The multi-aperture survey telescope for the INF project

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Abstract INF (INASAN Near Earth Objects Finder) project is a dedicated network of robotic telescopes to detect 10 m asteroids coming in the Near Earth Space. The main features of the project are short cadence time (1 h) of all-sky survey and moderate limiting magnitude (19^m) without filters, possibility of carrying out the additional scientific program. The INF multiaperture telescope consists of 8 VT-78d telescopes on fast mount. The VT-78d telescope provides unique combination of parameters: aperture of 250 mm, fast focal ratio F/1.58, large field of view (10 deg diameter, 78.5 sq. deg) and D_{80} image quality of 5 arcsec. The INF total field of view is 574 sq. deg (298 Mpixels) with 5.2 arcsec/pixel scale. The key features of INF for NEO observation program is the ability to find nearby small objects of size >10 m not included into existing catalogues at a distance less than 0.01 a.u., follow them to determine their orbit and report about potential impact to the Earth quickly (in few hours). INF can detect 10 m asteroid at a distance of 0.5-2.2 million kilometers what corresponds to approaching time of 9-40 hours for typical NEO speed of 15 km/s. The warning time, e.g. the time after preliminary orbit determination until possible impact will be in a range from few hours up to one day. In case of multiple sites operation (worldwide) INF can detect most of the dangerous asteroids with a size of >10 m coming from the night sky. According to our estimates INF will discover about 7330 NEOs of 10 m size in 5 years in case of every day operation (8 hours per night).

Keywords: Near Earth Objects, Wide Field Telescopes

1. Introduction

In recent years many countries have begun work on the development of systems for the detection and tracking of dangerous Near Earth Objects (NEOs). The majority (~90 %) of all large (>1 km) potentially hazardous objects has been revealed in the framework of Space Guard Program implemented in the United States. In the next decade the majority of >100 m NEOs will be discovered by large aperture survey telescopes such as Zwicky Transient Facility (ZTF), Catalina Sky Survey, Panoramic Survey Telescope & Rapid Response System (Pan-STARRS) and Large Synoptic Survey Telescope (LSST).

The situation is different with the prospect of detecting smaller bodies with sizes between 10 m and 100 m. The number of potentially hazardous bodies of 10 m sizes is estimated to be 10^8 pieces [1], the rate of their collisions with Earth is about one event per 10 years, smaller bodies have fallen annually. The problem of exhaustive detection of these bodies at long distance which provides the aforementioned warning times will not be solved for at least a few decades. It is more realistic to discover these bodies in the Near Earth Space and to provide alerts about possible collisions with Earth.

The ideal system capable of detecting 10 m class NEOs should have:

- short cadence time (< 1 h);
- limiting magnitude of 19^m and fainter to detect 10 m NEOs at a reasonable distance;
- reasonable angular resolution of a telescope to prevent contamination.

Asteroid Terrestrial-Impact Last Alert System (ATLAS) is an example of successful system designed to detect 30-50 m impactors about one week in advance coming from the night sky, but this system is not efficient enough to detect good share of 10 m NEOs because of survey rate (a cadence time of about 1 day).

The ground-based wide-angle camera array (GWAC) is a set of ground-based instruments in the framework of the SVOM Chinese – French space mission dedicated to detecting gamma-ray bursts (GRBs) [2]. GWAC is designed to comprise 36 cameras of 18 cm aperture each with a totally covered area of more than 5000 deg^2 in one shot. GWAC will monitor the sky to catch the prompt optical emission of GRBs. Besides monitoring of GRBs, GWAC has potential to search NEOs and operate as "last alert system" to provide alerts about possible collisions of asteroid with Earth. The GWAC system will be very fast but not sensitive enough to detect 10 m class NEOs at reasonable distance.

INASAN suggests the INF (INASAN Near Earth Objects Finder) project that was optimized for detection of 10 m class asteroids coming in the Near Earth Space. The worldwide network of about 10 INF telescopes will provide 24 h of operation. In this case the system will ensure completeness of detection and warning time from few hours up to one day.

