BOMBOLO: A 3-arms Optical Imager for SOAR Observatory

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ABSTRACT

BOMBOLO is a new multi-passband visitor instrument for the SOAR observatory. It is a three-arm imager covering the near-UV and optical wavelengths. The three arms work simultaneously and independently, providing synchronized imaging capability for rapid astronomical events. BOMBOLO leading science cases are: 1) Simultaneous Multiband Flickering Studies of Accretion Phenomena; 2) Near UV/Optical Diagnostics of Stellar Evolutionary Phases; 3) Exoplanetary Transits; 4) Microlensing Follow-Up and 5) Solar Systems Studies. The instrument is at the Conceptual Design stage, having been approved by the SOAR Board of Directors as a visitor instrument in 2012 and having been granted full funding from CONICYT, the Chilean State Agency of Research, in 2013. The Design Phase has begun and will be completed in late 2014, followed by a construction phase in 2015 and 2016A, with expected Commissioning in 2016B and 2017A.

Keywords: muti-passband optical imaging, rapid photometry, time-series astronomy

1. INTRODUCTION

BOMBOLO[1] is an instrument to perform fast and simultaneous multi-passband photometry at optical wavelengths, to be installed at SOAR Observatory on Cerro Pachón. We propose it as the single solution to a series of scientific questions emerging within our team. Currently, these needs of fast simultaneous near-UV to optical photometry cannot be completely fulfilled by the astronomical instrumentation available to the Chilean community. In this sense, BOMBOLO is an exemplary case of science exploration feeding technology development in Chile and we believe a key project in our long-term plan of becoming a significant player in world-class instrumentation for astronomy.

Although there are a few examples of instruments providing fast and simultaneous imaging capabilities in the optical [1], none of them are available in Chile and/or have different characteristics than BOMBOLO. We envision BOMBOLO as a cost-efficient instrument addressing broad scientific goals. In the framework of a general effort to gain independence and strengthen the position of instrument design and development in Chile, we plan to offer BOMBOLO to the entire Chilean community, in particular if the SOAR Observatory promotes BOMBOLO to become a facility instrument, once we have tested its capabilities and proved its performance and scientific productivity.

This article is structured as follows: in section 2, we present the science cases driving the design of BOMBOLO; in section 3 we present the Instrument Requirements; in section 4, we describe the current state of the design and in section 5 we present the future elements of the intrument's construction.

2. BOMBOLO SCIENCE CASES

The Science Cases that inspired the idea and are today driving BOMBOLO are summarized below:

[1] Franco Lechner (BOMBOLO) was an Italian comedian, 1931-1987

2.1 Accretion Processes at all Spatial Scales. From proto-planetary systems to interacting binaries, and beyond.

Simultaneous multi-band studies of rapidly variable phenomena as a result of accretion processes play an important role in astrophysics at basically all spatial scales, from proto-planetary systems to binary stars, up to galaxy clusters. The associated phenomenology shows a wide range of time-dependent behavior, whose systematic investigation has so far been driven predominantly by detector development and their capabilities - more than by the underlying science - with the result that the temporal domain below a few minutes remains virtually unexplored and is a field of future fore-front science [2].

Generally speaking, we know that accretion processes are expression of turbulence at work: in this sense, rapid photometric variability (hereafter simply "flickering") that arises from a heterogeneous group of astronomical systems (e.g., cataclysmic variables, X-ray binaries, young stellar objects, proto-planetary disks, etc.) can be seen as the result of turbulence in the accretion stream and/or disk. Flickering is also a powerful diagnostic of nuclear burning processes, and the study of any coherent short periodicity in the light curve could bring valuable information on a range of poorly studied magneto-hydrodynamic (MHD) phenomena [3].

Even though flickering studies on a few bright objects date back to the 90's [4], virtually no systematic study on the spectral energy distribution of this rapid photometric variability has been performed. Today, when multi-band information is desired, the only solution is to observe the same target simultaneously with more telescopes, e.g., like Zamanov et al. 2012 [5] have recently done by occupying at the same time up to 4 (!) telescopes for monitoring the cataclysmic variable AE Aqr and correlate the colors of the recorded flickering with the system physical parameters (e.g., the mass transfer rate and the size of the WD magnetosphere). As a matter of fact, it has been suggested that simultaneous multiband observations could be fundamental in assessing the magnetic character of any accreting star [6]. This would open a new research line where detailed theoretical modeling has unfortunately not corresponded yet to a parallel observational effort, aimed at collecting systematic and comparable data sets.

