A Giant Step: from Milli- to Micro-arcsecond Astrometry
Proceedings IAU Symposium No. 248, 2007
W. J. Jin, I. Platais & M. A. C. Perryman, eds.

doi:10.1017/S1743921308018619

Micro-arcsecond relative astrometry by ground-based and single-aperture observations

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Abstract. We present an observation method to obtain a relative astrometric precision of about $100\ldots150\,\mu as$ with ground-based and single-aperture observations. By measuring the separation of double or triple stars we want to determine the astrometric signal of an unseen substellar companion as a periodic change in the separation between the stellar components. Using an adaptive optics system we correct for atmospheric turbulences and furthermore by using a narrow band filter in the near infrared we can suppress differential chromatic refraction effects. To reach a high precision we use a statistical approach. Using the new observation mode "cube-mode" (where the frames were directly saved in cubes with nearly no loss of time during the readout), we obtain several thousand frames within half an hour. After the verification of the Gaussian distributed behaviour of our measurements (done with a Kolmogorov-Smirnov-Test) the measurement precision can be calculated as the standard deviation of our measurements divided by the square root of the number of frames.

To monitor the stability of the pixel scale between our observations, we use the old globular cluster 47 Tuc as a calibration system.

Keywords. astrometry, methods: statistical, instrumentation: adaptive optics, binaries: general, planetary systems, globular clusters: individual (47 Tuc)

1. Introduction

Up to now, most of the extrasolar planets have been detected with the radial velocity technique. Due to the unknown inclination angle i this technique just yields the lower mass limit $M \sin i$ and not the true mass of the substellar companion. Therefore, all radial velocity planets should be regarded as planet candidates, until their true mass is determined. In contrast to the radial velocity technique, astrometry yields the inclination angle by measuring the astrometric signal of the substellar companion and hence its true mass. Recently, Bean *et al.* (2007) measured the astrometric signal of the radial velocity planet candidate HD 33636 b ($M \sin i = 9.3\,M_J$) and obtained a value for the true mass of the companion of $M = 142 \pm 11\,M_J$, thus it is a low mass star. This clarifies the importance of astrometric follow up observations to determine the true mass of radial velocity planet candidates. The mass is one of the most important stellar and substellar parameters and plays a key role in our understanding of the distribution, formation and evolution of substellar objects. Besides all other methods to determine the mass, which are using theoretical predictions (like evolutionary models), astrometry is a method, which is independent from theoretical assumptions (hence, from theoretical uncertainties) by measuring the dynamical mass of the objects. Up to now, three radial velocity planet candidates have been confirmed with absolute astrometry using the Fine Guiding Sensor (FGS) of the Hubble Space Telescope (HST), GJ 876 b by Benedict *et al.* (2002), 55 Cancri d by McArthur *et al.* (2004) and ϵ Eridani b by Benedict *et al.* (2006).

The idea, to search for extrasolar planets with astrometry is not a new one. Already van de Kamp (1969) observed Barnard's star and believed to find a planetary companion because of the measured non-linear movement of the star (absolute astrometry). Later, different groups like Gatewood *et al.* (1973) could not reproduce the detection of an astrometric signal of a possible substellar companion. The origin of the measured residuals in the position and the movement of Barnard's star in the data by van de Kamp (1969) were unknown systematic errors of the observation technique. This clarifies the complexity of doing astrometry, especially absolute astrometry. Until the beginning of the 1980s, about 50 stars (including Barnard's star and ϵ Eridani) with assumed unseen stellar and substellar companions were discussed. A summary of the astrometric search for unseen companions and the discussed stars at this time can be found in Lippincott (1978).

About 20 years later Pravdo and Shaklan (1996) measured the position of about 15 members of the open cluster NGC 2420 from the ground and reached an astrometric precision in the optical of about $150\mu as$. They identified the atmospheric noise and the differential chromatic refraction (DCR) as the limiting effects in the reached precision. Pravdo and Shaklan (1996) also mentioned the importance of a careful and long-term calibration to handle the systematic errors.

2. Observation method

To reach a precision comparable to the HST observation, we observe double and triple stars and measure the separation between all stellar components, thus using relative astrometry. In the case of an unseen substellar companion, we would measure the astrometric signal indirectly as a relative and periodic change in the separations.

The quest of measuring the astrometric signal of a substellar companion needs a careful handling of all noise sources, such as atmospheric noise, photon noise, background noise, readout-noise, DCR and others. Our observations on the southern hemisphere are done with the 8.2 meter telescope UT4 of the ESO Very Large Telescope (VLT) and the NACO S13 (NAOS-CONICA) infrared camera. Using the adaptive optics system NAOS (Nasmyth Adaptive Optics System) we correct for atmospheric turbulence and by using a narrow band filter centered in the near infrared ($\lambda_{cen} = 2.17\,\mu m$) we suppress DCR effects. Due to the use of the double-correlated readout mode, we suppress readout noise and by choosing a suitable exposure time (to reach a high signal to noise ratio) we can neglect photon and background noise.

