BOOTES-IR: a robotic nIR astronomical observatory devoted to follow-up of transient phenomena

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ABSTRACT

"BOOTES-IR" is the extension of the BOOTES experiment, which has been operating in Southern Spain since 1998, to the near-infrared (nIR). The goal is to follow up the early stage of the gamma ray burst (GRB) afterglow emission in the nIR, as BOOTES does already at optical wavelengths. The scientific case that drives the BOOTES-IR performance is the study of GRBs with the support of spacecraft like *HETE-2*, *INTEGRAL* and *SWIFT* (and *GLAST* in the future). Given that the afterglow emission in both, the nIR and the optical, in the instances immediately following a GRB, is extremely bright (reached V = 8.9 in one case), it should be possible to detect this prompt emission at nIR wavelengths too. The combined observations by BOOTES-IR and BOOTES-1 and BOOTES-2 since 2006 can allow for real time identification of trustworthy candidates to have a ultra-high redshift ($z > 6$). It is expected that, few minutes after a GRB, the nIR magnitudes be H $\sim$ 10-15, hence very high quality spectra can be obtained for objects as far as $z = 10$ by much larger ground-based telescopes. A significant fraction of observing time will be available for other scientific projects of interest, objects relatively bright and variable, like Solar System objects, brown dwarfs, variable stars, planetary nebulae, compact objects in binary systems and blazars.

Keywords: Robotic telescopes, telescope software, near-IR instrumentation, cryogenics.

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Figure 1. BOOTES-IR (left) is located in southern Spain (right), atop Sierra Nevada mountains in Sierra Nevada Observatory (OSN).

1. INTRODUCTION

BOOTES-IR, the **B**urst **O**bserver and **O**ptical **T**ransient **E**xploring **S**ystem in the near-**I**nfra**R**ed[¶] is the extension of the BOOTES project[1] towards near-IR wavelengths thanks to a nIR camera developed in the context of Spain's Programa Nacional de Astronomía y Astrofísica AyA 2002-0802, placed in 2006 at the 60 cm telescope at the Observatorio de Sierra Nevada, under a controlled dome, also developed in the context of the Project.

BOOTES-IR was first proposed in 2001. The enclosure was built atop Sierra Nevada in the Summer of 2003. The telescope was installed at the end of 2004 and first (optical) light was obtained in February 2005. Since then the telescope is in commissioning phase and operating with an optical camera, and responding to some alerts within 20-30 s after occurrence. The nIR camera has had first light in Summer 2006.

Thus, BOOTES-IR will be the third astronomical nIR observatory of this kind, following REM (opt/nIR) at ESO La Silla Observatory in Chile[2] and PAIRITEL (nIR) at Mt. Hopkins in Arizona, USA[3] , but extending its wavelength coverage in the blue optical range.

2. THE SITE

Sierra Nevada Observatory[‖], owned by the Instituto de Astrofísica de Andalucía (IAA-CSIC), is located at 2 986m above sea level, not far from the city of Granada. Its high altitude and dry climate makes it ideal for nIR observations. It is located in the middle of a ski resort, so access and support is guaranteed all year round (see Fig. 1).

3. SCIENTIFIC OBJECTIVES

Similar to BOOTES in the optical range[4] , the main BOOTES-IR scientific goal is the GRB follow up observations of events detected with high energy satellites like *HETE-2*, *INTEGRAL* and *SWIFT* (and *GLAST* in the near future). All together they are providing around 100 detections/yr, but none of these missions carry instrumentation devoted to the nIR, that could complete the observations at longer wavelengths. Following the detection of a bright, prompt optical flash for GRB 990123 with $M_V = -36$[5] , such events were also expected to occur at nIR wavelenghts, as was proven for GRB 041219[6] . Although now it is widely accepted that the long duration GRB are related to massive star deaths, about 50% of the events are not detected in the optical,

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[¶] See http://www.iaa.csic.es/BOOTES-IR.html

