(3) For effective research, a federal level program is needed. The conceptual design of such a program is presented in Ref. [8].

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Wide-field subsecond temporal resolution optical monitoring systems for the detection and study of cosmic hazards

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1. Introduction

In the present paper, we discuss the possibility of using multi-objective optical telescopes equipped with detectors with high time resolution to discover and study rapidly moving cosmic objects of both natural and artificial origins. Two types of instruments (with six and nine channels) are considered here, which include the standard high-aperture objectives with small diameters (70 mm), panoramic detectors with high time resolution, and equatorial mounts. The instruments function in two regimes: the monitoring mode (with fields of view of 600 and 900 square degrees), and the follow-up mode (with a field of view of 100 square degrees) in which all objectives observe one field with a rapidly moving celestial object detected by monitoring. The re-pointing of objectives in a few fractions of a second is achieved by turning the flat mirrors mounted in front of the objectives, and color and polarization measurements are carried out using a set of filters and polaroids. We describe the features of the construction of prototypes of the devices, their characteristics, and the parameters of detectable dangerous objects. Also discussed are prospects for the development of such systems, in particular, the possibility of constructing one complex including several hundred 40-cm telescopes with a 1-square-degree field of view.

The search for and study of optical objects and phenomena rapidly variable (transient) in time and space relate to a fairly new field of modern astronomy. This problem was first clearly formulated by H Bondi in 1970 [1], who noted the need to discover and follow up nonstationary objects with unknown *a priori* localization. In such observations, very wide-field instruments (with a field of view of several hundred square degrees) equipped with panoramic detectors with at least sub-second time resolution must be utilized. The latter requirement is due to the short durations (down to 0.01 s) of transients (UV Ceti star type flares, gamma-ray bursts (GRBs), rising fronts of supernova and nova explosions, etc.) and/or the high velocities (up to several dozen degrees per second) of their proper motion (satellites, space debris, meteors, and bolides) [2].

Table 1 lists optical transients classified by their localization and duration. As examples, we note two — 'opposite' in some sense — classes of optical transients: natural and artificial objects which can be dangerous to the human race, and flashes associated with cosmic gamma-ray bursts.

Clearly, a deep detection limit (large-diameter objective) in combination with a wide field of view (short focus) and high time resolution (small size of the detector) are intrinsically contradicting; therefore, it is necessary to seek a reasonable compromise when choosing these parameters. This compromise seems to be found in the project for a wide-field camera which has a relatively small objective, an image intensifier for effective focus shortening, and a fast, low-noise CCD (charge coupling device) detector [2]. The prototype of such an instrument, FAVOR (FAst Variability Optical Registration), commissioned in 2003, is installed near

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Table 1. Classes of optical transients* according to their duration and localization.

Time	Near-Earth space	Galaxy	Extragalactic and cosmological distances
< 0.1 s	Meteors, satellites, space debris, upper-atmospheric events	Novae, flaring stars, stellar transits	Gamma-ray bursts, nearby supernovae
1 s	High-orbit satellites		
10 s			
100 s	**Asteroids**		**Active galactic nuclei, supernovae**
> 1000 s		**Variable stars, MACHO objects**	

* The boldface marks classes of objects which are constantly studied by wide-field instruments, such as ASAS (All-Sky Automated Survey), LINEAR (LIncoln Near-Earth Asteroid Research), and MACHO (MAssive Compact Halo Objects).

the 6-m BTA (Big Telescope Azimuthal) at the Special Astrophysical Observatory, RAS [3, 4]. A similar camera TORTORA (Telescopio Ottimizzato per la Ricerca dei Transienti Ottici RApidi) [5] was attached in 2006 to the robotic REM (Rapid Eye Mount) telescope at La Scilla (European Southern Observatory, Chile). With objective diameters of 12–15 cm (focal ratio of 1:1.2) and a field of view ranging 400–800 square degrees, the detection limits of these instruments are close to 10–11 stellar magnitudes in the B-band at an exposure time of 0.13 s (CCD frame-frequency of 7.5 GHz).

