Publication Year	2016
Acceptance in OA@INAF	2020-06-25T11:07:35Z
Title	Microarcsecond astrometric observatory Theia: from dark matter to compact objects and nearby earths
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DOI	10.1117/12.2234425
Handle	http://hdl.handle.net/20.500.12386/26208
Series	PROCEEDINGS OF SPIE
Number	9904

Microarcsecond Astrometric Observatory Theia : From Dark Matter to Compact Objects and Nearby Earths

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ABSTRACT

Theia is a logical successor to Gaia, as a focused, very high precision astrometry mission which addresses two key science objectives of the ESA Cosmic Vision program: the nature of dark matter and the search for habitable planets. *Theia* addresses a number of other science cases strongly synergistic with ongoing/planned missions, such as the nature of compact objects, motions of stars in young stellar clusters, follow-up of Gaia objects of interest. The *"point and stare"* operational mode will enable *Theia* to answer some of the most profound questions that the results of the Gaias survey will ask. Extremely-high-precision astrometry at 1-μas level can only be reached from space. The *Theia* spacecraft, which will carry a 0.8-m telescope, is foreseen to operate at L2 for 3,5 years. The preliminary *Theia* mission assessment allowed to identify a safe and robust mission architecture that demonstrates the mission feasibility within the Soyuz ST launch envelope and a small M-class mission cost cap. We present here the features of the mission that has been submitted to the last ESA M4 call in January 2015.

Keywords: space telescopes, visible domain, astrometry, high precision, detectors, dark matter, exoplanets, space mission

1. INTRODUCTION

The *Theia* mission has been submitted to the ESA call for M4 mission in January 2015. This paper summarizes the scientific objectives of the *Theia* mission as well as the concept and the mission profile at the time of the submission (beginning 2015).

The *Theia* mission will explore the Universe at unprecedented astrometric precision of 0.3μas over multiple chosen fields of about 1 degree. *Theia* is the divinity of sight and daughter of Gaia. Similarly, the instrument concept carries on the heritage of HIPPARCOS and Gaia missions combined to latest developments in precision metrology control. While giant telescopes and other observatories will do wonders in spectroscopy, imaging, photometry, etc. *Theia* will enable science cases unique to microarcsecond (μas) astrometry, a precision that

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Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, edited by
Howard A. MacEwen, Giovanni G. Fazio, Makenzie Lystrup, Proc. of SPIE Vol. 9904,
99042F · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2234425

will reveal the Universe in motion like Earth-like planets orbiting around our immediate stellar neighbors, the activity of the most extreme objects known (black holes and neutron stars) and unveil the local sub-structure of the dark matter halo in which the Milky Way resides). Conceived as an open observatory class mission, *Theia* will bring ultra-precise astrometry to the broader community, including target-of-opportunity science in the era of Extremely Large Telescopes and the James Webb Space Telescope.

2. THEIA SCIENCE

Sky survey telescopes and powerful targeted telescopes play complementary roles in astronomy. The *Theia* Astrometric Observatory, as a flexibly pointed instrument capable of high astrometric accuracy even on faint targets, is an ideal complement to current astrometric surveys and a unique tool for precision astrophysics. *Theia* will push the frontier of precision astrometry not only to detect and characterize planets down to the Earth mass around the nearest stars for evidence of habitable worlds, but also well out into distant Milky way objects up to the Local Group of galaxies. As we enter the era of the James Webb Space Telescope and the new ground-based, adaptive-optics-enabled giant telescopes, *Theia* can scrutinize for example the motion of clusters (young, open and globular) that can be used to study their evolution and physics and derive precise stellar masses, luminosities, and ages. By obtaining these high precision measurements on key objects that Gaia could not reach, *Theia* can consolidate our theoretical understanding of the local universe, enable extrapolation of physical processes to remote redshifts, and derive a much more consistent picture of cosmological evolution and the likely fate of our cosmos.

2.1 Dark matter, Galactic dynamics and stellar associations

As determined by the Planck mission, 85% of the matter in our Universe is in the form of Dark Matter (DM), whose physical nature is presently unknown although its gravitational potential dominates at the scale of galaxies, and affect how galaxies form and the universe evolves. *Theia* will probe the shape, radial profile, and lumpiness of DM halos, especially for the Milky Way and M31.

Theia can indeed constrain the physical nature of dark matter. The heavier the dark matter particles, the lower their velocity dispersion when their have collapsed and thermalised. Measuring the shape of the central DM density profile will give access to their velocity dispersion (equilibrium Jeans equation). Dwarf spheroidal (dSph) galaxies, e.g. Draco, occupy the least massive dark matter halos. Measuring the tangential components of the velocity of their brightest stars will break the present degeneracy between cusp and core models, giving a precise indication on their particle mass. Hundreds of their stars are $V = (17-19)$, so the statistical information obtained from simultaneous measurement of 1 degree fields is essential to perform these measurements.

From halo streams, to absolute and peculiar proper motions within globular clusters, microarcsecond level astrometry has the power to unveil not only the structure and distribution of dark matter in the Milky way, but also reveal the dynamics of these objects. While current HST and Gaia provide proper motions at $50\,\mu$as/yr (equivalent to $4\,\mathrm{km/s} \times D_{\mathrm{Kpc}}$, a 1 microarcsecond level astrometric mission with a wide field angle has the power to measure in 1 year baseline true tangential velocities and $100 \times D_{\mathrm{Kpc}}$ m/s precision level on thousands of objects per pointing, thus unveiling detailed dynamical maps of such associations. In clusters like Omega Centauri, very strong constrains (or detection) of their possible intermediate mass black holes (10^3-10^5 solar masses) will also be possible routinely.

Similarly, obtaining proper motions of tens of thousands of stars with respect to background galaxies and quasars will provide absolute proper motions of these associations thus tracing the large scale structure of the dark matter halo of the Milky Way and unveil the dynamical fate of our Galaxy (possible collision with Andromeda and the Triangulum Galaxy within 4 Gyrs?). Precision astrometry of peculiar objects, such as runaway and extreme halo stars, will unveil the origin of such exotic objects (ejected by the central black hole of the milky way, leftover of supernova explosions in massive binaries from OB associations, etc.).

2.2 Extreme astrophysical objects

Black holes, neutron stars and white dwarfs are examples of the most extreme objects known to exist. However, little is known about their fundamental properties such as masses or internal structures. These are the end-products of stellar evolution thus their masses and spins put strong constrains on how stars evolve and how elements heavier than hydrogen are formed in the observed abundances. Moreover, they exist at the limit of known physics where our extrapolations might not be valid at all. A micro-arcsecond level astrometry will provide distances and proper motions to binary stars with exotic/invisible companions such as black holes and neutron stars. Precise masses will also be obtained from measuring their orbits at micro-arcsecond level astrometry, even if they are kiloparsecs away from the Sun (e.g. Cygnus X-1). Perspective acceleration measurements will provide direct mass-radius determinations thus testing proposed equations of state of degenerate matter in strong gravitational fields, and astrometric microlensing events of high proper motion will provide single-star mass determinations. In a cluster context, e.g. globular cluster, *Theia* will follow across the cluster the binary/multiple star statistics understanding the evolution pathways creating these extreme objects. The *Theia*'s proposed mission concept should also be able to achieve 10^{-5} photometric precision at the same time, thus providing further astrophysical observables in the strong gravitational regime (asteroseismology of white dwarfs, self-lensing in binaries with compact objects).