A natural evolution from photometric flickering is spectroscopic flickering (i.e., the ability to monitor over fast time scales the relative intensity variations of emission/absorption lines coming from astrophysical objects). This approach, technically challenging and extremely time consuming, has been rarely utilized on just a handful of carefully-selected bright stars [7]. While we cannot obviously compete with real spectroscopic observations, BOMBOLO will still offer a kind of low-resolution spectroscopy by using simultaneously narrow band filters. In designing the instrument, we are in fact planning to provide each arm with a filter wheel on which to mount an optimized set of narrow-band filters, preliminary selected on the basis of the scientific inputs and needs of our science team.

2.2 Stellar Populations Diagnostics

The globular clusters (GCs) in the Local Group have been the cornerstone of stellar astrophysics and stellar population synthesis models for centuries. The stellar populations in these star clusters have been regarded as the best approximations to simple stellar populations, which are characterized by a collection of coeval stars with one well defined chemical composition. Spectroscopic studies of the past decades revealed peu à peu that some star clusters consist of multiple stellar sub-populations with distinct light-element abundance patterns, while recent HST studies bolstered these early findings by discovering that most massive star clusters in the Local Group contain at least two chemically distinct stellar sub-populations. High spectral resolution spectroscopic studies of GC member stars also show characteristic element (anti)-correlations that appear to scale with some GC properties. One of the most exciting recent findings is that the CNO element variations appear to scale with the GC initial dynamical parameters, such as initial half-mass radius and initial total dynamical mass. Such correlations emerge from the initial physical conditions of the earliest epochs of star cluster formation. Accessing the relative CNO abundances in tens of thousands of member stars becomes accessible through a combination of medium and narrow-band photometry at near-UV to optical wavelengths, and BOMBOLO will provide the necessary tool to conduct highly-efficient observations of stellar populations in a large number of Local Group GCs and nearby dwarf galaxies. This will provide invaluable first chemo-dynamic constraints for high-resolution hydrodynamical formation models for some of the oldest stellar populations in the Universe.

2.3 Microlensing Events

A direct consequence of the General Theory of Relativity is the deflection of light due to massive objects. The case in which the deflecting mass is that of a star is called microlensing. Star-star microlensing produces a discernible magnification of the flux of a background star by a foreground star on timescales of days to months. The "magnification curve" shown by such a microlensing event is an exceptional tool to probe different properties of both the foreground lens and the background source.

Microlensing is the only planet-finding method that allows identifying planets in very distant stars (several kpc away). Furthermore, of all methods that use ground-based observations, microlensing has the greatest sensitivity toward finding earth-mass extrasolar planets [8, 9]. Several campaigns are constantly monitoring the galactic bulge for microlensing events (e.g. OGLE, MOA). When an interesting event is detected by such campaigns, an alert is issued triggering the observation of the event by several follow-up campaigns around the globe (e.g. MICROfun, PLANET, MiNDSTEp, etc).

For such microlensing events, multi-band, high-cadence follow-up observations as facilitated by BOMBOLO are crucial ingredients in order to identify and accurately characterize planetary systems as well as source stars' stellar atmospheres.

2.4 Exoplanetary Transits

The discovery and characterization of exoplanets, i.e. planets orbiting stars other than the Sun, is one of the most exciting and fast moving areas of research in astronomy today. Among the many exoplanets being continuously discovered, the planets that eclipse their stars (or transit) as they orbit are especially interesting, as the fortuitous geometry allows the measurement of physical properties that are generally not accessible for other systems (accurate planetary masses and radii, relative orientation of orbital and stellar spin axis, atmospheric emission/transmission spectra). One of the most exciting possibilities transiting exoplanets allow is the study of their atmospheres. BOMBOLO will allow us to measure planetary radii at different wavelengths and therefore place constraints on their atmospheric composition, in a similar way to transmission spectroscopy. The advantage of this method is the higher signal-to-noise ratio than ground-based spectroscopy can achieve, which can provide constrains on phenomena such as Rayleigh scattering in exoplanet atmospheres.

