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Theia : High precision differential astrometry for exoplanets and dark matter

Manon Lizzana (1,2,3), Fabien Malbet (1), Fabrice Pancher (1), Thierry Lepine (4), Alain Leger (5)

Scientific objectives :

- The goal of Theia is to **explore planetary systems** in the Sun's vicinity and investigate the nature of the **dark matter in the Milky way**
- We focus here on **rocky exoplanets in the habitable zone** detection because it's the most demanding aspect of the Theia mission

$$\text{Astrometric signal : } A = 3\mu\text{as} \times \frac{M_{\text{Planet}}}{M_{\text{Earth}}} \times \left(\frac{M_{\text{Star}}}{M_{\text{Sun}}}\right)^{-1} \times \frac{R}{\text{IAU}} \times \left(\frac{D}{\text{1pc}}\right)^{-1}$$

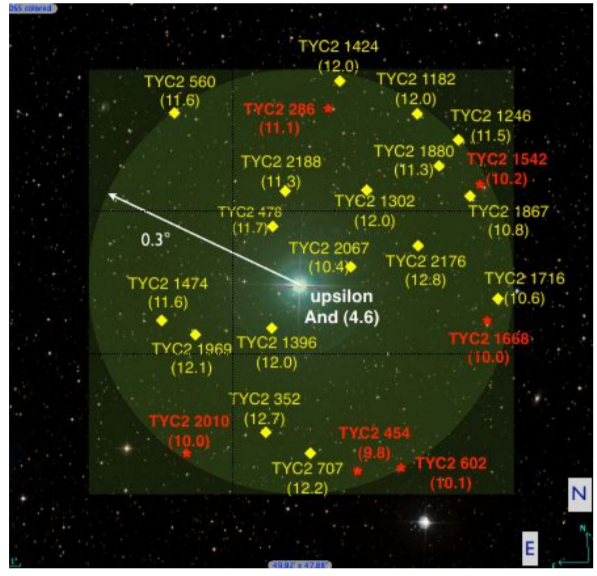


Fig 2 : example of field of view (target star at the center and reference stars all around)

