Adaptive Optics Capabilities at the Large Binocular Telescope Observatory

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ABSTRACT

We present an overview of the current and future adaptive optics systems at the LBTO along with the current and planned science instruments they feed. All the AO systems make use of the two 672 actuator adaptive secondary mirrors. They are (1) FLAO (NGS/SCAO) feeding the LUCI NIR imagers/spectrographs; (2) LBTI/AO (NGS/SCAO) feeding the NIR/MIR imagers and LBTI beam combiner; (3) the ARGOS LGS GLAO system feeding LUCIs; and (4) LINC-NIRVANA - an NGS/MCAO imager and interferometer system. AO performance of the current systems is presented along with proposed performances for the newer systems taking into account the future instrumentation.

Keywords: Natural Guide Star, Laser Guide Star, Adaptive Optics, Interferometry, Single Conjugate Adaptive Optics, Ground Layer Adaptive Optics, Multiple Conjugate Adaptive Optics, Laser Guide Stars, NIR, MIR Extreme Adaptive Optics

1. INTRODUCTION

The Adaptive Optics (AO) systems at the Large Binocular Telescope (LBT) represent a distributed AO system in that the wavefront sensor (WFS) and the wavefront corrector are not co-located on the same optical bench. The AO systems can and will provide a variety of AO correction to enable different science goals. These AO capabilities include: (a) Natural Guide Star (NGS) on-axis correction (Single Conjugate Adaptive Optics – SCAO) yielding 8.4m diffraction-limited performance and also permits Fizeau and nulling interferometry between the apertures with an unprecedented 23m baseline along one axis; (b) Rayleigh beacon multiple guide star Ground Layer Adaptive Optics (GLAO) which permits wider field partial correcting with a $\sim 2\times$ improvement in seeing-limited performance; (c) NGS Multiple Conjugate Adaptive Optics (MCAO) over a small field-of-view (FoV) for each aperture with a potential interferometric upgrade.

The wavefront corrector takes the form of a 672 actuator Adaptive Secondary Mirror (ASM), also known as a Deformable Secondary mirror (DSM), mounted on each side of the LBT. These ASMs are permanently mounted at the M2 positions and serve as “flat” secondaries for seeing-limited observations and as adaptive elements for AO operations. For seeing-limited observations, the ASMs maintain a “flat” shape, equivalent to that of a traditional rigid secondary for the Gregorian design of the LBT and which delivers an f/15 beam to each of the four focal stations on each side. Note that telescope collimation is achieved with an active optics (aO) system using an off-axis Shack-Hartmann (SH) WFS controlling actuators on the back of each of the 8.4m primary mirror. The LBT is the first telescope to use ASMs as permanently mounted M2 units. Both the prototype ASM system at the MMT [1] and the MagAO system [2] at the Magellan Telescope, which uses a similar ASM to the LBT ones, only mount the ASMs when they are required for AO observations. For this paper, we are not concerned with the details of the ASMs themselves. A more thorough discussion of the ASMs, their operation and maintenance is presented in references [3-6].

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For AO operation, the ASMs are controlled by WFSs at different focal stations of the telescope. Each side of the telescope has five focal stations; Prime Focus, Direct Gregorian, Front Bent Gregorian (FBG), Center Bent Gregorian (CBG) and Rear Bent Gregorian (RBG). The last three are the ones used for AO and these are mounted on the central structure of the telescope between the two 8.4m primary mirrors. This is illustrated in figure 1 which shows the six bent Gregorian ports with the front Gregorian ports at the bottom and the rear Gregorian ports at the top for the left side of the telescope (on the right hand side of the figure) and the right side of the telescope (on the left hand side of the figure). There are (or will be) different WFSs at each of these ports. These are the (a) NGS First Light Adaptive Optics (FLAO) systems and (b) the ARGOS (Advanced Rayleigh-guided Ground layer adaptive Optics System) at the FBG ports; (c) the Large Binocular Telescope Interferometer (LBTI) at the CBG ports and (d) LINC-NIRVANA (LN) MCAO systems mounted at the RBG ports (not shown in figure 1.)

Fig. 1: The central structure of the LBT between the two 8.4m primary mirrors showing the locations of the AO ports. Note that this is an early photograph before the LBTI and LN upper-instrument platform installation at CBG & RBG.

