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From Gaia to NEAT (Theia): synergies and results of the NEAT double-blind experiment

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Abstract

The Near-Earth Astrometric Telescope (NEAT, recently renamed into Theia) is a new mission concept to achieve sub-microarcsecond precision astrometry using pointed observations. This mission will be proposed as a candidate for the M4 call of ESA later this year. It will be a natural continuation of ESA's leadership in space astrometry by continuing and extending the work of the very successful HIPPARCOS and the recently launched Gaia missions.
The science top-level requirements for NEAT are set by the ability to detect potentially habitable Earth-mass planets around all G and K dwarfs within 10 pc. Given the versatility of the concept, many other science cases can be addressed by obtaining ultra-precise pointed astrometric observations of exotic objects detected by Gaia and other on-going projects.
Although Gaia is a mission that is not designed to search for exoplanets *per se*, it will make a major contribution to the field and to the NEAT mission in several aspects. The Gaia mission will produce an enormous wealth of data to mine and explore, so experience must be acquired to identify the simple traps of the analysis methods, design validation strategies and prepare scientists across the ESA community and beyond to exploit such wealth of data. In fact, the experience in astrometry precision and simulations acquired for Gaia, laid the foundation for the creation of the NEAT simulator. This simulator has been created in order to build a double-blind test program for astrometric planet detection, with the goal to demonstrate the exo-Earth planet finding capabilities of a pointed astrometric mission.
Results are presented from our participation in this double-blind test showing our capabilities in the detection of Earth-like planets orbiting nearby Sun-like stars based on the MLE method.

1 Introduction

Gaia is a cornerstone mission of the European Space Agency (ESA). It was successfully launched on December 19, 2014. It is now orbiting the Lagrange point L2 in about 1.5 million km distance to Earth. After an extensive commissioning phase the nominal mission phase with a minimum duration of 5 years has started.

The main objectives of this mission is to revolutionize astrometry science by mapping more than one billion stars of our Galaxy with an astrometric precision never reached before. The astrometric precision of 9–600 μas depending on the magnitude and color of the source for stars within the wide G (Gaia) magnitude range from 2 to 20 in combination with photometric, spectrophotometric and spectroscopic observations will allow a wide range of new science cases to be opened.

One example of these new science cases is the astrometric detection of large numbers of planets orbiting stars. A recent study [4] suggests that Gaia will be able to detect around 21 000 Jupiter-mass planets around stars within 500 pc distance. In the astrometric planet detection method planets around stars show up as a tiny wobbling motion of the star as the planet orbits around it. Thus, for the Solar system there is a reflex motion of the Sun of 500 μas observable from a distance of 10 pc. This reflex motion is dominated by the giant planet Jupiter. The much less massive Earth only yields an effect of about 0.3 μas for the same distance. This shows that another qualitative step in astrometry will be necessary after the Gaia era to detect Earth-like planets around nearby stars with the astrometric method. Currently, a mission able to deliver this ultra-high astrometric precision is being designed – it was called NEAT (Nearby Earth Astrometric Telescope) and now in its new updated incarnation it will be called Theia.

This new astrometric mission concept called Theia will apply for the M4 mission of ESA in 2015. It is still under study and we will concentrate on the early NEAT concept [3].

2 The concept of NEAT

Gaia is scanning the entire sky. The resulting astrometric solution will therefore be a global solution based on a fixed grid of background sources (mainly quasars). In contrast to this, NEAT is supposed to observe certain areas of the sky allowing for more precise local astrometric solutions.

The main objective of the NEAT mission was to find Earth-sized planets around up to 200 nearby F, G and K dwarfs within a distance of 20 pc from the Sun. An astrometric precision of 0.05 μas was targeted to obtain the necessary exoplanet detection capabilities. How can such a fantastically astrometric precision be achieved? Obviously such a telescope has to be very stable and the smallest movements and instabilities need to be determined. The telescope was supposed to have a 1 m diameter main mirror with a focal length of 40 m. To keep the entire construction as stable as possible it was targeted to have a simplistic construction with only one mirror. Thus, the focal plane with CCDs for detections needed to be in a distance of 40 m from the main mirror. The preferred solution was to use a free-flyer concept: one satellite carries the main mirror and a second satellite flying in exact formation with the first one carries the focal plane. An alternative solution was to have a boom connection between the two parts of the satellite.

Both concepts contained a metrology system for monitoring any geometry changes between the focal plane and the mirror. With the help of this metrology system it was aimed for knowing the position of a star image within 10^{-6} of a pixel of the CCD in the focal plane assembly. With help of fibers laser light would have been directed from the main mirror towards the focal plane every minute. The resulting fringe pattern positions in the focal plane would have been used for the monitoring of the stability. This technology is under development at the moment in laboratories and has almost reached to goal of being able to determine a position of a stellar image with an uncertainty of 10^{-6} pixels.