2.5 Solar System Objects

How the Solar System has evolved to its current state can be explored by characterizing both the dynamical and physical properties of large and small bodies at all distances from the Sun. The small objects represent a relic of their dynamical and physical interactions with the giant planets and each other since their creation. Simultaneous observations in multiple wavelengths minimize interpretation complications for object surfaces (small objects) and atmospheres (large objects), since all these bodies are rotating, some at very fast rates (a few minutes or hours) and some at slower rates (tens of hours to days). Studies of the photometric properties of individual and groups of small solar system objects provide insight on their collisional and space weathered surface histories. Studies of comets that come into the inner solar system from the outer solar system provide glimpses at old surfaces on their way in towards the Sun and fresh surfaces on their way out as material sublimes through Solar heating. Being able to observe all of these objects at a variety of wavelengths with a single instrument like BOMBOLO from a 4-m class telescope is a significant step for better characterizing these objects and in correctly interpreting their contribution to our understanding of the solar system's formation.

3. BOMBOLO INSTRUMENT REQUIREMENTS

3.1 General Requirements

From the science cases presented in the previous section, it is possible to derive the instrument requirements, which are presented in Table 3.1.

Table 3.1: BOMBOLO Instrument Requirements

Requirement	Value
Field Of View	7 x 7 arcminutes
Pixel scale	0.3 arcsec / pixel
Wavelength Coverage	320 – 900 nm
Dychroic Cutoff	390-400 nm and 550-560 nm
Readout time	≤ 10 seconds
Readout noise	≤ 5 electrons
Exposure	In-sync and independent

Each instrument requirement has been iterated through our science team. We include brief explanations for each item in Table 3.1:

Field-of-View (FoV): Although it is desirable that any astronomical imager has a very wide FoV keeping the Point-spread Function (PSF) well sampled, there are budgetary and technical complexities in widening the FoV. A 7 x 7 arcmin FoV optimizes science results and cost.

Pixel scale: The pixel scale has been defined by optimally sampling of the PSF, given the large FoV of the instrument. BOMBOLO will be a seeing-limited instrument, therefore 0.3 arcsec/pixel is found appropriate for a 0.7 arcsec PSF in the optical wavelengths, with ~2.5 pixel at full-width-half-max.

Wavelength coverage: is primarily driven by the Flickering science case. As we will be using three optical detectors, we will take advantage of choosing the AR coating on each of them.

Dychroic Cutoff: is driven by a combination of technical aspects as well as science cases. The dychroic at 390 nm allows us to isolate the particularly interesting near-UV wavelengths, while we can observe other interesting wavelengths at the same time with the other two cameras using narrow band filters on each one. The current optical design is considering 45 degrees for the dychroics, but in recent consultations with vendors, we expect to reduce the angle to 35 degrees, in order to preserve the cutoff wavelength at less than 40 nm.

Readout Time: The FoV and correct sampling of the PSF allows us to define the size of the detector, which is detailed in a section below. Although 'instantaneous' readout time will be the preferred requirement, realistically one has to read pixels out at the correct timing if readout noise considerations are taken into account. A compromise between limitations in the ability to measure photometric flickering and obtaining low-noise images has been found in defining 10 seconds as simultaneous detectors readout time.

Readout Noise: this is entirely driven by technical limitations on the detectors. For a defined readout time, the readout noise will be a consequence of how fast the detector needs to be readout pixel by pixel in order to comply with the overall readout time. 5 electrons noise is considered adequate for the 10 second readout time.

Exposure: this is directly required by our science cases and it is one of the unique characteristics of our instrument. Thanks to in-sync'ed readout controllers (see section below), we will be capable of start exposing the thee cameras at exactly the same time, while finishing each exposure at the required Signal-to-Noise Ratio (SNR), computed by the Exposure Time Calculator of the instrument.

A general concept for our instrument is presented in Figure 3.1.

