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On the use of the Virtual Observatory to select calibrators for phase-referenced astrometry of exoplanet-host stars

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ABSTRACT

Phase-referenced interferometric astrometry offers the possibility to look for exoplanets around bright stars. Instruments like PRIMA (Phase-Referenced Imaging and Micro-arcsecond Astrometry) will measure the astrometric wobble of a candidate star due to an exoplanet relative to a close-by ‘calibrator’ star, located within the instrument’s observing field (1 arcmin in the PRIMA case). Stars with already known exoplanets will constitute the first targets for this technique, as it will provide a way to further specify the characteristics of the known exoplanets, such as the inclinations. The main requirement is to have a calibrator in the vicinity of the star. We provide here a list of calibrators for all stars with known exoplanets obtained using data mining and Virtual Observatory techniques. This list is available online and revised regularly. The calibrators are found from catalogues available at Centre de Données astronomiques de Strasbourg (CDS) using the SEARCHCAL software developed at Jean-Marie Mariotti Center (JMMC). In our test case, the calibrators are found within 1 arcmin angular distance for approximately 50 per cent of the stars tested, and often closer. They are all faint objects from the Two Micron All Sky Survey (2MASS) with *K* magnitudes between 13 and 15. A list of the most promising targets is also given.

Key words: techniques: interferometric – astronomical data bases: miscellaneous – astrometry – proper motions – planetary systems.

1 INTRODUCTION

Since the discovery of the first planet outside our Solar system in 1995 (Mayor & Queloz 1995), more than 500 exoplanets have been identified, and the list is growing continuously (see <http://exoplanet.eu>). Most of these planets have been discovered by the radial velocity transits methods.

The increasing accuracy of spectrometers makes it possible now to detect planets down to masses of a few Earth masses (Udry et al. 2007). However, no planetary system really similar to the Solar system has been discovered yet. The reason may be the observational bias implied by the discovery methods, which favour the detection of close-in planets. The detection of planets orbiting their host stars at ~ 10 au and further away is still beyond the current capabilities of these methods, because of a too weak radial velocity signal and a long orbital time basis.

Contrary to the other methods (radial velocity, transits), astrometry is sensitive to large orbits (see below), and favours the detection

of planets at large distance from their host star. To detect planets with long orbital periods, astrometry must therefore be a long-term technique. The longest period *single* planet found by radial velocity monitoring known so far is HD 190984 b, with a period of 13.4 yr (Santos et al. 2010). Typically, planets with periods greater than ~ 20 yr will be detected by astrometry only or by direct imaging. Data on one given star will be gathered for at least ~ 10 years to provide a reasonable sample of the orbit. Note, however, concerning radial velocity that finding long period planets around a given star is easier when shorter period planets are already known for that star. The distant companions are searched for in the residuals of the radial velocity signal. Using a Bayesian analysis, Gregory & Fischer (2010) managed to detect a 38 yr additional planet to 47 UMa. There is also convincing evidence for long period companions to some other stars with already known planets (Wright, Marcy & Fischer 2007). This is also a reason why we focus in the present work on stars with already known planets (see below).

Accuracy is also a difficulty for astrometric observations. Taking a Solar system at 50 pc, all the giant planets generate astrometric displacements of the Sun below 0.1 milliarcsec (mas). Measuring absolute astrometry to this accuracy is not easy, especially if we

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assume that the precision of the astrometric measurements needs to be typically one order of magnitude below the quoted level to ensure a good resolution of the orbit.

To detect these small astrometric signals from the ground requires relative astrometry, measurements with respect to a nearby, assumed single object. The reference object will be called a calibrator for the star under study. Phase-referenced astrometry is at the core of several planned instruments, e.g. GRAVITY and PRIMA (Phase-Referenced Imaging and Micro-arcsecond Astrometry). PRIMA (Delplancke 2008; Sahlmann et al. 2009) is an instrument currently under tests on the Very Large Telescope Interferometer (VLTI), Cerro Paranal in Chile. It is designed to perform narrow-angle astrometry in the K band with two 1.8 m diameter ‘AT’ telescopes as well as external fringe-tracking for phase-referenced aperture synthesis imaging with 8 m diameter ‘ur’ telescopes and instruments like the Astronomical Multi-BEam Recombiner (AMBER) (Petrov et al. 2007) and the MID-infrared Interferometric instrument (MIDI) (Leinert et al. 2003). The PRIMA facility will provide an infrastructure to carry out an astrometric search for extrasolar planets.

Of course, a star can be monitored astrometrically only if at least one valid calibrator is found next to it in the observing field (1 arcmin in the case of PRIMA). In addition, high-accuracy astrometric measurements will require the calibrator to be even closer (typically $\lesssim 10\text{--}20$ arcsec). Two observational strategies can then be proposed: either one performs observations blindly towards all possible targets to look first for very nearby stars usable as calibrators and then start the monitoring, or one looks first in catalogues for known calibrators. We use the second strategy here, which serves to select targets: only stars for which valid calibrator(s) have been found will be retained for astrometric monitoring. Given that chance proximity of unrelated stars is random, this method does not bias the sample. In this paper, we address its potential with the use of Virtual Observatory (VO) tools.

Exoplanet-host stars are prime targets for the interferometric current projects of astrographs. For example, many planets that have been found by the radial velocity technique are planned to be re-observed by PRIMA. This will first validate the method, and furthermore specify orbital parameters that are not constrained by the radial velocity technique, such as the inclination and the longitude of ascending node. The determination of the inclination of a planet detected by radial velocity is of prime importance because this new measurement makes it possible to determine the planet’s mass.