Just these characteristics of the TORTORA camera allowed us to discover and study in detail the brightest known optical afterglow of GRB 080319B. In this experiment, the optical variability on time scales of one second was discovered for the first time and was compared to parameters of optical emission from other GRBs [7–9].

Using the FAVOR and TORTORA cameras, we have registered rapidly moving satellites and meteors of 9–10 stellar magnitudes in brightness [10]. In a certain sense, their detection also models the registration of moving meteoroids suddenly entering Earth's atmosphere, like the Chelyabinsk meteorite. Such cosmic bodies appear to be the most dangerous cosmic objects, since it is virtually impossible to detect them early and to predict their trajectory, although the potential damage due to their impact can be only local.

Indeed, the asteroid and comet danger is related, first of all, to impacts with Earth of large cosmic bodies having a size in excess of several hundred meters. In particular, the Spaceguard Survey program, carried out in the USA since the beginning of the 1990s, has allowed the catalogization of more than 8000 objects of size exceeding one km approaching Earth. Among them, more than 1000 potentially dangerous bodies (asteroids, as a rule) and about 70 comets have been identified [11]. At the same time, the sample of even such large objects is far from complete — several dozen of them have not been discovered. The situation is much worse with 100-m and 50-m bodies — we are totally unaware of more than 90% (10,000) and 99% (100,000) of them, respectively [11]. It is virtually impossible to forecast the appearance near Earth of fragments of disintegrated long-period comets which have high velocities. Although the number of these is small, the consequences of their sudden appearance could be catastrophic.

Finally, we stress that about half of the unknown objects, whose motion is not continuously tracked, cannot be observed at all in the nighttime. They can be partially registered only by space instruments. However, there are no optical telescopes in the world optimized for the systematic discovery of relatively small-sized dangerous objects (50–100 m in diameter) (see, for example, review [11]). Apparently, several such instruments will be in operation after 2015. These include, first of all, four telescopes 1.8 m in diameter of the PanSTARRS (Panoramic Survey Telescope And Rapid Response System) project and the 8-m LSST (Large Synoptic Sky Survey Telescope) [12, 13]. These instruments, which have a field of view of about 9 square degrees, in an exposure time of 30 and 15 s will have detection limits of about 24–25 stellar magnitudes and will be capable of surveying the sky hemisphere in several nights. However, it is clear that these beautiful instruments cannot detect objects suddenly emerging in an arbitrary point of the sky and that are rapidly moving.

To solve this problem, instruments with a field of view of several hundred (or even better a few thousand!) square degrees (ideally, the entire sky hemisphere should be observed simultaneously) and high time resolution are required. Moreover, such instruments must obtain maximum information about the detected object virtually in real time, being capable of measuring its velocity, color, polarization, and determining variability parameters. All this is necessary to predict the body's evolution — not only its mechanical motion, but also its physical properties (mass, density, composition, stability degree, etc.).

It appears that the multichannel high time-resolution MiniMegaTORTORA systems (the natural continuation of the FAVOR and TORTORA projects) developed by us will be capable of detecting and studying rapidly moving, suddenly emerging dangerous meteoroids.

2. Multichannel wide-field MiniMegaTORTORA monitoring system

The positive experience acquired from the exploitation of the FAVOR and TORTORA systems led to awareness of the need to further develop the wide-field technique to search for fast optical transients. It was necessary to improve the detection limit by at least 2–3 stellar magnitudes, while keeping the existing and even increasing the size of the instrument's field of view. This can be done by using multiobjective (or multitelescope) configurations and decreasing the field of view of individual elements, thus increasing their angular resolution [14]. To significantly suppress read-out noises of CCD matrices, it is necessary either to increase their quantum efficiency and the amplification coefficient of the image intensifier (II), or to use low-noise detectors [matrices with internal amplification or sCMOS (scientific Complementary Metal-Oxide Semicon-

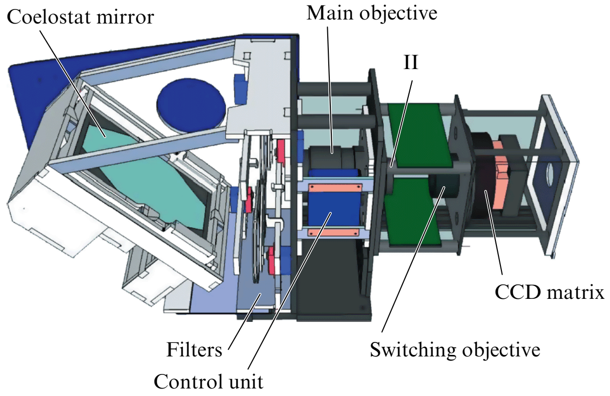

Figure 1. Individual registration channel. The basic registration block consists of several (six or nine) such channels.

