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Detecting and characterizing extrasolar planetary systems with astrometry: review from the Blue Dots astrometry working group

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Abstract. The astrometry technique is an important tool for detecting and characterizing exoplanets of different type. In this review, the different projects which are either operating, in construction or in discussion are presented and their performance discussed in the framework of the Blue Dots study. We investigate the sensitivity of astrometry to different sources of noise and we show that astrometry is a key technique in the path of discovering and characterizing new types of planets including the very challenging category of Earth-like planets orbiting the habitable zone of solar-type stars.

1. Introduction

In the Blue Dots study (see Foresto et al. in this volume) which aims at preparing a road map towards the detection and characterization of habitable exoplanets, precise stellar astrometry is one of the method identified to detect exoplanets and characterize them. The goals of the Astrometry working group within the Blue Dots initiative are to identify the type of exoplanets that astrometry can detect and characterize so that the Blue Dot table can be filled in with the astrometry prospects, to investigate the limitations of astrometry and finally emphasize the complementarity of astrometry with the other techniques. The

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Table 1. Expected astrometric signal for different flavors of planetary systems.

	Giants planets			Telluric planets		
Type of planet	Classical jupiter	Young jupiter	Hot jupiter	Hot super-Earth	Earth in HZ	Earth in HZ
Stellar spectral type	G2	G2	G2	M	G2	M
M_P ($\mathrm{M_{Earth}}$)	300	300	300	5	1	1
M_P ($\mathrm{M_{Jupiter}}$)	1	1	1	0.02	0.003	0.003
a_P (AU)	5	5	0.1	0.1	1	0.28
P (yr)	11	11	0.03	0.05	1	0.2
P (d)	4084	4084	12	17	365	82
M_* ($\mathrm{M_{Sun}}$)	1	1	1	0.45	1	0.45
d (pc)	10	150	10	2.5	10	9
Astrometric signal (in μas)	**495**	**33**	**10**	**1**	**0.3**	**0.2**

reader is invited to report to a deeper review on the subject by Sozzetti (2009) which is an essential resource for this work.

2. How astrometry can detect exoplanets?

The motion of a star projected onto the plane of sky is a combination of 3 types of apparent motion: parallax which is the apparent motion due to the change of perspective of the observer (mainly the location of the Earth during one year), the proper motion which is the motion of the star+planets system in the galaxy, and the reflex motion due to the presence of orbits. A precise orbit determination unravels the presence of planets of different masses, only if one is able to subtract the effect of parallax and proper motion.

It is generally assumed that a minimal signal-to-noise ratio of 5-6 on the reflex motion of the star is required to detect a planet. In this case, astrometric measurements of star motion yield the period P and the planetary mass M_P, but also the six parameters of the orbit: the semi-major axes a_P, the inclination of the orbit i, the eccentricity of the orbit e, the longitude of the ascending node Ω, the argument of periapsis ω and the mean anomaly ν at epoch T_o.

The contribution of a planet to the reflex motion of its host star is given by the following formula:

$$\Delta\alpha = 0.33 \left(\frac{a_P}{1\,\mathrm{AU}}\right)\left(\frac{M_P}{1\,\mathrm{M_{Earth}}}\right)\left(\frac{M_*}{1\,\mathrm{M_{Sun}}}\right)^{-1}\left(\frac{d}{10\,\mathrm{pc}}\right)^{-1}\mu\mathrm{as} \qquad (1)$$

Typical numbers corresponding to various flavors of planetary systems are given in Table 1. There are almost 4 orders of magnitude between a Jupiter in a Solar-like planetary system located at 10 pc which gives a signal of the order of 500 μas and a Earth-like planets in its habitable zone which gives a signal of 0.3μas. Astrometry, unlike some other methods, is best suited when looking to nearby sources.

There are a variety of techniques to measure accurately the astrometric motion of stars, i.e. to measure accurately the positions of stars on the sky plane. These techniques can lead to wide-angle or narrow-angle observations between stars, using relative or absolute measurements, with local or global strategy. The atmosphere turbulence is an important limitation to perform astrometry and therefore there are both ground-based and space-born astrometric projects.

