Mini–MegaTORTORA wide-field monitoring system with sub–second temporal resolution: observation of transient events

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Abstract Here we present a summary of first years of operation and first results of a novel 9-channel wide-field optical monitoring system with sub-second temporal resolution, Mini-MegaTORTORA (MMT-9), which is in operation now at Special Astrophysical Observatory on Russian Caucasus. The system is able to observe the sky simultaneously in either wide (~ 900 square degrees) or narrow (~ 100 square degrees) fields of view, either in clear light or with any combination of color (Johnson-Cousins B, V or R) and polarimetric filters installed, with exposure times ranging from 0.1 s to hundreds of seconds. The real-time system data analysis pipeline performs automatic detection of rapid transient events, both near-Earth and extragalactic. The objects routinely detected by MMT include faint meteors and artificial satellites. The pipeline for a longer time scales variability analysis is still in development.

Keywords: Telescopes Instrumentation, Gamma-Ray Burst, Meteorites, Meteors, Meteoroids

1. Introduction

Mini–MegaTORTORA is a novel robotic instrument just commissioned for the Kazan Federal University and developed according to the principles of MegaTORTORA multi–channel and transforming design formulated by us earlier [1] – [4]. It is a successor to the FAVOR [5] – [7] and TORTORA [8] single-objective monitoring instruments we built earlier to detect and characterize fast optical transients of various origins, both cosmological, galactic and near-Earth. The importance of such instruments became evident after discovery and detailed study of the brightest ever optical afterglow of the gamma-ray burst GRB080319B [9], [10].

The Mini-MegaTORTORA (MMT-9) system includes a set of nine individual channels (see Figure 1) installed in pairs on equatorial mounts (see Figure 2). Every channel has a coelostat mirror installed before the Canon EF85/1.2 objective for a rapid (faster than 1 second) adjusting of the objective direction in a limited range (approximately 10 degrees to any direction). This allows us either mosaicking the larger field of view, or pointing all the channels in one direction. In the latter regime, a set of color (Johnson's B, V or R) and polarimetric (three different directions) filters may be inserted before the objective to maximize the information acquired for the observed region of the sky (performing both three-color photometry and polarimetry).

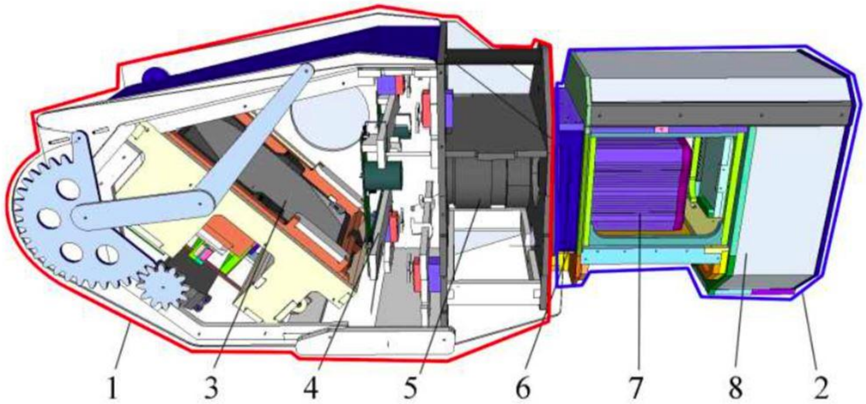

Fig1. *Schematic view of a MMT channel. 1 – coelostat unit, 2 – camera unit, 3 – coelostat mirror which can rotate by ~10 degrees around two axes, 4 – installable color and polarimetric filters, 5 – the Canon EF85/1.2 objective, 6 – optical corrector, 7 – the Andor Neo sCMOS detector, 8 – conditioner to keep stable environmental conditions inside the channel.*

The channels are equipped with Andor Neo sCMOS detectors having 2560x2160 pixels 6.4μm each. The field of view of a channel is roughly 9x11 degrees with an angular resolution of 16″ per pixel. The detector is able to operate with exposure times as small as 0.03 s. In our work we use the 0.1 s exposures providing us with 10 frames per second because on higher frame rates we are unable to process the data in real time.

