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High-precision Astrometric Studies in Direct Imaging with SPHERE

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Orbital monitoring of exoplanetary and stellar systems is fundamental for analysing their architecture, dynamical stability and evolution, and mechanisms of formation. Current high-contrast extreme-adaptive-optics imagers like the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), the Gemini Planet Imager (GPI) and the Subaru Coronagraphic Extreme Adaptive Optics/Coronagraphic High Angular Resolution Imaging Spectrograph combination (SCExAO+CHARIS) explore the population of giant exoplanets and brown dwarf and stellar companions beyond typically 10 au, but they cover

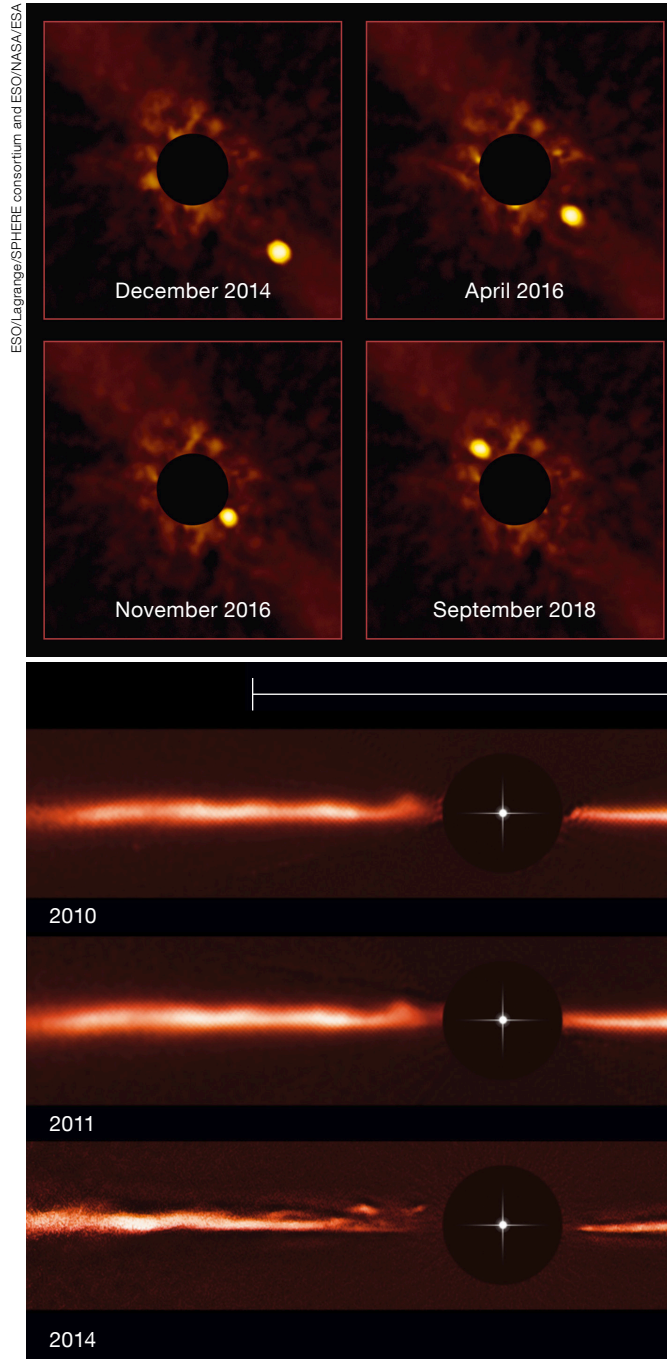


Figure 1. SPHERE images at different epochs of the giant exoplanet β Pictoris b (left) and of arch-like disc features in the debris disc of AU Microscopii (bottom). High-precision relative astrometry is fundamental to measuring the slow motions observed, from south-west to north-east for the planet and away from the star for the disc features. In the bottom panel, the scale bar at the top of the picture indicates the diameter of the orbit of the planet Neptune in the Solar System.

