DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

Alberto Krone-Martins
Donald Bren School of Information and Computer Sciences
University of California, Irvine
In this short talk...

What and why?

Challenges?

The future?
In this short talk...

What and why?

Challenges?

The future?
• “All that part of astronomy which specifies reference coordinate systems and/or determines the coordinates of celestial bodies and their derivatives.” H. Eichhorn
ASTROMETRY?

• “All that part of astronomy which specifies reference coordinate systems and/or determines the coordinates of celestial bodies and their derivatives.”
  - H. Eichhorn
ASTROMETRY AND EXOPLANETS

- Astrometry:
  - Not strongly affected by stellar activity;
  - Telluric planets around FGK stars.
ASTROMETRY AND EXOPLANETS

• Astrometry:
  • Not strongly affected by stellar activity;
  • No sin (i) effect on the mass;
• **Astrometry:**
  - Not strongly affected by stellar activity;
  - No sin (i) effect on the mass;
  - Full characterisation of the system masses and orbital information.
ASTROMETRY AND EXOPLANETS

• Astrometry:
  • Not strongly affected by stellar activity;
  • No sin (i) effect on the mass;
  • Full characterisation of the system masses and orbital information.

But very small effect!!

\[ \Delta \theta = 3 \left( \frac{M_p}{M_\oplus} \right) \left( \frac{a_p}{1\text{AU}} \right) \left( \frac{M_*}{M_\odot} \right)^{-1} \left( \frac{D}{1\text{pc}} \right)^{-1} \mu\text{as} \]
ASTROMETRY AND EXOPLANETS

• Astrometry:
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Earth at 1 AU of a Sun at 10pc ~ 0.3 uas
**ASTROMETRY AND EXOPLANETS**

- Astrometry:
  - Not strongly affected by stellar activity;
  - No \( \sin(i) \) effect on the mass;
  - Full characterisation of the system masses and orbital information.

Very simplistic way to perform a detection of a 1.5 MEarth planet at the HZ of a Sun at 10pc

---

Malbet et al. 2012 (NEAT proposal)
Differential Astrometry?

- Astrometry determines the coordinates of celestial bodies and their derivatives.

With respect to each other

Differential or relative astrometry
CONCEPTS OF DIFFERENTIAL ASTROMETRY
CONCEPTS OF DIFFERENTIAL ASTROMETRY

\[ \theta_{T,R1}, \theta_{T,R2}, \theta_{T,R3}, \theta_{T,R4}, \theta_{T,R5}, \theta_{T,R6}, \theta_{T,R7}, \theta_{T,R8}, \theta_{T,R9}, \theta_{T,R10}, \theta_{T,R11}, \theta_{T,R12}, \theta_{T,R13} \]
CONCEPTS OF DIFFERENTIAL ASTROMETRY
CONCEPTS OF DIFFERENTIAL ASTROMETRY
CONCEPTS OF DIFFERENTIAL ASTROMETRY

$$(x, y)_{R_{11}}$$  $$(x, y)_{R_{12}}$$  $$(x, y)_{R_{13}}$$  $$(x, y)_{R_{1}}$$

$$(x, y)_{R_{10}}$$  $$(x, y)_{T}$$  $$(x, y)_{R_{4}}$$  $$(x, y)_{R_{2}}$$

$$(x, y)_{R_{9}}$$  $$(x, y)_{R_{8}}$$  $$(x, y)_{R_{3}}$$

$$(x, y)_{R_{7}}$$  $$(x, y)_{R_{6}}$$  $$(x, y)_{R_{5}}$$
CONCEPTS OF DIFFERENTIAL ASTROMETRY
CONCEPTS OF DIFFERENTIAL ASTROMETRY
CONCEPTS OF DIFFERENTIAL ASTROMETRY

\[ \alpha_i = \alpha_{i0} + \mu_{\alpha i} t_j \]

\[ \delta_i = \delta_{i0} + \mu_{\delta i} t_j . \]
CONCEPTS OF DIFFERENTIAL ASTROMETRY

\[
\alpha_i = \alpha_{i0} + \mu_{\alpha i} t_j + \omega_i P_j \\
\delta_i = \delta_{i0} + \mu_{\delta i} t_j + \omega_i Q_j
\]
CONCEPTS OF DIFFERENTIAL ASTROMETRY

