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# MINI-MEGA-TORTORA WIDE-FIELD MONITORING SYSTEM WITH SUB-SECOND TEMPORAL RESOLUTION: FIRST YEAR OF OPERATION

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RESUMEN

Presentamos el resumen de los primera fase de operación del novedoso aistema óptico de 9 canales con resolución temporal inferior a 1 segundo, Mini-Mega-TORTORA (MMT-9), en operación en el Observatorio Astrofísico Especial en el cáucaso ruso. El sistema permite observar el cielo de manera simultánea, bien en modo de campo amplio (∼900 grados cuadrados), o en modo de campo estrecho (∼100 grados cuadrados); esto para imágenes sin filtro, con filtros (Johnson-Cousins B, V or R) o polarimétricas, y con tiempos de exposición en el rango de 0,1 a varios cientos de segundos. Los dataductos para el análisis de los datos posibilitan la detección automática de fenómenos esporádicos tanto cercanos a la Tierra como extragalácticos. Los objetos detectados de manera rutinaria por MMT incluyen meteoros débiles y satélites artificiales. El dataducto para el análisis de variabilidad a gran escala está todavía en fase de desarrollo.

ABSTRACT

Here we present the summary of first years of operation and the first results of a novel 9-channel wide-field optical monitoring system with sub-second temporal resolution, Mini-Mega-TORTORA (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.

*Key Words:* gamma-ray burst: general — instrumentation: miscellaneous — meteorites, meteors, meteoroids — telescopes

## 1. INTRODUCTION

Mini-Mega-TORTORA is a novel robotic instrument just commissioned for the Kazan Federal University and developed according to the principles of Mega-TORTORA multi-channel and transforming design formulated by us earlier (Beskin et al. 2010a, 2013, 2014; Biryukov et al. 2015). It is a successor to the FAVOR (Zolotukhin et al. 2004; Karpov et al. 2005, 2010) and TORTORA (Molinari et al. 2006) 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 the discovery and detailed study of the brightest ever optical afterglow of a gamma-ray burst, GRB080319B (Beskin et al. 2010c,b).

The Mini-Mega-TORTORA (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) adjustment of the objective direction in a limited range (approximately 10 degrees to any direction). This allows for either mosaicking the larger field of view, or for pointing all the channels in one direction. In the latter regime, a set of color (Johnson's B, V or R) and polarimetric filters (three different directions) 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).

The channels are equipped with an Andor Neo sCMOS detectors having 2560×2160 pixels 6.4$\mu$m each. The field of view of a channel is roughly 9×11 degrees with 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 0.1 s exposures

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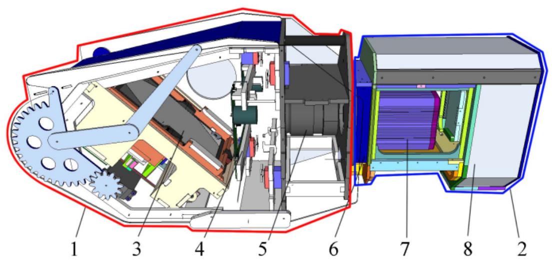


Fig. 1. Schematic view of a MMT channel. 1 – coelostat unit, 2 – camera unit, 3 – coelostat mirror which can rotate for ∼ 10 degrees around two axes, 4 – installable color and polarimetric filters, 5 – Canon EF85/1.2 objective, 6 – optical corrector, 7 – Andor Neo sCMOS detector, 8 – conditioner to keep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

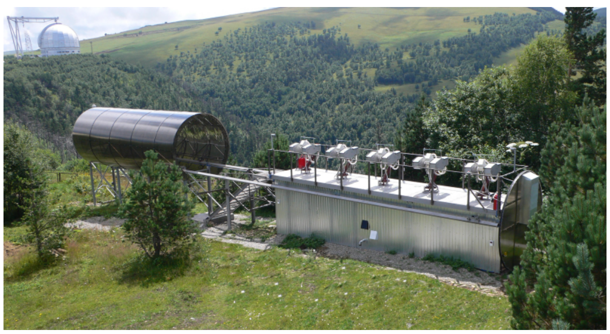

Fig. 2. Photo of the all 9 channels of MMT installed on 5 mounts in the single cylindrical dome, which is open at that moment. The russian 6-m telescope may be seen in the background.

providing us with 10 frames per second, as for higher frame rates we are unable to process the data in real time.