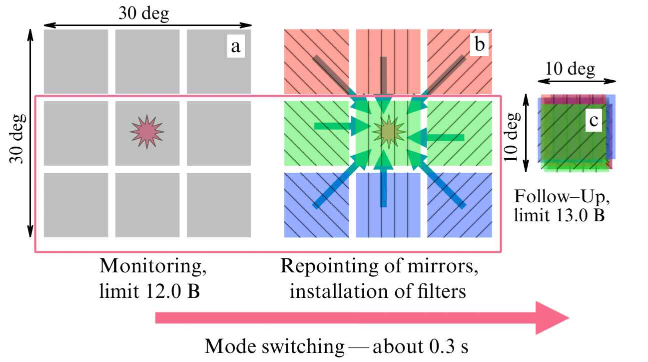

Figure 2. Different regimes of the basic block operation. (a) Wide-field monitoring mode in white color or with one of the color filters. (b) Instaling color and polarization filters into the light beam as the first step after the optical transient discovery. (c) Re-pointing of all objectives to transient's error box to observe it in three different photometric bands at three orientations of polarization planes (shown by different hatchings) simultaneously. The precise time needed for mode switching depends on the instrument configuration, but is expected not to exceed 0.3 s. (B — 'blue' stellar magnitude.)

ductor)-based detectors]. Early follow-up measurements of colors and polarization of the detected transients as soon as possible after their registration underlie another important improvement.

In 2009–2011, we started elaborating the design of exactly such an instrument with the support of the Russian Foundation for Basic Research. The MiniMegaTORTORA (MMT) system includes a set (six or nine) of individual channels-objectives (Fig. 1) installed in pairs on equatorial mounts. In front of each objective, a flat mirror is installed, which changes the orientation in two directions by $\pm 20°$ and, thus, the frame of the field of view of each channel. In addition, each channel is equipped with a set of color and polarization filters which can be inserted into the light beam path during observations. This enables rapid switching from the unfiltered wide-field monitoring regime to narrow-field observations in which all objectives are pointed at one region (for example, the error box of a just detected transient) and observe it using all possible combinations of color and polarization filters (Fig. 2). It is also possible to simultaneously observe the transient by all objectives with one filter to increase the photometrical accuracy due to data summation.

Each objective is equipped with a fast detector (fast CCD matrix with attached image intensifier or sMOS). The technical parameters of the channel with a fast CCD matrix equipped with image intensifier are listed in Table 2. Dedicated software similar to that employed in the FAVOR and TORTORA cameras [3–5] control the whole instrument and analyzes the data obtained in real time.

At the present time, we are completing the manufacturing and testing of the 6-channel version (MMT-6) of the instrument with a combined detector, and of the 9-channel variant (MMT-9) equipped with a Neo sCMOS detector from Andor Technology; the latter scheme of the instrument is simplified, since it does not contain image intensifier and the transmission optics.

An individual channel field of view measures about 100 square degrees, and the integrated MMT-6 and MMT-9 systems operating in the wide-field monitoring regime have a field of view of 600 and 900 square degrees, respectively. The detection limit in the B-band for MMT-6 is 11.5 stellar magnitude in 0.13 s (14 and 16.5 mag in 13 s and 1300 s, respectively); the detection limit for MMT-9 is 12 mag in 0.1 s (14.5 and 17 mag in 10 s and 1000 s, respectively). In the narrow-field regime of follow-up observations of individual objects, the size of the field of view decreases to 100 sq. deg, and the detection limit, which depends on the combination of color and polarization filters, falls within the range of 10.5–13.5 mag in 0.13 s or 0.1 s and reaches 18 mag in 1000–1300 s.