Fig2. *Photo of all 9 channels of MMT installed on 5 mounts in the single cylindrical dome, which is open at that moment. The dome of the Russian 6-m telescope is seen in the background.*

Every channel is operated by a dedicated PC which controls its hardware, acquires images from the detector and performs the data processing. The amount of data acquired by a single channel is about 3Tb in 8 hours of observation. The complex as a whole is being controlled by a separate PC.

Initial tests show that the FWHM of stars as seen by MMT channels is around 2 pixels wide. The detection limit in white light for 0.1 s exposure is close to 11 mag, when calibrating to V band magnitudes.

2. Mini–MegaTORTORA operation

Mini–MegaTORTORA started its operation in June 2014, and since then has been routinely monitoring the sky. The observations are governed by a dedicated dynamic scheduler optimized for performing the sky survey. The scheduler selects the next pointing for Mini–MegaTORTORA by simultaneously optimizing the following parameters: distances from the Sun, Moon and the horizon should be maximized, distances from the current pointings of Swift and Fermi satellites should be minimized, and the number of frames already acquired on a given sky position that night should be minimized. In this way a more or less uniform survey of the whole sky hemisphere is being performed while maximizing the probability of observations of gamma-ray bursts. As a non-optimized extension, the scheduler also supports observations of preselected targets given by their coordinates, which may be performed in various regimes supported by Mini–MegaTORTORA (wide-field monitoring of a given region of the sky with or without filters, narrow-field multicolor imaging or polarimetry with lower temporal resolution, etc).

Moreover, the scheduler and central control system supports various types of follow-up observations triggered by external messages and typically corresponding to transient events occurred outside the current Mini–MegaTORTORA field of view. It will try to rapidly repoint and observe the localizations of Swift BAT and XRT triggers in either multi-color or polarimetric mode, typically large error boxes of Fermi GBM in wide-field mode, etc. The large size of Mini–MegaTORTORA field of view in the wide-field regime makes such observations very promising for rapid pin-pointing of possible optical transients corresponding to triggers with bad accuracy of initial localization.

3. Data analysis

The main regime of Mini–MegaTORTORA operation is the wide-field monitoring with high temporal resolution and with no photometric filters installed. In this regime, every channel acquires 10 frames per second, which corresponds to 110 megabytes of data per second. To analyze it, we implemented the real-time fast differential imaging pipeline intended for detection of rapidly varying or moving transient objects – flashes, meteor trails, satellite passes etc. It is analogous to the pipeline of FAVOR and TORTORA cameras [11], [7], and is based on building an iteratively-updated comparison image of a current field of view using the numerically efficient running median algorithm, as well as threshold image using the running similarly constructed median absolute deviation estimate, and then comparison of every new frame with them, extracting candidate transient objects and analyzing lists of these objects from the consecutive frames. Then it filters out noise events, extracts the meteor trails by their generally elongated shape on a single frame, collects the events corresponding to moving objects into focal plane trajectories, etc.

Every 100 frames acquired by a channel are being summed together, yielding “average” frames with 10 s effective exposure and better detection limit. Using these frames, the astrometric calibration is being performed using locally installed ASTROMETRY.NET code [12]. Also the rough photometric calibration is being done. These calibrations, updated every 10 seconds, are used for measuring positions and magnitudes of transients detected by the real-time differential imaging pipeline. The “average” frames are stored permanently (in contrast to “raw” full-resolution data which is typically erased in a day or two after acquisition) and may be used later for studying variability on time scales longer than 10 s.

The Mini–MegaTORTORA typically observes every sky field continuously for 1000 seconds before moving to the next pointing. Before and after observing the field with high temporal resolution, the system acquires deeper “survey” images with 60 seconds exposure in white light in order to study variability of objects down to 14–15 magnitude on even longer time scales; typically, every point of the northern sky is covered by one or more such images every observational night.

As the first step of analysis of these survey data, we implemented the transient detection pipeline based on comparison of positions of objects detected in our images with Guide Star Catalogue v2.3.2, as well as with Minor Planet Center database. This pipeline routinely detects tens of known asteroids every night, and sometimes – the flares of dwarf novae and other transients.