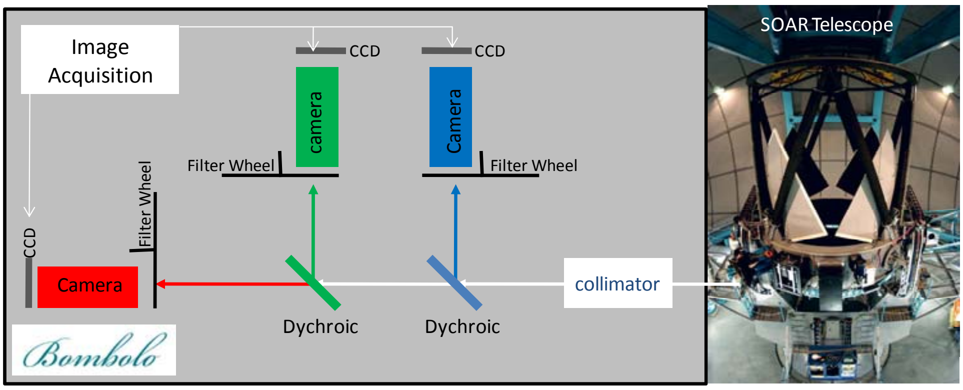

Fig. 3.1: BOMBOLO instrument general concept: visible light from SOAR Telescope comes at one of the Nasmyth focal stations. A broadband collimator directs the beam to a couple of dychroics, which divert short wavelengths to three cameras. A filter wheel, an optical camera and a cryogenic CCD run on each arm, all synchronized by one image acquisition system

3.2 BOMBOLO Exposure Time Calculator

The BOMBOLO Team has just started working on an Exposure Time Calculator (ETC) that will help the Observer verifying the technical feasibility of his/her observing strategy and to optimize the instrument configuration (i.e., selection of dychroic/filters) in relation to the specific science goals to be reached.

In this preliminary version, the ETC is basically built on the IRAF task *ccdtime*[2], and computes the standard quantities (either exposure time in seconds to reach a desired S/N, or S/N obtained integrating for a predefined exposure time) for either a point source or an extended astrophysical objects of given magnitude, taking into account the target airmass, expected seeing, and Moon phase.

Database files contain the SOAR 4m Telescope specifications (e.g., aperture diameter in meters, scale in arcsec/mm, and transmission of the optical surfaces), the dychroics and filters transmittance curves (which we are currently measuring in our labs), and the parameters of the CCD detectors (such as read-out noise in photons, dark rate in photons per second, pixel size in microns, and the effective QE curves for the different coatings).

At a later stage we plan to include in the BOMBOLO ETC: 1) the possibility of simulating different Spectral Energy Distributions (SEDs) built up on a library of synthetic spectra, as well as 2) a specific sky model for Cerro Pachon[3], able to take into account also site-dependent observing conditions (such as sky brightness, zodiacal light, telluric absorption/emission) which would make the ETC estimations much more realistic.

3.3 BOMBOLO System Throughput

As a first approximation to estimate the instrument system throughput, we are considering it as a composite function of the detector quantum efficiency (QE), mirror reflectivity, and filter throughput only. Figure 3.2 illustrates these individual contributions as a function of wavelength. We divide the wavelength range with one blue dichroic at ~390 nm between the blue and green-arms and with three red dichroic options at 530, 554, and 690 nm to separate the green and red arm of BOMBOLO. We compute the composite system throughput function by considering the detector QEs of the "Enhanced Midband" and "Basic Midband" using the manufacturer specifications (see section below), standard Aluminum mirror reflectivity of primary, secondary and tertiary mirrors of the SOAR 4m telescope (dotted line), and Sloan SDSS generation-2 ugrizY broad-band filters, Strømgren uvby intermediate-band filters, as well as O[III] and Halpha narrow-band filters. We note that at this point we do not include in our calculations the BOMBOLO optics throughput, which should only marginally affect the shown throughput curves. The resulting system throughput for each filter is depicted as filled colored curves. The SDSS filters are compared to the corresponding filter system throughput curves (open colored curves) taken from MegaCam on the 4-meter Canada-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii. The comparison shows that the expected performance of BOMBOLO is on par or better than that of CFHT/MegaCam, in particular in the blue arm (SDSS u-band).

The bottom panel of Figure 3.2 demonstrated some astrophysically interesting spectral energy distribution functions (SEDs) that BOMBOLO will be able to probe very efficiently, with simultaneous observations in three filters. The superb system throughput in the blue (>40%) will be particularly diagnostic to star formation, allowing us for instance to probe the lower end of the Kennicutt-Schmidt Law and young stellar populations.

4. BOMBOLO DESIGN

4.1 BOMBOLO Optical Design

Optical Principles

The SOAR telescope forms an image at a focal ratio of f/16 on a surface concave to the sky. The BOMBOLO optical design is in essence a focal reducer and consists of a collimator forming a beam 50 mm in diameter followed by 3 cameras each forming an image at a focal ratio of f/2.5.

