ROBOTIC ASTRONOMY AND ITS APPLICATION TO THE STUDY OF GAMMA-RAY BURSTS

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Abstract: An overview of Robotic Astronomical facilities (especially in Spain) is presented. The study focuses on two aspects: the control software (one of such example being the RTS2 system) and the network of BOOTES robotic telescopes, partly devoted to the study of gamma-ray burst counterparts at optical and near-infrared wavelengths. This potential application of small/medium size robotic telescopes will shed light on the high redshift Universe and should be used for triggering larger size instruments in order to perform more detailed studies of host galaxies and intervening material on the line of sight.

Keywords: Robotic Astronomy – Control Software – Gamma-ray Bursts.

1 Introduction

Robotic astronomical observatories (RAOs hereafter) were first developed in the 1990s by astronomers after electromechanical interfaces to computers became common at observatories. Following [1], let us introduce some definitions first:

- Robot: A mechanical system which executes repetitive tasks with good accuracy with human assistance. Example: Industrial robotic arm.
- Teleoperated Robot: A mechanical system which executes a given task with good accuracy and that can be modified with human assistance. Example: Submarine research robots.
- Intelligent Robot: A mechanical system which executes a task with good accuracy and is able to adapt itself to changes during the task execution without any kind of human assistance. Example: Rovers devoted to planetary research.

2 Robotic Astronomical Observatories: a brief history

The 1985 book *Microcomputer Control of Telescopes* by R. M. Genet and M. Truebl ood [2], was a landmark engineering study in the field. Since the comissioning of the Bradford telescope (in 1993) [3] and the Iowa Telescope (in 1997) [4], many researches and companies have put considerable effort in making robust systems.

The *first robots* were the telescopes with an absolute positioning control and guiding systems, and the automatic weather stations, introduced in astronomical observatories.

The *first robotic astronomical observatories* were those ones which were able to integrate and coordinate the different automatic subsystems at the observatory (telescope, dome, weather stations). But they require human assistance (teleoperation) for the taking of decissions regarding a given task and/or its supervision.

The *intelligent robotic astronomical observatories* are the following step, where human assistance in the taking of decissions is replaced by an artificial intelligent system. These are being developed nowadays.

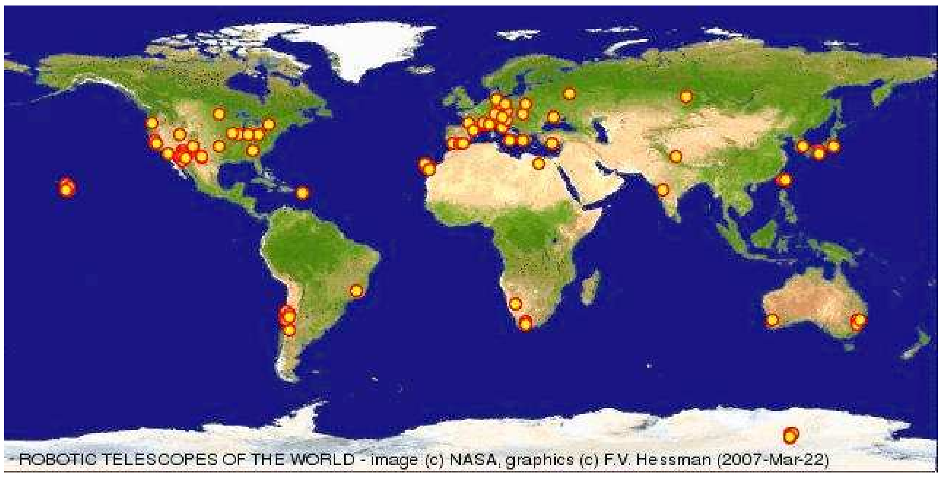

Figure 1: The RAOs location in the world. Adapted from Hessman [6].