3. Main astrometric projects

We have listed 5 main types of astrometric projects in the domain of exoplanet detection and characterization. We have sorted them by accuracy level and number of potential targets.

3.1. Large ground-based telescopes

For many years starting in the 1960's, a narrow-field astrometry was frequently tried for finding exoplanets. These attempts resulted in various discoveries, but none confirmed (Barnard's star, Lalande 21185). These failures caused by insufficient precision and systematic errors of the photographic technique cast doubt on use of the astrometry for exoplanet studies. Besides, the narrow-field astrometry was considered to be limited by a ~ 1 mas precision due to the atmospheric image motion which came from the expression $\varepsilon \sim \theta/D^{2/3}$ derived by (Lindegren 1980) for the r.m.s. of the image motion ε in the measurement of a distance θ between a pair of stars on a telescope of diameter D. Recently, Lazorenko (2002) has found that for the reference field represented by a grid of stars, the power law is $\varepsilon \sim \theta^{11/6}/D^{3/2}$ with an improvement with D. Above expression is however asymptotic and refers to the very narrow field mode of observations requesting use of very large telescopes. In practice, this opens a way to a $< 100\,\mu$as astrometry in a field of view limited to $\theta \leq 1'$ with integration times of a few minutes only, yet sufficient for the detection of massive exoplanets around nearby stars. This challenging precision, of course, assumes a proper handling of many other effects, in particular related to a highly complicated shape of star profiles at the sub-pixel level and to the unfixed, floating position of reference stars due to the differential color refraction, proper motion, parallax, etc. Incorrect treatment of these effects degrades precision to ~ 1 mas. Currently, astrometric search of exoplanets is renewed at three telescopes:

- The STEPS instrument installed on the 5-m Palomar telescope (Pravdo et al. 2004) with astrometric precision of 1 mas per a single series of 20-30 exposures is used for exoplanet search around 30 late M stars since 1997. In 2009, this resulted in the first astrometric discovery of the giant exoplanet VB 10b around a main-sequence star (Pravdo & Shaklan 2009), although it is still debated (Zapatero Osorio et al. 2009; Bean et al. 2009).

- The CAPSCam camera on the 2.5-m Las Campanas telescope has an estimated astrometric precision of $300\,\mu$as/h. Search program includes about 100 late M, L, and T dwarfs to be observed for 10 years (Boss et al. 2009).

- The FORS2 camera installed on one of the 8-m VLT telescope was tested in a series of theoretical and observational studies which revealed its long-term astrometric precision of $50-100\,\mu$as at time scales from a few days to a few years (Lazorenko et al. 2009). Science observations started in 2009 with the VB 10b as a program object and include 14 nearby L dwarfs.

Precision narrow-field astrometry is applicable to the targets of 12–17 mag at galactic latitudes up to $15-30°$ allowing for a sufficient number of reference stars. Astrometry enables the detection of $\sim$ $M_{Jupiter}$ planets at nearby low-mass red stars and brown dwarfs with orbital period of ≥ 1 year. We will take the range $0.3-1$ mas as a conservative number for the accuracy of large telescope astrometry.

3.2. Hubble Space Telescope / Fine Guidance Sensors

Relative, narrow-angle astrometry from space has been performed so far with the *Fine Guidance Sensors* aboard the *Hubble Space Telescope* (HST/FGS). For HST/FGS astrometry with respect to a set of reference objects near the target (within the 5×5 arcsec instantaneous field of view of FGS), $1-2$ mas single measurement precision down to $m_V \sim 16$ has been demonstrated (see Benedict et al. 1994, 1999) using an ad hoc calibration and data reduction procedures to remove a variety of random and systematic error sources from the astrometric reference frame (spacecraft jitter, temperature variations and temperature-induced changes in the secondary mirror position, constant and time-dependent optical field angle distortions, orbit drifts, lateral color corrections). The limiting factor is the spacecraft jitter. A single-measurement precision below $0.5-1$ mas is out of reach for HST/FGS. The first undisputed value of the actual mass of a Doppler-detected planet was obtained by Benedict et al. (2002) who derived the perturbation size, inclination angle, and mass of the outer companion in the multiple-planet system GJ 876 from a combined fit to Hubble Space Telescope/FGS astrometry and high-precision radial-velocities. Six other objects are under observation.