only a small fraction ($< 20\%$) of the orbit, leading to degeneracies and biases in the orbital parameters. Precise and robust measurements of the position of the companions over time are critical, requiring good knowledge of the instrumental limitations and dedicated observing strategies. The homogeneous dedicated calibration strategy for astrometry

implemented for SPHERE has facilitated high-precision studies by its users since it began operating in 2014. As the precision of exoplanet-imaging instruments is now reaching milliarcseconds and is expected to improve with forthcoming facilities, we initiated a community effort, triggered by the SPHERE experience, to share lessons learned for high-precision

astrometry in direct imaging. A homogeneous strategy would strongly benefit the Very Large Telescope (VLT) community, in synergy with VLT Interferometer instruments like GRAVITY/GRAVITY+ and future instruments like the Enhanced Resolution Imager and Spectrograph (ERIS) and the MCAO-Assisted Visible Imager and Spectrograph (MAVIS), and in preparation for the exploitation of the Extremely Large Telescope's (ELT's) first instruments: the Multi-AO Imaging Camera for Deep Observations (MICADO), the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI), and the Mid-infrared ELT Imager and Spectrograph (METIS).

Motivation

High-precision relative astrometry in direct imaging is crucial for various science cases, beyond determining the orbital parameters of exoplanets, brown dwarf companions or multiple stellar systems. For exoplanet surveys (Langlois et al., 2020), it is instrumental in testing the nature of the faint sources detected near the targeted stars (Figure 1, top). The fields of view used are typically too small for absolute astrometry, so astrometry relative to the targeted star is used. Multiple-epoch monitoring enables one to test whether the candidate companions are comoving, with proper and parallactic motions similar to those of the host star, by rejecting contamination by stationary (or slowly moving with the local field) background or foreground sources. More precise measurements allow for faster confirmations. This approach requires a second observation, for example from archival data. One must be aware of the possibility that a candidate companion having significant proper motion might mimic a physical companion with orbital motion (for example; Nielsen et al., 2017). Multiple-epoch monitoring remains the most reliable approach to confirming a candidate companion, and ultimately resolving its orbital motion to confirm that it is gravitationally bound.

Constraining the orbital parameters of a companion provides clues to its formation and dynamical history. Orbits with small eccentricities are consistent

with planet formation within circumstellar discs, and are similar to the Solar System's configuration. Larger eccentricities might be connected to star-like formation mechanisms; or they may indicate subsequent dynamical planet-planet interactions in multiple planetary systems that could explain the broad eccentricity distribution of exoplanets detected with the radial velocity technique. Another valuable output of orbital fits are predictions of positions. This is important for optimising follow-up observations at longer wavelengths (lower angular resolution) or with slit/fibre spectrometry.

There is a strong synergy between direct imaging, radial velocities and absolute astrometry for orbital fits. Firstly, it can constrain the masses of the companions, which is a fundamental step towards the calibration of models of the evolution of young giant planets, brown dwarfs, and low-mass stars. For imaged companions, most mass measurements come from evolutionary models, which suffer from large theoretical uncertainties (for example, clouds and molecular opacities for the atmosphere, initial entropy for the formation). Secondly, it allows for the breaking of degeneracies in the orbital parameters. Radial velocities are degenerate with the inclination (essential to constrain the mass), but the degeneracy is lifted by using imaging and absolute astrometry. For multiple-companion systems, direct imaging is valuable for breaking the degeneracies with radial velocities or absolute astrometry that are due to the unknown orbital phases, although analysis of the dynamical stability may also be used. Thanks to the 24-year baseline between Hipparcos and Gaia DR2, absolute astrometry can now detect massive substellar companions at the separations probed by direct imaging. Bridging these techniques will increase with Gaia and the ELT to closer-in and/or planetary-mass companions, with the prospect of a complete view of planetary and stellar systems.

Direct imaging offers a unique means to simultaneously analyse companions and their birth environment, the circumstellar discs. Determining the orbits of the companions provides insights into potential dynamical interactions. Such systems provide valuable benchmarks for planet formation and migration models. The

analysis of companion-disc dynamical interactions will also help to clarify which disc features (for example, spiral arms, rings, clumps) can be reliably associated with companions. Another research field that has recently emerged involves monitoring the motion of disc features to discriminate between different production mechanisms (Figure 1, bottom). For instance, misaligned inner discs or close-in companions have been proposed to explain shadows cast on the outer discs in various protoplanetary discs.

