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Marco Gullieuszik[a], Demetrio Magrin[a], Davide Greggio[a,b], Roberto Ragazzoni[a], Valerio Nascimbeni[b], Maria Bergomi[a], Federico Biondi[a], Simonetta Chinellato[a], Marco Dima[a], Jacopo Farinato[a], Luca Marafatto[a], Valentina Viotto[a], Matteo Munari[c], Isabella Pagano[c], Daniela Sicilia[c], Stefano Basso[d], Francesco Borsa[d], Mauro Ghigo[d], Daniele Spiga[d], Thimoty Bandy[e], Willy Benz[e], Mathias Brändli[e], Giordano Bruno[e], Thierry De Roche[e], Daniele Piazza[e], Martin Rieder[e], Alexis Brandeker[f], Maximilian Klebor[g], Valery Mogulsky[g], Mario Schweitzer[g], Matthias Wieser[g], Anders Erikson[h], and Heike Rauer[h]

[a]INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[b]Dipartimento di Fisica ed Astronomia, Università degli Studi di Padova, Vicolo dell'Osservatorio 3, 35122 Padova, Italy
[c]INAF - Osservatorio Astrofisico di Catania, Via S. Sofia 78, 95123 Catania, Italy
[d]INAF - Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milano, Italy
[e]Physikalisches Institut,University of Bern, Sidlerstaße 5, CH-3012 Bern, Switzerland
[f]Department of Astronomy , Stockholm University, SE-106 91 Stockholm, Sweden
[g]OHB System, Manfred-Fuchs Straße 1,82234 Weßling - Oberpfaffenhofen, Germany
[h]DLR - Institut für Planetenforschun, Rutherfordstraße 2, 12489 Berlin, Germany

ABSTRACT

Thermal effects in PLATO are analyzed in terms of uniform temperature variations, longitudinal and lateral temperature gradients. We characterize these effects by evaluating the PSF centroid shifts and the Enclosed Energy variations across the whole FoV. These patterns can then be used to gauge the thermal behavior of each individual telescope in order to improve the local photometric calibration across the PLATO field of view.

Keywords: Telescopes, Instrumentation: photometers, planetary systems

1. INTRODUCTION

The PLAnetary Transits and Oscillation of stars (PLATO,[1]) is one of the medium-class mission in ESA Cosmic Vision Programme 2015-2025. Its main goal is to find and characterize Earth-like exoplanets in the habitable zone of Sun-like stars by photometric planetary transit detection. A detailed mission overview is given in [2].

The PLATO instrument consists of an array of 32 *normal* cameras plus 2 *fast* ones –dedicated to improve the pointing stability– mounted on a common optical bench. Each of them consists of a 6 lenses telescope optical unit (TOU) with a pupil diameter of 120 mm and a focal plane assembly (FPA) equipped with a 2×2 array of four CCDs with 4510×4510 18 μm pixels having a pixel scale of 15 arcsec. The FoV of each camera is ~ 1100 square degrees. The 32 normal TOUs are arranged in four groups of 8 units each. Each group is pointed at a direction that is displaced of about 9.2° from the center of the overall field of view. The total sky coverage of PLATO is 2250 square degrees.

A detailed description of the TOU optical configuration is given in [3], presenting all the updates with respect to the baseline of the pre-selection phase [4].

The detection of the transits of Earth-like planets will require extremely accurate photometry. PLATO is expected to provide flux measurements with an accuracy of 34 ppm with an exposure time of 1h for stars with magnitude $V < 11$ mag. An extremely accurate instrumental calibration is a key-aspect to be considered to obtain photometric time-series with a photometric accuracy suitable to achieve the scientific goals of the mission.

Send correspondence to marco.gullieuszik@oapd.inaf.it

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Thermal variations are one of the main factors to be considered in this context; temperature variations produce deformations of the telescope structure and variations of the refractive index of the TOU optical elements that distort the PSF. Our work aims at studying these distortions and the effect on the photometric accuracy across the PLATO field of view.

2. GENERATION OF PSFS

The goal of our analysis is a preliminary description of the impact of thermal variations on PLATO photometry. We therefore developed a toy-model to provide a first-order description of PSF variations as function of TOU temperature variations in a limited set of ideal cases. PSF variations are characterized in terms of centroid coordinates and enclosed energy (EE).

