SYSTEM OF OBSERVATION OF DAY-TIME ASTEROIDS (SODA)

B. Shustov (1), A. Shugarov (1), S. Naroenkov (1), and I. Kovalenko(2)

(1)*Institute of Astronomy, Russian Academy of Sciences, 48 Pyatnitskaya str., Moscow, 119017, Russia, Email: {bshustov, shugarov, snaroenkov}@inasan.ru*

(2)*Space Research Institute of the Russian Academy of Sciences, 84/32 Profsoyuznaya Str, Moscow, 117997, Russia, Email: irina.kovalenko@iki.rssi.ru*

ABSTRACT

We describe the project of space system SODA (System of Observation of Day-time Asteroids) for detection of "all" 10-m class bodies entering near Earth space (i.e. approaching the Earth at distances less than 1 million km) from day sky. The main idea of the mission is to put one or two spacecraft (S/C) equipped with $\sim$ 30cm aperture wide-field telescopes into the vicinity of L1 point (in the Earth-Sun system). Observation will be performed in a barrier mode. The computer controlled fast slewing pre-aperture flat mirror ensures very flexible and quick changes of observational modes. The number of decameter size and larger bodies to be detected per year is about 600. The 5-m meteoroids can be detected either but completeness level will be lower. This makes possible some statistical test of current models of minor body population in the Solar system. From the other side SODA will provide very efficient (for two S/Cs option) instrument for detection bodies at collisional (with the Earth) trajectories. In this case SODA can provide and some tens km accuracy of determining the atmospheric entry point and ensure warning time of 4 hours or longer. We mention additional science goals of the mission, including such options as Earth climate monitoring and Sun observation (similar to DSCOVR projects goals). The necessity of collaboration with night-time observational systems that are focused on detection of NEOs in the near Earth space (e.g. ATLAS) is emphasized.

Keywords: Near Earth Objects; Day-time asteroids; survey space telescope.

1. INTRODUCTION

The 20-meter meteoroid, that exploded over Chelyabinsk on 15 February 2013 at about 9:20 a.m. local time, was not detected from any near Earth space- and ground-based observatories [1]. One of the major lessons of the Chelyabinsk event is quite obvious: to detect the NEO coming from the day sky and properly calculate its orbit we need space-born telescope located far away from the Earth.

Space-based systems for detecting hazardous celestial bodies are discussed by experts in various countries. Some of the projects also allow detection of bodies on the daytime sky. The first project of this type has already been implemented. The Canadian spacecraft NEOSSat (The Near-Earth Object Surveillance Satellite) was launched into orbit in February 2013 [2]. The microsatellite with a 15 cm Maksutov optical telescope aboard is used for detecting near Earth asteroids, whose orbits lie inside the Earth orbit. As the spacecraft is placed in a tight near Earth orbit, the area around the Sun with radius less than 45° is inaccessible for it. The small aperture of the telescope allows detecting only rather bright bodies.

In [3] an interesting idea to put a 1-m aperture telescope into an orbit about Lagrangian point L1 of the Sun-Earth system, in order to detect hazardous asteroids approaching from the Sun, was proposed. The telescope was assumed to browse an annular region of the celestial sphere around the Earth with an outer radius of about 25° and an inner radius of 5° over 24 hours. Frames of each region would be carried out twice every 24 hours. Unfortunately, the description of this interesting proposal was very sparse (slightly more than one page of text), and all the main calculations were relegated to future studies.

In ([4]) we proposed the System of Observation of Daytime Asteroids (SODA). SODA is a space mission project, which main objective is the detection and monitoring of celestial bodies approaching the Earth from the Sun direction. The system implies one or two spacecrafs (S/C) equipped with one to three small – about 30 cm aperture – telescopes each. The S/C should be launched into the vicinity of the L1 point.

The announced SODA project goals are:

- to detect "almost all" bodies larger than 10 m entering the near space (i.e. approaching the Earh at a distance of less than 10^6 km) from the Sun direction;
- to ensure quick selecton of bodies of special interest (e.g. asteroids at collisional orbits) and characterisation of them (e.g. precise orbit determination and evaluation of mass);

- in the case of collisional orbit to determine coordinates of atmospheric entry point with best possible accuracy to ensure warning time not less than 4 hours.