3.3. Ground-based dual star interferometry

Long-baseline optical/infrared interferometry is an important technique to obtain high-precision astrometry measurements (Shao & Colavita 1992). The idea is to operate an interferometer equipped with a dual instrument observing two stars simultaneously so that the optical delay between the fringes can be accurately measured. The first observations have been achieved by the Palomar Testbed Interferometer (PTI, Colavita et al. 1999) reaching $\sim 100\,\mu$as short-term accuracy for $30''$ binaries (Lane et al. 2000) and $20-50\,\mu$as for sub-arcsec binaries (Lane & Muterspaugh 2004) within the Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) program.

Two projects are underway: the *ASTrometric and phase-Referenced Astronomy*(ASTRA: Pott et al. 2008) on the Keck Interferometer and *Phase-Referenced Imaging and Micro-arcsecond Astrometry* (PRIMA: Delplancke 2008) at the VLT interferometer. These two projects are designed to perform narrow-angle interferometric astrometry at an accuracy better than $100\,\mu$as with two telescopes of a target and one reference star separated by up to $1'$. This is however a challenging technique requiring optical path difference errors less than 5 nm.

The Exoplanet Search with PRIMA (ESPRI) Consortium (Launhardt et al. 2008) foresees to carry out a three-fold observing program focused on the astrometric characterization of known radial velocity planets within ≤ 200 pc from the Sun, the astrometric detection of low-mass planets around nearby stars of any spectral type within ≈ 15 pc from the Sun, and the search for massive planets orbiting young stars with ages in the range $5-300$ Myr within ~ 100 pc from the Sun. The target list includes ~ 100 stars with good references.

3.4. Space-borne global astrometric Survey: Gaia

In its all-sky survey, Gaia, due to launch in Spring 2012, will monitor the astrometric positions of all point sources in the magnitude range $6-20$ mag, a database encompassing $\sim 10^9$ objects. Using the continuous scanning principle first adopted for Hipparcos, Gaia will determine positions, proper motions, and parallaxes for all objects, with end-of-mission precision between 6 μas at $V=6$ mag and 200 μas at $V=20$ mag and an averaged 80 transits per object in 5 years.

Gaia astrometry, complemented by on-board spectrophotometry and radial velocity information, will have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of the Milky Way Galaxy. One of the relevant areas in which the Gaia observations will have great impact is the astrophysics of planetary systems (e.g. Casertano et al. 2008), in particular when seen as a complement to other techniques for planet detection and characterization (e.g. Sozzetti 2009).

Using Galaxy models, our current knowledge of exoplanet frequencies, and Gaia estimated precision ~ 10 μas on bright targets ($V<13$), Casertano et al. (2008) have shown that Gaia will measure actual masses and orbital parameters for possibly thousands of giant planets and determine the degree of coplanarity of possibly hundreds of multiple-planet systems. Gaia will be sensitive as far as the nearest star-forming regions for systems with massive giant planets on $1 \leq a \leq 4$ AU orbits around solar-type hosts and out to 30 pc for Saturn-mass planets with similar orbital semi-major axes around late-type stars.

Gaia holds promise for crucial contributions to many aspects of planetary systems astrophysics, in combination with present-day and future extrasolar planet search programs. Gaia data over the next decade will allow us to (a) significantly refine of our understanding of the statistical properties of extrasolar planets, (b) carry out crucial tests of theoretical models of gas giant planet formation and migration, (c) achieve key improvements in our comprehension of important aspects of the formation and dynamical evolution of multiple-planet systems, (d) provide important contributions to the understanding of direct detections of giant extrasolar planets, and (e) collect essential supplementary information for the optimization of the target lists of future observatories aiming at the direct detection and spectroscopic characterization of terrestrial, habitable planets in the vicinity of the Sun.