Every channel is operated by a dedicated PC which controls its hardware, acquires the 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 observations. The complex as a whole is being controlled by a separate PC.

Initial tests show that the FWHM of the 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. MMT OPERATION

Mini-Mega-TORTORA started its operation in June 2014, and routinely monitors the sky since then. The observations are governed by the dedicated dynamic scheduler optimized for performing the sky survey. The scheduler works by selecting the next pointing for Mini-Mega-TORTORA 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 more or less uniform survey of the whole sky hemisphere is being performed while maximizing the probability of observations of gamma-ray bursts. As an un-optimized extension, the scheduler also supports the observations of pre-selected targets given by their coordinates, which may be performed in various regimes supported by Mini-Mega-TORTORA (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-Mega-TORTORA 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-Mega-TORTORA field of view in 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-Mega-TORTORA 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 the 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 (Beskin et al. 2004; Karpov et al. 2010), and is based on building an iteratively-updated comparison image of current field of view using numerically efficient running median algorithm, as well as threshold image using running similarly constructed *median absolute deviation* estimate, and then comparison of every new

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frame with them, extracting candidate transient objects and analyzing lists of these objects from the consecutive frames. It then 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 by Lang et al. (2010). Also the rough photometric calibration is being done. These calibrations, updated every 10 seconds, are used for measuring the 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 the variability on time scales longer than 10 s.

The Mini-Mega-TORTORA typically observes every sky field continuousy for 10000 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 the 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 a first step of analysis of these survey data, we implemented the transient detection pipeline based on comparison of positions of objects detected on 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 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 the 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-Mega-TORTORA survey images and hope to finish in 2016.

Below we will 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 Mini-Mega-TORTORA data stream. Meteor detection is performed on 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 single event. Dedicated analysis subroutine extracts the meteor trail using Hough transformation, detects its extent on every frame, and estimates the brightness along the trail, light curve, trajectory, angular velocity and duration. The majority of events are observed in white light (the brightness is then 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 to the database and are available online[5].

We are not able to perform any parallactic observations of meteors now (though we are working on installing a second version of Mini-Mega-TORTORA which will allow us to measure meteor parallaxes). However, huge amount of meteors measured every night might in principle allow to detect 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.

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).

### 3.2. *Satellites*

Detection of rapidly moving objects is implemented by comparing the lists of objects detected on consecutive differential frames and extracting the ones that moves 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 on the frame. After initial detection, the object is tracked until it fades below the detection limit or leaves the field of view, afterwards its trajectory and light curve is stored for a more detailed analysis.

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

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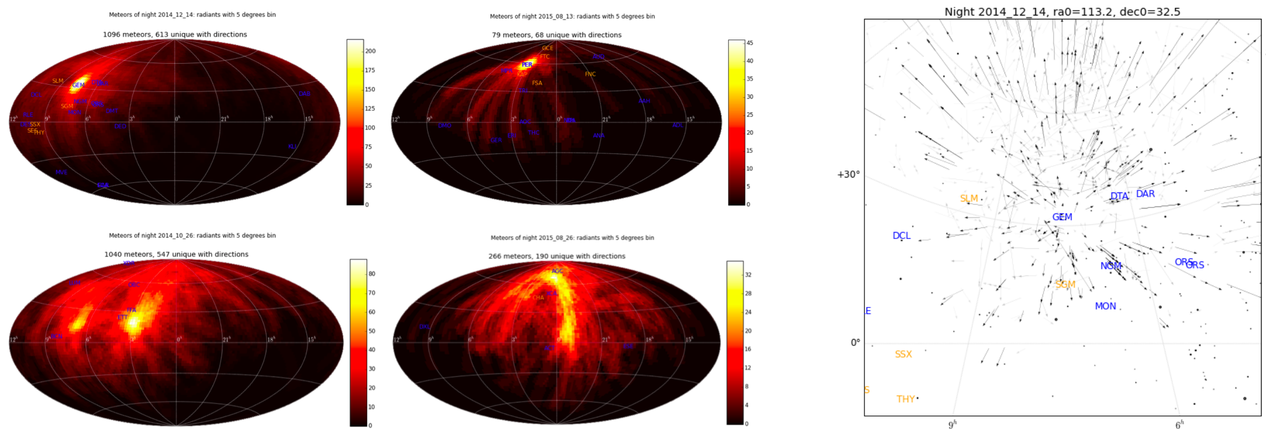


Fig. 3. Density of intersections of meteor trails from the night corresponding to the peak of 2014 Geminids (left) and meteor trails corresponding to the Geminids shower in gnomonic projection (right).

