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► To cite this version:

Fabien Malbet, Manon Lizzana, Fabrice Pancher, Sébastien Soler, Alain Léger, et al.. Challenges in focal plane and telescope calibration for high-precision space astrometry. Proceedings of SPIE, the International Society for Optical Engineering, 2024, 13092, pp.130920B. 10.1117/12.3019233 . hal-04681289

HAL Id: hal-04681289

<https://hal.science/hal-04681289v1>

Submitted on 29 Aug 2024

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Challenges in focal plane and telescope calibration for High-Precision Space Astrometry

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ABSTRACT

With sub-microarcsecond angular accuracy, the *Theia* telescope will be capable of revealing the architectures of nearby exoplanetary systems down to the mass of Earth. This research addresses the challenges inherent in space astrometry missions, focusing on focal plane calibration and telescope optical distortion. We propose to assess the future feasibility of large-format detectors (50 to 200 megapixels) in a controlled laboratory environment. The aim is to improve the architecture of the focal plane while ensuring that specifications are met. The use of field stars as metrological sources for calibrating the optical distortion of the field may help to constrain telescope stability. The paper concludes with an attempt to confirm in the laboratory the performance predicted by simulations. We will also address the possibility of using such techniques with a dedicated instrument for the Habitable World Observatory.

Keywords: astronomy, astrophysics, dark matter, exoplanet, astrometry, differential, visible, high precision, space mission

1. INTRODUCTION

ESA's *Hipparcos* and *Gaia* global astrometry scanning missions have revolutionized our understanding of the Solar Neighborhood and the Milky Way, providing fundamental new foundations for numerous fields of astronomy.

Global astrometry involves connecting stars at large angular distances in a network where each star is linked to several others in all directions. The network closure condition ensures the reduction of positional errors for all stars¹. The *Hipparcos* mission² demonstrated its capability to achieve global measurements, such as positions and changes in position due to proper motion and parallax, determined within a reference system consistently defined across the entire sky for a large number of objects. Milliarcsecond precision was achieved using a continuously scanning satellite that observes two directions simultaneously.

Similar to *Hipparcos* but with 100 times greater accuracy, 1,000 times greater limiting magnitude and 10,000 times greater number of stars observed, *Gaia*³ consists of two telescopes offering two directions of observation with a fixed wide angle between them. The spacecraft rotates continuously around an axis perpendicular to the lines of sight of the two telescopes. This axis of rotation slightly precesses across the sky while maintaining the same angle to the Sun. By precisely measuring the relative positions of objects in both directions, a rigid reference system is obtained. The two main features of the telescope are: a 1.45×0.5 m primary mirror for each telescope and a 1.0×0.5 m focal plane onto which the light from both telescopes is projected. This array

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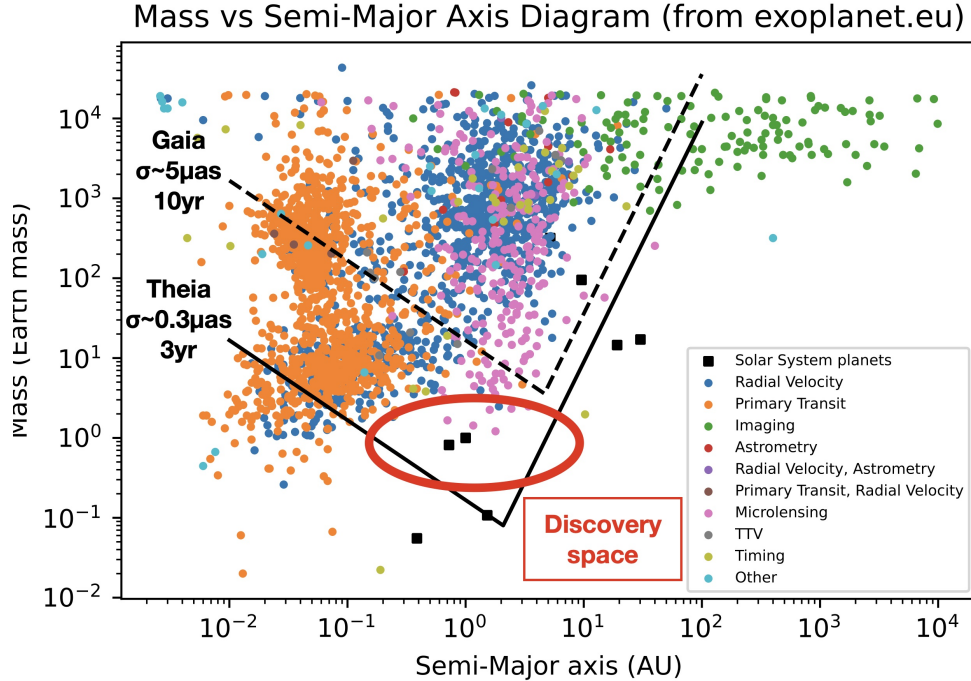