In ([4]) we described mostly astronomical issues related to this project. Since the project attracted some interest by Roscosmos we have continued the work on the project. In [5] we presented some general tecnical features of the SODA project and in [6] we considered main aspects of trajectory design for the SODA project at its initial stage. In this paper we describe current state of the SODA project. Major technical details are presented in Section 2. Special attention is paid to expectred productivity of the system and accuracy of NEO orbit detemination. We summarize major ballistic issues in Section 3. Summary and future plans are presented in Section 4.

2. THE SODA PROJECT

2.1. General features

As we argued in ([4]) one does not need a 1-m class space telescope to detect decameter size meteoroids in the near space. Even much smaller aperture telescope (25 – 30 cm) is efficient for observation of NEOs larger than 5 – 10 m since the NEOs are observed at the optimal phase angle and relatively short distance. To increase efficiency of survey and for redundancy reason we plan to install up to three telescopes at one S/C.

Telescopes are to use a barrier detection method instead of all-sky survey. Barrier mode of detection strategy significantly reduces requirements to survey rate, telescope's field of view, detector size, etc.

We suggest to put full-aperture slewing mirror in front of each telescopes for quick repointing. This ensures high flexibility of obseravtional program. Telescope can be easily switched from barrier mode to target mode (follow-up observation) of object of special interest. According to [7] the number of dangerous bodies that need to be observed in a target mode does not exceed few per day.

The optimal variant of the SODA system include two S/Cs well distributed in orbit around L1. The main advantages of two satellites option in compare to one S/C are:

- increased accuracy of orbit determination using triangulation method of observation;
- solution of problem of missing bodies flying close to the S/C (at a distance of less than 0.4 million km);
- increased detection area;
- improved system reliability.

Even single telescope would be capable to solve the main task though at limited level of completeness.

The general scheme of observation in SODA project for two S/Cs option is presented in Figure 1. For simplicity only one telescope is shown for each S/C, but S/C can be equipped with upto three telescopes to provide highest survey efficiency. Each telescope will survey only part of conical space. In the case of three telescopes a duty of each telescope is observation of about one third of conical barrier. The brief summary of operational parameters of SODA is presented in Table 1.

The NEO moving from the Sun crosses the optical barrier approximately one day before its closest approach to the Earth. Crossing time of barrier for typical NEO is about 30 minutes. This means that NEO will be observed about 8 times when crossing the barrier. The data will be transmitted to a ground center where preliminary orbit is to be calculated. This information seems to be sufficient to classify an object as an object of special interest (e.g. in the case of high collisional probability). If the NEO is classified as an object of special interest, ground center sends a command to S/C to observe the object in a target mode every 3 minutes. This brings sufficient number of observations to calculate NEO orbit with high accuracy. The last observation can be done at angular distance between NEO and the Earth of $\sim 5^\circ$. General requirement is to observe NEO during time interval sufficient to calculate most precise orbit. Final goal is to precisely calculate an atmospheric entry point and guarantee warning time not shorter than $\sim$4 hours.

To reduce scattered light from the Earth and to observe NEO at angular distance from the Earth down to 5° we suggest to put the mask (screen) in front of telescopes (see in Figure 4). Shadowed triangles in Figure 1 correspond to the screened area.

To use possibility of triangulation in two SC option one has to know the position of the SC in the Solar System with accuracy of about 1 km (good) or 10 km (still acceptable) and onboard time with accuracy of 0.01 s.

2.2. Telescope(s) of SODA Project

It is proposed to use the telescope with lens corrector designed by Terebizh [8]. Similar telescopes were widely used for ground-based observations.

One of the challenges of frame-by-frame construction of a barrier is the problem of very frequent repointing of the telescope (every few seconds). We suggest to put full-aperture slewing mirror in front of each telescopes for quick repointing. This makes possible very flexible observation program, possibility of tight duty-cycle and redundancy. The telescope, slewing mirror and a baffle are schematically shown in Figure 2, the main parameters the of telescope are listed in Table 2.