The full-scale photometric pipeline for survey images is still in preparation, as the precise photometry of these frames turned out to be quite a difficult task due to the large size of point spread function of a Canon objective with extended wings harbouring up to 40% of light. This leads to severe photometric errors in typical stellar fields, significantly crowded even outside the Galaxy plane. Now we are implementing the PSF-fitting code optimized for the accurate measurement of Mini–MegaTORTORA survey images and hope to finish it in 2016.

Below we briefly describe some of the data products of the high temporal resolution pipeline.

3.1. Meteors

The meteors are probably the most frequent astrophysical phenomena flashing in the sky, and easiest to detect in the Mini–MegaTORTORA data stream. The meteor detection is performed in a differential image based on their typically elongated shapes. Then the elongated trails from consecutive frames, having similar directions of elongation, are being merged into a single event. A dedicated analysis subroutine extracts the meteor trail using Hough transformation, detects its extent in every frame, and estimates brightness along the trail, light curve, trajectory, angular velocity and duration. The majority of events are observed in white light (then the brightness is calibrated to V magnitude), while some are being observed in Johnson-Cousins B, V and R photometric filters simultaneously. For such events, the colors are also derived automatically (see Figure 5). All these data are stored in the database and are available online[1].

We are not able to perform any parallactic observations of meteors now (though we are working on installing the second version of Mini–MegaTORTORA which will allow us to measure meteor parallaxes). However, huge amount of meteors measured every night might, in principle, allow detecting the radiants of meteor streams using purely statistical methods. Figure 3 shows the density of intersections of meteor trails from the night corresponding to 2014 Geminids, and the radiant is clearly visible here. Such radiant maps are built automatically and available online for every night.

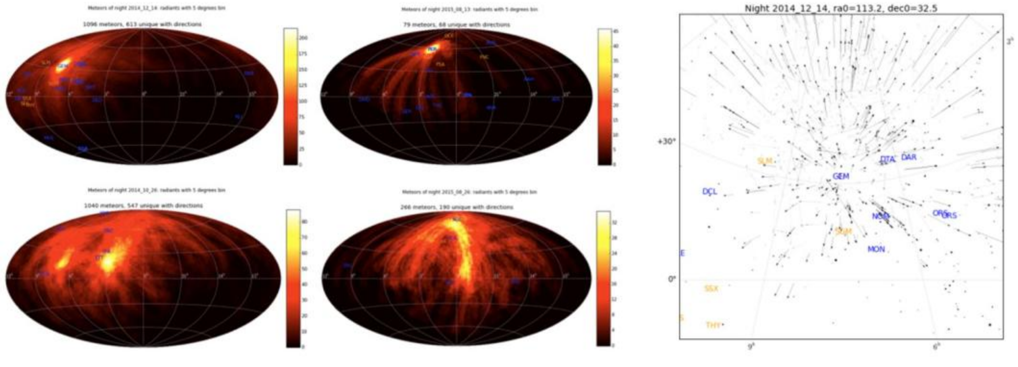

Fig3. Density of intersections of meteor trails from the night corresponding to the peak of 2014 Geminids (left) and meteor trails corresponding to the Geminids shower in the gnomonic projection (right).

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[1] The database is published at http://mmt.favor2.info/meteors and http://astroguard.ru/meteors

The database also contains the full-resolution imaging data, which may be useful for studying the peculiar events like meteors consisting of several particles flying in parallel, or the complex evolution of long lasting tails of brighter meteors due to atmospheric motions (see Figure 4).

