DETECTION AND CHARACTERIZATION OF EXTRA-SOLAR PLANETS WITH GAIA

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ABSTRACT

The scope of this paper is twofold. First, it describes the simulation scenario and the results of the large scale double-blind test campaign set-up by the Planetary System Working Group for the realistic simulation of the Gaia capabilities in detecting extra-solar planets. Present limitations and envisaged future improvements are also discussed. Then, the identified capabilities are put in context by highlighting the unique contributions that the Gaia exo-planet discoveries will be able to bring to the science of extra-solar systems of the next decade.

Key words: Astrometry; (Stars:) planetary systems; Space vehicles: Gaia.

1. INTRODUCTION

In recent years we have conducted detailed exploratory work (e.g., Lattanzi et al. 2000, Sozzetti et al. 2001, and 2002) which has shown in some detail what high-accuracy astrometric missions such as Gaia can achieve in terms of search, detection and measurement of extra-solar planets of Jupiter-like mass. In these studies we have adopted a qualitatively correct description of the observing strategy and elementary measurements that the mission will carry out, and we estimated detection probabilities and orbital parameters using realistic, non-linear least squares fits to those measurements.

In Lattanzi et al. (2002), we pointed out that the Gaia contribution is primarily understood in terms of the number and spectral type of targets available for investigation, and of the characteristics of the planets to be searched for. Several hundreds of thousands of solar-type stars (F-G-K) within a sphere of $\sim$ 200 pc centred on our Sun will be observed. Gaia will be particularly sensitive to giant planets ($M_p \sim M_{\rm Jupiter}$) on wide orbits, up to periods twice as large as the mission duration, the potential signposts of the existence of rocky planets in the Habitable Zone. Thousands of new planets might be discovered, and a significant fraction of those which will be detected will have orbital parameters measured to better than 30% accuracy. Also, by measuring to a few degrees the relative inclinations (coplanarity) of planets in multiple systems with favorable configurations, Gaia will also make measurements of unique value towards a better understanding of the formation and evolution processes of planetary systems.

Although valid and useful, those studies needed updating and improvements. There, we had largely neglected the difficult problem of selecting adequate starting values for the non-linear fits, by using perturbations of the simulated ('true') values instead. The study of multiple-planet systems, and in particular the determination of whether the planets are coplanar within suitable tolerances is incomplete. The characteristics of Gaia have changed, in some ways substantially, since Sozzetti et al. (2001). Last, but not least, simulations and analysis were carried out by a single team thus raising the issue of blind tests, for which simulations and analysis are truly independent.

The next sections will detail on the most recent simulation activities (Section 2) and on whether or not, based on our preliminary results, there is an impact on the Gaia potential contribution to extra-solar planetary science (Section 3).

2. GAUGING GAIA'S CAPABILITIES

In Casertano et al. (2003) we presented the protocol the Planetary Systems Working Group (PSWG)[1]had established to update and extend what we knew about Gaia's ability to detect and measure exoplanets orbiting nearby stars from the astrometric observations. This test program aims at verifying 1) the expected sensitivity of

[1]Established by the ESA Project Scientist in 2001 to support the activities of the Gaia Science Team.

Gaia's observations to exoplanets, as a function of mission parameters where applicable; 2) the compatibility and readiness level of the simulation and solution software that different groups have been developing in recent years; and 3) the ability of these groups to communicate information effectively and to understand the possible difficulties in the development of a shared analysis network and its integration with the mission data reduction system (Torra et al. 2005). The tests are carried out in double-blind format to ensure reliability of the results.

2.1. Test Protocol

The experimental campaign is conducted in double-blind mode, with three distinct groups of participants:

1. *Simulators*: the group(s) that define and generate the simulated observations, using clearly stated assumptions on the observation process; simulators also define the type of results that are expected for each set of simulations.
2. *Solvers*: the group(s) that receive the simulated data and produce 'solutions'—as defined by the simulators; solvers define the criteria they adopt in answering the questions posed by the simulators.
3. *Evaluators*: the group(s) that receive both the 'truth'—i.e., the input parameters—from the simulators and the solutions from the solvers, compare the two, and draw a first set of conclusions on the process.

