Search and study of optical transients with Mini-MegaTORTORA

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Abstract We present the four-year observation results of the Mini-MegaTORTORA (MMT-9) nine-channel wide-field optical sky monitoring system with subsecond temporal resolution. This instrument scans the sky on every clear night with a FoV as large as 900 deg^2. It is used for real-time detection and classification of optical transients, three-filter photometry close to Johnson's BVR system, and polarimetry of detected objects. The limiting magnitude of the system is V = 11m for 0.1 s (one frame duration) temporal resolution, and reaches V = 13-14 m for an exposure of several minutes. The system is equipped with a powerful computing facility and a dedicated software pipeline to perform automatic detection, real-time classification, and investigation of transient events of different natures moving in the near-Earth space located in the Galaxy and at cosmological distances. Properties of meteors and satellite samples, variable stars, and GRBs detected using MMT-9 are discussed.

Keywords: Gamma-Ray Bursts, Meteors, Satellites, Astronomical Databases, High Temporal Resolution

1. Introduction

In order to address the problems of detection and study of near-Earth (space debris, artificial satellites, meteors, minor bodies of the solar system) and deep space (flaring variable stars, novae and supernovae, gamma-ray bursts, etc.) transient events, a new field in astronomy has emerged – "Time Domain astronomy" (Table 1). The IAU website provides data on 62 instruments under "Time domain astronomy" [1]. They have various technical characteristics and are intended for investigating sources spanning a wide range of magnitudes, radiation duration, and angular velocities.

To detect optical emission from transient sources occurring at arbitrary moments in time and coming from random directions (gamma-ray bursts), the use of instruments with wide fields of view and subsecond temporal resolution was suggested in [2], [3].

Table1. *Transient events zoo*

Time scale	Near-Earth, the Solar system	Inside our Galaxy	Nearby galaxies	Cosmological Distances
< 0.1 s	meteors, LEO satellites and debris	novae, flaring stars, star occultations	nearby supernovae	GRBs, FRBs, gravitational wave events
1 s	HEO and GEO satellites and debris			
10 s				
100 s	asteroids, comets		intra-day variable AGNs	
> 1000 s		variable stars, MACHOs		supernovae

This approach was implemented with development of the FAVOR (2003-2009 in Nizhniy Arkhyz) and TORTORA (starting from 2006 in Chile, La Silla observatory, European Southern Observatory) facilities [3], [4], [5]. These are small-lens (120-150 mm) telescopes with an optical efficiency of 1/1.2. A combined system was used as the detector consisting of an electron-optical converter and a fast low-noise Sony IXL285 array. Such a combination gave a 340-760 square-degree field of view and a limiting magnitude of up to 10.5 in the B-band for a frame rate of 7.5 Hz (128 ms exposure).

With the TORTORA camera, the optical flare accompanying the Naked-Eye Burst of GRB 080319b was detected in 2008. A visual light curve was obtained with a resolution of less than one second, which allowed us to study the temporal structure of this event and match the optical flare with the structure of gamma-ray emission [6].

A large number of near-Earth objects were detected with the FAVOR camera: artificial Earth satellites and debris, including low-orbit space objects with angular velocities up to 1 degree/second. Many meteor events were also detected, including those with magnitudes of up to 8-9, previously undetectable in optical observations using other methods [7].

A natural modernization of this approach led to development of multichannel (multi-lens) systems with wide fields of view and subsecond temporal resolution. Such instruments allow one to monitor and study in detail the discovered transient event. In the latter case, individual channels register simultaneously in various color- and polarization filters the image of the region containing the new source. Thus, spectral and polarization studies are now possible for rapid events and processes.

The principles outlined above were implemented in the Mini-MegaTORTORA system.

2. Mini-MegaTORTORA (MMT-9)

Mini-MegaTORTORA is an automated multi-channel monitoring telescope. The system consists of 9 channels-objectives, installed on 5 mounts located under a common sliding cylindrical cover (Fig.1).

A movable coelostat mirror is mounted in an individual channel of MMT-9 in front of the objective allowing one to quickly change its field of view. It is also equipped with a set of BVR-filters and a polaroid, which can be introduced into the optical beam during observations should the need arise [8], [9].

Fig1. *Mini-MegaTORTORA*

Andor Neo sCMOS cameras are used as the detector. They have low readout noise (1-2,5 electrons per detector element) and a high quantum efficiency (up to 60% at 600 nm).

The field of view of a single channel amounts to ~100 square degrees; the total field of view is determined by the task at hand and depends on the selected sky area configuration (see observing modes below) and reaches 900 square degrees in the wide-field monitoring mode.

The entire system is controlled by the central server. The software installed on the server is responsible for planning and conducting observations. The server gathers data on the weather conditions obtained using the meteostation (Boltwood Cloud Sensor II + allsky camera + Sky Quality Meter), and signals the start of observations in the event of clear, favorable weather: the automated cover opens, the channels are calibrated, and observations begin. At the end of the night, or if the weather conditions become unfavorable, the server orders the stop of operations.

