High Contrast Imaging in the Visible: First Experimental Results at the Large Binocular Telescope

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Received 2016 May 25; revised 2016 September 8; accepted 2016 September 8; published 2017 July 28

Abstract

In 2014 February, the System for High contrast And coronography from R to K at VISual bands (SHARK-VIS) Forerunner, a high contrast experimental imager operating at visible wavelengths, was installed at the Large Binocular Telescope (LBT). Here we report on the first results obtained by recent on-sky tests. These results show the extremely good performance of the LBT Extreme Adaptive Optics (ExAO) system at visible wavelengths, both in terms of spatial resolution and contrast achieved. Similarly to what was done by Amara & Quanz (2012), we used the SHARK-VIS Forerunner data to quantitatively assess the contrast enhancement. This is done by injecting several different synthetic faint objects in the acquired data and applying the angular differential imaging (ADI) technique. A contrast of the order of $5 \times 10^{-5}$ is obtained at 630 nm for angular separations from the star larger than 100 mas. These results are discussed in light of the future development of SHARK-VIS and compared to those obtained by other high contrast imagers operating at similar wavelengths.

Key words: instrumentation: adaptive optics – instrumentation: high angular resolution – planets and satellites: detection – techniques: image processing

1. Introduction

The Large Binocular Telescope (LBT) and, more specifically, its First Light Adaptive Optics (FLAO) system (Esposito et al. 2010a, 2010b, 2012; Quirós-Pacheco et al. 2010; Bailey et al. 2014), recently opened a new frontier for the astronomical adaptive optics (AO) on the 8–10 m class telescopes, by routinely delivering strehl ratios (SRs) higher than 0.8 in the H band. This led to important scientific breakthroughs (Skemer et al. 2012; Esposito et al. 2013). The combination of the pyramid wavefront sensor, together with the high dynamic and spatial resolution of the adaptive secondary mirror (ASM), provide performance that has never been obtained on this class of telescope by either previous natural or laser guide star systems. In particular, we refer to the extremely low residual wavefront error (below 100 nm rms), reached by the FLAO systems working with bright guide stars ($R < 9.5$) in good seeing conditions (below 0.8 arcsec). These constitute very promising conditions for extending the operational range of the LBT AO to visible wavelengths.

In this regard, it is worth mentioning that there are several scientific advantages of working in the visible band (Close et al. 2014). First, visible detectors are less noisy and more linear. In addition, they are characterized by a larger dynamic range and are easier to operate than the current generation of near-infrared (NIR) ones. Second, visible skies are much darker than those in the NIR bands. In addition, from a scientific point of view, we remark that most of the strongest emission lines are in the visible bands (i.e., Hα line). Moreover, visible AO systems have higher spatial resolutions, up to a factor of $\sim 3$, than AO systems working in the K band. Furthermore, models of exoplanet atmospheres (Marley et al. 1999; Fortney et al. 2008; Marley & Sengupta 2011) show that at wavelengths shorter than 650 nm the planet albedo increases, and thus the probability of their detection is maximized. More recently, a large effort has been made to design two high contrast imagers at LBT, SHARK-VIS, and SHARK-NIR, exploiting FALO at visible and infrared wavelengths, respectively (Farinato et al. 2014, 2015; Stangalini et al. 2014). These imagers have been conceived to minimize non-common-path aberration (NCPA). Indeed, they are positioned very close to the pyramid wavefront sensor and minimize the number of optical surfaces employed. High contrast imaging is nowadays becoming attractive, with a number of recent instruments optimized for both visible wavelengths (VisAO, Close et al. 2014; Males et al. 2014a, 2014b) and NIR bands (i.e., GPI, Macintosh et al. 2008, 2014; Rantakyrö et al. 2014 and SPHERE, Beuzit et al. 2006; Bonnefoy 2015; Hardy et al. 2015). In this paper, we describe our recent results obtained on sky with the SHARK-VIS experimental imager, hereafter Forerunner. In order to estimate the Forerunner contrast, we injected faint synthetic targets into the acquired data at different angular separations from the bright source, and we applied the ADI post-processing technique. This approach was already proposed and employed by Amara & Quanz (2012) for testing different post-processing techniques and assessing their contrast enhancement. Such an approach also represents an accurate way to evaluate the performance of the instrument with on-sky data, thus without making use of complex, yet not completely realistic, numerical simulations.