Figure 1 illustrates the actual implementation of the experiment. Simulators are at the Observatory of Turin; Lattanzi and Spagna take care of defining the simulations, while Morbidelli and Pannunzio are responsible for the actual generation of the simulations and for the data management, archiving, and distribution.

There are two Solver teams involved: Pourbaix and Jancart at the Université libre de Bruxelles and Sozzetti at the Harvard-Smithsonian Center for Astrophysics. Finally, Casertano, at the Space Telescope Science Institute, is our Evaluator carefully looking at each and every bit of information he receives from the other parties.

The test program implemented adopts a rather realistic, although simplified, model for the process of observing stellar positions with Gaia. As the details of the Gaia error model, observational parameters, and data analysis are yet to be defined, we decided to adopt a geometric model in which the error in each individual measurement is described by a single number, without known correlations with other errors or quantities. We assume that each time a star is observed with Gaia, see Figure 2, its position ψ along the instantaneous great circle IGC is measured with a Gaussian error distribution of known dispersion σ_ψ, while the parameters of the IGC itself are known without error and no measurement is made on the position η of the star perpendicular to the IGC.

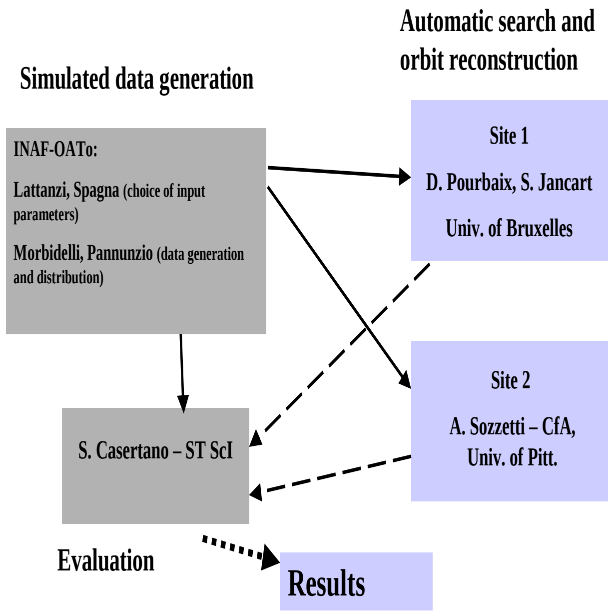

Figure 1. Double blind test organization.

We also assume that external elements that affect the measurement, such as aberration, general-relativistic effects (the deflection parameter γ, gravitational lensing), and uncertainties in the local reference system and in the sphere solution are eliminated by the standard data analysis process. In the first phase of the work, we also neglect perspective acceleration—equivalently, we assume that all stars have zero heliocentric radial velocity. The measurement process under these assumptions is described in detail in Casertano et al. (2003).

The work plan was organized in four tasks: T0, T1, T2, and T3. Task T0 was envisioned as a readiness test to ensure that all procedural aspects of the test are resolved—e.g., file formats are defined, the interpretation of simulation data is clear, the specifications of the geometric model of the measurement process are agreed upon, and so on—and that the software tools are all compatible and ready to go.

In the following paragraphs the details of the tasks from T1 through T3 are provided.

2.1.1. Task T1

Task T1 consists of the analysis of 10^5 stars, in order to establish under what conditions the presence of a planet can be detected, and with what reliability. The size of the sample makes T1 the most demanding task in terms of mass of data to analyze and processing time.

