



MASTER global robotic net

V. Lipunov^{1,2}, V. Kornilov¹, E. Gorbovskoy^{1,2}, A. Belinski¹,
D. Kuvshinov¹, N. Tyurina¹, A. Krylov¹, N. Shatsky¹, P. Balanutsa¹,
V. Chazov¹, A. Kuznetsov¹, D. Zimnuhov¹, A. Tlatov³,
A. Parkhomenko³, D. Dormidontov³, V. Krushinsky⁴, I. Zalozhnyh⁴,
A. Popov⁴, S. Yazev⁵, N. Budnev⁵, K. Ivanov⁵, E. Konstantinov⁵,
O. Gress⁵, O. Chvalaev⁵, V. Yurkov⁶, Y. Sergienko⁶, I. Kudelina⁶

¹*Sternberg Astronomical Institute of Moscow State University, Moscow*

²*“Extreme Universe” Laboratory of Lomonosov Moscow State University of Skobeltsyn Institute of Nuclear Physics, Moscow*

³*Kislovodsk Solar Station of the Pulkovo Observatory, Kislovodsk*

⁴*Ural Federal University, Kourovka observatory*

^{5,6}*Blagoveschensk Educational State University, Blagoveschensk*

Abstract. The paper presents the basic principles of the design of the robotic network of optical telescopes MASTER, developed to study the prompt optical emission of gamma-ray bursts. The robotic telescopes MASTER II near Kislovodsk, Ekaterinburg, Irkutsk and Blagoveshchensk were installed and started to operate, thanks to the support of Sternberg astronomical institute, High altitude astronomical station of the Pulkovo observatory, Ural state university, Irkutsk state university, Blagoveshchensk pedagogical university. The network span over the longitudes is greater than 6 hours.

Keywords : robotic observations – GRB – transients – Supernovae

1. Introduction

Ten years ago it was realized that robotic observatories were going to boost the capabilities of astronomical observations of non-stationary and short-lived phenomena in the Universe. Such facilities, built throughout the world, allowed to discover and study the prompt emission of the most powerful explosions — the gamma-ray bursts. Hundreds of supernovae were detected as well which enabled to infer the existence

of the energy of the cosmic vacuum. Additionally, the robotized telescopes discover thousands of new minor bodies of the solar system and many of exoplanets.

To serve these observations efficiently, the small apertures suite quite well (Paczynski 2006), with the field of view (FOV) being the most essential. Unpredictability of the majority of transient phenomena and their practically isotropic distribution on the sky makes probability of detection and measurement also proportional to the available yearly observation time at the site. The relative ease of installation of small telescope makes it possible to increase the efficiency by expanding the observational network placing the new telescopes in various geographical points (Jelínek *et al.* 2006; Akerlof *et al.* 2003).

Russia, as the most extended country over longitudes, is very attractive for studies of vast astrophysical transients. The first Russian robot-telescope MASTER was developed in 2002–2006 and installed near Moscow (Lipunov *et al.* 2007). It appeared not only scientifically fruitful (Lipunov *et al.* 2007, 2008) but also useful as an effective platform for methodology and technical studies devoted to optimize the use of small robotized telescopes of which the most essential is the unique software complex needed for automated multi-purpose astronomical observations.

In 2008–2010, the further development of the MASTER network was performed. Four new observatories equipped with MASTER II telescopes and very-wide-field cameras (Lipunov *et al.* 2010; Tyurina *et al.* 2010) were built. A key feature of the new MASTER system is a twin-tube telescope enabling the measurement of brightness of transient phenomena simultaneously in two spectral bands or with two different orientation of the polarizing filters. Clearly, such information is needed for the construction of the correct models of GRB events. This paper describes the structure and functioning of the nodes basic soft and hardware complex.

Potentially, the MASTER II telescopes network provides the following observational studies:

- Synchronous multi-color and polarimetric observations of gamma-ray bursts;
- Supernovae search;
- Exoplanets observations;
- Trans-neptunian objects, comets and meteors detection;
- Study of orphans GRBs;
- Gravitational micro-lensing observation.

