Nearby Earth Astrometric Telescope (NEAT)

Formation Flying For Very High Precision Astrometry: Neat And Micro-Neat Mission Concepts

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IPAG - Univ. Grenoble Alpes - CNRS

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M. Shao (JPL), A. Crouzier (IPAG) and the NEAT/microNEAT groups

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Munich (Germany) - 29/31 May 2013
Finding planets around other stars

- More than 850 exoplanets found since 1995
  radial velocities, transits, direct imaging, astrometry (Gaia)

- Kepler satellite results:
  • more than 70% of stars have planets P<200d
  • estimation of # Earth-size planets: ~5-10%

- Already transit spectroscopy on a few targets
  HST/Spitzer → JWST/EchO)

- Biomarkers can be observed thanks to direct spectroscopy
  visible coronagraph or nulling interferometry

- Requires to identify nearby planetary systems and Earth-mass planets
How to find our nearest neighbours?

RV, direct imaging, pointed astrometry

μlensing (>1 kpc)

Kepler’s Transits (<1 kpc)

Gaia’s astrometry (20 pc < d < 200 pc)

Less than 10% of nearby stars have known exoplanets so far!

Nearby FGK stars

<table>
<thead>
<tr>
<th>Distance (pc)</th>
<th>0-10 pc</th>
<th>10-20 pc</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGK stars with known exoplanets</td>
<td>6</td>
<td>36</td>
<td>42</td>
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<tr>
<td>FGK listed in the Hipparcos catalog</td>
<td>68</td>
<td>426</td>
<td>494</td>
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</tbody>
</table>

No known planets: 91.5%
Known planets: 8.3%
Habitable planets: 0.2%
Primary scientific objectives of very high precision astrometry

The prime goal of very high precision astrometry would be:

- to detect and fully characterize **planetary systems**
- with **all** components down to the **Earth mass**
- orbiting bright **solar-type stars** (FGK, V ≤ 9)
- in the **solar neighborhood** (d < 20 pc)

with planetary architectures:
- similar to that of our Solar System
- or any one with Earth mass planets

\(\mu\)NEAT is a smaller version of NEAT targeting Neptune-mass planets and super-Earth planets within 5 pc.

⇒ Key capability: detecting Earth-mass planets in the Habitable Zone
NEAT/μNEAT

collaboration
How to detect and characterize these planets with astrometry?

- The stars orbit around their center of mass because of **reflex motion**
- A precise orbit determination unravels the presence of planets of different masses
- The orbit can usually be extracted only from a common solution to 3 types of apparent motion: parallax, proper motion, and orbit

**Astrometry measures**

\[ P, a_P, i, e, \omega, \Omega, T_0 \mapsto M_P \]

\[
A = 0.33 \left( \frac{a_P}{\text{1AU}} \right) \left( \frac{M_P}{\text{1M}_\odot} \right) \left( \frac{M_*}{\text{1M}_\odot} \right)^{-1} \left( \frac{d}{1\text{pc}} \right)^{-1} \mu\text{as}
\]

<table>
<thead>
<tr>
<th>Sun @ 10pc</th>
<th>Giants planets</th>
<th>Terrestrial planets</th>
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<tbody>
<tr>
<td>( M_P ) (\text{M}_\odot)</td>
<td>300</td>
<td>1</td>
</tr>
<tr>
<td>( a_P ) (\text{AU})</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>( P ) (yr)</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>( A ) (\text{in \muas})</td>
<td>495</td>
<td>0.3</td>
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</table>
Typical NEAT field of view
Examples of NEAT measurements
Astrometry detection limit for Earth-like planets around nearby stars

Astrometric signal of an 1M\textsubscript{E} planet at 1AU (A in \(\mu\)as)

Luminosity (L\textsubscript{\odot})

# targets per bin

NEAT observing time
6000h
15600h
1100h
Total: 22100h

0.5M\textsubscript{E}
1M\textsubscript{E}
5M\textsubscript{E}

HZ outer edge
HZ inner edge
Earth-like flux

\(\alpha\) Cen A
\(\alpha\) Cen B

Earth seen at 10 pc

0.24\(\mu\)as/0.5M\textsubscript{E}
0.20\(\mu\)as/1M\textsubscript{E}
0.70\(\mu\)as/5M\textsubscript{E}
NEAT concept

1 fixed CCD (target star)

1 fixed CCD (telescope axis tracker)

8 movable CCDs (reference stars)