2. ADAPTIVE OPTICS SYSTEMS AND INSTRUMENTATION

As the ASMs are common to all the AO systems and are a fundamental part of the telescope, the following descriptions of the different AO systems will concentrate on the components of the AO systems and the science instruments located at the different Bent Gregorian ports.

2.1 Operational Systems

2.1.1 First Light Adaptive Optics (FLAO)

The FLAO systems are located at the FBGs of the two sides of the LBT. These are NGS/SCAO systems, conjugated to the ground, and each uses a modulated pyramid WFS (PWFS). The PWFS has a number of advantages over a conventional SH WFS including: (a) greater sensitivity for fainter AO reference stars; (b) reduced aliasing for brighter AO reference stars; and (c) the ability to easily change sub-aperture sizes by simply binning the detector pixels. The current FLAO system uses an 80×80 pixel CCD to sample up to 30×30 sub-apertures without any pixel binning [7]. Each of the FLAO systems were initially commissioned with the InfraRed Test Camera (IRTC) and the delivered AO

performance is shown in figure 2 for different seeing conditions, AO reference star brightnesses and sub-aperture pixel binning. Commissioning science was done with PISCES, an NIR camera on loan from Steward Observatory.

For routine LBTO science the FLAO systems will feed the newly redesigned, narrow-field, high-spatial resolution N30 cameras of the LUCI NIR imager/spectrographs [8]. On-sky commissioning of these camera in both LUCI instruments, in conjunction with FLAO systems, is currently ongoing. Figure 3 shows some preliminary results from the LUCI/AO commissioning in March 2016 of the globular cluster Messier 5 (M5). The density of stars permits measurements of the variation of the PSF across the field as determined by the full width at half-maximum (FWHM) which were obtained using SExtractor for J, H & K_s images.

Fig. 2: Measured H-band Strehl ratios from FLAO commissioning for a range of NGS brightnesses and under different seeing conditions as illustrated with the dashed lines corresponding to 0.6'', 0.8'', 1.0'', 1.2'', and 1.5''.

Fig. 3: (Left) LUCI/AO K_s commissioning image of M5. The large image is 30'' × 30'' and the above plot shows the FWHM variation across the field for J, H & K_s. The anisoplanatism behaves as expected with greater PSF variation away from the AO reference star at shorter wavelength. Data and analysis courtesy of J. Heidt (LSW) and the LUCI commissioning team.

LUCI/AO commissioning is ongoing including rotational angle dependent non-common path aberration (NCPA) mitigation and spectroscopic performance as well as operational testing. The expectation is that LUCI/AO, on both sides, will be offered to the community, initially as shared-risk, over the next two semesters 2016B & 2017A. Binocular operation is also undergoing commissioning. This will permit both LUCI/AO systems to operate simultaneously on the same target at different wavelengths or in different modes (imaging vs. spectroscopic). It is also possible for AO to be used on one side while wider field operation is used on the other side.

Fig 4: Demonstration of AO compensation with full AO correction and ESM modes compared with raw seeing for K-band imaging.

The FLAO systems can also be operated with a small number of modes basically to remove residual tip-tilt and correct the low-order aberrations so that the high-order aberrations remain uncorrected. We have initial tests using 10 modes which improves the “effective” seeing and is known as the Enhanced Seeing Mode (ESM). Figure 4 compares the improvement in image quality as determined from the measured stellar FWHM over the raw seeing across the field. The raw seeing (blue) K-band FWHM is $\sim 0.42''$ (3.5 pixels) across the field (corresponding to a V-band FWHM $\sim 0.55''$). With AO enabled in both full mode (red – labeled as ACE) and ESM (green – labeled as TTM in fig. 4) the FWHM is corrected to $\sim 0.25''$ at the center of the field degrading to $\sim 0.3''$ at the edge of the field at a separation of $120''$.

2.1.2: Large Binocular telescope interferometer (LBTI)

LBTI [9,10] is an AO fed nulling interferometer, which has a Fizeau mode, mounted at the CBG ports, as shown in figure 1, which permits single aperture, binocular and interferometric observations to be obtained. The AO systems are mounted at each end of the LBTI optical bench and are essentially clones of the FLAO systems with the major difference that there is no rotators on those ports, as there is for the FBG ports, so that the WFS environment does not require a de-rotator. The AO performance is similar to those of the FLAO systems as shown in figure 2.