The collimator consists of 4 components. The first component acts as a pupil imager or field lens. The 3 remaining components are arranged in a reverse telephoto configuration. The central negative and relatively thick meniscus components act to reduce the intrinsic system field curvature and control the system length. A pupil image is formed at a distance of 120 mm from the last lens so as to allow room for 2 beamsplitter (dychroics) folds. The pupil image is not well-corrected so as to allow the system to reach the best collimation.

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[2] http://iraf.net/irafhelp.php?val=astutil.ccdtime&help=Help+Page

[3] As a reference, see, e.g., *Night Sky Brightness at Cerro Pachon* http://www.ctio.noao.edu/site/pachon_sky/ and the *Cerro Paranal Advanced Sky Model* at http://www.eso.org/observing/etc/doc/skycalc/The_Cerro_Paranal_Advanced_Sky_Model.pdf

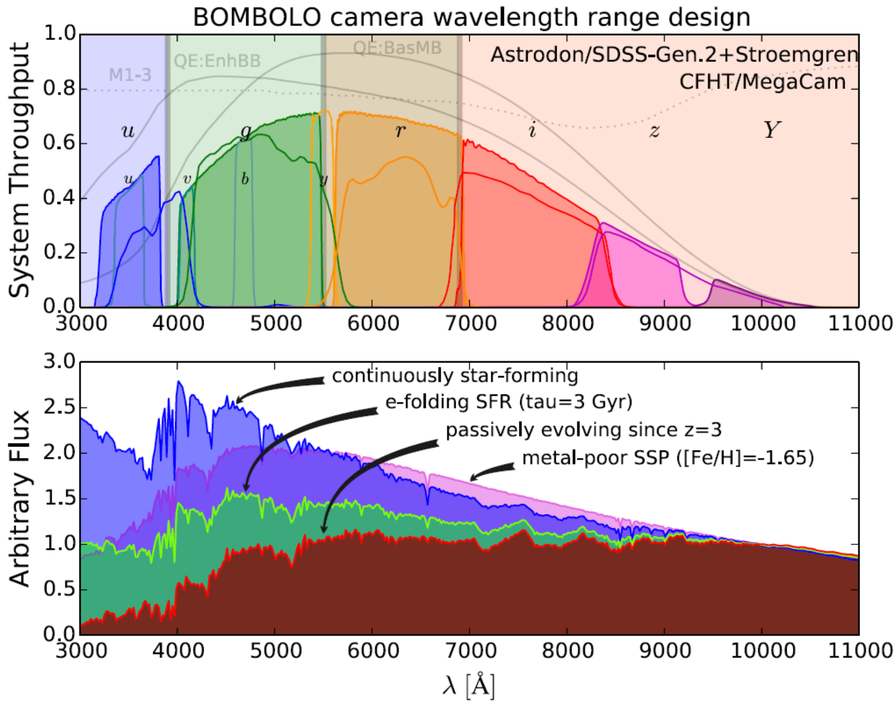

Fig. 3.2: BOMBOLO system throughput in filled color at the top panel and some interesting spectral energy distribution at the bottom panel

The 3 wavebands are: 0.32 – 0.4 microns (blue); 0.4 – 0.56 microns (green); and 0.56 – 0.9 microns (red). Some allowance will be made depending on the properties of the beamsplitters and the evolving functional requirements.

The 3 cameras are very similar to one another. They are 4-component Petzval constructions with field flatteners. The 3 wavebands require a different mix of glasses for each. Dimensional differences are primarily the result of the different relative location of the system pupil for each one.

The wavelength range that is covered is from 0.32 to 0.9 microns over a square field of side 7 arcmin. This is imaged onto a 2048 x 2048 detector with 15 micron square pixels. The imagery requirement is an "EN280" (ensquared energy width) of about 0.3arcsec or 15 microns at this scale.

Collimator

The short wavelength requirement from 0.32 to about 0.35 microns is exceptionally demanding. There are very few optical materials that can transmit efficiently this far into the UV. For this application any of the "fluoride" materials (such as CaF2, LiF, BaF2, MgF2) can be used as "crowns" with fused Silica as the "flint". CaF2 is by far the more "mainstream" and readily available "fluoride" so we choose this.

Unfortunately, the simple combination of CaF2 and fused Silica leaves the collimator with unacceptable sphero-chromatism. The only way that we have found so far to combat this is to use a second "flint" with different relative partial dispersion characteristics so as to render the system more apochromatic. However, this does come at a slight cost in throughput.