3 NEAT observations

NEAT would have targeted up to 200 bright stars in the R magnitude range from 4 to 8 for planet search. The target would have been centered on a CCD in the center of the FoV 0.6 deg wide. This central CCD would have been surrounded by 8 additional movable CCDs to observe reference stars. These reference stars would have been mainly single background giants with $R < 11$ as these would have shown very small proper motions in comparison to the target dwarf stars. The reference stars would have been preselected based on Gaia observations to avoid using any multiple stars or stars with giant planets.

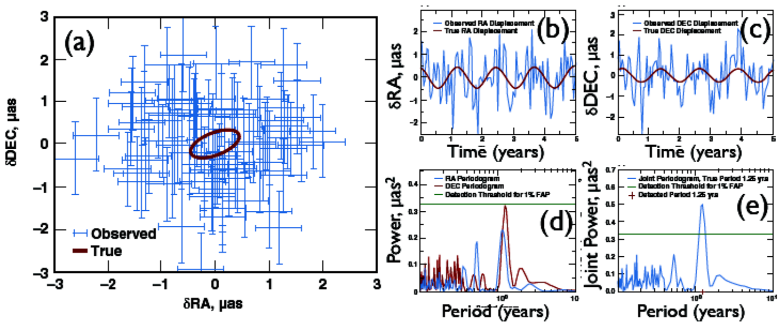

Figure 1: Example for 50 NEAT observations of a Sun-like star at a distance of 10 pc. The star is orbited by a planet with 1.5 Earth-mass in 1.25 years. Taken from [3].

50 pointings were foreseen for each target star within the nominal mission duration of 5 years. The exposure time would have been adapted to the magnitude of the target. An example for simulated observations of a typical Sun-like star in 10 pc distance is given in Fig. 1 demonstrating the feasibility of the project.

4 The double-blind experiment

In order to demostrate the exoplanet detection capabilities of NEAT, an open call to participate in a Double-Blind test experiment was issued in November 2013. The NEAT team generated mission-like observations, on a sample of 200 nearby F, G and K stars, generated using current knowledge of planet formation models and current expectations of nearby planetary systems. The NEAT dataset contains a list of target stars, and each target has an astrometry file with centroid positions, their errors and the parallax factors.

4.1 Method

In order to fit the parameters of a single/multiple-planet model of the target star astrometry, the maximum-likelihood (MLE) method is used. An adequate model for the parameterization to use in MLE fitting is defined and applied. By using this method, the parameters which describe the position of the planet in the sky are fitted, along with the estimated errors for each of them. The astrometric model is described in detail in [2]. In MLE, any model can be used. However, for meaningful results, models chosen must accurately describe the system being modeled. A set of algorithms has been created, which are able to fit any number of planets (also considering the zero planet possibility). Each of these algorithms contain the astrometric model, which describes the motion of a star, depending on the number of planets (e.g. the algorithm which detects one planet contains the astrometric model for one planet). The astrometric models implemented in the exercise are applied in maximizing the *likelihood*, which estimates the parameters of the model accordingly. The likelihood function is described in the next subsection. These algorithms are executed for all the stars until a maximum of three planets. However, the MLE fitting can be extended to an arbitrary number of planets. The results for each detection are provided and analyzed at the end of the execution, in order to choose the *best detection*. Two criteria are used in order to select the *best detection*: the Akaike Information Criterion (AIC) [1], and the Bayesian information criterion (BIC) [5].

4.2 MLE equations

The MLE is used to obtain the parameters of the model, including the parameters that describe the reflex motion of the star caused by a planet in a circular orbit. A likelihood function is required which gives the probability of a dataset given the model parameters. The likelihood $P(x|\theta)$, contains the data (x), and the model parameters (θ). Both data and model parameters are described in [2]. For the exercise, the data, x, is:

$$x = (X, Y, \sigma_x, \sigma_y, f_x, f_y, t) \tag{1}$$

where, X and Y are the positions, σ_x and σ_y are the observational errors, f_x and f_y the parallax factors and t the observation times. The parameters, θ are:

$$\theta = (\mu_x, \mu_y, \pi, A, B, F, G, Period) \tag{2}$$

We assume (as the simplest model for this work) that the observed position of the target star is normally distributed around the true value, which is given by the theoretical position (X_t, Y_t). Therefore, the probability of the data given the parameters is the following:

$$P(x|\theta) = \frac{1}{2\pi\sigma_x\sigma_y} e^{-0.5\left[\left(\frac{X-X_t}{\sigma_x}\right)^2 + \left(\frac{Y-Y_t}{\sigma_y}\right)^2\right]} \tag{3}$$

The astrometric model provides the true positions X_t and Y_t. Therefore, the probability is increased by choosing more realistic parameters for the statistical model.

5 Results and discussion

The sample containing the 200 target stars is separated in groups of 30 objects. As a straightforward example, the results of one star will be described. As is a double-blind experiment, at the end of the exercise, the simulation group and the analyses groups will know the 'true' values, but these are not yet known. Therefore, in order to compare the solutions with the true values, the selected star is taken from a test dataset, which contains the true solutions of the systems. However, the procedure to execute was exactly the same, as it was for those stars belonging to the double-blind dataset. Results for zero, one, two and three planet detections are given in 5.1. The selected star is HIP3765.