2.3 Nearby habitable terrestrial exoplanets

One of the objectives of *Theia* is a complete census of Earths ($M \leq 1.25\, M_{\oplus}$) and Super-Earths ($M \leq 5\, M_{\oplus}$) located in the Habitable Zone (HZ) of the 50 nearest FGK stars. Astrometry is unique in the sense that it can provide 3D orbits of planetary systems irrespective of their inclination and is quasi-insensitive to stellar activity. Transits require lucky orbital alignments and the Doppler technique can only reach extreme sub-m/s precision on a small fraction of non-active G & K dwarfs ($\sim 5\%$). While both transits and Doppler spectroscopy techniques can identify thousands of planetary systems providing statistics and follow-up opportunities on moderately bright stars, they are not able to identify our closest Earth-analog neighbours. Sub-microarcsecond astrometry combined with long-term radial velocities measurements provides the only feasible way to obtain a complete sample of the closest planetary systems for future direct imaging missions (closer than 10-13 pc, e.g. Alpha Cen, Tau Ceti, 61 Cyg). These planetary systems are of great importance since they will be the only ones that direct-imaging/spectroscopic missions, either in the visible or in the thermal infrared, will be able to study with sufficient details and where biosignatures could be searched for. As astrometry can measure planetary masses and fully characterize their orbits (period, inclination, semi-major axis, eccentricity, angles and ephemeris) in multiple systems, these pieces of information allow comparative planetology for systems containing all sorts of planets and a much more complete picture, with unprecedented sensitivity, peaking around the habitable zone. The main objective of such a census, is at least double: (i) detection and determination of true masses of nearby telluric planets, a mandatory piece of information to estimate the nature of the planetary surface, prior to any astrobiology possible statement, (ii) if the mean number of terrestrial planet in the HZ of solar-type stars is small, as pointed by the recent estimates by Kepler ($\approx 10\%$), stars with potentially habitable worlds are rather rare, and the valuable time of a prospective direct imaging mission should not be spent on stars without them.

2.4 Solar system observations and Fundamental astronomy

Micro-arcsecond astrometry for bright asteroids is very useful for mass determinations of these objects by close encounters and improvement of their ephemerides. Since these measurements require time-critical observations, an observatory class mission with flexible scheduling will be mostly needed. Dynamical drag due to thermal effects can be measured as well as constraints on the inner physics of asteroids deduced from these effects or from the bulk densities estimated with the close encounters.

Depending on the angular size and *Theia*'s ability to centroid asteroid-type objects, high precision measurements of the orbits of the Galilean satellites combined with orbital observations by the JUNO spacecraft, can be used to measure or at least put strong constraints on the internal structure of Jupiter (and the other gas giants). Global astrometry is required to make sensible experiments related with the reference frame because large angles have to be measured. Nevertheless, at a final accuracy of $0.3\,\mu$as, a number of subtle effects can be measured in the relativistic light deflection of Solar system bodies. Using selected optimally populated stellar fields with

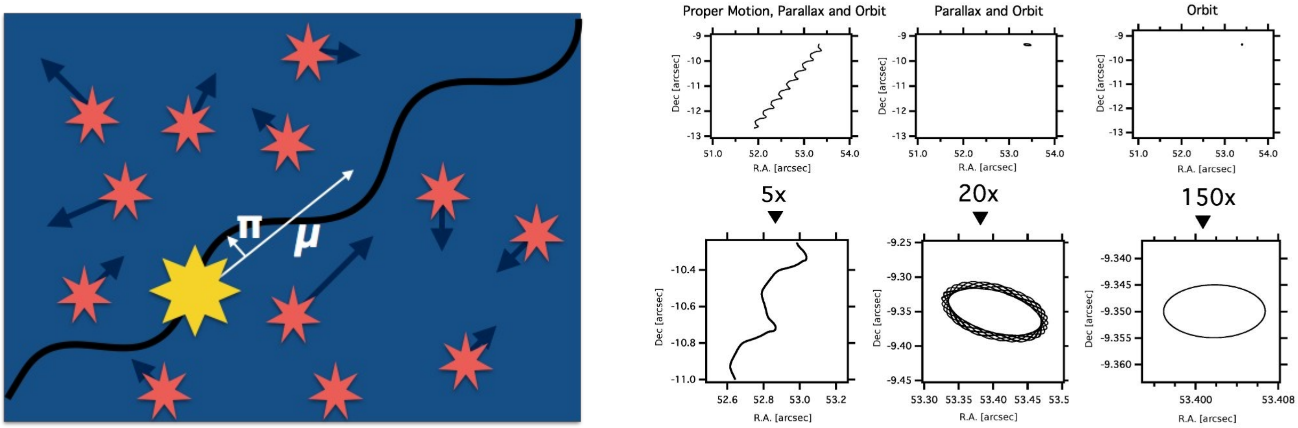

Figure 1. **Left.** Astrometric motion of a nearby star (20 pc) with a brown dwarf orbiting it. One effect is removed at a time from left to right to improve visualization. Bottom panels are magnified versions of the motion to appreciate the smallness of the planet's signal : proper motion is $4.2\,10^5$ μas/yr, parallax is $5\,10^4\,\mu$as and the induced wobble of the brown dwarf ($\sim$ 20 m$_j up$) is $5\,10^3\,\mu$as. The signal induced by an Earth-mass planet around this same star would be 6000 times smaller ($\sim$0.8 μas). **Right.** Cartoon representation of the differential astrometry principle. Our very nearby target star (yellow) is moving fast with respect to background stars (red). The wobble along its trajectory is the parallactic motion (π) and has a period of 1 year because it is caused by the observers motion around the Sun.

Jupiter in front of it and shortly afterwards without Jupiter, one can detect multipolar light deflection due to Jupiter's dynamical non-sphericity, gravito-magnetic light deflection due to both translational and rotational motions as well as leading enhanced post-post-Newtonian effects.

2.5 ...microarcsecond astrometry in 2025 and beyond

There is no ground based competition against space-based astrometry, even on fainter objects and large telescopes. While hundreds of echelle spectrometers and other precision techniques are available from the ground, achieving competitive astrometric precisions compared to HIPPARCOS is challenging even today, and can only be done on small samples of objects in very narrow field applications. As a result, astrometry has been relegated to large space-based projects (e.g. Gaia, L-class mission), with technology development cycles spanning decades and strongly protected/vetted science cases to newcomers, making astrometry very unattractive to young scientists and inter-disciplinary colleagues. The availability of an easy-to-use, observatory class instrument will allow systematic use of astrometry as one more tool to characterize astrophysical sources. *Theia* will build on the experience and legacy on Gaia to provide sustained access to micro-arcsecond precision astrometric measurements. Contrarily to other techniques, astrometry will not benefit from Giant telescopes as measurements are mostly limited by calibration uncertainties that require space-based conditions. The *Theia* mission is proposed as a true community observatory with a large fraction of open time including target-of-opportunity science (regular proposal cycles, and fast reaction target-of-opportunity proposals). *Theia* will be a 1 degree diffraction-limited imager, thus enabling numerous additional science cases requiring high resolution imaging and very high photometric stability.

3. DIFFERENTIAL ASTROMETRY

3.1 Principle

Differential astrometry measures the position of an object as a function of time, relative to a reference frame. A classic example of differential astrometry is the measurement of the parallactic wobble of a nearby star using distant background stars as reference stars, which provide a local reference frame (Fig. 1).