Figure 1. Exoplanets discovery space.

comprises over 900 megapixels. On average, each celestial object has been observed about 70 times over the five-year nominal mission, which has been extended to ten years, doubling the number of observations.

For specific astronomical objects, the accuracy of astrometric measurements can be enhanced by dedicating more observing time to determining their relative position to the stars in the field of view, known as relative astrometry or differential astrometry.

The topic of high-precision astrometry emerged from the *Space Interferometry Mission (SIM)* in the late 2000s, aimed at detecting Earth-like exoplanets while maintaining the methodology to achieve absolute astrometry. Following the cancellation of SIM by NASA in 2010, a small team proposed a new concept to address high-precision astrometry called the *Nearby Earth Astrometry Telescope (NEAT)*. NEAT, consisting of a single off-axis mirror directing light onto a detector in a formation flight configuration⁴, was presented for the M3 mission call at ESA. Subsequently, the *Theia* concept, featuring a single spacecraft with a Korsch three-mirror anastigmatic (TMA) telescope, a single focal plane, and instrument metrology subsystems, was studied and submitted, albeit unsuccessfully, to the M4, M5, and M7 medium mission calls at ESA⁵.

This article briefly reviews the scientific arguments in favor of high-precision space astrometry for exoplanets, then explores in more detail the challenges posed by focal plane and telescope calibration. The case for dark matter has been addressed in previous works^{6;7} and will not be discussed hereafter.

2. EXPLORING EARTH-LIKE PLANETS ORBITING NEARBY SUN-LIKE STARS

The detection and atmospheric characterization of temperate, potentially habitable terrestrial planets orbiting the nearest Sun-like stars is a key science theme in both the final recommendations of the senior Scientific Committee for ESA’s long-term scientific plan Voyage 2050 and the US Decadal Survey on Astronomy and Astrophysics 2020⁸ (Astro2020). *Theia*’s exceptional single-measurement positional precision in pointed, differential astrometric mode ($< 1 \mu\text{as}$) will enable the detection and high-confidence ($\geq 3\sigma$) true mass determination of Earths and Super-Earths ($M = 1\text{--}5 M_{\oplus}$) in the Habitable Zone (HZ) of the ~ 60 nearest solar-type stars (Fig. 1). This will be achieved through high-cadence observations (≈ 100 visits over 3 years) of each target and ≥ 100 reference stars⁷ (see Sect. 5.3).

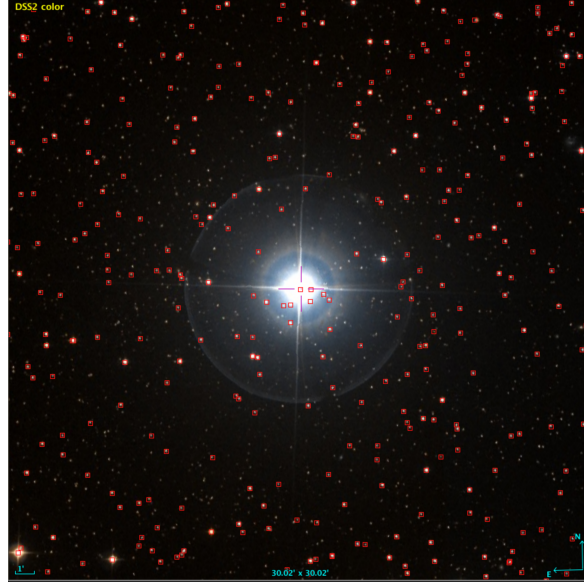


Figure 2. Image from Upsilon Andromedae from Digital Sky Survey. The field of view is $30' \times 30'$ and the red boxes correspond to GAIA DR3 sources. 261 sources are brighter than $G = 14$ mag within the $30' \times 30'$ field of view.