The commissioning of the MMT-6 instrument is planned for the end of summer 2013; the instrument is likely to be mounted on the territory of a meteorological station near the settlement Mazagón (Spain), where about 300 clear night skies per year are observed. The MMT-9 system, which is being manufactured jointly with the Kazan (Volga region) Federal University and the Parallax company, will be commissioned at the Engelgardt Astronomical Observatory (Kazan) in 2014.

3. Potential of the MiniMegaTORTORA instruments to detect dangerous meteoroids

The nine-channel MiniMegaTORTORA system can observe the sky hemisphere one and a half times per average night lasting for 8–9 h, i.e., half of the sky can be surveyed two times with a time interval of 6 h. Moving transients localized in this

Table 2. Technical parameters of an individual channel of the MiniMegaTORTORA instrument.

Main objective		Image intensifier		CCD matrix	
Diameter D	71 mm	Photocathode	GaAs	Model	SONY 2/3″ IXL285 interline
Focal length F	85 mm	Diameter	17.5 mm	Size	1388 × 1036 pixels
D/F	1/1.2	Amplification	40,000	Scale	30″ – 40″ per pixel
Field of view	10 × 10 deg	Scaling	1/1	Exposure	0.128 – 10 s
		Quantum efficiency	30% at 4500 Å	Pixel size	6.45 μm

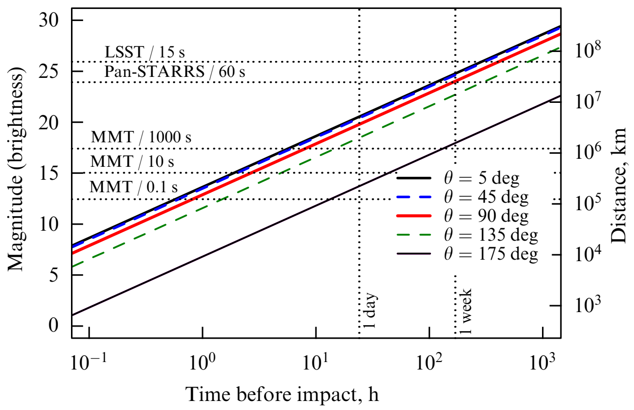

Figure 3. The relation between the brightness of a Chelyabinsk type meteorite (diameter 20 m, typical chondrite albedo 0.08) with a heliocentric velocity of 30 km s^{-1} (the parameter θ determines the angle of intersection of the meteorite trajectory with Earth's orbit) and the time before impact. The horizontal lines correspond to the detection limits of different monitoring systems (their exposure times are also given).

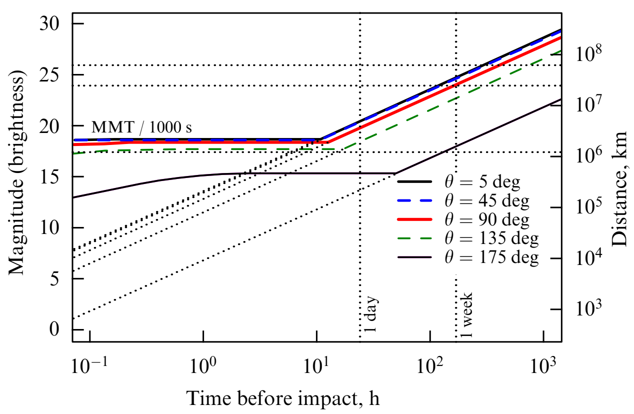

Figure 4. The same as in Fig. 3 but taking into account the image 'smearing' over the frame during the exposure time due to the object's proper motion in the picture plane. The sine of the angle between the object velocity and the direction toward the observer is set to the limiting value, which is equal to the ratio of the size of Earth to the distance to the meteoroid (at larger angles the object bypasses Earth). The horizontal part of the dependence does not correspond any more to a specific object's trajectory but restricts the region of its possible trajectories. The stellar magnitude on this interval corresponds to the light flux from the object per pixel (its surface brightness) and the detection limit of the instrument, which can reveal the object at a given distance. The break of the curve, determined by the exposure time, in all cases (the horizontal dashed lines in Fig. 3) but that shown in Fig. 4, is positioned significantly below the detection limit of the corresponding instruments.

area can also be detected by their proper motion. Nevertheless, the principal means of identification of newly appearing objects is the comparison of the position of any given visible object with the coordinates of all sources in all catalogs. The dedicated software allows us to perform this task in 0.2–0.4 s and to switch in this time interval to the follow-up mode to measure colors and polarization of the transient. As a result of the analysis of a totality of these data, the state of the surface of the object, its mass, density, rotation, degree of stability, etc. can be determined.