The problem of astrometric biases

The advent of the first dedicated exoplanet imaging instruments (SPHERE, GPI, SCExAO+CHARIS; for example, Beuzit et al., 2019) has improved the precision of relative astrometric measurements of young substellar companions, from about 10 milliarcseconds to about 1–2 milliarcseconds.

Measurements with higher precision are more sensitive to underestimated biases. These can be caused by the use of different methods for the data analysis and/or calibration, our limited knowledge of the thermo-mechanical stability of the instruments, and the use of different instruments (after upgrades, for example). Given the long orbital periods of the imaged companions compared to the lifetimes of instruments, maximising the measured orbital arc is vital if we are to derive more robust orbital constraints. Underestimated biases may also affect co-motion tests of candidate companions and trigger follow-up observations by mistake, wasting telescope time.

Figure 2 illustrates the importance of a good knowledge of the biases in co-motion tests of candidate companions using different instruments. For a star with many candidate companions, the biases can be estimated by assuming that most of them are background contaminants. For a star with a single candidate companion, a new observation is required to reach a conclusion.

Figure 3 illustrates the importance of a good knowledge of the biases in orbital fits for the exoplanet HIP 65426 b (Chauvin et al., 2017; Cheetham et al.,

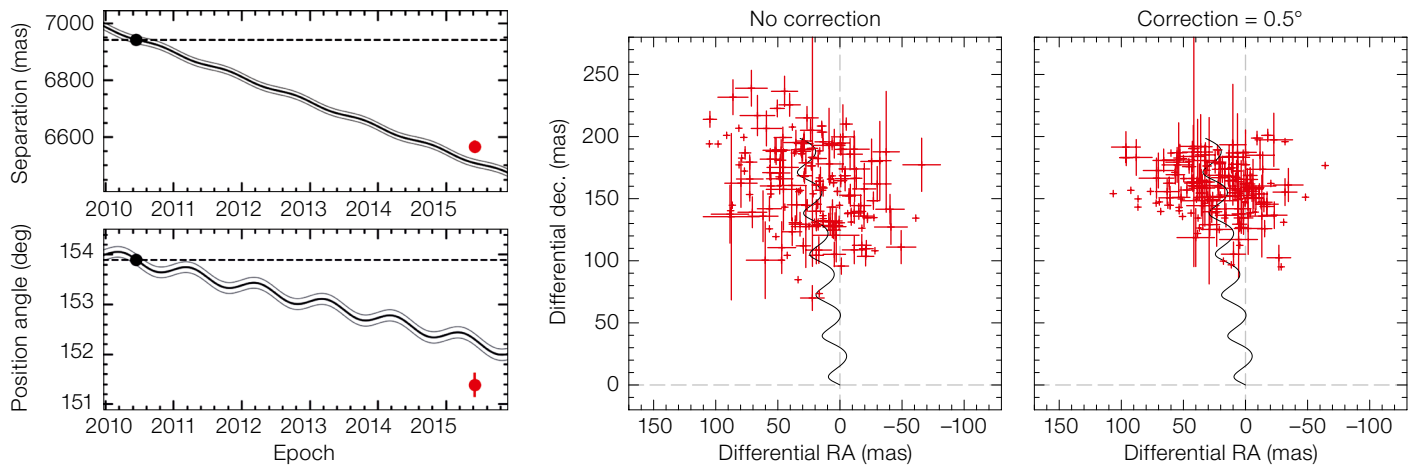


Figure 2. Tests for companionship of companion candidates detected around stars with SPHERE and NACO showing the importance of a good knowledge of the biases in relative astrometry for the interpretation. The left panel shows the temporal evolution of the separation from the star (top) and position angle relative to north (bottom, taken as positive from north to east) for a single candidate companion

compared to the evolution for a stationary background contaminant (black curve with grey areas). The motion of the point source does not follow the stationary background track, suggesting a physical companion. However, underestimated systematic uncertainties could account for the discrepancies. The right panel shows the differential declination as a function of the differential right ascension for a star

with many candidate companions (red data points) for two values of the assumed correction angle to the north. The black curves show the motion for a stationary background contaminant. If most candidate companions are assumed to be stationary background contaminants, a correction angle to the north is needed to make their motion compatible with the expected behaviour.

