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From Gaia to SIM-Lite: terrestrial planet detection with μas astrometry

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Abstract. The recently concluded SIM-Lite double-blind test campaign aimed at gauging the ability to characterize terrestrial mass planets orbiting nearby stars in multiple-component systems using a combination of the proposed astrometric space mission SIM-Lite and ground-based radial velocity (RV) observations. We discuss the outcome of the analysis carried out by our Team to model planetary orbits using astrometric+RV data focusing in particular on: 1) a study of the correlation between the presence of false positives in multiple-component configurations and the existence of long-period companions , and 2) an assessment of the regimes of signal-to-noise ratio and orbital period for which the combination of astrometric and RV measurements is most effective.

Key words. planetary systems — astrometry — techniques: radial velocities

1. Introduction

SIM-Lite (for an overview see Goullioud et al., 2008) is a proposed space–borne Michelson interferometer devoted to high-precision astrometry. It utilizes technology developed over the past ten years for the SIM mission (Unwin et al., 2008). In its narrow-angle astrometric mode, it will achieve 1 micro-arcsecond (μas) precision on bright targets ($V \approx 6$ mag) using sequences between the target and bright ($V \approx 9$ mag) reference stars in a two-degree field of regard lasting just under 20 minutes. The predicted end-of-mission noise floor for SIM-Lite is < 0.1 μas (Shao & Nemati, 2009), comparable to the white-light star-spot astrometric jitter expected for solar-type stars within 10 pc from the Sun (e.g., Sozzetti, 2005).

The exquisite astrometric precision achievable by SIM-Lite, exceeding Gaia's by over an order of magnitude (e.g., Casertano et al., 2008 renders it an ideal instrument to search for Earth analogs in the Habitable Zone of nearby stars (Figure 1). However, achieving the requisite measurement precision might not be enough in the presence of complex systems, in which the signal of a terrestrial habitable planet is 'polluted' by other planets with high eccentricities and/or long periods. A detailed simulation study was then carried out in double-blind mode, which set out to answer a number of questions relating to the detectability of Earth-like planets (terrestrial masses and Habitable-Zone orbits) in multi-planet systems, using a combination of SIM-Lite astrom-

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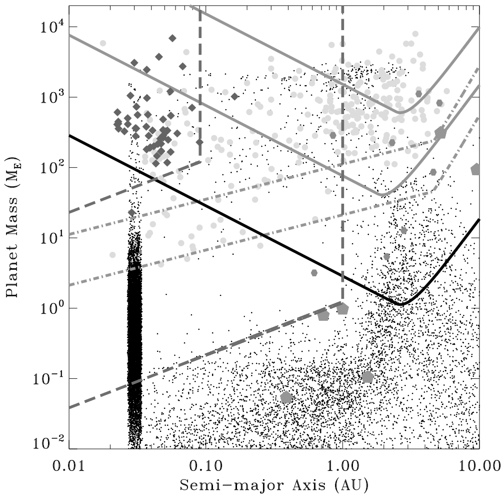

Fig. 1. Exoplanets discovery space for the astrometric (solid lines), Doppler (dashed-dotted lines), and transit (dotted lines) techniques. The lower solid line is the detection curve for SIM-Lite astrometry of a 1 $M_\odot$ star at 10 pc. See Sozzetti, (2009) for details.

etry and ground-based radial-velocity (RV) observations to 1 m/s (Traub et al., 2009). Our team was involved in this endeavour as part of Group C (the solvers) in charge of modeling planetary orbits using the simulated astrometric+RV data. Traub et al., (2009) have produced a preliminary report and drawn overall conclusions on the double-blind test campaign. We discuss here some issues related to the outcome of the analysis carried out by our team which can help with gauging some of the difficulties inherent to multiple Keplerian orbital fitting.