[‖] See http://www.osn.iaa.es

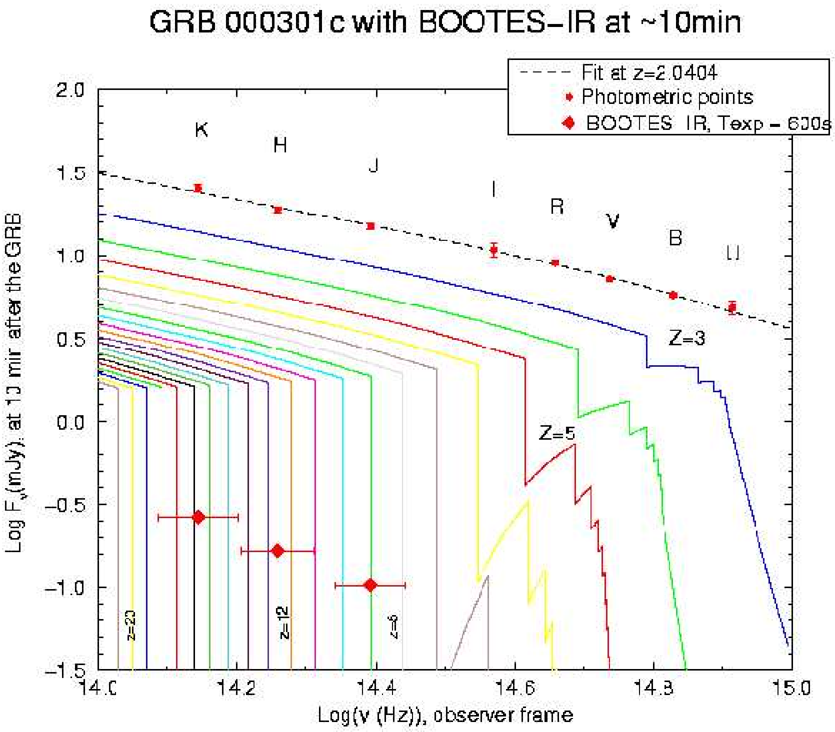

Figure 2. The GRB 000301c afterglow extrapolated at various redshifts, in case that it would have been observed 10 min after the event. This proves the capabilities of BOOTES-IR for studying the high-z Universe.

and this latter population of dark GRB should contribute significantly to the hidden star formation rate in the Universe[7] .

Thus, the BOOTES-IR scientific goal is doublefold: the study of dark GRBs and the "hunt" for ultra-high z events.

3.1. Dark GRBs

About 50% of events are not detected in the optical in spite of deep observations being performed minutes/hours after the event. This can be partly explained if the GRB do occur in a high density region in the host galaxy which will extinct the optical emission. Thus, even with no optical afterglow being observed, a bright nIR transient might be recorded by BOOTES-IR and, together with the BOOTES observations (in optical) might allow to determine the intrinsic extinction (as was done in GRB 980703[8] . In fact, it is expected that most of the dust will be sublimated by the prompt UV/optical emission, i.e., it is foreseen that the nIR flash should be observed prior to the optical one, allowing to determine an upper limit to the amount of dust in the surroundings of the GRB progenitor.

3.2. Ultra-high z GRBs

There will be a small fraction of events not detected in the optical due to a ultra-high redshift (with $z > 6$), i.e., with the Lyα break in the I band (0.9 μm) at that particular redshift. As BOOTES-IR will cover a redshift range $6 \leq z \leq 17$ (see Fig. 2), part of these ultra-high z population should be unveiled if prompt observations are conducted soon after the events. As it has been already pointed out, GRB are a powerful tool for the study

Exposure time (s)	J(10σ)	J(5σ)	H(10σ)	H(5σ)	K(10σ)	K(5σ)
5 s	15.5	16.3	14.3	15.1	13.1	13.9
30 s	16.4	17.2	15.2	16.0	14.1	14.8
600 s	17.3	18.0	16.3	17.1	15.4	16.1

Table 1. Estimated limiting magnitudes for BOOTES-IR.

of the high z Universe. The importance of prompt observations is based on the fact that the photons arrival time should be divided by a (1+z) factor. That is, that the elapsed time since the onset of the event has to be accounted for in the framework of the source. Thus, a GRB at $z = 4$ being observed 10 min after the event means that is being detected $10/(1+z) = 2$ min after the explosion, when the source is extremely bright. Thus, we can say that z might be an advantage, with a favourable K correction[9] .

A combination of the BOOTES (optical) and BOOTES-IR (nIR) datasets will allow us to distinguish a high z event. The identification of candidates in a color-color diagrame[10] will allow us to discern the most interesting candidates allowing larger size instruments to point to the GRB afterglow while it is still bright enough to ease spectroscopic observations. This will allow to study the distribution of Lyα clouds in the intergalactic medium as function of z, the metallicity, the interstellar medium in the host galaxy and the intergalactic medium reionization, expected in the $6 \leq z \leq 17$ range.

3.3. Additional science

A significant fraction of observing time will be available for other scientific projects of interest, objects relatively bright and variable, like Solar System objects, brown dwarfs, variable stars, planetary nebulae, compact objects in binary systems and blazars. The possibility of simultaneous optical/nIR monitoring will allow us to study in great detail the underlying physical emission mechanisms.

