Differential Delay Lines

Astrometric Survey for Extra-Solar Planets with PRIMA

Scientific Proposal

Doc. No.	Planets-PRI-SCI-0001
Issue	1.0
Date	26 September, 2003

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1 Introduction

In less than 10 years after the first detection of a planet orbiting another star, more than 100 giant extra-solar planets have been discovered. This avalanche of results has opened a very exciting field of research: exploration of the characteristics of other planetary systems. The discoveries of the past few years have stimulated new planetary formation models leading to a new picture of planet formation.

So far, all extra-solar planets found around stars in the vicinity of the Sun have been detected by radial-velocity measurements. Large surveys are conducted in both hemispheres with about 3000 G, K and early M stars being monitored regularly. While these surveys are very successful, their intrinsic biases imply some limitations both on the detection sensitivity and the data interpretation. In particular, this method is restricted to certain types of stars and leaves the inclination angle of the orbit (*sin i*) undetermined, thus providing only a lower limit to the mass of the planets.

The development of state-of-the-art optical long-baseline interferometric instruments like the Very Large Telescope Interferometer on Cerro Paranal opens new perspectives in this research area. The European Southern Observatory is currently acquiring the hardware for PRIMA, a facility that will enable astrometric observations with the VLTI. The PRIMA facility holds the promise to carry out an exciting program on the astrophysics of extra-solar planets through precise astrometry, which is a very complementary technique to the radial-velocity method. It has a different detection bias, favoring planets in large orbits versus the short-period orbits preferentially detected by the radial-velocity technique. Moreover, astrometry measures two components (right ascension and declination) of the stellar reflex motion versus the single radial component that is observable spectroscopically. However, to play a significant role, an astrometric accuracy of order 10 μarcsec is needed, which is beyond the performance of current instrumentation (including HST).

PRIMA consists of four main hardware elements: A star separator, fringe tracker, internal metrology system, and differential delay lines (DDL). For financial reasons ESO decided to start PRIMA without the DDLs. PRIMA is now in an advanced status, with all the components, except the DDLs, already being manufactured or procured. Without additional external contributions, PRIMA will for many years remain without its DDLs. Based on our current best estimates we are convinced that the modified PRIMA would not comply with the original accuracy requirements and will not reach the accuracy required for astrometric observations of extra-solar planets. In practice, this would mean that the European astronomical community would lose an unique opportunity to perform outstanding science and to strengthen its position in the field of extra-solar planet research.

2 Project Summary

The goal of this proposal is to contribute to the development of the PRIMA hard- and software, in order to speed up the implementation of this astrometric facility with respect to ESO's current plan and to enable an early start of high-precision astrometric observations. As compensation for this effort we would expect to receive guaranteed observing time with the VLTI (on the Auxiliary Telescopes only), negotiated according to the ESO standard rules for any instrument provided by the community. The guaranteed time will be used by our consortium to conduct a large astrometric survey for extra-solar planets.

Our core hardware contribution will be design and construction of the Differential Delay Lines, consistent with an astrometric precision of 10 μarcsec. We will also implement the data reduction software, define the calibration plan, and carry out the system analysis required to conduct a large astrometric survey program with capability to detect extra-solar planets.

When PRIMA becomes operational, the first immediate objective of our survey will be to constrain all orbital parameters of planetary systems detected by radial-velocity surveys in order to precisely determine the planet masses and the relative orientation of planetary orbits in multiple systems. We will dramatically improve our understanding of the planetary mass function and put constrains on planetary formation models. The observations will help us to understand possible dynamical interactions in multiple planetary systems. The detection sensitivity for planets with larger orbital radii will be considerably improved, the astrometric technique being more efficient than radial-velocity measurements for these kind of objects. Our second main objective will be to conduct a large planet search program for stellar types that cannot be efficiently observed by the radial-velocity surveys. This will extend our knowledge about extra-solar planets through the time (with younger systems) and mass of stars. It means observing young and chromospherically active stars, as well as more massive early-type stars with broad spectral lines (early F and A stars). This will provide us with unique data to understand both the impact of the stellar type on planet formation, and the orbital evolution in young planetary systems.

We estimate that this survey will require a minimum of 200 observing nights with two Auxiliary Telescopes (ATs). This rather large number of nights clearly calls for an international scientific consortium, which we have now formed and which is submitting this proposal.

3 Technical Background: Astrometry with PRIMA

3.1 PRIMA and the VLTI

The European Southern Observatory (ESO) is currently in the process of commissioning step by step the Very Large Telescope Interferometer (VLTI) in Chile. In its final configuration, the VLTI shall consists of four 8 m telescopes and up to eight movable 1.8 m "auxiliary telescopes" (four of them funded to date), plus delay lines and a laboratory for beam combination. Originally conceived as a facility for high-resolution imaging, the VLTI will initially be equipped with instruments for observations at near- and mid-infrared wavelengths (see Glindemann 2001a & 2001b for references).

The infrastructure of the VLTI is also well-suited to be turned into a powerful facility for an astrometric planet search program (Quirrenbach 1995; von der Lühe et al. 1995). This idea gained momentum after the discovery of 51 Peg B, and was embraced by ESO's Interferometry Science Advisory Committee (Paresce et al. 1996). The technical concept for the delay lines was changed to accommodate a dual-star operating mode (Derie et al. 2000), and ESO commissioned a detailed study to assess the feasibility of an astrometric facility at the VLTI. The PRIMA (Phase-Referenced Imaging and Microarcsecond Astrometry) report concluded that this was indeed possible, and provided a conceptual design of the most important components needed (Quirrenbach et al. 1998). After carrying out further design studies, ESO is now acquiring the main subsystems for PRIMA through industry contracts except for the Differential Delay Lines.

3.2 Astrometry with an interferometer

The total delay d in a two-element interferometer is given by the expression $d = \vec{B} \cdot \vec{s} + d_{\rm int}$, where $\vec{B}$ is the baseline vector, $\vec{s}$ the unit vector in the direction toward the star, and $d_{\rm int}$ the internal path-length difference between the two arms of the interferometer. White-light fringes are observed when $d = 0$, i.e.,when the external delay $\vec{B} \cdot \vec{s}$ is exactly compensated by the internal delay $d_{\rm int}$. One-dimensional stellar positions ϑ can be determined from measurements of $d_{\rm int}$ and the residual phase ϕ by using

$$-(d_{\rm int} + \lambda \cdot \phi/2\pi) = \vec{B} \cdot \vec{s} = |B| \cos\vartheta \quad . \tag{1}$$

The precision of ground-based astrometry is ultimately limited by "image motion" caused by atmospheric turbulence. This image motion is correlated over angles of many arc-minutes. Because of this correlation, it is possible to make *differential* astrometric measurements within small fields with several orders of magnitude better precision than what is achievable from the ground for *absolute* or wide-field astrometry. For small angles ϑ on the sky, the atmospheric error for a telescope with diameter b, or an interferometer with baseline length b, scales with $b^{-2/3} \cdot \vartheta$ (Shao & Colavita 1992). For typical turbulence and wind velocity profiles at good astronomical sites like Cerro Paranal and Mauna Kea, the atmospheric error on a 200 m baseline approaches 10 μas over a $10''$ arc for half-an-hour integration (Colavita 1994; von der Lühe et al. 1995).