2. Astrometry+RV orbital fits

The algorithm for planet detection and orbital fitting, as applied to the combined data sets of RV observations and SIM-lite astrometric measurements, draws from our previous studies on planet detection with both Gaia (Casertano et al., 2008, and references therein) and SIM (Sozzetti et al., 2003, and references therein). Our team developed an IDL-based pipeline for fitting the planetary systems. Our robust, global least-squares fitting procedure utilizes a multi-step minimization technique to optimally search the orbital parameter space and to carry out single- and multiple-planet orbital solutions on the combined high-precision astrometric+RV datasets. Simultaneous orbital fits can particularly strenghten the determination of orbital elements and companion masses, as they fully exploit the redundancy constraints of both types of data. Initially, significant orbital periods in the data are searched for by a combined approach which utilizes both classic Lomb-Scargle periodograms as well as grids of trial periods as input to linearized Keplerian models. For each successfully detected period (with a false-alarm probability threshold FAP < 1%), a local minimization scheme based on the Levenberg-Marquardt algorithm is utilized to fit simultaneously a full Keplerian orbit to both the RV and astrometric measurements. For this purpose, we utilize as figure of merit in the (iterative) minimization process the sum of the separate χ^2 values: $\chi^2_{\rm comb} = \chi^2_{\rm astr} + \chi^2_{\rm RV}$. At each iteration, the planet(s) orbital elements are fitted simultaneously with (possible) positional offsets, proper motion, and parallax for the astrometric data sets as well as an RV zero-point offset for the Doppler data. The quality of the solution is assessed based on a χ^2-test with a probability $p(\chi^2 > \chi^2_0) \leq 1\%$, where χ^2_0 is the observed value of the merit function after a fit. Then, the post-fit residuals are again inspected for significant periodicities and, in case, the newly identified components are fitted in an iterative scheme. Two successive solutions with n and $n+1$ components are subjected to an F-test with $p(F) \leq 1\%$ to verify the superiority, in a statistical sense, of the $n+1$-component model above the n-component model.

More in-depth details on the analysis algorithms and their code implementation will be presented in a forthcoming paper (A. Sozzetti et al. 2009, in preparation)

3. Lessons learned

We highlight here some problem areas identified during the double-blind test campaign. They all relate to the general fact that, in the presence of complex signals, different detection and orbit fitting algorithms, given the

Reliability	Team C1	Team C2	Team C4	Team C5
All	70%	87%	89%	98%
Terrestrial	41%	86%	80%	96%
HZ	44%	76%	79%	100%
Terr & HZ	40%	80%	71%	100%

Completeness	Team C1	Team C2	Team C4	Team C5
All	60%	91%	89%	95%
Terrestrial	28%	81%	81%	90%
HZ	53%	84%	84%	100%
Terr & HZ	42%	71%	71%	100%

Fig. 2. Left: reliability of detection (number of detected planets divided by the number of detected planets + the number of false alarms) vs. planet type, for various teams contributing to the SIM-Lite double-blind tests campaign. Right: completeness (number of detected planets divided by the number of detectable planets) vs. planet type, for the same teams. *Credits: Wes Traub*

same data sets, can perform in measurably different ways (an issue already pointed out in Casertano et al., (2008)).

For example, when it comes to estimates of the reliability of detection (i.e., the probability that a detection based on a periodogram analysis is true and not a false alarm) and completeness (i.e., the probability that a planet will be detected), our team, which adopted a fixed threshold[1] for detection in the period search, was more prone to miss low signal-to-noise ratio (S/N), high-FAP planets, i.e. those in the terrestrial mass regime (Figure 2).

Second, our team had difficulties in fully solving systems (i.e. obtaining a reduced $\chi^2 \simeq 1.0$) at the end of the analysis procedure. This happened not only in cases of low-S/N, high-FAP components missed, but also when all components were identified (Figure 3). This likely reflects limits in our IDL-based iterative procedure, possibly in connection with the identification, through the global search scheme, of good starting guesses for the local minimization process. Indeed, we noticed that improvements in the resulting χ^2 were obtained by utilizing best-fit configurations from other C teams as starting values for our procedure. In a more general context, this exercise allowed us to appreciate the importance of the availability of long-term RV monitoring at the 1 m/s level, particularly for the correct identification of long-period components (helping to disentangle orbital motion from proper motion in the astrometry) and very short-period planets (helping to resolve issues related to bad sampling and very low S/N) in systems containing terrestrial planets which would otherwise be very hard to detect.