Particularly, we also plan using BOOTES-IR in order to study comets and asteroids. In the wavelength range of the detector is feasible to analyze the radiative properties of the dust in cometary comae. Especially important can be the physical characterization of Near Earth Objects (NEOs). On the other hand, nIR observations of determining the luminous efficiency of meteoritic impact flares on the Moon are also feasible.

4. HARDWARE

4.1. The enclosure

The telescope building (8m × 4m, height 2.5m) was designed by VERIMO SL (Málaga, Spain) and built by ACONDIMA SL (Málaga, Spain), 20m from to the main OSN building hosting the 1.5m and 0.9m diameter telescopes. The interior is divided into the small control room housing the telescope electronics and computers, and the technical room directly below the dome containing the the liquid N_2 tank, and the telescope pillar (1m diameter, 2.5m height). The pillar is anchored in a separate 1.5m × 1.5m × 1.5m foundation.

A 3.6m diameter fibre-glass clamshell-dome provided by AstroHaven (Langley, Canada) was installed in summer 2003 (Fig. 3) in order to assure inmediate access to any part of the sky. An inner 3.4m diameter canvas clamshell-dome provided by Toldos La Nueva Granada (Granada, Spain) was installed as well, since the outer dome has proven not to be totally sealed against snow or rain during the severe winter conditions in Sierra Nevada. The 3.6m fiber-glass dome has been replaced by a 4.0m diameter dome in Summer 2006.

4.2. The telescope

The telescope was designed by ASTELCO GmBH (Munich, Germany) and delivered in November 2004. It is a 0.6m Ritchey-Chrètien working at f/8. Its direct drives allow it to slew at a speed of 10° per second, being capable of pointing any part of the sky within 20 seconds, with a typical slew time of 5 seconds. It has two Nasmyth foci, one of which is occupied by both the nIR and optical cameras. Initially the second Nasmyth will be idle, although future instrumentation is foreseen.

Figure 3. The BOOTES-IR building and enclosure, near other smaller enclosures at Observatorio de Sierra Nevada (IAA-CSIC).

4.3. The nIR camera

The BOOTES-IR camera, also dubbed BIRCAM, was designed by LT Calcoli SAS (Merate, Italy), in collaboration with optical designers of Osservatorio Astronomico di Brera (Merate, Italy), following the requirements of the BOOTES-IR Team, under a very fruitful collaboration. BIRCAM is placed at the Nasmyth focal station of the 60 cm telescope. It has high transmission optics and it is equipped with a high readout speed controller. The philosophy of design is compactness and light weight.

4.3.1. The dichroic

An interface dubbed "Dadone" is mounted on the flange with the function of linking the visual and nIR cameras. Both the dithering wedge and the dichroic lie within this interface.

A 45° dichroic placed before the entrance of BIRCAM has been purchased from OptoTL (San Petersburg, Russia) with the coating performed by Gestione SILO (Firenze, Italy). The incoming light is divided, with visible light at $\lambda\lambda < 0.7$ μm towards a blue-band enhanced optical camera while transmitting the infra-red light at $\lambda\lambda > 0.8$ μm. This will permit simultaneous observations in two bands. Colour-colour diagrams will help us to discriminate between GRB afterglows and other objects.

4.3.2. The dithering wedge

Since there are two instruments observing simultaneously, it is not practical to use a chopping secondary, or to nod the telescope in order to subtract the sky background. The solution is a motor-driven rotating dithering wedge, placed after the dichroic, slanted in our case at an angle of 20°, that allows a point source to be positioned on a circle 60 pixels in diameter.

Figure 4. The BOOTES-IR camera (BIRCAM) at factory in Spring 2006.