3 RAOs worldwide

Based on the compilation collected by F. V. Hessman [6], there are about 100 RAOs worldwide (see Fig. 1), with 35 of them being located in Europe. Some examples are:

- ROTSE (UM & LANL, USA): A network of four 0.45 cm diameter telescopes around the world, devoted to the search for optical transients [7].
- RAPTOR (LANL, USA): An array of telescopes that continuously monitor about 1500 square degrees of the sky for transients down to about 12th magnitude in 60 seconds and a central fovea telescope that can reach 16th magnitude in 60 seconds. Search for optical transients (OTs). See Fig. 2 [8].
- REM (Italy): Is a rapid reaction near-infrared (nIR) robotic telescope [9] dedicated to monitor the prompt afterglow of Gamma Ray Burst (GRBs) events [10].
- PAIRITEL (SAO, USA): It is a 1.3m telescope devoted to the study of nIR transients [11] by means of simultaneous JHK imaging [12].

Figure 2: The RAPTOR wide-field telescopes system [6].

- ROBONET (participated by 10 UK Universities) is a network of three 2m class robotic telescopes (see Fig. 3). The main aims are to detect cool extra-solar planets by optimised robotic monitoring of Galactic microlens events. In particular, to explore the use of this technique to search for other Earth-like planets. Another goal is to perform detailed studies of GRBs [13].

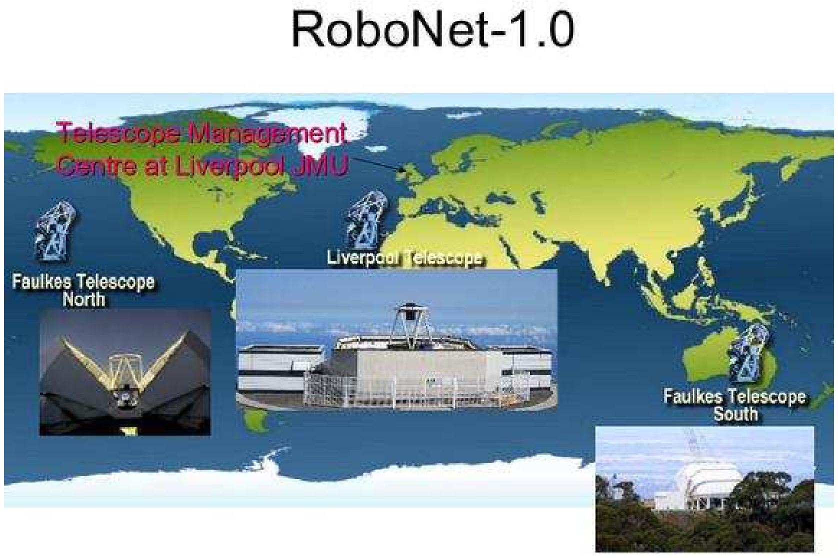

Figure 3: The 2m RoboNet Network. Adapted from [13].

4 RAOs in Spain

Amongst the ∼35 RAOs existing in Europe (see Fig. 4), a dozen of them are located in Spain, with some of them being automated systems and few others being robotic ones.

The Spanish automated systems are the Carlsberg telescope (since 1983), the IAA Tetrascope (4 x 0.35m) at OSN (2001-05) and La Sagra (since 2006), the 0.45m Astrograph at La Sagra (since 2007) and the DIMMA (IAC), an automated seeing monitor in operation since 2007.

The Spanish robotic systems are the 0.2m and 0.3m BOOTES-1 telescopes (since 1998), the 0.3m BOOTES-2 telescope (since 2001), the 0.6m BOOTES-IR telescope (since 2004), the 0.6m TROBAR telescope (since 2004), the 0.8m MONTSEC telescope (since 2005) and the 0.4m, 0.5m and 0.5m belonging to the CAB Robotic Telescope Network (since 2004).

