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# High Precision Astrometry Science in the Context of Space Mission Prospectives

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## ABSTRACT

Astrometry is one of the oldest branches of astronomy which measures the position, the proper motion and parallax of celestial objects. Following the Hipparcos and Gaia missions that have measured several billions of them using global astrometry, we propose to increase astrometry precision on pointed objects using differential astrometry in a large field in order to unravel rocky planets in habitable zones of stars in the Sun vicinity and investigate the nature of dark matter in galactic environments as recommended by the ESA Senior Committee in the Voyager 2050 prospective. Substantial technology developments in a number of critical areas is needed in order to reach the highest required precision of sub-micro-arcsecond. One of them is CMOS image sensors using the stitching technique to merge the multiple design structures on the wafer and produce array with very large number of pixels. Another one is to calibrate the pixel positions using projecting modulating interferometric laser fringes on the array. Finally, the distortion of the optical system can be monitored and compensated using reference stars as metrology sources. The final precision depends on the diameter and the field of view of the telescope that is used as well as the time spent on each target. We present here the science goals that can be achieved with such missions either within the framework of an ESA Medium-class mission or even in the NASA most challenging Habitable Worlds Observatory, a large space telescope recommended by the American Astronomy and Astrophysics prospective for the 2020s and designed specifically to search for signs of life on planets orbiting other stars.

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

## 1. INTRODUCTION

Astrometry, the science of measuring the precise positions and motions of celestial objects, has been a foundational tool in astronomy for centuries (Fig. 1). It began with the ancient Greeks, with astronomers like Hipparchus of Nicaea cataloging stars<sup>1</sup> as early as the second century BCE. Over the centuries, observational precision advanced incrementally; notable figures such as Tycho Brahe, John Flamsteed, and William van Altena contributed to refining stellar position measurements. While early astrometric efforts were limited to accuracies of several arcminutes, the introduction of telescopes in the 17th century revolutionized the field, making it possible to record stellar positions with increasingly precise instruments. By the early 19th century, telescopes equipped with advanced optics enabled measurements accurate to within a few arcseconds, allowing astronomers to compute stellar parallaxes and proper motions with greater confidence.

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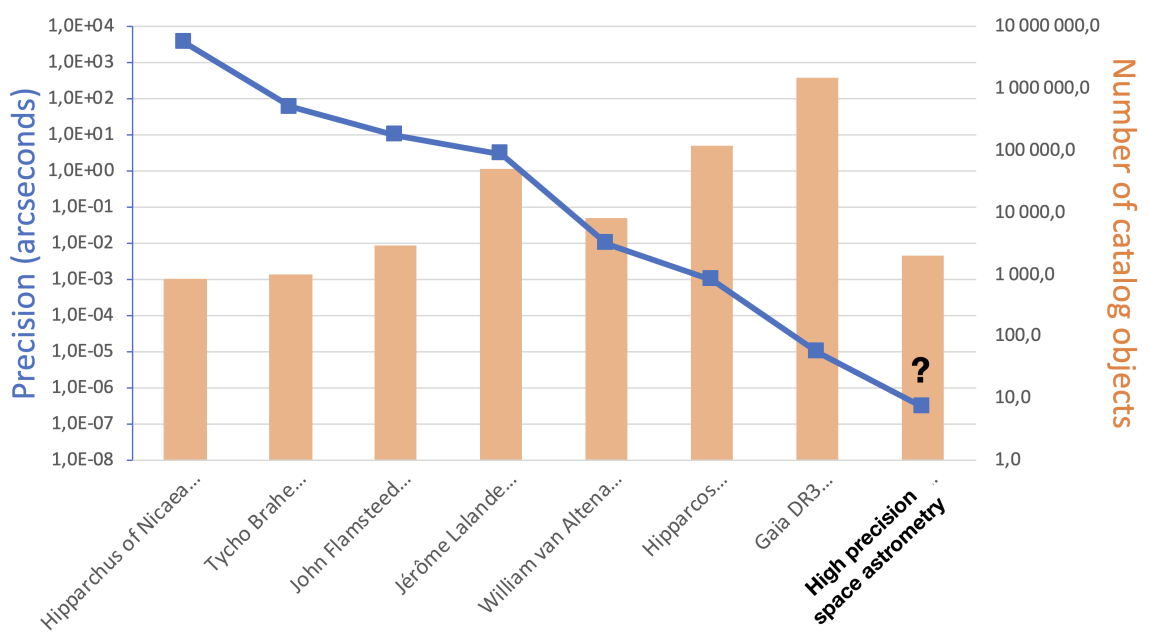


