Optimized photometric masks for deriving PLATO on-board lightcurves

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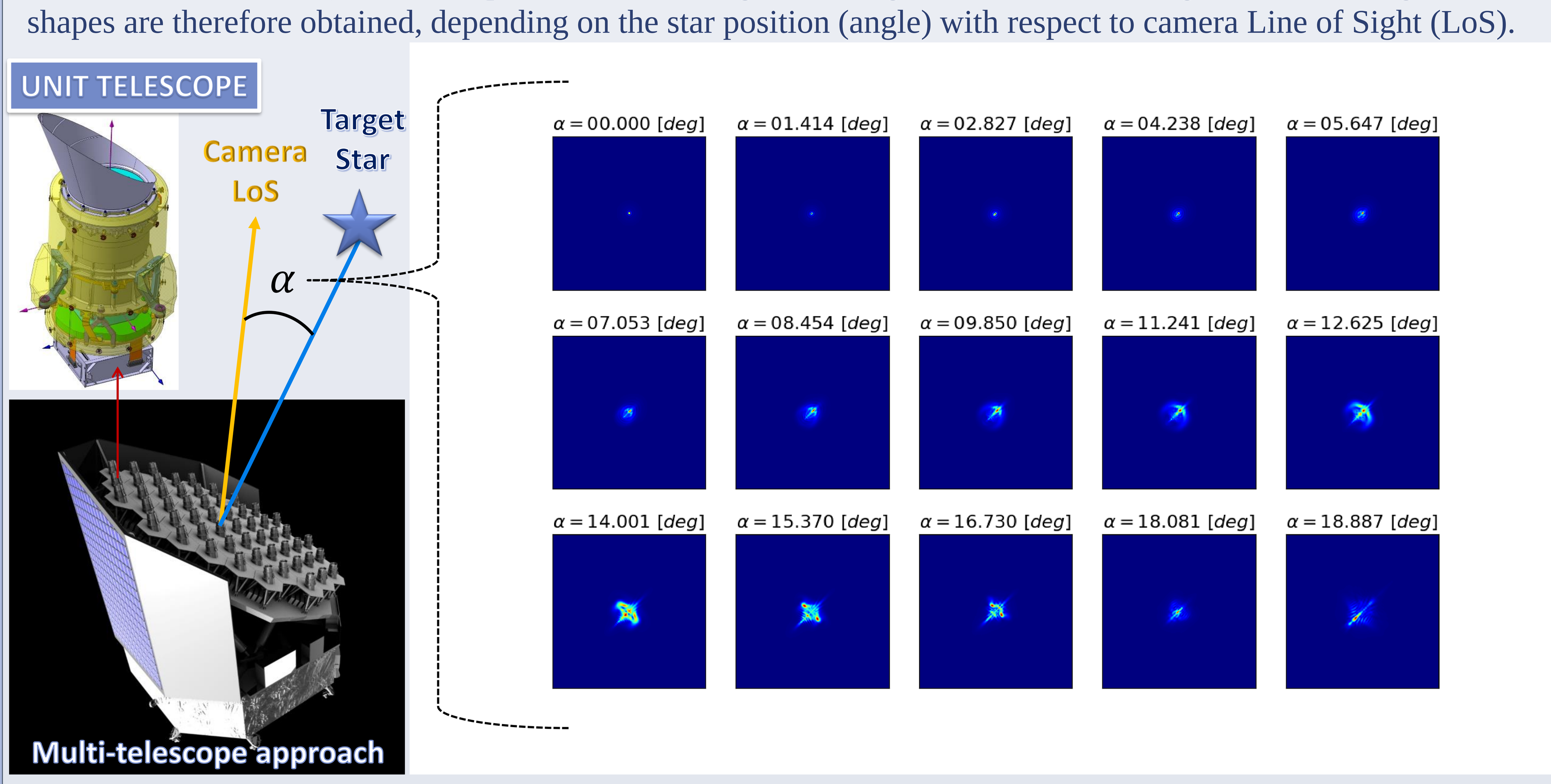
INTRODUCTION