We provide additional details for some of them:

- The Circulo Meridiano Carlsberg was initiated by KUO, IoA and ROA, with ROA being the only institution that run the instrument nowadays. It is an

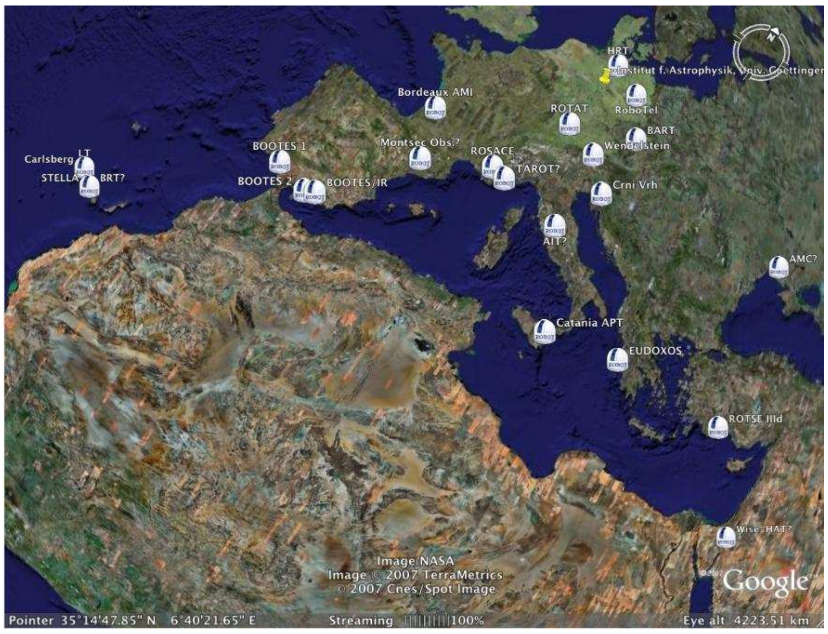

Figure 4: The RAOs location in Europe. Adapted from [6].

automated telescope placed at La Palma (Canary islands), which had first light in 1983 (see Fig. 5). It allows to observe between 100,000 and 200,000 stars a night, down to r'=17. This will give accurate positions of stars, allowing a reliable link to be made between the bright stars measured by *Hipparcos* and the fainter stars seen on photographic plates (as measured by the APM and similar measuring machines). The current area of the survey is between -30 and +50 degrees in declination and is completed [14].

- TROBAR (UV) is a 0.6m diameter robotic telescope located in Aras del Olmo (Valencia), which had first light in 2004. It is devoted to astroseismology and extrasolar planet research. NEOs and GRBs studies are also part of the scientific programme [15].

- The largest diameter robotic telescope in continental Spain is the 0.8m diameter telescope at Observatori Astronomic del Montsec (participated by UB, UPC, CSIC, Consorci del Montsec and Fundació Joan Oró). It had first light in 2005 and makes use of the TALON control system [16].

Figure 5: The Carlsberg meridian Circle, at La Palma, is operated by the Real Observatorio de la Armada in San Fernando (Cádiz).

- The CAB/INTA/CSIC Robotic Telescope Network is formed by a 0.4m diameter telescope in Torrejón de Ardoz (Madrid), a 0.5m diameter telescope in Calatayud (Zaragoza) and a 0.5m diameter robotic telescope in Calar Alto (Almería). [17].
- BOOTES-1 and BOOTES-2 (participated by INTA/CSIC/AUS/CVUT) started with robotic 0.3m and 0.2m diameter telescopes and wide-field lens systems, having first light in Huelva (1998) and Málaga (2001) respectively. The telescopes will be upgraded to 0.6m telescopes in 2008-2009.
- BOOTES-IR/T60 (CSIC) is a robotic 0.6m diameter telescope at Observatorio de Sierra Nevada (Granada), which had first optical light in 2004 and first near-infrared (nIR) light in 2007. Simultaneous optical/nIR imaging is foreseen for late 2008. Additional details for both BOOTES and BOOTES-IR are given below.

4.1 BOOTES

BOOTES, the **B**urst **O**bserver and **O**ptical **T**ransient **E**xploring **S**ystem, is mostly a Spanish–Czech international collaboration that works to fill in the space that actually exists in rapid variability Astronomy. It is specially aimed towards the detection and study of the optical transients that are generated in conjunction with the elusive

Figure 6: The BOOTES-1 0.2m and 0.3m diameter telescopes at Instituto Nacional de Técnica Aerospacial in Mazagón (Huelva). They will be replaced by a 0.6m telescope.

