The LARGE BINOCULAR CAMERA: description and performances of the first binocular imager.


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ABSTRACT

Since the very beginning of 2008, the Large Binocular Telescope (LBT) is officially equipped with it's first binocular instrument ready for science observations: the Large Binocular Camera (LBC). This is a double CCD imager, installed at the prime focus stations of the two 8.4m telescopes of LBT, able to obtain deep and wide field images in the whole optical spectrum from UV to NIR wavelengths.

We present here the overall architecture of the instrument, a brief hardware review of the two imagers and notes how observations are carried on. At the end we report preliminary results on the performances of the instrument along with some images obtained during the first months of observations in binocular mode.

Keywords: Imager, CCD, wide field, LBT.

1. INTRODUCTION

The LBC project stems from a call of ideas for the LBT instrumentation, dated 1997, with the support of the scientific community that claimed for a wide field imager capable of deep imaging at wavelengths shorter than those of Suprimecam (Miyazaki et al. 2002). It was soon clear that the unique mount of the LBT represented a good opportunity to study a double imager that could be optimized in both blue and red portions of the optical spectrum. Therefore, we developed an instrument composed by two CCD cameras to be installed at the prime focus stations of the fast (F# =1.14) 8.4m parabolic mirrors of the LBT (Ragazzoni et al. 2000, Pedichini et al. 2003). Thanks to the large telescope diameter and the fast final F# of the correctors, LBC is able to acquire very deep images over a FoV of 27arcmin diameter. Moreover, since the two imagers are installed on the double mount of the telescope, it’s possible to acquire the same target simultaneously at different wavelengths. As prefigured, this configuration required the realization of two challenging optical correctors to compensate the quite severe aberrations introduced by the mirrors shape.

Initially conceived as a PI instrument and further as a facility one, the LBC has been developed by three groups of the Italian Institute for Astrophysics (INAF): the Padova/Arcetri group designed and aligned the optomechanics of the two optical correctors, the Rome group have been involved in the development of cryomechanics, software and controls of the CCD cameras and the Trieste group realized the data archive facility.

Even if the two cameras are conceptually identical, they differ in some hardware components. Apart from the natural differences due to the wavelength optimization, the red camera (LBCR) was the second imager to be put in operation and it contains all the upgrades we made on the blue one (LBCB) during both the commissioning phase and science operations at the LBT. These improvements regarded nearly all mechanical and optical components of the camera (corrector, cryostat, shutter) as well as the CCD control electronics.

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2. THE LBC ARCHITECTURE

Figure 1 shows the LBC system just after the completion of the binocular mode with the LBCR installation in December 2007. The two imagers are mounted on two of the six LBT swing arms, just under the secondary mirrors ones. Each hub (Fig.1B) contains both the lenses of the corrector and the rotator field bearing that is equipped with two filter wheels and the camera cryostats that host the CCD array. The LBC also comprises 46 devices (motors, encoders, sensors) driven by a total of 12 electronic boards (Fauhlaber motor drivers, Goya cards for tracking trajectory, shutter drivers and CCD controllers) that are onboard the hubs and get the power from two cabinets (Fig.1C) installed on each elevation arm of the telescope. This system is managed by one single LINUX computer, the Central Management Unit (CMU), with the exception of the four CCD electronics that require four WINDOWS based PCs dedicated to the configuration of each controller and the acquisition of the image files. These five machines (Fig.1A) are located in one of the two “tree houses”, a small control cabins placed at the bottom of the LBT platform and communicate with the hardware on the hubs by means of eight optical fibers.

3. HARDWARE REVIEW OF THE LBC IMAGERS

3.1 Optical Correctors

Designing and building the two optical correctors was a very challenging task mainly because of the very fast focal ratio ($F# = 1.14$) of the primary mirrors and their parabolic shape. The design of both channels derived from a modification of the three lens Wynne's concept (Wynne, 1972)$^4$, where the second and third lens are split in two and an additional lens,
the cryostat window, is added for a total of six lenses. The layout of the two corrector is very similar (Fig. 2), they have the same number of lenses, the same focal plane scale and even the geometrical distortions have been forced to be the same. Filters are mounted on two different wheels and are placed between the last two lenses.

All the lenses of the blue corrector were made in fused silica which ensures a high transmittance in the wavelength of interest (UBV). The six silica blanks have been provided by Corning following very tight requirements on the refraction index homogeneity (<2x10^-6) and bubble cross section (<0.25 mm^2/100 cm^3) to minimize blurring and scattering effects, respectively.