The second "flint" that is used in just one of the negative elements is OHARA BAL35Y. An element of 6 mm axial thickness is used giving a 5% throughput penalty at 0.32 microns, dropping sharply to nearly zero at 0.35 microns.

The 4 collimator components are cemented doublets except for the first, which is a singlet of fused Silica. The second and third components are composed of fused Silica and CaF2 whilst the last is composed of OHARA BAL35Y and CaF2. This triplet of glasses delivers exceptional broad-band chromatic correction from the UV to NIR. The optimum power distribution for these components is positive-negative-negative-positive. All surfaces are spherical.

The collimator is designed first with a paraxial camera. This ensures that the best possible collimation is achieved. The "EN280" broadband performance across the field is calculated to be approximately 0.3 arcseconds. If the individual bands are measured separately this drops to a maximum of 0.2 arcseconds across the whole field because some of the small chromatic residuals can be focused out.

The collimator layout is shown in Figure 4.1.

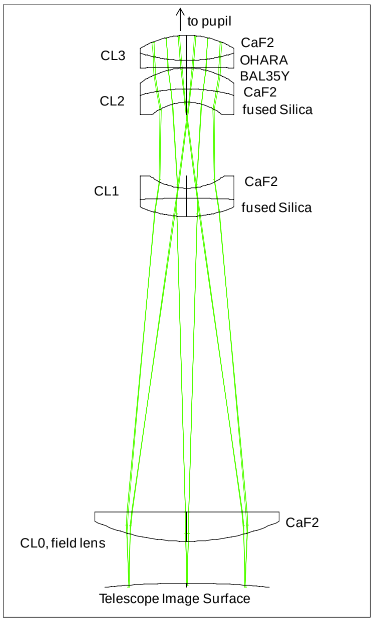

Fig. 4.1: Collimator layout – about 650 mm, top to bottom

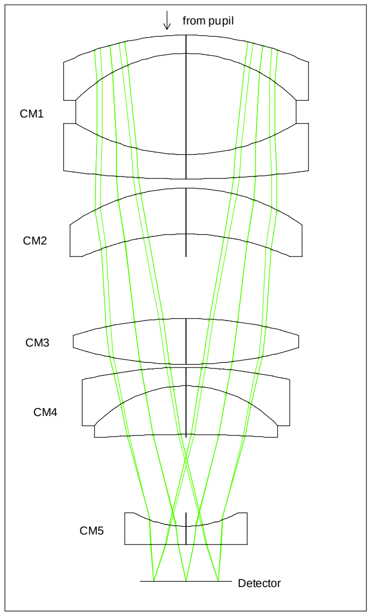

Fig. 4.2: Camera layout, typical – about 180 mm, top to bottom

Interestingly, most of the chromatic correction is provided by the BAL35Y "flint" in CL3. The consequent sphero-chromatic residual is then balanced by a small inequality in the power distribution between the CaF2 and fused Silica in CL1 and CL2. Note that to achieve this, the expected or normal crown-flint sequence in CL2 is reversed.

Cameras

The 3 cameras are based on a 4 component Petzval construction with a field flattener acting as the Dewar window. The blue camera again requires two elements of the second "flint", BAL35Y, so as to minimise sphero-chromatism. The resultant axial thickness of this material is 12 mm causing another 10% loss at 320 nm, again falling rapidly to nearly zero at 350 nm. The green and red cameras use varying amounts OHARA S-FPL51 in place of some of the CaF2 elements; and more BAL35Y.This allows much tighter control of chromatic effects. A generic layout (the green camera) is shown in Figure 4.2.

System Performance

Overall performance is demonstrated in the spot diagrams in Figure 4.3. The "EN280" ranges from 0.32 (red) down to 0.26 (blue) arcseconds. Somewhat paradoxically, the chromatic correction in the red band is not as good as the blue. Improving this balance will be the subject of further development. It will most likely mean the substitution of BAL35Y with a slightly different "flint".

The spot diagrams show a phenomenon which we call "chromatic variation of distortion" or "CvD". It can also be described as sphero-chromatism of the exit pupil. CvD is a consequence of the strong surfaces required for chromatic correction and to flatten the field. The bulk of it arises in the field flattener and would require an index break for its control. This would be very tricky to achieve opto-mechanically.

Improvements in chromatic correction will be pursued in the green and red cameras by testing a few more suitable "flints".