GRBs. It saw first light in 1998 [18] being one of the pioneering robotic observatories for OT follow ups [19]. There are two 250 km distant BOOTES stations. Thus,using parallax, it can discriminate against near Earth detected sources up to a distance of 10^6 km.

BOOTES-1 in Mazagón (Huelva) has two domes (1A and 1B), three Schmidt-Cassegrain telescopes (Fig. 6) and several wide field cameras. Following complementing schemes, all instruments carry out systematic explorations of the sky each night.

BOOTES-2, located near Málaga is in operation since 2002. It has one 30cm telescope with an attached wide-field camera. The station may observe in standalone as well as in parallel stereoscopic modes together with BOOTES-1. An ultra-light weight 0.6m telescope (TELMA) is replacing the existing one in Spring 2008 [20]. See Fig. 7.

Both stations are operated under the RTS2/Linux control system (see section 6).

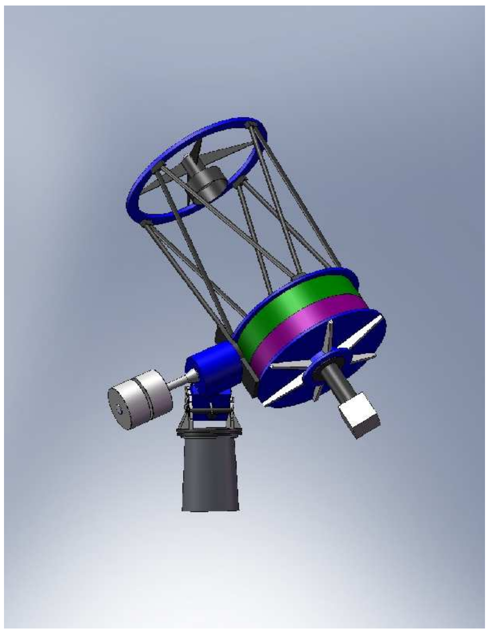

Figure 7: The TELMA ultra-light weight telescope concept for the BOOTES-2 station in Málaga (Spain).

4.2 BOOTES-IR

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 towards near-IR wavelengths thanks to a nIR camera developed in the context of Spain's Programa Nacional de Astronomía y Astrofísica, 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 (see Fig. 8).

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 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 2007 [21].

Thus, BOOTES-IR will be the third astronomical nIR RAO of this kind [22], following REM (opt/nIR) at ESO La Silla Observatory in Chile and PAIRITEL (nIR), but extending its wavelength coverage in the blue optical range.

Figure 8: The BOOTES-IR camera (BIRCAM) attached to the 0.6m robotic BOOTES-IR telescope at the Observatorio de Sierra Nevada.

5 Technology with RAOs

5.1 Range of apertures

According to recent statistical studies [6] and once instruments planned by 2010 are considered, nearly 50% of RAOs have diameter smaller then 0.25m, while 10% have diameter larger than 1.25m.Nearly 95% are equipped with optical instrumentation, with the remaining fraction being devoted to nIR studies.

5.2 Telescope Control Operating Systems and Observatory Managers

Control Operating Systems can be divided into commercial or specific ones, which can be open or closed source. For instance, a commercial automatization systems is TCS, developed by Optical Mechanics (OMI), for operating telescopes with diameters in the range 0.4 to 1.0 m [23]. A specific control system is the one built for 10 m Spanish GTC telescope.

Amongst *Observatory Managers* some examples are:

- AUDELA: Developed by A. Klotz et al. (Toulouse), starting in 1995. Open source code. Linux/Windows [24].

- ASCOM: Dessigned in 1998, by B. Denny (USA), as an interface standard for astronomical equipment, based on MS´s Component Object Model, which he called the Astronomy Common Object Model. Mostly used by amateur astronomers, has been also used by professionals, under the Windows operating system. It is widely used in supernovae and minor planet searches [25].