Differential astrometry is thus based on the principle that the exact position of a star on the sky is measured with regard to one or a few nearby stable reference stars. Because of the short coherence time of the atmosphere, pairs of target and reference have to be observed truly simultaneously, which leads to the dual-star interferometer design. The best performance is achieved when the light from the target and the reference star follow closely matched physical paths through the whole interferometer. In order to reach a 10 μarcsec astrometric accuracy, several basic requirements have to be met. First, the differential instrumental terms contributing to $d_{\rm int}$ have to be calibrated with a precision of about 5 nm. Second, the baseline vector $\vec{B}$ has to be known to $\sim 50\,\mu$m, for all orientations of the telescopes. Third, the fringe phase ϕ has to be measured with a precision of ~ 0.01 rad. Fourth, differential atmospheric effects have to be taken into account and modeled

precisely. In addition to these technical requirements, suitable reference stars — preferably stable at the 10 μas level themselves — have to be found in a very small patch of the sky around the science object.

The optical path difference between the two interferometer arms is not identical for the target and reference star, since they have different positions on the sky. To get simultaneous interference on both the target and its reference one has to add a differential delay between the two. It is in principle possible to use two independent long delay lines for the target and the reference to correct for these differential delays. However, this approach introduces a large physical separation between the target and reference beams, which makes this arrangement very prone to errors due to refractive index variations in the delay line tunnel. Furthermore, it introduces a large number of non-common optical elements (including the whole delay line optics), which further increases the number of error sources. With Differential Delay Lines in place, target and reference beams travel through the same main delay line and only the small differential delay terms are corrected by separate DDLs. The DDLs therefore play an important role to minimize differential instrumental errors which contribute to the final astrometric budget.

3.3 Astrometry vs. radial velocity and transit methods

The radial-velocity method is very efficient in detecting massive planets in short-period orbits close to the star. It requires stars with a sufficient number of narrow spectral lines, i.e., fairly old stars of about 1.2 $M_\odot$ or less. Hence, more massive stars ($M > 1.4\,M_\odot$) as well as young and chromospherically active stars are usually not accessible by this method. Moreover, radial-velocity measurements leave the inclination angle of the orbit (*sin i*) undetermined, and thus derive only a lower limit on the planetary mass.

Precise astrometry is a complementary technique to the radial-velocity method for planet searches. It has a different detection bias, favoring planets in large, long-period orbits (like in our own Solar System) versus the short-period orbits preferentially detected by the radial-velocity technique (see Fig. 1a). Moreover, astrometry measures two components (right ascension and declination) of the stellar reflex motion versus the single radial component that is observable spectroscopically. For this reason, astrometric orbit measurements are ultimately required to derive *the* fundametal parameter of a planet: it's mass.

Compared to space-based astrometry, ground-based observations have the considerable advantage of being able to cover longer time scales. This is very important for searching and characterizing planetary systems and cannot be fully accounted for by the higher precision and sensitivity of space-based interferometers.

Planetary transits in front of the stellar disk only occur for orbit inclinations close to 90°. Moreover, due to the low probability of an event to occur at a certain time, transit searches are inefficient and strongly biased towards very short-period planets. They require a huge amount of observing time, very high photometric precision, as well as enormous data reduction and analysis efforts. Although millions of stars have been monitored photometrically, only very few planetary transits have been found to date.

Based on these considerations we came to the conclusion that a high-precision astrometric planet survey is the most efficient and scientifically rewarding method to search for extra-solar planets and derive complete orbital parameters and precise planetary masses. In addition, this method is very complementary to the on-going high-precision radial-velocity surveys (e.g., the HARPS project) and it will enable us to fully characterize multiple planetary systems. In contrast to transit searches, most systems in which short-period radial-velocity planets have been detected can be evaluated with the astrometric method, thus increasing our chance to find multiple planetary systems with short and long-period planets. In summary, high-precision astrometry is the next logical step on our way to explore extra-solar planetary systems.

4 Research Plan: Observing Extra-Solar Planets

4.1 Present status of research in the field

More than 100 extra-solar planetary systems have been found since the first detection of a planet orbiting the star 51 Peg (Mayor & Queloz 1995). All these discoveries, including multi-planetary systems, have revealed the existence of planets with a large variety of orbital characteristics, raising many issues about the processes of giant planet formation. Such a diversity was not expected from the observation of giant planets in our own Solar System.

The radial-velocity technique is so far the only successful technique that has demonstrated reliable detections of extra-solar planets. Now about 3000 nearby stars in both hemispheres are regularly monitored by large surveys (see Queloz 2002 for details). The spectral types of stars of the surveys are G, K and few early M dwarfs located within a sphere of 100 pc. Young stars are usually avoided because of their broad spectral lines and strong activity that prevents planet detection (Queloz et al. 1999). In some cases, stable rotating spots at the stellar surface may even mimic a planetary motion (Queloz et al. 2001).

The discovery of giant planets in very short orbits is a real challenge for planetary formation theories. These systems do not fit into the standard paradigm of giant planet formation (Boss et al. 1995). Additional mechanisms, not envisioned by the study of the Solar System, have been suggested to explain their existence. These include the migration of planets in the proto-planetary disk and gravitational interactions in multiple planetary systems . However, the physical processes acting during migration are not yet understood in detail. Several points need to be clarified like, e.g., the mechanisms that stop the planet migration at around 0.04 AU, the simultaneous migration of several giant planets, and the formation of giant gaseous planets if the planetesimals have a rapid inward migration (type I migration).

