Holographic Imaging: A Versatile Tool for High Angular Resolution Imaging

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Speckle holography can be used to reconstruct high angular resolution images from long series of short exposures if the point spread function (PSF) from each frame can be measured reliably. We show that through use of multiple reference stars and iterative PSF subtraction, we can obtain highly accurate PSFs. The technique is optimised for crowded fields and results in images with excellent cosmetics and high Strehl ratio from the optical to the mid-infrared regimes. With examples from NACO, VISIR, and HAWK-I we show that holography opens up novel and unforeseen possibilities and can be an attractive alternative to adaptive optics.

In the past decade adaptive optics (AO) assisted observations have become the standard for obtaining images near the diffraction limit of large ground-based telescopes. At the ESO Very Large Telescope (VLT), the AO-assisted near-infrared (NIR) camera NAOS/CONICA (NACO) has been in operation since 2002 with spectacular success (see e.g., Lenzen et al., 2003; Rousset et al., 2003; Girard et al., 2010). Its AO capability can improve the angular resolution in the NIR (*viz.* 1–5 μm), which is typically limited by atmospheric turbulence, from the seeing, in the range 0.3–2.0 arcseconds, to 0.03–0.15 arcseconds depending on the wavelength.

Despite its immense advantages, AO is not a universal solution to the problem of diffraction-limited imaging through the Earth's atmosphere. AO systems need either a bright natural guide star, which seriously limits sky coverage, or a laser guide star (LGS), which entails some additional image degradation because of the cone effect (i.e. the finite distance of the LGS reference from the source) and tip-tilt anisoplanatism (elongation of the PSF when the faint tip-tilt star is off-axis). The field of view (FoV) with AO is also limited: the change of the incoming wavefront as a function of the line of sight leads to a rapid deterioration in the image quality at distances from the guide star larger than the isoplanatic angle (nominally around 15 arcseconds at 2.2 μm, the *K*-band). These anisoplanatic effects can be partially compensated for by the use of multi-conjugated AO (MCAO) systems and the use of multiple (laser) guide stars, but at great cost in instrumental as well as operational complexity. In addition to, and independent of, these effects, various technical limitations make it difficult to calibrate the AO PSF (Sivaramakrishnan et al., 2003; Lacour et al., 2011). Here, we show that holography can in many situations offer an attractive alternative to AO. It leads to high quality images, works with very faint (infrared) reference stars, and can compensate anisoplanatic effects in crowded fields. Details on the experiments described here, as well as more analysis and discussion can be found in Schödel et al. (2012).

Speckle imaging

Before the maturity of AO, speckle imaging was widely used to obtain diffraction-limited images. It played, for example, a key role in determining the proper motions and orbits of stars near the massive black hole at the centre of the Milky Way, Sagittarius A* (e.g., Eckart & Genzel, 1996). Speckle imaging is based on recording series of hundreds or thousands of images with exposure times around 0.1 seconds. In these frames stars appear as interference patterns or speckle clouds (see Figure 1, left). Image reconstruction is performed *a posteriori*, for example with the simple shift-and-add (SSA) algorithm: a different shift is applied to each frame so that the brightest speckle of the reference star always comes to lie at the reference pixel. Finally, the shifted frames are averaged. The PSF of the reconstructed image (Figure 1, middle) appears like a diffraction-limited core superposed on a broad seeing halo.

SSA was widely used because it is easy to implement, fast and robust. However, the achieved Strehl ratio is typically only around 10 % in the *K*-band with an 8-metre telescope. The Strehl (ratio) is a measure of the image quality and is defined as the ratio between the peak pixel in the normalised PSF and its theoretical maximum value. It is 100 % for a perfect image and ~ 1% for a seeing-limited image. Since turbulence is a statistical process, higher Strehl ratios can be reached by selecting only the frames with the most compact, high signal-to-noise PSFs. In recent years, this technique, termed lucky imaging, has become popular at optical wavelengths, where AO is still challenging. Lucky imaging suffers, however, from large overheads because typically a large fraction of the data (frequently > 90 %) must be discarded in the process. Since the number of speckles increases approximately with the square of the telescope aperture, lucky imaging becomes extremely inefficient for telescopes with apertures of more than a few metres.