Slewing pre-aperture mirror technology for repointing

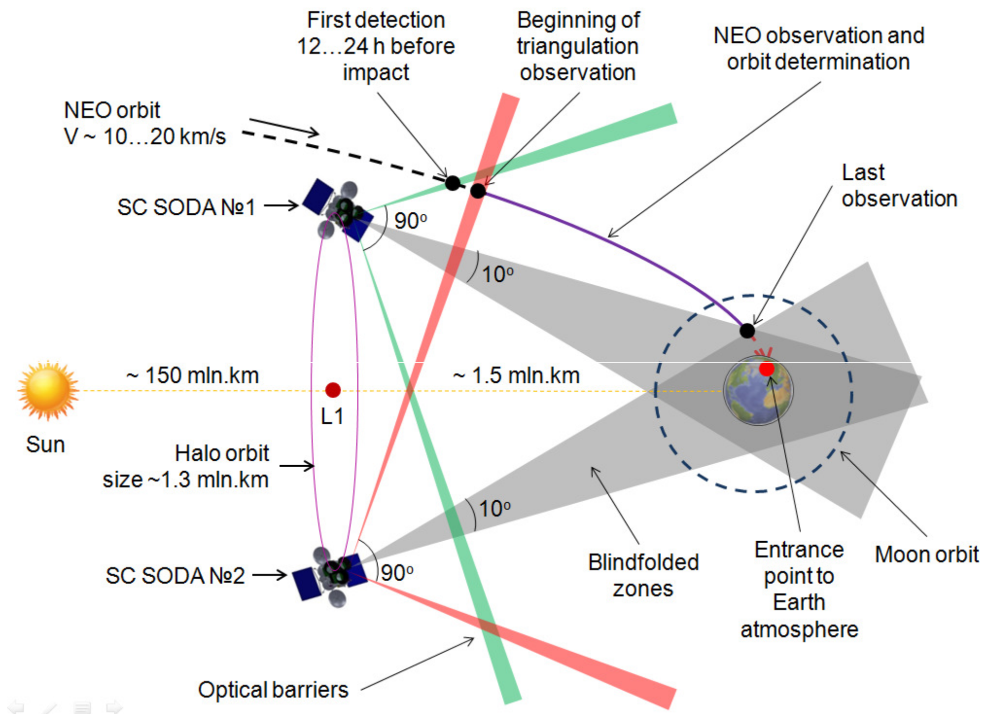

Figure 1. Scheme of observation in SODA project: a view from ecliptic pole.

Table 1. Operational parameters of SODA project.

Parameter	Value
Number of individual frames on optical barrier (for 3° FoV telescope and barrier cone angle 90°)	80
Exposure time of each frame	4 s
Limiting magnitude (30 cm aperture telescope)	17^m
Repointing time between adjacent fields	1 s
Total time of barrier observation with 3 telescopes	3.5 min
Typical time of crossing the barrier (for NEO speed 15 km/s and distance from S/C ~0.4 mln km)	30 min
Average number of exposures of NEO crossing the barrier	8
Observation in target mode	every 3 min

Table 2. The main parameters of SODA telescope.

Parameter	Value
Telescope aperture	30 cm
Field of view	3.5°
Focal plane size	$\sim$60$\times$60 mm
Pixel scale	2 arcsec/pixel
Spectral range	400-700 nm
Image quality	1.4 arcsec
Limiting magnitude	17^m @ 4 s exposure
Slewing mirror tilt angle	$\pm$ 23° two axis
Slewing mirror size	50$\times$40 cm
Slewing and settling time	1 s for 3° movement
Number of movements per 5 years	10^7

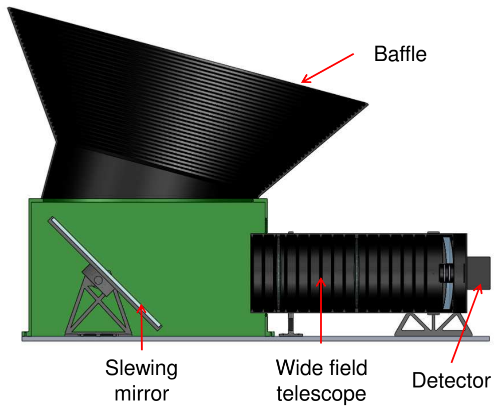

Figure 2. The concept of SODA telescope with slewing mirror.