Figure 1. The progression of astrometric precision over time, from Hipparchus to Gaia and Theia

The launch of ESA Hipparcos mission in 1989 represented a transformative moment in astrometry, as it achieved unprecedented positional accuracy from space, free from Earth atmospheric distortions. Hipparcos data enabled the creation of an extensive star catalog,<sup>2</sup> setting the stage for ESA Gaia mission. Launched in 2013, Gaia brought global astrometry to a new era, achieving several microarcsecond-level precision and mapping several billion stars. This Gaia DR3 dataset<sup>3</sup> has allowed astronomers to probe the Milky Way structure in remarkable detail, contributing to our understanding of stellar evolution, galactic dynamics, and the formation history of the universe. The upcoming data releases from Gaia, DR4 and DR5, are expected to incorporate measurements of faint stellar companions down to the planetary limit, with an anticipated discovery of approximately 10,000 Jupiter-mass planets. These releases promise to deepen our understanding of the diversity of planetary bodies within our galaxy, further reinforcing Gaia role in astrometric discovery.

Despite these advances, certain scientific challenges require even higher precision and a more targeted approach. Both ESA *Voyager 2050*<sup>4</sup> prospective roadmap and the US National Academies decadal survey for astronomy *Astro2020*<sup>5</sup> underscore the need for sub-microarcsecond precision to achieve critical scientific objectives. Key priorities include the detection of Earth-mass exoplanets orbiting nearby stars and the exploration of dark matter influence within galactic environments. Gaia global astrometry approach, while powerful, lacks the focused precision necessary for detecting the wobble motions of nearby stars caused by orbiting Earth-like planets. Similarly, understanding dark matter role in shaping galactic structures calls for precise measurements of positions and motions of faint stars that Gaia current capabilities cannot achieve.

In response to these challenges, the Theia\* mission proposes a new path forward. Designed as a medium-sized ESA mission, Theia will achieve sub-microarcsecond precision using differential astrometry, focusing on individual science targets with the aid of reference stars in the field. Theia high precision will be achieved through innovative technologies, including a large CMOS detector array with pixel-level calibration supported by interferometric fringes. These advancements will provide the positional stability and accuracy needed to reach Theia scientific goals.

Mass vs Semi-Major Axis Diagram (from exoplanet.eu)