In this one year, the star also moves μ (proper motion) due to its tangential motion with respect to the Sun. Background stars will also have a (smaller) parallactic and proper motion, meaning that the absolute parallax and motion of the target cannot be obtained unless those of the reference stars are determined as well. This can be done through a coupling with a known reference frame in which the stars have been measured before (e.g. provided by Gaia) or very distant sources such as quasars and galaxies can, in principle, be used to set the zero-point of the local kinematic reference frame.

For most stars the motion of a star on the celestial sphere can be described sufficiently well with just 5 astrometric parameters expressed with respect to a certain reference epoch T_0: two angular coordinates, two proper-motions (or μ) and the amplitude of the parallactic wobble, called parallax[1] (π).

Although all astrometric observations are in principle of differential nature, they are often expressed with respect to a (pre-defined) reference frame. A global astrometric reference frame provides the stellar positions in a well-defined global coordinate system but also provide the motions of the stars in such global frame (parallaxes and proper motions). This can be done for a differential astrometric instrument such as *Theia* if enough sources with known astrometric parameters (positions and motions as provided by Gaia) are simultaneously observed with the target stars. Alternatively one can also use a set of extremely distant reference objects with assumed proper motions and parallaxes of zero, e.g. quasars and distant galaxies.

Astrometric observables are not limited to the aforementioned five classic parameters. The extreme precision of *Theia* allows the measurement of non-linear displacements due to the presence of binary companions or planet. The full (Keplerian) orbit can be derived from these observations alone (in contrast to radial velocity measurements from which inclination cannot be measured). Differential astrometric measurements against reference stars are also used to measure trajectories of Solar System objects.

3.2 Point & Stare observing strategy

With a similar focal plane and dimensions ($\sim 1\,$m telescope, 40-m focal length, detector mosaic), *Theia* is a pointed version of Gaia (with a single field of view) on which extreme differential precision is reached by longer integration times and further optomechanical stabilization and calibration. That is, *Theia* will *"Point & stare"* instead of *"spin & scan"*. High dynamical range on very bright stars will be achieved by using fast windowed read-out modes in CMOS-like detectors. As a result, despite its access to a smaller number of objects, *Theia* will be able to achieve 50 times better precision than Gaia on selected targets and fields because:

- *Theia* can schedule observations and spend as much time as necessary on each target
- *Theia*'s field-of-view is calibrated down to < 1 μas precision using new laser metrology technologies and up-to-date detectors

In this sense, *Theia* is a natural follow-up of Gaia and significantly enhances the investment already made by ESA on space astrometry. *Theia* will be able to use millions of stars on each pointing to anchor the motion of the target sources to the Gaia reference frame, thus producing absolute parallaxes and proper-motions for faint and other exotic objects out of Gaia's reach.

As for other high accuracy astrometric applications (e.g. VLBI in the radio domain) a fully relativistic model of the observations is necessary. The relativistic model computes the deflections (and time shifts) of the observations due to the presence of close-by gravitational bodies (e.g. Sun, and planets) and allows the derivation of astrometric observables in the inertial reference frame of the Solar System Barycenter. Although *Theia* is conceived to be much more precise than Gaia, the same model[2] can be used to calibrate general purpose observations because only local astrometric effects for relatively small angles are needed instead of the large angle effects needed for global astrometric applications. For precisely focused experiments (e.g. light deflection by Solar System planets), more detailed existing models[3] will be required.

4. PAYLOAD INSTRUMENT

Achieving micro-arcsecond astrometric precision with a telescope requires mastering all effects that can impact the determination of the position of the point spread function. The typical apparent size of an unresolved star is about $1.22\lambda/D$, which corresponds to 160 milliarcseconds for a 0.8-m telescope operating in the visible domain. The challenge is therefore to control these systematics effects to the level of 1 part per 160 000. Such level of accuracy can only be reached in a space environment with no disturbances due to the atmosphere, but this

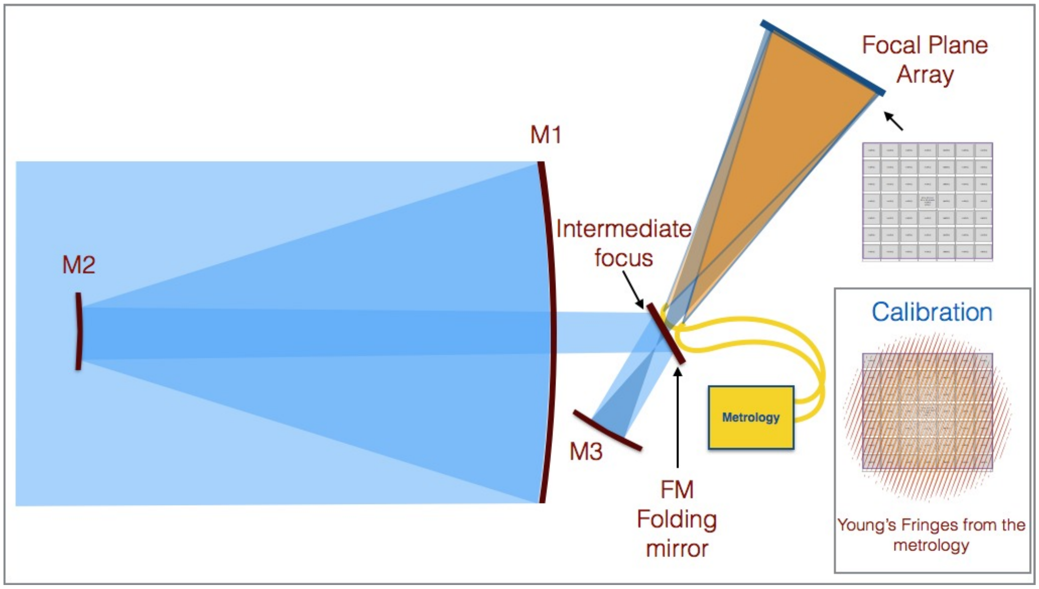

Figure 2. Proposed concept for a very high precision astrometry mission. It consists of a TMA telescope in Korsch symmetrical configuration with two curved mirror M2 and M3 and a folding mirror FM which has a semi-transparent hole in the middle. The light then goes onto a filled focal plane array calibrated by laser metrology. The blue beam corresponds to the enveloppe of the light coming from different directions and not a realistic beam..

requirement is somewhat relaxed by the fact it can be achieved with differential astrometry between the target and reference stars in the field of view of the telescope. The determination of the accurate position of a star on a focal plane is dependent of:

- the photon noise which can be either dominated by the target or by the reference stars in the field, depending on the science case ($R \leq 11$),
- the beam walk as soon as there are several optical surfaces and by its stability
- the geometrical stability of the focal plane array,
- the variation of sensitivity (quantum efficiency or QE) within detector pixels and between pixels.

All these effects usually impair space missions like HST or Kepler, unless they provide a large field of view in order to reach brighter reference stars, an optical path that is the same for the primary target and the reference stars, and a metrology system that monitors all geometrical changes in the telescope with time.

4.1 Instrumental concept

The proposed mission is resulting from a trade-off between the NEAT concept that is based on a formation flying configuration[4] and a more classical concept like the EUCLID visible instrument[*]. Our trade-off is the result of our experience gained in working with many astrometry concepts (SIM, SIM-Lite, corono-astrometry,[5] NEAT).