Ground-based extreme-precision, sub-m/s Doppler techniques are expected to provide a global census of temperate terrestrial planets around nearby late-type M dwarfs in the next years. However, for solar-type stars, the Doppler method might be limited by stellar activity, potentially missing any HZ Earth-mass companions whose orbits are not close to edge-on. *Theia*'s astrometric sensitivity will allow us to achieve three critical goals in exoplanetary science:

1. *Theia* astrometry will enable the determination of **the true mass function of temperate 1–5 M_{\oplus} rocky planets around solar-type stars, which is currently unknown.**
2. By measuring the true masses and full three-dimensional architecture in multiple systems, *Theia* will facilitate the study of **the full demographics of planetary systems that host temperate terrestrial planets around the nearest Sun-like stars**, in high synergy with *Gaia* and Doppler surveys.
3. The temperate terrestrial planets detected by *Theia* will provide **the fundamental input target list for direct-imaging and spectroscopic missions aimed at searching for atmospheric biomarkers.**

For such ambitious space observatories, either in the optical/near-infrared (e.g., NASA's proposed flagship missions HabEx, LUVOIR) or in the thermal infrared (e.g., the LIFE concept for an ESA's L-class mission), providing their target list will be crucial. This will avoid their research phase (about 50% of their mission time) and allow them to invest all their precious observing time performing spectroscopy of atmospheres, knowing exactly where to look. Prior knowledge of the true masses will also be essential in interpreting any molecular detections in these atmospheres.

Estimates of *Theia*'s sensitivity⁹ indicate that the median detectable mass across the full HZ for the *Theia* stellar sample is $\simeq 1.1 M_{\oplus}$. If current extrapolations of the occurrence rate of true Earth-like planets¹⁰ at 37^{+48}_{-21} % are accurate, we expect to detect between 9 and 57 such planets. Furthermore, the number of HZ Earths per star could be greater than one, as a typical HZ can dynamically sustain more than one planet.

Theia is a single field, visible-wavelength (400 – 900 nm) differential astrometry mission, meaning that the derived astrometric parameters for the target stars in a field will have position, parallax and proper motion relative to a local reference frame tied to a global one. At the time of the *Theia* mission, the most accurate and complete optical reference frame will be that of the *Gaia* catalog. By using *Gaia* global astrometry parameters

as priors, the astrometric solution of all the stars observed by *Theia* will be automatically tied to the *Gaia* frame, without the need of forcing physical priors on sources such as quasars or remote giant stars.

These characteristics make *Theia* much superior to several competitors. The deep fields will achieve 23 times the proper motion precision of *Gaia* (10 years)* and 14 times that of *HST*¹¹ (10 years). In the bright-star regime⁷, *Theia*'s 1- μ as precision in 1-hr integration at the reference value $R = 10$ mag exceeds that of *Gaia*¹², *Roman*¹³, and *VLT/GRAVITY*¹⁴ by factors of $\sim 40 - 50$, $\sim 10 - 20$, and $\sim 30 - 100$ respectively, and other missions/instruments (e.g., *HST*, *JWST*, *ELT/MICADO*, *Rubin*) by even larger factors.

3. *Theia* MAIN MISSION CHARACTERISTICS

The baseline *Theia* Payload Module leverages the heritage knowledge of consortium members in space mission concepts such as *Gaia*, *HST/FGS*, *SIM*, *NEAT/M3*, *Theia/M4+M5*, and *Euclid*. The *Euclid*-like mission, featuring a Korsch three-mirror anastigmatic (TMA) telescope, a single focal plane, and instrument metrology subsystems⁷, is favored to avoid formation flying constraints. The optimal configuration is a 0.8-m on-axis TMA telescope operating at visible wavelengths, as described in the *Theia/M5* proposal⁵, but with an upgraded optical design. The optics remain coaxial, but the field of view center is shifted by 0.45 deg to ensure the light beam avoids the plane mirror after reflection on M3.