- RTS2: The Robotic Telescope System version 2, is being developed by P. Kubánek, (Ondrejov/Granada) starting in 2000. The source code is open. It works under Linux/Windows (command line and graphical interface foreseen). Widely used in GRB searches.

- INDI: The Instrument Neutral Distributed Interface (INDI) was started in 2003. In comparison to the Microsoft Windows centric ASCOM standard, INDI is a platform independent protocol developed by E. C. Downey (USA). The source code is open too. Not so widely spread as the upper layer interface was not done [26].

Observatory Managers can also work as open or close loop systems. In an open loop system, a robotic telescope system points itself and collects its data without inspecting the results of its operations to ensure it is operating properly. An open loop telescope is sometimes said to be operating on faith, in that if something goes wrong, there is no way for the control system to detect it and compensate. A closed loop system has the capability to evaluate its operations through redundant inputs to detect errors. A common such input would be position encoders on the telescope's axes of motion, or the capability of evaluating the system's images to ensure it was pointed at the correct field of view when they were exposed [27].

6 RTS2

RTS is a system for complete observatory control. It can be regarded as a turnkey system. Once installed on any telescope, it should run and provide results. RTS consists of three major layers – device, service and monitoring, with components communicating over TCP using a simple text protocol. Detailed design and development history of RTS can be found in [28]. See Fig. 9.

6.1 Current RTS2 system operation

The current network of RTS controlled observatories operates as a set of separate nodes. The nodes run every night, paying attention to local conditions via sensors and controlling all aspects of the telescope operations.

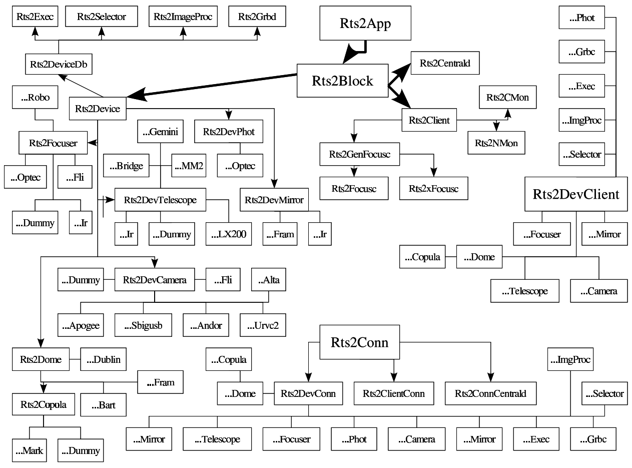

Figure 9: RTS2 class diagram (from software developer´s point of view).

All computers (with RTS software) are accessible via the Internet with Secure Shell (*SSH*). This shell access is used to control observatory operations through command line utilities for remote management of observation plan and observatory.

Telescopes using the RTS are observing every clear night. The instruments are active participants of the GCN (The Gamma ray bursts Coordinate Network) [29]. Each node has a dedicated connection to the GCN system, through which it receives real–time alerts containing GRB alert messages. In 2006, *RTS2* observations were responsible for 30 GCN circulars, roughly 2% of the year total. From 82 GRBs with optical transient, 2 optical transients were discovered by RTS – GRB060117 [30] and GRB060707 [31].

RTS supports two modes of observation planning: real–time merit function based scheduling, and prepared plan observing. Although observation of a fixed-time event can be ensured (in theory) by appropriate programming of a merit function scheduler, in practice there are significant drawbacks, primarily that it is tricky to prepare a merit function that will work as the observers want. For such cases, RTS provides the prepared-plan observing option, where the observer writes a script that RTS then executes as written (see Fig. 10). Any scheduled observation can be interrupted at any point should a Target of Opportuniy Observation (TOO) be performed.