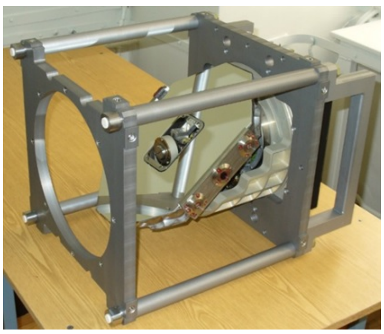

Figure 3. Slewing mirror for meteorological satellites Electro-L.

of space telescopes was used in a number of space experiments. The 10 cm telescope with 20 cm slewing mirror is used in the UFFO instrument onboard spacecraft Lomonosov [9]. The movable mirror provides the tilting range of 70° with repointing time less than 1 s. This system can be scale up for 25 cm telescope. Two-dimensional gimbals with flat mirror to track the objects were successfully used in the Moon-based Ultraviolet Telescope (MUVT) on Change-3 lunar lander [10]. Telescope has aperture of 15 cm and field of view of 1.27°$\times$1.27°.

We plan to use as a prototype a design of the slewing mirror that was implemented in a series of new-generation meteorological satellites Electro-L designed and constructed by Lavochkin Association (Russia). The satellites operate in geostationary orbit. The payload has an opto-mechanical scanner with flat slewing mirror (see Figure 3). The slewing mirror size is $\sim$30 cm, the mirror swing angle is $\pm$5°, lifetime is 7 years.

Due to a large number of frames (10^7 frames over 5 years) and short exposure time modern large-format CMOS detectors with electronic shutter are required to operate with SODA's telescope. A radiation-hard CMOS GSENSE6060BSI of Gpixel company is considered for system performance as a good candidate. The format of 6k$\times$6k with 10 micron pixel and readout time of 1 s makes this detector suitable for the project.

2.3. SODA spacecraft

The conceptual layout of the spacecraft with three 30 cm telescopes is shown in Figure 4. Parabolic high-gain antenna fixed on spacecraft is coaligned with the axis of the barrier cone. In front of the telescopes at distance of about 3 m a shamrock-shape mask is installed to screen the Earth light.

We propose to use a small space platform with an improved stabilization system. Propulsion system should be able to insert the spacecraft to the vicinity of point L1 and provide navigation around L1 for 5+5 years. The scientific payload mass estimation is 100 – 150 kg with power consumption of $\sim$100 W. Space platform should provide angular stabilization at level less than 0.5 arcsec/s.

The total mass of SODA spacecraft is estimated as $\sim$400 kg. To insert this mass to L1 orbit a medium-class

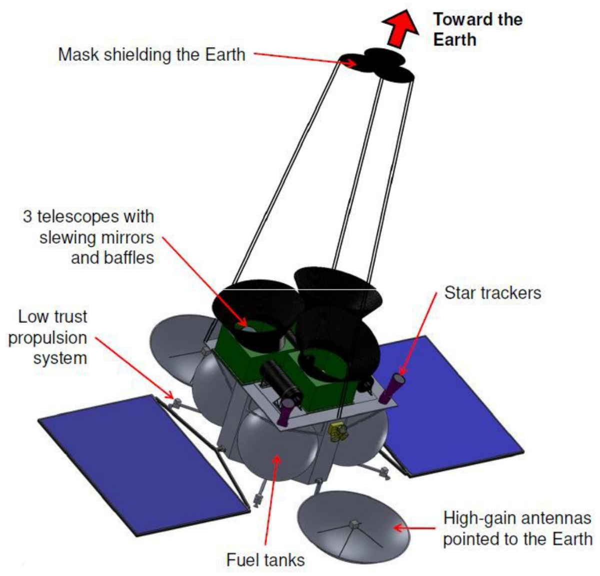

Figure 4. SODA spacecraft concept.