Holography

A more complex, but more efficient, algorithm than SSA is speckle holography, which makes use of the information and flux content of the entire speckle cloud of each frame, not just of the brightest speckle. This results in higher Strehl ratios and sensitivity. Efficiency is boosted because frame selection becomes (largely) unnecessary. Holography allows one to reconstruct the best estimate (in the least squares sense) of the astronomical object's Fourier transform: $O = \langle I_m P^*_m \rangle / \langle |P_m|^2 \rangle$ where O, I_m and P_m are the Fourier transforms of the astronomical object, of the m-th frame of the observed image and its instantaneous PSF, respectively (Primot et al., 1990). The brackets denote the mean over the total number of frames and the asterisk the complex conjugate. The final reconstructed image is obtained after multiplication of O with the telescope transfer function (TTF), followed by an inverse Fourier transform. The TTF is usually an Airy function. The main difficulty in the application of holography lies in obtaining reliable estimates of the P_m. In the ideal case, the field contains a single, bright, isolated reference star, whose speckle cloud can be used to estimate the P_m, similar to the role of the guide star in AO. This situation is, however, very rare and can be dealt with efficiently by AO.

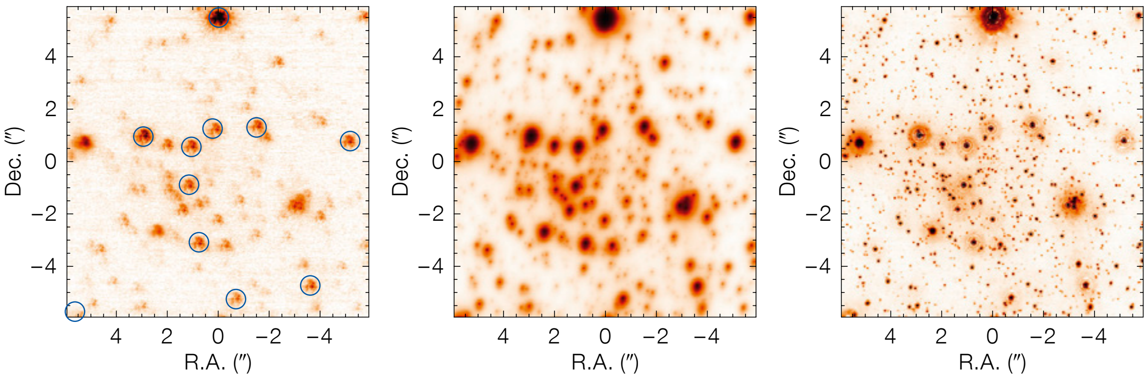

Figure 1. Speckle imaging of the Galactic Centre with NACO. Left: Individual short exposure. Middle: Simple shift and add (SSA) reconstruction. Right: Holographic reconstruction. The 11 reference stars have $7 \leq Ks \leq 10$ mag and are marked by circles in the left panel.

Therefore holography has rarely been used in practice.

Here we present a novel, game-changing approach that allows us to use holography even with faint guide stars in extremely crowded fields. It is based on: (a) iterative improvement of the PSF; and (b) the (optional) use of multiple reference stars. Relative fluxes and positions of stars in the observed field can initially be obtained from an SSA image (or from a previous holographic reconstruction). Subsequently, preliminary PSF estimates can be obtained for each frame from the median superposition of multiple reference stars, whose relative positions are now known with sub-pixel precision. Then, the preliminary PSFs can be used to subtract all secondary sources near the reference stars that were detected in the SSA image. Finally, high accuracy values of P_m are obtained from a median superposition of the reference sources from the cleaned frames.