To this end, we considered separately the effect of:

- Constant temperature variation. The temperature was uniformly changed with respect to the nominal value ($T_0 = -80.0\,^\circ$C) by $\pm 0.1\,^\circ$, $\pm 0.2\,^\circ$, and $\pm 0.3\,^\circ$.
- Temperature gradient along the TOU optical axis (OA). The temperature at the FPA was fixed to the nominal value T_0. The temperature at the entrance window was set to $T_0 + \Delta T$; we considered six different values of ΔT: $\pm 0.1\,^\circ$, $\pm 0.2\,^\circ$, and $\pm 0.3\,^\circ$. The temperature of each element (optical and mechanical) was set to a constant value corresponding to the geometrical position of the element center with respect to the OA, assuming a uniform thermal gradient along the OA from the entrance window to the FPA.
- Temperature gradient perpendicular to the OA. The temperature at one side (parallel to the OA) was fixed to the nominal value T_0. The temperature on the opposite side of the TOU was set to $T_0 + \Delta T$; also in this case we considered the six values $\Delta T = \pm 0.1\,^\circ$, $\pm 0.2\,^\circ$, and $\pm 0.3\,^\circ$. On the side at $T_0 + \Delta T$, we computed the structure length from the FPA to each mechanical constraint. Each optical element was then tilted around its mechanical constraint on the side at T_0, assuming the computed displacement of the mechanical constraint on the opposite side and an optical element diameter equal to the physical aperture. The temperature of the optical element was set to $T_0 + \Delta T/2$.

To evaluate the variations of the PSF across the TOU field of view, we simulated the PSF at different positions on the focal plane for each thermal configuration. The positions used for our analysis are shown in Fig. 1. Given the problem symmetry, in the cases with uniform temperature and temperature gradients along the optical axis, we processed the PSF only in the fields from 0 to 16, while in the cases of temperature gradients perpendicular to the OA we considered fields form 0 to 52 (see Fig. 1).

The three thermo-mechanical models were implemented in ZEMAX and the polycromatic PSFs were computed using HUYGENS method, adopting the pass-band filter foreseen for PLATO (see [2] for details). The pupil was sampled with 512×512 points; PSF images were sampled with 256×256 sub-pixels having size of 0.563 μm (i.e. 1/32 PLATO pixel size). Each image has therefore a size corresponding to 8×8 PLATO pixels. The EE was evaluated in squares with a side of 2.0×2.0 PLATO pixels centered at the centroid coordinates. As an example, three PSFs obtained in the case with constant temperature $T = -80.3\,^\circ$C at three different radial distances from the FPA center are shown in Fig. 2.

3. MODELING THERMAL EFFECTS ON THE PSF.

We computed the differences of the EE and of the centroid position with respect to the values obtained for the case with the TOU operating at the nominal temperature $T_0 = -80.0\,^\circ$C for each thermal configuration and each field. For each thermal configuration, the resulting values obtained for all positions on the FPA were then fitted using a linear combination of Zernike polynomials. The choice of the polynomials was driven by the symmetry of the problem. The best-fit Zernike coefficients are shown in Fig. 3 and 4. Their values as a function of ΔT for each of the three modes of temperature variation (constant temperature, gradient along OA and gradient perpendicular to the OA) were fitted using 1st or 2nd order polynomials. The resulting best-fit functions are shown in Fig. 3 and 4. These figures also summarize which Zernike polynomials were used to