The AO systems feed multiple science cameras via a front-end beam-combiner. This is the Nulling and Imaging Camera (NIC) which combines a near-IR Camera, LMIRCam, ($2\mu\text{m} - 5\mu\text{m}$) a mid-IR camera, NOMIC, ($8\mu\text{m} - 13\mu\text{m}$) and a phase sensor ($2\mu\text{m} - 2.4\mu\text{m}$). Recently an R $\sim$ 20 Integral Field Spectrograph (IFS) unit, Arizona Lenslet for Exoplanet Spectroscopy (ALES) has been successfully integrated into LMIRCam [11]. This has been achieved via magnifying optics and a lenslet array as illustrated in figure 5. Band-limiting filters prevent overlap of the low-order spectra with an L-band ranging from $2.9\mu\text{m} - 4.1\mu\text{m}$. Figure 6 show some first-light results using ALES for a couple of different targets.

The LBTI AO systems have been in use for a number of years with single-aperture and binocular operation, mainly for the LEECH (LBTI Exoplanet Exozodi Common Hunt) inter-partner project. Interferometric operation has been demonstrated and is now becoming more routine as vibrations, which affect the path-length differences are being addressed. One of the key LBTI programs over the next few years is the NASA HOSTS (Hunt for Observable Signatures of Terrestrial Systems) project. Figure 7 shows an example of the AO/interferometric capability of LBTI reaching the 23m baseline resolution looking at the volcanic structure on the Jovian satellite Io [12].

Fig. 5: How the IFU mode has been implemented into LMIRcam with the addition of a magnifier, a lenslet array and the dispersers.

Fig. 6: (Left) ALES first-light L-band results for the planetary nebula BD+30 3639 and (right) for Io showing spectra for Loki (bottom right) and full images stepping through the wavelengths.

Fig. 7: (Left) Reconstructed Io image obtained from individual interferometric images acquired over a range of parallactic angles. Io image clearly showing the volcanoes on 2013 December 24 compared to (center) a USGS map based on NASA fly-by images and (right) the Loki Patera (orange) laid over a Voyager image of the volcanic depression. The emission is mainly localized to the southern corners of the lake.

2.2 Commissioning Systems

2.2.1 ARGOS

ARGOS is a ground layer AO system comprising of three Rayleigh beacons on each side of the telescope which produce LGS references at a range of 12km using pockels cells for the range gating. Each of the six lasers operate at an average power of 15W-17W and produce an equilateral triangle “constellation” of 4' [13]. The lasers are launched from behind each of the secondary mirrors as can be seen in figure 8. The concept of GLAO is that the lower altitude turbulence is corrected yielding an effective “seeing” improvement over a wide angle. It does not produce diffraction-limited images. The ARGOS systems are designed to operate at the FBG ports in order to be used with the LUCI imagers/spectrographs. ARGOS uses a SH WFS on each side fed by a dichroic mounted at the port entrance unlike FLAO which uses the LUCI entrance window/dichroic. The FLAO system is used as a truth sensor to slowly measure ~ 20 modes which are then offloaded as the SH offsets. A separate NGS TT sensor, an avalanche photo-diode quad-cell, can be used for guide stars brighter than 18 – 18.5 magnitudes.

Both WFSs are now mounted and the systems have been undergoing on-sky commissioning[14]. Both systems are functional and demonstration science observations using LUCI imaging and spectroscopy has been successful. Upcoming commissioning work include a detailed performance analysis under different observing conditions, fully automated acquisition, binocular operation and simplification of the GLAO operation. Figure 9 compares open and closed loop data of the cluster NGC 2149. The improvement in effective “seeing”, as measured by the FWHM, is clearly seen with a factor of 2 decrease in the FWHM for this good seeing data. (Courtesy of S. Rabien and the ARGOS team.)

Fig. 8: The ARGOS 532nm lasers launched from behind each secondary. Each “beam” comprises the three LGS constellation.

Fig. 9: Left: $30'' \times 30''$ field-of-view (FoV) of the central region of NGC 2149 comparing the open-loop (top) with ARGOS closed-loop (bottom) in the H-band. The plot compares the FWHM for the open and closed loop images over the full LUCI $4' \times 4'$ FoV.

