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Choosing Suitable Target, Reference and Calibration Stars for the PRIMA Astrometric Planet Search

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Abstract. ESO's PRIMA (Phase-Referenced Imaging and Micro-arcsecond Astrometry) facility at the VLT Interferometer on Cerro Paranal in Chile is expected to be fully operational in only a few years from now. With PRIMA/VLTI, it will then be possible to perform relative astrometry with an accuracy of the order of 10 microarcseconds over angles of about 10 arcseconds. The main science driver for this astrometric capability is a systematic search for extrasolar planets around nearby stars. Target stars as well as reference and calibration stars for this astrometric planet search have to be very carefully chosen in order to make the measurements robust and effective. Various aspects of this search for suitable target, reference and calibration stars are discussed.

1. Introduction

ESO's PRIMA (Phase-Referenced Imaging and Micro-Arcsecond Astrometry) facility is expected to be fully operational by mid 2007 on Cerro Paranal in Chile. Using two of the 1.8m Auxiliary Telescopes, it will then in principle be possible to achieve $10\,\mu$as precision relative astrometry via phase referencing. The main purpose of PRIMA in combination with the Auxiliary Telescopes is an astrometric survey for extrasolar planets, which is complementary to a radial velocity survey since astrometry, in contrast to radial velocities, is more sensitive to planets in wider orbits. Furthermore, astrometry allows to determine all orbital parameters, so that precise masses as well as the orientation of the orbit in space can be derived. For more details, see Quirrenbach (1995).

The PRIMA instrument consists of four subsystems: a star separator, to observe two stars per telescope with two telescopes simultaneously, a fringe tracker, internal metrology and differential delay lines to measure the phase delay between the two stars with high precision, which gives the projected angular separation between the two stars onto the baseline. A consortium has been formed by the Geneva Observatory, MPIA Heidelberg and the Sterrewacht Leiden which is building the differential delay lines (see the contribution by Launhardt et al. in this volume) and also developing the software that is necessary to turn the raw outputs of the fringe sensor units into precise astrometric measurements (see de Jong et al. 2004), so that observations taken over many years can be compared and interpreted in a common reference system.

However, in order to ensure the success of an astrometric planet search program with PRIMA, additional preparations are necessary. Target stars have to be selected which maximize the scientific return of the observations; reference stars should be chosen that really provide a stable point of reference, and calibration stars that ensure that the instrument is properly calibrated. Each of these selections of stars has its own requirements that have to be taken into account, and the strategies to identify appropriate target, reference and calibration stars will be discussed in detail in the following. Many of the results are also applicable to other projects aiming at precise astrometry, like e.g. the Space Interferometry Mission (SIM, see contribution by Unwin et al. in this volume).

2. Target Stars

2.1. Anticipated Stellar Types

It is expected that the target stars for PRIMA will be primarily main-sequence stars, as appropriate for planet searches. The highest sensitivity for lowest mass planets is reached for the lowest mass primary stars, and for the closest distances, which both favors main-sequence M stars as target stars. However, one may not want to focus on just one class of objects, but rather include stars of different ages and masses in the target list in order to examine the frequencies and properties of planets as a function of stellar characteristics. This is a unique capability of the astrometric technique; in contrast, the radial velocity technique is only applicable to late-type main-sequence stars and giants. Additional targets will be composed of the class of planets that have been detected with radial velocities, where PRIMA will be able to determine the missing inclination and thus the true masses of the substellar objects rather than lower limits. Another class of promising targets might be visual binaries, where both components can serve as target and reference star at the same time (provided they are both bright enough, roughly brighter than 12 mag in the K band for target stars which will also serve as a phase reference for the fainter component, which can be as faint as 16 mag in K). However, if a signal is detected, another reference star is needed to determine around which of the components the putative planet orbits.

2.2. Requirements for Target Stars

The photocenter of a suitable target star should not move unpredictably by more than a few microarcseconds. Binary stars are in principle acceptable, as long as the period is either very large and the orbital motion over the time span covered by the PRIMA observations can be approximated by a straight line or a low-order polynomial fit, or otherwise it should be of the order of a few years so that the orbit can be precisely determined from PRIMA observations, simultaneously with a fit for a substellar companion. However, in both cases more PRIMA observations might be required to get accurate planet parameters, since the number of unknowns in the fit is somewhat larger. We are currently conducting simulations in order to assess the accuracy of planet parameters in the presence of a binary orbit (either target or reference star), as well as