The concept consists in a primary mirror, a focal length and focal plane that allows diffraction limited imaging and metrology-based calibration sources. The large distance between the primary optic and the focal plane can be implemented as two spacecraft flying in formation like NEAT, or using a more traditional three mirror anastigmat optical configuration like the one displayed in the left part of Fig. 2. The focal plane with the detectors having a field of view of about 0.6° is shown in the right part of Fig. 2 , and has a geometrical extent of $0.31\,m \times 0.34\,m$. The focal plane is composed of an array of 7×7 4048×4048 visible detectors. The detector pixels are 10μm in size.

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[*] EUCLID red book: http://sci.esa.int/euclid/48983-euclid-definition-study-report-esa-sre-2011-12/

The choice between the formation flying concept which remains as the backup concept for this mission and the TMA concept has been driven mainly by the need to use matured technology. The main advantage of formation flying is to avoid beam walk errors from optics additional to the primary mirror but is not as standard as a single spacecraft telescope.

Since $\lambda/D \sim 200\,\mathrm{mas}$, then M2 and M3 with $\lambda/200$ optical quality would lead to sub-mas astrometric bias for a state of the art TMA telescope. The proposed metrology system, which is launching laser lights from the edge of the last mirror (Figs. 2 and 3) is designed to measure errors in the focal plane, the positions of the pixels, and the QE gradients within each pixel. Such a metrology system placed on the edge of the primary mirror could in principle be used as well to monitor the beam walk errors in a TMA telescope. Unfortunately the footprint of the metrology beams (located in an object plane) would be very different from the foot- print of any of the stellar beams (pupil plane for star light).

The annual proper motion of nearby stars is typically $\sim 1\,\mathrm{arcsec/yr}$. Assuming that the proper motion of reference stars is negligible (because they are much further) and scoring the perfect central star, we are left with the reference stars shifted by 1 arcsec in image 2 relative to image 1 when taken at 1 yr interval, all in the same direction. This represents about 10 pixels. The traces of the beams would travel on the M3 by about 50-60 μm. With a roughness of 1 nm rms, it generates variations of about 2 nm WFE rms that create an error in the differential position of the reference star relative to the central star. To relax this severe requirement, *Theia* uses the advantage of the symmetry of the on-axis Korsch optical layout.

During the mission, the telescope will point first to a globular cluster and calibrate its field distortions, then make several visits to target fields, and return to the globular cluster for a new calibration. The period of these cycles is 10 h. In the quiet environment of L2, the main source of changes between calibrations and measurements is thermal expansion due to the variation of the solar angle. A special attention is paid to the telescope thermal insulation, and an active control of the structure holding the mirrors is made.

4.2 Focal Plane array

In the 2010 NEAT proposal, movable CCDs had been proposed in order to address the target and the reference stars. The gain was the cost of the system with only 10 relatively small CCDs but at the expense of more risky implementation with moving parts.

We propose for *Theia* a focal plane array filled with 7 × 7 detector arrays made of 4048 × 4048 pixels of 10 μm each. The 80% fill factor allows almost any reference stars to be addressed in the 0.6 deg field of view and to open the window for other astrophysics goals which would need to image precisely millions of objects.

The detector that has been chosen is the Teledyne's H4RG-10 HyViSI which are high performance hybrid silicon-based PIN CMOS image sensors with a high QE over a large visible spectral band. The advantages of CMOS in comparison to CCD include programmable readout modes, faster readout, lower power, radiation hardness, and the ability to put specialized processing within each pixel. The H4RG-10 readout circuit retains all of the CMOS functionality (windowing, guide mode, reference pixels) and heritage of its highly successful predecessor (H2RG) developed for JWST. The H4RG-10 array is mounted on a lightweight silicon carbide (SiC) package and has been qualified to Technology Readiness Level 6 (TRL-6). As part of space qualification, the HyViSI$^{\mathrm{TM}}$H4RG-10 array passed radiation testing for low earth orbit (LEO) environment.

4.3 Detector Calibration unit

To calibrate the distance between the stars, a metrology system is launched from the last mirror before the detecto and that feeds several optical fibers (3 or more) located at the edge of the beam. The fibers illuminate the focal plane and form Young's fringes detected simultaneously by each array. These modulated fringes allow the XYZ position of each array to be solved. To measure the QE of the pixels (inter-, and intra- dependence), the fringes have their phase modulated by optical modulators. The arrays are read at 50 Hz providing many frames yielding high accuracy. By measuring the fringes at the sub-nanometer level using the information from all the pixels of each array, one is able to solve for the position of all reference stars compared to the central target with an accuracy of 1 μas per hour. The field of view of 0.6 deg corresponds to 6 to 8 reference stars brighter than $V = 11$ around the target in most fields.

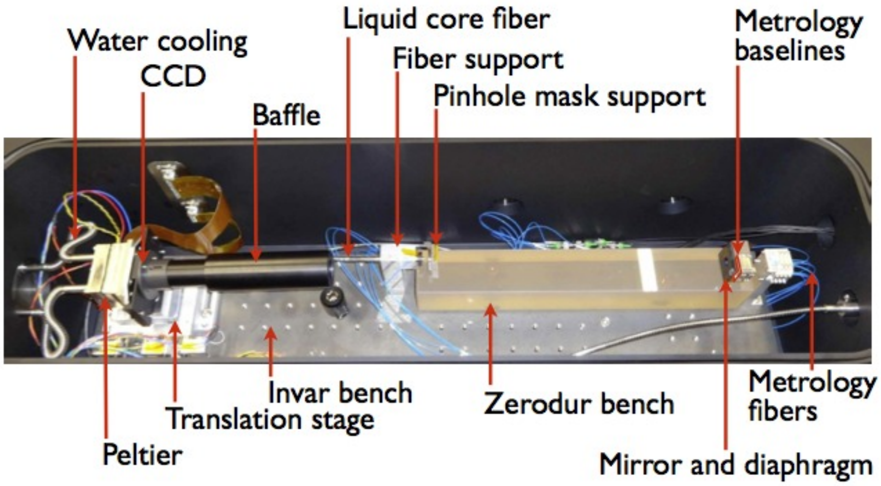


Figure 3. Picture of the NEAT-demo tested at IPAGalso called DICE, inside its vacuum chamber (see also Crouzier et al. in this volume).

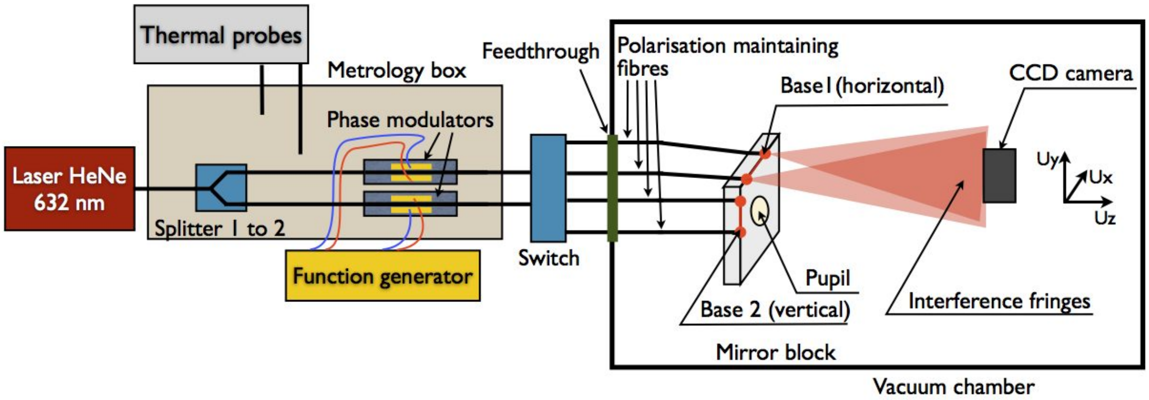


Figure 4. Schematic of the metrology for the NEAT-demo/DICE testbed.