3.5. Space-based astrometric observatory: SIM-Lite

The *Space Interferometry Mission* is a space borne instrument (Marr-IV et al. 2008) which would carry out astrometry to micro-arc second precision on the visible light from a large sample of stars in our galaxy and search for earth-like planets around nearby stars (Unwin et al. 2008). SIM-Lite is an alternative concept for SIM and it is the current proposed implementation for SIM for NASA program on Search for Earth-like planets and life. The SIM-Lite instrument is an optical interferometer with a baseline of 6 meters which include a guiding interferometer and a guiding siderostat for spacecraft pointing and a Science interferometer to perform high accuracy astrometric measurements on target stars. The primary objective for SIM-Lite is to search 65 nearby stars for exoplanets of masses down to one Earth mass, in the Habitable Zone. SIM-Lite is designed to deliver better than 1 μas narrow-angle astrometry in 1.5 hr integration time on bright targets ($m_V \leq 7$) and moderately fainter references ($m_v \simeq 9-10$) (Goullioud et al. 2008). An accuracy on the position of the delay lines of a few tens of picometers with a 6-m baseline must be achieved (Zhai et al. 2008). Furthermore, a positional stability of internal optical path lengths of ~ 10 nm is required, in order to ensure maintenance of the fringe visibility.

SIM-Lite has planned for 3 planetary system survey. (1) The *deep planetary survey* will focus on less than one hundred nearby stars of the main sequence within 10 parsecs from the Sun. The main objective is to identify planetary system with Earth-like planets in the habitable zone around these Sun-like stars. This deep survey requires the highest possible astrometric accuracy, below the single micro-arc-second. This accuracy is achieved by multiple visits to the target stars with between 12 to 60 chops per visits in order to lower the instrument accuracy down to the required level for detection of one Earth mass planet. A 60 chop visit to a magnitude 6 target will require less than two hours of observation time. The target would then be observed several hundred times during the lifetime of the mission. (2) The *broad planetary survey* will study more than one thousand set of stars of many types including O, B, A, F, binary with a reduced astrometric accuracy of 5 μas in order to cover the diversity of planetary systems and to increase our knowledge on the nature and the evolution of planetary systems in their full variety. This accuracy can be achieved by short visits to the target stars. To determine accurately the orbit parameters of the planets, 100 visits per target star will be scheduled over the 5 year mission. (3) The *young planetary system survey* will observe less than one hundred nearby solar type stars with ages below 100 millions years within 100 parsecs from the Sun with the aim to understand the frequency of Jupiter-mass planets and the early dynamical evolution of planetary systems. This survey can be conducted with a reduced astrometric accuracy of 4 μas achieved with 4-chops visits requiring about eight minutes of observation time for a $V \sim 11$ young star.

4. Limitations and performance

Using astrometry to detect and characterize extra-solar planetary systems is challenging in many aspects. In this part we focus on the main issues that astrometry will have to face especially in the field of Earth-mass planets.

4.1. Influence of giant planets on Earth-like planets detection

Correct determination of the astrometric orbits of planetary systems involves highly non-linear orbital fitting procedures, with a large number of model parameters. Particular attention will have to be devoted, for example, to the assessment of the relative robustness and reliability of different procedures for orbital fits (and associated uncertainties). The quality of the coplanarity analysis for multiple systems has to be measured against the achieved single-measurement precision and available redundancy in the observations. Correctly identifying signals with amplitude close to the measurement uncertainties is a challenge particularly in the presence of larger signals induced by other companions and/or sources of astrophysical noise of comparable magnitude, like Jupiter-like planets for telluric ones (500 μas signal compared to 0.3 μas signal in the case of a Solar System located at 10 pc.

All these issues could have a significant impact on the capability of Gaia and SIM-Lite to detect and characterize planetary systems. Double-blind test campaigns have been carried out to estimate the potential of both Gaia and SIM-Lite for detecting and measuring planetary systems (Casertano et al. 2008; Traub et al. 2009). The Gaia *Data Processing and Analysis Consortium* (DPAC) is developing the modeling of the astrometric signals produced by planetary systems implementing multiple robust procedures for astrometric orbit fitting (such as Markov Chain Monte Carlo and genetic algorithms) and in order to determine the degree of dynamical stability of multiple-component systems. A similar work is also underway for SIM-Lite (see Traub et al. in this volume) which shows that detection completeness is 90% for all planets reaching 95% for terrestrial planets in the habitable zone and a reliability of respectively 97% and 100%.