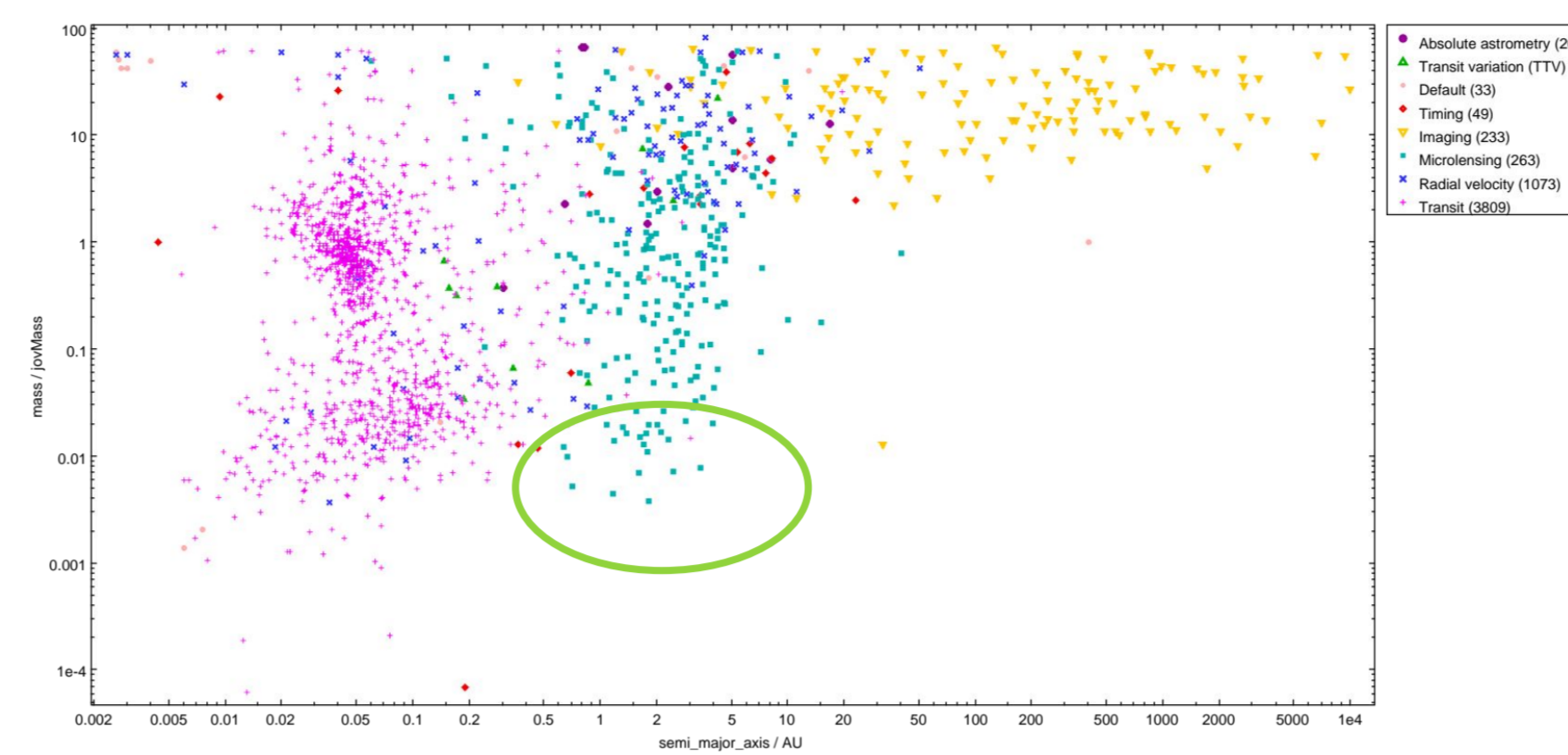


Fig 1 : Detected exoplanets (12/2023 Exoplanets.eu)

Key points of the poster :

- The reflex motion of the star produced by an Earth like planet orbiting a sun like star 10pc from us is **0.3 μas corresponding to 5e-6 px** in the case of Theia mission (see Theia's characteristics in the right panel)
- This precision can only be reached by **long exposure on pointed targets using relative astrometry**, contrary to Gaia which performs absolute astrometry over the entire sky
- To achieve this goal, the TRL (technology readiness level) of 2 specific aspects must be improved :
 - **calibration of new detectors** with very large number of pixels → see 1, 2
 - **telescope stability** or its monitoring by **calibrating the field distortion thanks to the stars in the field of view** → see 3

Theia mission :

- Space telescope
- Diffraction-limited telescope
- 0.7 m in diameter
- A large field of view (0.5°)
- A fine resolution (0.3 μas)
- Stability monitored in real time → see 3
- Wavelength : visible

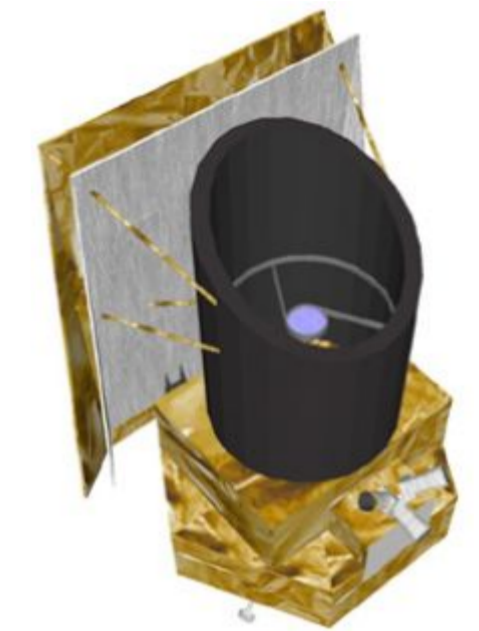


Fig 3 : Theia telescope design (Malbet et al. 2021)

1 - Characterize an adequate CMOS detector with an integrating sphere

New technologies supply **large detectors made of small pixels** (4.4 μm), that allow to observe small movements in a large field of view

To cover the whole field of view of Theia 30 000 x 30 000 px are needed, but for now experiments are carried out with a 8320 x 5436 px = 46 Mpx, see fig 4. Pyxalis company plans to make 220 Mpx detectors, meaning that 4 of them will cover the whole field of view.