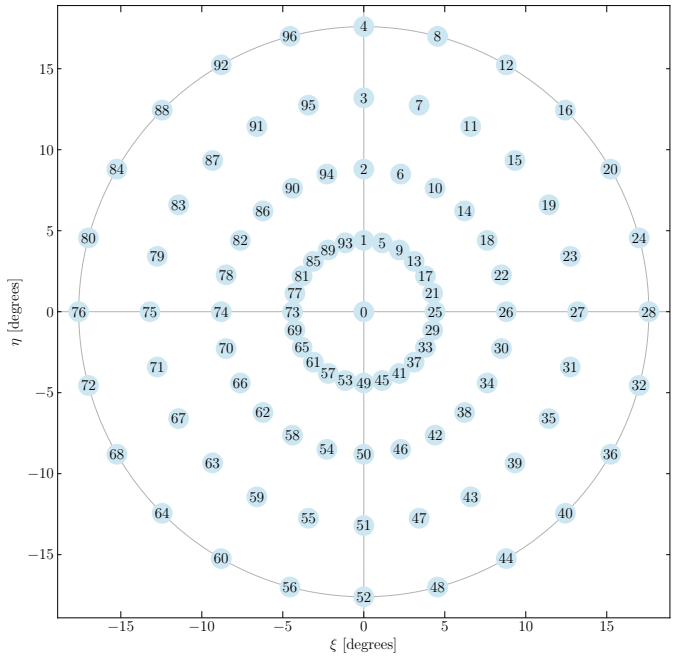

Figure 1. Positions of the fields used to evaluate the PLATO TOU PSFs. Coordinates are expressed as angular distances from the nominal center of the FPA.

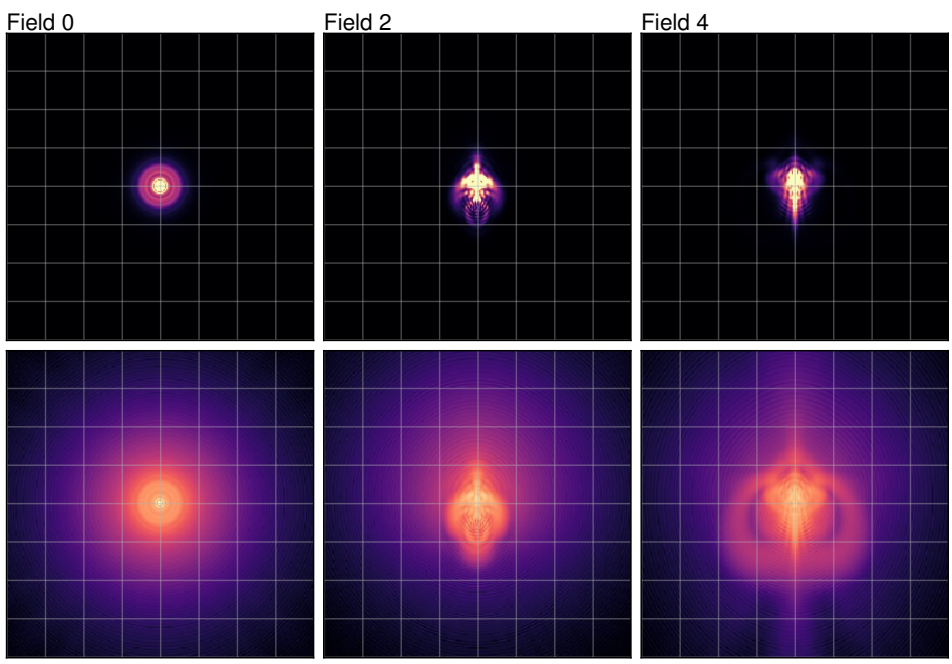

Figure 2. An example of three PLATO PSFs obtained for the configuration at constant temperature $T = -80.3°$C. To better display both the bright central core and the faint halo of the PSF, the images are displayed in linear scale in the upper panels and in logarithmic scale in the lower panels. The grid in each panel corresponds to the PLATO pixels.

fit the EE variations and the centroid displacements. To conclude, the variations of EE and centroid position were fitted using Zernike polynomials expansions with coefficients dependent on the temperature variations: $\sum_i (a_i \Delta T^2 + b_i \Delta T)\, Z_i(r, \alpha)$, where (r, α) is the position in the FPA, Z_i are the Zernike polynomials, Δt is the temperature variation (or the temperature gradient), a and b are constants (see Fig. 3 and 4).