4.2. Impact of stellar activity

In the domain of terrestrial planets, the expected signal is so small (0.3μas for an Earth at 10 *pc*) that one must take into account the effect of the presence of spots on the surface of the target stars. These spots will introduce a spurious signal the level of which should be evaluated all the more beacuse lifetime of these spots can last several weeks. This phenomenon also impacts the other detection techniques like transits and radial velocity measurements. Several works have addressed this issue in the case of astrometry at least for the most sensitive instruments, Gaia and SIM-Lite (Eriksson & Lindegren 2007; Desort et al. 2009; Makarov et al. 2009).

The general conclusion is that, unlike the radial-velocity case, μas-level astrometry is significantly less affected by the above astrophysical noise sources. For example, a Sun-like star inclined at $i = 90°$ at 10 pc is predicted to have a jitter of 0.087 μas in its astrometric position along the equator below the expected signal of an Earth at a level of 0.3 μas, and 0.38 m/s in radial velocities above the expected signal from a Earth at 0.09 m/s. If the presence of spots due to stellar activity is the ultimate limiting factor for planet detection, then the sensitivity of SIM Lite to Earth-like planets in habitable zones is about an order of magnitude higher that the sensitivity of prospective ultra-precise radial velocity observations of nearby stars.

4.3. Performance and mission scales

Table 2 summarizes the various projects presented in Sect. 3. with their status, since when they are operating or when they will happen, the expected accuracy and their main targets. We have also indicated their scale in the *Blue Dots* terminology (see Foresto et al. in this volume). Ground-based facilities are categorized in existing low cost projects whereas Gaia is in the M-type mission class and SIM-Lite in the L-type mission even though if approved it will fly and operate earlier than some ground-based instruments (like spectrographs on extremely large telescopes).

Table 2. Summary of the astrometry mission scopes and their scales.

Type of astrometry mission	**Ground-based large telescope large field imaging**	**Ground-based optical interferometry differential narrow-angle astrometry**	**Space-borne wide-angle astrometry survey**	**Space-borne narrow angle astrometry**
Project	Palomar/STEPS, VLT/FORS	VLTI/PRIMA (ESO), KI/ASTRA (NSF/NASA)	Gaia (ESA)	SIM-Lite (NASA)
Status	in operation	commissioning	launch date:T2/2012	end of phase B
Availability	now	2011	2012	2015-2017?
Accuracy	**0.3-1mas**	**10-50 μas**	**25 μas**	**0.2 μas**
Exoplanet targets	Giant planets around M stars	Giant planets around solar-type stars	Giant planets around several 10^5s of stars of different types	Earth in HZ of F-G stars
		Neptunes around M stars		survey of 1000 systems around different stars
	Neptunes around brown dwarfs	Young planetary systems		Young planetary systems
Mission scale	**Existing**	**Existing**	**~M-type mission**	**~L-type mission**

5. Conclusion: specificity of astrometry in the exoplanet field

This review has allowed us to show that astrometry can detect and characterize new categories of exoplanets especially in the Solar neighborhood. It encompasses techniques ranging from ground-based instruments limited to the largest planets to space borne missions allowing Earth-like planets to be detected in the habitable zone around solar-type stars. Astrometry will obtain full characterization of orbits which gives us (a) masses and tells us (b) where and when to look with spectroscopic characterization missions.

Astrometry is mostly immune to stellar activity even at the signal level due to Earth-like planets and therefore is well positioned for identifying and characterizing planets for future direct detection and spectroscopic follow-up projects like DARWIN/TPFI or TPF-c.

Astrometry is a difficult and challenging technique, yet it may be the only way to detect and characterize Earth-like planets in the habitable zone of solar-type stars. Last but not the least, astrometry projects are underway or technically ready and should soon contribute significantly to the exoplanet field.

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