This work presents the preliminary results of the development carried out to design optimized photometric masks to derive on-board lightcurves for an ample set of target stars of the ESA's space mission PLAnetary Transits and Oscillations of stars (PLATO). PLATO possess a unique and unprecedent multi-telescope approach. Each telescope (24+2=26 in total) built is such that 90% of its point spread function (PSF) energy is concentrated within about four pixels of the detector. While this configuration is key to maximise the number of observed stars, it has though an inconvenient: the size of the pixels is significantly large with respect to the size of the PSF, leading to considerably higher photometric sensibility to spacecraft *jitter*, contaminant neighbouring stars and long-term star position drift. Hence, to reduce the sensibility to *jitter* and the flux pollution induced by the presence of a contaminant star, rather than using classical aperture binary masks to derive on-board photometry, it is proposed the use of weighted Gaussian masks. This choice allows to retrieve most of the star flux located at the centre of the star image and – in comparison with the classical (binary) aperture masks – smoothly minimize the flux contribution of neighbouring contaminants as well as the noise induced by the satellite. To prevent the target stars from going out of the mask due to the long-term star position drift, the mask positions will be updated on-board. Compared to the classical aperture masks, weighted Gaussian masks are expected to minimize the discontinuities introduced by each mask update. In this context, this work presents the methodology behind the development of weighted masks, with a highlight on the preliminary results obtained from a study of impact of contaminant stars on their performance. The photometric parameters evaluated in this analysis are the signal-to-noise ratio (SNR), the flux stability and the contamination rate. The sources of noise introduced in the simulations include at this stage photon noise, readout noise, and background noise.

Keywords: PLATO, correction algorithms, stellar photometry, aperture photometry, stellar seismology, exoplanet search.

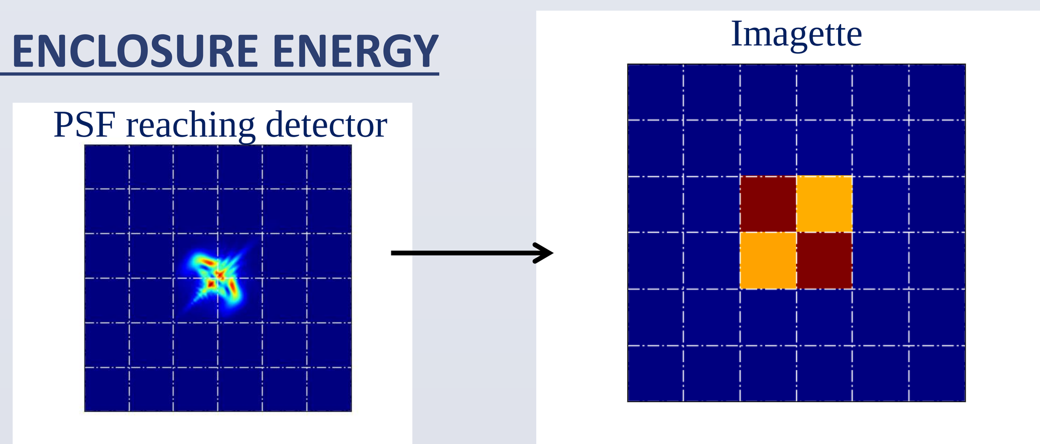
INSTRUMENT OPTICAL RESPONSE vs STAR POSITION IN FOV

Each PLATO camera (unit telescope) can cover a large 1100 deg² FoV. Within this region, a wide range of PSF shapes are therefore obtained, depending on the star position (angle) with respect to camera Line of Sight (LoS).