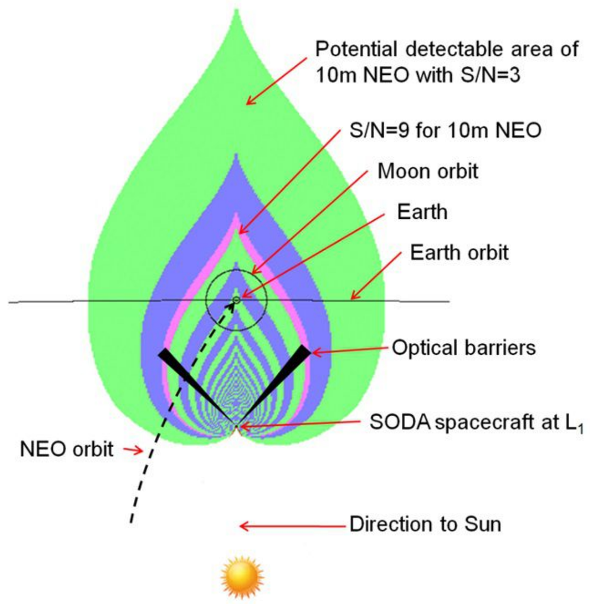

Figure 5. Visibility zone of 10 m NEO from L1 for SODA telescope.

launcher with upper stage is required.

One of the challenge of the SODA project is a big raw data flow from detectors (150 Mbps) and requirement to have almost continuous transfer of scientific data from L1 to ground data processing center in the case of NEO of specific interest. From L1 point typical downlink data rate provided with available equipment is about 250 kbps. This implies necessity of onboard real time data processing. Downlink channel will be used for transfer of observation data (coordinates, intensity) and transfer of small cropped image around the selected object(s) in a target observation mode.

It is necessary to organize SODA dedicated network of ground stations evenly distributed longitudinally. Moderate size 6 m class antennas are sufficient. Each time at least one (two for reliability) of the stations should be on the day side of the Earth.

2.4. Expected system performance

Detection zones for space telescope located in an L1 orbit with a given value of signal to noise (S/N) ratio are shown in Figure 5. Isophote zones of constant S/N are shown with a step of 3 units. A separate pink isophote is given for S/N = 9 which corresponds to a reliable detection of the NEO. The calculations were made for 10 m size NEO with albedo of 0.13, 30 cm telescope and exposure time of 4 s.

The results of calculations demonstrate that sensitivity of the SODA telescope is sufficient to detect 10 m NEO at distances up to 2 million km, or 5 m NEO at distances up to 1 million km.

2.5. Expected number of observed objects

An important question is how many NEOs enter the detection zone of the SODA S/C per year. To estimate the number we constructed a population of small virtual NEOs. We used the Granvik-Bottke-Morbidelli model ([11]). Two populations of the near-Earth asteroids have been considered: asteroids of $H < 25^m$ and asteroids with $H \in 25^m - 27^m$. According to the Granvik-Bottke-Morbidelli model, the number of Near-Earth Asteroids which $H < 25^m$ is estimated at ∼0.9 million; the total population of the near-Earth asteroids which $H < 27^m$, i.e. bodies larger than 15 m is estimated at 15 million. Of course, only a small fraction of these 15 million virtual asteroids enters the observation zone of the two SODAs spacecrafts per year.

We estimated number of asteroids accessible for observations with SODA 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 each of the SODA spacecraft. The solution of the numerical equations of motion of the 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 considered asteroids which angle S/C-Earth-asteroid is less than 45 °.

The following results were obtained. For larger asteroids $H < 25^m$ the number of objects that could be detected by SODA spececrafts is 1282 asteroids over 5 years. For asteroids with $H \in 25^m - 27^m$ SODA can detect 2680 objects in 5 years. In total, the system of two SODA spacecrafts will be able to detect about 3,500 – 4,000 near Earth asteroids. This is consistent with our preliminary estimates ([7]). The overwhelming majority of objects (more than 95%) are available for observation from both S/C which makes it possible to use triangulation mode and accurately determine the orbit of an object.

2.6. On the accuracy of orbit determination of bodies detected by SODA

The accuracy of calculation of entry point into the atmosphere is very important component of the effectiveness of the SODA project. It is critical point for future actions of prevention and mitigation. The accuracy depends first of all on the accuracy of the calculated NEO orbit which is determined mostly by details of observation: characteristics of telescopes, configuration of S/C and program of observation, e.g. on the length of observed orbit arc, number of observation points, etc.