2. The Forerunner

The Forerunner was installed at the right bent Gregorian focus of LBT in 2014 February and was finally tested on sky in
2015 June. The simplicity of this instrument (see Figure 1), together with the Adaptive Secondary Mirror (ASM) of LBT, reduces the number of refractive optical surfaces between the sky and the detector to only two optical elements. The first one corresponds to an interference filter centered at 630 nm with a bandwidth of 40 nm, and the other is a divergent lens of 250 mm of focal length used to achieve a slight Nyquist oversampling of the point-spread function (PSF), with a spatial scale of 3.73 mas/pixel. The filter bandwidth has been limited to only 40 nm because of the lack of an Atmospheric Dispersion Corrector (ADC) in the optical layout of this basic pathfinder experiment. This particular configuration allows operation only up to 10° of Zenith distance. However, this limitation will be overcome in the final design of SHARK-VIS, where an ADC is foreseen.

NCPAs are reduced by positioning the detector close, and mechanically connected, to the LBT Interferometer (LBTI) main frame, which is holding the pyramid wavefront sensor of the AO system. Small residual static aberrations on the science camera (∼15 nm) were minimized by offsetting the zero point values of low order modes of the wavefront reconstructor. The camera used is an Andor Zyla6 hosting an sCMOS sensor cooled to 0°Celsius. This camera can perform high speed imaging acquisition with low noise (≤1e−/pixel). In fact, the deployed system allows for the recording of 2 k × 2 k pixel images at 50 Hz, and 200 × 200 pixel subfields (the format used in this experiment) at 1 kHz.

In Figure 2, we show examples of both a short exposure (1 ms) image with its relative radial profile and a long exposure (5 s) image (obtained by co-adding 5000 images), with their own radial profiles after subtracting the dark frame from the images and co-registering the data series by means of a fast Fourier transform (FFT) phase correlation technique. Several diffraction rings and the control radius are also evident in the (1 ms) image. The control radius, which is evident in the long exposure of Figure 2 (right upper panel) as an annulus of increased brightness at ≈240 mas from the central peak of the PSF, marks the region within which the action of the AO takes place. Its radius, which depends on the number of actuators (on the telescope pupil), is in perfect agreement with the theoretical value of 206,265 × N_{act} × λ/D = 0.238 arcsec, where N_{act} = 15 is the number of actuators on the LBT pupil radius and D = 8.2 m is the effective pupil diameter set by the undersized secondary mirror size.

3. Data Set

The data set we present in this paper is composed of a sequence of 1,200,000 images of the target Gliese 777 recorded at 1 ms cadence (200 × 200 pixel subfields) on 2015 June 4th starting from 08:21:58 UT. The LBT AO system was correcting 500 modes in closed loop, while seeing conditions were rapidly varying in the range 0.8–1.5 arcsec. This can be seen in Figure 3 (upper left panel), where we plot the evolution of the sharpness of the images, normalized to its maximum, versus time. Here we have used the same definition of sharpness as that in Muller & Buffington (1974):

\[ S = \int dx dy I^2(x, y), \]

where x and y denote coordinates in the image plane and I is the intensity. In the upper right panel of the same figure, we plot the probability density function (PDF) of the sharpness. This distribution shows the presence of at least two peaks, which manifest different seeing conditions during the observation. In the bottom panel of Figure 3, we also show the SR behavior. We note that the SR undergoes rapid fluctuations ranging from a few percent up to 50%. Its average value over the whole duration of the observation is 27%. A residual tip-tilt with an rms amplitude of ∼17 mas and main frequency of ∼13 Hz has been found in the raw data, probably due to wind excited modes of the secondary and tertiary mirror spider supports. The Forerunner has no image rotator, hence the image de-rotation is performed by post processing of short sub-exposures. It is worth stressing that the high frame rate of the data allows the post-facto minimization of the residual tip-tilt. Indeed, this would not have been possible using longer integration times.

4. Methods and Results

Here we focus our attention on the assessment of the performances of the SHARK-VIS Forerunner in terms of contrast. Using on-sky data as a realistic benchmark for estimating contrast capabilities of the instrument has already been done by Amara & Quanz (2012). Following the latter work, in each frame of our data sequence, we inject faint objects at different radial distances from the central source with flux ratios of 10^{-4} and 5 × 10^{-5}. This is done by rescaling the instantaneous PSF and adding it to the image at different separations from the central object.

The data reduction strategy based on the ADI concept can be summarized as follows.

1. Subtracting the dark frame.
2. Co-registering images through an FFT phase correlation technique. This registration method, being applied in the Fourier space, allows for the registration of the whole series of images with sub-pixel accuracy, thus minimizing the residual tip-tilt error.
3. Injecting synthetic faint objects, for each one of the sub-frames (at different orientations reflecting the parallactic angle and thus the field rotation), with a shifted and amplitude-rescaled PSF. These objects have been placed at different distances from the optical axis (i.e., 45 mas, 95 mas, 190 mas, and 290 mas), and their fluxes

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6 http://www.andor.com/scientific-cameras/neo-and-zyla-scmos-cameras/ zyla-55-scmos
correspond to different contrast ratios with respect to the peak value of the bright source at the center of the field (i.e., $10^{-4}$, and $5 \times 10^{-5}$).  