Another puzzling feature is the troublesome similarity of the distributions of orbital eccentricities of extra-solar planets and spectroscopic binaries. The formation mechanisms of double stars and giant planets are believed to be completely different: collapse and fragmentation of the initial protostellar cores for the former versus dust agglomeration, gravitational akkumulation, and migration in a circumstellar disk for the latter. Several mechanisms have been proposed to explain the wide range of eccentricities of giant planets (Weidenschilling & Marzari 1996; Rasio & Ford 1996; Levison et al. 2000). However, when comparing with our Solar System, one should remember that the limited duration of radial-velocity surveys has not allowed the detection of planets on orbits further than 4 AU yet. Moreover, the mass detection threshold of the radial-velocity surveys are biased toward the detection of systems on short orbits, close to their stars. One-third of the planets detected by the radial-velocity surveys have periods shorter than 100 days. The lack of detection of a planet with orbital characteristics similar to Jupiter's could be a result of the lack of sensitivity of the radial-velocity method as well as the long duration needed to get a full orbit.

The large number of planets detected makes a first crude estimate of the mass distribution of planets possible. The companion mass function computed over a wide mass domain ranging from stars to planets suggests different formation mechanisms between planets and stars. In the stellar and sub-stellar regime down to $10\,\mathrm{M_{Jup}}$, the binary mass function is decreasing as $dN/d\log(m) \sim -1$, leading to very few brown dwarfs. This is also known as the "brown dwarf desert". For masses below $10\,\mathrm{M_{Jup}}$, the mass function rises while the observational bias limits the detection of small-mass companions. Therefore, we can consider that the break in the mass function at about $10\,\mathrm{M_{Jup}}$ is both the low mass limit of brown dwarfs, as well as the upper mass limit of planetary companions (Zucker & Mazeh 2001; Jorissen et al. 2001). This is probably telling us something very important about the physical processes involved in the formation of these two populations: stars, even the very low-mass ones, are thought to be formed as the result of the gravitational collapse and fragmentation of a cloud of gas and dust. On the other hand, a planet forms in a circumstellar accretion disk.

A significant fraction of stars with a planet actually host a multi-planetary system. Moreover, many stars that are already known to harbor a planet also show systematic trends in radial-velocity, suggesting a second remote companion as part of the system. The probability to find another planet in a known system is more than 10% (Queloz 2002). This means that the best place to look for a planet is in systems where at least one other planet has already been found. Some of these systems show spectacular resonant orbits that may be understood in the context of the simultaneous migration of several gaseous giant planets during the lifetime of the accretion disk.

The dominant role of the radial-velocity technique as the only efficient planet-finding tool is slowly eroding. Last year intensive photometric monitoring of dense stellar fields of the Galaxy by Udalsky et al. (2002) have lead to the detection of 60 stellar candidates with very small amplitude variations that are compatible with planetary transits. For the star HD 209458, which was known to host a short-period planet, complementary accurate photometry lead to the determination of its radius and therefore an estimate of its mean density. The year following the detection of the transit (Charbonneau et al. 2000), Brown et al. (2001) obtained a photometric curve of unprecedented quality with the Hubble Space Telescope that is a perfect illustration of the potential of future space missions like Eddington (ESA).

Among encouraging new prospects one also finds the first accurate mass determination of an extra-solar planet by astrometry measurements (Benedict et al. 2002). A long time series of observations made with the HST of the star Gl 876, which was known to have a massive giant planet with an orbital period of 60 days, has achieved 100 μarcsec accuracy. This is sufficient to obtain a clear detection with less than 5% error on the mass of the planet of this very nearby system. Although limited in this case, this measurement demonstrates the usefulness of astrometry to determine an accurate mass of known systems when there is no transit.

4.2 Scientific goals of the project

We want use PRIMA with the VLTI to carry out an intensive observing program to detect reflex motions of stars in the plane of the sky due to orbiting planetary companions. To be successful, an astrometric accuracy of order 10 μarcsec is required for this program. By comparison with the radial-velocity surveys, a high-precision astrometric planet program will address the following outstanding issues:

- Resolve the $\sin i$ uncertainty from planet masses found by high precision radial-velocity surveys and derive accurate planet masses. This measurement is fundamental to study in detail the planetary mass function, in particular the upper mass cut-off.
- Confirmation of hints for long-period planets in radial-velocity surveys. Many of the stars with detected short-period planets also show long-term trends in the velocity residuals (e.g., Fischer et al. 2001). These are indicative of additional long-period planets, whose presence can be confirmed by astrometric measurements.
- Inventory of planets around stars of different masses and ages. The radial-velocity technique works well only for stars with a sufficient number of narrow spectral lines, i.e., fairly old stars of about 1.2 solar masses or less. Interferometry can detect planets around more massive stars as well as pre-main sequence stars of different ages to study planet formation with time.
- Detection of multiple systems with masses decreasing from the inside out. Whereas the astrometric signature increases linearly with the semi-major axis a of the planetary orbit, the radial-velocity signature scales with $a^{-0.5}$. This leads to opposite detection biases for the two methods (see Fig. 1). Systems in which the masses increase from the inside out (such as υ And, Butler et al. 1999) are easily detected with

the radial-velocity technique because the planets produce signatures of similar amplitudes. Conversely, systems with masses decreasing with increasing a are more easily detected by astrometry.

- Measure whether multiple systems are coplanar or not. Many of the known extra-solar planets have highly eccentric orbits. A plausible origin of these eccentricities would be strong gravitational interaction between two or several massive planets (Lin & Ida 1997; Papaloizou & Terquem 2001). This could also lead to orbits that are not aligned with the equatorial plane of the star, and to non-coplanar orbits in multiple systems.

In summary, astrometry provides unique capabilities to determine masses and orbits of young and old planetary systems and it will give new insights into the mechanisms of planet formation, orbital migration and evolution, orbital resonances, and interaction between planets. The search for extra-solar planets is inherently a long-term project, which requires a homogeneous data set and consistent data reduction. It is therefore expected that our planet survey will be continued over many years. However, we decided to focus our program on a 3-year period with two science cases to demonstrate that we can address some of the outstanding issues listed above. Correspondingly, we define two core programs which are described in the next two sections:

1. Accurate measurement of the mass of extra-solar planets detected by radial-velocity surveys.
2. Planet search through the main sequence and time.

4.3 Core program 1: Accurate measurement of the mass of extra-solar planets detected by radial-velocity surveys

Our first and primary goal will be to observe all stars with known radial-velocity planets that *(i)* are in reach of PRIMA, *(ii)* have at least one suitable phase reference star, and *(iii)* will produce a detectable astrometric signal. For these stars we will resolve the $\sin i$ uncertainty of the planet masses and measure the orbital eccentricity. For stars with multiple planetary systems we will derive the relative inclination of the orbits, an important indicator of gravitational interaction between the planets. Due to the different detection biases of both the radial-velocity and astrometric methods, we expect to identify more multiple systems than currently known.