Each channel has an individual computer dedicated to equipment control and data collection functions. Data obtained in the process of observations is transferred to the channel computer in the form of a flow of frames and is reduced in real time. This allows one to detect transient events independently during the night.

Observations are conducted in several modes: wide-field monitoring, deep survey, research mode, work with internal and external alerts. The main mode is the wide-field monitoring. The system targets the selected region in the sky, positions the channels in a 3×3 configuration (one area equals 900 square degrees), and obtains a frame flow with 0.1 second exposures (10 Hz frame rate); the limiting magnitude in this mode reaches 11 st.mag. The areas targeted for monitoring are computed using the observation planning software in a way that would allow the maximum area of the celestial sphere to be covered in a single night, with the positions of the Sun and Moon also taken into account. If the fields of view of the FERMI and Swift gamma-ray space telescopes come into the MMT-9 visibility range, the region where these two fields of view overlap is selected for wide-field monitoring. Each sky area is monitored for 1000 seconds, then the next area is selected.

For independent transient detection in real time, this mode uses specialized software, allowing one to detect light variations in the frame flow and determine the type of the possible source. If the registered object is stationary and newly emerged, it is classified as a flare. Moving new sources are defined as satellites and meteors depending on the angular velocities and durations [5]. Discovered transients are saved in the corresponding databases. When registering events are classified as flares, the system goes into internal follow-up observing mode. All channels position their fields of view based on the coordinates of the detected burst (10×10 degree total field of view). Each channel is set with its own filter configuration and exposure time. As a result, the transient event is observed simultaneously in three color bands as it passes through three polaroids with different orientations, which allows one to determine its spectral and polarization (3 Stokes parameters) properties.

When the MMT-9 system receives telegrams from the FERMI and SWIFT telescopes in the event of gamma-ray burst registration, and, if the coordinates of the discovered alert are in the visibility zone, the system goes into external follow-up mode. The total field of view dimensions, exposure times for each channel, and the filter sets are determined depending on information in the received telegram. After carrying out alert-based observations, the system returns to the basic mode.

Before the start of wide-field monitoring of each area with a high temporal resolution and immediately after such, a deep survey of that sky region is carried out. Frames are obtained with 60 second exposure and 900 square degree field of view, the limiting apparent magnitude reaches 14-15 mag. Images obtained in this mode are stored in the database since August 2014. Based on this array of frames, one can conduct studies of transient objects with long times of light variations (variable stars, minor bodies of the Solar System).

A possibility is provided to observe selected sources or events in different modes, the data on which are entered into the planning software. The software incorporates this task into the observation list and executes it when the source is in the visibility zone.

3. Four-year work results

MMT-9 carries out regular monitoring of the celestial sphere continuously since June 2014.

3.1. Rapid Flashes and Gamma-ray bursts

Observations of regions where Swift and Fermi gamma-ray space telescopes registered transients are conducted since 2015; this mode was implemented 71 times: 15 follow-ups to Swift and 56 to Fermi. The diagram in Fig.2 shows the time distribution of realignment based on telegrams.

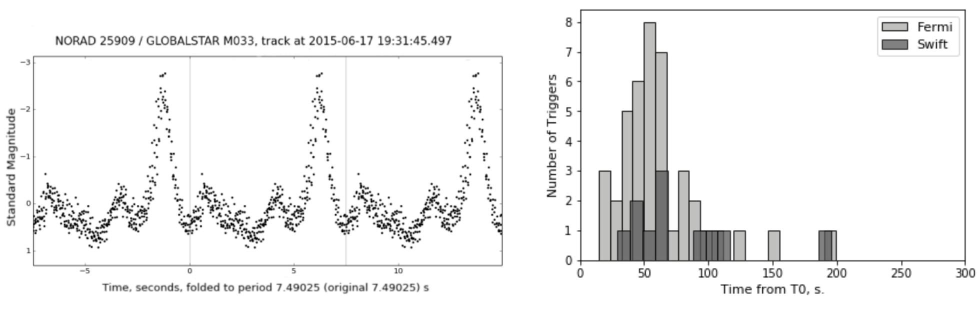

Fig2. *Right: time between observations in the follow-up mode after Fermi and Swift telegrams received and T0. Left: photometry of satellites with MMT-9 example*

Time of switching to observations of areas noted in the telegrams varies in the range from 14 seconds to several minutes from the moment of transient detection from space (T0). Long delays in the start of optical observations (exceeding 5 minutes) are usually related to either a delay in the emergence of this sky region above the horizon, or waiting for better weather conditions.

In particular, in 2016, 2 minutes after the Fermi telescope detected the GRB160625B gamma-ray burst, the follow-up mode allowed us to detect an optical flare accompanying the hard emission from this source [10].

3.2. Artificial Satellites and debris

MMT-9 allows us to register several hundred near-Earth space objects every clear night (artificial satellites, space debris). The program for detecting all sources classified as satellites determines the coordinates and derives magnitude estimates for each frame. The sequence of the object's positions in all frames where it was detected will henceforth be referred to as one follow-through.