In addition, phase-referenced astrometry monitoring of stars that are already known to host exoplanets provides a means to probe the presence of more distant planets in these systems that would be difficult to detect with the radial velocity technique. Hence, the combination of both methods can provide complementary and valuable data to the understanding of the whole structure of extrasolar planetary systems [see recent results on specific systems by McArthur et al. (2010), Benedict et al. (2010) and Martioli et al. (2010)].

The purpose of this paper is to provide a set of calibrators for stars that are already known to host at least one exoplanet. We have used as a ‘template’ instrument the only one available at this time (PRIMA); however it will be possible to adjust the set for the peculiarities of other, future, instruments. The list is detailed in Table 4 (later) and has been established with the use of SEARCHCAL in its faint objects mode. SEARCHCAL is a software developed by the JMMC (Jean-Marie Mariotti Center, data reduction centre of the CNRS). It is designed to find suitable reference stars to calibrate long baseline interferometric observations of a scientific target. SEARCHCAL uses a web-based interface as a VO portal to build a dynamical list of stars for which astrometric and photometric

data are extracted from the data base at the Centre de Données astronomiques de Strasbourg (CDS) and the angular diameters computed using a dedicated surface-brightness versus colour-index relation. The first version of SEARCHCAL was dedicated to the search for bright calibrators ($K_{\text{mag}} \leq 5$; Bonneau et al. 2006). Following the expected rise of the limiting magnitude of new interferometric facilities, a new version adapted to the search for faint calibrators has recently been implemented (Bonneau, Delfosse & Mourard 2011). In this ‘faint objects’ version of SEARCHCAL, the Two Micron All Sky Survey (2MASS) and Deep European Near-Infrared Southern Sky Survey (DENIS) catalogues have been chosen to extract the infrared K , H , J and I magnitudes, and new surface-brightness versus colour-index relations are used to compute the angular diameters.

In our automated search, calibrators are not found for every star, but a significant fraction of them do exhibit calibrators. In Section 2, we detail how the astrometric measurements are used to extract information on exoplanet orbits. In particular, we point out all additional effects that may sometimes overcome the expected signal. In Section 3, we present the catalogue itself and its limitations. In Section 4, we discuss its future developments and present our conclusion.

2 CALIBRATORS AND EXOPLANET SEARCH

2.1 Fundamentals of the astrometric method

Consider a planet of mass m orbiting a star of mass M , with a semimajor axis a , an eccentricity e , an inclination i , a longitude of ascending node Ω and an argument of periastron ω with respect to a referential frame where the XOY plane corresponds to the plane of the sky and where the Z -axis points towards the observer. The distance r between the planet and the star is given by

$$r = \frac{a(1 - e^2)}{1 + e \cos v}, \quad (1)$$

where v is the true anomaly. Then, the displacement of the star with respect to the centre of mass of the system is, by the standard Keplerian formalism,

$$\delta x = -\frac{m r}{M} [\cos \Omega \cos(\omega + v) - \cos i \sin \Omega \sin(\omega + v)]; \quad (2)$$

$$\delta y = -\frac{m r}{M} [-\sin \Omega \sin(\omega + v) + \cos i \cos \Omega \cos(\omega + v)], \quad (3)$$

and where we have assumed $m \ll M$. Once this displacement is given in au, it just needs to be multiplied by the parallax π (expressed in arcsec) to get the corresponding angular displacement (in arcsec). Obviously, the size of the displacement is just proportional to a , so that the wider the orbit, the larger the signal.

If several planets are present, the total displacement of the star will be the sum of the individual displacements generated by the planets, assuming purely Keplerian orbits. The exact shape of the astrometric orbit of the star can therefore be rather complex depending on the various angular parameters (ω s, i s, etc.) that are often unknown. However, in the most favourable case where all the apsidal lines of all orbits are aligned, the *maximum* amplitude of the astrometric wobble (in arcsec) of the star can be computed as

$$A = \sum_i \frac{m_i}{M_*} \pi a_i (1 + e_i), \quad (4)$$

where the sum extends over the exoplanets known to the star, m_i is the mass of the i th planet, a_i its orbital semimajor axis (in au) and e_i its eccentricity. π is the stellar parallax (in arcsec). Note that this

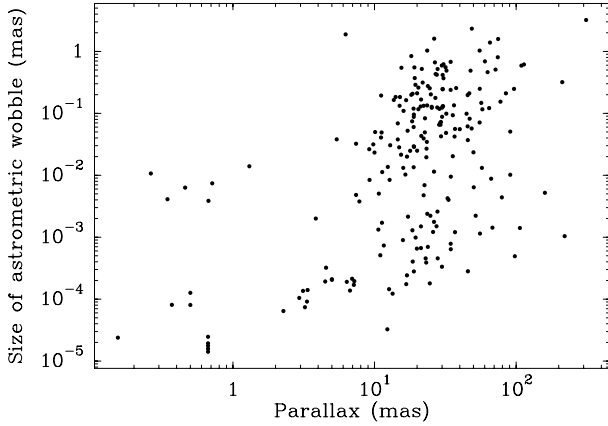


Figure 1. Approximate expected amplitude of the astrometric reflex motion of the known exoplanet-host stars, versus the parallax of the star.

is a fairly crude approximation as only $m_i \sin i$ is known for most stars with planets found using the radial velocity technique. We will nevertheless use this expression to estimate the expected amplitude of the astrometric motion for a given star.