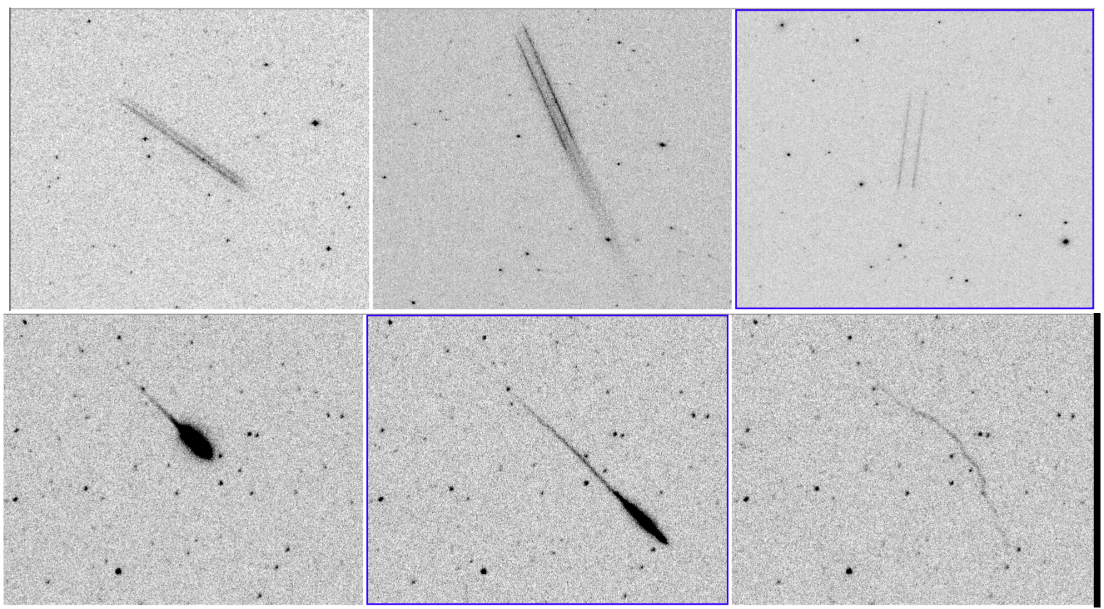

Fig. 4. Example of multi-particle meteor trails (top) and the complex temporal evolution of a bolide trail in the atmosphere (bottom).

The accuracy of coordinate determinations 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 (US Department of Defence 2015; McCants 2015). We are routinely performing such identification and as a result acquire the large amount of high resolution photometric information for these objects, which we publish online as a fully searchable online database of satellite light curves[6].

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

The database includes the following parameters for every satellite track observed: light curves in apparent and standard (calibrated to 1000 km distance and 90° phase angle) magnitudes, 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%.

The periodicity of the satellite light curve may

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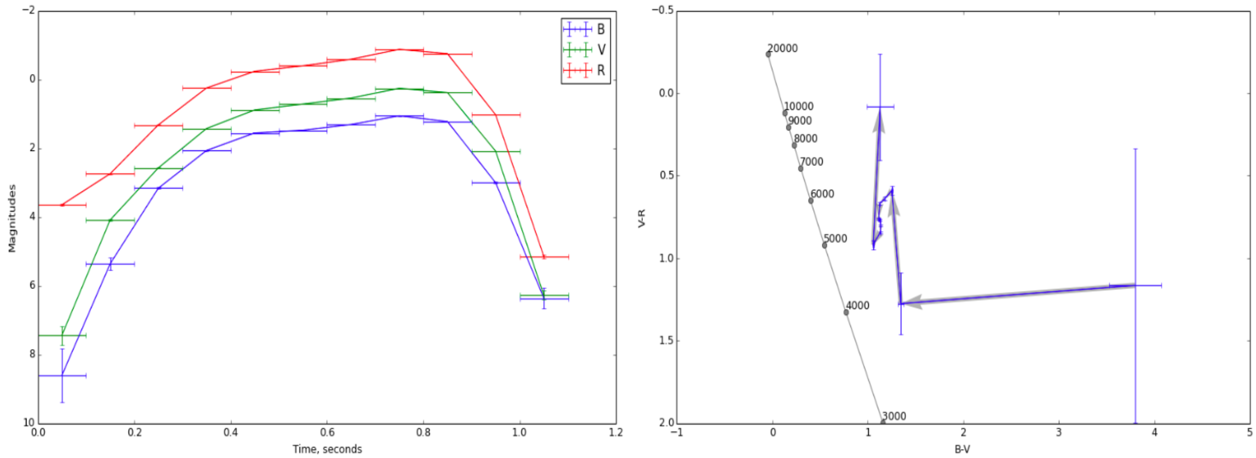