2.2.2 LINC-NIRVANA (LN)

LINC-NIRVANA is the second AO system currently undergoing commissioning and has yet to be mounted onto the telescope. This is planned for 2016B after the clean room integration and testing is completed. LN is a self-contained AO system/instrument feeding its own NIR detector and making use of on-board PWFSs and deformable mirrors in addition to the ASMs. LN is designed as an NGS multi-conjugate AO (MCAO) and Fizeau interferometer so that it can produce relative wide-field ($10'' \times 10''$) image utilising the full 23m diffraction-limited resolution. This is complementary with LBTI in that there is trade for high on-axis Strehl ratios with reduced but uniform Strehl ratio across the field. Figure 10 shows the assembled LN instrument at MPIA in Heidelberg before being disassembled and shipped to Arizona. The reassembled instrument will occupy the platform at the RBG ports as indicated in figure 1.

In its initial phase, LN will operate in Lean-MCAO modes with $10'' \times 10''$ FoV MCAO correction from each 8.4m pupil. The MCAO correction is obtained using 2-layer correction. The lower layer is a GLAO system using up to 12 NGS PWFSs distributed in a 2' - 6' diameter annular ring and the measured wavefronts from each are co-added to control the 672 actuator ASM. There are 8 NGS Mid-High layer PWFSs, conjugated to 7.1 km, distributed within a 2' central circle and their wavefront are co-added to control a 349-actuator Xinetics piezo-stack deformable mirror [15]. There is also the path for a potential upgrade of the detector to provide a larger focal plane of $\sim 60'' \times 60''$ over which the PSF is expected to be uniform. LN commissioning is expected to take a full 30 nights through to 2018B [16].

Fig. 10: The assembled LN instrument undergoing testing at MPIA before being shipped to the LBT.

2.3 The SOUL Upgrade

The SOUL (Single Conjugated Adaptive Optics Upgrade for LBTO project affects both the FLAO and LBTI AO systems. The major component of this upgrade is the implementation of a new generation of low-noise, visible detectors for wavefront sensing – EMCCD [17]. These will permit higher spatial- and temporal-sampling of the wavefront at a reduced noise level and will allow access to fainter guide stars (by 1-2 magnitudes) thereby increasing sky coverage as well as improving AO correction at shorter wavelengths enabling $S \leq 60\%$ in the I-band. (see figure 11). The number of sub-apertures across the pupil will be increased from 30 to 40 so that the ASM firmware will need to be upgraded to handle the increased number of slopes for reconstructing the wavefront. The SOUL upgrade project has recently been approved with replacement of the LBTI WFSs proposed for 2017b and the FLAO WFSs during the following summer shutdown in 2018.

The new detectors, OCAM²K, are in the process of being acquired from First Light². These will replace the current CCD39 and have the advantage of a faster frame rate (2KHz compared with 1KHz) coupled with a shorter readout time by close to a factor of 2, and significantly reduced read noise from $10e^-$ to $< 2e^-$ at the maximum frame rate without any pixel binning. After completion of SOUL, LBTO will assume operation of the LBTI-AO systems with LBTI being solely involved with the beam combination.

² <http://www.first-light.fr/category/ranges/emccd/>

Fig. 11: AO correction Strehl ratio as a function of wavelength for both FLAO and LBTI-AO before and after the SOUL upgrade. (Courtesy S. Esposito and E.Pinna).

2.3 Potential LBTI Optical Bench Instrumentation

LBTI is currently in the process of evaluating new science instruments to take advantage of the excellent AO correction especially after the SOUL upgrade. However “real-estate” for these instruments is limited and the FLAO systems are designed to only feed the LUCI imagers/spectrographs. However, there is room on the LBTI optical bench where small instruments can be mounted between the AO WFSs and the beam combiner. There are three new candidate instruments, which can be mounted on the LBTI optical bench, which are currently undergoing review. These are described below. More details about these instruments can be found in the references below and the paper by C. Veillet [18].