Telescope spacecraft

Metrology

Telescope axis beam

Dynamical Young’s interference fringes

Detector spacecraft

Malbet, Léger, Shao et al. (2012, Exp. Astron 34, 385)
Error budget and target list

Minimum detectable 1AU planet mass at:
- 20 pc: 5.0 Earth mass
- 10 pc: 1.8 Earth mass
- 5 pc: 0.5 Earth mass

Number of planets in the system (P)
3

Min. detectable astrometric signature for 3-planet system
- 0.8 uas
- 0.5 uas
- 0.3 uas

Integration time for 1 visit (t)
- 0.5 h
- 1 h
- 3 h

Total number of visits during the mission lifetime (N)
50

Differential Measurement
Astrometric accuracy per 1h observation and per axis (X,Y)
0.8 uas

Astrometric end-of-mission noise per axis (X, Y)
- 0.15 uas
- 0.11 uas
- 0.06 uas

Astrophysical Errors
- Stellar aberration
- Ref. star geometry
- Companions

Error budget and target list

Astrometric error
Target star
0.12 uas

Astrometric error Reference stars
0.61 uas

Focal-plane metrology differential error
0.14 uas

Parabola axis Tracker metrology error
0.08 uas

CCD Calibration Errors
0.26 uas

Astrophysical Errors
0.32 uas

Number of planets in the system (P)
3

# of parameters for a P-planet system (m)
26

m = 5 + 7P

SNR
6

Integration time for 1 visit (t)
- 0.5 h
- 1 h
- 3 h

Total number of visits during the mission lifetime (N)
50

Differential Measurement
Astrometric accuracy per 1h observation and per axis (X,Y)
0.8 uas

Integration time for 1 visit (t)
- 0.5 h
- 1 h
- 3 h

Total number of visits during the mission lifetime (N)
50

Parabola axis Tracker metrology error
0.08 uas

Residual calibration error
5.0E-06 pixel

- Stellar aberration
- Ref. star geometry
- Companions

M = (d/10)*(A/0.3)
A = DMA*SNR/sqrt((2N-m) t)
## Error budget and target list

### Minimum detectable 1AU planet mass at:

<table>
<thead>
<tr>
<th>Distance (pc)</th>
<th>Earth mass</th>
<th>3-planet system</th>
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<tr>
<td>20 pc</td>
<td>5.0</td>
<td>0.8 uas</td>
</tr>
<tr>
<td>10 pc</td>
<td>1.8</td>
<td>0.5 uas</td>
</tr>
<tr>
<td>5 pc</td>
<td>0.5</td>
<td>0.3 uas</td>
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</table>

\[ M = \frac{(d/10) \times (A/0.3)}{10} \]

\[ A = \frac{\text{DMA} \times \text{SNR}}{\sqrt{(2N-m) \times t}} \]

### Number of planets in the system (P)

3

### # of parameters for a P-planet system (m)

26

\[ m = 5 + 7P \]

### Minimum detectable astrometric signature for 3-planet system

- 0.8 uas
- 0.5 uas
- 0.3 uas

### Integration time for 1 visit (t)

- 0.5 h
- 1 h
- 3 h

### Total number of visits during the mission lifetime (N)

50

### Differential Measurement Astrometric accuracy per 1h observation and per axis (X,Y)

0.8 uas

### Rank | Star_ident. | Name | Vmag | SpType | D (pc) | Log'RHK HZ in (AU) | \( t_{tot} \) (h) | A (uas) | t\(_{visit} \) (h) | A (uas) | t\(_{visit} \) (h): A (uas) | (visit (h)) |
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</table>
NEAT Spacecraft

- Mission orbit: L2 large Lissajous
- 2 satellites flying in formation
- 20,000 reconfigurations
- Reconfiguration time: 30mn