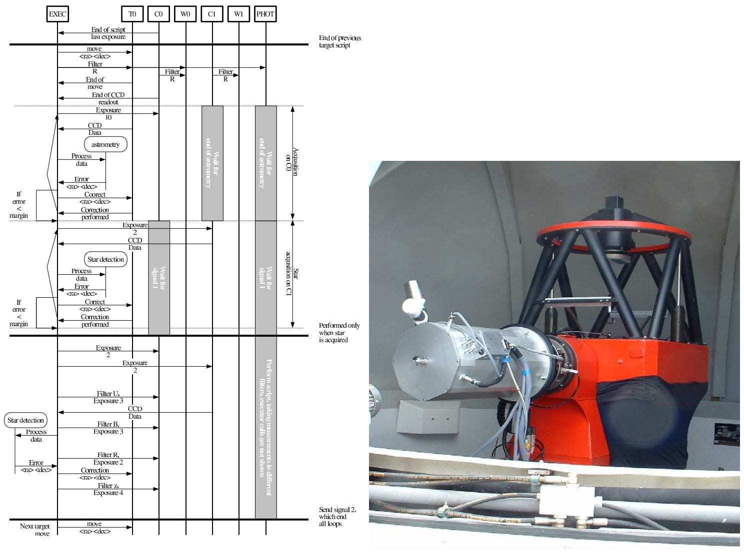

Figure 10: RTS2 executor working procedure.

6.2 Additional RTS2 image processing software

These additional software packages are available and undergoing significant improvement:

- 1. Astrometry pipeline (to check telescope pointing and improve the accuracy)
- 2. Pipeline for automatic data analysis: i) Astrometry and photometry; and ii) Transient object detection, with JIBARO [32].

7 Science with RAOs

7.1 Scientific use

Different fields will have benefits from RAOs: GRB research, service observations, photometric monitoring, education, all-sky surveys, exoplanet searches, SN search, asteroids, spectroscopy, astrometry, AGN/QSO monitoring, (micro)lensing, etc.

A significant fraction of observing time at RAOs should be available for many scientific projects of interest. Objects relatively bright and variable, like Solar System objects (see Fig. 11), brown dwarfs, variable stars, planetary nebulae, compact

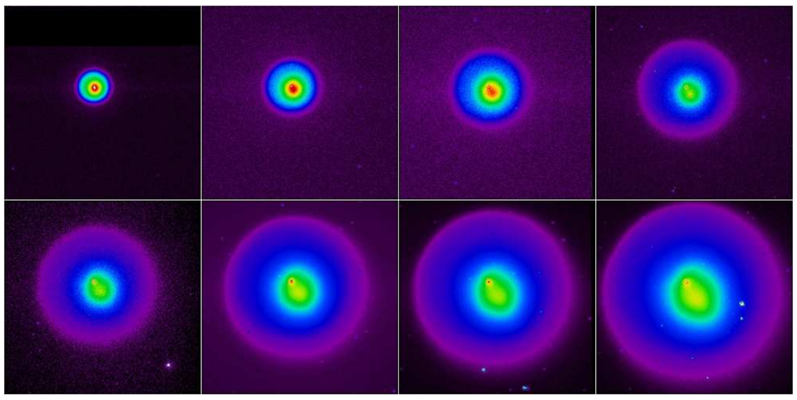

Figure 11: The evolution of comet 17P/Holmes following the October 2007 outburst, imaged on a nightly basis with the 0.3m BOOTES-2 telescope in Spain. The despicted field of view is the same (∼10′ ×10′) in all frames.

objects in binary systems and blazars should be easily observable. The possibility of simultaneous optical/nIR monitoring will allow us to study in great detail the underlying physical emission mechanisms.

Particularly, RAOs can be used 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, optical-nIR observations can help to determine the luminous efficiency of meteoritic impact flares on the Moon.

8 Study of GRBs

8.1 GRBs at the edge of the observable Universe

Cosmology is starting to constrain the nature of the earliest galaxies formed in the Universe but direct observations of galaxies at $z > 4$ remains largely challenging due to the observational constraints imposed for their large luminosity distances. Long-duration Gamma-ray bursts (long-GRBs), those ones usually lasting more than 5s and originated at cosmological distances, can be used as beacons to point to the location of these high-z galaxies, thanks to their extreme luminosities (with energy releases of 10^{51}–10^{53} ergs).