2.3.1 SHARK (System for Coronagraphy with High-Order Adaptive Optics from R to K Band)

The first two are separate components of SHARK which was a proposal to “exploit unique challenging science from exoplanet to extragalactic topics with simultaneous spectral coverage from R to K band, taking advantage of the outstanding performances of the binocular ExAO LBT capability.” Initially envisaged as a single instrument, the decision was made to separate the two channels into two separate instruments one at each side of the LBTI optical bench. V-SHARK is the visible channel instrument and SHARK-NIR will handle the near-infrared wavelengths. Figure 12 shows a schematic of the LBTI optical bench layout with the two SHARK components and LMIRCam. If approved, these instruments are expected to see first light in 2018 and 2019.

Fig. 12: LBTI optical bench schematic showing the relative placements of V-SHARK, LMIRCam and SHARK-NIR. Note that each SHARK can be accessed from only one side of the telescope and LMIRCam can be accessed from both. So this permits any combination of two of these three instruments for binocular operation. (Courtesy J. Farinato)

2.3.1.1 V-SHARK

V-SHARK is a high-contrast diffraction-limited imager with a FoV of $10'' \times 10''$ operating in the 600nm – 900nm range. The imager also permits a low-noise fast-frame mode ($< 1\text{KHz}$) for a 200×200 pixel field and has an intermediate focal-plane for coronagraphy and possibly IFUs with a $5'' \times 5''$ field. The V-SHARK project is led by F. Pedichini (INAF) involving a number of INAF centers and in collaboration with the LBTI team [19]. The viability of AO correction at visible wavelengths was demonstrated using the V-SHARK forerunner [20,21]. These results show that extremely good AO performance can be obtained at short wavelengths (630nm) with Strehl ratios $\sim 50\%$ for bright targets under typical seeing conditions. However, it was noted that there was significant residual tip-tilt of ~ 17 mas at $\sim 13\text{Hz}$ which needs to be addressed and the V-SHARK design incorporates a fast TT mirror to stabilize the image on the detector. The on-sky performance is shown in figure 13. From these data, a contrast of $\sim 5 \times 10^{-5}$ is obtainable at 630 nm for angular separations from the star larger than 100 mas.

Fig. 13: V-SHARK Forerunner image (left) of GL 777 at 630nm after correction of the residual TT jitter (right). The PSF has a Strehl ratio of 50% and a FWHM of 17.3 mas.

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2.3.1.2 SHARK-NIR

SHARK-NIR is a complementary instrument to V-SHARK. It is a diffraction-limited imager designed to provide high-optical quality with $S \sim 99\%$ on-axis dropping to $S \sim 96\%$ at a separation of $10.8''$ so that the final performance, like that of V-SHARK, primarily depends upon the AO compensation. The SHARK-NIR project is led by J. Farinato (INAF) and is collaboration between various INAF centers, MPIA, IPAG and LBTI [22]. The instrument design is non-cryogenic enabling imaging in the J- and H-bands but not the K-band. The effect of coronagraphy in the H-band is shown in figure 14 comparing a classical and Gaussian Lyot, masks for seeing of $0.4''$ and $0.8''$. In addition to the coronagraph, a low-resolution spectrograph (LRS) is also being considered.

Fig. 14: Expected contrast for SHARK-NIR using coronagraphs with an inner working angle of 160 mas for H-band imaging for seeing values of $0.4''$ (left) and $0.8''$ (right).

2.3.2 iLocator

iLocator is designed as an ultra-stable and precise near-infrared spectrograph which will be fed AO corrected light via the LBTI optical bench [23]. It is a diffraction-limited Doppler spectrometer operating in the Y-J bands and will offer a

unique ability to generate high spatial resolution and high spectral resolution observations simultaneously. Like SHARK, it will have applications for exoplanet observations and will also be useful for a broad range of astronomical science applications. The AO corrected beam is fed into ilocater by means of a single mode fiber. Recent engineering tests at the LBT have demonstrated a 15%-20% coupling efficiency [24].

3. SUMMARY

The LBTO is designed as an AO fed interferometric telescope and the baseline AO systems, FLAO & LBTI/AO, by way of the PWFS systems and the 672 actuator ASMs, are capable of ExAO performance. Additionally the use of Rayleigh beacons permit enhanced seeing performance with GLAO using ARGOS and low-order uniform correction over a small FoV using Lean-MCAO with the potential of a wider-field upgrade and eventually interferometric performance. Table 1 summarises the existing and upcoming imaging AO capabilities at the LBT. Its facilities are competitive with other 8m class telescopes and in interferometric mode, the LBT is capable of achieving the diffraction-limit of the future ELTs and will pave the way for the future AO systems, especially those dependent of large adaptive elements.