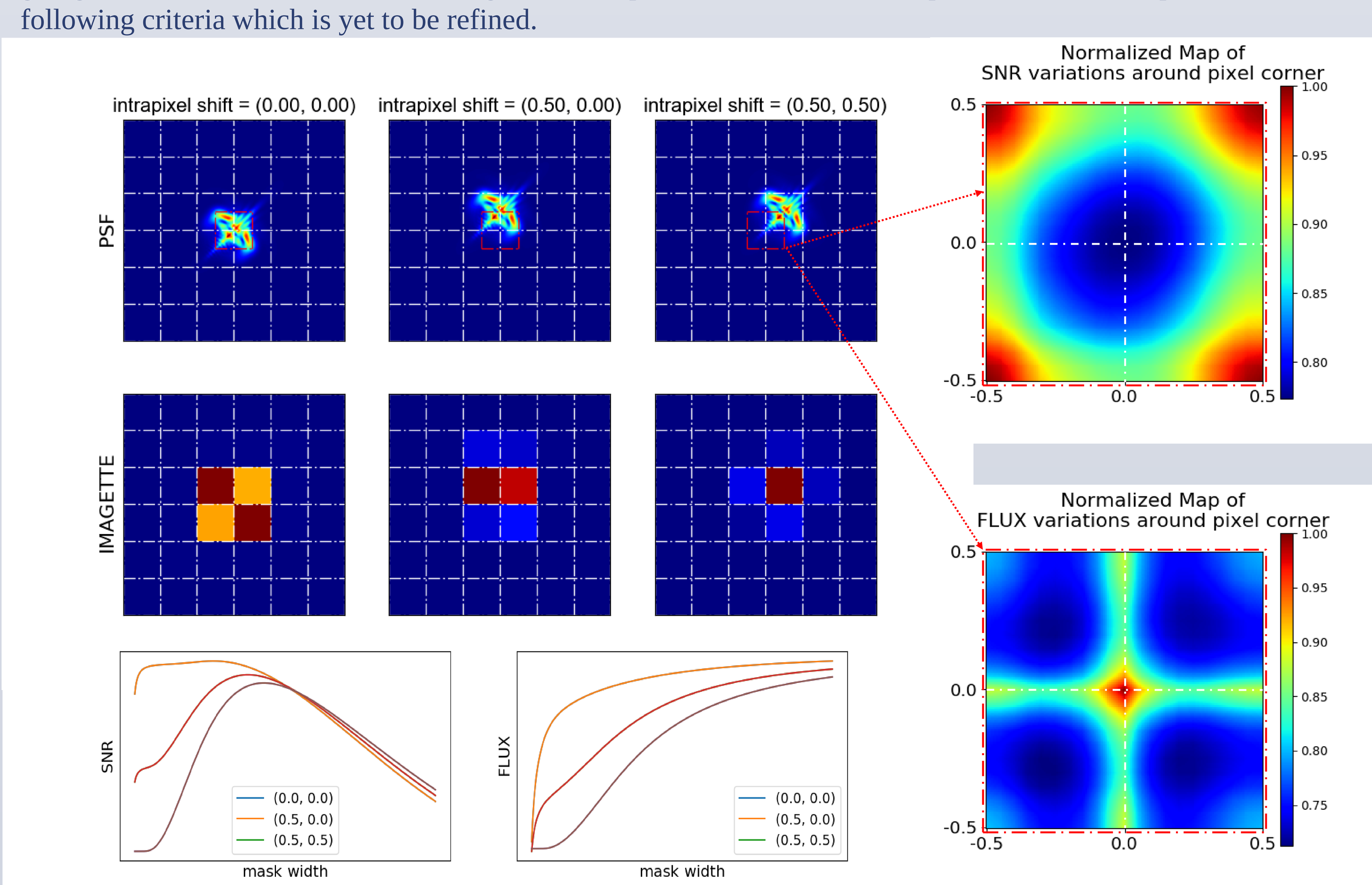
PSF ENCLOSURE ENERGY

To maximise the number of observed stars, 90% of the PSF energy is concentrated within about 4 pixels of the CCDs. At detector level, star flux are translated into low spatial resolution images called imagettes.



LONG-TERM DRIFT OF STAR CENTROIDS

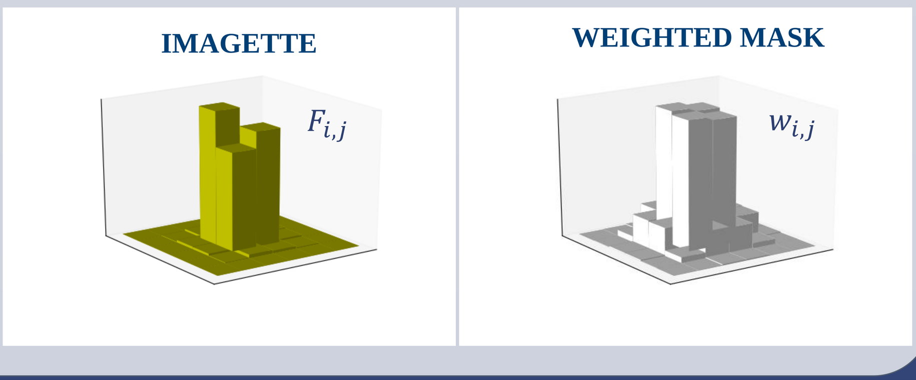
At any given moment, star centroids may be located up to half a pixel near a pixel corner (symmetry point). Over time, thermoelastic distortion and kinematic aberration may primarily account for star centroid displacements that can reach up to 1.3 pixel over 3 months (worst case). Since star PSFs are very small with respect to pixel dimensions, important variations on the low-resolution PSF models arise as their centroids moves in the vicinities of a pixel corner. As a consequence, photometric aperture mask parameters, such as Signal-to-Noise Ratio (SNR) and flux are sensible to the target star intrapixel centroid position. To prevent the target stars from going out of the mask due to the long-term star position drift, the mask positions will be updated on-board following criteria which is yet to be refined.