Compared to the proposed *Theia/M5* mission concept, a significant advancement is the incorporation of new types of CMOS (complementary metal oxide semiconductor) detectors, which allow up to 10^9 small-size ($\sim 4\mu$ m) pixels with well-controlled systematics. These detectors can read pre-determined windows around objects with pixel readout rates ≥ 1 kHz to prevent saturation of bright stars. Such detectors simplify the payload considerably by requiring fewer or even a single detector and read-out electronics to cover the necessary $\sim 0.5^\circ$ field-of-view (FoV) in the focal plane array (FPA). They also shorten the focal length to approximately 13 m.

Achieving sub- μ as-level differential astrometric precision requires controlling all factors that affect the relative positions of the Nyquist-sampled point-spread function (with an apparent size of 136 mas for a 0.8-m telescope in the visible). The precision of relative position determination on the detector depends on photon noise (limited by the reference stars), the geometric stability of the focal plane array, optical aberrations, and variations in detector response between pixels. This necessitates a fundamental precision requirement of approximately $5 \cdot 10^{-6}$ pixel.

To monitor the various sources of distortion in the FPA and correct the associated systematic errors, *Theia* will rely on metrology powered by a laser source through optical fibers placed behind the nearest mirror and projecting Young's fringes onto the detector(s) that can be used to measure the relative positions of each pixel.

In addition the telescope geometry is expected to vary, even at very stable environments such as L2 and therefore a baseline telescope metrology subsystem was proposed, based on a concept of linear displacement interferometers and piezo activator applied independently on each linear element of the structure. However, a new method to derive the astrometry signal using the reference stars allows us to measure the telescope distortion described in Sect. 4 and therefore considerably relax the initial requirement set for the M5 proposition from several hours to fraction of a second.

4. HIGH PRECISION DIFFERENTIAL ASTROMETRY FOR EXOPLANET DETECTION

Table 1 gives the main parameters required to perform the detection of an Earth-like planet in system located at 10 pc from the Sun with *Theia* and HWO. The difference between the two telescope is the size of the telescope and therefore the size of the diffraction-limited point-spread function. The factor 10 between the two means that we can go deeper with HWO to look for faint reference stars in a limited field of view, but also the required precision on the focal plane is not as strong as with *Theia* ($\sim 5 \cdot 10^{-5}$ pixels instead of $\sim 5 \cdot 10^{-6}$ pixels).

In the case of the search for Earth-like planets orbiting nearby Sun-like stars, one can take the example of *v* Andromedae (Fig 2) where we see the field of view of $30' \times 30'$ of the Digital Sky Survey image around this target. Using *Gaia* DR3 catalog, we can retrieve 261 sources fainter than $G_{\max} = 14$.

*<https://www.cosmos.esa.int/web/gaia/science-performance#astrometric%20performance>

Table 1. Focal plane parameters relevant to the different space missions

	Theia	Habitable World Observatory (HWO)
Wavelength of operation	$400 \text{ nm} \leq \lambda \leq 900 \text{ nm}$	UV, visible, and infrared
Mission status	Proposed project (next call M8)	NASA flagship mission, foreseen launch ~ 2040
Telescope diameter	0.8 m	between 6.5 m and 8 m
Diffraction limit	134 mas	14 mas
Signature of an Exo-Earth @ 10 pc ($0.3 \mu\text{as}$)	$\sim 5.10^{-6}$ pixels	$\sim 5.10^{-5}$ pixels
Field of view	$0.5^\circ \times 0.5^\circ$ or $30' \times 30'$ $25.6 \text{ kpx} \times 25.6 \text{ kpx}$	$2' \times 3'$ (wide field imager, TBC) $17.1 \text{ kpx} \times 25.6 \text{ kpx}$
Faintest reference stars with a $m_V = 6$ science target	$m_V(\text{ref}) \leq 14$	$m_V(\text{ref}) \leq 20$
Resulting required minimum dynamic range	10^3	10^5

5. LABORATORY TESTBEDS AT IPAG

In order to increase the Technology Readiness Level (TRL) of the mission, we have decided to implement several laboratory testbeds at IPAG with the help of the LabEx FOCUS and CNES.

5.1 Detector classical characterization

We have procured a 46 megapixel detector from Pyxalis (Gigapix 4600) in order to test the new type of large CMOS detector and also redo the interferometric measurements made by Crouzier et al. ¹⁵.