We use speckle data of the Galactic Centre (GC) obtained with NACO's cube mode on 7 August 2011 to demonstrate the effectiveness of this algorithm (*Ks*-band, S27 camera, 12 500 frames, Detector Integration Time [DIT] = 0.15 s, DIMM seeing ~ 0.5 arcseconds, coherence time τ_0 = 2–3 ms). Figure 1 shows a speckle frame as well as an SSA and a holographic image reconstruction. While the Strehl of the SSA image is only ~ 9 %, the holographic image has a Strehl of ~ 82 % and also excellent PSF cosmetics.

High quality images

A comparison between AO and holographic imaging of a small region around Sagittarius A* is shown in Figure 2. Ideally, the comparison has to be done between contemporary data taken under similar conditions. In the absence of such data, we try to stay on the conservative side and use one of the highest quality NACO GC datasets ever taken (31 March 2009, DIMM seeing ≤ 0.5 arcseconds, $\tau_0 \approx$ 47 ms). The comparison underlines the extraordinary image quality obtained with the holography technique. In addition, also in Figure 2, we show a holographic image reconstruction that has been obtained by using only the faintest stars (*Ks* ~ 13) as reference stars. Those stars are barely visible in the individual frames. Nevertheless, a high Strehl (~ 45%) could be obtained by using a large number of them (24 in this case).

Sensitivity is, however, one aspect where AO clearly wins out over holography, where it is fundamentally limited by the readout noise of the detector electronics. The point source detection limit is about 1.5 magnitudes deeper in the AO image (*Ks* ~ 20.5) than in the holography image (*Ks* ~ 19). This cannot be seen in Figure 2 because the region shown is completely dominated by crowding. However, due to the high PSF quality, holography can deliver smaller astrometric and photometric uncertainties on bright sources than AO.

Although holography is closely related to deconvolution techniques like Wiener filtering or Lucy–Richardson deconvolution, it does not suffer the typical problems of those methods, like ringing, photometric biases, difficulties in dealing with extended emission, or creation of spurious sources. Holography is an entirely linear process, leads to well-behaved noise properties in the reconstructed images, and provides reliable photometry.

A highly flexible technique

As we have shown above, holographic imaging works with rather faint reference stars. Moreover, an arbitrary number of

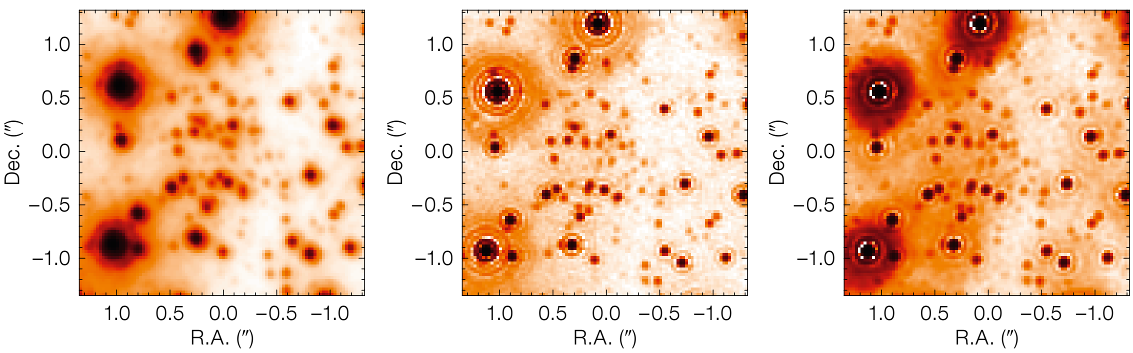

Figure 2. Comparison of speckle holography and AO. Left: AO image of the immediate environment of Sagittarius A*. Middle: Image reconstructed from speckle data via the holography technique, using ten reference stars of $7 \leq Ks \leq 11$. Right: Holographic reconstruction using 24 *Ks* ~ 13 reference stars.

them can be combined, a possibility that lies beyond the capabilities of current AO systems. Therefore, holography can free us from many constraints imposed by classical, single conjugate AO. Holography is thus naturally suited to imaging highly embedded fields, for example in the Galactic Bulge or near the Galactic Centre, that have so far never been possible to observe at high angular resolution from the ground because of the absence of suitable natural guide stars or tip-tilt reference stars for (LGS) AO.