Using estimated parameters of the Chelyabinsk meteorite, we calculated its light curve before entrance into the atmosphere as a function of arrival time (Figs 3, 4). As a result, it turned out that a meteoroid encountering Earth may be detected at a distance up to 1 mln km in an exposure time of 1000 s or up to 100 thousand km in 0.1 s; the time interval from the detection of the object till its entrance into Earth's atmosphere can last from 0.5 h to a week, depending on whether its velocity is directed opposite to that of the Earth or is overtaking.

Thus, the MMT system can reliably detect dangerous cosmic objects 10 m in diameter and more. Obviously, on the time scale before the collision of order hours–days, it is currently impossible to change the object trajectory; however, it is possible to specify the region of the fall of the impinging object and to take necessary countermeasures to defend populations. Clearly, the larger the number of monitoring systems, the more probable the detection and the more precise the forecast. With several monitoring systems in operation, the weather and time constraints (such as the sunrise) are minimized, and the possibility of estimating the distance to the object by triangulation appears.

4. Multichannel optical telescope SAINT

The concept of multichannel monitoring systems with high time resolution can be naturally developed into a multi-element network consisting of small-aperture optical telescopes with rapidly changeable pointing, which can operate both independently and synchronously. To a certain degree, such a system is similar to radio telescopes such as VLA (Very Large Array), ALMA (Atacama Large Millimeter/submillimeter Array), SKA (Square Kilometer Array), not attempting, however, to operate in the interferometer regime.

We believe that the SAINT (Small Aperture Imaging Network Telescope) multichannel optical telescope can be very effective in discovering dangerous cosmic objects of any size already at large distances from Earth (in contrast to the MiniMegaTORTORA instrument) and can compete with Pan-STARRS and LSST. At the same time, SAINT, with its high time resolution and the possibility of operating in both the monitoring and follow-up (narrow-field) modes, can surpass these projects by the efficiency of discovering and studying suddenly appearing and rapidly moving objects. In addition, SAINT can search for and study any other rapidly varying phenomena in near and remote space, which have purely astrophysical importance.

SAINT comprises several hundred (about 500) small-aperture telescopes (40 cm in diameter), each with a 1-square-degree field of view, and a total field of view of 500 square degrees and a time resolution of 0.1 s. One possible variant of its parameters is presented in Table 3. Each channel is attached to the individual equatorial mount (Fig. 5) that has the maximum possible repointing speed (ideally 30–40 deg s^{-1}).

In the monitoring mode, the telescope accumulates information about all stationary and transient (both in time and in position space) emission sources localized at the celestial hemisphere (20,000 sq. deg) up to the 20 mag for one night of observations; each field with a size of about 500 sq. deg is observed for 15 min once per night.

When an optical transient is detected, all telescopes of the instrument are repointed in a few fractions of a second at its localization error box for further detailed study (polarimetric, photometric, and spectroscopic). In this (follow-up) mode, SAINT is equivalent to an 8-m telescope and can be used to solve a wide range of the standard astrophysical problems.

Table 3. Parameters of the SAINT telescope

Channel diameter	40 cm
Effective telescope diameter	867 cm
Optical efficiency	0.5
Angular pixel size in the sky	1.7 arcsec
Number of channels	470
Channel field of view	1.1 sq. deg
Total field of view	506.6 sq. deg
Limiting B-magnitude of one channel on time scales: 0.1 s 10 s 1000 s	 16.8 19.3 21.8
Limiting B-magnitude for all channels on time scales: 0.1 s 10 s 1000 s	20.1 22.6 25.1

Figure 5. One of the nine channels of the SAINT basic unit.