The red corrector has a FoV 10% larger than the blue one to remove the small vignetting that affected the LBCB. It has been optimized in the range between V and Z band with a possible extension to J and H bands up to 1.8µm. For this corrector the BK7 has been chosen for slightly better performances and being cheaper than silica. The blanks, provided by Schott, had the homogeneity index comparable with the silica ones and the bubble class was even better.

All blanks have been grinded, polished and coated by Sagem-Reosc and then sent to the Astrophysical Observatory of Arcetri where a clean room was set up and several handling tools to move, lift and align the lenses into the hubs (designed by ADS and provided by Tomelleri) were manufactured.

For a detailed description of the optical design, the alignment and mounting procedures of the correctors see E. Diolaiti et al. (2003, 2004), R. Ragazzoni et al. (2004, 2006), G. Gentile et al. (conference 7014)9.

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**Fig. 2 - Structure of a LBC imager.** Diameters (in mm) of the corrector lenses are reported beside the lens name.
3.2 Arrays and detector alignment

The arrangement of the detectors on the focal plane is the same for both cameras (Fig. 3): an array of four E2V 4290 (4.6Kx2.5K) covers the corrected field of 27 arcmin diameter with a sampling of 0.23 arcsec/pixel providing the scientific image, while two E2V 4210 (0.5x2K) placed at two lateral sides are used to acquire short exposure images for tracking and wavefront control to perform active optical corrections of the two primary mirrors. Since the 4210 devices are used without the shutter to get several images for guiding and AO during the longer scientific exposure, they have been customized by E2V that masked the first 256 lines with an Al deposition and they are driven using the frame transfer technique.

![Figure 3](image1.jpg)

Fig. 3 [left] A LBC array with the 4x4290 and 2x4210 - [right] the Quantum Efficiency of the 4290 detectors (by E2V).

Being the camera focal ratio very fast, the alignment of the detectors was a crucial point. Furthermore, we asked E2V to select, among the high QE (Fig. 3) science grade 4290, the ones having a surface roughness <7 µm peak to valley. To maintain the good optical quality everywhere on the focal plane, the four detectors had to be mounted on the invar plate with a precision comparable to the dimension of the pixel, i.e. ±13.5 µm.

The array alignment have been done in one of the clean rooms at G&A Engineering near Rome, equipped with a laser measuring machine (Quick Vision by Mitutoyo) able to measure the height of the CCD with a 1 µm accuracy without touching their surfaces (Fig 4).

![Figure 4](image2.jpg)

Fig. 4: [left] LBCR array during the alignment at G&A labs. [right] the "map" of the red array (unit is µm).
Once verified that the detector plate was aligned with the window plane, all the measurements were done taking this plate as the reference plane. After installing the detectors, the focal plane was sampled with 406 laser spots, (91 for each 4290 detectors and 21 for 4210 ones). As guaranteed by E2V, all the four 4290 chips resulted to be within the specifications without any shimming. On the other side we had to use calibrated invar shims to align the guide detectors (that have to be coplanar to the scientific array) and the AO detectors positioned under the focal plane (by a well determined spacing) to obtain extrafocal images for pupil analysis.

3.3 Rotator flange

The rotator flanges of the two cameras are made of a stainless steel (AISI 4130). They are completely different in shape (Fig. 5) mainly because the LBCR has a wider optical window (156mm instead of 130mm). As described above, the optical quality is very sensitive to misalignments, even those due to the deformation of the flange. For this reason, we performed a FEA of the 3D model to verify that the flexures did not exceed just a few arcsec in both the directions.

![Fig. 5: The two rotator flange interfaces. [left] The blue one with a dummy window. [right] The red one with the array flange mounted on.](image)

The optical windows are held in place by a circular stainless steel ring that is equipped with a resistive wire able to dissipate a few tens of Watts on the lens to prevent moisture from accumulating on the surface of the glass, when housekeeping system is switched on. In order not to dissipate heat to the cryostat, the window flange is isolated from the cryostat by a fiberglass ring.