2019). Low eccentricities and a bimodal distribution of the time at periastris are favoured when combining data obtained in 2016–2017 from SPHERE and the Nasmyth Adaptive Optics System/COudé Near-Infrared CAmera (NAOS-CONICA, or NACO), whereas the eccentricity is not well constrained and can be high and the periastris is in the future when fitting SPHERE data obtained in 2016–2018. These discrepant results point to underestimated systematic uncertainties between the SPHERE and NACO data.

SPHERE astrometric strategy

A homogeneous and regular astrometric calibration is crucial to minimising the biases and analysing the astrometric stability over time. Good astrometric stability eases co motion tests and orbital monitoring of imaged companions. It relaxes the need to take calibration data close to the science observations and reduces the calibration overhead at the telescope.

The astrometric strategy for the SPHERE INfrared survey for Exoplanets (SHINE) was devised by the consortium before commissioning and was subsequently refined. It relies on: 1) an observing procedure to precisely determine the star's location behind the coronagraph (Langlois

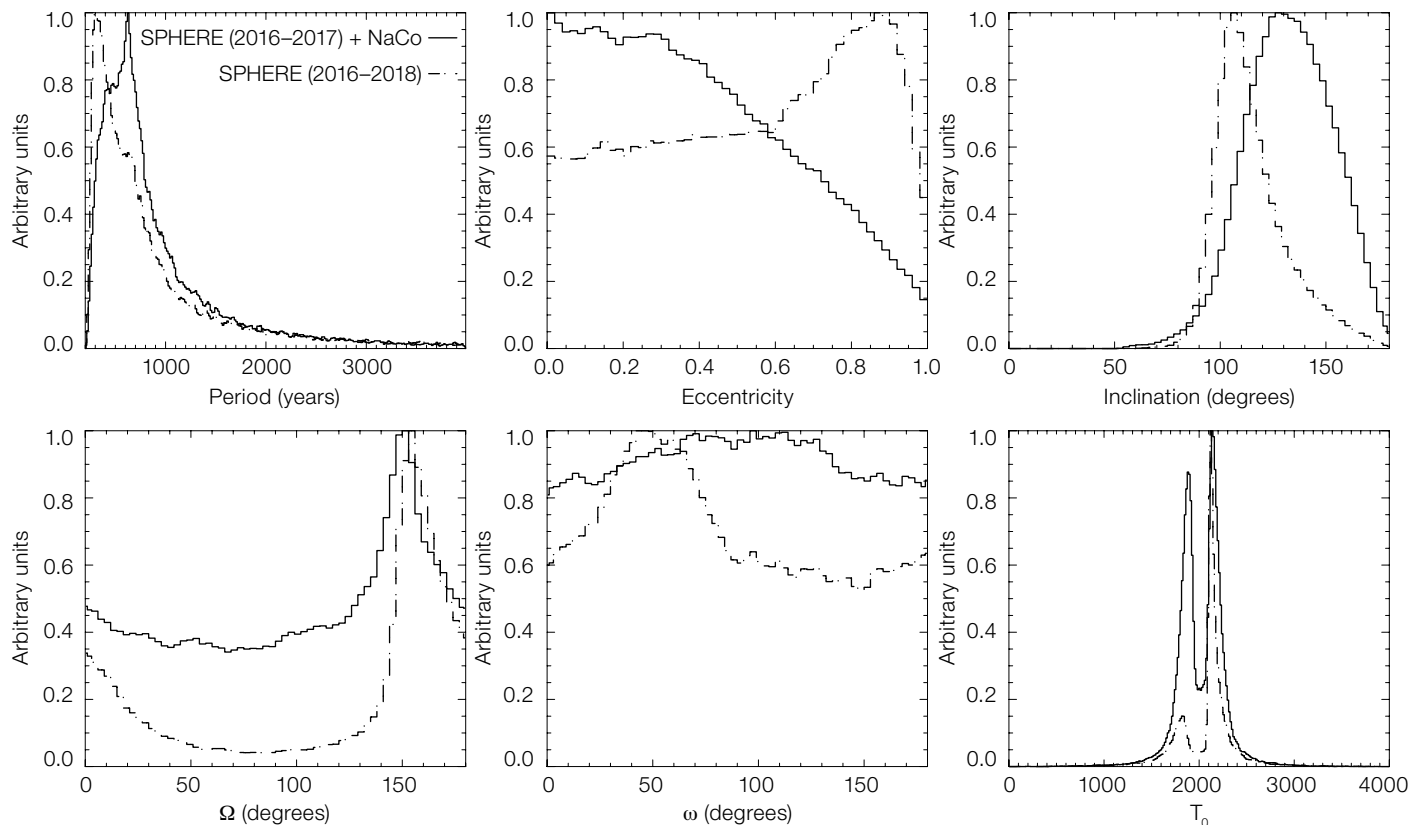
et al., 2020); 2) an accurate determination of the instrument overheads and metrology; and 3) regular observations of fields in stellar clusters for the astrometric calibration (Figure 4; Maire et al., 2016).