The simulations consist of a mix of stars with no or one planet, in roughly equal numbers, and with a small number of multiple-planet cases. Signature significance ranges from 0.25 to 10, thus going from the non-detectable to the 'easily' detectable. Short, medium, and long periods are all represented, with short periods essentially unresolved by the mission, medium periods well-

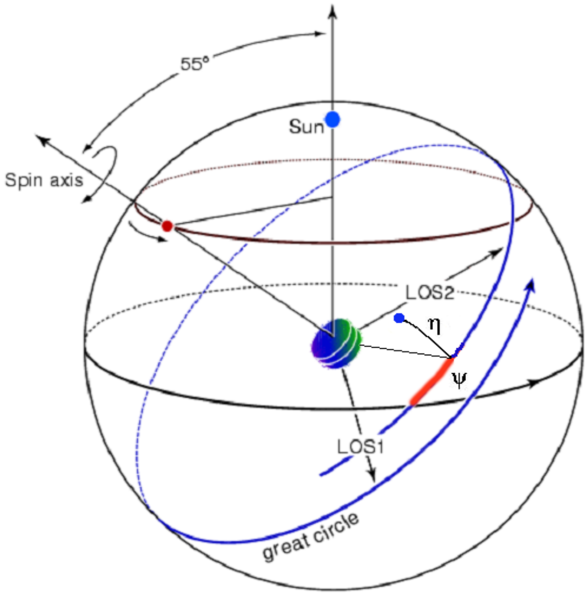

Figure 2. Basic geometry of Gaia's observations adopted for the generation of simulated data for the double-blind test program.

resolved and well-sampled, and long periods sampled only for a fraction of their orbital motion. Each 'bin' of period and significance are occupied by several hundred cases, each with orbital parameters distributed randomly over the relevant range, so that detection probability can be established with confidence.

Each Solver group is free to establish their own detection test, with a significance level of their choice.

2.1.2. Task T2

Task T2 determines how well the orbital parameters of a single planet can be measured for a variety of signature significance, period, inclination, and other parameters. The simulations consists of 5×10^4 stars, each with a single planet with significance ranging from 2 (barely detected) to 200. Solvers derive the best-fit orbital parameters, *together with an error estimate for each and covariances* if appropriate. Evaluators first assess the quality of the solutions and of their error estimates. Evaluators then study the distribution of orbital parameter errors vs. the stellar and orbital parameters themselves, with the goal of deriving simple expressions that can predict the accuracy of the orbital solution for various types of planets as a function of the Gaia error model.

2.1.3. Task T3

Task T3 is devoted to studying how well multiple planets can be identified and solved for, as well as how well their coplanarity can be established. In addition, the accuracy of multiple-planet solutions is compared with that of single-planet solutions for planets with comparable properties. The Task is based on $\sim 10^3$ simulations of stars with 2 to 4 planets each, including a small number of stars with a single planet.

Planets are assumed to be strictly non-interacting, in that each planet follows pure Keplerian orbits around the center-of-mass of the system. Solvers find how many planets can be detected and solved for in each case, as well as whether they are coplanar within a pre-specified tolerance. The method to be used for the coplanarity test is up to the Solvers; one possibility is a Likelihood Ratio test between a coplanar and a general solution. Solvers also produce error estimates, and covariances if appropriate, for the orbital parameters they determine. Simulators ensure that some simulations have a dominant planet with parameters similar to those of a case studied in Test T2, so that the quality of the single- and multiple-planet solution can be compared on a case-by-case basis. (Alternatively, single-planet simulations and solutions for the dominant planet in each case can be carried out after the fact.) Evaluators will 1) assess the quality of the solutions and of the estimated errors; 2) study the distribution of orbital error parameters in comparison with the single-planet case, and 3) assess the quality and reliability of the coplanarity test. T3 is undoubtedly the most complex test of the campaign.

2.2. Simulation

The main *a priori* assumptions of the simulation are (Casertano et al. 2003):

- the position of the pole of each IGC is considered known *a priori* (perfect attitude);
- the IGC abscissa ψ is only affected by random errors; no systematic effects are considered (e.g., zero-point errors, chromaticity, etc...);
- light aberration, light deflection, and other apparent effects are as if they were perfectly removed from the observed abscissa.