As the central engines that power these extraordinary events are now considered to be the collapse of massive stars ([35, 36]), they can be used as tracers of star formation.

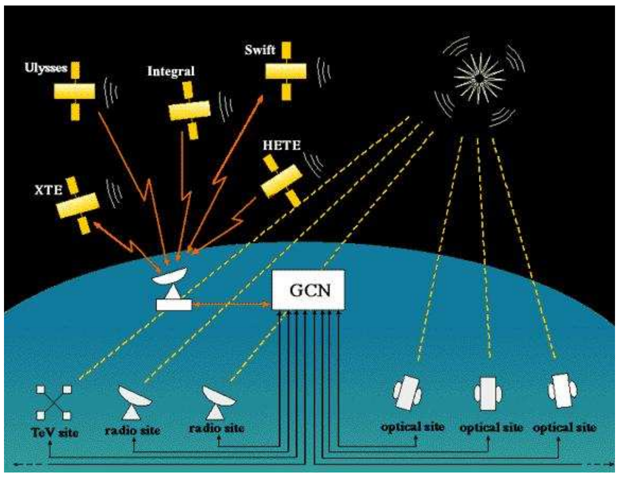

Figure 12: The GCN/Bacodine alert system assures rapid dissemination of GRB alerts thru Internet, so RAOs can quickly respond to them [33].

Early observations of the afterglows (the multiwavelength emission that follows the gamma-ray emission) allow to provide redshifts and additional spectral observation which cannot be derived from the direct observations of the galaxies themselves. This is most essential as some of these host galaxies (the ones a $z > 6$) are responsible of a significant proportion of ionizing radiation during that reionization era.

INTEGRAL and *Swift* are providing around 100 detections/yr, whose alerts are promptly distributed by the GCN/Bacodine Network (see Fig. 12). However, 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 $\mathrm{M_V} = -36$ [37], such events were also expected to occur at nIR wavelenghts, as was proven for GRB 041219 [38].

But since the first GRB with a fading X-ray afterglow *without* an optical counterpart was detected by *BeppoSAX* in Jan 1997, the number of similar events has increased significantly since the launch of *Swift* in Nov 2004. Nowadays, these dark GRBs seem to constitute a significant fraction ($\sim$ 50%) of the GRB population (e.g. [39]).

This latter population of dark GRB should contribute significantly to the hidden star formation rate in the Universe [40]. Important scientific goals for some RAOs are the study of dark GRBs and the "hunt" for ultra-high z events.

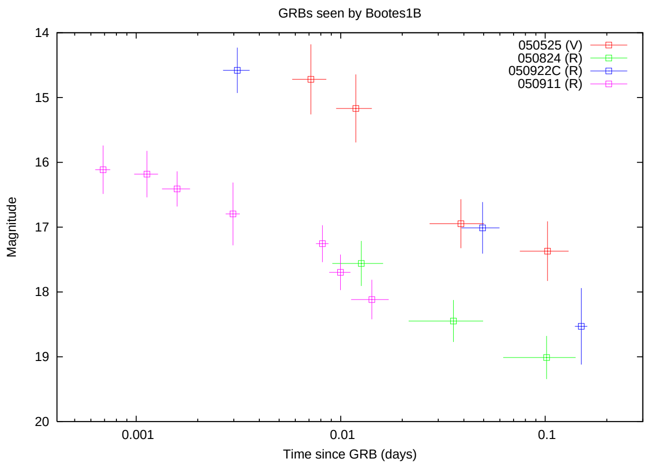

Figure 13: Optical afterglows lightcurves of some GRBs detected by BOOTES and rapidly imaged (∼ 1 min) after the detection by scientific satellites.

8.2 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 and, together with the derived upper limits in the optical, might allow to determine the intrinsic extinction. 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.