2. MASTER II observatory instrumentation

Each MASTER II observatory was aimed to be equipped with as much as possibly a standardized hardware configuration in order to provide a more homogeneous data

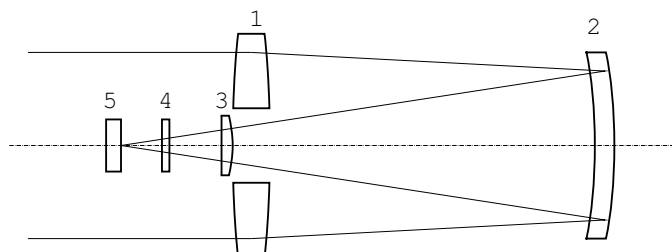


Figure 1. Simplified sketch of the Hamilton optical system. 1 – positive entrance aperture lens, 2 – Mangin mirror; 3 – field lens; 4 – optical filter; 5 – CCD detector.

set and the minimal expenses for its maintenance. The main element is the twin fast telescope installed on the equatorial mounting at both sides of the mount.

The Hamilton optical system of the telescopes contains the slow positive lens at the entrance pupil and the Mangin primary mirror at the bottom of the tube (Fig. 1). The focal plane is in front of the lens so the back-focal distance of ≈ 140 mm is provided for filters and detector. The field lens is located near the entrance aperture and is used for fine focusing. The telescope primary characteristics are the following:

- Entrance aperture diameter $D = 400$ mm
- Focal ratio $F/2.5$;
- Effective focal length $F = 1000$ mm;
- Plate scale $s = 206''/mm$;
- Maximal field of view diameter $2\omega = 4^\circ$;
- Central obscuration (by the CCD camera body) is $q = 25\%$ of the area;
- The unobstructed aperture area is $S = 940$ cm².

The working field of view is restricted by the detector in use to $2.1^\circ \times 2.1^\circ$. The used camera Apogee Alta U16M with the detector format $4K \times 4K$ shows good images across its area. This CCD provides the scale of $1.85''/\text{pixel}$.

The tubes supports provide two modes of tube collimation: 1) the co-linear position (both optical axes coincide with the mount pointing vector); and 2) the diverged position (optical axes are at $\pm 1^\circ$ with respect to the pointing vector). The first mode is used for transient alert observations simultaneously in two photometric bands or linear polarization states, while the diverged mode is normally used in surveys.

The mount in use for the MASTER II telescopes is the ASTELCO NTM 500 mount with direct drive motors. The absence of gears allows for speeds up to $30^\circ/\text{s}$ and also provides the needed robustness for extreme working conditions (especially in Siberian sites).



Figure 2. Left: MASTER II telescope assembly at Kourovskaya astronomical observatory, with no photometric units and CCD attached. Right: custom steel enclosure for Irkutsk university polygon in Tunka valley.

The photometric unit (Lipunov et al. 2010) provides the four photometric filters or polaroids insertion on the optical axis. The particular set of filters installed in eastern and western photometric unit depends on the actual scientific program. Normally both tubes are equipped with Johnson *V* and *R* filters for surveys, one polarizer with the direction perpendicular to the opposite tube one, and *B* or *I* Johnson filter in the free slot left to provide the multi-color photometry in the co-linear mode.

In order to protect the telescope from bad weather, two types of enclosure are used (see Fig. 2): the fiberglass clam-shell 3.6-meter Astrohaven dome and steel custom enclosure for more harsh conditions of Siberia. Both enclosures provide the full-hemisphere access.

3. MASTER II nodes location

While choosing the nodes location, we considered the following main factors: 1) the longitude distribution of nodes; 2) the existence of the local personnel interested in joint scientific collaboration and general infrastructure; 3) the clear skies night-time fraction. The work experience and results of similar programs prove the validity of such criteria (Paczyński 2006; Yost et al. 2007; Castro-Tirado et al. 1999).

The Table 1 provides the geographical data for the observatories of the network. The site MASTER-URAL is situated on the territory of Kourovskaya astronomical observatory of Ural state university since fall 2008. It is far enough (≈ 80 km) from the nearest city Ekaterinbourg. This site is the northern most node of the network so some time in summer is characterized by the absence of astronomical night.



Figure 3. The MASTER II telescope at Pulkovo solar station (The MASTER-KISLOVODSK node of network)

Installation of the MASTER-KISLOVODSK complex was also started in late 2008 with assembly of the clam-shell dome atop the 9-m high steel tower at Highland astronomical solar station of Pulkovo observatory which is 30 km to the south from Kislovodsk city. The southern neighborhood of the site to the Caucasus main ridge 40 km away is free from any light sources while the northern part of the horizon is illuminated by the Caucasus Mineral water region towns. In summer 2009 the temporary optical tube assembly was replaced with a MASTER standard instrument (40 cm Hamilton system twin telescope) which enabled its full-featured operation. This site is currently the western and southern most node in the network, located also at the highest elevation above the sea level.