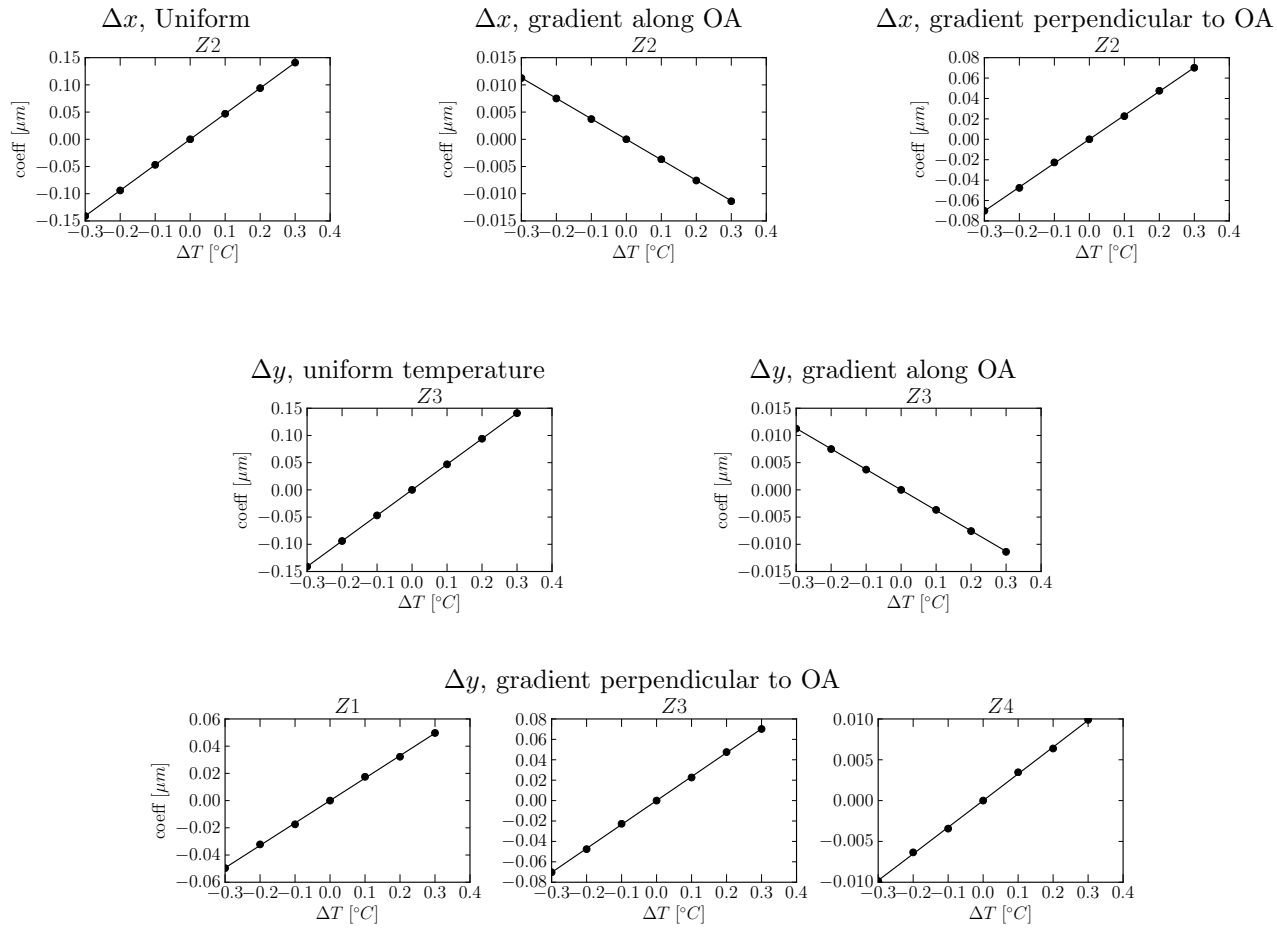

Figure 3. Best-fit Zernike coefficients for the centroid position displacements (in x and y) for the three temperature variation modes.

Examples of the resulting best-fit solutions for the three temperature variations modes are shown in Fig. 5 for the cases with $\Delta T = +0.3°$C and $-0.3°$C. To summarize our analysis, we found that temperature variations of 0.3°C result in EE variations up $\sim \pm 4500$ ppm across the FPA. The centroid position displacements strongly depends on how the temperature varies across the TOU; in the case of temperature gradients along the OA, the position of the PSF centroid do not change significantly, while it can be displaced up to $\sim 0.2\mu$m in the case of uniform temperature variations and/or temperature gradients perpendicular to the OA. These variations are however of the order of 0.01 pixels and would therefore not represent a major issue. On the other hand, we showed that thermal effects on the EE need to be properly taken into account in the photometric calibration of PLATO data.