The pixel scale of the detector (NACO S13) is about $13.25\,mas$, which means a Field of View (FoV) of about $14'' \times 14''$. A guide star for the AO system is always one of the stellar components. The separation of our observed multiple systems is typically four arcseconds. Hence, the angular separation is (with normal seeing conditions) always smaller than the isoplanatic angle.

Furthermore (besides the use of relative astrometry), we use a new observation mode, called "cube-mode". This mode saves frames directly into a cube and thus has nearly a zero loss of time during the readout. With the minimal exposure time of 0.35 seconds using the double-correlated readout mode it is possible to obtain 2500 frames in 15 minutes.

The following statistical principle is similar to the method of measuring the radial velocity with hundreds of spectral lines to reach a higher precision, which is used in the radial velocity technique. In our astrometric case we measure the separation between all stellar components in each frame and obtain several thousand measurements of the same separation. After a verification of the Gaussianity of measurements (done with a Kolmogorov-Smirnov-Test) and a two sigma clipping (to reject frames with low quality due to the non-constant performance of the AO system and the dynamical seeing behaviour), the measurement precision (Δ_{meas}) can be calculate as the standard deviation of the measurements (σ_{meas}) divided by the square root of the number of Gaussian distributed measurements (N), $\Delta_{meas} = \frac{\sigma_{meas}}{\sqrt{N}}$.

We have to keep in mind that the above value is just the measurement precision and describes only the statistically distributed sources of random errors. To determine the sources of systematic errors, which affect in the case of relative astrometry the pixel scale and the position angle, we need a special calibration reference system.

3. Calibration

Because we are dealing with relative astrometry we do not need an absolute astrometric calibration of our data, but we have to monitor the stability of our pixel scale to correct our measurements for possible variations of the pixel scale. The "normal way" of relative astrometric calibration is to use a Hipparcos binary system. This method results in the case of the NACO detector in a pixel scale of typically $13.25 \pm 0.05\,mas$ per pixel (see Neuhäuser *et al.* (2005)), which means a relative error of about 4/1000 of a pixel per pixel. Our measurement precision for our first observed binary system (HD 19994) are lower than 3/1000 of a pixel for a separation of about 175 pixel (see Fig. 1). This means, we need a calibration system where we can monitor the pixel scale down to a relative value of better than 2/100000 per pixel. Taking the $13.25\,mas$ as a given and fixed "reference pixel scale" for our first epoch, we have to use a calibration system, where we can detect changes in the pixel scale down to $0.2\,\mu as$ per pixel within one year.

The requirements for such a calibration system are a high intrinsic and known stability, a lot of "calibration stars" in the FoV of NACO and it should be bright enough for observations with the narrow band filter in the near infrared (due to DCR). We choose a core region of the old globular cluster 47 Tuc as a suitable calibration system for our targets on the southern hemisphere. The reasons are a relative large number of stars within the NACO FoV and a known intrinsic stability. McLaughlin *et al.* (2006) determined the transversal velocity dispersion of the 47 Tuc cluster members and obtained a value of about 630 μas yr^{-1}. To monitor the pixel scale we take hundreds of frames of 47 Tuc per epoch, measure the separation from each star to each star and compute the mean of all these separation measurements on every single frame. This mean of the separations represents the relative alignment of all observed cluster members and should have, within the errors (intrinsic instability and measurement errors), the same value every epoch. Using a Monte-Carlo-Simulation with our observed cluster members and a Gaussian distributed transversal velocity dispersion of $630\,mas$ yr^{-1}, we obtain an intrinsic stability of our used calibration cluster of about 3/100000 per pixel and year, which results for the given pixel scale of $13.25\,mas$ an intrinsic stability of about $0.4\,\mu as$ per pixel and year. This means, with 47 Tuc we are able to determine a change in the pixel scale down to $0.5 \ldots 1\,\mu as$ per pixel and year (including the typical measurement errors of the 47 Tuc cluster members). Due to the fact, that we are using a fixed and given "reference pixel scale" in our first epoch, we can not determine the absolute value of the pixel scale, but we are able to detect changes very precisely.