The MASTER-TUNKA node is built in the Tunka valley (Buryat Republic) some 50 km from the southern end of Baikal lake, at the polygon of Irkutsk state university. The complex assembly was begun in 2009 when the automated custom steel enclosure

Table 1. Geographical coordinates of MASTER II network observatories.

Node	Longitude	Latitude	Altitude, m
MASTER-URAL	03 ^h 58 ^m 11 ^s .2	+57°02'13"	290
MASTER-TUNKA	06 ^h 52 ^m 16 ^s .1	+51°48'34"	700
MASTER-AMUR	08 ^h 29 ^m 56 ^s .0	+50°19'07"	215
MASTER-KISLOVODSK	02 ^h 50 ^m 04 ^s .0	+43°45'00"	2067

was erected. In November 2009, this site has entered into operation with the temporary tube equipped with the Alta 16U CCD-camera. The standard twin telescope has replaced this tube in summer 2010. The light pollution from the Irkutsk region cities is fully blocked by the Eastern Sayan mountain ridge.

The eastern point of the network (MASTER-AMUR) is located at the territory of discontinued Blagoveschensk latitude station two kilometers from Blagoveschensk city. Alike other sites, half a year of assembly works were completed in November 2009 with a temporary robot-telescope installation in the steel enclosure and the standard telescope tubes were put into operation a year later. The site operates full-time since January 2011.

4. Hardware structure of the MASTER II complex

The digital hardware structure of the MASTER II complex reflects its functional aiming. It is optimized for effective operations for data and command transfer for the telescope and astronomical and auxiliary equipment. The complex is organized as a distributed computer system for data acquisition and processing which is united with the help of a local Ethernet segment. The core of the complex is a server based on a two-processor 8-core platform Intel Xeon 54xx equipped with a high performance RAID-system providing the following functions:

- The gateway of the complex linking the local net to Internet using VSAT equipment.
- The precise time service based on *ntpd*.
- The database PostgreSQL server is used for storage of meta-information about images, objects detected on them and auxiliary data.
- The image processing system providing automatic processing of acquired images.
- Data storage: a dedicated disk subsystem stores the original images as well as the processing results in the FITS format.
- The GCN-center alerts program: a permanent socket connection is maintained with the GCN server for prompt delivery of the gamma-ray events observed by space observatories.
- HTTP-server service for external access to observation control and to image and object databases.
- The observations supervision with help of the continuously running software.
- Observation scheduler on the basis of pre-selected observation strategies and lists of targets.
- The local weather station additionally equipped with an infrared cloud sensor is attached to the server.

5. Software general structure

The software consists of several independent components which are communicating to each other. This simplifies the logical structure of the components, and also enhances the stability and flexibility in the system organization. All the machines of the complex are running the GNU/Linux operation system which is best suited for optimal local, distributed and remote work. The distributed character of the software reflects the hardware level distribution. The basic inter-program communication method is the network TCP/IC connections where some programs perform the role of servers and others work as clients.

It should be stressed that client-server architecture implies the use of a dedicated logical command protocol. Such a protocol was developed earlier for another project of the Sternberg institute and is based on enumerated command messages with a restricted set of command words followed by optional parameters. The essential feature of this protocol is the obligatory acknowledgment that the command was received, passed and executed.

The raw and processed data transmission (mainly images) is implemented using another method which is the database requests. Three main databases (DB) are maintained in the system: image DB, weather DB and object DB (the list of targets for observations).

6. Data processing

To process the data, the synchronization of the work of separate programs is done by a special program, named *Head*, started on the server. After the initialization, the program connects to the needed components as a client and provides the observation stages via commands or data requests. The particular sequence of pointings and acquisitions is made given the data from the objects list which is formed by the *Planner* program or manually, using the respective web-interface. Three modes of observations are supported: survey, special and alert observations.

Separate daemon *Robot* monitors continuously the weather conditions (clear night) from evening to morning twilights. It is the *Robot* which makes the decision about observations possibility. Just as the decision is made, *Robot* connects to the enclosure program in order to open it and to the *Head* to initialize it. Likewise, if conditions become worse, *Robot* parks the *Head* program and closes the dome. Additional responsibility of the daemon is starting and stopping the surveys and checking the telescopes and domes state after dawn in order to ensure the equipment safety.