Our models aim at a first-order estimate of the thermal effects on PLATO PSF. In particular we implemented very simple recipes to account for thermal effects on the mechanical structure of the TOU. However our toy-model provides an important first set of results that need to be taken into consideration to develop the strategy to calibrate PLATO observations.

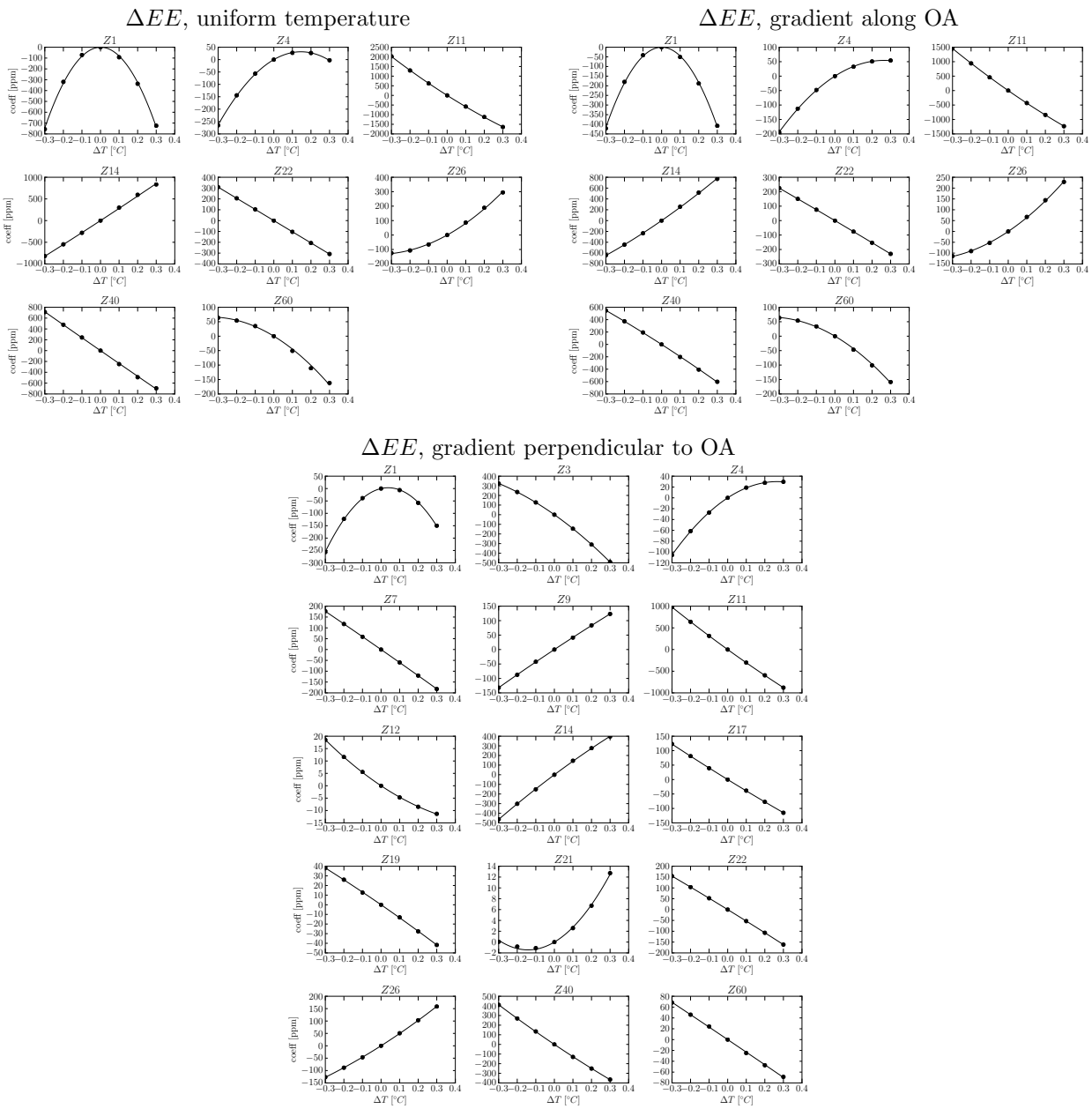

Figure 4. Best-fit Zernike coefficients for the EE variation for the three temperature variation modes.