The 45° tilt of the beamsplitters may need to be reduced to 35° so that sharp cut-offs and good efficiencies can be achieved. This will require some adjustment to the collimator and camera designs as the pupil reliefs will need to be increased everywhere. This is not expected to impact the system performance.

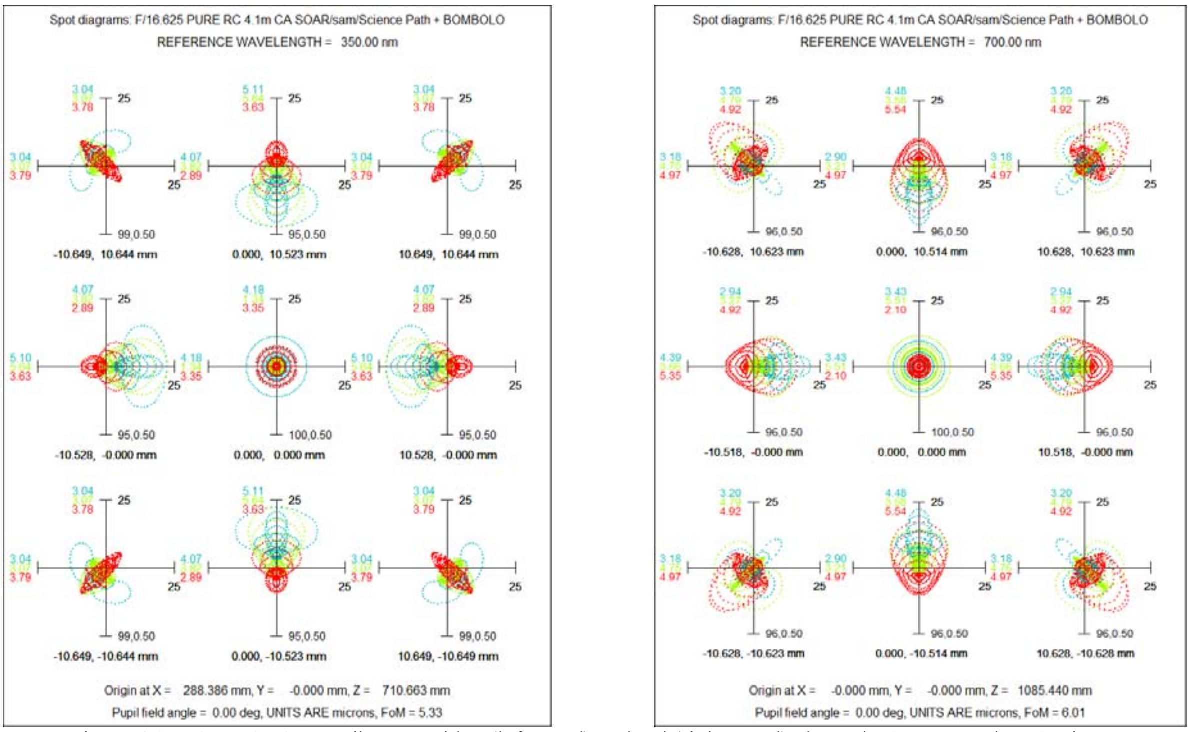

Figure 4.3: BOMBOLO spot diagrams, blue (left panel) and red (right panel) channels. 1 arcsecond = 50 microns

4.2 BOMBOLO Mechanical Design

Having recently completed the optical design presented here, we have started to devise the mechanical design. Fig. 4.4 presents a solid model view of the optical design, for clarification on the mechanical concepts described here.

The optics manufacturer will provide the optics mounted in barrel; therefore, the main task of the mechanical design is to provide a support structure that will hold the field lens, barrels and beamsplitters in positions, with predicted as well as minimum flexures.

The current baseline for focal station at SOAR for BOMBOLO is the “Bent Cassegrain” flange, which involves adding a spacer, de-rotator and guider. The gravity vector will vary while observing, thus the mechanical design must assure flexures within the instrument will be under control.

The mechanical design will be based on two kinds of structures: the collimator/camera structure and the beamsplitters structure. The former will be light, truss-based structures that will serve the purposes of holding lens barrels as well as offering a stiff mounting point for the mating structure. The beamsplitters structure will be a solid cube to hold the two dychroics, with provisions to exchange them easily, should there are interest on changing cutoffs wavelengths for different type of observations. This structure will also hold three filter wheels, one per arm.

