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Holographic Imaging: Sharp Images for Everyone

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Abstract

Obtaining images near the diffraction limit of large telescopes is key to the success of many observational projects, but requires either adaptive optics (AO) equipment or the application of speckle techniques. While AO is expensive, complex, and requires long development times, speckle imaging is far easier to implement. However, the most frequently used image reconstruction techniques, like simple shift-and-add and the related lucky imaging, suffer from important limitations in sensitivity and efficiency. Here, we present an improved version of the speckle holography technique, that is particularly optimized for crowded fields. Holography is highly efficient, generally supersedes lucky imaging, and can rival and even surpass AO imaging, particularly at short wavelengths. It is a highly flexible technique and can be used with a broad range of existing instruments, thus imbuing them with novel high angular resolution capabilities at no (or hardly any) additional cost. Speckle holography makes high-angular resolution imaging available whenever an imaging instrument offers fast readout capability combined with adequate sampling of the image plane.

1 Introduction

Since more than a decade, AO systems have become the standard for obtaining subarcsecond resolution images in the near infrared (NIR) at large telescopes. In spite of its great success, however, AO is an expensive technique and does not provide a universal solution to the problem of obtaining sharp images through the Earth's turbulent atmosphere. Its main limitations are the patchy sky coverage because of the requirement for a suitable guide star (or tip-tilt star when a laser guide star is used) sufficiently close to the target, on the one hand, and anisoplanatic effects, on the other hand. The latter lead to a degradation of the correction at distances more than an isoplanatic angle (about $15''$ at $2.2\,\mu$m) from the target as well as to a spatially variable PSF and thus limited photometric accuracy. AO systems can be improved to deal with these problems, for example, in the form of multi-conjugate adaptive optics with multiple (laser) guide stars (e.g. [12]), but this comes at great cost and increased complexity and vulnerability of the systems.

Before the advent of AO, *speckle imaging* (or *speckle interferometry*) was frequently used for diffraction-limited imaging. This technique is based on taking long series of images with exposure times corresponding to the atmospheric coherence time (in practice, somewhat longer exposure times are used, typically on the order of 0.1 s). The instantaneous PSF of stars in these short exposures is very complex and appears as a *speckle cloud* (Fig. 1), which is the resulting interference pattern of the distorted wavefront over the telescope aperture. Images can be reconstructed from speckle data by a range of algorithms (e.g. [8, 6, 14, 9, 2, 1]).

Perhaps the most popular and widely used of these methods is the so-called simple shift-and-add (SSA) algorithm (e.g. [1, 4]). SSA is based on the assumption that each speckle in the instantaneous PSF can be regarded as a diffraction limited image of a point source. Image reconstruction then proceeds via applying a shift to each short exposure in the stack. The shift is given by the offset of the brightest speckle of the reference star from a chosen reference pixel. The final image is obtained after averaging the stack of shifted frames (Fig. 1). SSA is simple and fast, but results only in low Strehl ratios, on the order of 10% (depending on seeing, wavelength, and telescope aperture). Since seeing is a stochastic process significantly higher Strehl can be achieved through rigorous selection of the best speckle frames. This method is called *lucky imaging* and has recently become very popular to achieve diffraction-limited images at visible wavelengths with telescopes of 2-4m apertures (e.g. [5, 7]). The great disadvantage of lucky imaging is the need for strong frame selection (frequently over 90% of frames are not used), which leads to reduced sensitivity and low observing efficiency.

2 Holographic imaging

Speckle holography is based on the mathematical relation

$$O = \frac{\langle I_m P_m^* \rangle}{\langle |P_m^2| \rangle}, \tag{1}$$

where O is the Fourier transform of the object, and I_m and P_m are the Fourier transforms of the m-th image (speckle frame) and of its instantaneous PSF (the speckle cloud), respectively. The brackets denote the mean over N frames. P_m^* is the conjugate complex of P_m. It can be shown that Equation 1 describes the best estimate of the object's Fourier transform in the least squares sense [11]. The final, diffraction-limited image is obtained after apodization with the telescope transfer function, usually an Airy function, followed by an inverse Fourier transform. A brief description and a flow diagram of the algorithm are provided in [10].

Holography has the advantage that the information and flux content of the entire instantaneous PSF of each speckle frame are used. This means that much higher Strehl ratios and sensitivities can be achieved than in SSA. The main problem for the practical application of holography is the challenge to extract an accurate PSF from each speckle frame. This is trivial if there exists a bright, isolated star within an isoplanatic angle of the target. But this situation is rare.