Indeed, even in the absence of optical errors, major errors ($\gg \mu$pixel) occur at the detector in the focal plane. The errors are at the first order caused by the non uniformity of pixel sensitivities (i.e. quantum efficiencies), and their offsets. The pixel layout is not perfectly regular, and we have what we call offsets which are the differences between the exact positions and a perfect regular grid structure. With CCD and CMOS detectors, the issue of pixel sensitivities is well known and is routinely calibrated by taking a flat field, but the pixel offset is usually not an issue and is thus not investigated. To reach a micropixel accuracy however both the sensitivities and the offsets have to be calibrated accurately. For *Theia* the requirement is to obtain a calibration error on the centroid of less than 10^{-5} pixel.

Several technology testbeds have been set up to demonstrate that we can achieve this objective. Two testbeds were built at the JPL, at first MCT (*Micro-pixel Centroid Testbed*), and then a second version called VESTA (*Validation Experiment for Solar-system STaring Astrometry*). In order to build their own expertize and to capitalize and improve on the work done at the JPL, European scientists have assembled another testbed at IPAG[6] (Fig. 3). This testbed, called NEAT-demo or later DICE (for *Detector Interferometric Calibration Experiment*, see Crouzier et al. in this volume) was built in the aftermath of the NEAT proposal of 2010 and specified to reach the accuracy required for detection of exo-Earth in the solar neighborhood (5×10^{-6} pixel).

The NEAT-demo/DICE experiment has achieved first light in July 2013. Crouzier et al. in this volume show that the calibration system yielded in 2016 the pixel positions to an accuracy estimated at 4×10^4 pixel. After including the pixel position information, an astrometric accuracy of 6×10^5 pixel was obtained, for a PSF motion

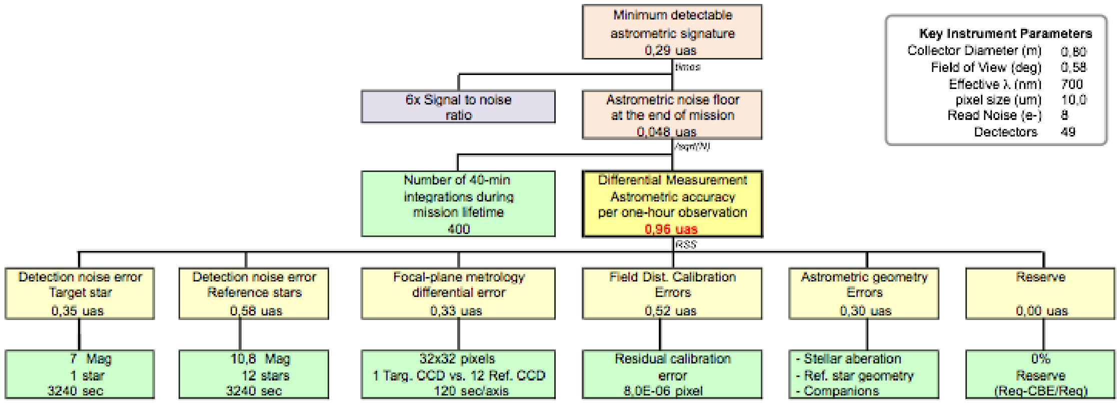


Figure 5. Top-level error budget for *Theia*. It shows how the 1 μas accuracy enables the detection of 0.3 μas signatures with a signal to noise of 6 after 360 h of observation. It also shows the major contributors to the astrometric error.

over more than 5 pixels. In the static mode (small jitter motion of less than 1×10^3 pixel), a photon noise limited precision of 3×10^5 pixel was reached.

Precise astrometry requires calibrating both the detector and the field mapping of the optical system. Field mapping transforms the location of an object in the sky (ξ, η) to a position in the telescope imaging plane (X, Y). It includes both the field distortions shown in a simple single-lens imaging system and the complex effects caused by field dependent footprints on optics after the primary mirror due to beam walking in a compound imaging system.

With detector responses well calibrated using the laser metrology, the field mapping can be calibrated by observing a dense star field, a globular cluster by default. The key to field mapping calibration is to observe a globular cluster multiple times by putting it at different locations in the field to obtain diversity.

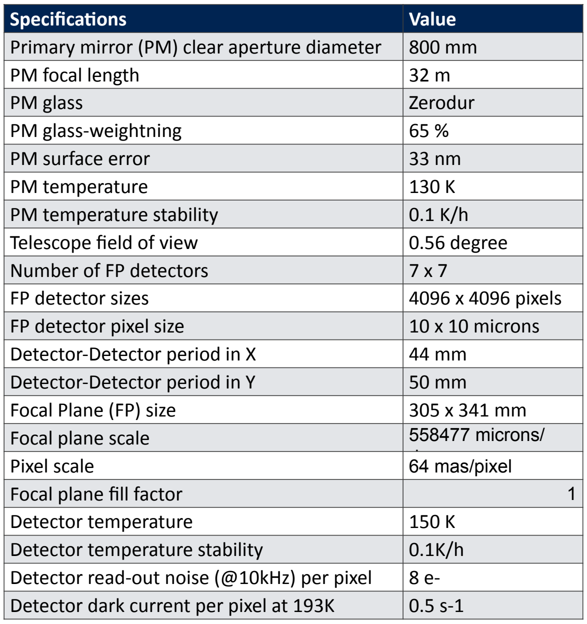
4.4 Performance assessment and error budget

A detailed error budget was developed for this mission concept. The six major errors terms are captured in the simplified version of the error budget shown in Fig. 5.

The biggest term is the brightness dependent error for the set of reference stars. There are thousands stars in the FOV. Assuming a limit to no more than one star per detector, there is 48 potential reference stars. However the error budget has been done with 12 stars as a compromise: more stars improve astrometry and reduce systematic errors, fainter stars have lower SNR and contribute very little to the astrometry. Combined flux from all the stars of $V < 13.5$ mag in the FOV gives an equivalent magnitude of magV = 8.13. Equivalent 12-identical stars would then produce the combined flux of $V = 10.83$. Therefore in the error budget, 12 stars of $V = 10.8$ mag are used. After 1 s of integration, 8×10^5 photoelectrons are detected for each of the 10.8-mag reference stars. Since all the stars are measured simultaneously, the stars do not need to be kept centered on the detector at the sub-mas level, but only to a fraction of the PSF width to avoid spreading of the photon outside of the PSF and therefore cause the PSF effective width to be larger. A tenth of pixel (1 μm) stability over the one-second integration is sufficient. After 3240 s of integration, the statistical averaged position of the barycenter of the set of reference stars (e.g. 12 stars with $R \sim 10.8$ mag) will be measured with a residual 0.091 nm (0.58 μas) uncertainty. Similarly, the position of the target star ($R \sim 7$ mag) will be measured with a residual 0.055 nm (0.35 μas) uncertainty. Although the spacecraft will have moved by several arc-seconds, the differential position between the target star and the barycenter of the set of reference stars will be determined to 0.58 μas.

Similarly, the focal plane metrology system will have determined the differential motion of the target detector relative to the barycenter of the set of reference detectors with an error smaller than 0.52 μas after 60×1 s metrology measurements.

Table 1. Payload key characteristics and specifications.



