Probing μ-arcsec astrometry with NACO

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Relative astrometric measurements with a precision far better than 1 mas (milli-arcsec) are commonly regarded as the domain of interferometry. Pioneering work by Pravdo & Shaklan (1996), made in the optical, reached a precision of $150\,\mu$arcsec in direct imaging but is ultimately limited by atmospheric turbulence and differential chromatic refraction (DCR) effects. Neuhäuser et al. (2006, 2007) demonstrated that AO assisted observations with NACO in a near-infrared narrow band filter allow measurements with a precision of $\sim 50\,\mu$as (micro-arsec) on a 0.6 arcsec binary within one hour and are unaffected by DCR effects. This opens new possibilities for astrometric detections of extrasolar planets and the determination of their true masses. We discuss here how to improve the measurements and address the necessary calibrations.

1 Motivation and Introduction

The search for extrasolar planets and their physical characterization has become an important field in today's astronomy and astrophysics. Dedicated instruments, such as HARPS on the ESO 3.6m telescope on La Silla were designed for precise radial velocity (RV) measurements to find the fingerprints of extrasolar planets, imprinted in the RV signal of their host stars. With this method more than 200 extrasolar planet candidates have been found. *Candidates* – because their masses are determind only to a lower limit, $m \sin i$. The inclination angle of the extrasolar planets are not constrained from RV measurements and the true mass of the planets is unknown.

Only two methods can add enough information to allow the determination of the inclination angle and thus the true mass of an extrasolar planet. In case of a nearly edge-on viewing geometry the planet can be seen in the lightcurve of the host star as a transit. However, such events are rare. Only astrometric measurements of the induced positional *wobble* of the host star can solve for the inclination of the system in all other cases.

Moreover, searches for extrasolar planets by astrometry are sensitive to planets in wide orbits, in contrast to the RV technique. A number of target classes unsuitable for RV measurements, such as early-type stars and

ultra-cool dwarfs, as well as fast rotating and otherwise active stars are also unproblematic for astrometry.

Astrometric measurements have the only intrinsic limitation that a large number of suitable reference stars have to be in the field of view (FOV) to define a local restframe. This restricts observation to fields of high stellar density, e.g. to low galactic latitudes. In addition the reference stars itself have to have known proper motion and parallaxes. Moreover, chromatic refraction effects as well as atmospheric turbulence limits the achievable precision. Thus, the only successful observations of the astrometric wobble of exoplanet host stars have been achieved from space, namely for GJ 876 b, 55 Cancri d and ϵ Eridani b, using the Fine Guiding Sensor (FGS) of the Hubble Space Telescope, see e.g. Benedict et al. (2006)

Neuhäuser et al. (2006, 2007) proposed the use of adaptive optics (AO) in the near infrared to (a) work in a regime where DCR effects are much smaller than in the optical and (b) to suppress the atmospheric turbulence. Since the usable field of view of AO assisted measurements is limited to the isoplanatic angle, measurements have to concentrate on physical binaries or multiple systems where the astrometric wobble of one component is measured relative to the other component(s). With this approach the problem of relative motion of the reference stars is solved since parallax and proper motion are identical for both components, leaving only the orbital motion as an open parameter. First measurements, conducted with NACO on the VLT in December 2004 and October 2006 let to unprecedented precision in ground based astrometry.

2 Results from the feasibility study

A first feasibility study, started in 2004, concentrated on the binary systems HD19994 and HD19063. The brighter component in HD19994 has a known exoplanet candidate as RV measurements by Mayor et al. (2004) revealed. The expected astrometric signal is at least 131 μas, when assuming the minimum mass $m \sin i$ as true mass and adopting the reported excentricity of the orbit.