\[
\begin{align*}
\alpha_i &= \alpha_{i0} + \mu_{\alpha_it_j} + \omega_i P_j + L_{ij} \\
\delta_i &= \delta_{i0} + \mu_{\delta_it_j} + \omega_i Q_j + M_{ij}
\end{align*}
\]
CONCEPTS OF DIFFERENTIAL ASTROMETRY

\[ \alpha_i = \alpha_{i0} + \mu_{\alpha i} t_j + \varpi_i P_j + L_{ij} + \epsilon_{\alpha}(t_j) \]
\[ \delta_i = \delta_{i0} + \mu_{\delta i} t_j + \varpi_i Q_j + M_{ij} + \epsilon_{\delta}(t_j) \]
In this short talk…

- What and why?
- Challenges?
- The future?
SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

- REFERENCE FRAME
- INSTRUMENT STABILITY
- PHYSICAL MODELLING
- METHODOLOGY
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

REFERENCE FRAME

INSTRUMENT STABILITY

PHYSICAL MODELLING

THE FRAME AGES AND DEGRADES

METHODOLOGY
REFERENCE FRAME DEGRADATION

- Primary system materialization: QSOs
  - QSOs are not really point sources; they do have structure after enough resolution is reached

Credit: R. Hurt (IPAC/Caltech)/The GraL Collaboration

de Witt, Charlot, et al., 2022
REFERENCE FRAME DEGRADATION

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REFERENCE FRAME DEGRADATION

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    - and this structure evolves with time: instability in positions
REFERENCE FRAME DEGRADATION

- Primary system materialization: QSOs
  - QSOs are not really point sources; they do have structure after enough resolution is reached
    - and this structure evolves with time: instability in positions
  - Small uncertainty in the overall frame motion due to galactic acceleration ($\sigma \sim 0.5 \text{ uas yr}^{-1}$)
Primary system materialization: QSOs

- QSOs are not really point sources; they do have structure after enough resolution is reached
- and this structure evolves with time: instability in positions
- Small uncertainty in the overall frame motion due to galactic acceleration ($\sigma \sim 0.5$ uas yr$^{-1}$)

The most accessible system materialization: stars
Reference Frame Degradation

- Primary system materialization: QSOs
  - QSOs are not really point sources; they do have structure after enough resolution is reached
  - and this structure evolves with time: instability in positions
  - Small uncertainty in the overall frame motion due to galactic acceleration ($\sigma \sim 0.5$ uas yr$^{-1}$)

- The most accessible system materialization: stars
  - Need to propagate the stars to the epoch of observations
Primary system materialization: QSOs

- QSOs are not really point sources; they do have structure after enough resolution is reached
- and this structure evolves with time: instability in positions
- Small uncertainty in the overall frame motion due to galactic acceleration \((\sigma \sim 0.5 \text{ uas yr}^{-1})\)

The most accessible system materialization: stars

- Need to propagate the stars to the epoch of observations
- But proper motions are uncertain! So for large \(t\),
  \[
  \sigma_{\alpha^*}(t) \sim \sigma_{\mu_{\alpha^*}}(t - t_0) \\
  \sigma_{\delta}(t) \sim \sigma_{\mu_{\delta}}(t - t_0)
  \]
REFERENCE FRAME DEGRADATION

Brown et al., 2017 (Gaia Mission Extension)
SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

- Reference Frame
- Instrument Stability
- Physical Modelling
- Methodology
- Imperfect, Unstable Instruments
SOME INSTRUMENT STABILITY ISSUES
SOME INSTRUMENT STABILITY ISSUES
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

SOME INSTRUMENT STABILITY ISSUES

Credit: R. Hurt (IPAC/Caltech)/The GraL Collaboration

2022 Sagan Summer Workshop
SOME INSTRUMENT STABILITY ISSUES

Displacement Map Bottom
SiC, dT=100mK

disp. uas

9000
8000
7000
6000
5000
4000

X [deg]

Y [deg]
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

SOME INSTRUMENT STABILITY ISSUES

Thermal distortion corrected field
Chebyshev 8, SiC structure, dT=100K

Median residuals 3.31 uas
SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

- Reference Frame
- Instrument Stability
- Physical Modelling

**We consider most, but not all, physical phenomena**
PHYSICAL MODELLING

- Stochastic time-variable GW effects: **fundamental limitation?**
- Apparent astrometric oscillations