The scanning law for the time being is that devised for Gaia, i.e., precession angle around the Sun direction $\xi = 50°$, precession speed of the satellite's spin axis $V = 5.22$ rev per year, spin axis rotation speed 60 arcsec s^{-1}. We assume in our double-blind tests program that detectors behave in a way that astrometric errors still scale with magnitude at V $\sim$ 12, and adopt a single-measurement error σ_ψ defined by:

$$\sigma_\psi = \frac{\sigma_{\rm fin} * \sqrt{N_{\rm obs}}}{f_g} \qquad (1)$$

If the end-of-mission error $\sigma_{\rm fin}$ is 10 μas at V = 15, the geometrical factor $f_g = 2.2$, and $N_{\rm obs} = 42$, and assuming a scaling factor of 0.25 for V $\sim$ 12, then the constant single-measurement error $\sigma_\psi \simeq 8$ μas. This value reflects the changes in the present scanning law with respect to the one envisaged before (less observations per object, but longer integration times, for a globally unchanged total observing time spent on each given target).

The mission lifetime is set to 5 years, and the ecliptic longitude of the Sun (with the Earth assumed to go about the Sun in a perfectly round orbit) is $\lambda_\odot = 90°$ at the catalogue reference epoch $t_0 = 2.5$ years.

The values of the astrometric parameters are drawn from simple distributions, not resembling any specific galaxy model. The distribution of ecliptic coordinates is random, uniform. The distribution of proper motions is gaussian, with dispersion equal to a value of transverse velocity $V_T = 15$ km s^{-1}, typical of the solar neighbourhood.

Concerning the other relevant parameters, we will produce experiments where stellar mass is for simplicity always kept fixed to 1 M$_\odot$, and express detection probabilities and the efficiency in orbit reconstruction as a function of distance, orbital elements, planet mass, and astrometric signal-to-noise ratio α/σ_ψ, where

$$\alpha = (M_p \times a_p)/(M_s \times D) \qquad (2)$$

is the astrometric signature in seconds-of-arc if M_p and M_s, planet and stellar mass, are in M$_\odot$, a_p (planet orbital semi-major axis) in AU, and D (distance to the star) in parsec. Clearly, the results will also be a function of the details of the fitting procedures adopted by the different teams, which is one of the questions we are addressing with this testing program.

The effect of each planet in multiple systems is added linearly, i.e., mutual perturbations are not simulated. This is somewhat justified when comparing the mission duration to the typical time scales of planetary perturbations. However, given Gaia's microarcsecond accuracy, some systems with giant planets on relatively short orbits might generate measurable resonant effects on a time scale of 5 years.

2.3. Results

The status of the double-blind experiment is summarized in Table 1. Presently, we have completed tasks T1 and T2 (T0 was considered a *readiness* test) while T3 is on-going at the time of this writing and completion is expected for the end of 2004.

2.3.1. The T1 test

Of the 100 000 stars, 45 202 have no planets, 49 870 one, 3878 two, and 1050 have three planets. The astrometric signature of each planet ranges from 2 to 80 μas, corresponding to signal-to-noise values in the range 0.25–10, and the period from 0.2 to 12 years. For systems with multiple planets, there is no specific relationship between periods, phases, or amplitudes of the planetary signatures.

Table 1. Status of the double blind test campaign described in the text.

Test name	Test description	Status
T0	Readiness test	done
T1	Planet detection and its significance (astrometric S/N range 0.25 – 10; 10^5 stars, 50% with planet; Period from 0.2 to 12 yr)	done
T2	Star + Planet fits and their significance (S/N range 2 – 200; 5×10^4 stars, all with planets)	done
T3	Multiple planets fits and coplanarity	on-going

Two Solvers participated in this test and provided completely independent solutions: Alessandro Sozzetti (AS) and Dimitri Pourbaix (DP). Both solvers approached test T1 on the basis of the quality of the single-star, five-parameter solution for the astrometric measurements.

As detailed in Casertano et al. (2004b), AS adopts two criteria to identify candidate planets, one broad, aimed at detecting as many candidates as reasonable, and one strict, designed to reduce the number of false positives. Specifically, AS uses $P(\chi^2)$, the probability that the observed χ^2 of the single-star solution is as bad or worse than the value observed in the presence of pure measurement errors, and $P(F)$, the F-test probability on the same fit. A large value of χ^2 or of the F statistic can readily arise if the deviations due to the presence of a planet are much larger than the expected measurement errors, and thus a low value of $P(\chi^2)$ and $P(F)$ signifies likely planet (and unlikely false positive).