Specifications	Value
Primary mirror (PM) clear aperture diameter	800 mm
PM focal length	32 m
PM glass	Zerodur
PM glass-weightning	65 %
PM surface error	33 nm
PM temperature	130 K
PM temperature stability	0.1 K/h
Telescope field of view	0.56 degree
Number of FP detectors	7 x 7
FP detector sizes	4096 x 4096 pixels
FP detector pixel size	10 x 10 microns
Detector-Detector period in X	44 mm
Detector-Detector period in Y	50 mm
Focal Plane (FP) size	305 x 341 mm
Focal plane scale	558477 microns/
Pixel scale	64 mas/pixel
Focal plane fill factor	1
Detector temperature	150 K
Detector temperature stability	0.1K/h
Detector read-out noise (@10kHz) per pixel	8 e-
Detector dark current per pixel at 193K	0.5 s-1

Theia will not be able to measure the separation between the target and the set of reference star to 1 μas. Our contribution will be to measure the change in the relative position of those stars between successive observations spread over the mission life, with an error of 1 μas for each one hour visit.

Static figure error of the primary mirror will produce centroid offsets that are mostly common-mode across the entire field of view. Differential centroid offsets are significantly smaller than the field dependent coma and are in fact negligible. Similarly, changes in the primary mirror surface error produce mostly common-mode centroid shifts and negligible differential centroid offsets. On the other hand, displacement and changes in the shape of PSF would couple with the detector response if the detector response is not properly calibrated. The detector needs to be calibrated such that the centroid position could be measured with an accuracy of 8×10^{-6} to 10^{-5} pixel.

4.5 Design of the payload subsystem

The main specifications of the payload are summarized in Table 1.

The demanding image quality requirements for the point spread function are the driving parameters in the telescope design. Two mirror telescopes do not yield good enough image quality for the *Theia* large field of view. The alternative is a three mirror configuration, either an off axis three mirror anastigmat (thus, without central obstruction) or a Korsch configuration. With three mirrors, there are enough degrees of freedom (three curvatures, three conic constants and two distances between mirrors) to achieve a good level of aberration correction (quasi diffraction limited images) and the required image scale and low distortion. The needs for symmetrical aberrations led us to choose a symmetrical design provided with a Korsch configuration. The mirrors are being used on-axis with a special fold mirror that have a central hole to let the on-axis light goes through the mirror. The fold mirror is located at the exit pupil near the cassegrain focus at the same time. Therefore the pupil is re-imaged on the same fold mirror by the tertiary mirror. The pupil fits in the region between roughly 0.01 and 0.07 deg where there is a hole in the folding mirror and therefore goes through it to be imaged on the focal plane (Fig. 6). If we keep the center part of the fold mirror reflecting the light in the inner 0.01 degree radius and leave the ring located between transmissive from the radius 0.01 to 0.07 deg diameter and reflective again from 0.07 deg to the edge, then we could use the on-light axis, with the target star at the center, and the reference in the region from 0.07 to 0.3 deg (or more) degree around the target.

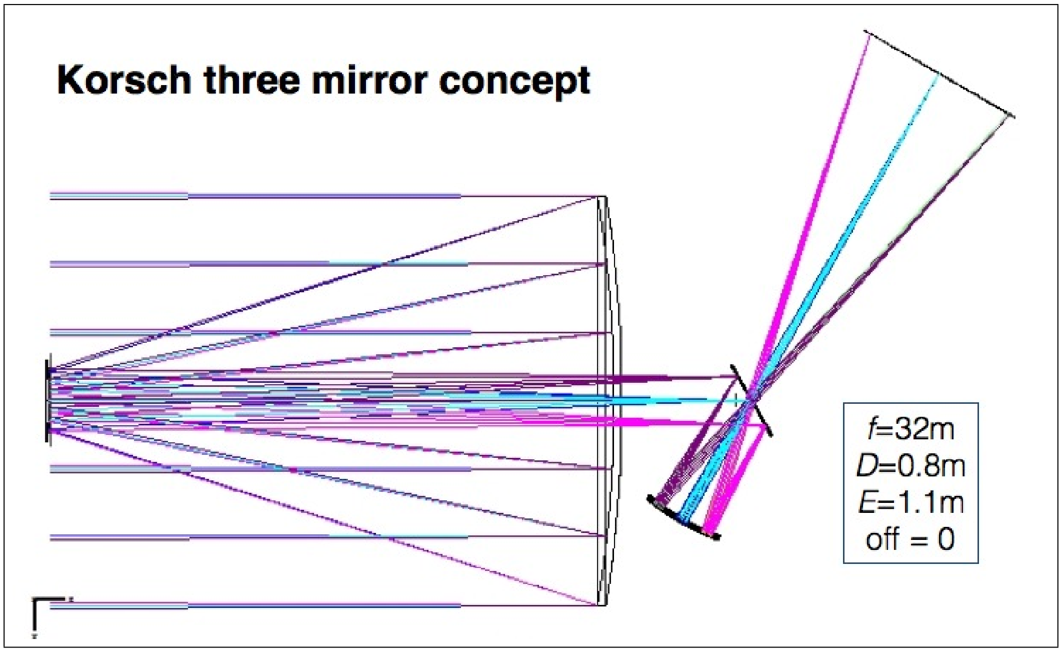


Figure 6. A possible optical lay-out of the *Theia* telescope. It is a three mirror anastigmat with a centered Korsch configuration s. The main parameters of this Korsch telescope is a mirror diameter of $D = 0.8\,\mathrm{m}$, a focal length $f = 32\,\mathrm{m}$, ellipticity of $E = 1.1\,\mathrm{m}$.

The window which is transmissive at located at the pupil plane does not have field dependent aberration, only common mode error across the pupil. At $f/32$, the dispersion from the glass is mostly common mode and we can adjust the folding angle to minimize the dispersion.

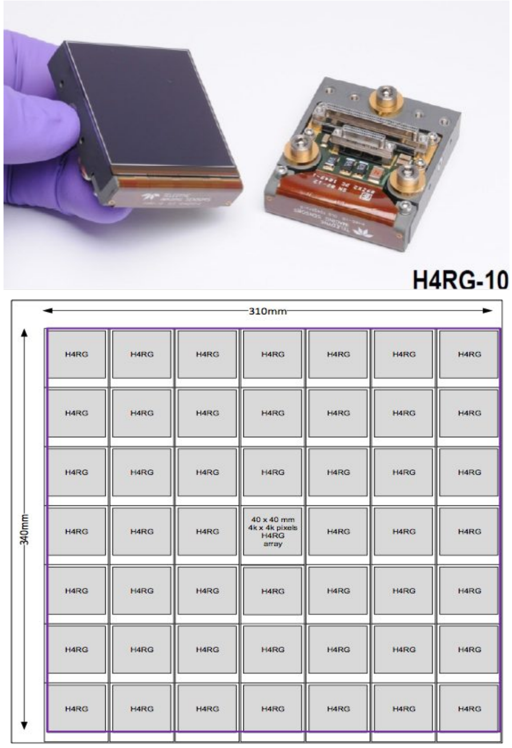
The mirrors would be fabricated in either Zerodur or ULE with a light-weighting process applied on M1 mirror to lower its mass at a maximum.[7,8] Krödel et al.[9] showed that an areal surface density of $25\,\mathrm{kg/m^2}$ is possible, therefore leading to a weight around 12 kg. The surface quality should be better than $\lambda/4$ PV and would be coated with protective aluminum.