Position of ATLAS, GWAC, INF and some other survey telescopes on survey merit diagram is shown in Fig. 1. INF seems to be efficient instrument to detect 10 m class NEOs because of optimal combination of cadence time and sensitivity.

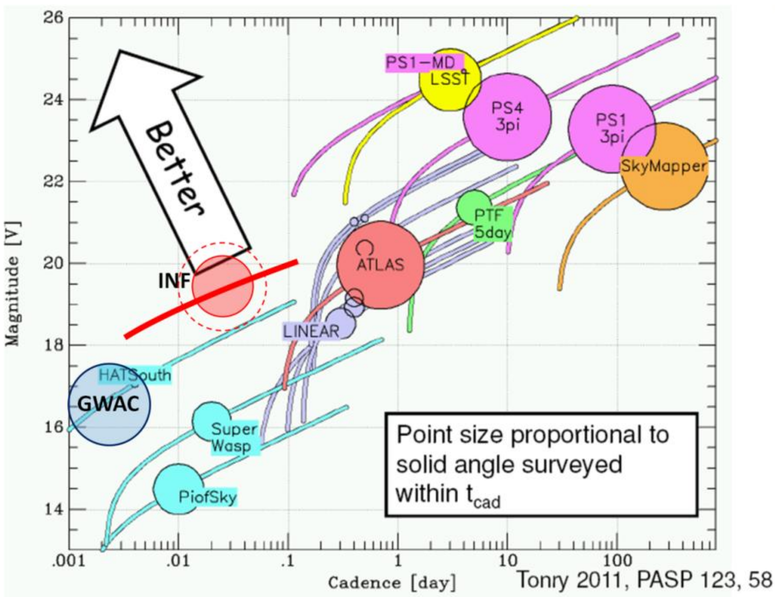

Fig1. *INF on survey merit diagram.*

Beside detection of 10 m class NEOs, INF will be useful for many others scientific goals, such as:

- Discovery and characterization of Near Earth Asteroids and Main Belt asteroids
- Search for new comets
- Monitoring, discovery and characterization of space debris
- Study of

  - transiting exoplanets
  - variable stars
  - young and active stars
  - supernovae
  - gamma-ray bursts
  - AGN / QSO variations
  - microlensing events
- Gravitational wave sources

2. INF and VT-78d telescope

The INF multiaperture telescope (Fig. 2) consists of eight VT-78d telescopes at one fast-track mount ASA DDM160. The main parameters of single VT-78d telescope and multiaperture INF telescope (8 tubes) are presented in Tables 1 and 2 respectively.

For fast repointing INF will be installed in a “shell type” dome.

Fig2. *INF multiaperture telescope: 8 x VT-78d telescopes on ASA DDM160 mount.*

Table1. *Main parameters of the VT-78d telescope*

Parameter	**Value**
Entrance pupil diameter	250 mm
Effective diameter	212 mm
Effective focal length	395 mm

F-ratio	F/1.58
Field of view angular diameter	10 deg
Field of view linear diameter	69.5 mm
Scale	1.915 μm/arcsec
Spectral range, nm	450-850 nm
D_{80} in integral light, center-edge	8-10 μm 4-5 arcsec
Maximum distortion at 550 nm	0.45 %

Table2. *Main parameters and all-sky (20000 sq. deg) survey efficiency of the INF telescope (8x tubes)*

Parameter	**Value**
Detector of single tube	CMOS GSENSE6060BSI 6k × 6k, 10 μm pixel
Pixel format	12k × 24k
Number of pixels	298 Mpixel
Pixel scale	5.2 arcsec/pix
Field of view	17.6 × 35.2 deg 574 sq. deg
Readout time	< 0.25 s
All-sky survey @ 10 s exposure	10 min @ 18.3^m
All-sky survey @ 30 s exposure	20 min @ 18.9^m
All-sky survey @ 100 s exposure	1 h @ 19.4^m

The VT-78d telescope is a new generation wide field telescope designed by V. Terebizh (INASAN patent №162010 (RU)). The telescope provides a unique combination of 250 mm aperture, 10 deg field of view and 5 arcsec image quality. The VT-78d optic (Figs. 3, 4) consists of simple optical elements, all surfaces are spherical, simple glass is used.