We have started a global characterization of this detector (Fig. 3) : linearity, dark current, readout noise, gain, map of defective pixels, etc.

5.2 Detector pixel geometry using a interferometric calibration

In a real detector the stars are misaligned because of fine pixel structure, quantum efficiency local variations, etc. This is why, we need to calibrate them using the following sequence :

- Fibres create Young's fringes on the detector ;
- Phase modulators make the fringes scroll ;
- The modulation observed by each pixel provides the position of the centroids
- The precision required is below $5e-6$ px (corresponding to $0.3 \mu\text{as}$, an exo-Earth signal)

The proof of concept on small matrices has been performed in 2016 by Crouzier et al. ¹⁵ but the performance needs to be validated now on large matrices. This is why we have developed a simplified testbed at IPAG using the components from Crouzier.

5.3 Distortion calibration experiment

The optical components of the telescope induce optical aberrations that can shift the positions of stars on the detector of thousand of pixels⁴. Whereas the required precision is $0.3 \mu\text{as}$ corresponding to 5.10^{-6} px on the detector, hence the optical aberrations must be calibrated.

Fixing this issue thanks to laser metrology is possible but add a lot difficulties is the use the stars in the field of view (reference stars) as metrology sources in order to compute the distortion function. The distortion function links the positions of stars on the sky with the positions of stars images on the detector. We use bivariate

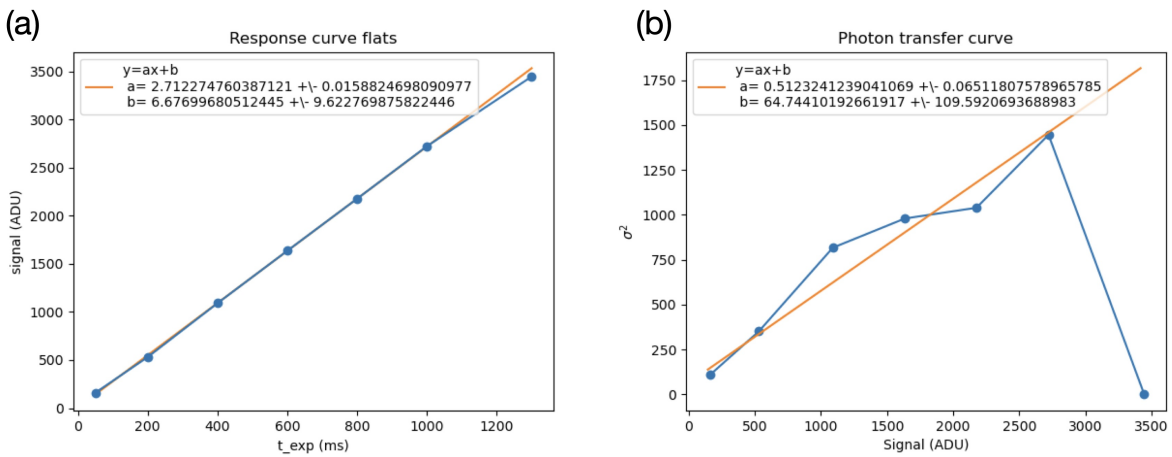
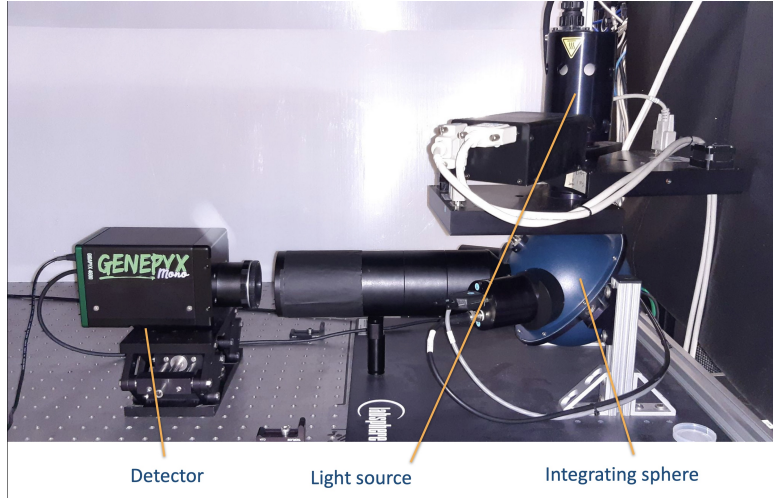


Figure 3. Top panel : Detector characterization testbed with on the left part the Gigapix detector embedded in the GenePyx camera and on the right part the integrating sphere. Bottom figures : (a) the response curve obtained with images of flats; (b) photon transfer curve.