Only those stars will be selected that, based on the radial-velocity orbits, will produce an astrometric signal larger than $1.5\,\sigma$ rms for the minimum mass of the planet. Out of currently more than 100 stars with known radial-velocity planets, 77 stars can be observed from Paranal. Of these, 44 stars have at least one reference star within 30 arcsec. About 25 of these systems will produce an astrometric signal that can be detected with more than $1.5\,\sigma$ rms with PRIMA, provided the system is operated with DDLs and reaches an astrometric precision of 10 μarcsec. In Table 2 we list all stars with known extra-solar giant planets that fulfill these criteria. The angular separation to the reference star and an integration time of 30 min have been taken into account in the calculation of the astrometric uncertainty. Most systems will produce a larger astrometric signal than listed since we used the minimum mass of the planets, i.e., $sin\ i = 90°$. Most stars also have more than one suitable reference star, but we list only the one that provides the lowest variance on the differencial phase.

To measure the astrometric signal from a star, one must first measure the dominant signal coming from the parallax motion. In Fig. 3, we illustrate the result of a simulation of GJ 876, HD 162020, and HD 114386 where both the parallax motion and the astrometric signal of the planet have been simulated and successfully recovered by a global fit to 30 astrometric measurements. Simulations have shown that a three-year period is more than enough to measure the parallax with high precision. The planetary effect is detected in the parallax residuals, while in practice all parameters are fitted together in a global way. If one assumes that the period

of the system as well as its eccentricity are known from radial-velocity measurements (which will be the case for most of the targets in the first core program) we get even better constraints on the final result (see Table 3).

Considering the detection statistics of past radial-velocity programs and the number of targets, sensitivity, and duration of ongoing and new programs (e.g., HARPS), we estimate that the number of PRIMA target stars with known radial-velovity planets will double within the next three years, i.e., until we can start our astrometric survey. In order to achieve the desired precision, each program star has to be observed for about 30 min per night. We estimate that 30 measurements per star spread over 3 years are required to derive all orbital parameters. We therefore estimate that this program requires about 70 to 100 nights with two ATs in order to be successfully completed.

4.4 Core program 2: Planet search through the main sequence and time

The search for planets by the radial-velocity technique is restricted to stars with narrow spectral lines and stable line profiles. This means that A and most F stars with their broad spectral lines as well as young, chromospherically active and fast rotating stars are so far excluded from radial-velocity surveys. This prevents us from getting a comprehensive understanding of the planetary formation around massive stars as well as the possible evolution of planetary systems in their early stages where we expect violent orbital evolution. The astrometric search for these categories of stars will form our second core program.

The detection efficiency of an astrometric survey depends on the stellar mass, the mass and orbital period of the planet, and the distance from the Sun. In Fig. 2, the planetary mass detection limit for stars of different mass and at various distances from the Sun is shown for an astrometric survey with $5\,\sigma$ accuracy of 50 μarcsec and duration of 3 years. This diagram together with Fig. 1 shows that such an astrometric survey has the capability to detect Jupiter-size planets even around early-type A stars out to a distance of about 40 pc. Moreover, it shows that we will be sensitive for even Uranus-size planets around the nearest M stars. Table 1 lists the number of main sequence stars of certain spectral type (i.e., mass) as function of distance from the Sun.

Based on these considerations, we have identified three subgroups of target stars for our second core program:

1. **Very low-mass MS stars with 0.1-0.8 $M_\odot$ (spectral types M and K):** Although planet detections in RV surveys are relatively rare around very low-mass stars, the discovery of two planets around GJ 876 has shown that planets do exist around such stars. We will be much more sensitive to low-mass planets with long periods than radial-velocity surveys. Therefore, we expect to find more planets and to put serious constraints on the frequency and type of planets around around these stars. We may also be able to put constraints on the minimum mass required for a star to be able to efficiently form planets in its circumstellar disk. Since the number of available target stars in this mass range is much higher than we can observe, we will concentrate on the nearest stars with very close-by reference stars only. This guarantees the highest sensitivity for even planets of relatively low mass around these stars.

2. **Low to intermediate-mass MS stars with 0.8-3 $M_\odot$ (spectral types F, G, and A):** While for solar-mass stars we will also concentrate on the nearest ones, we will observe all accessible stars with masses higher than 1.4 $M_\odot$, which could not be observed with the radial-velocity technique. Although sensitivity and number statistics will be low, we may be able to draw first constraints on the frequency of massive planets around these stars.

3. **Young low-mass stars with age 1-100 Myr and mass 0.3-1.5 $M_\odot$:** Around stars in this age range we expect to find planets and planetary systems with properties (e.g., mass, multiplicity, eccentricity, periods) considerably different from those around main sequence stars, thus helping us to lift the veil of planetary system formation and orbital evolution. The lower limit to the age is set by the disk dispersal

Distance	Number of target stars				
	M	K	F & G	A & B	Young stars
10 pc	71	31	14	4	3
20 pc	232	217	140	14	10
30 pc	384	536	456	48	21
40 pc				84	
50 pc				175	35

Table 1: Number of main sequence stars of given spectral type with $-75 < DEC < +25$ at a given distance from the Sun. The selection is based on the spectral types and parallaxes given in the Hipparcos catalog. Giant stars have been removed from the selection. Young stars of age 1 to 100 Myr and mass 0.3 to 1.5 $M_\odot$ are selected from different catalogues and studies.

and (only theoretically constrained) giant planet formation time scales which are both of order 1 to a few Myr. As upper age limit we use the giant planet formation time scale and low-mass PMS time scale which are both of order 100 Myr, somewhat depending on star and planet mass. Since the number of known nearby young stars is relatively small (see Table 1), we will observe all accessible targets in this group out to the distance limit given by Fig. 1.

Preliminary cross-correlation of the main sequence stars in the Catalog of Nearby Stars (CNS3R, Gliese & Jahreiß 1998) with the 2MASS and USNO-B1.0 catalogs (Monet et al. 2003) indicates that about 10 to 20% of the possible target stars have potential reference stars within 10 arcsec. After final characterization (see 4.5), we expect to find suitable reference stars for 5 to 10% of all potential target stars. While this still leaves a large number of observable very low-mass stars (cf. Table 1), we may have to increase the search radius for more massive and for young stars to 30 arcsec.