ON-BOARD PHOTOMETRY PERFORMANCE EVALUATION

$$SNR = \frac{\sum_{i,j}(F_{i,j} * w_{i,j})}{\sqrt{\sum_{i,j}(F_{i,j} * w_{i,j}^2) + \sum_{i,j}(B_{i,j} * w_{i,j}^2) + \sum_{i,j}(R^2 * w_{i,j}^2)}}$$

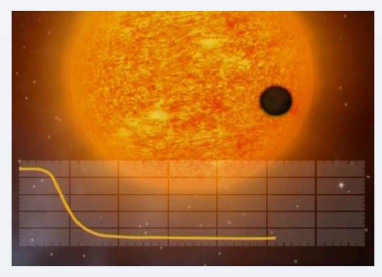
$F_{i,j}$ = star flux at pixel (i, j)
$w_{i,j}$ = mask weigth at pixel (i, j)
B = background noise at pixel (i, j)
R = readout noise at pixel (i, j)
$*$ = term by term multiplication



PRESENCE OF CONTAMINANT FLUX WITHIN THE APERTURE MASKS

IMPACT ON PLANETARY TRANSIT SCIENCE

PLATO will observe moderately crowded fields, which will lead to target star flux contamination and thus degraded performance and/or reliability of mission's planetary transit science.

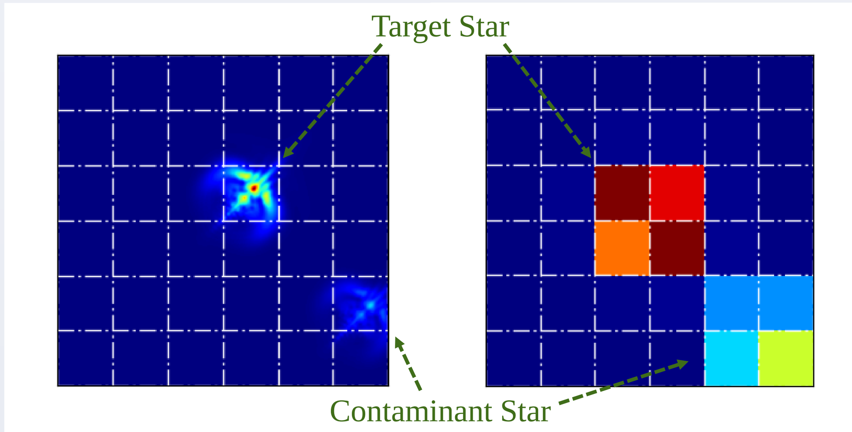


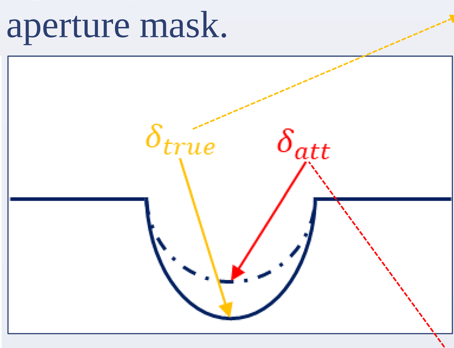
TRANSIT ATTENUATION

An example of performance degradation is transit attenuation. When contaminant flux from a parasite star falls within the aperture mask, a true planet transit δ_{true} appears to be less deeper than it really is, making it more difficult to be detected. In such scenario, the corresponding attenuated transit depth δ_{att} can be computed directly from the flux contamination rate τ_C within the aperture mask.

TYPICAL TRANSIT DEPTHS

Gas giant: $\delta_{true} \sim 0.01$
Neptunian: $\delta_{true} \sim 0.001$
Earth: $\delta_{true} \sim 80$ppm





PHOTOMETRIC FLUX CONTAMINATION RATE

$$\tau_C = \frac{F_C}{F_T + F_C}$$

F_C = contaminant star flux within mask
F_T = target star flux within mask

ATTENUATED TRANSIT DEPTH

$$\delta_{att} = (1 - \tau_C) \cdot \delta_{true}$$

FALSE TRANSIT GENERATION

An example of reliability degradation is false transits, as it can lead to false positive detections. When the flux from a background eclipsing binary falls within the aperture mask, it generates a false planet transit that cannot be distinguished from a true one by simply evaluating the lightcurve. The observed false transit depth δ_{obs} depends on the background eclipsing binary transit depth δ_{back} and on the flux contamination rate τ_C within the aperture mask. It can also be computed as a function of δ_{back} and the effective differential magnitude Δm_{eff} between the target star and the binary system. The effective differential magnitude stands for the differential magnitude between the target star and the binary system evaluated from their relative flux within the aperture mask.