4. SIMULATION OF PLATO PHOTOMETRY

Photometric variations due to PSF distortion produce an apparent variation of the photometric zero-point. This needs to be corrected for in order to obtain reliable light curves to be used for planetary transit detection. PLATO will detect a large number of bright stars in each image and therefore it will be possible to evaluate local photometric zero-points variations by comparing and modeling the magnitude differences measured for the same stars at different epochs. In principle, this is complicated by stellar variability and planetary transits. In this section we provide a simple approach to show that planetary transits would not be a major issue for the computation of local photometric zero-point corrections.

We took as a reference a simulation of PLATO observations of the South PLATO field (SPF) at $l = 253°$,

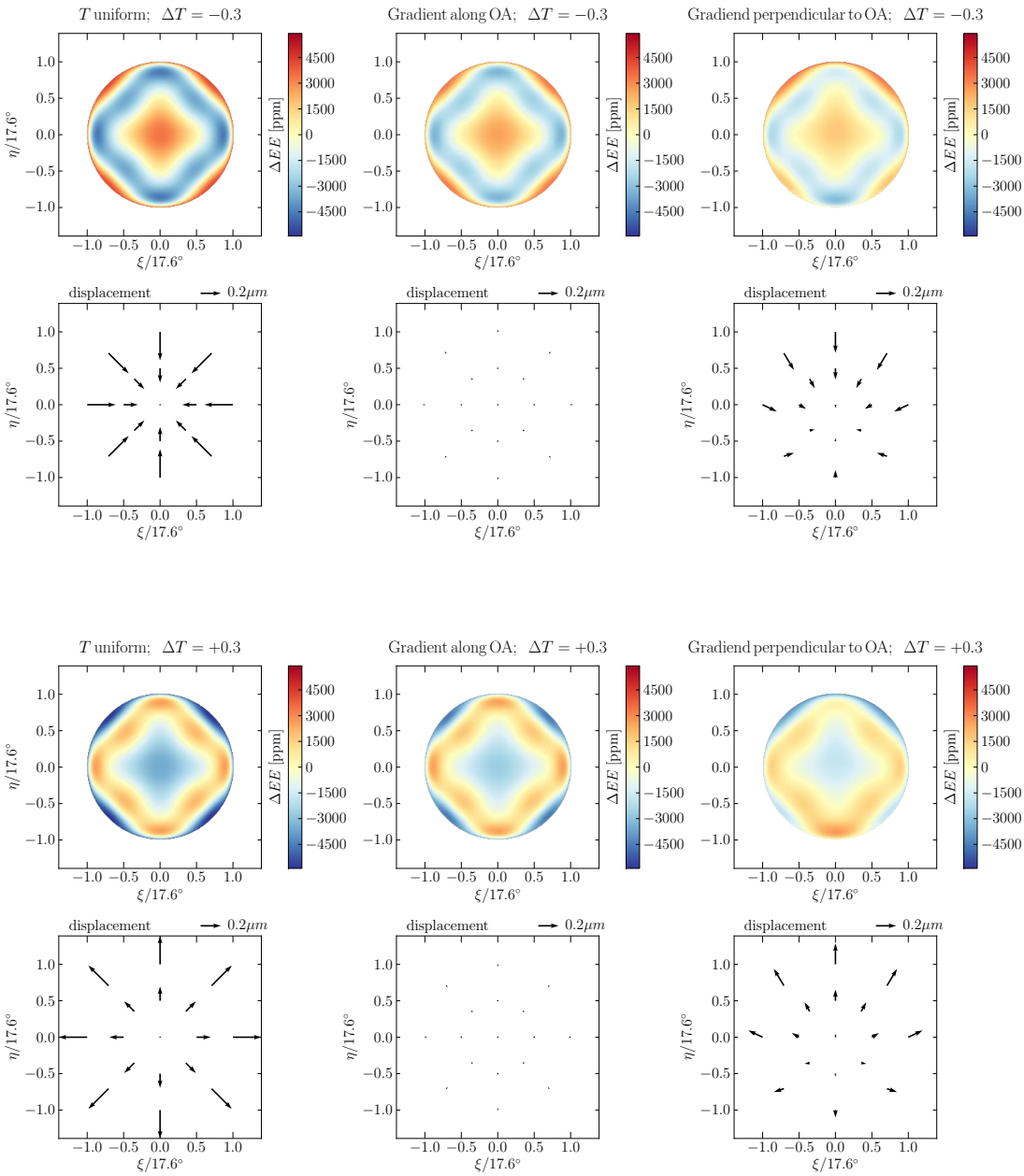

Figure 5. Variations on the EE (upper panels) and on the PSF centroid positions (lower panels) for uniform temperature variations (left panels), temperature gradients along the OA (central panels) and perpendicular to the OA (right panels). The six upper panels refer to the case with $\Delta T = -0.3°$ and the lower ones to the case with $\Delta T = +0.3°$.