Moore et al., 2017 (Phys. Rev. Lett. 119)
see also Klioner, 2018 (Classical and Quantum Gravity, 35)
PHYSICAL MODELLING

- Stochastic time-variable GW effects: **fundamental limitation?**
- Apparent astrometric oscillations

Moore et al., 2017 (Phys. Rev. Lett. 119)
see also Klioner, 2018 (Classical and Quantum Gravity, 35)

Garcia-Bellido et al., 2021

Garcia-Bellido et al., 2021
SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

- REFERENCE FRAME
- INSTRUMENT STABILITY
- PHYSICAL MODELLING
- METHODOLOGY

BREAKING MODEL DEGENERACIES, GOING DEEPER IN THE NOISE
In this short talk...

- What and why?
- Challenges?
- The future?
### Differential Astrometry for Earths at Micro-Arcsecond Precision

#### Some Differential Astrometry Challenges for Planets

<table>
<thead>
<tr>
<th>Reference Frame</th>
<th>Frame Ages and Degrades: Future Global Space Astrometry Missions as GaianIR Are Vital to Astronomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Modelling</td>
<td>At the Sub-Mas Regime: Gravitational Effects Depending on FOV and Mission Profile</td>
</tr>
<tr>
<td>Methodology</td>
<td>Breaking Model Degeneracies, Going Deep in the Noise Integrating Signal Processing + Statistical + Mathematical + Computer Science Knowledge</td>
</tr>
</tbody>
</table>
Relative "large" FoV

+ Non dedicated missions that can (and hopefully will) do relative astrometry as Roman, Euclid, etc.

Relative Diffraction-based or interferometric

Absolute Global All-Sky
THEIA MAJOR SCIENCE CASES

• To probe small-scale properties of Dark Matter
• To reliably probe the shape of MW DM halo
• To detect and study habitable exo-Earths around nearby FGK stars unambiguously and to probe their planetary system architectures
• Significantly improve the knowledge of Neutron Star EOS and of matter around Black Holes
• Micro-arcsecond astrometry dead-time due to stabilization dedicated to photometry

arXiv:1707.01348
THEIA MAJOR SCIENCE CASES

- Measure true mass function of \textit{temperate} 1–5 M$_{\oplus}$ rocky planets around solar-type stars

- \textbf{Study the three-dimensional architecture} of FGK systems harboring telluric planets

- Provide input target lists of stars with \textit{telluric planets for direct-imaging / spectroscopic} missions aimed at searching for atmospheric biomarkers.
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

THEIA PROPOSAL

Theia core team

Alessandro Sozzetti  
INAF - Osservatorio Astrofisico di Torino, Italy

Fabien Malbet  
Université de Grenoble Alpes/CNRS/IPAG, France

Lucas Labadie  
Universität zu Köln, Germany

- The core team includes members from **Italy, France, Germany, Sweden, Spain, Switzerland and Portugal** (and USA)
- Additional contributions from **Austria, Denmark, The Netherlands and Poland**.
- Participants from several countries outside Europe: Australia, Israel and USA (“non-enabling” contribution). Several countries have expressed their interests
- In M5 proposal: 22 countries, 209 researchers

Europe

- Antonio Amorim (Universidade de Lisboa, CENTRA, Portugal)
- Guillem Anglada-Escudé (ICE CSIC, Spain)
- Alexis Brandeker (Stockholm University, Sweden)
- Enzo Brocato (INAF - Osservatorio Astronomico d’Abruzzo, Italy)
- Lars Buchhave (National Space Institute & Niels Bohr Institute, Denmark)
- Deborah Busonero (INAF - Osservatorio Astrofisico di Torino, Italy)
- Silvano Desidera (INAF - Osservatorio Astronomico di Padova, Italy)
- Antonaldo Diaverio (Università degli Studi di Torino, Italy)
- Luca Fossati (OEAW, Austria)
- Mario Gai (INAF - Osservatorio Astrofisico di Torino, Italy)
- Juan García-Bellido (Universidad Autónoma de Madrid, Spain)
- Manuel Güdel (University of Vienna, Austria)
- Berry Holl (Geneva Observatory, Switzerland)
- Markus Janson (Stockholm University, Sweden)
- Anne-Marie Lagrange (Université de Grenoble Alpes/CNRS/IPAG, France)
- Mario Gilberto Lattanzi (INAF - Osservatorio Astrofisico di Torino, Italy)
- Alain Leger (IAS-CNRS, France)
- Gary Mamon (JSPS, CNRS, France)