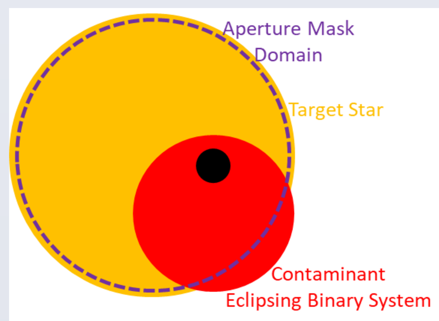
$$\delta_{obs} = \frac{\tau_C}{1 - \tau_C}\left(1 - 10^{-0.4\delta_{back}}\right) = 10^{-0.4\Delta m_{eff}}\left(1 - 10^{-0.4\delta_{back}}\right)$$

CONTAMINATION RATE

$$\tau_C = \frac{\delta_{obs}}{\left(1 - 10^{-0.4\delta_{back}}\right) + \delta_{obs}}$$

EFFECTIVE DIFFERENTIAL MAGNITUDE

$$\Delta m_{eff} = -2.5\log_{10}\left(\frac{\delta_{obs}}{1 - 10^{-0.4\delta_{back}}}\right)$$

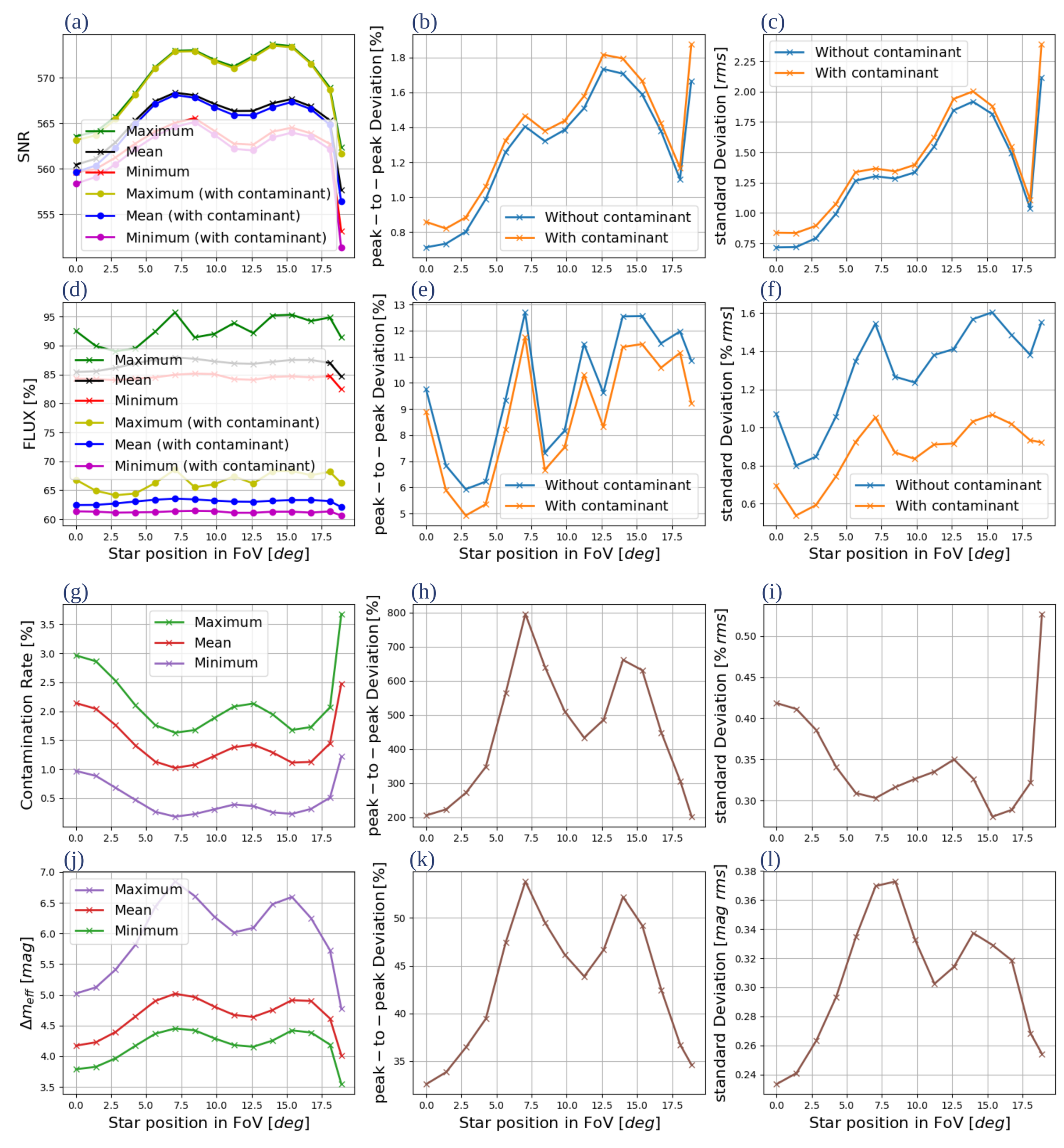


Critical values of contamination rate (τ_c) and effective differential magnitude (Δm_{eff}) that can simulate some typical planet transits

δ_{back} [mag]	Typical δ_{obs}					
	Gas giant		Neptunian		Earth	
	0.01		0.001		80ppm	
	Critical τ_C [%]	Critical Δm_{eff} [mag]	Critical τ_C [%]	Critical Δm_{eff} [mag]	Critical τ_C [%]	Critical Δm_{eff} [mag]
0.2	5.61	3.06	0.59	5.56	0.048	8.31
0.4	3.14	3.72	0.32	6.22	0.026	8.96
0.6	2.30	4.07	0.23	6.57	0.019	9.31
0.8	1.88	4.29	0.19	6.79	0.015	9.54
1.0	1.63	4.45	0.17	6.95	0.013	9.69

PERFORMANCE OF WEIGHTED SYMMETRIC GAUSSIAN MASKS

SIMULATION PARAMETERS
Target star temperature = 6000K ; Target star magnitude = 10.7
Parasite star temperature = 6000K ; Parasite star magnitude = 11.7 ; Distance between target star and parasite star centroids = 3 pixels



Without the presence of contaminant stars within the aperture, symmetric Gaussian masks present, for a 6000K and $m_V = 10.7$ target star, compliant SNR levels (a) at all star positions within FoV and intrapixel positions at the detector. Variations are under 1.8% pic-to-pic (b) and 2.5 rms (c). Photometric FLUX are less stable, with variations close to 13% pic-to-pic (e) and up to 1.6% rms (f). Such variations are going to be anyway efficiently corrected on ground with the knowledge of the PSF and the star displacement.

Under the presence of a 6000K and $m_V = 11.7$ contaminant star with centroid located three pixels far from the target star (illustrative but not necessarily typical), similar results are obtained in terms of absolute SNR (a), SNR stability (b, c) and FLUX stability (e, f).