Anisoplanatic effects are among the most adverse problems encountered in AO imaging. In holography, we can deal with these effects if the density of reference stars is sufficiently high. The latter constraint is probably fulfilled for most fields in the Galactic Plane, taking into account that stars of K = 12–13 mag can serve as a reference. The image can then be sliced into overlapping subfields that are corrected separately and subsequently stitched together again. Thus, holography can work like an efficient "poor man's MCAO".

For different wavelength regimes, we tested the performance of holography successfully in the J-band (with NACO on the core of NGC 3603, see Figure 3) and I-band (FastCam at the Nordic Optical Telescope on the core of the globular cluster M15), achieving Strehl ratios of ~ 40% and ~ 18%, respectively. We have also successfully tested holography with NACO in the L′-band, with excellent results.

The short integration times necessary for speckle imaging can make it necessary to window NACO's detector to 512 × 514 pixels. Longer DITs are desirable in order to use the full detector array. This was tested using DITs of 0.4 seconds (≫ 10 times longer than the atmospheric coherence time). The diffraction limit was reached, albeit at low Strehl (~ 10%).

Holography with VISIR and HAWK-I

The primary aim of our experiment with the VLT's wide-field NIR imager HAWK-I was to test whether holography can also serve to improve the image quality of cameras that undersample the diffraction limit, but significantly oversample atmospheric seeing. A very brief series of 128 frames was taken in Ks–band during twilight on the core of the globular cluster M30 (in Ks-band, DIMM seeing ~ 0.9 arcseconds). Figure 4 compares a standard long exposure (simple average of all frames) with a holographically reconstructed image. As can be easily appreciated, the holographic image is of superb quality (a Gaussian of 0.27 arcseconds full width at half maximum [FWHM] was used as TTF). Although the total integration time was only 28 seconds, stars as faint as Ks ~ 20 are detected at 5σ. The high sensitivity is due to the fact that more photons are collected in each pixel than when the diffraction limit is sampled. This means that in one hour of integration time, stars of Ks ~ 22 should become accessible to the holography technique with HAWK-I.

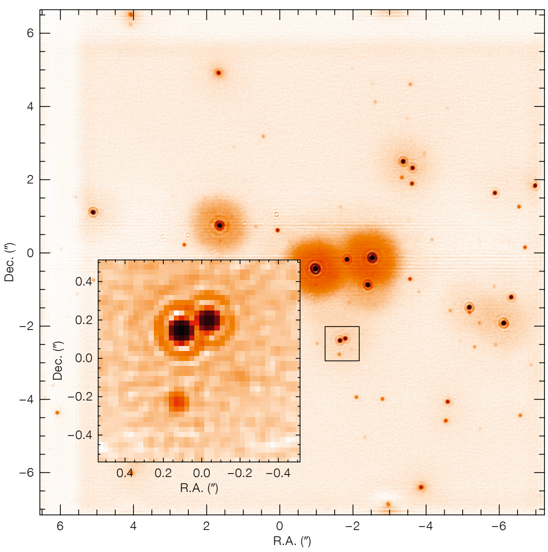

Figure 3. Holographic image of the core of NGC 3603 with NACO in the J-band (about 5000 frames, DIT = 0.11 seconds). The inset shows a zoom onto the region marked by the black box: the two closely spaced stars have J = 12.0 and 12.6 mag and a separation of 0.078 arcseconds.

Although, for technical reasons, we only show a small field in Figure 4, we note that the FoV of HAWK-I with the exposure time used (DIT = 0.2 secsonds) is 2048 × 512 pixels, or roughly 3.25 arcminutes squared. We believe that even longer integration times and thus larger FoVs, up to 2048 × 1024 pixels (~ 6.5 arcminutes squared) are feasible. We note that stars as faint as K ~ 16 can be identified on the speckle frames. Since the density of such stars is relatively high over the entire sky this means that it is a realistic hope to be able to correct HAWK-I's large FoV with the holography technique.