Altogether, we plan to observe up to 100 target stars within this second core program. While our program will include all accessible main sequence stars of mass higher than about 1.5 $M_\odot$ as well as all stars younger than 100 Myr within the distance limit described above, we will observe only a small fraction of M, K, and G main sequence stars that are within the reach of PRIMA. We want to note that longer period planets can also be detected around stars of higher-mass and at larger distance from the Sun than included in our target list. This means that there is quite a number of potential target stars for planet searches that are not covered by our program but could be observed by other groups. To carry out efficiently such a survey, a minimum number of 100–150 nights spread over 3 years is needed for this second part of our program.

4.5 Selection of phase reference stars

Which targets that can actually be observed with PRIMA is constrained by the availability of suitable reference stars. The isoplanatic angle in K-band is about 2 arcmin, considering that the ATs are fully coherent with a simple tip-tilt correction. For a reference star with $K \leq 16$ mag within 10 arcsec of the target star, the estimated integration time to reach 10 μarcsec astrometric accuracy on a 200 m baseline on Paranal is about 30 min. However, the observing time scales quadratically with the separation between target and reference star and the limiting magnitude also decreases (see Shao & Colavita 1992 and Delplancke et al. 2000).

With a targeted astrometric accuracy of 10 μarcsec, unpredictable motions of the center of light of a reference star should be smaller than about 3 μarcsec. The main concern for the astrometric stability of a reference star are companions; stars, brown dwarfs, as well as giant planets. To avoid unwanted jitter due massive planets, which occur around any star, we can define a minimum distance from the Sun for every reference star of given mass. Brown dwarf companions with separations smaller than about 5 AU are very rare and should thus not

present a big concern (see, e.g., Halbwachs et al. 2000). Stellar companions are not easily avoidable, especially if one keeps in mind that a large fraction of stars occurs in binary systems. We are currently defining a complete list of requirements that a to a suitable phase reference star as well as a preparatory observing program to fully characterize our potential target and reference stars (e.g., spectroscopy with $\sim$20 m/s precision and multi-band photometry). Since it becomes clear that the data required to sufficiently characterize a reference star cannot be extracted from any published catalog or data base, every high-precision astrometric observing program has to be prepared by dedicated preparatory observations. Therefore, we will not provide ESO with a reference star selection tool, but will instead deliver an Astrometric Reference Star Selection Criteria Document which will help observers to prepare their astrometric measurements.

4.6 Astrometric calibration and observation strategy

The anticipated astrometric performance requires an accuracy on the baseline knowledge of $\approx 50\,\mu$m, which cannot be provided a-priory by geodesic measurements and telescope specifications (Delplancke et al. 2000). Therefore, the baseline must be calibrated on a set of stars whose absolute positions on the sky are known. In addition, some astrometric parameters have color-dependent terms that have to be calibrated by observing stars of different color. We will investigate all calibration requirements, work out a calibration strategy, and define a catalog of calibration source requirements which will also be delivered to ESO. To reach our ambitious scientific goals and make the best possible use of the instrument, we will define an optimized short and long-term calibration and observing strategy for our astrometric planet search program (see Operations and Software Proposal, Doc. No. Planets-PRI-AOS-0003).

5 The need for Differential Delay Lines

5.1 Why do we need Differential Delay Lines?

PRIMA consists of four main hardware elements: A star separator, a fringe tracker, an internal metrology system, and differential delay lines. For financial reasons ESO decided to start PRIMA without the DDLs. It is indeed possible to use the long delay lines in a differential mode to "simulate" differential delay lines. However, this scheme gives up one of the most important design goals for precise differential measurements, namely to maintain as much commonality between the light paths for the target star and its reference. Without the DDLs, the two light beams travel through widely separated paths in the delay line tunnel, and use separate delay line carts. Based on the current best estimates we are convinced that PRIMA without the DDLs will not reach the accuracy required for astrometric observations of extra-solar planets.

In contrast, by using the DDLs the two stars share the same delay line cart and travel on intertwined paths in the delay tunnel. The differential OPD is then introduced by the DDLs only, which will very likely be operated under vacuum. Based on the current best estimates, an astrometric accuracy of 10 μarcsec can be achieved in this mode. This improvement by one order of magnitude in accuracy is by far more then just a quantitative improvement. It is *the* necessary jump in accuracy that will make extensive astrometric planet searches possible after all! Figure 1 clearly demonstrates that useful astrometric planet searches from the ground become only possible when an astrometric accuracy of order 10 μarcsec can be reached, i.e., when PRIMA is equipped with DDLs.

5.2 Why now and not later?

According to our proposed time line, high-precision astrometric observing programs at the VLTI with the enhanced PRIMA facility can start in 2008. No other ground-based optical/IR instrument will reach such high astrometric precision on a comparable time scale. Funding and installation of the Keck outtriggers is uncertain, or at least delayed. This means that ESO and the European astronomical community could take the lead in the field of extra-solar planet research if the high-precision astrometric capability of VLTI/PRIMA is enabled soon. The space-based interferometric facilities Gaia (ESA) and SIM (NASA), capable of very efficient high-precision astrometric measurements, are scheduled for launch in 2011 and 2009/10, respectively. Here we have to keep in mind the usual uncertainties and delays of such space missions. However, it becomes clear that the implementation of the Differential Delay Lines for PRIMA should not be delayed. Only if the DDLs are built now, we will be able to explore the field of high-precision astrometry, in particular precise determination of orbital parameters and masses of extra-solar giant planets, before large surveys will be undertaken by these future space missions. Furthermore, only if we stick to the proposed time line and build the DDLs now, we will be able to provide important inputs to these and other future space missions dedicated to the exploration of extra-solar planetary systems.

5.3 Other science areas that benefit from the PRIMA enhancement

The DDLs will provide the possibility to carry out precise astrometry with PRIMA, at a level of about 10 μarcsec. Besides extra-solar planet searches, many different branches of astronomy would benefit from the VLTI being capable of microarcsecond astrometry. Astrometric parameters that could be measured include, e.g., parallaxes, proper motions, orbital motions, and photocenter shifts due to other events.

Accurate mass determination by measuring orbital motions: High-precision astrometric orbit measurements of spectrocopic binary stars will allow to accurately determine the masses of the individual stars and

the distance to the system. Such measurements will allow to test and calibrate stellar evolutionary models and would thus have a great impact on our understanding of stellar physics. This method could also be expanded towards systems with a more exotic component, like black holes, neutron stars, or white dwarfs.

Binarity of massive stars: While spectroscopic measurements are very efficient in deriving binary frequency and orbital characteristics of low-mass stars, almost no data are available for massive stars. Precise astrometry could put constraints on the duplicity statistics of massive stars, which would have a great impact on our understanding star formation in general and the formation of massive stars in particular.