Figure 4.4: Solid model of BOMBOLO optics. The start point for the mechanical design

4.3 BOMBOLO Detectors System

After a down-select process, where technical as well as budgetary constraints were considered, we have selected E2V's CCD230-42. The QE of this CCD with different coatings is presented in Fig. 4.5. Some basic parameters appear in Table 4.1.

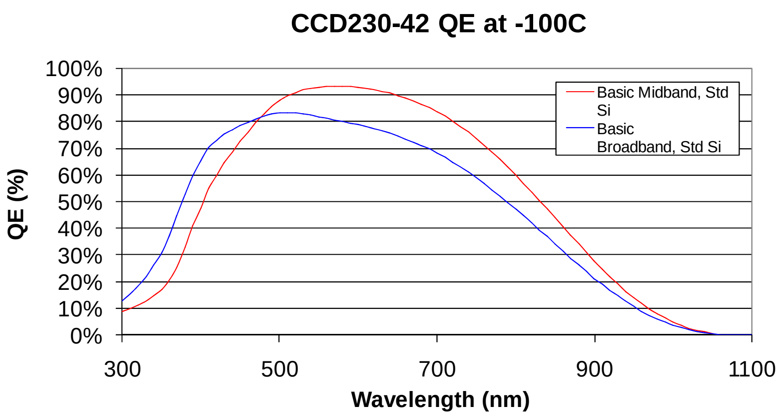

Figure 4.5: QE at -100C for the selected detectors (data courtesy E2V)

Table 4.1: CCD230-42 Main Parameters

Parameter	**Value**
Number of Pixels	2048 x 2048
Pixel size	15 µm square
Outputs	4
Package size	42.0 x 61.0 mm
Readout noise	8 e- @ 1 MHz 4 e- @ 50KHz
Charge storage	150,000 e-
Dark current	0.2 e-/sec/pixel @ -25 C

The baseline for the detector controller is *Torrent*, the open-source controller developed by NOAO. We have one system on loan from CTIO, with which we are experimenting on Digital Correlated Double Sampling filtering techniques[4]. See

[4] See Alessandri et al. on this conference

Fig. 4.6 for a picture of the *Torrent* controller. There is provision in *Torrent* to synchronize the 3 CCD cameras, in order to run simultaneous exposures, with different exposure times.

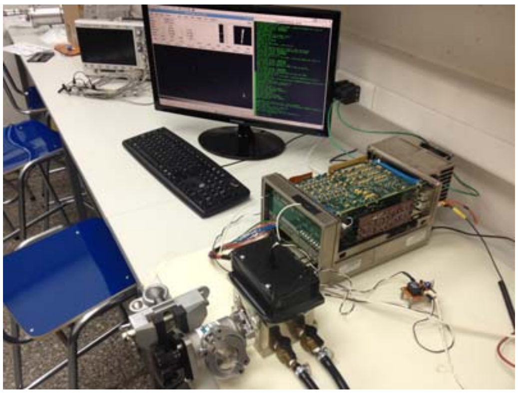

Figure 4.6: *Torrent* controller running at our Laboratory

4.4 BOMBOLO Instrument Control

The instrument will have three filter wheels and no other moving parts. We will implement standard instrument control techniques using “smart motors” and home positions to control the wheels.

The detectors will be run by the three Torrent controllers, all commanded from one PAN (Pixel Acquisition Node) computer. PAN is the standard SOAR/CTIO acquisition system.

5. FUTURE ACTIVITIES

We plan to finish the Design Phase of the instrument by the end of 2014, issuing a report on the main aspects of the design as well as a revised budget. 2015 will be devoted to purchasing the optics and building the mechanical structures described in this article. We foresee starting the assembly of the instrument by Q3 2015, extending to 2016. The extra structures to install the instrument at the Bent Cassegrain focal station at SOAR telescope will be designed and built in 2015, while the main components are being manufactured. Commissioning at the telescope should occur in late 2016 and early 2017, with Science Verification sometime in 2017.

BOMBOLO is a unique instrument in terms of Chilean direct involvement in astronomical instrumentation at one of the observatories on Chilean Ground. As such, we will take the opportunity to present the project to a broad audience, in an attempt to attract attention from young students, who can be interested in science and technology development. We are working with an interdisciplinary academic team at our institution to plan these activities.

6. ACKNOWLEDGMENTS

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