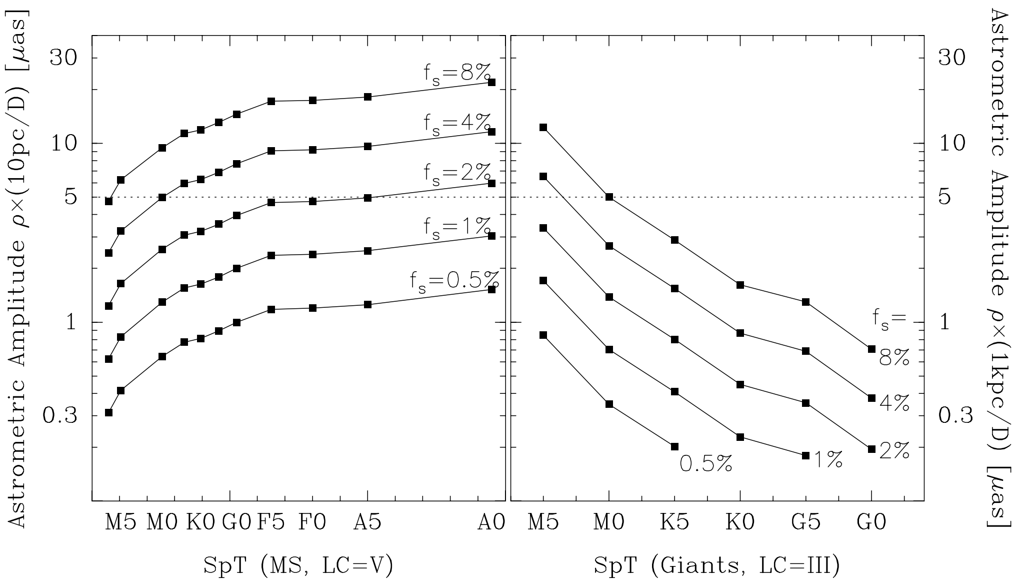

Figure 1. Astrometric amplitude at K-band due to rotational modulation by starspots for main-sequence stars (luminosity class V) at $d = 10\,\mathrm{pc}$ and for giant stars (luminosity class III) at $d = 1\,\mathrm{kpc}$ for various spot filling factors f_{s} (normalized to the stellar hemisphere) as a function of spectral type. The worst case of one single big spot at the stellar equator has been assumed. Mean stellar parameters (T_{eff}, ΔT_{spot}, R_*, limb-darkening coefficients) used for the calculations were compiled from the literature.

the required number, spacing and accuracy of PRIMA observations for various planet parameters.

2.3. Photometric Variability

Photocenter shifts associated with photometric variability might present an obstacle to microarcsecond astrometry in a few cases. The largest contribution to photometric variability is expected to be caused by starspots. Fig. 1 shows the expected astrometric amplitude ρ in the K band at a reference distance of 10 pc for main-sequence stars and 1 kpc for giant stars caused by starspots, assuming typical values for all stellar parameters and spot temperatures. As can be seen, for a G0 V star at a distance of 10 pc, a 2% spot filling factor would already cause a photocenter movement of about $3\,\mu$as, modulated with the rotation period of the star. The corresponding difference in photometric brightness is less than 2%, which is about the photometric precision of the Hipparcos Catalogue. However, the tolerable amount of photometric variability depends on the angular diameter of the star to be measured; it should be smaller (in percent) than twice the fraction of the measurement accuracy with respect to the angular diameter. For example, if the best photometry that we have for our target stars is 2%, and we want to do astrometry with a precision of $10\,\mu$as, a conservative estimate to limit photocenter displacements caused by photometric variability to less than $10\,\mu$as would be to require a star of radius $0.5\,R_{\odot}$ to be located at a distance of at least 5 pc, so that its angular diameter becomes less than 1 mas.

For the most nearby stars, closer than 5 pc, it might not be possible to ensure that photocenter shifts caused be starspots will be less than 10 μas, because the required photometric precision would be too demanding.

Photocenter changes caused by pulsations or granulation of the stars are much less problematic. While pulsations in a radially pulsating star should not change the photocenter, non-radial pulsations lead to local temperature and radius variations and thus could also give rise to photometric variations, which eventually will lead to a displacement of the photocenter. Townsend (1997) tried to predict typical photometric variability for a star undergoing non-radial pulsations; in the models he investigated, the photometric variations were never larger than 2%. If the angular diameter is not too large, as discussed above, this should not lead to any measurable photocenter shifts with PRIMA. Similarly, granulation should not pose any problems for the types of target stars considered for PRIMA, although it could become a problem for nearby giant stars with GAIA (Svensson & Ludwig 2005).