$b = -30°$, developed by the PLATO science team in the framework of the PLATO stellar sample count estimate and preliminary field selection (Nascimbeni, priv. comunication). This simulation produced a catalog of target stars positions and photometric measurements (flux and associated uncertainty). For our analysis we considered only the brightest stars, with $V < 11$ mag, which result to be $\sim 10^4$ in the FoV of a single TOU. The instrumental noise budget for each target star was calculated assuming an exposure time of 1h. As a reference, it results to be ~ 200 ppm for a star with $V = 11$ mag. We simulated two-epoch PLATO observations; the telescope was assumed to operate at a constant temperature $T_0 = -80°$C during the first one and in a random thermal condition

during the second one. We randomly selected ΔT values in the range $-0.3°$C and $+0.3°$C and we defined the total ΔEE and centroid displacements as the sum of the ΔEE and displacements for the temperature variation modes defined in the previous section. To account for the inclination of the thermal gradient perpendicular to the OA, we introduced a forth mode that is obtained by rotating 90° the ΔEE maps derived for the temperature gradient along the y axis in Fig. 5. The thermal state is therefore defined by 4 ΔT values. We assumed that 3% of target stars shows a transit during the second epoch; all transits are assumed to have a depth of 500 ppm. The assumed number of transiting planets is clearly overestimated (the *total* number of candidate planets found by KEPLER is $\sim 3\%$). This is a conservative choice, because a large number of stars showing transits clearly makes it more difficult to recover the correct photometric variations induced by thermal effects.

For each simulation we randomly selected the four ΔT values and we built the ΔEE and displacement maps by summing the four ΔEE, Δx and Δy obtained from the functions in Fig. 3 and 4. The resulting values were perturbed with Gaussian noise corresponding to the photometric uncertainty of the target stars. We then randomly selected the stars with transiting planets and we subtracted 500 ppm to their flux. We performed 50 independent simulations and for each of them we fitted the resulting ΔEE with a combination of Zernike polynomials. We repeated the fitting procedures using Zernike polynomials up to different radial orders, from 3 (10 Zernike polynomials in total) to 10 (66 Zernike polynomials) and analyzed the fit residual distribution. In the ideal situation of a perfect correction for the thermal effect on PLATO photometry, the distribution of the residuals should be equal to the distribution of the target stars photometric errors. The lower panel of Fig. 6 shows the r.m.s. of the residuals for all 50 simulations obtained with different number of Zernike polynomials. In the upper panel we show the corresponding values for the reduced χ^2. This was calculated as the sum of the residuals divided by the photometric error of each star normalized to the number of degrees of freedom. When a low number of Zernike polynomials are used, the r.m.s. of the fit residuals and the χ^2 are quite large in most cases because it was not possible to provide a sufficiently accurate description of the ΔEE across the FPA. The optimal results are found when all Zernike polynomials up to radial order of 10 (up to $Z66$) are used. This is an obvious result because in this case we are using all Zernike polynomials used to define our base functions (the highest order Zernike polynomial used was $Z60$; see previous sections and Fig. 3). Using the optimal number of Zernike polynomials, the r.m.s. result to be on average of 145 ppm, and for all 50 simulations we obtained $\chi^2 = 1$. In conclusion, our analysis shows that it will be possible to fully correct for thermal effects with a negligible final impact on the photometric accuracy of PLATO. Once the thermal effects will be accurately accounted for, temperature variations would not be a major issue for the planetary transit detection and characterization capability of PLATO.