The focal plane concept has been presented in Sect. 4.1 and in Fig. 2. A proposition for implementation is shown in Fig. 7. The table summarizes, the typical characteristics of this off-the-shelves detector, showing how the complete feasibility of the whole focal plane data handling may be achieved in this realistic case. According to these characteristics, 7×7 H4RG10-HyVisi detectors combined with possibly related tapers to increase the filling factor from 79% to 100% will allow the focal plane to be covered completely.

The high demand number of large scale detectors to be supported and processed requires a modular approach. Indeed the key mission goal being the throughput processing rate requirement, a distributed data handling would have the advantage to locally and in parallel provide the data acquisition, providing the proper buffering and computation capability for each detector module of the FPA array. Only after the local parallel processing of the data, would the data be forwarded to the central DPU for final formatting and ground transmission minimizing the risk of resources collapsing. Moreover the modular approach when properly decoupled in term of H/W resource may provide an additional redundancy and extended life time, at most paid in term of focal plane reduction in the case one or more detectors (or an element of their direct processing chain) would die or remain damaged.

Each detector will have its own Local Digital Processing (L-DPU) which will power and drive the detector, sampling and processing its data outputs. The combination of a detector and a L-DPU will constitute a FPAM (Focal Plane Assembly Module) which will

- control and manage the detector low level functionality;



Focal Plane Array Detectors

7x7 Hybrid silicon PIN CMOS sensors, HyViSI™ Teledyne H4RG-10™

ITEM	VALUE
Pixel Number	4096 x 4096
Optical format	44 x 50 mm
Pixel size	10 x 10 um
Full well charge	100 Ke
QE	> 90%
Number of outputs	1, 4, 16, 32 or 64
Max Pixel rate readout rate	up to 5MHz
Full frame rate (fast mode)	19 fps w 64 outputs @ 5Mpix/s/output
Dark Current (room temperature)	5-10 nA/cm
Readout noise	< 10 e

Figure 7. Top left : photograph of a Teledyne HR4G-10 HyViSI detector. Bottom left: schematical display of the focal plane with its 7 × 7 Teledyne detectors. Right: Characteristics of the Teledyne H4RG10-HyViSI detector.

- support the acquisition at the maximum throughput rate, from up 64 channels.
- support image buffering of at least 4 complete frames.
- receive from the Instrument Control Unit (ICU) the roto-translational parameters to adjust the current data set of data.
- accumulate (add) sequentially roto-translated corrected ROI (Region Of Interest).
- possibility to communicate with the closest 8 FPAMs[†] to support the transmission of the pixels residing in overlapping ROIs.

5. MISSION

5.1 Mission profile

Theia is an astronomy mission that aims at surveying the full sky. From the two possible classical orbits (HEO and L2), L2 is the best option for overall stability because of the absence of gravity gradients, the time available for observation, the environmental conditions with no crossing of the van Allen belt. An L2 orbit also has the advantage over the HEO that the thermal conditions over the orbit remains the same, i.e. the thermo-elastic design issues are simplified. The *Theia* spacecraft will be injected into trajectories to L2 in a large Lissajous or Halo orbit at L2.

In order to avoid parasitic light from the Sun onto the telescope and the detector, *Theia* spacecraft have baffles that protect them from Sun light at angle larger than ±45° in the Sun direction.

[†] located at North, North-East, East, South-East, South, SouthWest, West, North-West

Table 2. Mission main characteristics and reference mission timeline

Launch date	No constraints, allowing launch date in 2025
Orbit	Large Lissajous in L2
Lifetime	• 3 years of nominal science operations • Technical operations: orbit transfer (3m), instrument commissioning (1m overlap +1m), decommissioning (1m)
Concept	Single spacecraft
Communication architecture	5Mbits/s, twice a week during a total of 4h

Considering the preliminary assessed mass for the *Theia* satellite, the best suited launcher is Soyuz with the enhanced capacity version Fregat MT for the upper stage. The launch strategy would consist in a unique burn of Fregat stage injecting directly the S/C onto a L2-transfer trajectory, avoiding a coasting on a parking orbit. The separation of the satellite would occur after about $1/4$ of rotation around the Earth, preventing the Sun illumination to enter into the instrument during ascent and up to the separation.

After the completion of its last burn, the Fregat upper stage would re-orient the S/C into a 3-axes stabilized attitude, with the Sun in the Sunshield normal direction. As for Herschel satellite, *Theia* spacecraft would require a reactive *Safe Mode* control to maintain roughly the Sun in this direction and ensure the instrument protection.

The use of Soyuz launcher induces a limit in terms of allowable volume for the spacecraft and its payload. The Soyuz fairing allows a maximum diameter of 3800 mm, which conditions:

- The maximum primary diameter;
- The maximum Service module size and thus its internal accommodation capacity;
- The maximum Sun shield and V-groove screens size, linked also with the telescope size and required sky accessibility requirements.

The use of Soyuz launcher limits also the maximal wet mass be lower than 2145 kg including margins and launcher adapter for a direct transfer at L2 point.

The time baseline to properly investigate the science program of *Theia* is 3 years including some time devoted to orbit maintenance. A total of approximatively 4 months has been estimated for the orbit transfer (3 m) and the instrument commissioning (2 m), leaving $\sim 26,300$ h for the scientific program including 15 mn per visit for reconfiguration, station-keeping,... A part of the commissioning (about 1 month) will be done during the orbit transfer.

The primary objective requires 22,330 h of nominal time. The remaining 3,940 h will be used for open time observations. This timeline is flexible and can be optimized with the target list and the main instrumental characteristics.

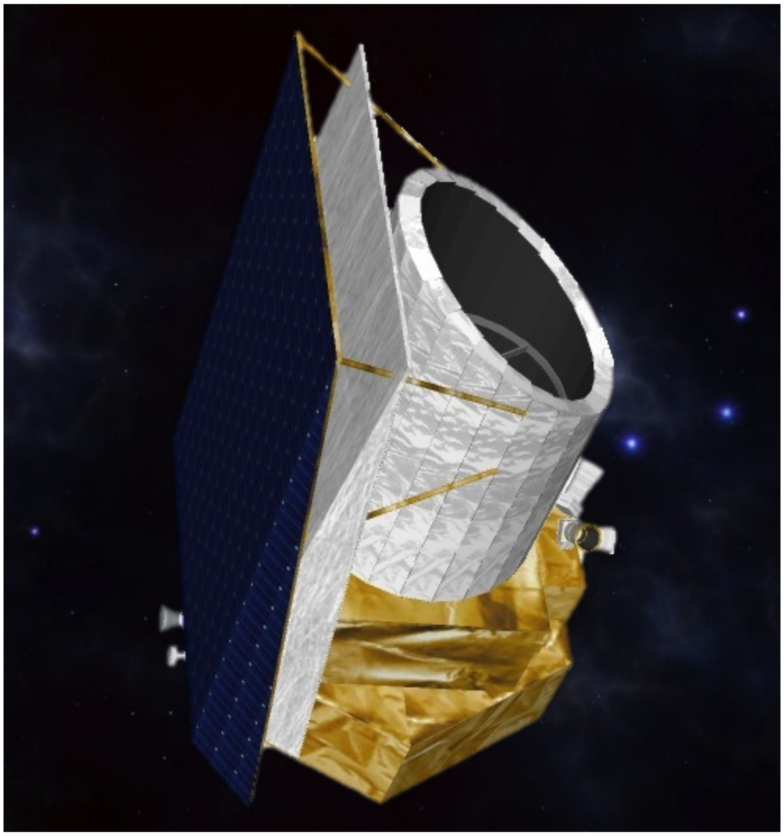


Figure 8. View of *Theia* spacecraft showing the thermal sunshield.