We performed a simulation to estimate the accuracy of entry point into the Earth atmosphere calculation for Chelyabinsk meteoroid orbit[12]. The telescope parameters are as given in a previous sections of this paper, the SODA SCs was put on SOHO orbit [13]. Three variants of SODA configuration around the point L1 were analyzed:

- variant 1: single S/C;
- variant 2: two S/C in L1 orbit in counter-phase mode at maximal distance between SC or at phase shift $\sim 180°$;

Length of observed arc was considered in a range of 2 – 16 hours. We used approach described in [14]. For each virtual asteroid that could be detected by the SODA spacecraft, a series of virtual observations were created. Having in mind the 3 min interval between observations one can expect to get up to 600 observations of the object (with two telescopes). The accuracy (sigma) of a single observation for a telescope and detector described above is $\sim$ 2 arcsec. For each virtual asteroid an orbit was refined using the differential Gauss-Newton method. A set of virtual particles that simulate the uncertainty of the orbital vector of the object have been obtained with method based on the Cholesky covariance matrix. Uncertainty of atmosperic entry point region was considered as a projection of dispersion ellipsoid on layer of Earth atmosphere at altitude of 110 km, i.e. on the border of dense layers of the atmosphere.

Using the example of the Chelyabinsk meteoroid, we examined the accuracy of determining the orbit of an object from the length of the observation arc. Main results, i.e. estimates of size and form of uncertainty region of the entry point, are presented in Table 3. Sizes of uncertainty region was estimated using 3 sigma approach. The first factor of the product is the length of the region of uncertainty along the trajectory of the body, the second factor is the size across the path.

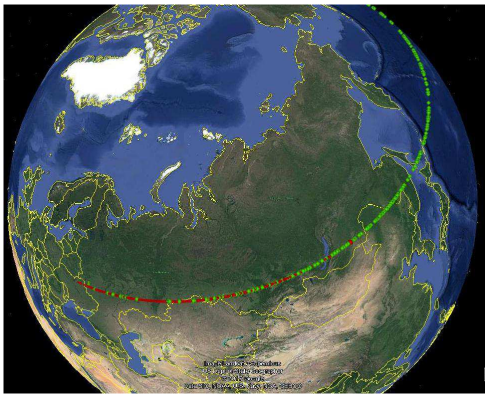

Figure 6. Dispersion (of entry points) region for Chelyabinsk meteoroid being observed with SODA system by single S/C (variant 1). Green points correspond to length of arc 8 hours, red - 15 hours.

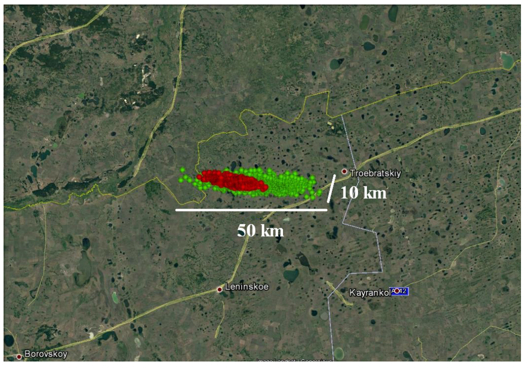

Figure 7. Dispersion (of entry points)region for Chelyabinsk meteoroid being observed with SODA system in two S/C option. Green points correspond to length of arc of 8 hours, red ones – 16 hours.

General conclusions that can be derived from the Table 3 are as follows.

- For Chelyabinsk body being observed with SODA in the case of single SC (variant 1) the accuracy of size of the uncertainty region of entry point is poor. One needs to use maximal length of arc (observed piece of orbit) to get practically valuable accuracy (Figure 6).

- Two SCs (variant 2) seems to provide much better accuracy. For longer arc the accuracy of determination of uncertainty region can be as high as few tens km. This is quite acceptable for making decision on mitigation (see Figure 7).

Table 3. Dependence of size and form of uncertainty region of entry point on length of observed piece of orbit (arc) and SC configuration.