8.3 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 nIR RAOs will cover a redshift range $6 \leq z \leq 17$ (see Fig. 14), 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 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

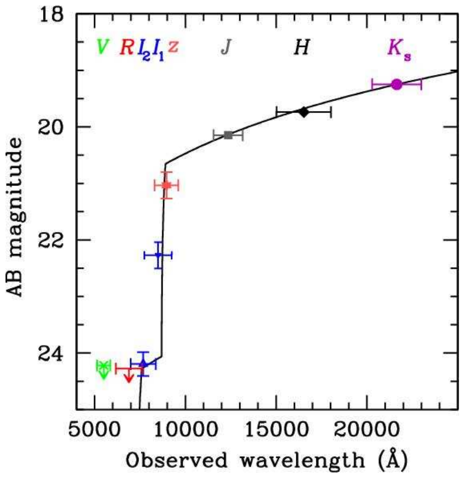

Figure 14: GRB 050904 holds the highest redshift recorded so far for a GRB ($z = 6.3$). The Lyman-α break is quite noticeable in the broadband optical-nIR photometry [41].

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 [42].

For instance, 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[43] 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.

8.4 Coordinate observation of GRBs in different filters

Only a few GRBs have exceptionally bright optical counterparts. Observers are of course interested in collecting as much data as possible, with the best possible resolution.

One of the goals of the observers is to take spectra of the transient while it is bright enough, so the transient redshift and other properties can be measured. Using data taken with different filters, one can construct a spectral energy distribution of the event and estimate object redshift. The networked RTS telescopes (like BOOTES) at favourable locations can simultaneously observe objects in different filters.

The idea is to enable those telescopes to communicate with each other and provide simultaneous images in two or more filters. This system should balance the need to take some data with possibility to take data in multiple filters. It can be achieved by sending commands for taking images in different filters when the system knows that it has at least some images of the event. This kind of decision is best done in a single component – observation coordinator.

The coordinator will be connected to two or more telescope nodes. It will collect information from GCN and from all connected nodes. A node will report to the coordinator when it receives a GCN notice, when it starts its observation and as soon as it gets image passed through astrometry and it contains whole error area of the GRB. It will also report when the transient detection software identifies a possible optical transient.

When the coordinator receives messages about correct observation by two telescopes, it will decide which filter should be followed at which telescope, and send out commands to carry out further observations. The coordinator will periodically revisit its observing policy, and send out commands to change filter accordingly.

As the system is "running against the clock" for the first few minutes after the GRB event, trying to capture the most interesting part of the transient light curve, it cannot wait for the completion of the transient source analysis. In the case of two telescopes, the coordinator will command different filters as soon as it knows that both telescopes have acquired the relevant field. The current astrometry routines take a few seconds to run, and it is expected that observations with different filters can already have started within this time–frame.

9 Coordinated World-wide observation of Targets

One step further from the GRB observation is coordinated observation of targets – e.g. observation of variable stars for more then 12 hours (i.e. taking advantage of telescopes in different time zones). The observer should contact the coordinator, and either add a new target, or select a predefined target which he/she wants to observe. The coordinator should list to the observer telescopes which can observe target of his/her choice, and propose filters and exposure times.

The observer could then decide which telescopes to be used, and the coordinator would send observation requests to the nodes, and collects back information about observation progress. Currently only observer–selected coordinated observations are envisioned. Once that will work properly, observer can be replaced by a network scheduling software.

10 Conclusions

Robotic Telescopes are opening a new field in Astrophysics in terms of optimizing the observing time, with some of them being able to provide pre-reduced data. The big advantange is that they can be placed in remote locations where human life conditions will be hostile (Antartica now, the Moon in the near future).

Technological development in differen fields is pretty much involved and some of the robotic astronomical observatories are moving towards intelligent robotic astronomical observatories.

One immediate application of small/medium size robotic telescopes is the study of GRBs, which can be considered the most energetic phenomenon in the Universe. In combination with space missions like *Integral* and *Swift* (nowadays), *GLAST* (to be lunched in mid 2008) and *EXIST* (if approved) should be used for triggering larger size instruments in order to perform more detailed studies of host galaxies and intervening material on the line of sight. These RAOs will provide a unique opportunity to unveil the high-z Universe in the years to come.

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