Outside Europe

- Nadege Meunier (Université de Grenoble Alpes/CNRS/IPAG, France)
- Andrés Moitinho (CENTRA, Universidade de Lisboa, Portugal)
- Sascha Quanz (ETH-Zurich, Switzerland)
- Rafael Rebolo (Instituto de Astrofisica de Canarias, Spain)
- Alberto Riva (INAF - Osservatorio Astrofisico di Torino, Italy)
- Ignas Snellen (Leiden, Netherlands)
- Andrzej Udalski (Warsaw University, Poland)
- Eva Villaver (Universidad Autónoma de Madrid, Spain)
- Céline Boehm (University of Sydney, Australia)
- Renaud Goullioud (JPL/NASA, USA)
- Alberto Krone-Martins (University of California, Irvine, USA)
- Tom Maccarone (Texas Tech University, USA)
- Barbara McArthur (University of Texas at Austin, USA)
- Adi Nusser (Technion - Israel Institute of Technology, Israel)
- Michael Shao (JPL/NASA, USA)
## THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

<table>
<thead>
<tr>
<th>Instrument Stability</th>
<th>Simple Optical System, Low CTE and Well Understood Materials, Almost No Moving Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metrological Systems (Sub-UAS)</td>
</tr>
<tr>
<td></td>
<td>Calibration (UAS)</td>
</tr>
<tr>
<td></td>
<td>Multiple Thermal Monitoring Points</td>
</tr>
</tbody>
</table>

Credit: R. Hurt (IPAC/Caltech)/The GraL Collaboration

2022 Sagan Summer Workshop Alberto Krone-Martins
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

INSTRUMENT STABILITY

SIMPLE OPTICAL SYSTEM, LOW CTE AND WELL UNDERSTOOD MATERIALS, ALMOST NO MOVING PARTS
THEIA: SIMPLE OPTICAL SYSTEM

Korsch Three Mirror Anastigmat (TMA): no aberrations up to third order

- Airy disk
- Spot diagram

Korsch TMA
0.8m primary mirror
Effective Focal Length (EFL) : $f = 13$ m
FoV : $0.5 \times 0.5$ deg

- All optics are coaxial
- M1: 800mm CA diameter, 220mm hole diameter, $R=2547$mm (same as previous THEIA proposal), $C=0.98615$
- M1 to M2: $d=1050$mm
- M2: 180mm CA diameter, $R=530$mm, $C=1.7567$
- M2 to Fold: $d=1477$mm
- Fold to M3: $d=488$mm
- M3: 180x180mm square CA, $R=661.7$mm, $C=-0.6391$
- Field of View: $0.5x0.5$deg square
- Field of View bias: $0.45$deg (in order for the light beam to avoid the plane mirror after reflection on M3).

Labadie et al., to appear in SPIE 2022
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

Korsch on-axis TMA
0.8m primary mirror
EFL 32m

Optics: Zerodur, ULE or Sitall
Structures: SiC or Si3N4
Rigid Hexapod configuration

Lifetime: 4yr (built considering 8 yrs)

arXiv:1707.01348
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

- INSTRUMENT STABILITY

- SIMPLE OPTICAL SYSTEM, LOW CTE AND WELL UNDERSTOOD MATERIALS, ALMOST NO MOVING PARTS

- METROLOGICAL SYSTEMS (FOR SUB-UAS)

- TELESCOPE STRUCTURE METROLOGY

- FOCAL PLANE METROLOGY
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

Independent linear interferometers: continuously monitoring instrument changes during the lifetime of the mission for corrections on ground.

arXiv:1707.01348
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

18 retroreflectors

18 microinterferometers

18 polarised fibers

36 signals (18/24 x I/Q redundant outputs)

Nominal electronics

Redundant electronics

Amplification
Digitalization

Power supply
Control

Power supply
Control

Amplification
Digitalization

Laser 1

Laser 2

1 to 18 splitter

2 to 1 combiner

~50 pm

Independent linear interferometers: monitoring for corrections on ground.