On account of the necessarily short exposure times, the mid-infrared (MIR) is a natural regime for speckle techniques. This was recognised at ESO many years ago with the implementation of VISIR's burst mode. This allows VISIR observers to significantly improve the image quality compared to a standard long exposure (Doucet et al., 2006). We tested holography with VISIR on data obtained in May 2007 when the seeing was as bad as 2–3 arcseconds. A fully diffraction-limited, high Strehl image could be reconstructed. A comparison between a tip-tilt corrected long exposure and the holography image is shown in Figure 5.

This experiment demonstrates that holography can enable astronomers to obtain MIR images of the highest quality even under the most adverse seeing conditions. Additionally, it shows that extended sources can be used as a PSF reference as long as they contain a point-like object. The bright star IRS 3, which sits atop extended, diffuse emission, served as reference source (see Figure 5). When extracting the PSFs from the speckle frames, the diffuse emission was suppressed by flux thresholding. Thus, the holography technique may be very useful for the study of objects such as active galactic nuclei or details of the interstellar medium in star-forming regions. Unfortunately, with VISIR's current detector the reference source (or sources) must be relatively bright, at least 1 Jy (strongly dependent on seeing conditions), but we hope that significantly fainter point sources can be used with the new and more sensitive AQUARIUS detector currently being installed.

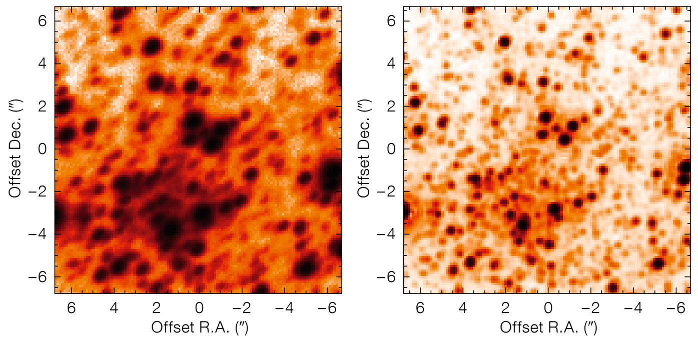

Figure 4. Holographic imaging of the core of the globular cluster M30 with HAWK-I. Left: Standard long exposure. Right: Holographic reconstruction.

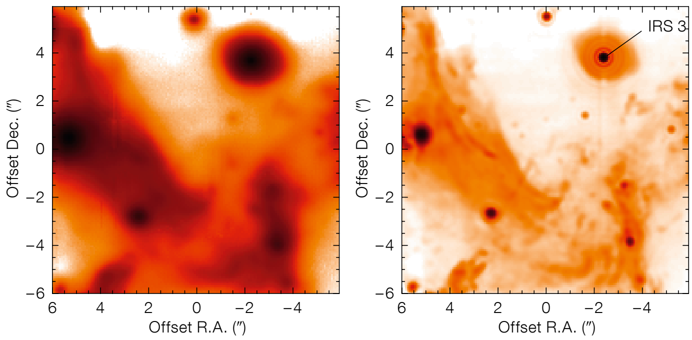

Figure 5. VISIR 8.6 μm observations of the Galactic Centre, taken in May 2007. Left: Tip-tilt corrected long exposure, PSF FWHM ~ 1 arcsecond. Right: Holographic reconstruction with a PSF FWHM ~ 0.25 arcseconds. The brightest source in this image, IRS 3, was used as reference source for the image reconstruction. The vertical line running through IRS 3 is a detector or electronics artefact. Sagittarius A* is located at the origin.