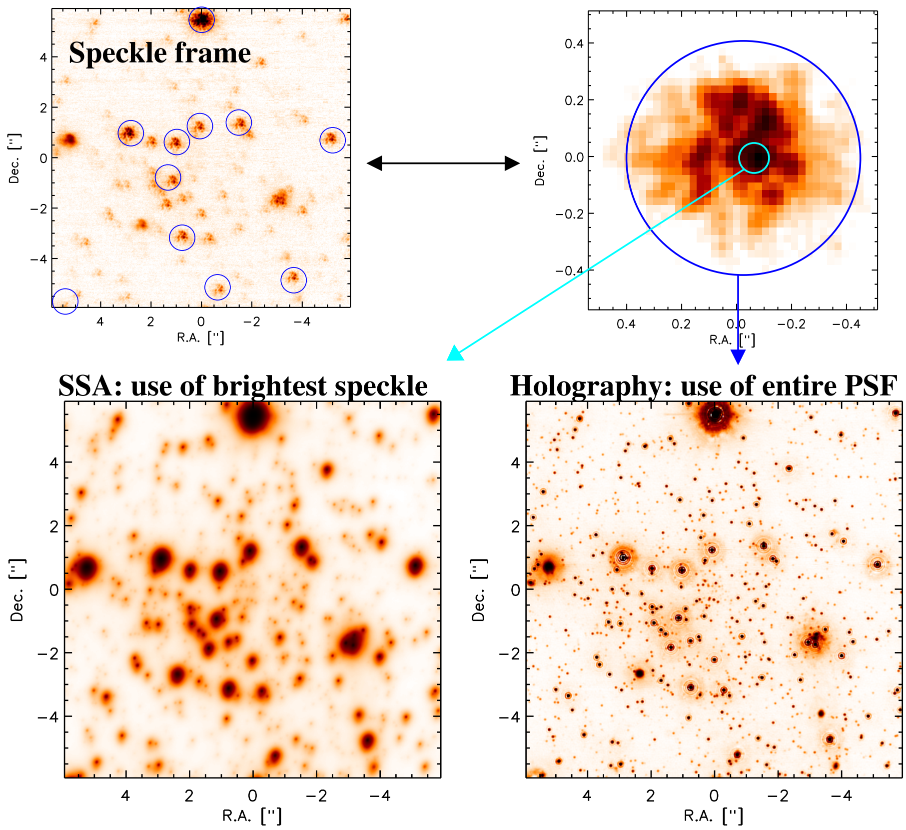

Figure 1: Speckle observations of the Galactic Center with VLT/NACO. *Upper left panel:* Single speckle frame. *Upper right panel:* The corresponding, instantaneous PSF determined from the reference stars (marked by circles in the speckle frame). *Lower left panel:* SSA image reconstruction. *Lower right panel:* Holographic image reconstruction.

Here, we present a modified version of the holography algorithm that can also work in highly crowded fields and with relatively faint reference stars. Key to our method is the use of multiple reference stars and an iterative extraction of the P_m. We start with an SSA image reconstruction. Stellar positions and fluxes are then measured in the SSA image with PSF fitting software (we use *StarFinder*, see [3]). Since the stellar positions can be easily measured with sub-pixel accuracy, it is then possible to create initial estimates of the P_m by a median superposition of the reference stars' images in each speckle frame. These preliminary P_m are then used to subtract faint, secondary sources close to the reference stars from each speckle frame. Subsequently, final, accurate P_m are then obtained by median superposition of the speckle clouds of the reference sources that are now largely free of contaminating flux. After extraction of the P_m, the final image can be reconstructed. A further iteration can now be done by measuring the stellar positions and fluxes in the holographically reconstructed image, which is of significantly higher quality than the SSA image, and repeating the work flow. However, this additional step is usually only necessary in extremely crowded fields.

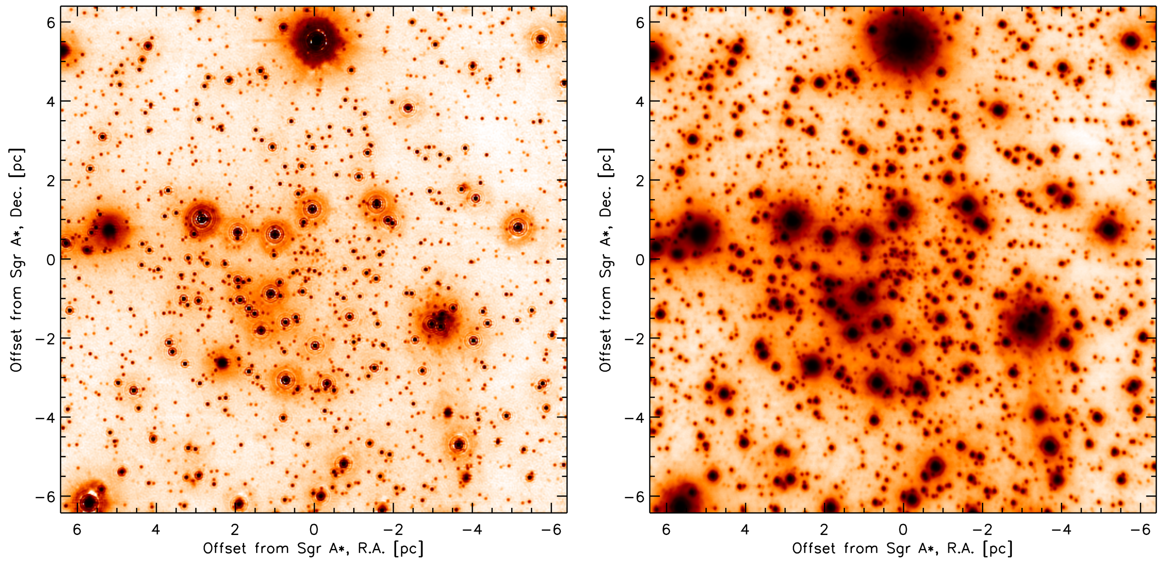

Figure 2: *Left panel:* Holographic imaging of the Galactic Center with VLT/NACO (7 August 2011). *Right panel:* AO imaging with VLT/NACO (31 March 2009). Sagittarius A* is located at the origin in both plots.