arXiv:1707.01348
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

Overview of a possible payload
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

Interferometric FPA callibration
Prototype @ IPAG
reaches \( \sim 5 \times 10^{-5} \) pixel size

arXiv:1707.01348
EARTH'S AT MICRO-ARCSECOND PRECISION

THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

Detection noise error
Target star: 0.35 uas
Reference stars: 0.58 uas

Photon noise (R~7)

Local Reference

Focal-plane metrology
differential error: 0.33 uas

Field Dist. Calibration
Errors: 0.52 uas

Astrometric geometry
Errors: 0.30 uas

Physics
Modelling

Differential Measurement
Astrometric accuracy
per one-hour observation:
0.96 uas

Metrological
callibration

arXiv:1707.01348

2022 Sagan Summer Workshop
Alberto Krone-Martins
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

Astrometric end-of-mission **proper motion**

- LSST 10yr accuracy
- Gaia 5yr accuracy (~0.8h, V-I=0.75, no prior)
- Gaia reference stars max grid accuracy
- Theia 4yr precision: 40h
- Theia 4yr precision: 1000h

Astrometric end-of-mission **parallax**

- LSST 10yr accuracy
- Gaia 5yr accuracy (~0.8h, V-I=0.75, no prior)
- Gaia reference stars max grid accuracy
- Theia >2yr precision: 40h
- Theia >2yr precision: 1000h

arXiv:1707.01348
THEIA EXOPLANET CASE

- Nearby telluric planets in the HZ of AFGKM stars

arXiv:1707.01348
Differential astrometry: relative measurements
Differential astrometry: relative measurements

Measurement precision depends on:
instrument stability and/or monitoring and callibration
Differential astrometry: relative measurements

Measurement precision depends on:
instrument stability and/or monitoring and callibration

Relative to absolute transformation depends on some external Reference Frame that degrades with age
Differential astrometry: relative measurements

Measurement precision depends on:
instrument stability and/or monitoring and calibration

Relative to absolute transformation depends on some
external Reference Frame that degrades with age

Exciting concepts are being proposed for dedicated
micro-arcsecond relative astrometry missions to study faint
objects and telluric planets in Habitable Zones of nearby stars
THANK YOU!
Results of a recent blind test on Theia targets, including the expected stellar activity in the simulation but not accounting for them in the modelling.

Meunier&Lagrange, 2022 (adapted)
M5 Focal plane array

Specifications:
Diffraction-limited 0.5° FOV
~ 30,000 x 30,000 pixels
≤ 1 billion pixels

6x6 Elliptical FoV
Science Array
of 4k vs. 4k
Detectors

Wavefront sensors

Detectors:
-FPA: 24 e2V 4k² CCD
-WFS: 4 e2V 4k² CCD

DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION
New large detectors with small pixels!

- Pixels of ~4µm => array of 12 cm x 12 cm can be manufactured on a wafer of 12” (300mm)

SONY IMX411 BSI 150MP
11648 x 8542
[43.8 x 32.87 mm]

Large detector arrays starting in 2016 thanks to the stitching technology
Detector Interferometric Calibration Experiment (DICE)

Laboratory results

Best results so far:
- JPL/VESTA: $10^{-4}$ pixels
- IPAG/CNES: $6 \times 10^{-5}$ pixels (Crouzier et al. 2016)

Proposed strategy to reach $10^{-5}$ pixel calibration:
100 independent positions, a space of $\sim 40 \times 40$ pixels for Nyquist-sampled centroids
Mission profile

- ESA-led, ESA-operated mission with consortium funded payload (this is the normal type of ESA mission)
- Submitted for the ESA M7 call as an Ariane 6.02 launch
- Spacecraft dry mass with margin: 1063 kg. Total launch Mass: 1325 kg

### Differential Astrometry for Earths at Micro-Arcsecond Precision

#### Nominal Theia Science Operations

- **Launch date**: No constraints, allowing launch date in **2037**
- **Orbit**: Large Lissajous in L2
- **Lifetime**: 4 years of nominal science operations
  - Technical operations: 6 months orbit transfer plus instrument commissioning and 1 month decommissioning
- **Concept**: Single spacecraft, single telescope in the PLM, single camera in the focal plane, metrological monitoring of PLM
- **Communication architecture**: 75 Mbps, 4h/day
### TRL evaluation and foreseen development plans for the Theia payload