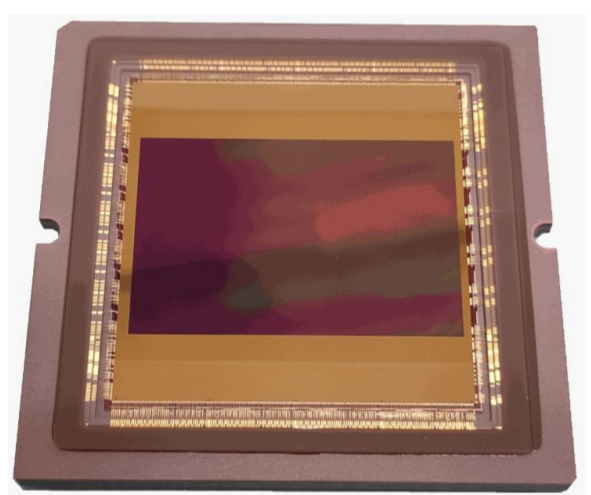


Fig 4 : Gigapix 4600 Pyxalis detector

2 - Interferometric calibration of the pixels centroid position (blue beam)

On fig 5, the blue beams originate from fibers which illuminate the detector with Young's fringe. Each pixel sees a modulation of the light when the phase modulators are in action. This allows to calculate the **exact positions of pixels centroids**.

Previous work has shown that this is possible with small detector matrices (Crouzier et al. 2016, A&A 595, A108), see fig 6. The goal is now to check the performances and validate this method with the new very large detectors.