5.1 Detections

Table 1 shows the estimated astrometric values for the system, for the zero, one, two and three planets detection. The μ_x, μ_y and π 'true' values, which were provided by the NEAT simulation team, also are given. The criteria for the best detection, AIC (Akaide Information Criterion) and BIC (Bayesian Information Criterion), $\log L$ and the minimum residual values are given for each detection.

Table 1: Comparison between the astrometric parameters resolved for the star HIP3765, in zero, one, two and three planets detection. The minimum AIC and BIC values are shown in bold.

Parameter	True value	0 planet detection	1 planet detection	2 planets detection	3 planets detection
X_0 (deg)	–	0.031 ± 0.074	0.0031 ± 0.076	0.0031 ± 0.077	0.0031 ± 0.079
Y_0 (deg)	–	–0.0039 ± 0.074	–0.0039 ± 0.075	–0.0039 ± 0.09	–0.0039 ± 0.079
μ_x (mas yr^{-1})	758.04	758.039 ± 0.0002	758.039 ± 0.0002	758.039 ± 0.0002	758.039 ± 0.0002
μ_y (mas yr^{-1})	–1141.22	–1141.22 ± 0.0002	–1141.22 ± 0.0002	–1141.22 ± 0.0002	–1141.22 ± 0.0002
η_x (mas yr^{-2})	–	–0.013 ± 1.87e-07	0.018 ± 1.88e-07	0.013 ± 1.89e-07	0.064 ± 1.93e-07
η_y (mas yr^{-2})	–	–0.16 ± 1.85e-07	–0.12 ± 1.86e-07	–0.23 ± 2.48e-07	–0.053 ± 2.01e-07
π (mas)	134.04	134.04 ± 0.044	134.04 ± 0.04	134.04 ± 0.04	134.04 ± 0.04
AIC	–	5475.52	2466.66	1156.58	**997.73**
BIC	–	5501.03	2510.39	1218.52	**1077.91**
$\log L$	–	–2730.76	–1221.33	–561.29	–476.86
min. residual	–	0.96	0.67	0.43	0.39

Table 2 shows the results for the Thiele-Innes constants and the period with their errors, for the one, two and three planets detection.

The Thiele-Innes constants detected for the 1st planet are almost the same for the three detection cases. However, once can notice that the constants for the 2nd planet appear to change after the inclusion of one more planet. This is probably because the signal of the 2nd planet is smaller than that of the first. Table 3 shows the period, mass of the planet, statistic and the confidence evaluator, for the current example of HIP3765.

In this study, a planet-finding tool has been developed under the assumptions of the NEAT double-blind experiment. It has been tested using realistic astrometric measurements provided by the NEAT team. The presented results confirm that the method performs as

Table 2: The Thiele-Innes constants and period resolved for the star HIP3765.

Detection	B (μas)	F (μas)	G (μas)	A (μas)	$Period$ days
Planet 1	–0.98 ± 0.047	1.03 ± 0.037	–0.85 ± 0.044	–0.68 ± 0.05	52.74 ± 0.016
Planet 1	–0.99 ± 0.047	0.95 ± 0.038	–0.86 ± 0.045	–0.71 ± 0.0488	52.75 ± 0.016
Planet 2	–0.49 ± 0.033	1.07 ± 0.033	0.08 ± 0.045	–0.03 ± 0.064	221.58 ± 0.51
Planet 1	–1.01 ± 0.047	1.01 ± 0.037	–0.88 ± 0.044	–0.69 ± 0.049	52.75 ± 0.015
Planet 2	0.4 ± 0.037	–0.066 ± 0.053	0.28 0.044 ±	0.69 ± 0.033	264.71 ± 0.84
Planet 3	0.24 ± 0.04	–0.49 ± 0.058	0.31 ± 0.046	0.58 ±0.047	100.76 ± 0.14

Table 3: Required fields for the NEAT double-blind contest.

Planet	$Period$ days	M_{Planet} ($M_{\oplus}$)	Statistic (AIC, BIC)	Confidence
1	52.75 ± 0.015	10.41	997.73, 11077.91	3.2×10^{-35}
2	264.71 ± 0.84	2.07	997.73, 11077.91	3.2×10^{-35}
3	100.76 ± 0.14	3.74	997.73, 11077.91	3.2×10^{-35}

expected and the results obtained until the moment are reasonable and comparable with the other teams involved. 200 target stars have been processed, and their results sent to the NEAT team, however, the definitive results are unknown for the moment. This experiment cannot only be used under NEAT requirements, but also can be used for any type of astrometric measurements. As a future work, the model can be improved by introducing prior information about the physical process regarding the estimated parameters, and periods can be studied by introducing periodograms. Also, radial velocity measurements can be used to provide additional information of the orbits and clues about the more complicated systems.

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