Dynamics and mass distribution in the galactic center: A particularly interesting PRIMA target is the galactic center. When high-precision astrometry is combined with radial-velocity measurements, 3-D space velocities can be derived, which would improve our understanding of the dynamics, mass distribution, and history of the galactic center.

Measuring distances throughout the Galaxy: With 10 μarcsec astrometry, trigonometric parallaxes can be measured with a precision of 0.1% out to distances of 100 pc and 10% out to 10 kpc. Although the conversion into absolute parallaxes is a very complex task, distances of Cepheids could be derived with much higher precision than from Hipparcos, thus helping to fine-calibrate the galactic distance scale. Another application is the derivation of rotational parallaxes for nearby spiral galaxies via proper motion measurements of stars at various locations in these galaxies. When combined with radial velocities and rotation curves, these measurements can yield distances with an accuracy of a few percent for the most nearby spiral galaxies. A parallax program of a few especially interesting stars can easily be carried out within a few nights stretched over 1 to 2 years and is thus suitable for a relatively small observing program.

Dynamics through proper motion measurements: Proper motions are known for all Hipparcos objects with a precision of about 1 milliarcsec, and for fainter stars from the Tycho-2 catalog or the UCAC2 catalog with somewhat less precision. Proper motion measurements of stars in globular clusters with an accuracy of 10 μarcsec/yr would give access to fundamental dynamical parameters in all galactic globular clusters. When combined with radial-velocity measurements, 3-D space velocities can be derived, which would strongly improve our understanding of the internal dynimacs of these objects. The same method applied to a carefully selected set of stars in the galactic disk could help to improve our understanding of galactic kinematics and dynamics, such as local surface density of the stellar disk, rotation curve, and ellipticity of the Milky Way. Another unique contribution of PRIMA could be the measurement of proper motions of Local Group Galaxies, which are too small to be measured with current methods (about 20 to 100 μarcsec/yr). Provided suitable stars in these galaxies can be identified and reference stars be found, such measurements would help to derive the overall mass distribution in the Local Group. Again, such proper motion programs could be carried out with a modest amount of nights stretched over a few years, since only a small number of stars need to be observed.

AGNs: Although limited by the availability of reference stars, 10 μarcsec astrometry would be capable of measuring the photocenter shift of starburst AGN due to supernova explosions.

This incomplete list shows that microarcsecond astrometry with the complete PRIMA facility at the VLTI will open new perspectives and address important scientific questions in many different areas of galactic as well as extragalactic research.

Interestingly, the development of astrometric capabilities of PRIMA would also bring immediate benefits for a completely separate scientific field, namely high-resolution observations of “faint” objects such as quasars and active galactic nuclei. Interferometric imaging of these sources relies on a nearby reference star to stabilize the phase. This technique is closely related to astrometry and sets similar, but somewhat relaxed, requirements on the understanding of the instrumental and atmospheric pathlength errors.

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A Tables and Figures

Target:									Reference star:	
Star	Planet	K [mag]	D [pc]	M_1 [$M_\odot$]	$M_2 \sin i$ [M_{Jup}]	Period [days]	ρ [μas]	SNR	Δ [as]	K [mag]
HD 142	b	4.47	25.6	1.16	1.36	338.0	45	1.8	24	14.0
HD 13445	b	4.12	10.9	0.85	4.00	15.6	47	1.5	31	13.9
HD 27442	b	1.75	18.2	2.13	1.43	426.0	43	1.5	28	11.2
HD 33636	b	5.57	28.7	0.99	7.80	1620.0	742	40	19	12.3
HD 37124	c	5.95	33.2	0.98	1.20	1495.0	92	2.2	41	12.8
HD 38529	c	4.21	42.4	1.68	12.7	2174.3	655	36	18	14.0
HD 50554	b	4.57	31.0	1.05	4.90	1279.0	357	17	21	14.5
HD 74156	c	6.21	64.6	1.20	7.50	2650.0	434	10	43	10.6
HD 82943	c	5.11	27.5	1.08	1.63	444.6	64	4.0	16	13.2
HD 92788	b	5.72	32.3	1.01	3.80	340.0	109	7.2	15	14.1
HD 114386	b	6.35	28.0	0.81	0.99	872.0	70	6.0	12	13.2
HD 114729	b	5.14	35.0	1.16	0.90	1136.0	46	4.6	8	9.5
HD 114762	b	5.81	40.6	1.11	11.0	84.0	73	5.0	15	13.6
HD 128311	b	5.14	16.6	0.83	2.63	414.0	203	12.7	16	13.0
HD 136118	b	5.60	52.3	1.24	11.9	1209.6	430	30	14	13.8
HD 141937	b	5.76	33.5	1.02	9.70	653.2	432	27	16	14.3
HD 147513	b	3.93	12.9	0.97	1.00	540.4	101	9.0	11	10.0
HD 160691	b	3.68	15.3	1.11	1.70	638.0	151	5.9	25	12.8
HD 162020	b	6.54	31.3	0.82	13.7	8.4	38	3.8	8	12.0
HD 168443	b	5.21	37.9	1.17	7.70	58.1	50	4.5	11	11.1
HD 168443	c	5.21	37.9	1.17	16.9	1739.5	1083	97	11	11.1
HD 169830	b	4.69	36.3	1.27	2.96	230.4	53	4.9	11	9.3
HD 196050	b	6.03	46.9	1.12	3.00	1289.0	143	13.2	11	9.8
HD 210277	b	4.80	21.3	1.02	1.28	437.0	65	3.9	17	13.2
HD 213240	b	5.35	40.7	1.18	4.50	951.0	191	8.7	22	10.8

Table 2: List of known extra-solar giant planets that can be observed with PRIMA and detected with a SNR > 1.5. Astrometric signal and SNR listed here are lower limits since minimum planet masses have been used for this calculation (i.e., $\sin i = 90°$). The astrometric uncertainty was calculated with an integration time of 30 min and with the angular separation between target reference star listed in the table. Most systems have more than one suitable reference star and only the one that results in the highest astrometric accuracy is listed here.