Fig. 1 shows this expected amplitude for all stars with known exoplanets, as a function of their parallax. The amplitudes typically range from a few mas to less than 1 μ as. Note that with a very good accuracy of 10 μ as (such as expected for PRIMA), many known exoplanets will remain undetectable this way. The smallest amplitudes in Fig. 1 concern stars with close-in very short period exoplanets known as hot Jupiters. This perfectly illustrates the complementarity of the various techniques. The radial velocity technique is particularly sensitive to such planets while the astrometry technique is not, and conversely for large period orbits.

2.2 Specifications of calibrators to detect exoplanets with astrometry

For a science target (such as an exoplanet-host star), a calibrator is a faint object located close to it. This nearby object must be close enough to permit a simultaneous observation within the field of view of the phase referencing technique used (the maximum separation for the dual beam mode of PRIMA is 1 arcmin, for example). Several pieces of information are needed before a selected calibrator can be used as a reference for astrometric follow-up. The observations aim at finding a modulation of the relative position between the target and the calibrator (separation and PA) that can be ascribed to an astrometric wobble of the target caused by the presence of an exoplanet. But several other effects, often much stronger than the planetary wobble, can influence the relative position of the star and its calibrator. We may classify them into two subsets.

(i) The proper motion of the objects. Usually, the proper motion of the target is known, but not that of the calibrator. The host stars have typical proper motions of a few hundreds of mas yr^{-1} (Fig. 2). Most calibrators are faint objects with magnitudes in the K band ranging between 12 and 15 (see below). They are very probably distant background stars. Their proper motion is thus expected to be much less than that of the targets, at least by one order of magnitude. However, it remains still well above the amplitude of the reflex motion of the star due to its exoplanet(s).

(ii) The changes due to the motion of the Earth, i.e. the parallactic orbits of the stars. In most cases, as these are bright stars, the parallax of the target is known and listed in catalogues. The targets

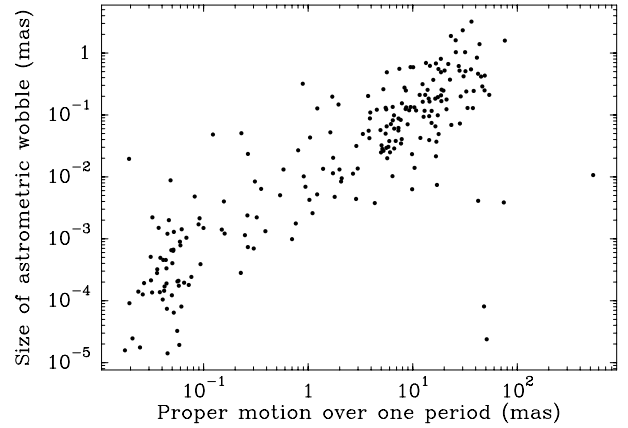


Figure 2. Same as Fig. 1, but as a function of the size of the proper motion displacement of the star over one orbital period of the planet. When several planets are known, the largest period is assumed.

have typical parallaxes of a few tens of mas, well above the expected reflex wobble to their exoplanets (Fig. 1). But the calibrators also have parallactic motions, which are in general unknown. As the target and the calibrator are located at very different distances from the Earth, they have different parallactic orbits in size (although identical in shape). But even if the parallactic motion of the calibrator is significantly smaller than that of the star, it may be comparable to the astrometric wobble of the star due to its exoplanet(s). As the parallax of the calibrator is most of the time unknown, it will have to be considered as an extra parameter to be fitted in the procedure in addition to the orbital parameters of the planet(s). Another possibility is to derive the parallax of the calibrator using an estimate of its absolute magnitude on the basis of its colours and spectral type (McArthur et al. 2010).

Both the proper motion and the parallax of the star appear in most cases well above the expected size of the astrometric orbit. An *astrometric model* describing these effects, such as described in McArthur et al. (2010), Benedict et al. (2010) and Martioli et al. (2010), is required. It is in particular necessary to take into account all the small effects contributing to the Earth motion (orbital eccentricity, planetary perturbations...) and to the barycentric motion of the Sun. A standard procedure is to use an accurate predictor for the motion of the planets (McArthur et al. 2010).

To achieve the required accuracy to detect exoplanets (10 μ as–1 mas), however, even fainter effects must be taken into account. We must, for instance, consider the real proper motion of the star in space. Once projected on to the sky, a constant velocity in space does not yield a strictly linear motion in (α, δ) . Consider a star with an instantaneous proper motion ($v_\alpha = \cos \delta \, d\alpha/dt$, $v_\delta = d\delta/dt$). If we assume that the real velocity of the star in space is a constant, then the motion of the star in (α, δ) is not strictly linear. After a time delay t , the departure from the strict linear motion can be expressed to lowest order as

$$\begin{aligned} \Delta\delta &= \left(\frac{v_r}{d} v_\delta + \frac{1}{2} \tan \delta v_\alpha^2 \right) t^2, \\ \Delta\alpha \cos \delta &= \left(\frac{v_r}{d} v_\alpha - \frac{1}{2} \tan \delta v_\delta^2 \right) t^2. \end{aligned} \quad (5)$$

Table 1 gives an estimate of the various error terms in astrometric motion expected for a star located at a distance of 50 pc (as this is a typical distance for exoplanet-hosting stars; see Fig. 1). We see that many of these errors are comparable to or even above the

Table 1. List of small additional terms in the proper/parallactic motion, estimated for a star located at 50 pc from the Earth.