We chose fields in stellar clusters as main astrometric calibrators because the large number of stars available allows for precise measurements. They also allow for measuring the distortion from the telescope optics. We selected cluster fields with positions measured precisely by the Hubble Space Telescope, which has a good absolute calibration. We further selected fields with a bright star for adaptive optics (AO) guiding ($R \leq 13.5$ mag). Finally, we repeatedly observed two fields to cover the whole year, 47 Tucanae and NGC 3603. We chose 47 Tucanae as the reference field because the catalogue provides the stellar proper motions (Bellini et al., 2014). Langlois et al. (2020) compared the relative astrometry for widely-separated and bright candidate companions observed with SPHERE and present in the Gaia DR2 catalogue. The mean offset in separation is -2.8 ± 1.5 milliarcseconds (3.9 milliarcseconds RMS) and in position angle is 0.06 ± 0.04 degrees (0.11 degrees RMS). The RMS measures agree well with the expected uncertainties in these quantities in SPHERE data.

To analyse the astrometric data and derive the calibration, we developed a tool (Maire et al., 2016) that is included in the SPHERE Data Centre¹. The distortion is mainly due to the optics in SPHERE and is stable in time (see Table). It produces differences in the horizontal and vertical pixel scales which amount to 6 milliarcseconds at 1 arcsecond. The astrometric requirement is 5 milliarcseconds (the goal being 1 milliarcsecond).

Figure 5 shows the temporal evolution of the pixel scale and correction angle to the north (Maire et al., in preparation). Except for pixel scale measurements obtained during commissioning, SPHERE has demonstrated a remarkable astrometric stability over five years. The standard deviation for the pixel scale measured on 47 Tucanae is 0.004 milliarcseconds pixel⁻¹ and for the correction angle to the north 0.04 degrees. These variations translate into uncertainties at 1 arcsecond of 0.33 and 0.70 milliarcseconds, respectively, which is within the baseline astrometric requirements. We plan to release the measurements in the SPHERE Target Data Base².

The pixel scale and correction angle to the north have also been monitored in the ESO monthly calibration plan. The SHINE astrometric fields have been



observed without the coronagraph. We analysed the data at the SPHERE Data Centre to compute an astrometric table for the reduction of the open-time data. About 80% of the observations were not suitable for deriving a good calibration. Work is ongoing with the ESO staff to improve the setup of their observations.

The astrometric calibration of the SPHERE images also requires measurement of the offset angle of the pupil in pupil-tracking mode. The pupil-tracking mode allows for subtracting the aberrations in the images that are due to the telescope and the instrument. We monitored this parameter in 2014–2016 and showed that it is stable. Work is ongoing to monitor it in the ESO calibration plan.