DP adopts a similar method, using specifically the $F2$ indicator (see the Hipparcos Catalogue, vol. 1, p. 112), which is expected to follow a normal distribution with mean 0 and dispersion 1. His criterion, DP1, requires $|F2| > 3$, which in essence is a 3-sigma criterion.

The experiments run by the Solvers show that the detection tests they designed, although completely independent, perform consistently and according to expectations. For example, DP recovers ∼38% of the simulated systems with a number of false positives, 106, quite consistent with the confidence level of the $F2$ test and the number of stars without planets. Planets down to astrometric signature $\sim 20\mu$as, corresponding to ∼2 times the assumed single-measurement error, can be detected reliably and consistently, with a very small number of false positives[2]. Even better, the choice of the detection threshold is an effective way to distinguish between highly reli-

[2]The ratio between astrometric signature and single-observation

able and marginal candidates. Under the assumptions of this test (perfectly known noise model) potential planet-bearing stars can be identified and screened reliably. This is the case of Sozzetti's AS2 criterion (Casertano et al. 2004b): designed to investigate the possibility of a very pure sample of detected planets, its application resulted in 28 655 detections out of the 45 202 simulated systems, but none of them was a false positive.

Finally, refinements of the detection criterion based on additional considerations, e.g., the quality of the orbital fit, can potentially make an improvement in the fitting procedure.

Figure 3 illustrates the distribution of inclination and eccentricity for a sub-sample of $\sim$ 500 one-planet systems. The asterisks mark the three planets not detected by AS, while the open boxes the 5 planets missed by DP, which include those not detected by AS. This is important evidence of consistency of the different criterions devised by the two Solvers. As expected, both detection methods failed on planets with large inclinations and high eccentricity, but more importantly these failed on largely the same objects.

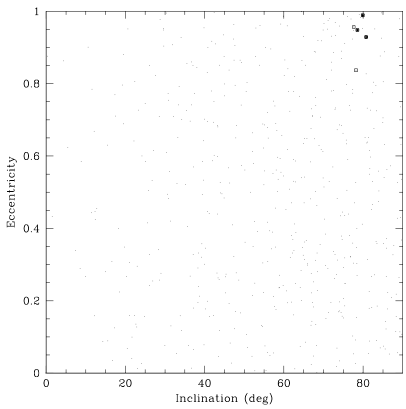

Figure 3. Inclination and eccentricity of a sample of 500 stars with one-planet. Asterisks mark the 3 planets not detected by Sozzetti; open boxes the 5 planets not detected by Pourbaix and Jancart, which include those not detected by Sozzetti.

Figure 4 presents the distributions of period and astrometric signature for the planets missed by the two Solvers: AS's missed planets are on the bottom panel and those undetected by DP are on the top panel. The details of the two distributions do have some minor although important differences; however, the overall impression is that the two distributions are remarkably similar. In practice, both Solvers show that it is possible to detect, again to a high degree of consistency, most of the planets with periods below 6 years and signatures above $\sim$ 20 μas, while maintaining the contamination of false planets to a very low level.

In conclusion, the performance of a straight χ^2 or $F2$ test is already extremely good; such tests, if properly applied, can yield candidates with the expected range of sensitivity and with a powerful discrimination against false positives.