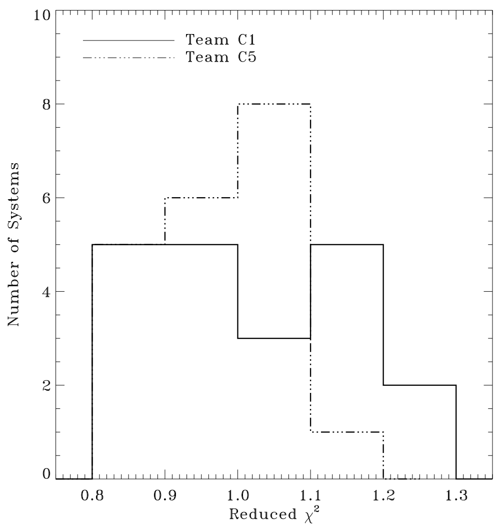

Fig. 3. Distribution of reduced χ^2 for a batch of systems for which both our team (C1) and team C5 identified all detectable components.

Finally, another general topic concerned the selection of the 'best' solution among those obtained by different solver teams. Indeed, as

[1] As opposed to an adaptive threshold.

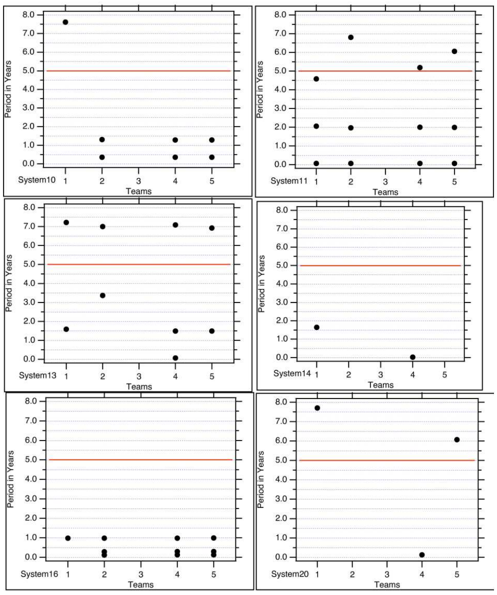

Fig. 4. Orbital periods of identified planets in a subset of 'fully resolved' systems as a function of the solver team number (system numbers are in the left bottom corner of each panel). The line at 5 years indicates the time baseline of the simulated astrometric measurements. *Credits: Barbara McArthur*

shown in Figure 4, even for systems which appear fully resolved (i.e. for which all teams find final values of the reduced $\chi^2 \approx 1.0$, all statistically indistinguishable), the actual orbital configuration can be significantly different from team to team.This is true not only for components with long periods, exceeding the time baseline of the observations (a feature somewhat expected), but also for short period planets. This problem arises because of the large parameter space to be investigated and due to the fact that for highly non-linear fitting procedures the statistical properties of the solutions are not at all trivial (and significantly differ from those of linear models). Doppler surveys are already facing the challenges of fitting multiple-component orbits, and it is not uncommon to find strong disagreement between solutions (and sometimes number of planets detected!) presented by different teams (e.g.,Butler et al., 2006; Gregory, 2007).

4. Conclusions

Moving from the 10–μas precision regime, expected for Gaia on bright stars, to positional errors of 1 μas, or better, as it is envisaged for SIM-Lite, will allow for a tremendous gain in the matter of exoplanets detection and characterization, especially for multi-component systems. From our standpoint, the SIM-Lite double-blind test campaign has highlighted some important issues, such as the need for variable FAP levels to increase the likelihood of detecting low-S/N planets (while keeping the number of false positives under control), the importance of additional, long-term RV monitoring (particularly for systems with long-period planets), and the essential role of multiple teams with independent orbital fits procedures (a strong confirmation of the results obtained by the analogous double-blind test exercise conducted for Gaia, see Casertano et al., 2008). Overall (see Traub et al., 2009 for details), the SIM-Lite double-blind test campaign demonstrated that terrestrial planets in the Habitable Zone of nearby solar-type stars (i.e., within 10 pc) can be reliably detected and characterized, even in the presence of additional planets in the systems, confirming the potential of μas astrometry as one of the few techniques capable of addressing the question of the existence of Earth analogs in the solar neighborhood within the next decade.

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