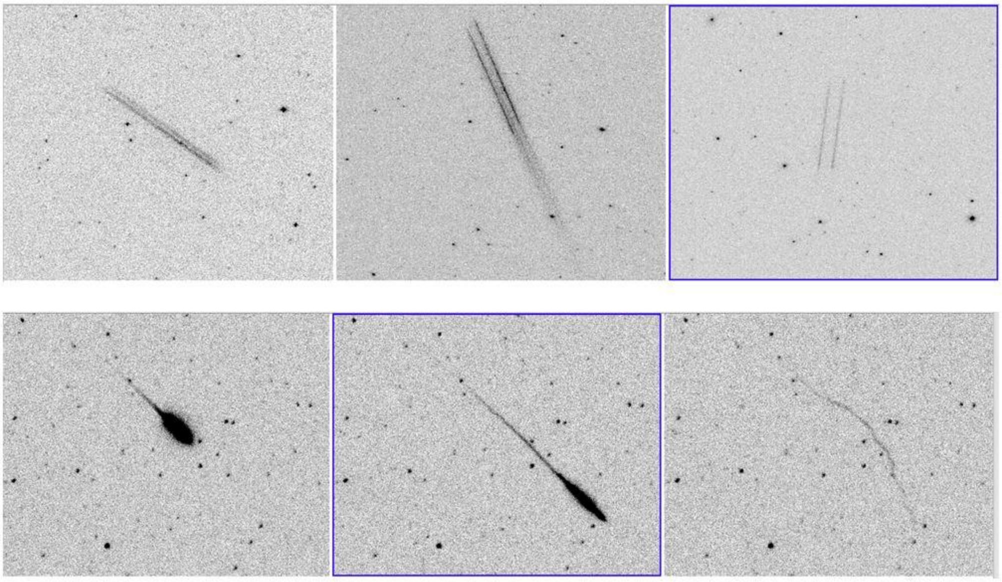

Fig4. *Example of multi-particle meteor trails (top) and the complex temporal evolution of a bolide trail in the atmosphere (bottom).*

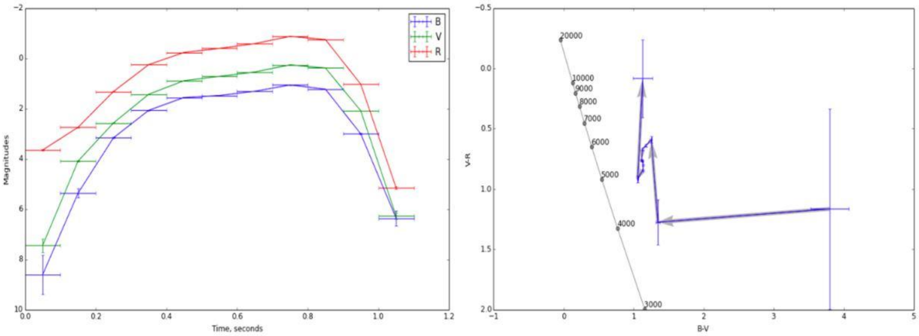

Fig5. *Example of a multi-color light curve of a meteor detected by Mini-MegaTORTORA (left) and the corresponding evolution on a two-color diagram (right).*

3.2. Satellites

Detection of rapidly moving objects is implemented by comparing the lists of objects detected in consecutive differential frames and extracting those ones which move along (nearly) straight lines with (slowly varying or) constant velocity in the focal plane. This is being done iteratively starting from the third appearance of the object in the frame. After initial detection, the object is being tracked until it fades below the detection limit or leaves the field of view. Afterwards its trajectory and light curve are stored for a more detailed analysis.

The accuracy of coordinate determination of the real-time transient detection pipeline, which is typically 5-30″, is quite enough for reliable identification of satellites on low and medium-altitude orbits using publicly available orbital elements [13], [14]. We are routinely performing such identification and as a result acquire a large amount of high resolution photometric in- formation on these objects, which we publish online as a fully searchable online database of satellite light curves[2].

The database includes the following parameters for every satellite track observed: light curves in apparent and standard magnitudes (calibrated to the distance 1000 km and the phase angle 90°), distance and phase angle over time, whether the satellite was inside the penumbra, and a light curve period if it displays a periodicity. For every satellite it also contains the general information and classification of activity taken from public sources (active, inactive, debris etc), as well as variability type estimated by us (periodic variability, variable but aperiodic, non-variable). The number of periodic light curves is up to 20%.