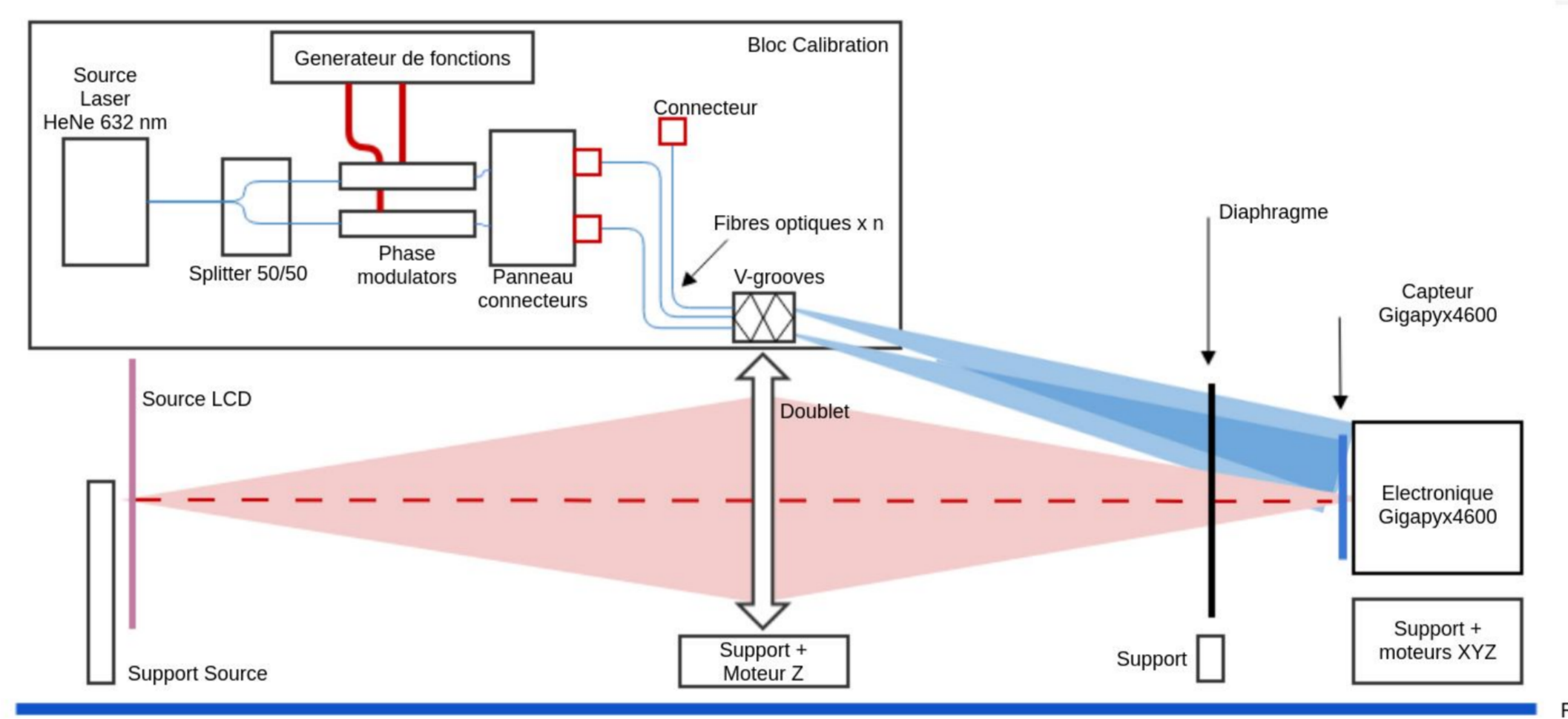


Fig 5 : test bed design for interferometric and distortion calibrations

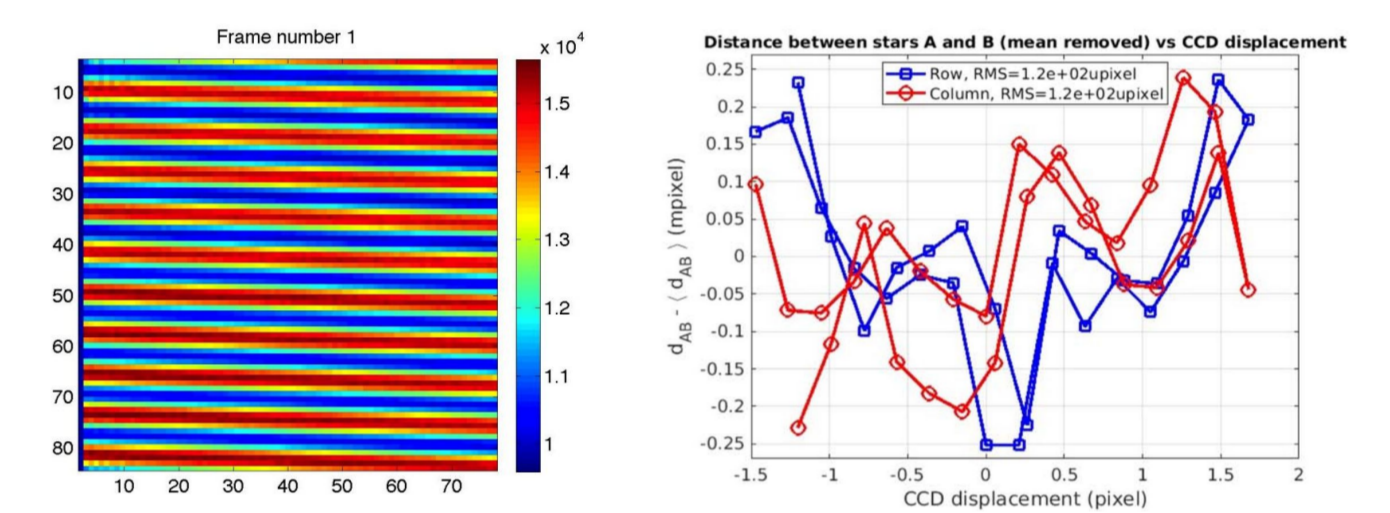


Fig 6 : Illustration of interferometric calibration with Young fringes (Crouzier et al. 2016, Shao et al. 2023)