<table>
<thead>
<tr>
<th>Technology Item</th>
<th>Heritage or Comments</th>
<th>Current TRL</th>
<th>Foreseen TRL by end of Phase A (2026)</th>
<th>Development plans for the baseline design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera detectors</td>
<td><strong>Option 1</strong> several 50-150 Mpixel CMOS (Sony IMX411, Pyxalis GP4600). Current baseline.</td>
<td>4-5</td>
<td>6</td>
<td><strong>Option 1</strong> Performance demonstrated for the operational environment. Flight model qualified for nanosat with a smaller format (50Mpixels). Option 1 will require a 2x2 GP4600 mosaic for the FPA or small reduction of science.</td>
</tr>
<tr>
<td></td>
<td><strong>Option 2</strong> A single new gigapixel visible CMOS (30k x 30k). Desired option.</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Camera electronics</td>
<td>CMOS TDI platform product families for line scanning in Earth observation.</td>
<td>6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Camera system</td>
<td><strong>Options 1 &amp; 2</strong> 2x2 detector array or single detector if FOV reduction is scientifically acceptable.</td>
<td>7</td>
<td>8-9</td>
<td><strong>Option 1</strong> Simpler system solution as only one detector is implemented, but further test of the detector chip must be performed.</td>
</tr>
<tr>
<td></td>
<td><strong>Option 2</strong> A single sensor and electronics. Implemented in Earth observation.</td>
<td>7</td>
<td>8-9</td>
<td></td>
</tr>
<tr>
<td>Camera WFS</td>
<td>Gaia. But modifications to fit Theia optics are necessary.</td>
<td>6-9</td>
<td>6-9</td>
<td>Use of the corner of the gigapixel detector</td>
</tr>
<tr>
<td>FPA metrology laser source</td>
<td>Meteosat Third Generation (MTG)</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>FPA metrology optical components</td>
<td>High NA single/multimode fibers required and commercially available on ground. Space qualification is being addressed by fiber manufacturers.</td>
<td>5</td>
<td>6-7</td>
<td>Work on radiation hardening data with companies like Nufern. Data on Gamma and Proton irradiation exist (Alam 2006; SPIE 6308, 630808)</td>
</tr>
<tr>
<td>FPA metrology electronics</td>
<td>Laboratory benches.</td>
<td>4</td>
<td></td>
<td>Laboratory work foreseen for FPA calibration</td>
</tr>
<tr>
<td>FPA metrology system</td>
<td>Laboratory benches, but not yet for Theia FPA scale.</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescope metrology laser source</td>
<td>Tesat USA, MTG.</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Telescope metrology interferometers</td>
<td>Interferometers performing at the level required by Theia already flying (Gaia-BAM).</td>
<td>5</td>
<td>5-6</td>
<td>Independent active actuators (piezo) coupled to standard nm laser metrology to maintain position. However, TMA design with gigapixel array (Option 1 &amp; 2) will relax the needs for metrology of the telescope structure considering few tens of mK environmental stability. Telescope metrology is also relaxed with alternative design with only one mirror (Formation Flying, deployable boom).</td>
</tr>
<tr>
<td>Telescope metrology electronics</td>
<td>Based on Actel RTG4 and Gooch &amp; Housego.</td>
<td>5</td>
<td>5-6</td>
<td></td>
</tr>
<tr>
<td>and optoelectronics components</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescope metrology system</td>
<td>Each actuator with its own metrology at TRL &gt;5.</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescope structure</td>
<td>Ceramics telescopes have been used in Herschel, Gaia, Euclid.</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Telescope optics</td>
<td>Several flying TMA. Design similar to Euclid. Straylight needs assessment.</td>
<td>5</td>
<td>8</td>
<td>Laboratory tests and optical design analysis</td>
</tr>
<tr>
<td>Thermal control system</td>
<td>Euclid, Ariel.</td>
<td>6-7</td>
<td>8</td>
<td>Optimize V-groove passive cooling configuration coupled to e.g. active IT coolers</td>
</tr>
<tr>
<td>Fine Guidance Sensor</td>
<td>Euclid, Ariel.</td>
<td>6-7</td>
<td>8</td>
<td>Similar to existing FGS designs</td>
</tr>
</tbody>
</table>