Object	π [$\mu arcsec$]	$\mu\alpha$ [$\mu arcsec$]	$\mu\delta$ [$\mu arcsec$]	e	P [day]	a_1 [mas]	i [$deg.$]
Period and eccentricity are fixed							
Gl 876	214599.99±0.554	960310.24±1.562	-675610.78±1.578	0.10±0.000	61.02±0.000	0.25±0.003	83.96±0.636
HD 162020	31988.04±1.103	20986.19±2.318	-25201.75±1.301	0.28±0.000	8.42±0.000	0.04±0.004	81.63±3.004
HD 114386	35652.76±1.393	-138237.62±1.024	-325102.24±0.549	0.28±0.000	872.00±0.000	0.07±0.003	84.31±1.870
All parameters are fitted							
Gl 876	214599.51±1.225	960311.67±2.629	-675608.24±1.396	0.10±0.004	60.99±0.025	0.25±0.007	83.93±1.512
HD 162020	31991.59±2.034	20989.41±5.085	-25200.65±1.769	0.28±0.026	8.40±0.001	0.05±0.008	83.43±8.816
HD 114386	35660.88±1.244	-138226.28±3.825	-325099.03±1.550	0.31±0.033	889.69±19.232	0.07±0.004	82.99±4.937

Table 3: Modeling astrometric observations and orbit fits with information from radial-velocity observations. Illustration of the effect on the final result when the eccentricity and the period is known from the radial-velocity orbit. In this case, 30 measurements are spread on 3 years and evenly distributed over the orbital phase (see also Fig. 3).

Target: Star	SpType	V [mag]	D [pc]	M_1 [$M_\odot$]	log(age) [Myr]	ρ(5AU) [μas]	ρ(1AU) [μas]	Reference star: Δ [as]	R [mag]
Main Sequence stars:									
GJ 3097	M4	12.6	31	0.28	-	535	108	5.6	12.5
GJ 620	M2	10.2	17	0.4	-	1400	280	16	16.6
GJ 2061	M2V	11.0	31	0.44	-	348	60	3.3	13.6
HD 219437	K3V	9.6	32	0.56	-	264	53	0.1	10.6
HD 161296	K3V	9.4	33	0.61	-	234	47	4.3	8.5
HD 137628	K3V	8.9	32	0.68	-	216	43	0.9	8.4
GJ 1181	K5	9.5	17	0.7	-	800	160	4	13.8
HD 98736	G5	8.0	32	0.86	-	175	35	5.1	12.3
HD 209635	F8V	6.7	30	1.15	-	138	28	6.6	10.8
HD 125040	F8V	6.3	32	1.38	-	107	21	4.4	7.9
m Hya	F0V	4.9	30	1.94	-	80	16	9.0	8.0
tet Ind	A5V	4.4	30	2.25	-	71	14	7.7	6.6
					-				
Young stars (1 to 100 Myr):									
PZJ 160240.9-213042	M2	12.1[a)]	145	0.33	6	99	21	17.4	11.3
HD 37572	K0V	7.9	24	∼0.8	7.7-8	249	52	18.5	8.9
HD 131156	G8V	4.5	6.7	∼0.8	7.7-8	885	180	8.4	6.2
HD 96064	G5	7.6	25	∼0.9	7.7-8	214	44	9.8	11.9
HD 48189	G1.5V	6.2	23	∼1.0	7.7-8	219	45	0.2	8.0

[a)] I magnitude

Table 4: Examples of main sequence and young target stars (without known RV planets) with suitable reference stars that can be observed with PRIMA. The expected astrometric signal ρ for a 1 M_{Jup} planet at 5 and 1 AU distance from the star (semi-major axis) is also given.

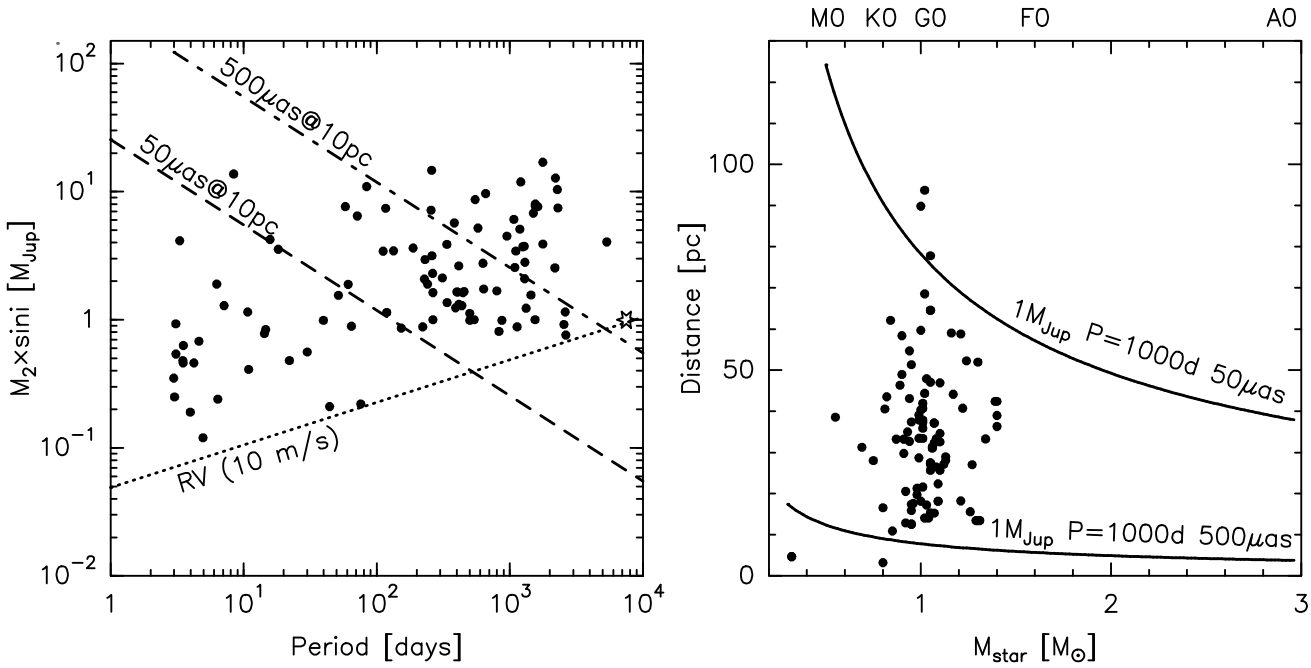

Figure 1: Detection limits of astrometric planet searches with PRIMA without DDLs ($5\,\sigma = 500\,\mu$arcsec) and with DDLs ($50\,\mu$arcsec).

Left: Distribution of known planet masses (from radial-velocity searches, with *sin i* uncertainty) as a function orbital period. Note that the actual planet masses are higher, on average by 25% for randomly distributed orientations. The location of Jupiter is marked by an asterisk. The dotted line with the (10 m/s) indication shows the typical detection limit of radial-velocity suveys. The upper dashed line indicates the detection limit of PRIMA without DDLs for planets around a $1\,M_\odot$ star at a distance of 10 pc. The lower dashed line shows the capability of PRIMA with DDLs. Only planets located above these lines can be detected by the respective method.