Fig. 5. Example of a multi-color light curve of a meteor detected by Mini-Mega-TORTORA (left) and the corresponding evolution on a two-color diagram (right).

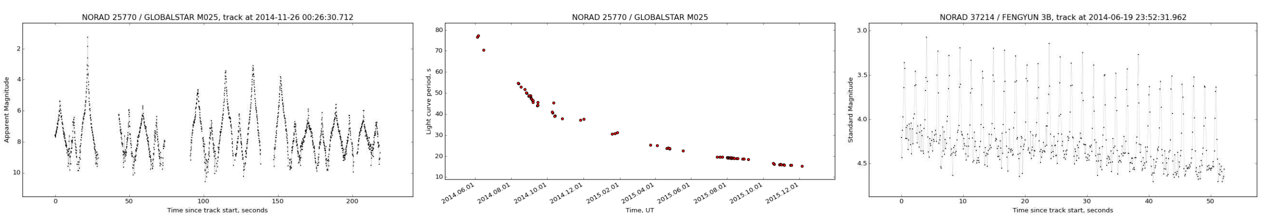


Fig. 6. Light curve of an freely rotating inactive satellite detected by Mini-Mega-TORTORA (left), its period evolution over time due to interaction with atmosphere and residual technological processes (center) and the rapid variablity of an active satellite due to stabilized antenna rotation with 1.8 s period (right).

be caused by either 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 some rotating element like an antenna (see Figure 6). The rotation period of inactive objects often changes over time some residual technological processes inside the object itself.

### 3.3. *Fast optical flashes*

The original aim of Mini-Mega-TORTORA differential imaging pipeline is the detection of rapid optical flashes of astrophysical origin, which is being performed by detecting the stellar-like objects visible on 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 by 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 NORAD database (US Department of Defence 2015).

An example of such event is shown in Figure 7.

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

## 4. CONCLUSIONS

The Mini-Mega-TORTORA (MMT-9) instrument is already operational and shows a performance close to expected. We hope it will be useful for studying various phenomena on 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 reconfigure itself from a wide-field to narrower-field in-

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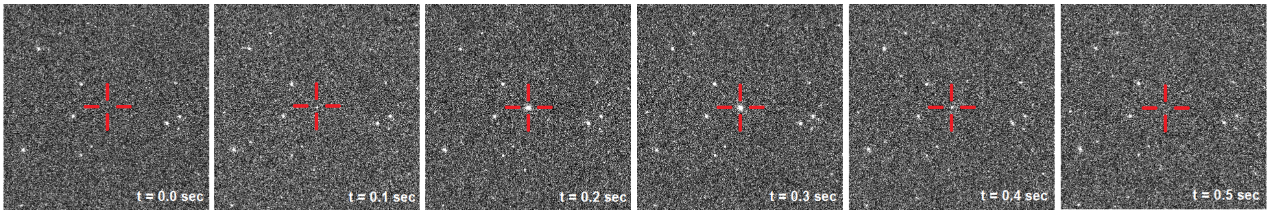


Fig. 7. Rapid optical flash detected by MMT, with duration less than 0.5 s and peak brightness reaching $\sim 6.5^m$. The flash coincides with the high-altitude passage of MOLNIYA satellite.

strument, which may open new ways of studying the sky, as it may, in principle, autonomously perform thorough study of objects it discover – to simultaneously acquire three-color photometry and polarimetry of them.

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