The information on gamma-ray bursts (alert events) which is received from the Gamma Center Network (Barthelmy 2008) server of NASA by a special daemon-server *Alert handler*, is immediately handed over to the *Head* by a special connection.

This request will be ignored in a parked state only when observations are impossible. In the standalone or survey observations state this alert request will be immediately processed even if the current exposure will have to be aborted.

The alert observations logic is the following: 1) point a telescope to the GRB position, 2) set the needed filters and correct the focus respectively, 3) put the tubes in the co-linear position and 4) start the exposure with the duration $\sim 0.2 \Delta t_{GRB}$. The observations thus started are continued as long as possible.

Survey observations are performed in different ways depending on the survey task. The main survey is executed for the search of the non-cataloged objects of various nature and maintaining the base of reference images in the MASTER telescopes photometric systems. This is made in the *R*-band or white light with the diverged tubes. The supernovae search survey is a bit more special. It is made with co-linear tubes in a multicolor way (usually with *V* and *R* filters). During the survey, the *Head* performs the quality control of the images and, if necessary, starts the autofocussing process.

7. Real-time image processing, images database

The image processing is started after its insertion in the database (≈ 25 s after the image readout which are needed for image transmission to the server and insertion itself). The alert images are separated from survey frames from the very beginning. Alert images have the highest priority for processing. If necessary, the image processing programs may be started in parallel so up to 8 (the number of CPU cores) images may be reduced simultaneously.

The first stage is the primary data reduction including the bias and dark frame subtraction and flat-fielding. Calibration master frames are prepared in advance as a library of images for all the detector temperature set-points used. The calibration images are stored in the same table as the reduced science frames for subsequent inspection if needed.

The next stage is the objects detection and their coordinate and photometric referencing. As a base for object detection and classification, the *SExtractor* package was adopted for our images application. The table of detected objects is used for identification and calculation of the coordinates conversion coefficients. The coordinates are those from the Tycho 2 catalog or the USNO B1.0.

The photometric reduction is made using the same catalogs given the photometric band in use. The precision of such a calibration is $\approx 0^m.2$ which is quite enough for searching tasks and transients detection.

The detected objects are classified into three categories:

1. known stars — objects identified using their coordinates (with the allowed difference not more than $2 - 3''$ with catalog position) and fitting the catalog by magnitude ($\pm 0.5 - 1^m$);
2. flashes — objects on the place of cataloged ones but having higher difference in magnitude;
3. unknown – objects absent in catalogs.

The known stars are excluded from subsequent consideration and these are only class 2 and 3 objects i.e. flashes and unknowns – the potential transients (PT) — which are analyzed. Image artifacts like unaccounted hot pixels, diffraction rays from bright stars, on-edge objects could be bi-passed with help of a special filter program. Then the PT is checked for coincidence with additional catalogs (AGN, asteroids and SNe).

All the PT objects (including those marked as potentially false) are added to the database in the object table and the subsequent analysis is made already using this table. The table already contains the information on all the previous area observations.

The supernova candidates are selected from unmarked PT which are located within the doubled radius of the closest galaxy 25th isophote taken from the HYPERLEDA catalog (Paturel et al. 2003). Then the previous observations are checked. Unknown objects lying within more than 0.75 fraction of the 25th isophote radius are accounted as candidate “pure” supernova (Pruzhinskaya et al. 2011; Tsvetkov et al. 2011) and inspected with a first priority.

The optical transients (OT) are selected only from objects observed more than twice. As candidate OTs, the unmarked PTs are considered having a large ($> 2^m$) magnitude difference for which an archive frame exists showing no object on the detection place. Such a frame must be obtained at least one week before the observation and its limiting magnitude should allow for the candidate OT detection.

8. Observation external control

For the control of the observation, special web-interfaces were developed which allow to monitor the state of and manage the process in any observatory. The main page of each site contains all the necessary information on current conditions: weather parameters, Sun altitude, dome and telescopes state, main programs status.

Another web-interface allows the operator to ease the observation data analysis. The web-control and results analysis systems represent the user interfaces to browse the content and/or modify the data in the databases in use. For example, the table used by the *Head* program as a priority object list is filled by the operator using the respective form.