4. Applying the ADI technique (Marois et al. 2010; Vigan et al. 2010) on the data. For each one of the frames, the bright star PSF is removed, subtracting its estimate computed by the median operator over 5000 random frames selected throughout the overall sequence. Then the residuals of each frame are de-rotated and combined with a median operator to retrieve the final image. This is finally flatted, removing low spatial frequencies estimated using a boxcar median operator with 11 pixel width.

It is worth noting here that large variations of the seeing during the observation may lead to inaccuracies in the subtraction of the PSF from each time frame, because this is obtained as a median over time of evolving PSFs.

In the left panel of Figure 4, we show the final ADI detection map obtained by following the procedure described above and representing the final result of 1200 s of exposure on GLIESE 777 without discarding any image during the post processing. All planets located beyond 100 mas from the host star are well detectable, though they have different S/N ratios due to different contrast ratios ($10^{-4}$, and $5 \times 10^{-5}$) as well. Planets located closer to the bright source are comparable to the noise level so they cannot be well detected. In order to compare the achieved contrast inside and outside the AO control radius, in Table 1 we report the fluxes and S/N of the photometry of fake planets injected at 190 and 290 mas, respectively. The flux values are measured using circular apertures of 4 pixel radius and the local sky level, to be subtracted, is measured inside an annulus of, respectively, 5 and 7 pixel radii. We estimate the noise of these measures as the rms value of a set of similar photometric estimates taken away from the “planet” location, but distributed along the same radial distance, as shown in the left panel of Figure 4. Other more sophisticated photometry algorithms may provide better results, but we prefer the use of this very conservative approach for the assessment of our detection limit.

In the right panel of Figure 4, we plot the photometric signal measured in apertures at two constant radial distances (see the left panel of the same figure) as a function of the azimuth. The radial distances chosen are 190 and 290 mas, corresponding to the distance of the injected planets, within and outside of the control radius of the AO. Please note that, for graphical reasons, the number of apertures plotted in the left panel of Figure 4 was largely reduced with respect to the exact number used to estimate the signals shown in the right panel of the same figure.
5. Concluding Remarks

We have used the first on-sky data acquired by the Forerunner as test data for an accurate assessment of the overall performances of the instrument in terms of contrast. To this aim, we have injected synthetic faint sources (a.k.a., fake planets) into the data at different distances from the optical axis and have applied the ADI post-facto technique to estimate the contrast. Figure 3 shows the results of this analysis, with a sharpness normalized to its maximum as a function of time, and the probability density function of the sharpness. Figure 4 displays an ADI detection map after removing a background map estimated through a 11 pixel width median filter, along with photometry measurements over the circular apertures shown in the left panel. Table 1 presents the fluxes and their S/N ratios for different radial distances.

### Table 1

| mas  | 1e-4 flux | 1e-4 S/N | 5e-5 flux | 5e-5 S/N |
|------|-----------|----------|-----------|----------|
| 190  | 13.4      | 8.1      | 10.0      | 5.9      |
| 290  | 17.8      | 15.1     | 9.5       | 8.1      |
contrast enhancement achieved. As noted by Amara & Quanz (2012), using on-sky data offers several advantages over the use of end-to-end simulations since the residual wavefront aberrations, and any possible quasi-static speckles induced by the instrument are the real ones. This allows for an accurate assessment of the performance of the instrument without making use of complex, yet not fully realistic, numerical simulations. Our analysis shows that the Forerunner can reach contrast down to $5 \times 10^{-5}$, with a good S/N at radial distances greater than 100 mas. This is an excellent result considering that it is obtained at visual wavelengths, where the effects of residual seeing aberrations are stronger than at longer ones. Our results are comparable to those obtained by the VisAO instrument, which operates at similar wavelengths ($0.63–1.05 \mu m$), even if they can reach a contrast of $10^{-5}$ at the different angular separation of 500 mas, but exploiting better seeing conditions and our seeing conditions were much less favorable than those that occurred during the on-sky test of VisAO, the Forerunner can be regarded as a very promising experimental instrument. This is especially the case if one considers the unforeseen upgrades Single conjugated adaptive Optics Upgrade for LBT (SOUL) of the LBT AO system and the future SHARK-VIS instrument for high contrast imaging in the Visual bands at LBT. For more information about SOUL, we refer the reader to Pinna et al. (2016).

The LBT is an international collaboration among institutions in the United States, Italy, and Germany. LBT Corporation partners are The University of Arizona on behalf of the Arizona Board of Regents; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Leibniz Institute for Astrophysics Potsdam, and Heidelberg University; The Ohio State University, and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota and University of Virginia. This work was partially funded by ADONI, the ADaptive Optics National laboratory of Italy.

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