Last results :

6e-5 px (Crouzier et al. 2016)
3e-5 px (Shao et al. 2023)

3 - Calibration of optical distortion with fictive stars (red beam)

Goal of this study :

We want to show that a **polynomial model** is able to calibrate the telescope distortion with a precision smaller than **5e-6 px** that allows us to detect an Earth like planet

Recent work on telescope stability (Malbet et al. 2022, SPIE 12180, 1F) has shown that the **reference stars in the field of the telescope can be used as metrology sources** in order to compute the distortion function

We want to show that this procedure works in laboratory with simulated stars (red beam)

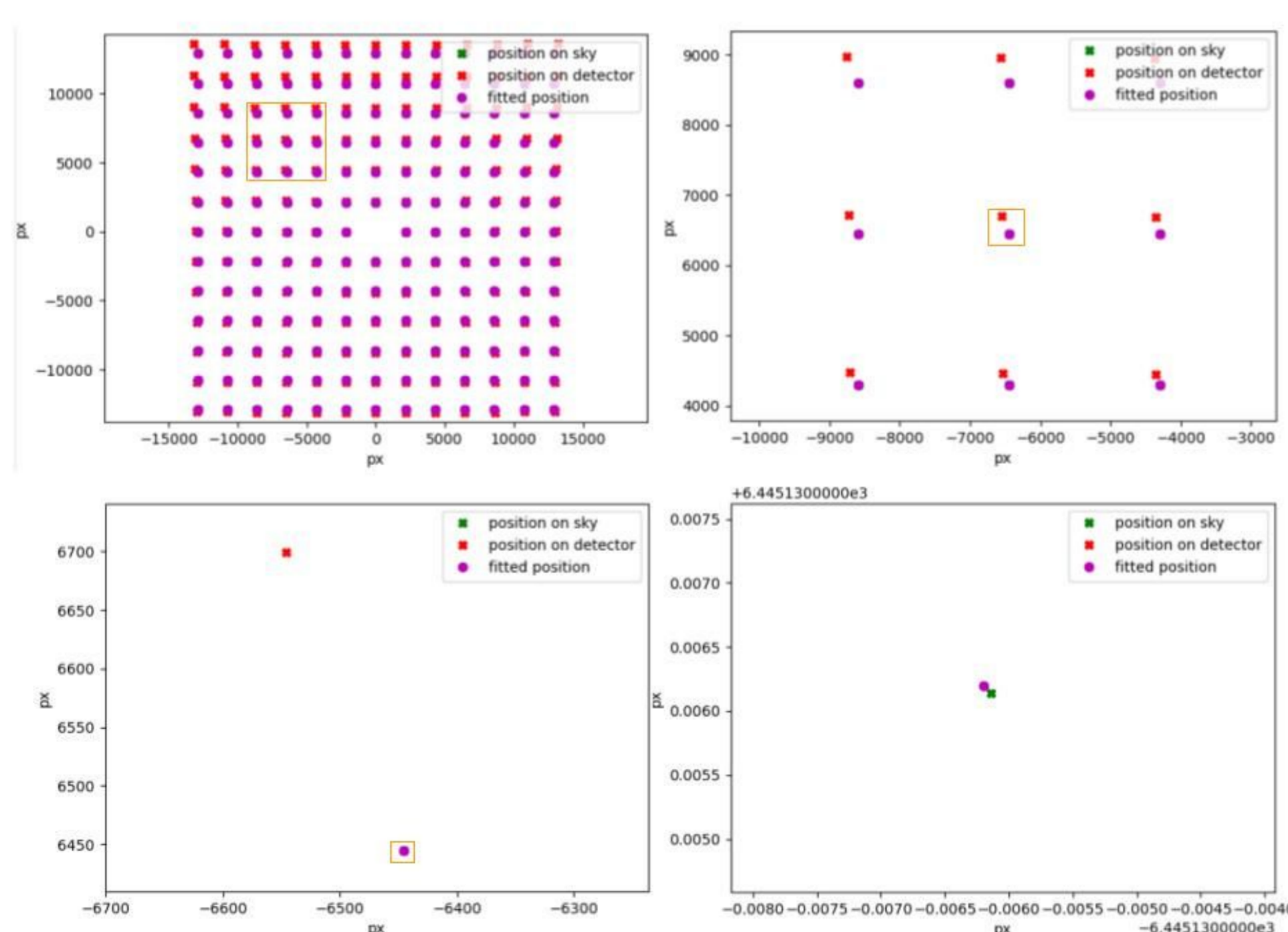


Fig 8 : Example of distortion calibration with polynomials

First results :

A precision of 5e-6 px can be reached with about 100 stars and an 8th order polynomial, if the M2 tilt is below 7e-5" for that exposure , see fig 9

Ongoing work :

Implement the errors due to Gaia Catalog, photon noise ... and test the robustness of the results