In contrast, the astrometric calibration for NACO was heterogeneous, irregular, and mostly left to the observing teams. NACO also underwent technical interventions to commission new observing modes or fix issues, and was moved to another Unit Telescope of the VLT. This resulted in poor astrometric stability, making the use of the data for high-precision relative

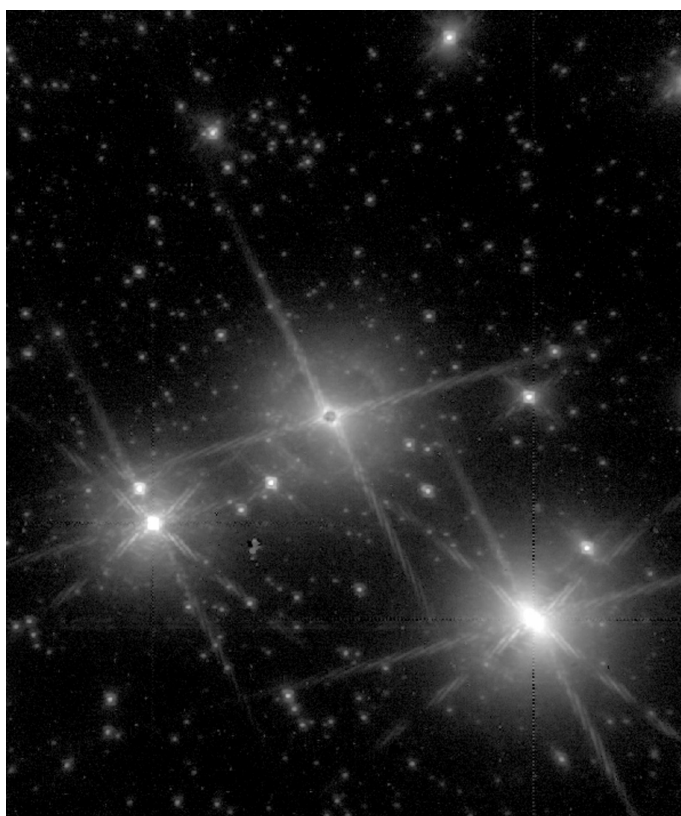


Figure 3. (Above) Distributions of the orbital parameters of the exoplanet HIP 65426 b using two different sets of relative astrometric measurements. A good knowledge of the biases is mandatory in order to derive unbiased constraints. The panels show the period, eccentricity, inclination, longitude of the node, and argument and time at periastris, from left to right and top to bottom.

Figure 4. (Left) SPHERE image of the 47 Tucanae field used for the astrometric calibration. The field of view is ~ 11 arcseconds on one side.