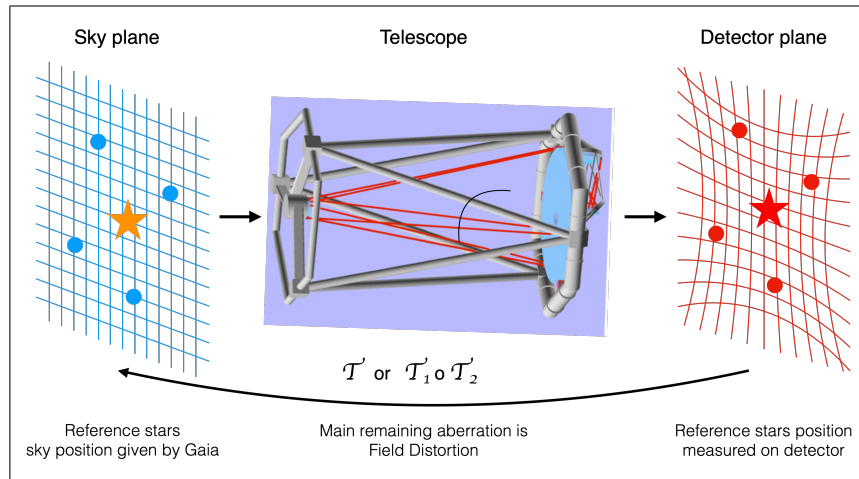


Figure 4. General illustration of the calibration of the distortion. The reference stars are used to adjust a bivariate polynomial \mathcal{T} (or a combination of two polynomials \mathcal{T}_1 and \mathcal{T}_2) that relates the positions of the detector plane to the sky positions. The motion of the target is observed using this transformation.