Non-linear proper motion after 1 yr	:	0.1 μs
Non-linear proper motion after 30 yr	:	100 μs
Eccentricity of the Earth's orbit (period 1 yr)	:	300 μs
Barycentric motion of the Sun (period ~ 12 yr)	:	150 μs
Planetary perturbations on Earth after 1 yr	:	1 μs
Planetary perturbations on Earth after 30 yr	:	30 μs

expected astrometric signature of an exoplanet (see Figs 1 and 2 or Column 6 in Table 4). Some of these effects are periodic, such as the eccentricity of the Earth's orbit, and the motion of the centre of mass of the Solar system (mainly due to Jupiter, hence the 12 yr period). But some others are cumulative. If they are negligible over a small time-span, they appear significant over a longer time basis. One has to keep in mind that contrary to the radial velocity method, the detection of exoplanets using astrometry is more sensitive to wide (thus long period) orbits. We must consider the cumulative effects on the longest time basis possible, here 30 yr in Table 1.

In addition to these effects, the astrometric motion of the star with respect to a given calibrator will also be affected by the uncertainty we have on some of the parameters we use. The error on the proper motion of the target stars is typically $\sim 1 \text{ mas yr}^{-1}$. This also concerns their parallaxes. Note that these error bars are already above some of the errors listed in Table 1. Moreover, in most cases, the proper motion and the parallax of the calibrator are unknown. Even if we expect these parameters to be significantly smaller than those of the target star, they will probably contribute to the relative motion at a level comparable to the small effects of Table 1. We conclude that any attempt to detect exoplanets in a differential astrometric signal will result in an accurate determination of the unknown or poorly known parameters. In practice, a parametric fit of the astrometric signal will be needed to derive simultaneously the parallax and the proper motion of the target, of the calibrator, and the signature of the eventual exoplanet(s).

2.3 Calibrator selection

In our test-case (PRIMA-like), we will look for objects located closer to the target star than a 1 arcmin distance. In fact, the accuracy of the interferometric differential astrometric measurement is clearly increased if the angular separation between the target and the calibrator is smaller. This is related to the isopistonc angle, an interferometric parameter somewhat similar to the isoplanetary angle in adaptive optics (Launhardt 2009). Calibrators as close as possible to their targets will therefore be preferred. The angular separation between the calibrator and the target will be a critical parameter. This angular distance is also subject to change with time due to the proper motion of both objects. It is thus worth knowing whether a given calibrator observed today at a given distance to the target is expected to get closer or to move away from the target during the time-span of the monitoring.

To ensure the most accurate astrometric measurements, the calibrators need to be objects as stable as possible. SEARCHCAL returns variability and multiplicity flags associated with any object found. All calibrator candidates quoted as variable or multiple will be rejected.

It also turned out that a minimum angular distance between the calibrator and the science star needed to be fixed to retain calibrators, otherwise SEARCHCAL is bound to return the science star itself as a calibrator. To avoid this, we decided to reject all calibrators found closer than 1 arcsec from the science star afterwards. We

checked a posteriori that only the science stars were rejected by this requirement.

Finally, SEARCHCAL returns an estimate of the angular diameter of the calibrators. A surface-brightness versus colour-index relation is used to estimate the value of the angular diameter from the J , H , K magnitudes extracted from the 2MASS catalogue. For each star, the angular diameter θ_* is taken as the average of the values obtained with the different colour indexes θ_{JH} , θ_{JK} and θ_{HK} . The uncertainty on the estimated angular diameter is better than 17 per cent which is yet acceptable for faint stars (typically $K_{\text{mag}} > 7$) with very small angular diameter (typically $\lesssim 0.1 \mu\text{s}$; for more details see Bonneau et al. 2011). For each star, the consistency of the photometric measurements is tested by comparing the computed diameters at different colour indexes. If $|\theta_{\text{CI}} - \theta_*| > 0.2\theta_*$ for at least one colour index CI, the star is flagged as a possible bad calibrator and rejected from the list of potential calibrators. The main rejection causes of a star are:

- (i) large errors on the photometric measurements;
- (ii) the star is at the limit of validity for the magnitude versus colour-index relation giving a large uncertainty on the angular diameter;
- (iii) the star can be an intrinsic variable object or is an unresolved double system;
- (iv) the star has incoherent photometric diameters due to the bias of the photometry by a strong reddening due to extinction.

In the last case, the position of the photocentre of the source can be variable at a scale of a few $0.1 \mu\text{s}$ and the star cannot be used as an astrometric calibrator for PRIMA observations.

However, there are reasons not to reject all these objects. Most calibrators found are indeed faint stars at small angular distances to the science targets but are located much further away. It is not surprising that the photometry of such objects is not very well constrained. Some of them could, however, act as valuable calibrators (i.e. a fixed astrometric reference) as they are mainly point sources. We thus decided to publish *online*, in addition to the main list of Table 4, a complementary list of those potential calibrators with non-consistent diameter, but with a mean value well beyond the limit of observability with a 150 m baseline in the K band.

3 THE CATALOGUE

3.1 Description

Table 4 (see full version online as Supporting Information to this article) lists the catalogue of calibrators *with consistent diameters* found with SEARCHCAL within 1 arcmin around all exoplanet host stars known on 2010 December 6. Both lists (with consistent and with inconsistent diameters) can be found at <http://www.jmmc.fr/calex> and they are revised at regular intervals. The whole process, including (i) retrieving the list of stars from the Extrasolar Planets Encyclopaedia (<http://exoplanet.eu>), (ii) interrogating the CDS data base to get accurate astrometric and photometric data, (iii) using SEARCHCAL to search for calibrators and make a selection, and (iv) generating the online table, has been implemented as an automatic procedure so that it can be easily updated. It takes approximately 1 h to run on a standard workstation.