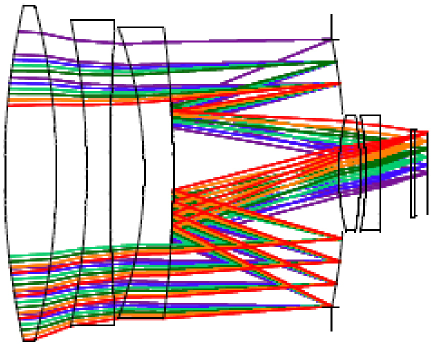

Fig3. *VT-78d optical layout.*

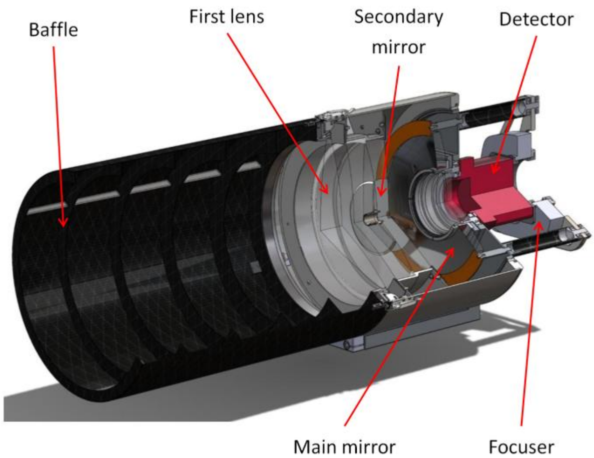

Fig4. *VT-78d mechanical layout.*

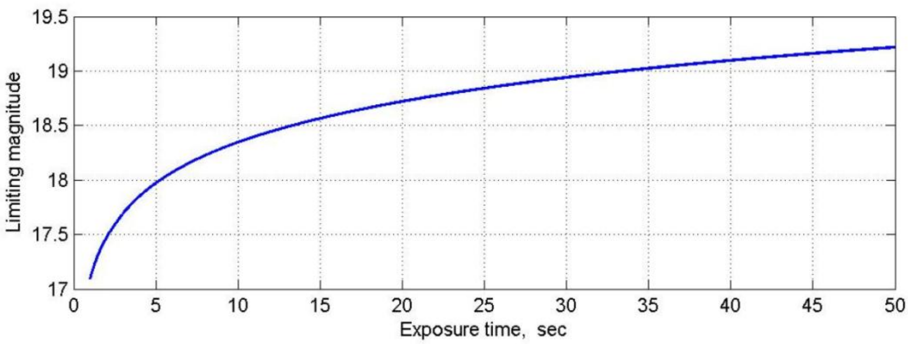

Fig5. *VT-78d limiting magnitude (SNR = 7) vs exposure time.*

The telescope was designed to be used with the cost-effective CMOS detector GSENSE6060BSI (6k × 6k, 10 μm pixel) with electronic shutter. The CMOS-camera NEVA6060 with 4 Hz frame rate is planned to be used. For specific scientific tasks [3,4] the short series of frames can be taken with frame rate of up to 44 Hz.

The telescope limiting magnitude versus exposure time is shown in Fig. 5. Calculation was done for atmosphere FWHM quality of 1.5 arcsec, sky background of 20.5 mag/arcsec^2 and bandwidth of 500 nm.

All tubes of INF multiaperture telescope can be aligned by special mechanism to look at one field in order to perform multicolor photometry or to improve telescope sensitivity and sampling.

In case of all tubes looking at one field (71 sq. deg) the limiting magnitude will be about 20.4^m for 100 s exposure without filters at good observation conditions (low background light).

It is possible to put a filter change mechanism with one specific filter for each telescope. In this case it will be possible to do 8-bands photometry with a limiting magnitude of 18.4^m for 100 s exposure.