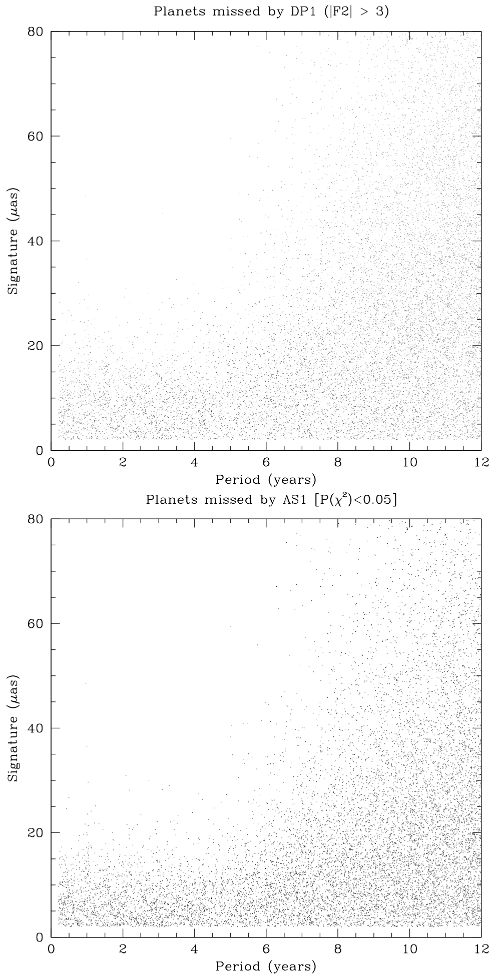

Figure 4. Distribution of period (in years) and signature (in μas) for the planets missed by Pourbaix (top panel) and Sozzetti (bottom panel). If more than one planet is present, the one with the largest signature is plotted. Generally, only planets with signature $\leq$ 20 μas or period longer than 6 years are missed.

2.3.2. The T2 test

Results for the T2 tests were obtained only recently and are presented here for the first time.

The Solvers run their respective pipelines (detection+orbital reconstruction) on the 50 000 simulated stars, each with one planet, without knowing anything about their orbital properties.

The Evaluator compared the derived orbital parameters to the simulated ones and his plots show remarkable agreement. In particular, Figure 5 shows how the derived periods compare to the true ones for the complete set of 50 000 solutions. AS results are on the top panel, while

noise (8 μas in the case of Gaia) was recognized as the main detection parameter in the extensive simulations of Lattanzi et al. (2000) and Sozzetti et al. (2002).

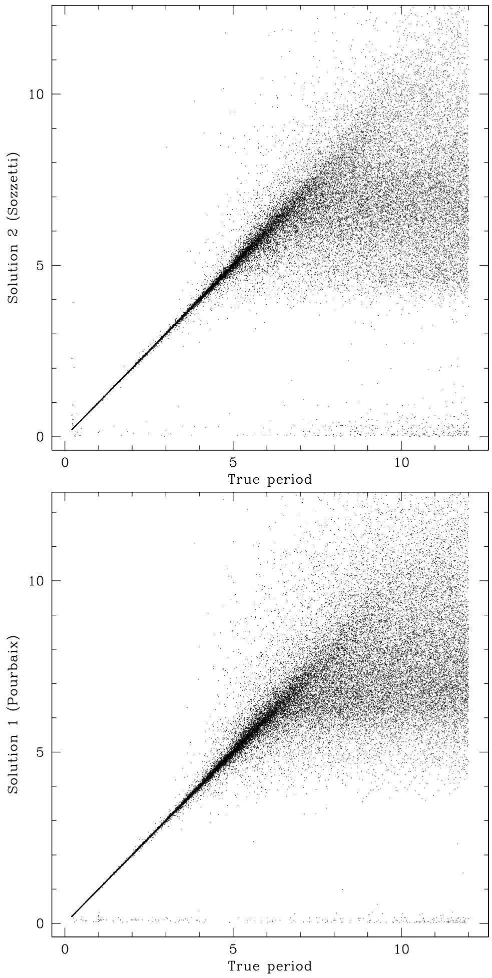

Figure 5. T2 results: simulated (true) vs derived periods (in years). The two panels show AS (top) and DP (bottom) findings.

DP periods were used in the bottom panel. The two panels testify again that the overall appearance of the two reconstructions is quite similar; the small but interesting features present are being investigated. The increasing difficulty of correctly estimating the periods beyond 6-yr is striking in both panels. Expectations from our earlier results were that periods up to approximately twice the mission duration ∼9 yr) should have been reliably recovered. However, this was when the scanning law was such that the average number of observations (epochs) available for orbit reconstruction was ≃80, two times what is provided by the current scanning law. Therefore, we believe that the 6-yr limit represent the new limit given the adopted scanning law.