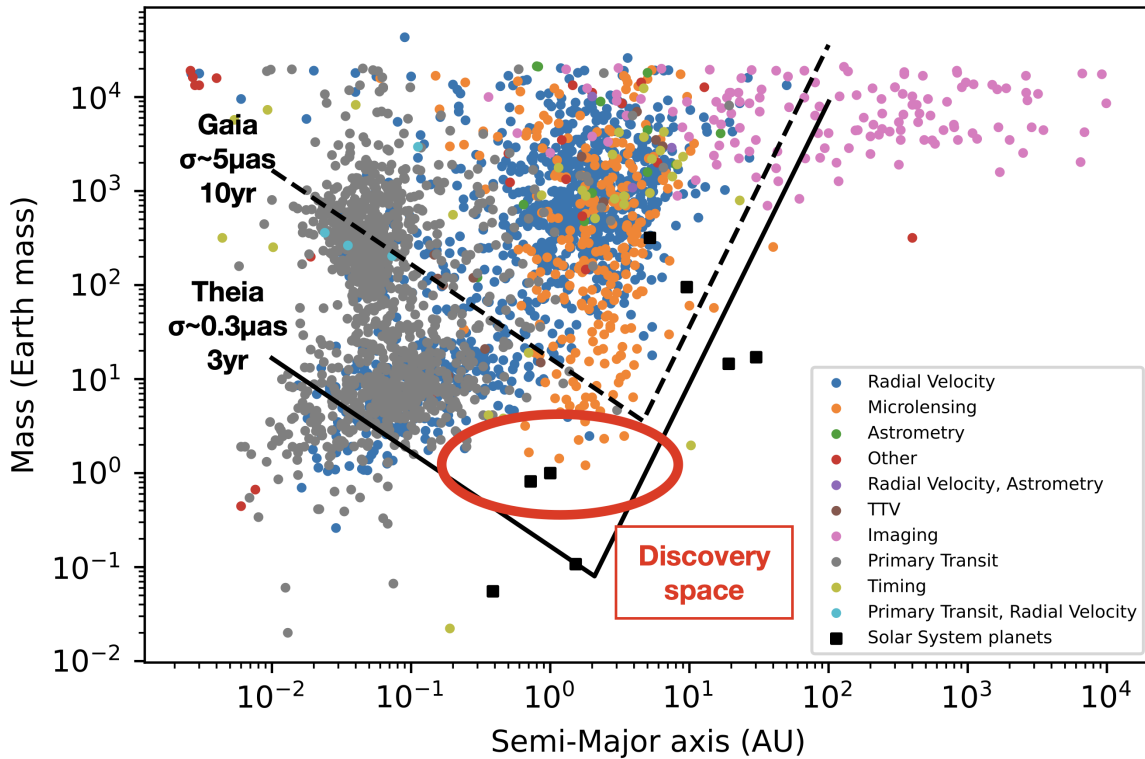


Figure 2. Comparative plot for the discovery spaces of Gaia and Theia, emphasizing Theia higher precision which enables the exploration of a new discovery space (data extracted from the 22-Oct-2024 version of the [Encyclopaedia of exoplanetary systems](#) catalog).

## 2. SCIENCE OBJECTIVES

The Theia mission has been designed<sup>6</sup> to accurately track the positions of the stars over time in order to fulfil two major scientific objectives.

The first main objective is the detection of rocky, Earth-like exoplanets located in the habitable zones of nearby stars. By employing differential astrometry, Theia can measure the subtle shifts in a star position caused by the gravitational tug of orbiting planets. This technique allows for the discovery of planets as small as Earth within a distance of 15 parsecs, especially those orbiting Sun-like stars. Such discoveries will refine the census of nearby exoplanets and provide new insights into the formation and diversity of planetary systems (Fig. 2).

The second objective of Theia is to probe the nature of dark matter (DM), in particular testing if it is collisionless and cold as assumed in the usually assumed Cold Dark Matter (CDM) model. This can be done by measuring stellar motions in specific galactic environments. By studying dwarf spheroidal galaxies, where DM is thought to dominate gravitational interactions at all scales, the proper motions of the inner stars will test that the DM inner density profile is steep as predicted in CDM for DM-dominated galaxies. Proper motions of stars above and below the Milky Way disk may highlight the passage of the numerous dark subhalos predicted by CDM. Finally, the directions of proper motions of a few, distant, hypervelocity stars thought to originate from 3-body encounters with the supermassive black hole at the Galactic center will enable to test if the shape of the Milky Way's outer halo is prolate as predicted by CDM.