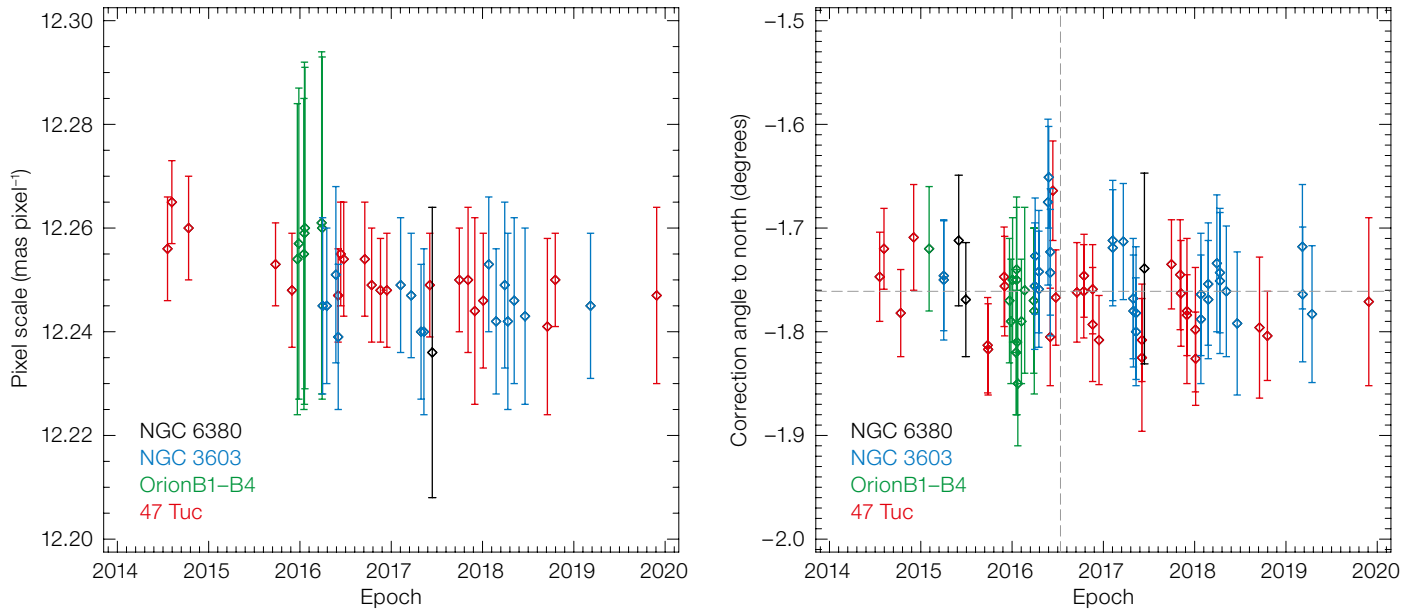


Figure 5. Evolution of the pixel scale (left) and correction angle to the north (right) of SPHERE. A good instrument stability is mandatory for high-precision relative astrometry over time because it reduces potential systematic uncertainties. Fewer measurements are shown for the pixel scale because it depends on the filter and coronagraph configuration. For the right panel, the dotted-dashed vertical line indicates the epoch when the time reference issue was solved (Maire et al., 2016). All previous measurements were corrected. The dashed horizontal line shows the weighted mean of all the measurements.

astrometry more difficult. The limitations encountered with NACO were taken into account in the astrometric strategy of SPHERE.

Required separation precision (mas)	5 (goal: 1)
Required position angle precision (deg)	0.2
Achieved precision calibration pixel scale at 1" (mas)	0.33
Achieved precision calibration distortion at 1" (mas)	0.2
Achieved precision calibration angle to north (deg)	0.04
Achieved precision calibration angle pupil tracking (deg)	0.06

Highlights from SPHERE results

Thanks to the good astrometric precision and stability of SPHERE, most users rely on the calibration derived by the instrument consortium. SPHERE has enabled the discovery of 15 substellar

and stellar companions next to stars. It has been used for about 20 orbital studies, in combination with other imaging, radial velocity, and/or absolute astrometric measurements.

The orbital analyses of the exoplanets β Pictoris b (Lagrange et al., 2019) and 51 Eridani b (Maire et al., 2019) are good examples of where biases between different instruments had to be dealt with. β Pictoris b was monitored with NACO and then SPHERE. It was recovered in September 2018 after conjunction with the star. The SPHERE data are now probing the north-east part of the orbit, which was only covered by one NACO measurement in 2003, and they favour low eccentricities. 51 Eridani b was monitored for three years. Coupled with GPI data, orbital curvature was detected in this system for the first time and the fit suggests a high eccentricity (~ 0.3 – 0.6). A high eccentricity hints at dynamical interactions that perturbed the orbit of the planet, possibly by another as-yet-undetected planet.

The orbital predictions were also used for GRAVITY observations to get spectra at longer wavelengths and higher resolutions (2.0 – $2.4 \mu\text{m}$, $R \sim 500$) compared to SPHERE (1.0 – $2.3 \mu\text{m}$, $R \sim 50$) and to get exquisite astrometry (~ 30 times more precise), confirming the robustness of the SPHERE calibration plan. Companion-disc dynamical interactions were studied

in several systems, including systems with a brown dwarf within the cavity of the debris disc. HR 2562 B could carve the disc cavity, whereas another companion may be needed around HD 206893. Disc features were monitored, such as the arch-like features moving away from the star AU Microscopii. The current scenario involves dust produced by an unseen parent body and expelled by the stellar wind. The rotation of the spiral arms of MWC 758 was shown to be compatible with a planet-driven mechanism.

Future astrometric studies with direct imaging facilities at ESO

Further monitoring of known companions and disc features will be important for refining their orbits and their formation mechanisms, respectively. Moreover, Gaia is expected to detect a large number of giant exoplanets. Young exoplanets detected from acceleration measurements will be prime targets for imaging, to confirm and firmly constrain their orbits and masses. This large sample of exoplanets beyond a few au will allow for statistical analyses of the distributions of eccentricities and relative inclinations to the stellar equatorial planes (for multiple-planet systems and also mutual inclinations). Such analyses will be crucial to understanding their formation and evolution, and the relation between planet and binary-star formation mechanisms.