5. CONCLUSIONS

We presented a study of the effects on PLATO PSF due to temperature variations. We implemented in ZEMAX a simple thermo-mechanical model to analyze the effect of uniform temperature variations, temperature gradients parallel to and perpendicular to the telescope's optical axis. PSF variations were analyzed in terms of EE variations and centroid displacements with respect to the nominal working conditions, at a constant temperature $T_0 = -80.0°$C. We found that the uniform temperature variations and/or temperature gradients of $\Delta T = \pm 0.3°$C would produce variations of the EE up to $\sim \pm 4500$ ppm across the field of view. The effect on the PSF centroid position is at the most of the order of $0.2\mu m$, which corresponds to ~ 0.01 pixel; temperature gradients up to $\Delta T = \pm 0.3°$C parallel to the optical axis instead do not significantly affect the PSF centroid position. To complete our analysis we made a number of simulations of PLATO observations under random thermal conditions by combining the results obtained from our analysis of the three simple cases. We found that the large number of stars that will be observed in a single PLATO pointing will provide enough data to precisely fit and correct for photometric variations due to thermal variations. Our analysis is based on simple assumptions and a number of approximations but it provides important first-order estimates for the thermal effects on PLATO PSF. A much more detailed analysis based on complete thermo-mechanical modeling of the telescope structure is foreseen after the finalization of the PLATO opto-mechanical design.

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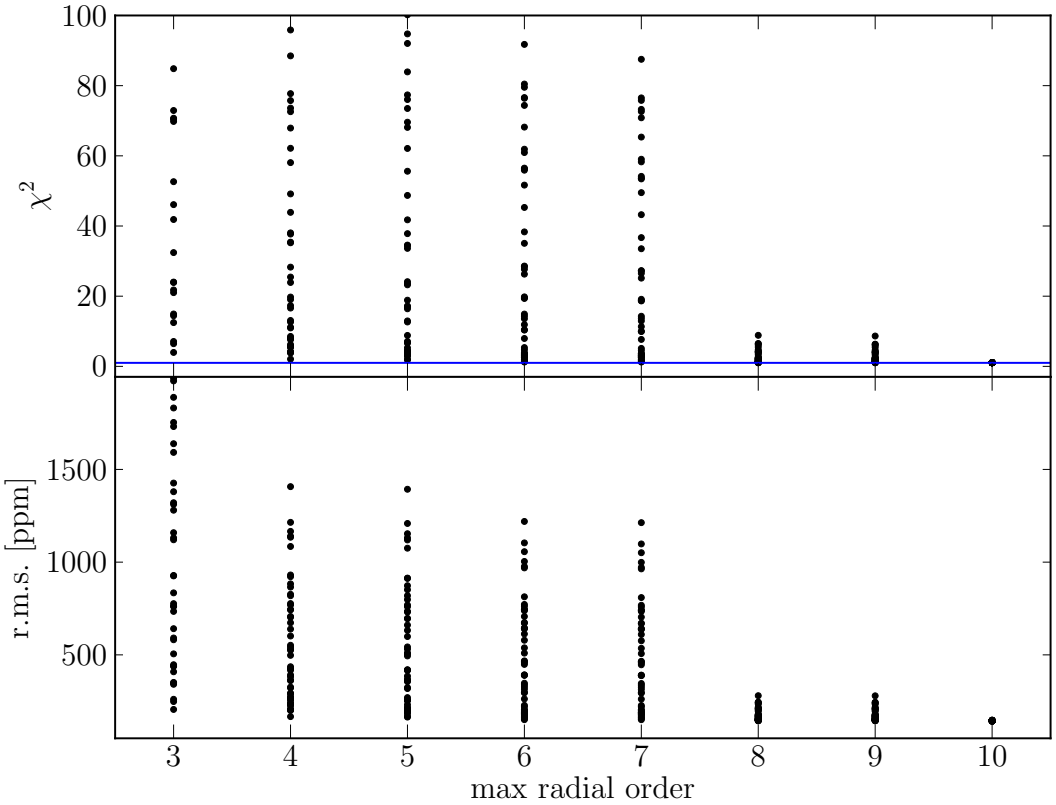

Figure 6. Reduced χ^2 and r.m.s of the fit to the ΔEE obtained for the 50 simulations of PLATO observations under random thermal conditions (see text). We show results obtained using series of Zernike polynomials with different maximum radial order, from 3 (10 Zernike polynomials) to 10 (66 Zernike polynomials). Each dot show the value corresponding to each simulation. The horizontal line show the value $\chi^2 = 1$ as a reference.

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