3.4 Cryostats

The two cryostats used to cool the CCD arrays have been developed by the Rome group in collaboration with Forestal S.r.l., a space-qualified mechanic shop in Rome. The design and, mostly, the overall geometry of both cryostats are the same. They are composed by three independent modules: a stainless steel rotator interface flange holding the detector array and its cabling, a spherical bimetallic nitrogen vessel and the spherical aluminium housing (Fig. 6). This configuration provides a useful separation between the electrical part (detector flange, cables, etc) and the cryogenic assembly, allowing an easy maintenance and upgrade of the two parts independently.

The spherical nitrogen vessels are both bimetallic. They are made by two layers of different metals: a high conductivity one for the inner surface, (copper for the blue channel, aluminium for the red one) and a harder one (nickel in both cases) attached by galvanic deposition on the outer surface and polished to reduce the radiative thermal input. The top of the vessels are closed by welding an "umbrella-shaped" stainless steel (LBCB) or electroformed nickel (LBCR) flange acting as the interface with the external part of the cryostat.

The main difference between the two cryostats concerns with the technology we used to build the vessels. The blue one has been completely electroformed in a galvanic bath starting from a plastic spherical mandrel. It took several weeks of metal accretion (copper first and then nickel) to obtain the desired surface thickness. Once the sphere was formed, it was welded to the stainless steel flange using a galvanic bath.

The spherical vessel of the red cryostat has been shaped from a bulk cube of aluminium using a CNC lathe and then joined to the nickel flange. This procedure was a challenging issue and took several months to test and design properly the pieces, to compensate for the differential thermal expansion, and tune the electrodeposition technique for welding aluminium with nickel and steel alloys.

The technology developed for the construction of the vessels is now largely used by Forestal for making unique high efficiency microwave guides used in telecommunications satellites.
The detector flange is mounted in the rotator interface by means of three fiberglass supports to be isolated from the outer warm surface. On the other side of the CCD flange we mounted the thermal link (Fig. 7) with the aim to cool down to 170K the array without any temperature active control. For the LBCB we used springs with copper pads welded with calibrated wire, while for the LBCR we made copper/brass cylinders, properly sized, that co-penetrate each other once the spherical part is connected to the rotator flange. This second solution ensures a more robust thermal connection than the one used for the LBCB.

After more than two years of operations of the blue cryostat at the LBT we can say it showed excellent performances in terms of vacuum levels and nitrogen consumption. In operative conditions the time between two refills is ranging from 40 to more than 48 hours mainly depending on the season of the year.

Due to several modifications made on the red channel cryostat (larger window, the use of copper wires for grounding and video signals, larger number of fiberglass supports), the LN$_2$ consumption of the LBCR is higher than the LBCB. Since the available volume of the vessel is the same (7.5lt), we covered it with ten layers of MLI (Multi Layer Insulation, fig. 7 right) to achieve the requested minimum holding time of 24 hours (at T=20°C), being around 28-34 hours at the LBT.
3.5 Shutter

Three main constraints have driven the design of the LBC shutters (Fig. 8): a wide unvignetted shutterable aperture with a diameter greater than 130mm (LBCB) and 160mm (LBCR), the maximum thickness of 15mm (LBCB) and 20mm (LBCR), an exposure uniformity on the whole field better than 0.01 sec. exposure time, a lowest working temperature of –20°C. The basic concept is based on two thin blades (1mm thick) mounted on three teflon pads that are operated alternatively by two electric Faulhaber mini-motors equipped with a 2048 step encoder and connected with two M6 linear screws. Three hall sensors are positioned along the chassis: two for the homing detection of the blades and one for the real exposure time measurement detecting the transit of small neodymium magnets glued inside the teflon pads.

The red shutter is the evolution of the prototype built for the LBCB that actually has been working for more than two years. The design was changed taking into account the larger size of the cryostat window, to host all the cablings of the motors and sensors and to realize a pipeline to spread out the boiling off nitrogen on to the window surface to keep it clean and dry when the heater is turned off. Furthermore the two linear screws were made using aluminium instead of stainless steel, having the same thermal expansion of the main structure. This change increased both the precision of the blades and the reliability of the shutter at low temperatures. We also decided to change the pads material using teflon mixed with graphite to have the same friction of teflon but with a longer lifetime.

The requirement related to the precision of the exposure time can be achieved if the two blades follow exactly the same motion curve. Using the telemetry of the control electronics, we can tune the PID parameters of motion reducing the position error of the blade (actual - desired) down to ±5step (2.5µm) corresponding to a time error 3.3x10−5 sec during the constant speed phase. Even the error increase when ambient temperature decreases, becoming three times larger at TAMB=−20°C, still largely fulfills the initial requirement.