The prime objective of the monitoring process is to discover new objects and to study known nonstationary objects of various origins with different localizations. For the first time, a dynamical picture of ever-changing space, both near and remote, can be obtained with a subsecond time resolution.

The objects studied relate to the following classes (here, we clarify the data given in Table 1).

• Near space:

— artificial objects: satellites (about 10,000 passings per night), space garbage — construction debris of size 1–100 cm (about 2000 per night);

— meteors (about 100,000 per night).

• Solar System:

— asteroids ($\approx$ 50,000 new objects per year);

— comets ($\approx$ 1000 per year).

• Milky Way (about 500 mln stars available for observations):

— flaring stars (about 5000 new objects);

— novae ($\approx$ 100 per year);

— exoplanet transits (10–20 systems per year);

— variable stars (about 10 mln new objects);

— microlensing events (MACHO) (about 100 events per year).

• Cosmological distances:

— active galactic nuclei, quasars, blasars (about 3,000,000);

— supernova explosions (about 10,000 per year);

— optical afterglows of gamma-ray bursts (about 10 bursts per year).

The principal differences between the SAINT system and other optical instruments consist in the following:

• the ultimately high time resolution (0.1 s) combined with a wide total field of view (500 sq. deg) and sufficiently deep detection limit (16–17 mag in 0.1 s). Almost none of the enumerated variable objects has been studied on time scales shorter than 10 s. However, exactly this time range is critical to study the initial phases of explosions of nova and supernova stars and the fine structure of light curves of optical transients associated with gamma-ray bursts, not to mention meteors and cosmic garbage;

• the universality of the observational method and the initial data processing, which gives the possibility of using the same data arrays to detect and to study various types of objects and to solve disparate astrophysical problems always related to rapidly variable processes;

• the online processing and analysis of the results of real-time monitoring, as well as in a few fractions of a second after the discovery and identification of transients. This allows sending alerts to the astronomical community about new transients or dangerous meteoroids and to immediately start their detailed investigation;

• the possibility of switching in a few fractions of a second to the detailed follow-up mode of observation of the object, in which all small-aperture telescopes are pointed at one area (1 sq. deg), which increases the sensitivity of the system by 3 mag and allows the determination of spectral and polarimetric characteristics of the transient. To this end, each telescope will be supplied with a set of BVR (Blue Visible Red) filters and differently oriented polaroids or a multimode photospectropolarimeter [15].

The proposed surveying telescope has no equivalent among existing optical instruments.

The package of algorithms and programs for online and *a posteriori* data processing must allow the automatic detection of both stationary and moving transients, their identification with known sources from catalogs or classifying them as being new, the determination of their parameters, and taking decisions to possibly switch to the follow-up mode. The *a posteriori* analysis will enable us to sum up consecutively taken frames, thus increasing the detection limit in the follow-up mode up to 25 mag in 1000 s, to identify different kinds of objects, and to determine the parameters of their variability (Fig. 6).

The information system of the instrument also performs:

• maintenance of the database for each type of already known objects and the online comparison of the obtained characteristics with information from other catalogs and databases;

• maintenance of the database of newly discovered objects, the detailed study of their properties, the comparison with results of observations in other spectral bands, drawing conclusions about their nature;

• maintenance of a specialized database for transients related to space debris, the analysis of dynamics of this rapidly evolving ensemble of objects, the construction of its statistical models, and the choice of methods to determine the properties of this sample.