On the other hand, we are investigating how we could discriminate between 'bad' (underestimated) and 'good' (still visible in Figure 5) periods beyond the ∼6-yr limit in an objective way through the correlations of the orbital solutions with quantities like the number of observation epochs (or ecliptic latitude), error estimates, and other relevant information that might be available during data reduction.

The scope of the T2 experiment was also to test for the first time the quality of the estimates of the statistical properties (errors and correlations) of the orbital solutions.

The Evaluator has compared the distribution of true errors of the parameters, i.e. $(adjusted - true)$, with the error estimates from each Solver and the visual appearance of the results is very positive. He finds that in the core, the actual errors have a narrower distribution than a Gaussian with the expected width; however, as may be expected, the tail (beyond 1.5 σ) seems higher than Gaussian. Figure 6 shows one of those plots, and in particular that for the relative error of the Thiele-Innes element B.

Eliminating planets with the apparent semi-major axis below ~ 400 μas (approximately 25% of the sample) the peak of the histogram becomes more Gaussian but the long tails remain. Excluding periods > 5 yr the distribution becomes much more similar to a Gaussian with a 2% of outliers (beyond 5 σ). This implies that the error on B is underestimated in the presence of long period planets and overestimated in the presence of low signal.

A full report on T2 results is in preparation.

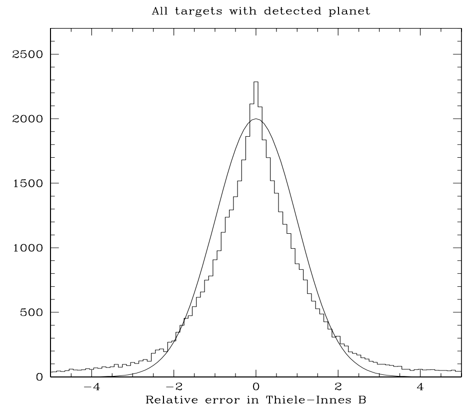

Figure 6. Relative error distribution of the Thiele-Innes parameter B for the 50 000 orbital solutions. The relative error is calculated as $(B_{adj} - B_{sim})/\sigma_{adj}$, where B_{sim}, B_{adj}, and σ_{adj} are the simulated (true), adjusted, and estimated error of the orbital element B, respectively.

2.4. Summary and Discussion

The results presented in the previous sections, although partially preliminary, are already providing new important insight, both technical and scientific, into the Gaia potential in discovering and measuring extra-solar planets through its high accuracy astrometric measurements.

From the technical side the results suggest that:

(i) We have two completely independent detection and orbital fitting and analysis packages, which achieve good performances and quite consistent results when run on the same simulated data. Moreover, both codes are already 'mission ready', i.e., they would be compliant with the operational phase as no *a priori* knowledge of the orbital elements is needed and a reliable estimation of the covariance matrix is provided along with the orbital solution;

(ii) from the mission point of view, the experimental configuration adopted appears even more realistic than it might initially seem as it is likely that the solution of the observation equations for the planet search will not explicitly contain additional attitude or instrumental unknowns;

(iii) the experiments done also provided the opportunity for first realistic evaluations of computing time per candidate system, thus allowing to extrapolate to the real case. We evaluate that the entire task of searching for planets in the Gaia data would only take several weeks, after taking into account the expected technical advancements of the computing hardware that would be in use at the time of the Gaia data reduction.

As for the more scientific related aspects, we can already highlight at least two points. One is the possibility discussed in Section 2.3.1 of building a list of very secure candidates by properly tuning the thresholds of the adopted detection criteria. The other aspect is related to Figures 4 and 5, which point to the existence of a clear 'selection function' which Gaia, through its intrinsic astrometric properties (timing of observing epochs, accuracy, etc), applies to the detected candidates thus determining those systems which will have their orbital data reliably recovered.