Right: Distribution of distances of stars with known RV planets vs. stellar mass. The two curves show the maximum distance at which a $1\,M_{\rm Jup}$ planet with a 3 yr orbit (approximate duration of our program) can be detected with the astrometric method with PRIMA without and with DDLs. Only planets located below these lines can be detected by the astrometric method. This diagram illustrates clearly that useful astrometric planet searches from the ground are only possible when PRIMA is equipped with DDLs.

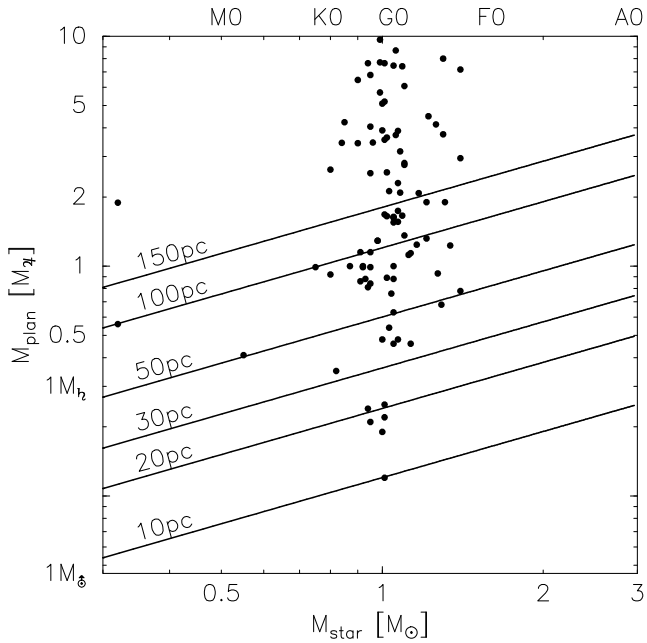

Figure 2: Mass detection limit for extra-solar planets around stars of different mass and at various distances from the Sun. Lines are shown for a 3 year orbit, the expected duration of our coherent guaranteed time program. For planets above a certain line, at least one full orbit with SNR > 5 ($5\,\sigma = 50\,\mu$arcsec) can be measured within 3 year period. For longer-period planets, the detection thresholds decrease towards lower planet masses. Known radial-velocity planets are shown for comparison (with $M \sin i$ instead of $M_{\rm Plan}$), without indicating their orbital period.

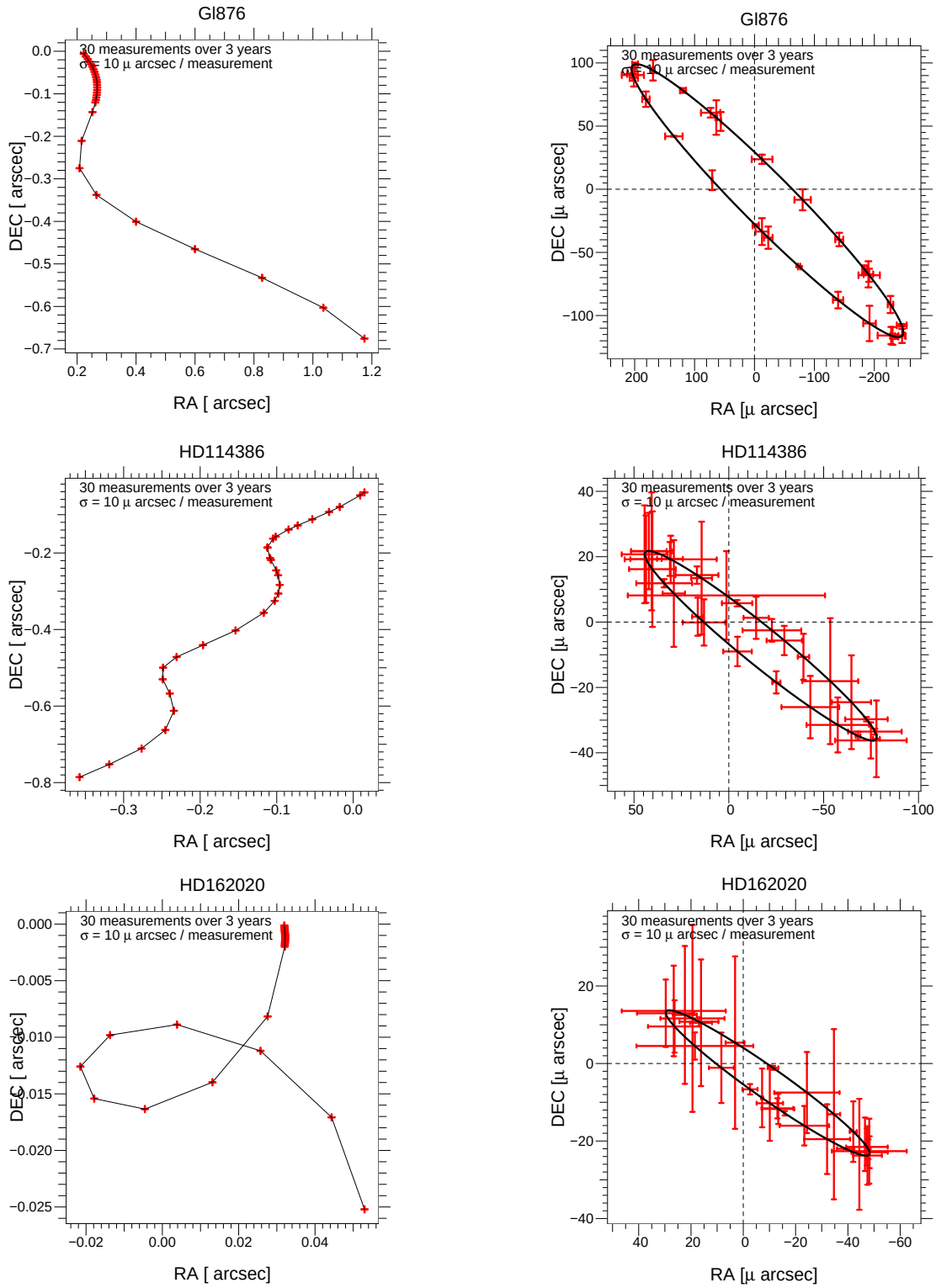

Figure 3: Illustration of parallax and orbital parameters retrieved from a global fit on the astrometric measurements for Gl 876, HD 162020 and HD 114386. For this simulation we assumed $i = 84$ deg, $\Omega = 25$ deg, and 30 measurements spread on 3 years and evenly distributed over the orbital phase.