414 stars taken from the Extrasolar Planets Encyclopaedia (<http://exoplanet.eu>) have been analysed for a grand total of 1089 calibrators, including 582 accepted with consistent diameters. The average number of calibrators per analysed star is 1.406 if we only consider the accepted calibrators, and jumps up to 2.630 if we

consider all calibrators. This is enough for validating our approach, as the fraction of stars with calibrators is significant. Note that despite this significant fraction, 211 stars have no calibrator found if we restrict ourselves to accepted calibrators (158 if we retain all calibrators). The maximum number of calibrators found for a given star is 25.

The catalogue (Table 4) is organized as follows. For each star, we first list its name (Column 1), its coordinates (α , δ) (Columns 3 and 4), its proper motion (Columns 5 and 6), its parallax (Column 7), the expected size of its astrometric orbit (Column 8), using equation (4) on the basis of the planets known so far, and the K magnitude (Column 9). Note that not all these data are available for all stars. Proper motion and parallax information are missing in some cases. For those stars, the search for exoplanets with PRIMA observations will be less easy but not impossible, as finally the proper motion will need to be retrofitted in the signal. For each star the calibrators are listed in the lines following the star information in increasing angular distance to the target star. The stars themselves are listed in increasing right ascension order. For each calibrator, the following data are given: name (Column 2), coordinates (Columns 3 and 4), proper motion (if available, Columns 5 and 6), K magnitude (Column 9), angular distance to the target in 2000.0 (Column 10) and in 2020.0 (Column 11), and the minimal angular distance attained over time, assuming linear proper motions (and neglecting parallax effects; Column 12). The last two data are calculated on the basis of the proper motions of the star and calibrator. When no proper motion is given for the calibrator, zero is assumed. For stars with no proper motion information, these data cannot be calculated. Only the distance in 2000.0 is given.

Information about the relative motion of the calibrator with respect to the star is interesting because it could help the choice of a calibrator when several are identified. As the observations to detect planets will be conducted over a long period (tens of years), choosing a calibrator that is expected to get closer to the target during this time span should be preferred with respect to another one that gets further away.

All calibrators found are objects from the 2MASS catalogue. They are typically faint object with $K \simeq 14$, probably distant red giants. Stars with no calibrator found are not listed here. Several stars in the list exhibit theoretical astrometric motions close to 1 mas (see Table 3). These stars are therefore very good candidates for the first targets to be monitored with PRIMA.

3.2 Discussion

In Fig. 3, we have placed all the calibrators we found in a $(\Delta\alpha \cos \alpha, \Delta\delta)$ plane with respect to their reference stars, behaving as if they were all located close to the same star, by convention put at the centre. Figs 4 and 5 show some statistics on the calibrators found. Fig. 4 shows a histogram of the number of calibrators found per science star while Fig. 5 shows a histogram of the number of calibrators as a function of their distance to the science target. The number of calibrators increases with the distance to the star, but if the density of calibrators was constant, we should have a strict proportionality, which is not the case here. There are significantly fewer calibrators found closer than ~ 10 arcsec to the science stars. This also shows up in Fig. 3. This is arguably due to the lack of completeness of the catalogues so close to bright stars. The brighter the star, the stronger the effect. Actually, the brightest stars ($K \lesssim 4$) in the exoplanet-host stars list (ν Andromedae, ϵ Eridani, HD 62509. . .) do not appear in Table 4, because no calibrator was found within 1 arcmin of them, due to their brightness.

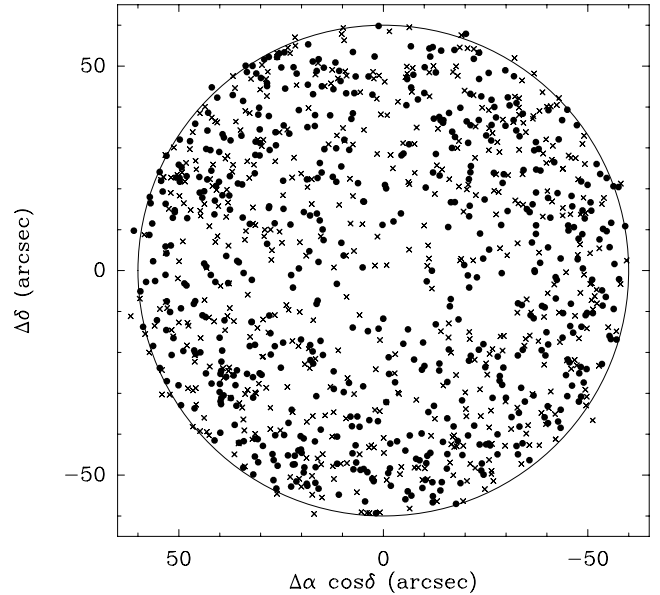


Figure 3. Relative position on the sky of all calibrators found in Table 4 with respect to their reference stars, as if all the stars had been put at the centre of the chart. The outer circle sketches the 1 arcmin radius field of PRIMA. The black dots indicate calibrators returned by SEARCHCAL with consistent diameter determinations and the crosses those returned with bad diameter flag.