3. INF system performance

One of the main characteristics of a NEO discovery system is a visibility zone, e.g. the volume where NEOs of a given size (10 m) can be detected [5].

To calculate NEOs visibility zones the following parameters should be taken into account:

- the size and albedo of the NEO, phase angle, distance to the Sun and observer;
- the main characteristics of a telescope and detector;
- the background illumination, i.e. sky background and scattered light in a telescope;
- exposure time;
- NEO proper motion.

For night-time hemisphere the value of sky background in a range of 20.5-21 mag/arcsec^2 was taken. For the day-time hemisphere we use the values in a range of 20.5-18 mag/arcsec^2 for the NEO-Earth-Sun angle between 90 deg and 70 deg, which means the observation during twilight and/or close to horizon. For the NEO-Earth-Sun angles less than 70 deg the distance of NEO detection drops down very quickly because of phase angle and background light. To take into account the effect of star contamination because of pixel scale and scattered light inside INF multi-lens optical system we increase the sky background by 1 mag/arcsec^2.

Fig. 6 illustrates the INF performance to detect asteroids of 10 m size with the 60 s exposure time. The Earth coordinates are (0,0) and those of the Sun are (0, about -150). Isophote bands (green and blue) of constant SNR are shown with a 3 unit increment. A separate pink isophote is given for SNR = 9 which corresponds to a reliable detection.

You can see that INF provides reliable detection of NEOs approaching the Earth from solid angle of 2 π sr (night sky) at a distance of 0.5-2.2 million km from the Earth. The asteroid with typical approaching speed of 15 km/s crosses this distance in 9-40 hours. For NEOs with large proper motion the detection distance will be shorter.

For exhausting detection of NEOs it is necessary to install few telescopes at different location both in the northern and southern hemispheres of the Earth. We can say that in one night INF will detect practically every asteroids coming inside its visibility zones, getting enough measurements to calculate preliminary orbit and provide the alert about potentially hazardous objects. To determine the orbit of dangerous NEOs and to calculate the entrance point into Earth atmosphere the follow-up telescopes with better sensitivity and angular resolution should be used. The warning time for typical 10 m size asteroid will be in a range of few hours up to one day.

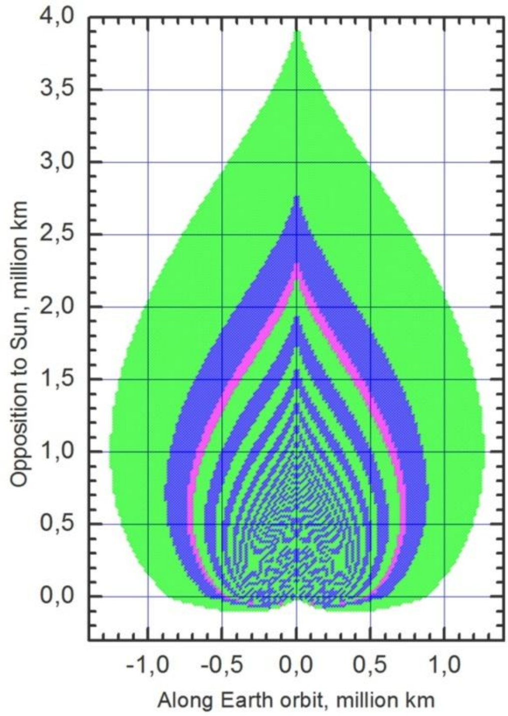

Fig6. *Visibility zone of 10 m NEOs for INF project with 60 s exposure time. The SNR is shown by color coding (green and blue) isophotes with 3 unit increment, the pink isophote shows SNR = 9. The Earth coordinates are (0,0), the Sun is at (0,-150).*

An important question is how many NEOs will be detected by INF in 5 years. To estimate the number we constructed a population of small virtual NEOs. We used the Granvik-Bottke-Morbidelli model [6]. According to the Granvik-Bottke-Morbidelli model, the number of Near Earth Asteroids with $H < 25^m$ is estimated as 0.9 million.