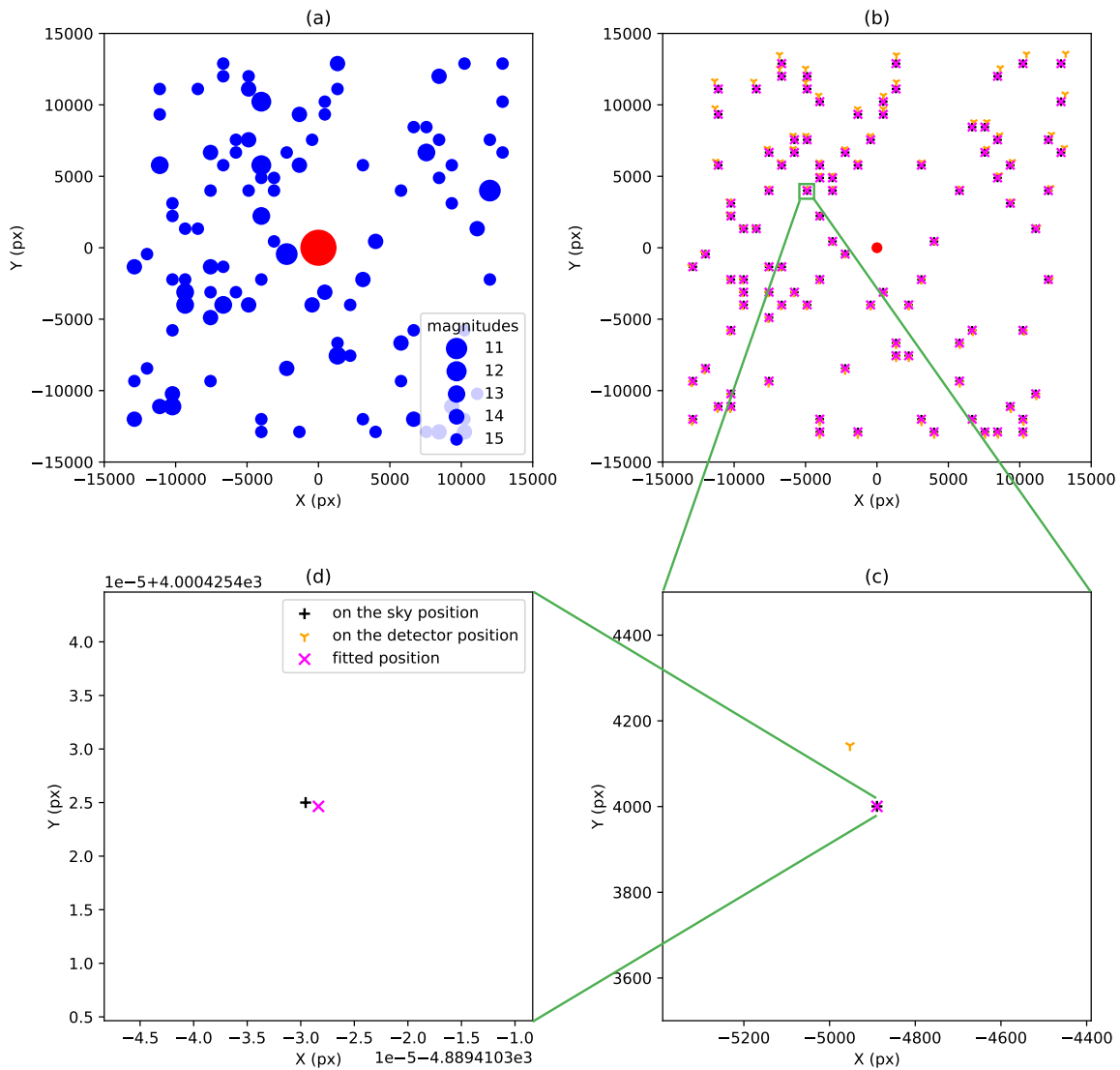


Figure 5. Example of on-sky and simulated fields at different magnification rate : (a) Sky field : the image of a star is a circle with size function of its magnitude; the red star is the target star; (b) On-sky and detector positions at full scale: detector positions are slightly shifted compared to on-sky positions due to distortion, but on-sky and fitted positions are indistinguishable; (c) at the scale of the distortion which reach a few hundred pixels, the on-sky and fitted positions are still indistinguishable; (d) at the micropixel scale the on-sky and fitted positions are separated.

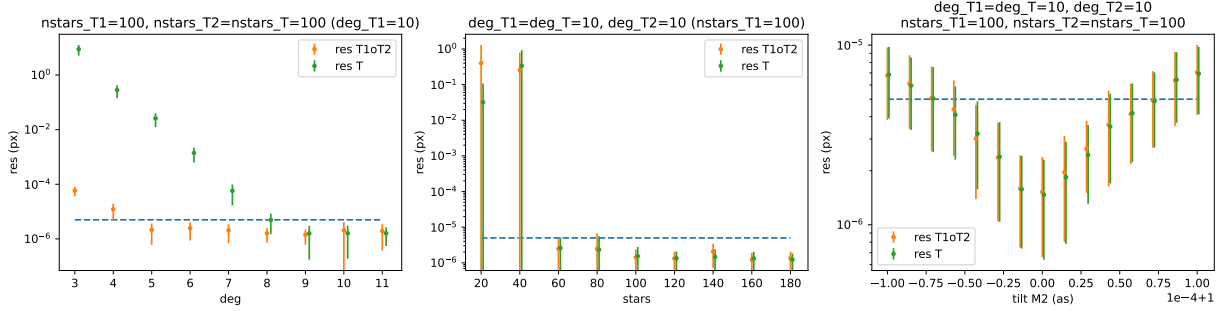


Figure 6. Evolution of the position residuals (i.e. the difference between the sky positions and the positions computed with the polynomials after a chi-squared adjustment on the grid of optical rays) with respect to the degree of the polynomial, the number of reference stars and the tilt of the M2 (expressed in arcsec). `n_stars_T`, `n_stars_T1`, `n_stars_T2`, is the number of stars randomly chosen for the computation of the coefficients of the polynomial of `deg` degree to perform the fit. See text for details. The dashed blue line corresponds to the specification for exo-Earth detection, i.e. 5.10^{-6} pixels.