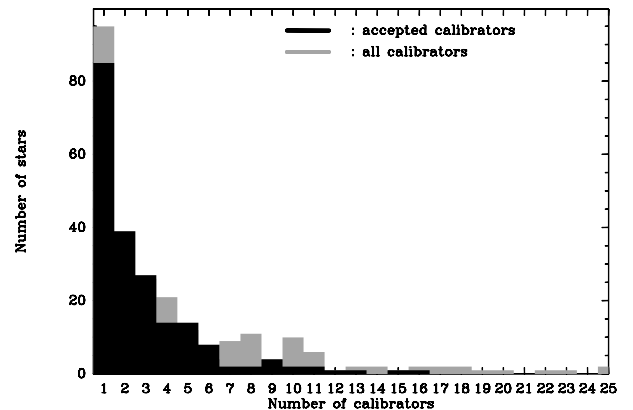


Figure 4. Histogram of the number of stars as a function of the number of calibrators found for each star. The black bars correspond to accepted calibrators, while the grey bars stand for all calibrators. Note that the stars with no calibrator found are not shown in this plot.

For calibrators the closest is the best, because instruments like dual-beam PRIMA are expected to gain accuracy if the optical path difference between the two beams is minimal. According to Launhardt (2009), the best angular resolution of PRIMA ($\lesssim 20 \mu\text{as}$) will be only attained with calibrators within $\lesssim 10$ – 20 arcsec from the science star. Even if there are fewer calibrators within this radius, many are still found. A list of all calibrators within the 20 arcsec limit to their reference star is given in Table 2. This shows that our approach can help to define good science targets for monitoring with dual-beam phase-referenced astrometric instruments, in particular for PRIMA.

Fig. 6 gives an indication of the nature of the calibrators. It shows a histogram of the number of calibrators found as a function of their Galactic latitude. For comparison purposes, the same plot for the science stars is superimposed. The distribution for the science

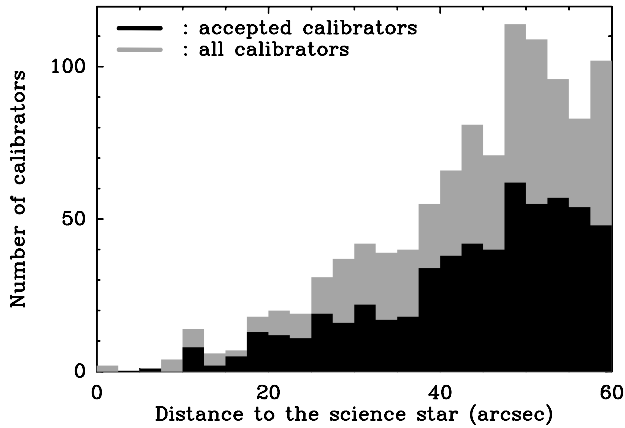


Figure 5. Histogram of the number of calibrators found as a function of their distance to the science stars. Again, the black bars correspond to accepted calibrators, while the grey bars stand for all calibrators.

Table 2. Shortlist (out of Table 4) of all calibrators closer than 20 arcsec to their reference star.

Name of star	Name of calibrator	K magnitude of calibrator	Distance to the star (arcmin)
OGLE-TR-211	2M10401272–6227201	14.358	0.19191
OGLE-TR-113	2M10522683–6126529	14.572	0.30465
Lupus-TR-3	2M15301948–4258460	13.712	0.16895
Lupus-TR-3	2M15301690–4258431	14.265	0.32093
HAT-P-1	2M22574592+3840272	8.405	0.18199
CoRoT-1	2M06481918–0306192	14.611	0.18701
NGC 4349 No 127	2M12240798–6152054	11.641	0.19667
NGC 4349 No 127	2M12240750–6152305	13.826	0.20375
NGC 4349 No 127	2M12240947–6152269	12.258	0.26266
OGLE-TR-132	2M10503527–6157410	14.467	0.29124
OGLE2-TR-L9	2M11075337–6108335	11.555	0.30476
HAT-P-7	2M19285944+4757551	13.945	0.23690
HD 16760	2M02422094+3837212	7.762	0.24386
CoRoT-5	2M06450613+0048404	14.087	0.25948
CoRoT-7	2M06434998–0103329	13.34	0.26352
HD 178911 B	2M19090438+3436011	5.212	0.26707
WASP 2	2M20305447+0626033	14.525	0.29383
WASP 3	2M18343025+3539340	11.062	0.29856
CoRoT-3	2M19281435+0007111	13.976	0.29514
HD 143361	2M16015177–4426151	13.239	0.29680
TrES-3	2M17520839+3732378	14.423	0.30326
XO-4	2M07213107+5815559	14.89	0.30677
NGC 2423 3	2M07370889–1354061	10.433	0.30892
CoRoT-2	2M19270544+0123119	13.436	0.31778

stars is not very peaked and is actually compatible with a uniform distribution in the celestial sphere ($\propto \cos \lambda_g$). Actually most targets are stars from the solar neighbourhood. This remark does not apply to calibrators. The distribution is strongly peaked around 0, showing that most calibrators are located within the Galactic plane. As expected most calibrators are distant Galactic objects, typically red giant. As a consequence science stars with low Galactic latitude potentially have more calibrators.