We estimated the number of asteroids accessible for observations with INF in the following way. For each virtual asteroid we integrated asteroid motion for 5 years and estimated the conditions of visibility of the asteroid from the observatory B18 (Peak Terskol, Russia) in the sky. The solution of numerical equations of motion of asteroids was carried out by the Everhart integrator of 17 orders, the model of forces included perturbations from the planets, the Sun and the Moon. We counted asteroids whose visual magnitude is less than 19.7^m, and altitude is more than 15 degrees above horizon at the night time.

According to our estimates the INF will discover ~7330 NEOs in 5 years in case of every day operation (8 hours per night) with a limiting magnitude of 19.7^m. Model distribution of discovered NEOs over the sky is shown in Fig. 9.

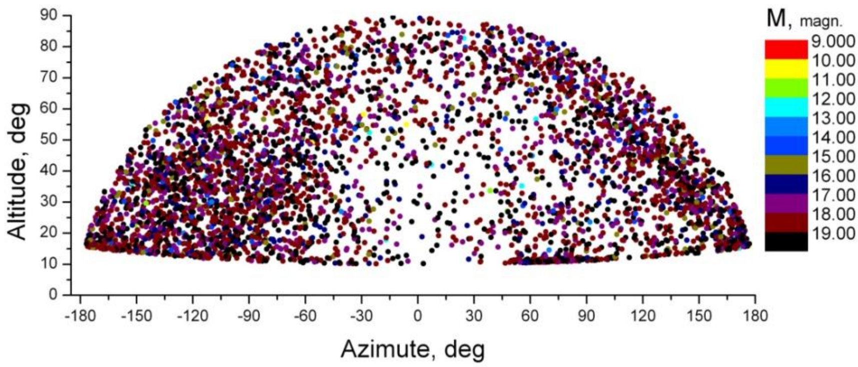

Fig7. *Distribution of possible NEO on (Az-Alt) plane that could be detected by INF.*

2.4. Combed visibility zones for INF and SODA projects

The Chelyabinsk event of February 15, 2013 has clearly shown that the collision of a rather small body of a size about 17 m with Earth at a populate area may cause significant damage. Chelyabinsk asteroid coming to the Earth from the day sky could not be discovered by any ground-based or Near Earth Space telescopes because of unfavorable phase angle and light scattering [7]. The only way to detect these bodies reasonably well beforehand is to put a telescope relatively far from the Earth.

The project of Space system SODA (System of Observation of Day-time Asteroids) was proposed [8] for exhaustive detection of decameter (and larger) bodies approaching the Earth from the Sun direction (Chelyabinsk type meteoroids). The main idea of the mission is to put one or two spacecrafts equipped with medium-size (30 cm) wide field telescopes with pre-aperture active mirrors into the vicinity of L1 point of the Sun-Earth system. This position is very comfortable for detecting asteroids coming from the Sun direction due to relatively short distance between a telescope and an asteroid and optimal phase angle.

In Fig. 8 the visibility zone of 10 m NEOs with 0.15 albedo is shown for INF project with the 60 s exposure time and for SODA project with the 4 s exposure time. The blue doted isophote shows a confident (SNR = 9) detection zone for INF project and the red doted one for SODA project. SODA project was unable to observe asteroids close and behind the Earth because of light scattering from the Earth and the Moon. INF project can operate only at a night hemisphere. You can see that INF and SODA projects complement each other to provide detection of asteroids coming from all directions with the warning time from few hours up to one day.