5.2 Preliminary spacecraft design

The preliminary *Theia* analyses performed with the current mission definition allowed to identify a safe and robust mission architecture, relying on high TRL technologies, and leaving safe margins and mission growth potential that demonstrates the mission feasibility within the Soyuz ST launch envelope and small M-class mission cost cap.The proposed mission architecture relies on the use of a Korsch three mirror telescope accommodated vertically on top of a platform including all support subsystems.

A high thermal stability of the telescope necessary to ensure its performances is obtained through the use of a Sun Shield on which is accommodated the Solar Array and a vertical V-groove screen. The pointing of the satellite is performed though the use of reaction wheels for large attitude motions between targets. At the approach of the correct pointing, the Satellite will use a cold gas micropropulsion system for fine relative motion acquisition.

The design of satellite is highly based on the concept of the EUCLID service module downscaled to better suit to the specific *Theia* needs and to be compliant with the maximum dry mass recommended for the Cosmic Vision M4 mission. It uses a central tube and standard 1194 mm interface compatible with Soyuz existing adapters and an hexagonal shape structure providing large volumes for platform units and fluid tanks accommodation.

Similarly to EUCLID and HERSCHEL satellites, *Theia* Korsch telescope is accommodated on top of the service module in a vertical position. This concept allows the main mirror size to be maximized though remaining compliant with the launcher fairing volume limits.

A key driver for *Theia* mission is the structural stability of the payload and particularly of the primary-secondary mirrors distance which shall not vary by more than 2 nanometers during 10 hours of observation. This stringent requirement requires first a very stable payload structure with low thermo-elastic deformations. The preliminary analyses led to the selection of a telescope structure largely making use of Silicon Nitride Si_3N_4

ceramic material having a very low coefficient of thermal expansion. Such material can be used in a large number of different structure components (truss, brackets, plates,). Assuming a M1-M2 distance of 0.8 m consistent with the selected Korsch optical configuration, such a concept requires a thermal stability of about 30 mK over 10 hours.

One way of improvement would be the use of the thermal concept as described before, (V-groove screen(s), active thermal control) that will better filter the temperature variations during repointing, reduce the transient duration and limit the temperature drift in steady-state. With such improvements, the feasibility of *Theia* thermal performances is deemed achievable.

Theia communication subsystem would use an X-Band medium gain antenna supported by 3 LGAs ensuring 4π steradians coverage for LEOP and cruise, coupled with a 35W RF TWTA. The medium gain antenna is preliminarily supposed to be fixed but still offering the possibility to allow simultaneous data acquisition and downlink thus optimizing the spacecraft availability. However, the need for a steerable antenna will have to be confirmed with a more detailed analysis.

Data Handling units would derive from EUCLID ones, with a Control and Data Management Unit (CDMU) including the software and a Mass Memory Unit having a storage capacity of several Tbytes.

6. PERSPECTIVES

The *Theia* mission for ESA M4 call is a multipurpose *ultra precise astrometric observatory* which will observe dark matter (34%), nearby Earths (17%), compact objects (11%), Gaia follow-up (11%), open time (15%). The instrument concept and performances compared to NEAT (the previous proposed mission) have changed with a single spacecraft and a new optical concept. There has been instrumentation efforts for detector calibration and optical calibration and stabilization. Ultra precise calibration is underway : 6×10^{-5} pixels (see Crouzier et al. in this volume).

The mission has not been selected for M4 mostly because of cost and instrument complexity. We are working hard in order to submit an improved version of *Theia* for the ESA M5 call for mission to be closed in Oct. 2016.

ACKNOWLEDGMENTS

We would like to thanks CNES and Thales Alenia Space for their support.

REFERENCES

[1] M. A. C. Perryman, L. Lindegren, J. Kovalevsky, E. Hoeg, U. Bastian, P. L. Bernacca, M. Crézé, F. Donati, M. Grenon, M. Grewing, F. van Leeuwen, H. van der Marel, F. Mignard, C. A. Murray, R. S. Le Poole, H. Schrijver, C. Turon, F. Arenou, M. Froeschlé, and C. S. Petersen, "The HIPPARCOS Catalogue," *A&A* **323**, pp. L49–L52, July 1997.

[2] S. A. Klioner, "A Practical Relativistic Model for Microarcsecond Astrometry in Space," *AJ* **125**, pp. 1580–1597, Mar. 2003.

[3] A. Hees, S. Bertone, and C. Le Poncin-Lafitte, "Relativistic formulation of coordinate light time, Doppler, and astrometric observables up to the second post-Minkowskian order," *Physical Review D* **89**, p. 064045, Mar. 2014.

[4] F. Malbet, A. Léger, M. Shao, R. Goullioud, P.-O. Lagage, A. G. A. Brown, C. Cara, G. Durand, C. Eiroa, P. Feautrier, B. Jakobsson, E. Hinglais, L. Kaltenegger, L. Labadie, A.-M. Lagrange, J. Laskar, R. Liseau, J. Lunine, J. Maldonado, M. Mercier, C. Mordasini, D. Queloz, A. Quirrenbach, A. Sozzetti, W. Traub, O. Absil, Y. Alibert, A. H. Andrei, F. Arenou, C. Beichman, A. Chelli, C. S. Cockell, G. Duvert, T. Forveille, P. J. V. Garcia, D. Hobbs, A. Krone-Martins, H. Lammer, N. Meunier, S. Minardi, A. Moitinho de Almeida, N. Rambaux, S. Raymond, H. J. A. Röttgering, J. Sahlmann, P. A. Schuller, D. Ségransan, F. Selsis, J. Surdej, E. Villaver, G. J. White, and H. Zinnecker, "High precision astrometry mission for the detection and characterization of nearby habitable planetary systems with the Nearby Earth Astrometric Telescope (NEAT)," *Experimental Astronomy* **34**, pp. 385–413, Oct. 2012.

[5] O. Guyon, E. A. Bendek, J. A. Eisner, R. Angel, N. J. Woolf, T. D. Milster, S. M. Ammons, M. Shao, S. Shaklan, M. Levine, B. Nemati, J. Pitman, R. A. Woodruff, and R. Belikov, "High-precision Astrometry with a Diffractive Pupil Telescope," *Astrophysical Journal Supplement* **200**, p. 11, June 2012.

[6] A. Crouzier, F. Malbet, O. Preis, F. Henault, P. Kern, G. Martin, P. Feautrier, E. Stadler, S. Lafrasse, A. Delboulbe, E. Behar, M. Saint-Pe, J. Dupont, S. Potin, C. Cara, M. Donati, E. Doumayrou, P. O. Lagage, A. Léger, J. M. Le Duigou, M. Shao, and R. Goullioud, "Metrology calibration and very high accuracy centroiding with the NEAT testbed," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9143**, p. 4, Aug. 2014.

[7] M. R. Krödel and C. Devilliers, "SPIRALE: the first all-Cesic telescopes orbiting earth," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7425**, p. 0, Aug. 2009.

[8] M. Krödel, D. Wächter, F. Stahr, and C. P. Soose, "Recent development of fabrication of extreme lightweighted ceramic mirrors," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9151**, p. 0, July 2014.

[9] M. R. Krödel, P. Hofbauer, C. Devilliers, Z. Sodnik, and P. Robert, "Recent achievements with a cryogenic ultra-lightweighted HB-Cesic mirror," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7739**, p. 2, July 2010.