3. Reference Stars

3.1. Requirements for Reference Stars

Reference stars in the context of the PRIMA Astrometric Planet Search are astrometrically stable stars located in a narrow field with radius 10–30$''$ around the target stars against which the relative positions of the targets are measured. The narrow field requirement (imposed by atmospheric motions) will usually mean that the K band brightness of the reference star is much less than that of the target star, typically between 15 and 16 mag for the reference star, while the target star is required to be brighter than about 12 mag (both in K). The photocenter of a suitable reference should not change unpredictably by more than a few microarcseconds, very similar to the requirements imposed on the target stars themselves. Note however that the distances of typical reference stars are much larger than the target star distances, so that many of the issues with target stars (like photometric variability) are not an issue for the reference stars (cf. Fig. 1). However, since much less is known a priori about a faint and largely anonymous reference star, it is also more difficult to asses whether the star e.g. is a multiple star, or whether a planet might be orbiting around it.

Unwanted sensitivity towards planets around reference stars can be greatly reduced by placing the reference star at a minimum distance for a given mass, so that a certain reference planet will not affect the PRIMA measurements. For most stars it will not be known whether they are main-sequence stars or giants, so a conservative approach would be to assume a main-sequence star for the calculation of the photometric parallax for a star of given $V{-}K$ color. E.g., if a K5 star is fainter than about 13 mag in K, it will not be sensitive to a planet with a mass of 1 $M_{\rm Jup}$ irrespective of its evolutionary status (see Frink et al. 2004 for a figure showing the limiting magnitude as a function of spectral type). However, M stars later than about M3 can only be accepted as reference stars if they are giants (as a dwarf, they would be too close and prone to planets). Fortunately, M dwarfs and M giants can be distinguished in an infrared color-color diagram (see e.g. the 2MASS documentation).