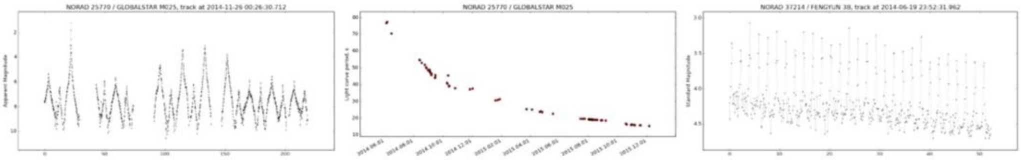

Fig6. *Light curve of a freely rotating inactive satellite detected by Mini-MegaTORTORA (left), its period evolution over time due to interaction with atmosphere and residual technological processes (center) and the rapid variability of an active satellite due to stabilized antenna rotation with 1.8 s period (right).*

Periodicity of a satellite light curve may be caused either by rotation of an object as a whole (which is typical for both inactive satellites, upper stages or debris, and active satellites stabilized by rotation), or by some rotating element like an antenna (see Figure 6). The rotation period of inactive objects often changes over time due to some residual technological processes inside the object itself.

3.3. Fast optical flashes

The original aim of Mini–MegaTORTORA differential imaging pipeline is the detection of rapid optical flashes of astrophysical origin, which is being performed by detecting the stellar-like objects visible in several consecutive differential images (to filter out sporadic noise events and cosmic rays) and not changing their position. As of now, we are still in process of calibrating this part of pipeline, as it is being highly contaminated by stellar scintillations and detector noise spikes. We are, however, able to detect a number of rapid flashes caused the rotation of high-altitude slowly moving satellites, which produce short (up to half a second) events with negligible motion. Such flashes are practically indistinguishable from anticipated astrophysical bursts, and may be filtered out only by comparing their positions with predicted ones of known satellites, which is being done using the NORAD database [13].

An example of such an event is shown in Figure 7.

As of now, we did not detect any rapid flash not coincident with such a high-altitude satellite and not having the light curve identical to ones produced by such satellites.

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[2] The database is published at http://mmt.favor2.info/satellites and http://astroguard.ru/satellites

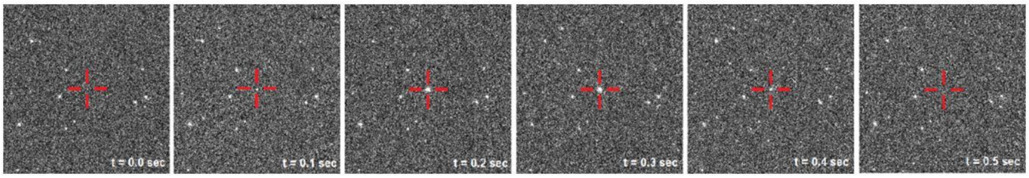

Fig7. *Rapid optical flash detected by MMT, with duration less than 0.5 s and peak brightness reaching ~ 6.5*^{m}*. The flash coincides with the high-altitude passage of MOLNIYA satellite.*

4. Conclusions

The Mini–MegaTORTORA (MMT-9) instrument is already operational and shows the performance close to the expected one. We hope it will be useful for studying various phenomena in the sky, both astrophysical and artificial in origin. We expect it to be used for studying faint meteoric streams crossing the Earth orbit, for detecting new comets and asteroids, for finding flashes of flaring stars and novae, studying variable stars of various classes, detecting transits of exoplanets, searching for bright supernovae and optical counterparts of gamma-ray bursts.

The novelty of the MMT is its ability to re-configure itself from a wide-field to narrower-field instrument, which may open new ways of studying the sky, as it may, in principle, autonomously perform thorough study of objects it discovers – to simultaneously acquire three-color photometry and polarimetry of them.

Acknowledgements

This work was supported by the grants of RFBR (No. 09-02-12053, 12-02-00743-A), by the grant of European Union (FP7 grant agreement number 283783, GLORIA project). Mini–MegaTORTORA belongs to Kazan Federal University and the work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University. Observations on Mini–MegaTORTORA are supported by the Russian Science Foundation grant No. 14-50-00043.

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