The best candidate stars in our list will be not only those that have calibrators very close to them, but also those with the largest expected size of astrometric orbit. Figs 1 and 2 show that many stars have expected astrometric wobbles well above the resolution of PRIMA (based on the present-day known exoplanets). These stars

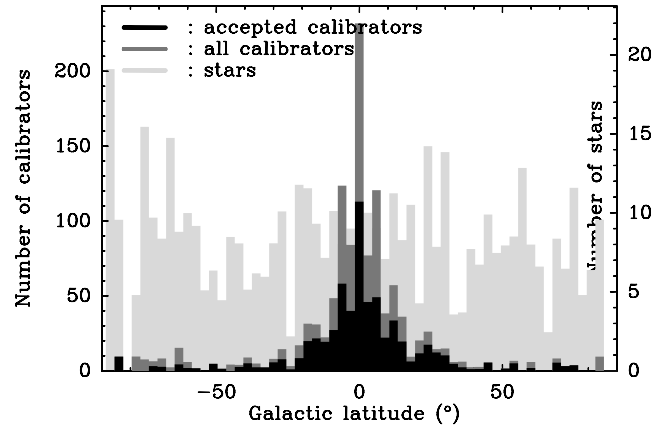


Figure 6. Histogram of the number of calibrators found as a function of their Galactic latitude, with the same conventions as for Figs 4 and 5. In addition, the same histogram, but for the science stars, is superimposed in light grey for the purpose of comparison.

Table 3. Shortlist (out of Table 4) of the potentially most interesting candidates for exoplanet search with astrometry: stars with calibrators *and* large expected astrometric motion (>0.4 mas).

Name	Size of astrometric orbit (mas)	Number of calibrators (accepted/total)	Distance of the closest calibrator (accepted/total) (arcmin)
HD 169830	0.421	4/8	0.802/0.657
HD 43848	4.16	1/3	0.617/0.617
HD 74156	0.544	1/1	0.719/0.719
VB 10	9.59	6/14	0.459/0.272
HD 142022 A	0.520	3/5	0.342/0.342
HD 33564	0.488	1/1	0.426/0.426
HD 111232	0.679	2/8	0.562/0.490
HD 131664	1.48	3/4	0.645/0.478
HD 183263	0.432	5/11	0.575/0.550
HD 141937	0.593	2/3	0.769/0.769
HD 30177	0.841	1/2	0.775/0.775
HD 50554	0.490	2/3	0.786/0.786
HD 168443	1.61	2/7	0.847/0.797
HD 38529 ^a	1.03	1/1	0.873/0.873
HD 190360	0.463	2/3	0.457/0.457
GJ 317	0.590	0/2	–/0.674
HD 222582	0.410	0/1	–/0.707
ChaHa8	1.88	0/1	–/0.496
GJ 849	0.616	0/1	–/0.939

^a A mass for HD 38529 c has already been established astrometrically (Benedict et al. 2010).

are among the best candidates for phase-referenced astrometry of planet-hosting stars. Table 3 gives a shortlist of the most promising candidates from Table 4 according to this criterion, i.e. stars with large astrometric reflex orbits for which calibrators have been found.

Finally, another difficulty can arise from the brightness of the calibrators. All of them have K magnitudes less than 15. This is clearly not a physical limit (fainter calibrators may exist), but a limitation due to the depth of the 2MASS catalogue. Moreover, most calibrators have K magnitudes between 13 and 15. This shows that fainter potential calibrators must be very numerous. However, a calibrator must not be too faint to be used as a reference object for astrometric monitoring of a science target:

Table 4. List of *accepted* calibrators found by SEARCHCAL for all exoplanet-host stars on 2010 December 6. This is a sample of the full table, which is available with the online version of the paper (see Supporting Information).