NEAT Pathfinder experiment with PRISMA
### NEAT target list and mission lifetime

<table>
<thead>
<tr>
<th>Rank</th>
<th>Star_ident.</th>
<th>Name</th>
<th>Vmag</th>
<th>SpType</th>
<th>D (pc)</th>
<th>log R'HK HZ in (AU)</th>
<th>t_tot (h)</th>
<th>A (uas)</th>
<th>t_visit (h)</th>
<th>A (uas)</th>
<th>t_visit (h)</th>
<th>A (uas)</th>
<th>N_limit = 0.5 M_E</th>
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<th>Cumulated time (h)</th>
<th>Number of visits</th>
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<th>Program</th>
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<td>Main</td>
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<tr>
<td>Total</td>
<td>43,800 h (5 yrs)</td>
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would be illuminated pairwise to create various fringes. In the experiment, the aperture diameter was reduced to allow better sampling. Also mounted on the ULE block was a low-expansion optical bench with a collimator parabola glued to it. The parabola was masked to allow a 14 mm primary mirror to be switched on. Laser light was sent to a pair of optical fibers, and a frequency shift was induced on the light to one of the two fibers by a few Hz relative to the other. In general, an optical fiber projects laser light at a divergent cone of about 10 degrees in diameter. On the other hand, the CCD in the experiment could be rotated at up to 50 frames per second (fps). If the applied phase shift is, for example, 4 pixels, then adjacent pixels will have a phase shift of a quarter-wavelength with a known phase shift. If the fringe spacing is, for example, 30 microns, then the measured phase difference between any two pixels is directly proportional to the distance between the pixels along the direction of the traveling fringe. By illuminating pairs of pixels, we can produce fringes traveling in different directions. The sampling of the point spread function (PSF), defined as the number of pixels per effective focal length of 1.1 m and an F# of about 80. The middle image, top row, shows three of the seven stars defined. A bundle consisting of 7 closely packed fibers was mounted with a defocus in such a way to create an image at the traveling fringe. By illuminating pairs of pixels along the direction of the traveling fringe, we can produce fringes traveling in different directions. In other words, the measured phase difference between any two pixels is directly proportional to the distance between the pixels along the direction of the traveling fringe. By illuminating pairs of pixels along the direction of the traveling fringe, we can produce fringes traveling in different directions. The measured phase difference between any two pixels is directly proportional to the distance between the pixels along the direction of the traveling fringe. The sampled centroid on the CCD surface and hence derive the relative position deviations from a reference position. With the MCT testbed, we were able to calibrate the focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy. Using simulation we found that our image position sensing algorithm is capable of 4 micro-arcseconds in astrometric accuracy. We have developed an approach that uses precision metrology to calibrate the otherwise intractable focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy. We have developed an approach that uses precision metrology to calibrate the otherwise intractable focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy. We have developed an approach that uses precision metrology to calibrate the otherwise intractable focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy. We have developed an approach that uses precision metrology to calibrate the otherwise intractable focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy. We have developed an approach that uses precision metrology to calibrate the otherwise intractable focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy. We have developed an approach that uses precision metrology to calibrate the otherwise intractable focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy. We have developed an approach that uses precision metrology to calibrate the otherwise intractable focal plane systematic errors that would be encountered in getting down to micro-arcseconds in astrometric accuracy.
A scalable concept

<table>
<thead>
<tr>
<th>Mission name</th>
<th>Mirror diameter</th>
<th>Focal length</th>
<th>Field of view diameter</th>
<th>Focal Plane size</th>
<th>Ref. star mean magnitude</th>
<th>DMA in 1h</th>
<th># targets for a given mass limit</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>(m)</td>
<td>(m)</td>
<td>(deg)</td>
<td>(cm)</td>
<td>(R mag)</td>
<td>(µas)</td>
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<tr>
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<td>35</td>
<td>10.5</td>
<td>1.0</td>
<td>4</td>
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<tr>
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<td>0.85</td>
<td>30</td>
<td>10.1</td>
<td>1.4</td>
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<td>µNEAT (*)</td>
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<td>12</td>
<td>0.6</td>
<td>15</td>
<td>11</td>
<td>10.2</td>
<td>2</td>
</tr>
</tbody>
</table>

$DMA = \text{Differential astrometric Measurement Accuracy (rms)}$; (*) centroiding requirement relaxed to 4e-5

**EXAM (NASA)**

Shao et al.

**µNEAT (ESA small mission)**

Brandeker et al.
Current status

Science highly ranked in ESA Astrophysical Working Group.

Technology assessment for proposition to Medium-class mission

- Formation Flying at mm-precision
  ➤ NEAT pathfinder experiment ✓

- Lab demonstration of 5 micropixel precision
  ➤ NEAT CNES laboratory experiment in progress

- Focal plane with movable CCD vs. fixed CCDs, control strategy between platform and payload?
  ➤ CNES phase zero study starting 7 June 2013

- Mission performance assessment
  ➤ NEAT simulations and double blind test → until end of 2013

What next?

- Contacts with industrial partners interested in the concept
- M4 proposal in Spring 2014