The next step for exoplanet imaging will be made with the ELT and its first three instruments: MICADO, HARMONI, and METIS. They will access smaller planet-star separations, down to 1 au, to detect predominantly giant exoplanets. Thanks to the combination of increased angular resolution and larger collecting aperture, diffraction-limited ELT observations will at the same time access smaller angular separations and achieve higher astrometric precision at angular separations accessible to 8-metre-class imagers. MICADO and HARMONI will be sensitive to young planets, whereas METIS will reach mature planets. Before the ELT, ERIS, GRAVITY+, and a potential SPHERE upgrade will be operational on the VLT/I. ERIS will be suitable for imaging giant exoplanets around young stars, and more mature giant exoplanets which are too faint for the SPHERE AO system. GRAVITY+ will have better sensitivity than GRAVITY to access mature exoplanets.

A joint and homogeneous strategy shared by the exoplanet imaging facilities at ESO will enhance their use for high-precision astrometry, by minimising biases. The successful calibration plan implemented for SPHERE could be applied and adapted to these instruments. If proposed by future instrument consortia, interactions with ESO would be valuable to check whether such a calibration plan could be adopted. As SPHERE is expected to be operational during the first years of the ELT's opera-

tion, parallel observations could be used to check the astrometric consistency. GRAVITY could be used to test/validate the absolute calibration of coronagraphic instruments, thanks to the absolute calibration provided by its internal metrology system (Lacour et al., 2014).

We recently started an initiative between the SPHERE team and the teams in charge of the high-contrast imaging modes of forthcoming ESO exoplanet imaging facilities at the VLT/I and ELT to share the SPHERE experience and the lessons learned in the field of astrometric characterisation of exoplanets and discs. We firmly believe that this offers the opportunity to federate our community: 1) to revisit past studies through archival data mining, 2) to push the calibration strategy and performance of current instruments in operation, and 3) to share this expertise with consortia of forthcoming instruments at the VLT/I and ELT to optimally prepare their scientific exploitation. We expect to prepare a workshop on this topic in the future.

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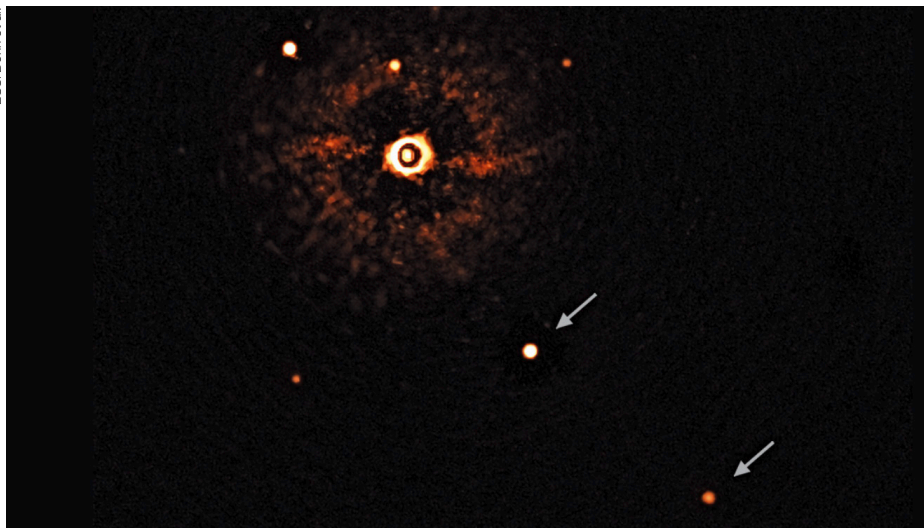
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Links

- ¹ The SPHERE Data Centre: <https://sphere.osug.fr/spip.php?article45&lang=en>
- ² The SPHERE Target Database: <http://cesam.lam.fr/spheretools>

ESO/Bohn et al.



This image, captured by the SPHERE instrument on ESO's Very Large Telescope, shows the star TYC 8998-760-1 accompanied by two giant exoplanets, TYC 8998-760-1b and TYC 8998-760-1c (annotated with arrows). This is the first time astronomers have directly observed more than one planet orbiting a star similar to the Sun.