2.5. Future Work

The understanding of the technical specifications of the Gaia satellite and its astrometric instrument will develop further with time; therefore, some of the simplifications in our simulations will be progressively relaxed and more realistic error models (including zero point uncertainties, calibration errors, chromaticity effects, error propagation from the IGC solution) and a realistic error distribution for ψ, including possible bias and magnitude terms, adopted.

We also plan to add some more realism to our reference model of planetary systems by considering likely distributions of orbital parameters, and realistic values of planetary frequency. Also, we will include some degree of dynamical perturbations in representative cases, and certainly more realism in evaluating/simulating possible sources of astrometric 'noise' that might pollute/mimic the planetary signature. These will include binarity/multiplicity of the parent star, stellar spots, and the presence of stellar discs, which can manifest themselves as extra dynamical perturbation or as contamination by scattered light.

3. UPDATING THE IMPACT OF GAIA ON EXTRA-SOLAR PLANETARY SCIENCE

As the test campaign is still on-going we have only started looking at the results in the same way as our earlier investigations, i.e., by analyzing detection probabilities and quality of orbital solutions as a function of distance from the Sun and the intrinsic orbital properties (period, inclination, eccentricity, longitude of the ascending node). Preliminary indications are that most of our earlier conclusions remain valid with the noticeable exception of the reduced sensitivity to longer orbital periods caused by the adoption of the current scanning law. Nevertheless, with most of its potential intact, the Gaia contribution to the science case remains as strong as ever.

Gaia's main strength continues to be the ability to measure actual masses and orbital parameters for possibly thousands of extra-solar planetary systems. The Gaia data have the potential to: (1) significantly refine our understanding of the statistical properties of extra-solar planets; (2) help crucially test theoretical models of gas giant planet formation; (3) improve our comprehension of the role of dynamical interactions in the early as well as long-term evolution of planetary systems; (4) provide fundamental information to optimize the selection of targets for DARWIN/TPF

3.1. Statistical Properties of Extra-Solar Planets

With hundred of thousands of candidates of all spectral types the size of the sample of extra-solar planets detected and measured by Gaia will be a very significant contribution to the statistical investigations on orbital data. In particular, as a large fraction of the sample to 200 pc is F–G–K stars, Gaia will detect and reliably measure > 2000 Jupiter-mass planets around these stars in a range of periods which adds critically to the sample of systems harboring rocky planets in the Habitable Zone (Lattanzi et al. 2000, 2002).

3.2. Crucial Test of Theoretical Models of Giant Planet Formation

There are $\sim$ 1500 metal-poor stars known in the field, with $V < 13$. For all of these, Gaia will provide statistically firm results on the possibility of them to harbor giant planets on wide orbits, thus complementing the shorter-period RV surveys (Sozzetti et al. 2005).

Core accretion is a slow process ($\sim 10^6$–10^7 yr), while disc instability is capable of forming Jupiter-sized clumps in $\sim 10^3$ yr. Gaia will observe hundreds of optically visible pre-main sequence stars down to $V \sim 14$ in a dozen of nearby SFRs (< 200 pc), searching for giant planets with orbits in the 1 to <5 AU range, thus helping to discriminate between the two competing gas giant planet formation mechanisms.

3.3. Role of Dynamical Interactions in the Evolution of Planetary Systems

By measuring the mutual inclination distribution of systems of planets Gaia will decisively help to: (a) understand if the main responsible for eccentricity excitation is a nearby stellar companion, or planet-planet resonances during or post-migration, and confirm or rule out the possibility of e–i_{rel} correlations; (b) verify the long-term stability issue for such systems, and the possibility of formation and survival of terrestrial planets in the Habitable Zone of the parent star.

A sample of $\sim$15 000 solar-type stars is available for these investigations out to $\sim$60 pc!

3.4. Preparing the Stellar Data Base for DARWIN/TPF

Gaia will search for the presence (or absence) of Jupiter signposts around ALL stars within 25 pc from the Sun, including the large data base of M dwarfs.

This valuable knowledge will help complete the information coming from other techniques at the moment of the final selection of targets for DARWIN/TPF.

For the reasons above the Gaia sample remains a unique treasure for the future advancement of extra-solar planetary science.

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