AO Correction	Diffraction-Limited					Improved Seeing		
Instrument Location	FLAO	LBTI AO Bench			LN Bench	ARGOS	FLAO/ESM	
AO Fed Instrument	LUCIs Imager - Spectrograph	LMIRcam - ALES Imager - Coronograph - IFU Fizeau Interferometer	NOMIC Imager - LR Spectr. Fizeau Interferometer	V-SHARK Imager - Coronograph	SHARK-NIR Imager - Coronograph	Lean-MCAO Multi-Conjugate Adaptive Optics Near-IR imaging	LUCIs Imager - Spectrograph	LUCIs Imager - Spectrograph
Science Wavelength Coverage	J, H, K	LMIRcam (K, L, M)	NOMIC (N) (8-13 μ m)	R, I, Z (500 - 900 nm)	J, H (1.0 - 1.8 μ m)	J, H, K	J, H, K	J, H, K
AO Performance (on-axis Strehl Ratio)	J ~ 45%; H ~ 65%; K ~ 80% (FWHM = 0.6") J ~ 22%; H ~ 35%; K ~ 65% (FWHM = 1.0") for I ~ 11 (NGS)* * Assume 0.3 $\leq$ (R - I) $\leq$ 0.9 mags	K ~ 75%; L ~ 85%; N ~ 95% (FWHM = 0.6") K ~ 40%; L ~ 75%; N ~ 90% (FWHM = 1.0") for R ~ 11 (NGS)	N ~ 90% (FWHM = 1.0") for R ~ 11 (NGS)	R ~ 50% (FWHM = 0.6") R ~ 30% (FWHM = 1.0") for V ~ 5 - 7 (NGS)	H $\leq$ 85% for FWHM ~ 0.7" and R $\geq$ 11 (NGS)	J $\leq$ 20%; H $\leq$ 40%; K $\leq$ 60% for FWHM = 0.8"-1.0" seeing R_NGS $\leq$ 18.5 (NGS)	FWHM ~ 0.2" for 0.8"-1.0" seeing R_NGS $\leq$ 18.5	FWHM ~ 0.3" for 0.8"-1.0" seeing (TBD) R_NGS $\leq$ 17
NGS Science Magnitude Range	R $\leq$ 18	R $\leq$ 18	R $\leq$ 18	V $\leq$ 14	10 $\geq$ V $\geq$ 15	R ~ 12 - 14	R $\leq$ 18	R $\leq$ 18
Field-of-View	30" x 30"	LMIRcam: 10" x 10" upgrade to 20" x 20"	~12" x 12"	10" x 10" 20" x 20"	15" x 15"	Initially: 10"x 10" 41"x 41" Baseline 82"x 41" Baseline+	4' x 4'	4' x 4'
Sky coverage	~80% at Galactic Plane (K) ~ 2% at Galactic Plane (J) SR ~ 10%	(Should be similar to FLAO)	(Similar to FLAO)	Specific Targets	Specific Targets	99% at Galactic Plane 48% at Galactic Pole for SR ~ 10%	~ 100%	~80% at Galactic Plane (K) ~ 2% at Galactic Plane (J) SR ~ 10%
Anisoplanatism	50% Strehl Reduction $\theta(K) = 30''$; Z = 8"; J = 12"; H = 17"; K = 24"; L = 41"; M > 60" $\theta(K) = 20''$; Z = 6"; J = 8"; H = 12"; K = 16"; L = 28"; M = 40" $\theta(K) = 10''$; Z = 3"; J = 4"; H = 6"; K = 8"; L = 14"; M = 20"	(Should be similar to FLAO)	(Similar to FLAO)	On-axis Science (Similar to FLAO)	On-axis Science (Similar to FLAO)	~uniform over ~ 1' (depends on NGS asterism)	Uniform across the FoV	Uniform across the FoV

Table 1: Summary of existing and commissioning AO systems and science instruments at the LBT.

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