At one pixel distance though (not showed in the plots), SNR values drop down by 12.5% with respect to the contamination-free case, with variations reaching up to 10% pic-to-pic and 11 rms. FLUX variations reach up to 17% pic-to-pic and 2% rms under the same condition.

When it comes to contamination rate (g), at three pixels distance between the target star and the contaminant star, levels can be higher than 3.5%, which is enough to generate gas giant false transits for δ_{back} values as small as 0.4 mag (see table above).

The above results show that the contamination rate is a critical parameter that has to be taken into account for optimizing the aperture masks of PLATO target stars. In other words, the strategy of defining aperture mask models that only aims to maximize the SNR, as done for CoRoT and Kepler missions, is not enough to provide adequate photometry products for the PLATO planetary transit science. Thus, a compromise between SNR and contamination rate must be defined to derive optimized photometric masks for the PLATO targets. Next steps in the development include crossing information of contamination rate with the upcoming PLATO Input catalogue (PIC) data, as well as stellar densities as a function of their relative magnitudes and distances. These complementary information will help us to determine the most probable contamination scenarios. Future work also include evaluating the impact of satellite jitter, CCD Charge Transfer Inefficiency (CTI), Brighter-Fatter Effect (BFE) on the masks performances, as well as developing on-ground algorithms to correct for those effects and to minimize the detection of false positives. Possible use of asymmetric Gaussian mask will be evaluated as mitigation strategy. The whole performance analysis is also being executed with the use of binary and optimal weight mask structures.

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