Since the red shutter performed very well from the beginning of the LBCR operation, we decided to rebuilt the blue one for a final upgrade on the LBCB.

![Fig. 8: [left] Comparison between blue (smaller) and red shutter. [right] Details of the LBCR shutter.](image)

3.6 CCD Controllers

Each camera is equipped with two CCD controllers to manage the scientific and technical detectors. They have been developed by the Rome group in collaboration with the italian firm Skytech. Actually the LBCR is equipped with a second generation controller that is more reliable and faster than the previous release. For this reason we foresee to update the LBCB controllers in a near future.

To save room and weight at the focal stations, this system is split in two parts: as for the other devices, they get the power supply from the cabinets on the elevation arms, while the controller boards only (Fig. 9) are mounted onto the cryostats. All data images are then sent from the instrument via optical fibers to the four control pcs equipped with a dedicated PCI acquisition board.

Each controller is composed by just two cards: the SPC clock card for the generation of the waveforms and the CDS board for the generation of bias signals and the 16bit sampling of four video channels. The core of the system is the programmable Xilinx FPGA, installed on the CDS board that, together with the clock generation, accomplishes several
different tasks like the bias telemetry, the optical fiber data link with the PCs and the processing of the video signals. In the actual configuration the FFPGA’s gates are used by a 70% leaving a huge space for future expansion of the system like the use of IR and optical CMOS detectors and for the onboard data reduction processing.

A strong care has been dedicated to synchronize all the hardware components of the controllers (waveform generation, sampling the video signal, downloading data, etc) and to lower the RON that resulted to be less than $10^{-18}$ @500 Kpix/s/ch. This system is entirely scalable and each controller can hold up to four video boards (16 video channels) to be usable for larger CCD/NIR arrays.

For a complete description on the CCD cameras see Pedichini et al. (2003)\textsuperscript{10}, Speziali et al. (2004, 2006)\textsuperscript{11,12}

4. OBSERVING WITH LBC

4.1 OBs and control software

In order to use the LBC, a general user has to prepare an observing block (OB), i.e. a file that contains all parameters of the acquisition run (exposure times, filters, dithering pattern, etc). Even if the control software has an online routine to create an OB, this operation is usually done off-line by using a OB creator tool developed by the LBC team\textsuperscript{13}.

Fig. 10: The four panels of the control software. A) systems power supply - B) cryostats parameters - C) OB execution and observation status - D) system logs.
With the binocular mode on, observations are carried out in a master/slave mode, where one of the cameras (master) takes care of the telescope guiding, and the other keeps the second telescope (slave) copointed by tilting the primary mirror. Since the two telescopes point the same sky area within 4 arcsec, a small adjustment to the slave telescope is needed to obtain properly guided frames. Currently the LBCR is used as a master because chances of having at least one star on the guide chip are higher than using the blue bands. Note that while the pointing is unique, in principle, one can choose different position angles for the two cameras.

The observer can operate the LBC and execute the OBs via the CMU using any web client (javascript enabled) inside the LBT network. The LBC control system software layout is based on four web pages (Fig. 10): with the first one the user can remotely switch on/off the single units (housekeeping, CCDs, filters and rotators); the second is dedicated to the vacuum level and temperatures surveillance of the cryostats; the third one, is the interface to execute the OBs and follow the status of the observation; the fourth one, is a technical interface showing a system log with the devices status of the instrument and is useful for hardware debugging.

For a complete description of all the LBC devices, system and software architecture see Di Paola et al. (2004)\textsuperscript{14}.

A second feature is related to focusing and AO analysis (see J. M. Hill et al., conference 7012)\textsuperscript{15}. This is done at present by taking an extrafocal image with both telescopes and analyzing the pupils to obtain corrections to be applied to reduce optical distortions. A new system is being implemented that uses the second auxiliary chip placed aside the main array. Extrafocal images taken with this chip will be analyzed online and proper corrections for the active optics system derived in real time, considerably reducing the overheads.

4.2 Archiving LBC data

In parallel with the construction of the imager, the Italian Center for Astronomical Archive (IA2) based in Trieste, developed the archive system of the LBC with the goal of storing and distributing data and images to the whole LBT community as fast as possible and in secure mode.