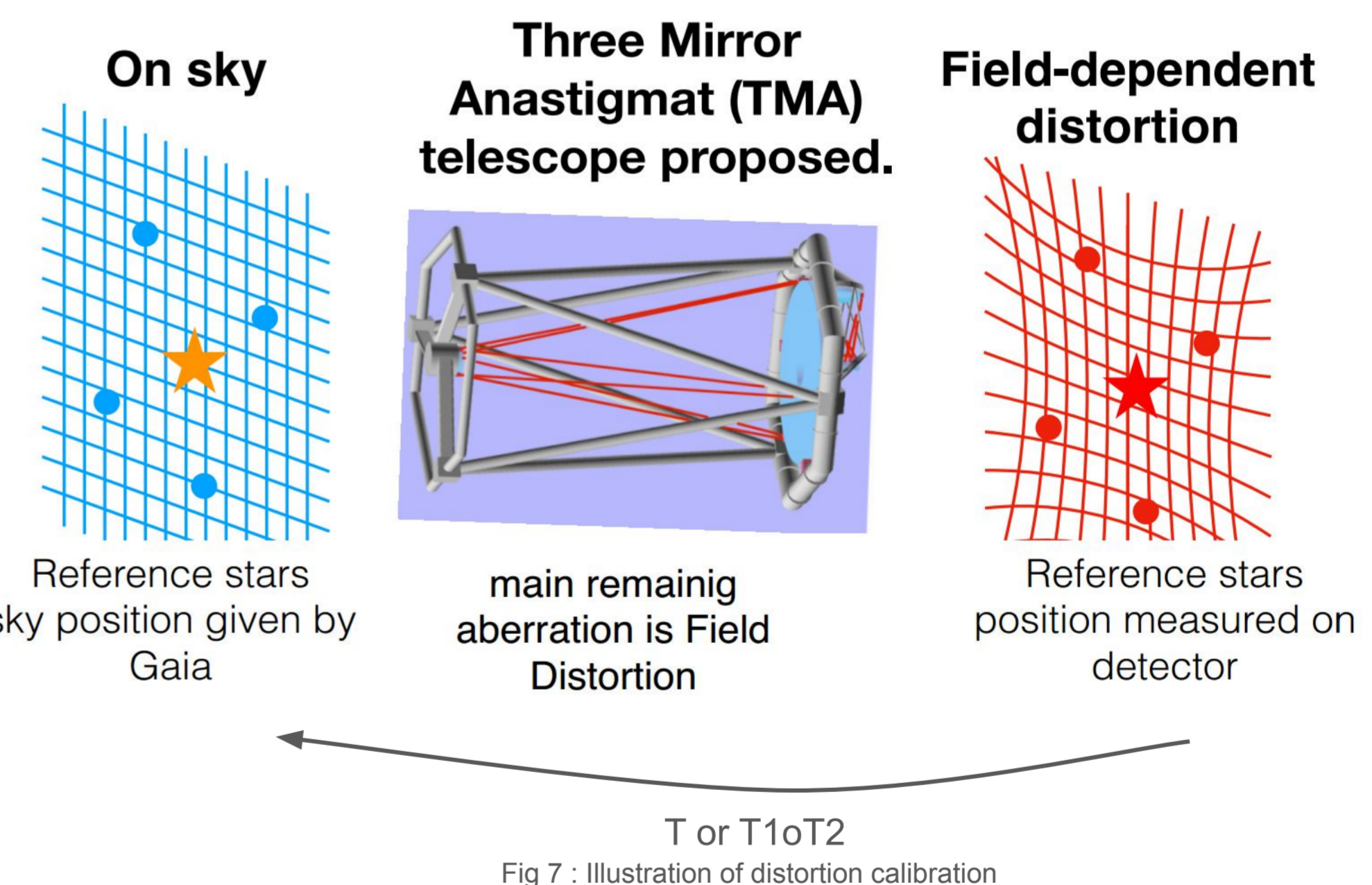


Fig 7 : Illustration of distortion calibration

Main idea of the simulation :

- Simulate a star field
- Calculate the position of the stars on the detector (thanks to optical computing)
- Fit a polynomial function (T or T1oT2) between the star position on the sky and on the detector, see fig 7,8

Procedure during the space mission :