Our method is illustrated in Fig. 1, that shows a speckle frame and the results of image reconstruction with the SSA and with our modified holography algorithms. We used 12,500 K_s-band speckle images of the Galactic Center obtained with VLT/NACO on 7 August 2011. Visual seeing varied between 0.6" − 0.9" with a coherence time of a few milli seconds. The exposure time of the speckle frames was 0.15 s, i.e., about an order of magnitude longer than the coherence time in the visual regime.

The quality of the image reconstructed via our technique is very high: PSF cosmetics is excellent and the Strehl is $82 \pm 5\%$ (∼9% in the SSA image). The quality of holographic imaging can be further appreciated in Fig. 2, where we show a comparison between the holography image and an AO image of the Galactic Center.

3 A highly flexible technique

In order to explore the capabilities and limitations of our method, we have tested it with different instruments, on a range of targets, and from visual to mid-infrared wavelengths (see Fig. 3). PSF cosmetics and Strehl were excellent in all cases.

Since image reconstruction from speckle data is done *a posteriori*, one can deal with anisoplanatic effects by reconstructing sub-fields smaller than the isoplanatic angle and then creating a final large mosaic image that is largely free from anisoplanatic effects. This is a unique advantage over (single conjugated) AO and can allow one to exploit an almost arbitrarily large FOV as long as the detector can be read out fast enough and the density of possible reference stars is sufficiently high across the FOV. The possibility to combine an

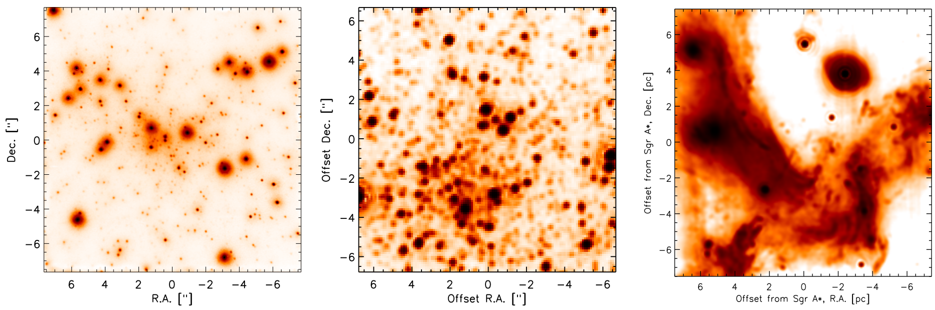

Figure 3: Holographic imaging applied to different data sets. *Left panel:* Core of M15, I-band, NOT/FASTCAM. *Center panel:* Core of M30, K_s-band, VLT/HAWKI. *Right panel:* Galactic Center, $PAH1$ filter, VLT/VISIR.

arbitrarily large number of reference stars means that our method can work on fields devoid of bright guide stars. For example, from the data shown in Fig. 1 we have reconstructed an image with $\sim$ 45% Strehl using 24 $K_s \sim 13$ reference stars. Thus, holography is uniquely suited to peer into highly extincted regions of the Galaxy, for example its central region.

Holography can also be useful to improve the image quality of instruments that undersample the diffraction limit. In the middle panel of Fig. 3 we show an image of the core of the globular cluster M30 obtained with VLT/HAWKI using our speckle holography method (the diffraction limit of the VLT at K_s is ~0.06"; the pixel scale of HAWKI is 0.106"/pixel). The quality of the reconstructed image is high and PSF FWHM is $\sim$0.27$''$, or about half the value imposed by atmospheric seeing. The fact that holography works on under-sampled data means that sensitivity can be boosted in this way and very large FOVs can be achieved.

4 Summary

Although holographic imaging cannot replace AO, particularly when the targets are very faint, it is a highly useful technique in the toolbox for high angular resolution imaging. There exists a broad range of situations in with holography can provide unique advantages, e.g.:

- Need for a homogeneous PSF and good PSF cosmetics over the FOV
- Need for a large FOV that cannot be provided by single conjugate AO
- Need for high dynamic range in a field with bright stars that would saturate with AO
- Observations of fields devoid of suitable guide or tip-tilt stars for AO
- Backup when the AO system fails to close the loop on a target
- High angular resolution imaging with an instrument that is not equipped with AO
- Subarcsecond resolution imaging in the optical or short near-infrared regime at telescopes with apertures larger than a few meters, e.g. 10m-class telescopes or the future extremely large telescopes, where lucky imaging will be extremely inefficient (deselection of $>$ 99% of frames required).

Due to the size constraints of these conference proceedings we could only provide a brief overview of our speckle holography method and its applications. Further details and more examples are provided in [13].

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