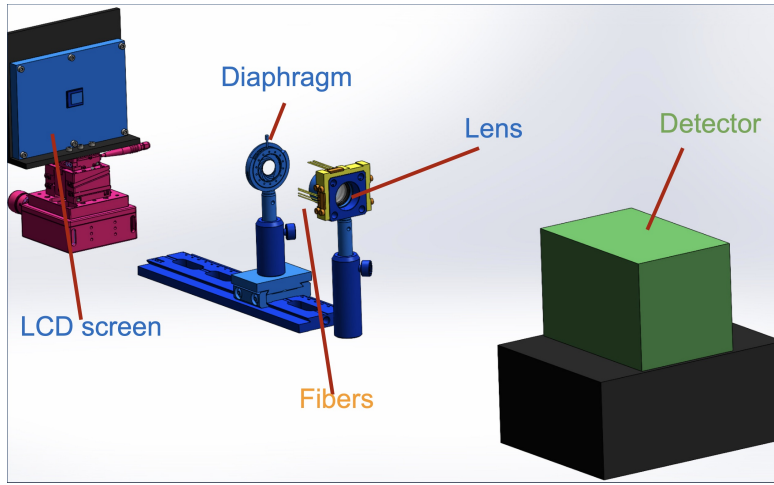


Figure 7. Testbed for distortion calibration. The sources on the LCD screen are images onto the detector in a $2f - 2f$ optical setup with no magnification factor. By moving the position of the diaphragm, one will change the distortion of the image. Using the reference stars, we will retrieve the distortion function.

polynomials to model the optical aberration based on the knowledge of the reference star position by *Gaia* (see Fig. 4).

The main results are presented in Fig. 6. In our simulations a precision of $5 \cdot 10^{-6}$ px can be reached with about 100 stars and an 8th order polynomial, if the M2 tilt is below $7 \cdot 10^{-5}$ arcsec for that exposure. In addition, the residuals are almost constant all over the field of view. The fit with \mathcal{T} and $\mathcal{T}_1 \circ \mathcal{T}_2$ seems to reach the same precision.

We can conclude that the stars in the field of view can be used as metrology sources, and a 2D polynomial model seems to be able to calibrate the telescope’s distortion with a precision better than 5.10^{-6} px.

The positions of the reference stars on the sky are known with a certain error thanks to the *Gaia* catalog and the positions on the detector will be measured by the telescope as the photocenter of the diffraction spot. The distortion function $\mathcal{T}(x, y)$ is calibrated with the reference stars and applied to the measured position of the target star to estimate its real position the sky . Then the movement of the target star is measured relative to the barycenter of the reference stars. This procedure must be repeated for each exposure because the distortion function can change due to the thermal expansion for instance.

We plan now to reproduce the simulation in the lab (Fig. 7) using a simple optical bench where we change the distortion by moving the pupil position in the z -direction.

6. CONCLUSION

Theia is a project for an astrometric observatory based on high-precision differential astrometry measurements on a limited single field (0.5 deg×0.5 deg). The two main science cases are nature of dark matter and Earth-like planets around solar neighbourhood. Theia’s payload is a 0.8 m diameter diffraction limited TMA Korsch telescope. New very large format CMOS visible detectors are being investigated in order to cope with a diffraction-limited yet large field of view without too many detectors. Telescope stability impacts performances except if one is able to calibrate the telescope distortion during each exposure duration (e.g. 0.1 s) using reference stars with *Gaia* positions.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of the researchers and engineers who are not co-authors of this article but who have participated in the proposed missions and provided valuable input in response to ESA’s successive calls for proposals: NEAT (M3), micro-NEAT (S1), and Theia (M4, M5, M7).

The co-authors would like also to express their gratitude to Alberto Riva for presenting this contribution at the conference session.

With regard to the funding of our research, we would like to acknowledge the support of the LabEx FOCUS ANR-11-LABX-0013 and the CNES agency. ML would like to acknowledge the support of her PhD grant from CNES and Pyxalis.

This research has made use of NASA’s Astrophysics Data System Bibliographic Services and of the Aladin sky atlas, CDS, Strasbourg Astronomical Observatory, France.

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