For each class of objects, whose search is made in real-time (supernovae, optical

Table 2. The number of acquired images and the accumulated exposure in the MASTER network observatories as for the 2011, mid-March.

Site	Surveys		Alerts	
	<i>N</i>	<i>E</i> , min	<i>N</i>	<i>E</i> , min
MASTER-URAL	30 561	76 928	1 941	4 713
MASTER-TUNKA	27 688	59 900	1 124	2 465
MASTER-AMUR	53 088	64 960	3 696	3 825
MASTER-KISLOVODSK	63 214	179 850	6 131	17 500

transients, asteroids), a special web-page is designed. For example, the sky patch is output around the potential transient and the full supplementary information on the respective data reduction is shown as well. Additionally, the same sky area images are generated giving the most informative DSS and SDSS surveys as well as the repeated and archive images.

Each frame inserted in the image database may be retrieved either in FITS format for subsequent thorough analysis or as a jpeg picture for visual inspection in complex cases. It is possible to retrieve a full image or a particular region of the observed sky.

9. Conclusions

With the new facility, alert observations occupy less than 10% of time and rest of the time is spread between the surveys and special observational tasks. As an example, the number of images recorded in different MASTER sites for March 2011 are shown in Table 2.

In Fig. 4, the visual representation of the survey execution at MASTER-TUNKA node of the MASTER network is shown for the one-year period since Summer 2010. A similar picture could be seen at other nodes — after about half a year from the time of the node deployment about 90% of the accessible sky is covered by our own archive images. Most dark sky patches correspond to the most deep searches made in course of alert events observations, transients candidate or supernovae.

The efficiency of the MASTER robotic network is validated by its total input in the GRB optical observations: in 2009-2010 about 50 alerts were observed and in 6 cases the GRB optical emission was detected (see details (Lipunov 2012)). During Sep 2010 – June 2011, the MASTER II network provided 50% of the first prompt pointing on *Swift* GRBs (see Fig. 5). In the same period, 30 supernovae were independently detected in spite of fact that the SN search is a secondary program.

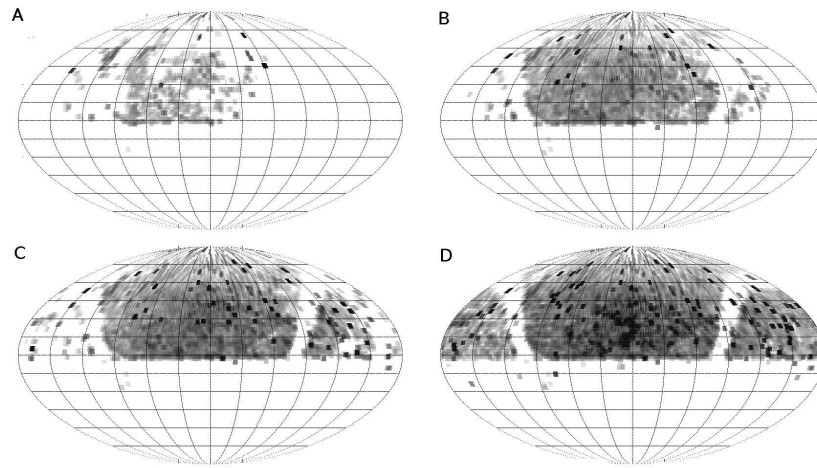


Figure 4. The map of observations performed at MASTER-TUNKA node: A – after 30 days from the site start-up, B – after 90 days, C – after 180 days and D — a year after.

Prompt pointings

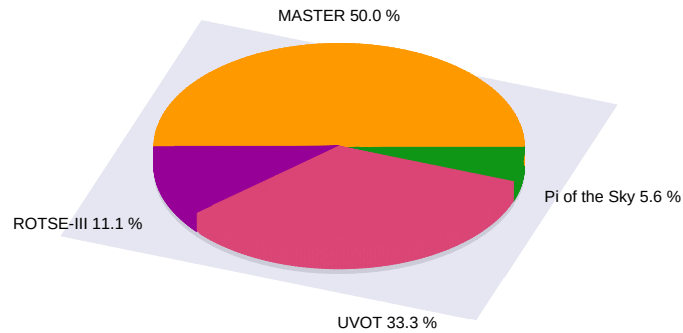


Figure 5. Numbers of first prompt pointing on Swift GRBs from 01 September 2010 to 01 June 2011.

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