Length of orbit observed with SODA (h)	Size of dispersion region of entry points (km) variant 1	variant 2
2		1600×90
3	Uncertainty	490×35
4	region exceeds	235×25
5	Earth size	135×18
6		96×15
7		65×13
8		50×10
9	15000×10	43×10
16	5000×10	21×5

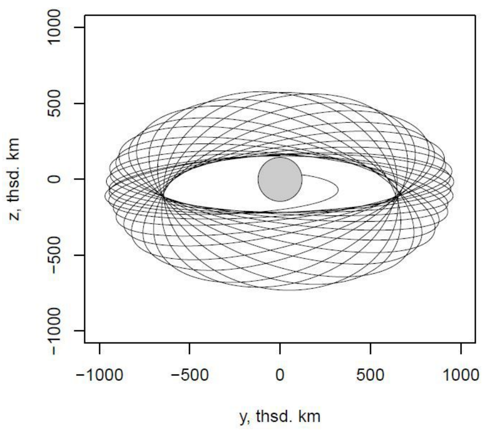

Figure 8. Lissajous trajectory about a halo orbit propagated over 10 years. View looking towards the Sun from the Earth. The exclusion zone (gray circle) corresponds to 5 offset angle due to excessive solar interference.

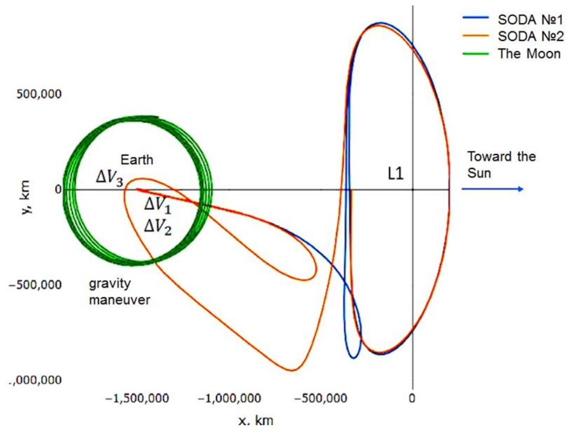

Figure 9. Transfer scenario for a double launch of two S/C from a LEO. Ecliptic plane projection. $\Delta V1 = 3.2$ km/s, Correction manoeuvres $\Delta V2$ and $\Delta V3$ are about 10 – 15 m/s.

3. TRAJECTORY DESIGN FOR SODA

As it was demonstrated above the most promising variant of the SODA system is to put two S/C in the vicinity of L1 point. In [6] possibilities of transfer trajectories, orbits in the vicinity of L1 point and the configuration of the two SODA satellites have been discussed. Launch from Baikonur by the Soyuz 2.1b launch-vehicle with Fregat-SB upper stage has been considered in the work. This configuration allows launching two SODA satellites to the vicinity of L1 from a LEO with inclination 51.5°. Moreover, a shared launch with another mission is also possible. The transfer to L1 takes about 100 days to reach an operational orbit. Scientific operations, however, can begin about 30 days after launch once the S/C is in the vicinity L1. Wherein, in this scenario mainly the propellant of the upper stage is used for the transfer orbit insertion, thereby keeping the fuel stored on board of the S/C for stationkeeping tasks and for achieving an appropriate configuration of the two S/C.

Lissajous orbit that we have proposed doesn't cross the exclusion zone for at least 10 years, satisfying the mission objectives and can be an appropriate choice for the SODA project (see Figure 8). Stationkeeping manoeuvres can be performed in the Sunward or anti-Sunward directions. With an average frequency once per month, the cost of the stationkeeping manoeuvres will be about 1 m/s per year.

The configuration of two SODA satellites spaced apart in the vicinity of L1 can be achieved with a double launch of two satellites. For this purpose either phase-changing manoeuvres or a lunar gravity assist can be used. This second solution has been proposed and discussed in [6]. The scheme considers one S/C directly inserted into a transfer orbit towards L1, while the second S/C will carry out a lunar gravity assist in the second revolution about the Earth after separation from the upper stage (see Figure 9).

4. CONCLUSIONS AND PROSPECTS

The Chelyabinsk event changed our priorities in asteroid and comet hazard problem. We understand that it is necessary to create special facilities to detect the decameter size bodies coming from day sky. In this paper we demonstrate the possibility of implementation of the cost-saving (using off-shelf technologies) space system to detect such NEOs. Several hours of warning time provided by SODA project is sufficient to decrease risks. Larger warning time implies dramatically larger cost.