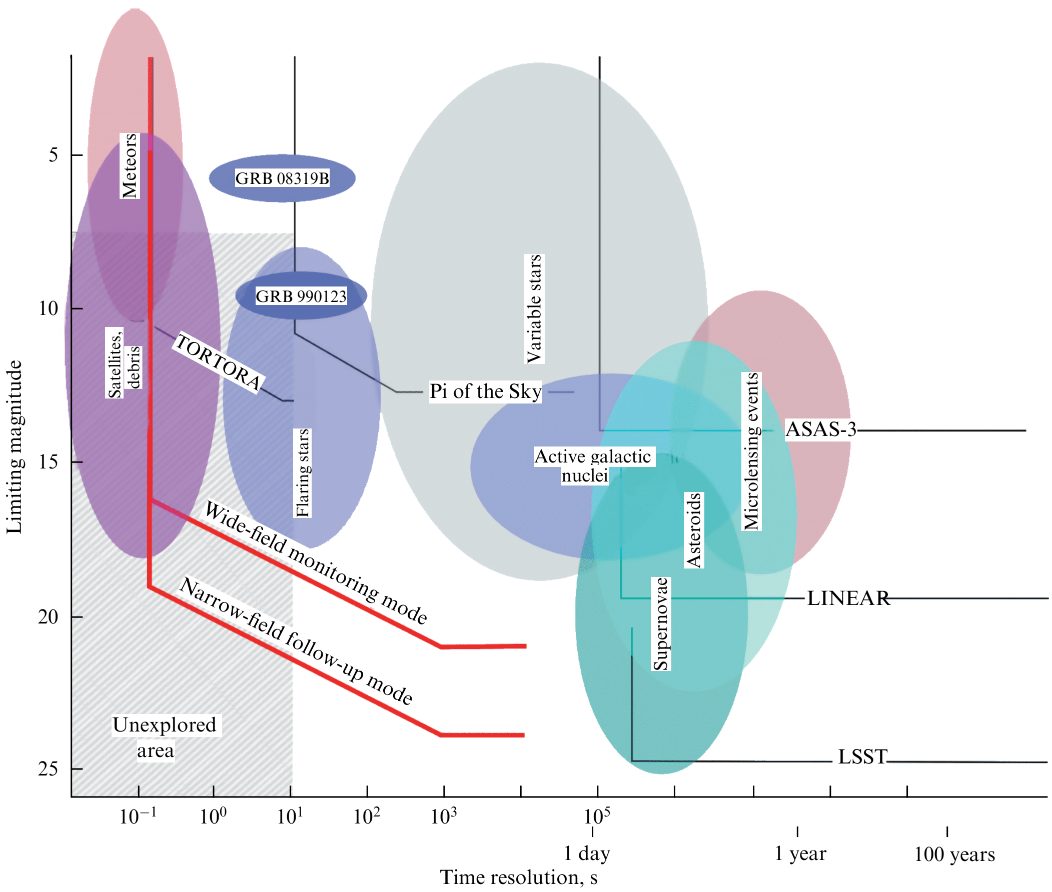

Figure 6. Efficiency of SAINT in observing different classes of objects and a comparison with the efficiency of other instruments, both in operation at the present time (ASAS-3, LINEAR, Pi of the Sky, FAVOR/TORTORA) and under construction (LSST).

Table 4. Comparison of the etendue $A\Omega$ of different survey telescopes (D_{eff} is the effective diameter, A is the effective collecting area, and Ω is the field of view).

Telescope	D_{eff}, m	Ω, sq. deg	$A\Omega$
LINEAR	1.0	2.0	1.5
SDSS *	2.5	3.9	6.0
CFHT **	3.6	1.0	8.0
SUBARU	8.1	0.2	8.8
Pan-STARRS	3.6	7.0	60
LSST	6.5	9.6	190
SAINT	0.4 – 8.7	1.1 – 506.6	81.1

* Sloan Digital Sky Survey.
** Canada–France–Hawaii Telescope.

From the informational point of view, SAINT is an autonomic robotic system capable of performing a wide range of preliminary formulated tasks in an optimal way by taking into account the changes in external conditions and the results obtained online.

Table 4 demonstrates that the efficiency of SAINT exceeds all survey instruments comparable in price. The wide-field LSST telescope to be commissioned at the end of 2021 is an exception; however, its cost is an order of magnitude higher.

The main result of the realization of the project will be the construction of a new type of instrument to discover and study rapidly variable (in time and in position) optical sources with *a priori* unknown location. Ultimately, a general sample of objects variable on time scales as short as a few fractions of a second will be constructed. In the distant Universe, hundreds of thousands of nonstationary objects of a known nature and thousands of unknown origin will be discovered and studied.

Essentially, this project proposes constructing a universal system of space monitoring, which can provide global space security.

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