When to use holography

Requirements for the use of holography on the instrumental side are a sufficiently fine spatial sampling of the detector plane and the capability of rapid readout and data storage. On the target side, one or several reference stars bright enough to be detected in individual frames are necessary. Crowded fields are ideal. Holographic imaging can be used with the ESO VLT facility instruments VISIR, NACO and HAWK-I, and with the guest instrument AstraLux Sur.

Holography cannot replace AO. Particularly when the targets are faint (most extragalactic observations) or when specialised techniques like spectroscopy or coronagraphy are used, there is no alternative to AO. Also, holography is not a good choice when the target and reference star coincide, as in the search for faint companions or discs around isolated bright stars. In the latter case, extreme AO and techniques like sparse aperture masking (Lacour et al., 2011) or apodising phase plates (Kenworthy et al., 2010) should be used. However there exist a broad range of situations in which holography can provide unique advantages over (single-conjugated) AO:
- necessity for a homogeneous PSF and good PSF cosmetic quality over the FoV;
- demand for a large FoV;
- need for high dynamic range in a field that contains bright stars that would saturate with AO;
- observations of fields devoid of AO guide stars and of suitable tip-tilt reference stars for LGS AO;
- backup when the AO fails to close the loop on a target;
- high angular resolution imaging with an instrument that is not equipped with AO;
- minimisation of systematic errors in photometry and astrometry of bright stars;
- unstable AO correction with highly variable PSF.

In the latter case, holography can also be applied to AO imaging data when the correction is unstable. By combining the advantages of both techniques, holography can enable fainter targets to be reached and considerably boost the performance of AO at short wavelengths, with faint guide stars, or when conditions are adverse. Note, however, that use of AO will freeze anisoplanatic effects into the imaging data.

Holography thus offers a broad range of novel observing possibilities for instruments at ESO's (and other observatories') telescopes. Our work shows how important it is to implement and optimise fast readout modes on imaging instruments. ESO's next generation high angular resolution imager, ERIS, which has just successfully passed its Phase A study, should provide full support for fast readout while maintaining good detector cosmetics. In addition, the novel "zero-noise" infrared and optical detectors under development are very attractive for speckle techniques because they will boost sensitivity both for guide stars and in the reconstructed image, by the order of 2–3 magnitudes (Finger et al., 2010).

A dedicated speckle camera can be very low cost, weight, and complexity, while providing a large field of view. Holography is thus an attractive possibility to equip any telescope with MCAO-like capabilities within a short time. The low weight of a speckle camera minimises flexure, and the lack of complicated optics may make it a well-suited instrument for astrometry (and also polarimetry).

Finally, we note that holography opens up the possibility for optical imaging near the diffraction limit of telescopes of 8 metres and larger class, where lucky imaging is too inefficient. Sensitivity can be adjusted by an optimised trade-off with spatial resolution, to enable the technique to work with relatively faint reference stars. Holography may also be our best chance to quickly realise sub-0.1 arcsecond resolution optical imaging with the future European Extremely Large Telescope (E-ELT).

References

Doucet, C. et al. 2006, in *Visions for Infrared Astronomy, Instrumentation, Mesure, Métrologie*, ed. V. Coudé du Foresto, D. Rouan, & G. Rousset, 25
Eckart, A. & Genzel, R. 1996, Nature, 383, 415
Finger, G. et al. 2010, SPIE Conference Series, 7742
Girard, J. et al. 2010, SPIE Conference Series, 7742
Kenworthy, M. et al. 2010, The Messenger, 141, 2
Lacour, S. et al. 2011, The Messenger, 146, 18
Lenzen, R. et al. 2003, SPIE Conference Series, 4841, ed. M. Iye & A. F. M. Moorwood, 944
Primot, J. et al. 1990, Journal of the Optical Society of America A, 7, 1598
Rousset, G. et al. 2003, SPIE Conference Series, 4839, ed. P. L. Wizinowich & D. Bonaccini, 140
Schödel, R. et al. 2012, MNRAS, in press (arXiv1110.2261)
Sivaramakrishnan, A. et al. 2003, SPIE Conference Series, 4860, ed. A. B. Schultz, 161