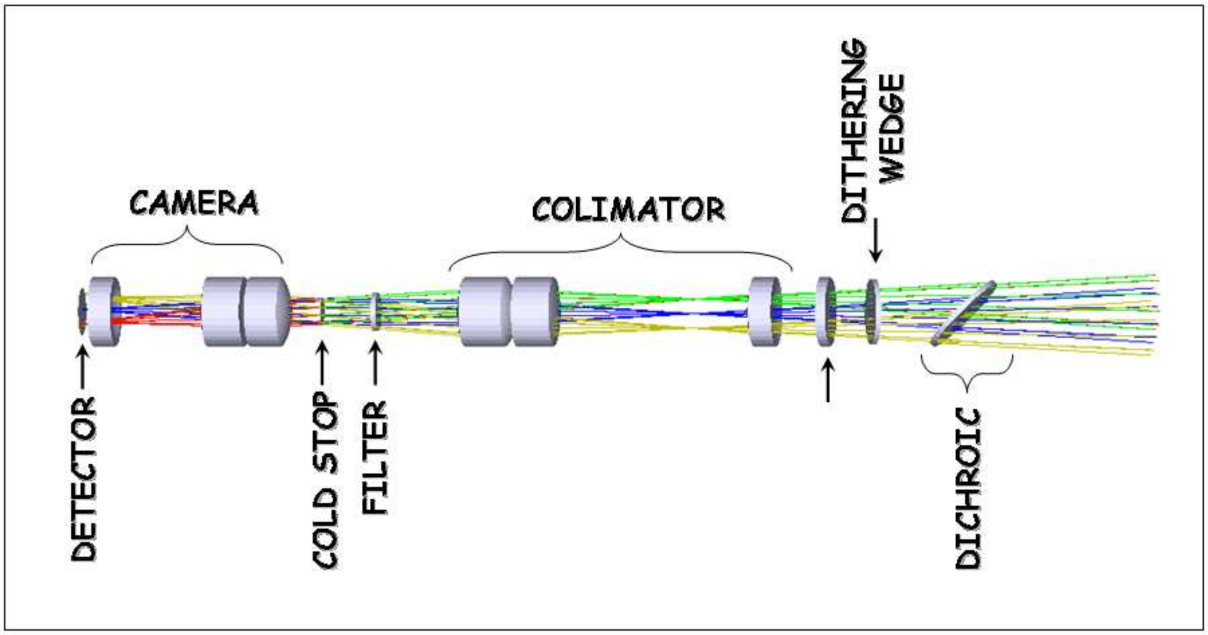

Figure 5. The BOOTES-IR camera (BIRCAM) optical train.

4.3.3. The dewar

The detector is cryogenically cooled to a working temperature of 77 K by a charge (8 litres) of liquid N_2 half-filling an annular tank inside the vacuum dewar (fig. 4). The system is manufactured by RIAL Vacuum (Parma, Italy) , and operates equally well in all rotations about the cameras long axis, as required by the position of the camera on the telescope de-rotator. single charge gives a hold time in excess of 24 hours.

4.3.4. The optics

The BIRCAM optics have been designed in Osservatorio Astronomico di Brera (Merate, Italy) and purchased from OptoTL (San Petersburg, Russia) and Ottica Colombo (Rovagnate, Italy). The optical train is composed of two types of glass: CaF_2 and SFTM-16 (from the O´Hara catalogue). The infrared beam leaving the dichroic and dither-wedge beam leaving the Nasmyth passes through a dichroic (CaF2) that divides the light between nIR and visible. The visible path is reflected 90°, while the nIR one goes along the axis. After the dichroic is placed a dithering wedge, slant by a angle of 20°. After that, the light enters into the dewar through a CaF_2 window, a collimator (three lenses: two SFTM-16, one CaF2), a filter wheel, and the collimated beam is refocused onto the detector through a camera composed of a further three lenses (two CaF2 plus one SFTM-16). The field of view is $12'.7 \times 12'.7$ with a scale of $0{,}74''$/pix. See Fig. 5.

4.3.5. The filter set

The filter wheel has 8 × 25mm filters, and is driven by a stepper motor outside the dewar, via a low-conductivity shaft. The filter set contains five broad band filters ($zYJHK_s$) plus two narrow band filters (H_2 and $Br\gamma$). The JHK_s filters are similar to those operating in REM and were ordered from Barr Asociates, Inc. in 2001. Expected limiting magnitudes in JHK_s are given on Table 1.

4.3.6. The detector

We are making use of a HAWAII-1 1 024 x 1 024 HgCdTe detector (0,9 - 2,5 μm range) produced by Rockwell. It has a high-resolution 18.5 μm pixel pitch and comprises four independent quadrants with direct bus outputs, and low dark current below 78 K. These science-grade detectors are well suited for Astronomical research and have been used in several astronomical instruments already.