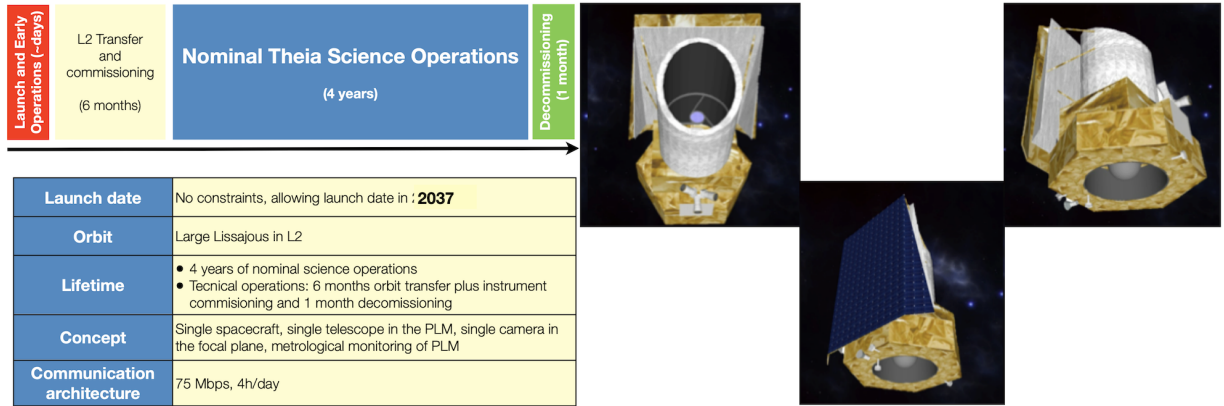


Figure 3. Theia mission timeline and operational phases, including launch, transfer, and nominal science operations

### 3. THEIA MISSION PROFILE

The Theia mission (Fig. 3) will operate from a Lissajous orbit around the Earth-Sun L2 point, providing a stable and thermally consistent environment essential for long-term high-precision measurements. The mission operational plan includes a 6-month transfer and commissioning phase, followed by four years of nominal science operations and a one-month decommissioning period.

Theia telescope is designed as an 0.8-meter diffraction-limited instrument with a 0.5-degree field of view, ideal for conducting detailed astrometric observations of targeted fields. The telescope optical design, a Korsch three-mirror anastigmat, minimizes aberrations, supporting Theia high-precision objectives (see next session).

The telescope will operate in two modes to accommodate different science cases: a “bright star mode” for detecting exoplanets around nearby solar-type stars and a “faint observing mode” for observing high-velocity stars and galactic structures. Each observation session will be calibrated using metrology sources, ensuring consistency across the mission lifetime.

### 4. THEIA OPTICAL DESIGN

A 3-mirror telescopes have much better corrected aberrations than 1 mirror (Newton) and 2-mirror (Cassegrain) telescopes. Among all possible solutions for a 3-mirror telescope, we studied the Korsch configuration<sup>7–10</sup> which is an anastigmat (i.e. no spherical aberration, no coma, no astigmatism), with an almost flat field, a reasonable obstruction, and a large focal length that should match the diffraction limit in the visible ( $\lambda = 0.55 \mu\text{m}$ ) with the current size of CMOS pixels.

The design and the optimization of the telescope (Fig. 4) were done using *Ansys-Zemax OpticStudio*. The tolerancing and the stray light will be studied later. The specifications were the followings : the primary mirror has a diameter of 80 cm, the focal length is equal to 13 m, and the field of view is squared and equal to  $0.5^\circ \times 0.5^\circ$ . Finally, the obstruction is governed by the size of the mechanical mount of M2 and has a diameter of 24 cm, ie. 30% of the diameter of the primary.

We used for the degrees of freedom only the 3 radii, the 3 conic constants and the back focal length. We used a field bias ( $0.45^\circ$ ) in order to avoid the obstruction due to the flat mirror between M2 and M3. But it is important to note that all the mirrors are centered. The solution we obtained on the top of Fig. 4 is diffraction limited, as can be seen at the bottom left of Fig. 4. The primary and tertiary mirrors are concave ellipsoids while the secondary mirror is convex hyperboloid. The distortion displayed at the bottom right is smaller than 2.2%.

\*In mythology, Theia is the daughter of Gaia and revered as the goddess of sharp vision, a fitting name for a mission designed to extend Gaia legacy with unparalleled precision in astrometric vision.