Simulation showed that the observation of Chelyabinsk meteoroid for 8 hours with two SCs would be sufficient to define the uncertainty region of entry point within a few tens of kilometres, which is quite practical. Observations with one SC does not provide so good result. Note that the accuracy of the entry point of the body may be improved if error of a single observation will be decreased.

Apart from practical issue of solving NEO problem the SODA project will provide experts with valuable data on statistics and kinematics of the population of minor bodiesh. To increase the scientific outcome from the SODA mission we suggest to install additional scientific payload for Sun observation and Earth-observation on Sun-side and Earth-side of spacecraft respectively.

Today the SODA project is in Pre-Phase A stage (Mission Analysis and Identification). The request for funding for Phase A (Feasibility) was submitted to Roscosmos. International collaboration is welcome for the project as well as cooperation with other ground-based projects focused on detection of 10 m class NEOs.

We believe that combination of space-based (SODA) and ground-based (e.g. ATLAS [15]) projects is a proper way to provide realistic warning system against small (decameter size) impactors.

ACKNOWLEDGMENTS

One of the autrors (B.Shustov) expresses sincere gratitude to organizers of very interesting and encouraging MIAPP Program "Near Earth objects: Properties, Detection, Resources, Impacts and Defendig Earth".

REFERENCES

1. Emel'yanenko V. V., Popova O. P., Chugai N. N., et al., (2013). Astronomical and physical aspects of the Chelyabinsk event (February 15, 2013). *Solar System Research*, **47**(4), 240–254
2. Laurin D., Hildebrand A., Cardinal R., et al., (2008). NEOSSat: a Canadian small space telescope for near Earth asteroid detection. *Proceedings of SPIE*, **7010**, 701013-701013-12
3. Dunham D. W., Reitsema H. J., Lu E., Arentz R., (2013). A concept for providing warning of earth impacts by small asteroids. *Solar System Research*, **47**(4), 315-324
4. Shustov B. M., Shugarov A. S., Naroenkov S. A., Prokhorov, M. E., (2015). Astronomical aspects of cosmic threats: new problems and approaches to asteroid-comet hazard following the Chelyabinsk event of February 15, 2013. *Astronomy Reports*, **59**(10), 983–996
5. Shugarov A., Shustov B., Naroenkov S., (2018). System of observation of day-time asteroids (SODA). *Open Astronomy*, **27**, 132–138
6. Kovalenko I. D., Shustov B. M., Eismont N. A., (2018). Trajectory design for the System of Observation of Daytime Asteroids. *Acta Astronautica*, **148**, 205–209
7. Shustov B. M., Naroenkov S. A., Efremova E. V., (2017). On population of hazardous celestial bodies in the near-Earth space. *Solar System Research*, **51**(1), 38–43
8. Terebizh V., (2011). New designs of survey telescopes. *Astronomische Nachrichten*, **332**, 714–742
9. Jeong S., Ahmad S., Barrillon P., et. all, (2012). The Slewing Mirror Telescope of the Ultra Fast Flash Observatory Pathfinder. *Proceedings of SPIE*, **8443**, 84432S
10. Wen Wei-Bin, Wang Fang, Li Chun-Lai, et. all, (2014). Data preprocessing and preliminary results of the Moon-based Ultraviolet Telescope on the CE-3 lander. *Research in Astronomy and Astrophysics*, **14**, 1674–1681
11. 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
12. Emel'yanenko V. V., Reitsema H. J., Naroenkov S. A., et. all, (2014). The orbit and dynamical evolution of the Chelyabinsk object. *Meteoritics and Planetary Science*, **49**, 2169–2174
13. Rodriguezcanabal J., (1986). Operational halo orbit maintenance technique for SOHO", *ESA Special Publication*, **255**(5), 335–341
14. Naroenkov S. A., Shustov, B. M., Emel'yanenko, V. V., (2013). On the arc length of observations of a small solar system body sufficient to classify it as hazardous. *Cosmic Research*, **51**(5), 335–341
15. Tonry . L., Denneau L., Heinze A. N., et. all, (2018). ATLAS: A High-cadence All-sky Survey System. *astro-ph.IM, arXiv*, 1802.00879