Astrometric measurements with NACO were conducted in December 2004. The technique for high precision astrometry is based on a principle used in RV measurements. If the resolution and sampling of a measurement is not sufficient, statistics over many independent measurements have to be used to reach the necessary precision. In the RV technique, measurements over many hundred spectral lines provide the necessary statistical basis. For astrometric measurements a high number of images have to be taken. Separation measurements in each individual frame are checked for a Gaussian distribution and the error of the mean separation can be computed from the standard deviation of the mean divided by the square root of the number of frames. From 120 frames of HD19994 and 60 frames of HD19063 that passed the statistical tests, a precision in the separation of the binary components of

$\sim 92\,\mu$as and $\sim 50\,\mu$as, respectively, was reached within one hour. This marks the best relative astrometric precision ever achieved with a single aperture telescope from the ground.

3 Improvements: NACO cube mode

Each individual frame was taken through a narrow-band filter and the exposure time was set to the minimum DIT. Hence the measurements in 2004 where fully overhead dominated. Narrow band images with the fine pixel scale of NACOs S13 camera are read-noise limited up to several minutes of exposure time. Hence no jitter observations are necessary for sky subtraction and frames can be taken in staring mode. Thus, we used the cube mode of NACO in our second observation campaign in October 2006 to obtain more frames per given time than in autojitter mode. The chip had to be windowed to handle the high data rate. The readout overheads are strongly suppressed and several thousand frames can be taken per hour. Compared to the results from the previous run, we could improve our efficiency by more than a factor of 50.

4 Calibration Issues

The precision achieved here marks a breakthrough in ground based relative astrometry. It demonstrates that measurements in the separation of a close binary with a precision to about 4/100,000 are possible with NACO. This raises the question on the calibration of such measurements. In the scheme presented here, we do not need to provide an absolute calibration of the pixel scale. We are aiming to determine relative changes in the separation of a stellar binary of about 1/100 of a pixel, but not its absolute value. Thus, the uncertainties in the determination of the absolute pixel scale, typically of the order of 4/1000 (see Neuäuser et al. 2006, or Chauvin et al. 2004) are not the dominating error source, especially since we are not aiming for high accuracy but for high precision. Instead we have to assure the stability of the pixel scale (or reversely the f-ratio of the imager) to better than 4/100,000. The typical calibration sources, HIPPARCOS binaries, have precise coordinates but the uncertainties in their proper motion multiplied by the time since the HIPPARCOS epoch of 1991.25 rule out these sources as calibrators on the needed level of precision. The same holds for the SiO masers in the galactic center. Eventhough these objects have possibly the best known astrometric properties (from VLBA measurements), they are not fitting into the FOV of the S13 camera.

Hence, we have to look for an intrinsically stable reference system that would fit into the FOV of the S13 camera. After a concise literature study,

we selected 47 Tuc as a reference system. 47 Tuc is an old globular cluster with a known and small velocity dispersion. McLaughlin et al. (2006) recently determined the two dimensional velocity dispersion in a spherical region around the cluster core within a 20 arcsec radius. For the red giant stars a value of $\sigma_\mu = 0.631^{+0.020}_{-0.025}$ mas/year was reported. To determine the intrinsic astrometric stability, we have measured all separations between any two stars in one sub-field of 47 Tuc for the first time in October 2006 over a large number of frames and we will monitor these quantities in the next observing campaigns.

The relative stability of the pixel scale, obtained with measurements of 47 Tuc depends on the number of stars in the observed sub-field and their mean separation. Due to error statistics, the standard deviation of the separation measurements can be divided by the square root of the number of independent separations, which is $n-1$ with the number n of stars. This relation has been confirmed by a Monte Carlo simulation, tested on a Gaussian distributed field of 20 stars as well as on our true measurements that have the same field density. Adopting a random velocity dispersion of 630 mas/year (hence, no symmetry), the stability of the pixel scale can be assured with a precision of $\sim 60\mu$as for one year. Hence, the intrinsic relative stability of the reference system is mainly limited by the velocity dispersion and the number and geometry of the stars within the sub-field.

We conclude that high resolution astrometry with NACO is neither limited by the atmosphere nor by the instrument itself but by suitable reference objects with a high intrinsic stability. This is true as long as the stability of the pixel scale on a level of a few in hundred thousand can not be implied but has to be confirmed and monitored with on-sky measurements.

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