- Fit the polynomial on reference stars using the Gaia catalog
- Apply the polynomial to the target star position on the detector to estimate the position on sky
- Measure the movement of the target star relative to reference stars

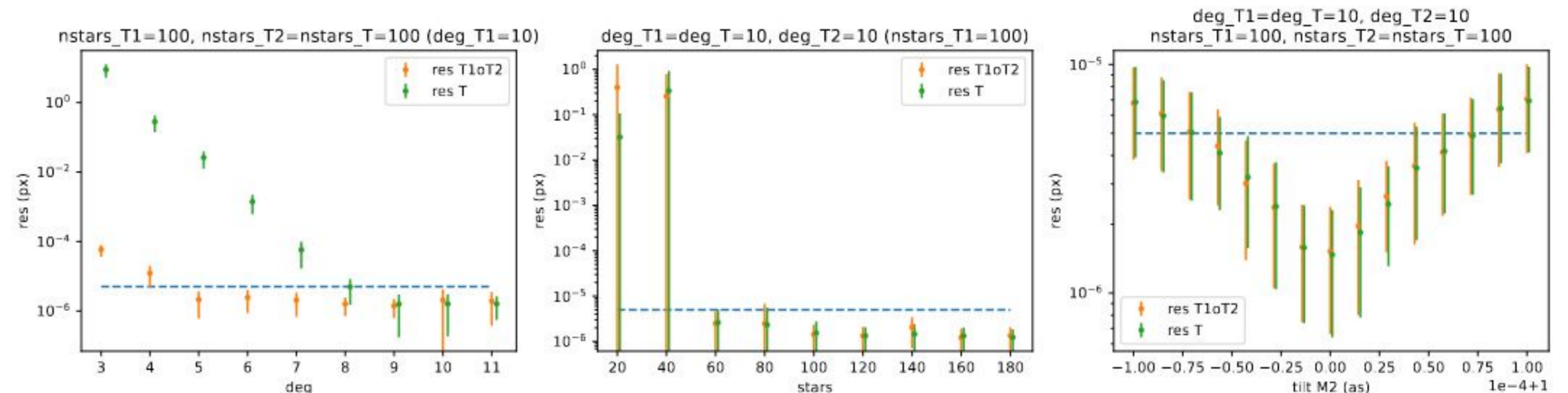


Fig 9 : Evolution of residuals relative to the degree of polynomials, the number of stars and tilt of M2