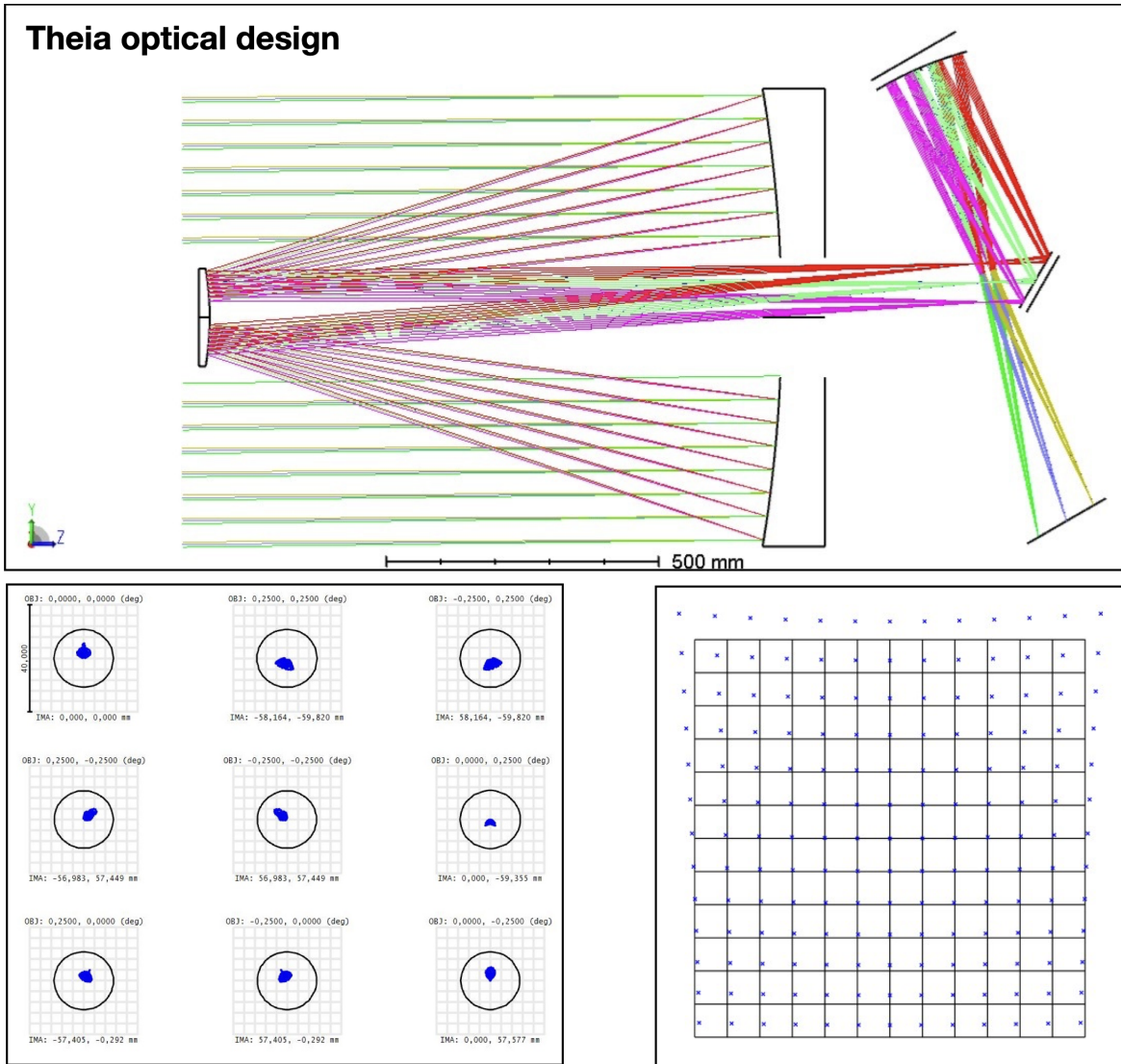


Figure 4. Theia optical design using an anastigmat Korsch configuration with an almost flat field, a reasonable obstruction, and a large focal length.

## 5. TECHNOLOGICAL ADVANCEMENTS IN LABORATORY

To achieve its ambitious science goals, Theia leverages recent technological advancements in detector design, calibration, and data processing. The mission success hinges on innovations that allow for the precise detection of minute positional changes.

Theia imaging system use a CMOS detector array with stitched pixels, enabling a large field of view while maintaining high positional accuracy across the detector. This approach maximizes the effective area of the sensor, essential for differential astrometry, and minimizes the effect of pixel-level imperfections. Each pixel position will be calibrated using interferometric laser fringes<sup>11</sup> projected onto the array, correcting for any distortions that could affect astrometric measurements.