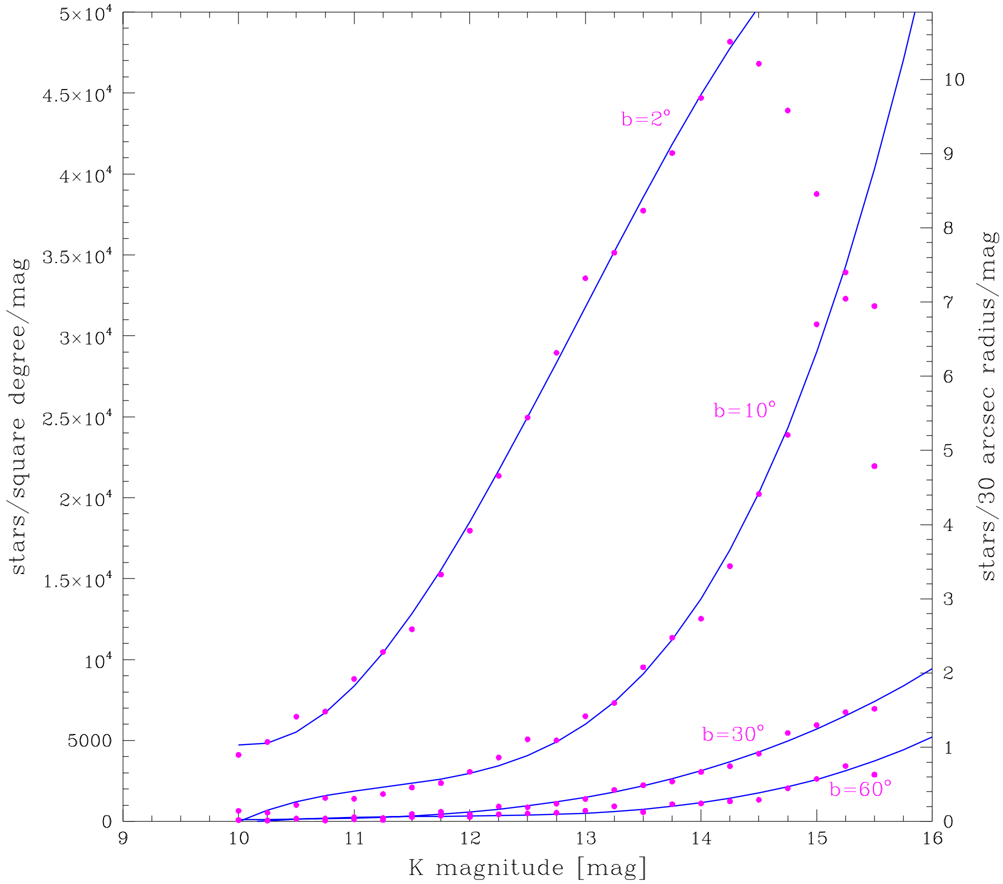

Figure 2. *K* band starcounts based on the 2MASS catalog for various galactic latitudes. Dots denote the star density per square degree and magnitude bin, while the solid line is a fit to the data up to the highest density point at a given latitude; data beyond that point were discarded for the fit because of incompleteness of the catalog. Note that the incompleteness is a function of galactic latitude. The scale on the right side of the plot is the conversion of star density per square degree and magnitude bin into the number of stars per area with a 30 arcsec radius and magnitude bin, the quantity of interest for PRIMA.

3.2. Reference Star Statistics

In Frink et al. (2004), we presented preliminary results on the number of available reference stars in the 2MASS and USNO-B1.0 catalogs. Using main-sequence stars from the Catalog of Nearby Stars (CNS), we found that only about 10–20% of the candidate target stars had possible reference stars listed in these catalogs within a radius of 10″. Using a search field with a radius of 30″, the fraction of possible target stars which have possible reference stars around them increases to 60–70%. Both 2MASS and USNO-B1.0 are not really appropriate to accurately derive reference star statistics in the *K*-band. The 2MASS catalog is only complete down to a *K*-magnitude of 14.5 mag, at least in the galactic

Table 1. Average number of stars $\bar{N}_{\rm stars}$ with K-magnitudes between 15 and 16 mag in search fields with 10″ and 30″ radius, respectively, for various galactic latitudes b. Also given are the corresponding probabilities $P_{\geq 2\ \rm stars}$ to find at least two stars within the given field size. The numbers in the table were derived based on the starcount results from Fig. 2. Binary stars were neglected in deriving the statistics.

	r=10″		r=30″	
	$\bar{N}_{\rm stars}$	$P_{\geq 2\ \rm stars}$	$\bar{N}_{\rm stars}$	$P_{\geq 2\ \rm stars}$
b=10°	1.0	26.3%	8.8	99.8%
b=30°	0.2	1.7%	1.6	47.5%
b=60°	0.1	0.5%	0.8	18.9%

plane, whereas the USNO-B1.0 has only very rough photometry in the R and the B bands and might also contain spurious sources, especially in the spikes of bright stars, so that the above numbers should only be regarded as a very rough approximation.

In order to investigate the number of possible reference stars as a function of galactic latitude, we counted the stars in the 2MASS catalog as a function of magnitude in the 2MASS catalog; the result is shown in Fig. 2. For galactic latitudes b of 2° and 10°, the incompleteness of the 2MASS data for K magnitudes fainter than about 14 mag is apparent; these data are not taken into account in the star density fits in the figure (solid lines), which should be regarded as an extrapolation to fainter magnitudes. Galaxy models predict that extrapolations at these magnitudes are still valid (Hutchings et al. 2002); number counts start to drop at K magnitudes beyond 20 mag, due to the edge of our Galaxy. What changes however is the relative number of disk giants and disk dwarfs, the latter one being more numerous for fainter K magnitudes, whereas the density of the former one is basically constant for K magnitudes fainter than 10 mag. Galaxies also start to occur in reasonable numbers beyond 16 mag, but cannot be be used as astrometric references.

The scale at the right hand side of the plot gives the average number of stars that are expected in a certain magnitude interval in a field with 30″ radius as appropriate for PRIMA, and the numbers for various galactic latitudes and search fields can be found in Table 1. Also provided are the probabilities to find two or more stars with K magnitudes between 15 and 16 mag within the respective search fields as derived from the 2MASS starcounts. E.g., at a galactic latitude of 30°, there is an average number of 1.6 stars in the 30″ field of interest for PRIMA, while at a galactic latitude of 60° there are only half as many. These star densities translate into a probability of about 50% to find at least two possible reference stars within a given 30″ field at a galactic latitude of 30°, and a probability of about 20% for a galactic latitude of 60°. For galactic latitudes below 10°, this probability is almost 100%. Considering only a field with radius 10″ and a galactic latitude of 10°, there is still a 26% chance that any target star will have at least two possible reference stars available. For higher galactic latitudes and the small field, probabilities to find two or more candidate reference stars are however quite low, less than a few per cent. Note however that in calculating these probabilities binary stars were not taken into account, so that the actual probabilities might be somewhat higher than these lower limits, especially at higher galactic latitudes.