This system relies on three main centers based on Oracle databases: the LBT Observatory in Tucson, the Max-Planck-Institut für Astronomie in Heidelberg (Germany) and the IA2 itself in Trieste. The archive started to run since the very beginning of the operation of the blue channel at the end of 2005 and has been largely tested during the Science Demonstration Time (SDT). It has been developed to fulfill the following requirements: to transfer all scientific data from the LBT to the LBTO; to transfer from the LBTO to European partners the SDT data only; to provide a user friendly web interface for data retrieval and a simultaneous and secure access from the SDT community.

To minimize the impact with the local networks, all data acquired during an observing run, are compressed using gzip and then copied early in the morning from Mt. Graham to the LBTO database (Fig. 11). Then, in the evening (Tucson time) they are transferred to Heidelberg and Trieste (via Rome Observatory) using multiple parallel sessions. Once the data are present on all data centers, they become visible and retrievable from the LBC users. All the three archives have the same web interface to search and download data. All data can be downloaded individually or by group. In the latter case, a tar file is created and saved in a temporary directory accessible only from the current user. If the total dimension of the file is more than 700 MB, multiple tar files are created to simplify the data retrieval process.

A subset of the fits keywords of each image are extracted to form the metadata that are archived separately from image data. They are also sent to the mirror archive and are updated every time a image is processed and additional information derived by any post processing pipeline. So, while images data propagate daily, metadata can propagate every hour between partners.
During SDT observations, more than 1 TB was acquired and copied from Tucson to LBT partner with a peak of 30 GB transfer rate. The LBC/SDT archive is actually used by the whole LBTO community. Its reliability convinced the LBT Board to commission to IA2 the development of the LBT Spread Archive (IVOA compliant) that will be released before the end of 2008.

5. PERFORMANCES

Although still under analysis, the data obtained in the first months of 2008 during the commissioning of the red camera and binocular mode show encouraging preliminary results. We compared the performances in the two $V_{\text{Bessel}}$ bands, that are the only identical ones between the two cameras. The performances in this band are fairly the same within the uncertainties. A raw estimate of the count rate on the sky gives the same ADU level well within random errors, and the first photometric calibrations show similar zeropoints: 27.99 (LBCB) and 27.86 (LBCR), obtained in the same, probably non-photometric, night. Color terms are almost negligible.

Limiting magnitudes depend on several factors like seeing, sky transparency, etc. The images obtained during the commissioning of both channels were taken in seeing conditions slightly worse than average (1.2" in the SDSS-like R filter). In these conditions the 10$\sigma$ limiting magnitude with 30 min exposure time is $R_{\text{LBC}} = 25.93$, while in LBCR, limiting magnitude with 5 min exposure time and seeing ~ 1.6" is $R_{\text{Bessel}} = 23.93$. Both results confirm the expectation from the Exposure Time Calculator. Table 1 below reports a summary limiting magnitudes in various filters of both cameras. Results for LBCB are taken from Giallongo et al. (2008)\textsuperscript{16}.

<table>
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<th>LBCB</th>
<th>Exp. T [s]</th>
<th>LBCR</th>
<th>Exp. T [s]</th>
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</tr>
</tbody>
</table>

Tab. 1: LBC limiting magnitudes.

Geometrical distortions are an issue in a wide-field prime focus imager like this. Although the lens system considerably reduces their effect on the focal plane, some corrections have to be applied to optimally remove them. The reduction pipeline, developed by the LBC team\textsuperscript{17}, uses the astrometric solution found by matching the USNO catalog to find a geometrical correction map that is then applied to the raw image. With this procedure the distortions are removed almost all over the whole image area, with the possible exception of the chip corners, and the image is resampled to a uniform pixel scale. This effect is visible on the raw frames as a background enhancement in the central part of the images, that must not be confused with a genuine flat field effect. The pipeline takes into account both phenomena, producing a well corrected scientific image (Fig. 12 and 13).
Fig. 12: M33 - three-colour image I_{Bes}(31x20sec) + V_{Bes}(12x50sec) + B_{Bes}(12x60sec). FWHM = 0.8" ÷ 1.1" (Astrometry reduction by M. Radovich)

Fig. 13: NGC5907 four-colour image r(13x180sec) + g(14x240sec) + U_{Bes}(5x120sec) + U_{spec}(3x120sec). FWHM ≈ 1.1"
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