Additionally, Theia distortion correction system uses Gaia global astrometric data to provide reference points for calibration.<sup>12</sup> This method significantly reduces the telescope stability requirements, making it possible to achieve high precision without the need for exceptionally stable mechanical structures. With a focus on pointed differential astrometry, Theia can accumulate many exposures for each target, enhancing the accuracy of its



measurements through repeated observations.

To support Theia ambitious precision goals, the Institut de Planétologie et d’Astrophysique de Grenoble (IPAG) has set up advanced test benches<sup>11</sup> to refine and verify key aspects of detector calibration and optical performance. These test benches simulate Theia observational conditions, enabling testing of detector characterization, distortion correction, and metrological accuracy. The setup includes an integrating sphere as a stable light source, an OLED screen to simulate star fields, and a high-precision GIGAPYX 4600 detector with a  $4.4\mu\text{m}$  pixel pitch, which is used to test pixel-level response under various lighting and distortion conditions. Each component is designed to ensure that calibration measurements remain consistent with the sub-microarcsecond accuracy required by Theia.

Furthermore, the test bench allows for assessments of field-dependent distortions by emulating Theia operational field of view. This enables the research team to fine-tune methods for real-time distortion monitoring and correction, a critical capability for maintaining high positional accuracy across the telescope wide field. The insights gained from IPAG test benches will be instrumental in refining Theia focal plane array design, ensuring that laboratory-tested precision is maintained during in-flight operations.

More details on the technical work being performed in lab can be found in this volume in Lizzana et al.<sup>12</sup> and Pancher et al.<sup>11</sup>

## 6. ALTERNATIVE WITH THE HWO WIDE FIELD IMAGER

In parallel with ESA high-precision astrometry prospectives, NASA planned Habitable Worlds Observatory (HWO)<sup>13</sup> represents a significant step toward discovering exoplanets and characterizing galactic environments at even greater observational depths. The HWO, set to launch in the 2040s, is envisioned as a large-aperture telescope operating across ultraviolet, visible, and infrared wavelengths, with a primary mirror diameter of 6.5 to 8 meters. This instrument will allow for extremely detailed observations of planetary systems around nearby stars, particularly targeting the characterization of exoplanetary atmospheres within the habitable zone.

The HWO observational design<sup>13</sup> includes a high-resolution imager with an anticipated point-spread function (PSF) precision of 14 milliarcseconds (mas), which enables direct imaging and astrometric analysis of exoplanets. Notably, for an Earth-like planet located at 10 parsecs, HWO expected PSF can achieve an astrometric signature detection down to 0.3 microarcseconds. This level of precision, combined with a Nyquist-limited PSF resolution of approximately  $5.10^{-5}$  pixels, positions HWO as a powerful observatory for direct exoplanet characterization, though at a much longer observational cadence compared to differential astrometric missions. The HWO will also feature a relatively modest field of view of approximately  $2 \times 3$  arcminutes, a limitation imposed by the design for deep, focused investigations on individual targets.

Both Theia and HWO allows the limits of high-precision astrometry to be pushed. In addition HWO direct imaging capabilities will provide essential follow-up observations of exoplanets identified by astrometric missions, particularly for spectroscopic characterization of atmospheres. Theia differential astrometric measurements, on the other hand, can be essential for identifying and cataloging habitable exoplanets within 15 parsecs, providing high-accuracy stellar motion data that can enhance subsequent direct imaging missions like HWO.

## 7. CONCLUSION

Theia represents a significant step forward in space-based astrometry, building upon the legacy of Hipparcos and Gaia to achieve higher precision and focused observational capabilities. By leveraging cutting-edge technology in detector design and calibration, Theia will open new frontiers in exoplanet discovery and dark matter research. If successful, Theia will solidify Europe position in astrometric innovation and contribute invaluable data to the global astronomical community. Through its ambitious science objectives and technological advancements, Theia promises to extend our understanding of the universe composition and the possibility of life beyond Earth. The Habitable Worlds Observatory (HWO) presents also an alternative path for achieving high-precision space astrometry, offering a complementary approach that warrants close consideration as we advance toward the next generation of astrometric missions.

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