The difference between our intrinsic stability and the measurement precision of our first observed double star (HD 19994) shows, that we are limited by our used calibra-

https://doi.org/10.1017/S1743921308018619 Published online by Cambridge University Press

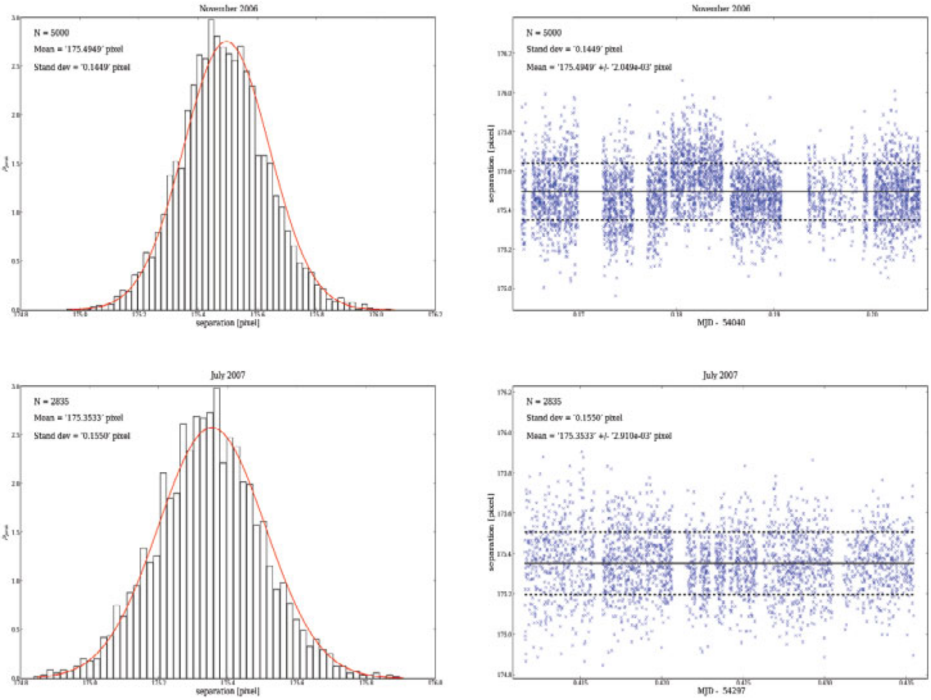

Figure 1. Separation measurements (right) and the Gaussian distribution of the measurements (left) of the stellar binary HD 19994 from 2006 (top) and 2007 (bottom)

tion system and not by noise sources like atmospheric noise, DCR or readout noise, which affect the measurement error. At the end, we achieve a total relative precision of $100 \ldots 150\,\mu as$ per epoch for the double star HD 19994. Mayor *et al.* (2004) found a radial velocity planet candidate of $M \sin i = 1.68\,M_J$ around HD 19994 A. The expected change in the separation (due to the astrometric signal of the planet candidate) depends on the orientation of both orbits (planetary and double star orbit) and is about $300\,\mu as$, for $\Delta i = 35°$ ($M_{true} = 2.6\,M_J$), about $450\,\mu as$ for $\Delta i = 50°$ ($M_{true} = 4.9\,M_J$, $2\,\sigma$ detection) and about $600\,\mu as$ for $\Delta i = 80°$ ($M_{true} = 6.9\,M_J$, $3\,\sigma$ detection). In the case of an astrometric non-detection we are able to exclude differences in the inclination of more than $\Delta i = 80°$ ($3\,\sigma$ detection) and thus to exclude true masses of more than $7\,M_J$.

References

Bean, J. L., McArthur, B. E., Benedict, G. F., Harrison, T. E. *et al.* 2007, *ApJ*, 134, 749
Benedict, G. F., McArthur, B. E., Forveille, T., Delfosse, X. *et al.* 2002, *ApJ*, 581, 115
Benedict, G. F., McArthur, B. E., Gatewood, G., Nelan, E. *et al.* 2006, *ApJ*, 132, 2206
Gatewood, G. & Eichhorn, H. 1973, *AJ*, 78, 769
Lippincott, S. L. 1978, *Space Sci. Revs*, 22, 153
Mayor, M., Udry, S., Naef, D. *et al.* 2004, *A&A*, 74, 238
McArthur, B. E., Endl, M., Cochran, W. D., Benedict, G. F. *et al.* 2004, *ApJ*, 614, 81
McLaughlin, D. E. & Anderson, J. & Meylan, G. *et al.* 2006, *ApJS*, 166, 249
Neuhäuser, R., Guenther, E. W., Wuchterl, G. *et al.* 2005, *A&A*, 435, 13
Pravdo, S. H. & Shaklan, S. B. 1996, *ApJ*, 456, 264
van de Kamp, P. 1969, *AJ*, 74, 238

https://doi.org/10.1017/S1743921308018619 Published online by Cambridge University Press