1	2	3	4	5	6	7	8	9	10	11	12
Star name	Calibrators	Right ascension (h min s)	Declination (° ' ")	Proper motion (α) (mas yr ⁻¹)	Proper motion (δ) (mas yr ⁻¹)	Parallax (mas)	Size of astrometric orbit (mas)	K mag	Distance in 2000.0 (arcmin)	Distance in 2020.0 (arcmin)	Minimal distance
WASP-1	2M00204133+3159461	00 20 40.077	+31 59 23.79	-4.8	-5.6			10.276	0.46309	0.46137	0.41164 in 3125.0543
	2M00203762+3158478	00 20 41.342	+31 59 46.44	-16	-4			13.879	0.79308	0.79432	0.55484 in -4519.3359
		00 20 37.613	+31 58 47.99	-10	-6			12.705			
HAT-P-16		00 38 17.5616	+42 27 47.249	-21.70	-4.10		6.0×10^{-4}	9.553			
	2M00381567+4227456	00 38 15.694	+42 27 46.08	6	-4			11.922	0.34499	0.33577	0.01824 in 2746.2171
	2M00381608+4228037	00 38 16.069	+42 28 03.96	-26	-2			11.218	0.39160	0.39310	0.12946 in -2633.8264
	2M00381833+4228169	00 38 18.315	+42 28 16.77	12	-10			13.147	0.51126	0.51255	0.50861 in 1908.7748
	2M00381641+4228155	00 38 16.401	+42 28 15.77	0	0			14.138	0.52132	0.51964	0.50683 in 2331.6655
	2M00381705+4228273	00 38 17.053	+42 28 27.69	0	0			14.614	0.68051	0.68091	0.67971 in 1910.4359
	2M00381359+4227365	00 38 13.590	+42 27 36.83	0	0			11.278	0.75278	0.74542	0.03464 in 4043.0579
	2M00382067+4228286	00 38 20.661	+42 28 28.73	4	-10			11.844	0.89706	0.90103	0.80172 in 1084.2885
2M00382207+4228096	00 38 22.065	+42 28 09.91	0	0			14.178	0.91239	0.91955	0.21692 in -407.8125	
HIP 5158	2M01060512-2227337	01 06 02.0482	-22 27 11.350	201.83	-107.22	22.32	5.2×10^{-2}	12.237	0.80395	0.72801	0.18664 in 2199.7361
HD 6718		01 06 05.134	-22 27 33.64	-26	-50			6.876			
	2M01074594-0814194	01 07 48.6625	-08 14 01.341	191.71	18.75	18.18	0.10	14.221	0.73303	0.79425	0.22982 in 1783.1840
HD 7924		01 07 45.953	-08 14 19.13	0	0			5.159			
	2M01215485+7641550	01 21 59.1153	+76 42 37.024	-34.12	-34.45	59.46	1.3×10^{-4}	14.626	0.73927	0.72472	0.31878 in 2825.3900
WASP-33	2M01215720+7643317	01 21 57.161	+76 43 31.87	0	0			11.918	0.92097	0.93107	0.72305 in 1294.1142
		02 26 51.0590	+37 33 01.737	-0.31	-8.82	8.61		7.468			
30 Ari B	2M02265167+3732133	02 26 51.675	+37 32 13.16	-7.5	-8.48			9.397	0.81877	0.81830	0.80295 in 3335.3631
		02 36 57.7405	+24 38 53.027	150.58	-12.55	25.36	0.27	5.822	0.63449	0.63027	0.16665 in 4794.1233
HD 16175	2M02370051+2438500	02 37 00.524	+24 38 49.99	137.66	-14.98			5.479			
		02 37 01.9110	+42 03 45.479	-38.74	-39.91	16.71	0.17	5.853	0.68880	0.69104	0.68476 in 1919.7107
HD 16760	2M02365952+4204174	02 36 59.543	+42 04 17.30	0	0			12.265	0.89443	0.87611	0.39413 in 2784.8653
	2M02370060+4202533	02 37 00.628	+42 02 53.75	2	6			14.335			
		02 42 21.3139	+38 37 07.204	82.84	-110.65	19.93	0.37	7.033	0.24377	0.24589	0.11026 in 175.5698
	2M02422094+3837212	02 42 20.946	+38 37 21.18	77.87	-105.51			7.762	0.65303	0.68484	0.48368 in 1809.5511
HD 17092	2M02422198+3837457	02 42 21.950	+38 37 45.67	0	0			14.673	0.98523	0.93929	0.07354 in 2426.4751
	2M02422399+3836168	02 42 24.027	+38 36 17.37	0	0			12.317			
	2M02462359+4939407	02 46 22.1153	+49 39 11.063	37.40	-13.80		2.6×10^{-2}	4.807	0.55035	0.54921	0.54769 in 2081.3526
		02 46 23.600	+49 39 40.77					10.498			

Sahlmann et al. (2009) estimate the theoretical K magnitude limit for effective fringe tracking with the Auxiliary Telescopes (ATs) at VLTI to be 10.7 (this being due to the intrinsic limitations of the fringe sensor unit of PRIMA). In Table 4, only 26 calibrators are below this limit. This seems to constitute a strong limitation to the number of exoplanet-host stars that could be monitored with PRIMA.

4 FUTURE DEVELOPMENTS AND CONCLUSION

A natural development of the catalogue is its extension. First, the list of exoplanet-host stars is growing continuously, so our catalogue is updated regularly. Also, the list of faint object catalogues available at CDS will evolve, so that even for a given star, the set of calibrators may change. Finally, SEARCHCAL itself is subject to improvement, so that objects with initially inconsistent diameters could be re-introduced in the table.

Another natural development will be the introduction of new interactive function. At present, the catalogue is a fixed HTML page. We first plan to add other parameters of interest to the table, such as photometry, mean diameters and flags returned by SEARCHCAL. In addition to these data, we plan to allow the table to be reorganized online upon request. At present the table (see below) is listed in ascending distance to the star of the closest calibrator. We will add the possibility for the table to be sorted upon request by ascending/descending order of various criteria, such as the size of the astrometric orbit, magnitudes, etc. All these improvements will be implemented in the future.

The present list of calibrators probes the use of catalogues as a tool for preparing any phase-referenced differential astrometry observations of exoplanet-hosting stars, with PRIMA as a practical example. Our study shows the possibility offered by current VO techniques, noticeably by the data base interoperability they permit, to implement an automated search for the best candidates to look for planets with phase-referenced differential astrometry. We also point out that using known figures for the PRIMA instrument, it is the K magnitude limit for fringe tracking with PRIMA that may present the main limitation to the number of exoplanet-hosting stars this instrument could monitor. The present work can be also viewed as a potential tool for future astrometric instruments (*GAIA*, ...). In fact, *GAIA* will provide accurate *absolute* astrometric data not only for most of these stars, but also for the calibrators. This will help to refine the differential astrometry between both objects and to find smaller planets. We also point out that the way we designed the automated procedure to generate the table makes it possible to handle much larger sets of targets. It takes approximately a 1 h run to generate the table with a set of ~ 500 stars. The list of exoplanet-host stars is growing rapidly. Instruments like *Kepler* are expected to provide many more candidates. We can therefore reasonably expect the list of potential targets to reach several thousands within the next decade. It will only take less than one day to generate the calibrator table from this extended list of targets.

Finally, the method used here is not restricted to find calibrators for exoplanet-host stars listed in the exoplanet data base. It can be used to identify various types of targets which could be imaged using the phase-referenced imaging principle, e.g. T Tauri stars, X binaries or active galactic nuclei. In this context the implementation of automatic sorting such as described above will be useful for potential observers. It will provide a tool to select the most appropriate targets among a large sample for which a systematic search on the sky for calibrators will not be realistic.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 4. List of *accepted* calibrators found by SEARCHCAL for all exoplanet-host stars on 2010 December 6.

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