Although in principle just one reference star in each field would be enough, two possible reference stars are much preferred. As long as there is no signal apart from parallax and proper motion movements, one reference star is probably enough, but as soon as there is some excess astrometric signature that could be explained by an orbiting companion, it is essential that this result is confirmed by using another reference star. This would also establish that the signal indeed originates in the target star as opposed to in the other reference star.

4. Calibration Stars

4.1. Requirements for Calibration Stars

Calibration stars are needed for baseline calibration as well as for a consistency check for PRIMA observations throughout the survey, very much like radial velocity standard stars for a radial velocity monitoring program. Very likely, several of these calibration stars will be observed every night. For the baseline calibration, the stars should be distributed over large areas of the sky.

While there is a long record of radial velocity observations of stars, so that over a time a subset of stars with constant radial velocities has emerged, nothing comparable is available for precise astrometry. The best astrometric measurements today for a significant number of stars stem from the Hipparcos satellite with an accuracy of about 1 milliarcsecond, two orders of magnitudes larger than the intended PRIMA precision. Therefore, a different approach has to be adopted to identify suitable calibration stars for PRIMA. The basic and most important requirement is again that the two stars do not move unpredictably with respect to each other by more than a few microarcseconds. One of the components should be brighter than K=12 mag, the other one brighter than K=16 mag.

4.2. Identifying Suitable Calibration Stars

As a first step we searched the high precision subset of the *Sixth Catalog of Orbits of Visual Binary Stars* (Hartkopf & Mason 2004), which are recommended for calibration purposes. We found 13 systems, with declinations between $-70°$ and $+20°$, as appropriate for Paranal, and with separations between $2''$ and $10''$. This final sample of possible calibrators mainly contains binary stars with periods of the order of several hundred to several thousand years, and all are bright enough to be observed with PRIMA (by design, no stars had to be rejected due to brightness). While the orbital elements of these systems might not be accurate enough to predict the relative positions of the components at any given time with microarcsecond precision, this sample might be a good starting point.

Alternatively, if one cannot find binary stars whose orbits are known with sufficient precision, one might want to turn to pairs of stars which hold a high prospect of not moving relative to each other with a rate larger than a few microarcseconds per year, which would be undetectable by PRIMA over a few years. In order to find such stars, we searched the Washington Double Star Catalog (WDS, Mason, Wycoff & Hartkopf 2004) for visual double stars which were observed at multiple epochs, but for which no orbital motion was detected so far, that is, the separation and position angle for those systems were constant over at least a few years (up to 100 years or more for many systems) to within the measurement precision. Even if orbital motion was detectable in these systems with PRIMA, these motions would probably be slow, and the systems could be used for calibration purposes at least from night to night. Without constraints on the angular separations in these systems, we identified eight pairs that would be observable from Paranal and satisfy the above conditions, of which four have separations between 1″ and 30″.

In principle, other binary stars for which no orbital motion would be detectable with PRIMA should exist. Those binaries would have long periods and at the same time small angular separations, which calls for large distances. Assuming the most extreme values for stars that are still observable with PRIMA, the pair would be made up of giant stars. For a K giant brighter than 12 mag in the K band, the largest possible distance would roughly be 8–10 kpc. A 20″ separation at that distance corresponds to a semi-major axis of the orbit of the order of at least 20 000 AU. The orbital period in such a system would be of the order of several million years, which just corresponds to the largest observed periods (Duquennoy & Mayor 1991). However, although these systems should in principle exist, it is not clear how to identify them.

5. Conclusions

The discussion in the preceding sections makes it clear that the selection of suitable target, reference and calibration stars is not an easy task. In fact, additional observations might be necessary to identify stars that fulfill the necessary requirements. We are in the process right now to acquire infrared images of possible target star fields, in order to characterize both target as well as reference stars.

While precise astrometry is opening up a new parameter space for extrasolar planet searches (at wider separations precise astrometry is more sensitive to smaller mass planets than precise radial velocities), as well as new classes of possible target stars (e.g., earlier type stars and young stars, which are not easily accessible with the radial velocity method), this added sensitivity comes at the price of a carefully selected target list, which is dominated by the availability of suitable reference stars. Furthermore, the dependence of the astrometric signal on distance helps a lot in increasing the sensitivity to smaller mass planets around nearby M stars, but on the other hand also greatly limits the number of suitable targets to the most nearby stars.

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