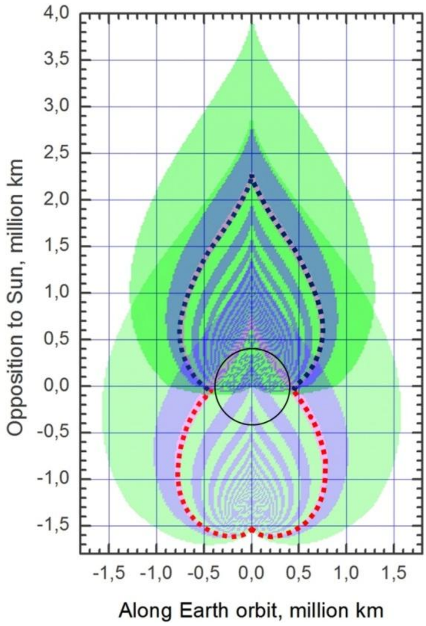

Fig8. *Combined visibility zone of 10 m NEOs for ground-based INF project (blue dotted) and space-based SODA project (red dotted) located at L1 point of the Sun-Earth system (0,-1.5). The SNR is shown by color coding (green and blue) isophotes with 3 unit increment, the pink isophote shows SNR = 9. The Earth coordinates are (0,0), the Sun is at (0,-150), the Moon orbit is indicated by the black circle.*

Fig9. *INF prototype drawing, 2 x VT-78d telescopes on ASA DDM85PRO mount.*

4. INF prototype

INASAN is finishing construction of a prototype of the INF multiaperture telescope. The prototype consists of 2 identical wide-field telescopes VT-78d (Fig. 9) equipped with 4k×4k

CCD cameras on a fast-track mount. First light is expected in 2019. The INF prototype consists of:

- 2 x VT-78d telescopes, 2 x FLI ML16803 CCD cameras;
- 2 x FLI Atlas focusers, ASA DDM85PRO mount;
- ScopeDome 3m full robotic dome;
- control computer and equipment;
- observation planning software;
- data processing software.

5. Conclusion

The Chelyabinsk event changed our priorities in the asteroid and comet hazard problem. We understand that it is necessary to create special facilities to detect decameter size bodies coming both from day and night sky.

INF can operate as "a last alert system" to provide alerts about possible collisions of small asteroids with Earth. In case of multiple sites operation (worldwide) INF can detect most of the dangerous asteroids of a size of >10 m size coming from night sky with the warning time from few hours up to one day. We believe that combination of ground based (INF, ATLAS, GWAC) and Space based (SODA) projects is a proper way to provide realistic warning system against small decameter size impactors.

References

[1] Emel'yanenko, V. V. & Naroenkov, S. A., Dynamical features of hazardous near-Earth objects. 2015, Astrophysical Bulletin, 70, 342, DOI: 10.1134/S199034131503013X

[2] Motch, C et all, The SVOM mission. 2017, Astronomische Nachrichten, 338, 9-10, p. 978-983, DOI: 10.1002/asna.201713415

[3] Beskin, G., et al., Astronomy and Astrophysics Supplement, v.138, p.589-590, 1999

[4] Beskin, Grigory; Bondar, Sergey; Karpov, Sergey; Plokhotnichenko, Vladimir; Guarnieri, Adriano; Bartolini, Corrado; Greco, Giuseppe; Piccioni, Adalberto; Shearer, Andrew. "From TORTORA to MegaTORTORA-Results and Prospects of Search for Fast Optical Transients", 2010, Advances in Astronomy, 2010, article id. 171569, DOI: 10.1155/2010/171569

[5] Shugarov, A. S., Simulation of the detection zone of dangerous celestial bodies for space-based systems. 2013, Solar System Research, 47, 296, DOI: 10.1134/S0038094613040187

[6] Granvik M., Morbidelli A., Jedicke R., Bolin B., et.all, (2018). Debiased orbit and absolute-magnitude distributions for near-Earth objects. Icarus, 312, 181–207

[7] Shustov, B. M., Shugarov, A. S., Naroenkov, S. A., & Prokhorov, M. E., Astronomical aspects of cosmic threats: new problems and approaches to asteroid-comet hazard following the Chelyabinsk event of February 15, 2013. 2015, Astronomy Reports, 59, 983, DOI: 10.1134/S1063772915100066

[8] Shugarov, A., Shustov, B., & Naroenkov, S., System of observation of day-time asteroids (SODA). 2018, Open Astronomy, 27, 132, DOI: 10.1515/astro-2018-0023