Based on the data of the obtained follow-throughs, the sources are identified with satellites and space debris listed in available orbital data catalogs, and are stored in the photometry database of MMT-9 [11], [12].

As of January 1, 2019, the artificial satellite database of MMT-9 contains photometric data on 6048 space objects on near-Earth orbits, measured in 201157 follow-throughs.

For each object we compute the average reduced (to a distance of 1000 kilometers and a 90° phase angle) magnitude based on all obtained measurements. When working in the BVR-filter mode, the reduced magnitude in the specified filter (figure) is computed. An example is shown in Fig.2.

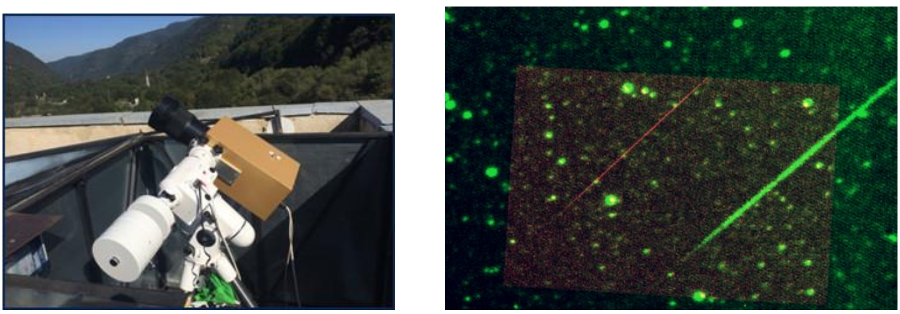

Fig3. *Right: the FAVOR camera was mounted with a base of 3.5 km from MMT-9; Left: image with combined frames of one meteor, parallax is seen*

Information stored in the artificial satellite database is used to analyze light variations of the space objects. For objects with obvious light periodicity, we determine the period of magnitude variations (in seconds).

In addition to the measured and reduced magnitudes of the objects, data on distance and phase angle during the observations are stored in the database.

3.3. Meteors

Several hundred meteor events are registered with Mini-MegaTORTORA during every observing night.

The detection program classifies objects as meteors in real time and analyzes them. For each meteor event we determine the coordinates, visual magnitude, angular velocities, durations, etc. This information is stored in the Database [13].

As of the end of December 2018, the meteor database contains over 220 thousand events detected with MMT-9 since 2014 and 10117 events detected with FAVOR in 2006-2009 [14].

To improve the capabilities of MMT-9 in studying meteor events, base observations (in the test mode) are being conducted since the end of 2018 with FAVOR, which was modernized and equipped with a time service. As a pair, they form a base of 3.5 km (Fig.3). Primary meteor observations allow one to estimate heights and velocities of the meteor particles burned up in the atmosphere, which, in turn, allows one to switch to the heliocentric coordinate system and study the orbital parameters of both individual meteoroids and meteor showers. Base test observations in the fall of 2018 have shown that the accuracy of height determination amounts to about 1.5-3%. Over one hundred primary meteors have been detected. We show examples of computing the absolute magnitude variations of several observed meteors with loss of height and motion along the trajectory (Fig. 4).

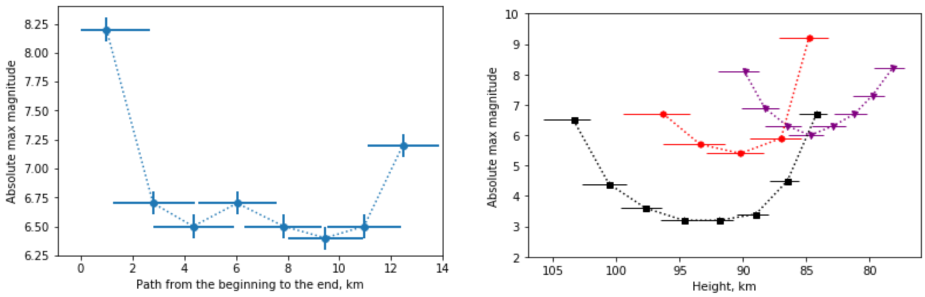

Fig4. *Dependence of absolute magnitude on height and path*

The number of meteor events observed during a night allows one to study their apparent sky distribution. Meteor tracks, extrapolated backwards by 50 degrees, are plotted on the map of the sky, and the more of these tracks cross in one area, the higher their density there [13]. The so-called "statistical" radiants are detected in zones with the highest density. The same map is used to plot radiants of meteor showers listed in [15]. Based on many confirmed showers, there is a correspondence with the areas of maximum density of meteor tracks and radiants, which is especially noticeable for major meteor showers (PER, GEM, LYR, SOA, DRA, NOA, ORI, LEO, etc.). These statistical radiants may be used to determine meteor shower candidates, which must then be studied in base observations.

Observing meteors with BVR-filters enabled us to estimate the color change of the meteors along the track [13]. Evidently, a meteor track does not exhibit black body radiation, but a combination of the continuum and various emission lines. The conducting of future joint multicolor observations with MMT-9 and FAVOR will allow us to investigate the possible connection between belonging to meteor showers, meteor velocities, and their color indices.

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