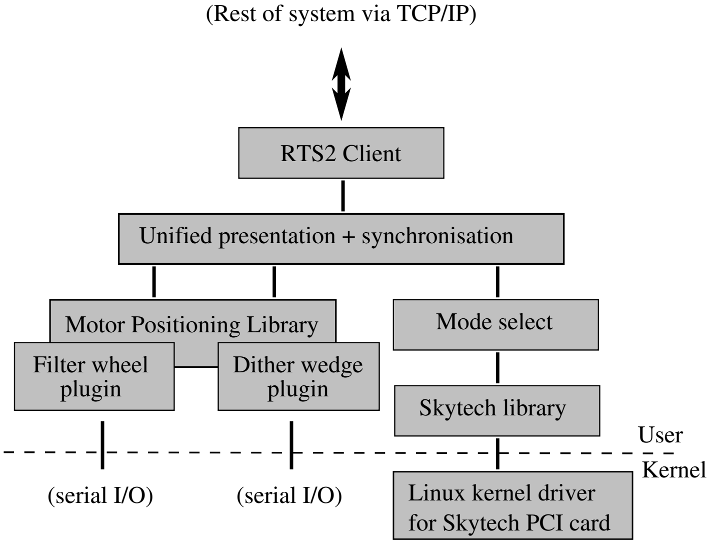

Figure 6. The BOOTES-IR software scheme.

4.3.7. The electronics

The camera control electronics were manufactured by SkyTech (LaSpezia, Italy). This is a modular system, comprising a 32-bit PCI card communicating via fibre-optic link with the controller, which is a single unit containing the power supply, exactly one clock and bias generation board at the other end of the fibre-optic link, and one or more readout boards. Detailed discussions of the system design and early performance results are available elsewhere[11−12] . In the BOOTES-IR configuration, all four quadrants of the HAWAII chip are controlled by a single set of 6 clock lines, and a single readout board is able to handle the four video channels in parallel at rates of up to 1 Mpixel/sec/channel.

5. SOFTWARE

5.1. The telescope control system

The BOOTES-IR control system is based on RTS2, a robotic observatory environment developed by P. Kubánek[13] which interacts with PILAR (the telescope software). The system controls all the devices in the observatory and is able to interrupt observations and immediately start slewing and exposing when a GRB alert arrives[14] .

5.2. The nIR camera software

The camera software for the IR camera resolved initially to the problem of writing independent support for the three pieces of hardware - the Skytech controller, the dither wedge, and the filter wheel, and of writing interfaces to RTS2 for them. However, the final design choice was to build a single integrated (and somewhat more complex) RTS2 client.

This carefully leaves the door open for future optimisation. The scientific goals during prompt GRB observation call for maximising both the total light gathered, and the number of exposures. It is critical here not to waste any time between exposures (0.1 second is significant if the exposure time is 1 second, as it is expected to be in prompt GRB follow-up). Most of the conventional readout techniques are concerned with minimising noise, not minimising waste time. It should prove possible for the BOOTES-IR camera to explore variations on the reset-anomaly-free idea used by the TRIDENT camera[15] with higher time-efficiency than double-correlated-sampling, but this is only available if we can precisely synchronise the HAWAII readout pattern with the motion of the dither wedge (and to a lesser extent, the filter wheel).

The Skytech controller was provided with Windows-based software, but the manufacturers provided extensive help (including source code), simplifying the challenge of writing Linux support. A kernel driver was written from scratch, and the Windows DLL source code modified to suit the Linux driver.

The Skytech controller provides immense flexibility in the way the array is controlled - simple scripting commands acting on fully programmable waveform tables. However, this flexibility is too cumbersome (and too technically arcane!) for ordinary astronomy. So an extra layer of software - the mode layer - has been added to both provide a set of choices, and to restrict observing astronomers to those choices. From the outside, control of the camera is reduced to two parameters: mode and exposure time.

The other two devices, the filter wheel and dither wedge, are logically very similar - they are motor-driven positioning units with a fixed set of logical destinations. The only differences lie in the number of positions - 8 for the filter wheel, 360 for the dither wedge - and in the specific commands used to interact with the hardware. So, rather than writing (and then debugging) two nearly identical control stacks, a single motor control library was written to present a generic interface to applications, removing the hardware-specific code to plugins loaded at runtime. As the simplest method of controlling multiple pieces of hardware in parallel, the library devotes a thread of execution to each device, which also permits the controlling application to use the the motors asynchronously - to command a movement then then complete other tasks without waiting for the movement to finish.

The three devices then combine into a single RTS2 client, accepting exposure requests with 4 parameters: camera mode, exposure time, filter, and dither wedge position. See Fig. 6.

5.3. The image analysis software

Image reduction and analysis is achieved using JIBARO[16] , a package of utilities developed in optical BOOTES and now extended for the nIR. It is capable of operating in real-time producing reduction, astrometry, photometry and detection of transient sources (such as GRB afterglows). The position of GRB afterglow candidates can be immediately transmitted to the project scientist, who can then report any discovery to the scientific comunity and request observations with bigger telescopes to complement the observations by BOOTES-IR.

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