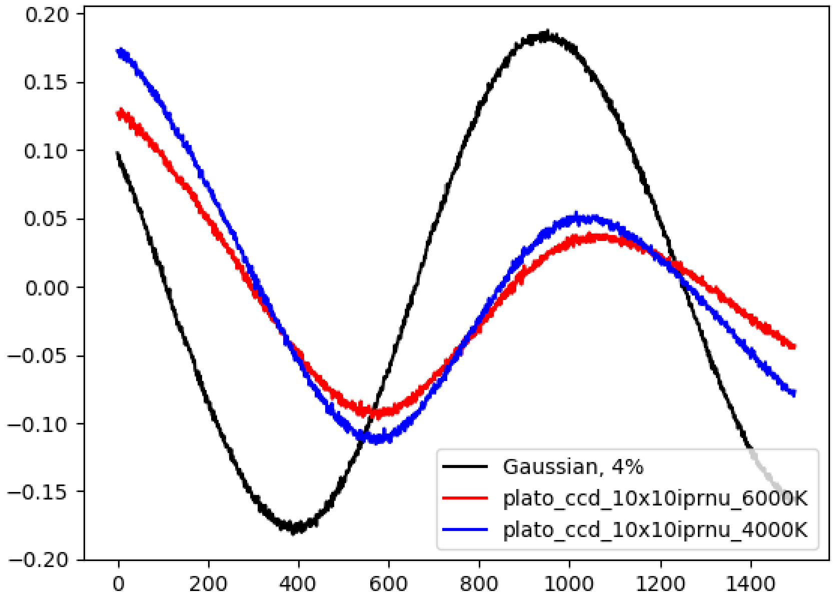
Credit: Carsten Parpoth (DLR)

- Weights depend on transmittance, QE, and G0 spectrum
- About 4% overall IPRNU peak-to-peak

6,000 K　　4,000 K



Residual light-curve:



The configuration file

```
# PLATO Solar-like Light-curve Simulator (PSLS) configuration file (V 1.2)

# Observation conditions
Observation:
  Duration : 730. #  [days]
  MasterSeed : 1704040900 # Master seed of the pseudo-random number generator

# Instrument parameters
Instrument:
  Sampling : 25. # Sampling period of each camera [s]
  IntegrationTime : 21. # Integration time [s]
  NGroup : 4 # Number of camera groups (1 -> 4)
  NCamera : 6 # Number of cameras per group (1 -> 6)
  TimeShift : 6.25 # Time shift between camera groups [s]
  RandomNoise:
    Enable: 1
    Type: PLATO_SIMU #  either 'User' or 'PLATO_SCALING' or 'PLATO_SIMU'.
    NSR :  73.
  Systematics:
    Enable : 1
    Table : PLATO_systematics_BOL_P1_V1.npy
    Version: 1
    DriftLevel: low  # Amplitude of the drift:  'low', 'medium', 'high' or 'any'. Applicable only for Version>0
```

The configuration file (2)

```
# Stellar parameters
Star:
  Mag : 10. #  Magnitude
  ID : 12069449  #  star ID
  ModelDir: # Directory containing the single models or the grid
  ModelType: single  # Type of model: 'grid' or 'single' or 'UP'
  ModelName: 0012069449  # Name of the input model, to be specified when ModelType = 'single'.
  ES : ms  # Evolutionary status: 'ms' for the main-sequence phase, 'sg' for the sub-giant phase, 'rg' for redgiants (Red
Giant Branch or clump stars)
  Teff : 5750.  # Effective temperature [K]
  Logg : 4.353 # Surface gravity, ignored for the UP
  SurfaceRotationPeriod :  0. # Surface rotation period [days], not used with the UP
  CoreRotationFreq :  0. # Core rotation frequency [muHz] [rad/s], used only with the UP
  Inclination : 0. # Inclination angle [deg.]

# Oscillations parameters
Oscillations:
  Enable: 1
  numax : 179.3 # frequency at maximum power [muHZ], used only with the UP
  delta_nu : 13.68 # Mean large separation [muHz], used only with the UP scaling relation
  DPI : 80.58 # Asymptotic values of the gravity mode period spacing [s], used only with the UP modes to be included
  q : 0.15 # Mixed mode coupling factor, used only with the UP
  SurfaceEffects: 1 # Include near-surface effects in mode frequencies, not implemented for the UP
```

The configuration file (3)

```
Activity :
  Enable: 1
  Sigma : 40. # Amplitude of the activity component [ppm]
  Tau : 0.2 # Time-scale of the activity component [days]

Granulation :
  Enable: 1

# Transit parameters
Transit :
  Enable: 0
  PlanetRadius : 0.5   # in jupiter radii
  OrbitalPeriod : 10.  # in days
  PlanetSemiMajorAxis : 1.  # in A.U.
  OrbitalAngle : 0. # in deg
  LimbDarkeningCoefficients: [0.25,0.75]
```