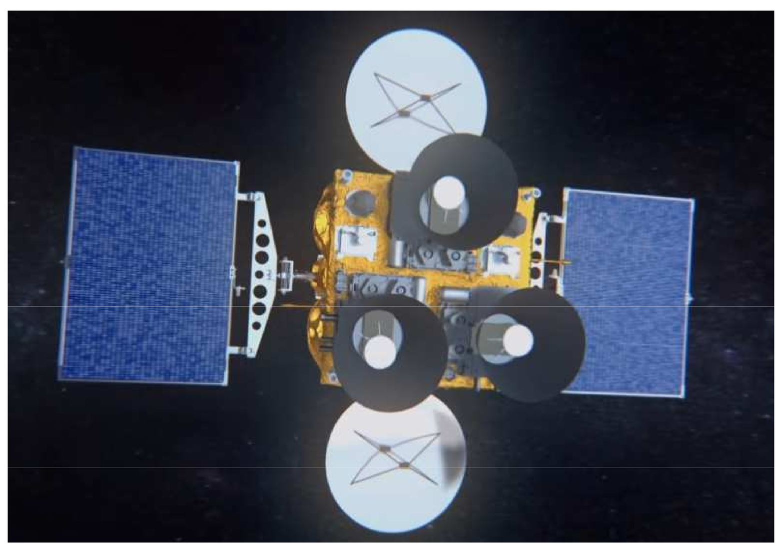

System of Observation of Day-time Asteroids (SODA)

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The Chelyabinsk event has revealed new challenges in the near Earth objects (NEOs) problem. Meteoroids of decameter size are considerably dangerous and they should be included in the coming programs of massive detection of potentially hazardous bodies. It is impossible to detect a good share of the bodies coming from the Sun by ground based instruments. To have an efficient system of detection it is strictly required to add space born telescope(s) to the ground based facilities.

We proposed the project of space system SODA (System of Observation of Day-time Asteroids) for exhaustive detection of decameter (larger than 10 m) bodies coming from the Sun direction to the near Earth space (Chelyabinsk type meteoroids). The set of medium-size (30 cm) wide field telescopes will be put into vicinity of L_1 (Earth-Sun) point. Observations will be performed in barrier mode. We describe major constituents and options of the project. The entire project could be implemented with off-shelf components. International cooperation is welcome.

Introduction: 10 m class NEOs problem

Main lessons of Chelyabinsk event on February 15, 2013 are as follows:

- NEOs of decameter size and larger can be dangerous.
- Chelyabinsk body that entered the Earth's atmosphere from day sky could not be discovered by any ground-based or near Earth space telescopes.
- We could not prevent such collisions. The only way to decrease the danger is to warn peoples about coming collision.
- Warning time should be not less than 4 hours.
- To detect the NEOs coming from the day sky and properly calculate its orbit we need space-born telescope located far away from the Earth.

We proposed the project of space system SODA (System of Observation of Day-time Asteroids) with aim to detect practically all day-time 10 m class NEOs.

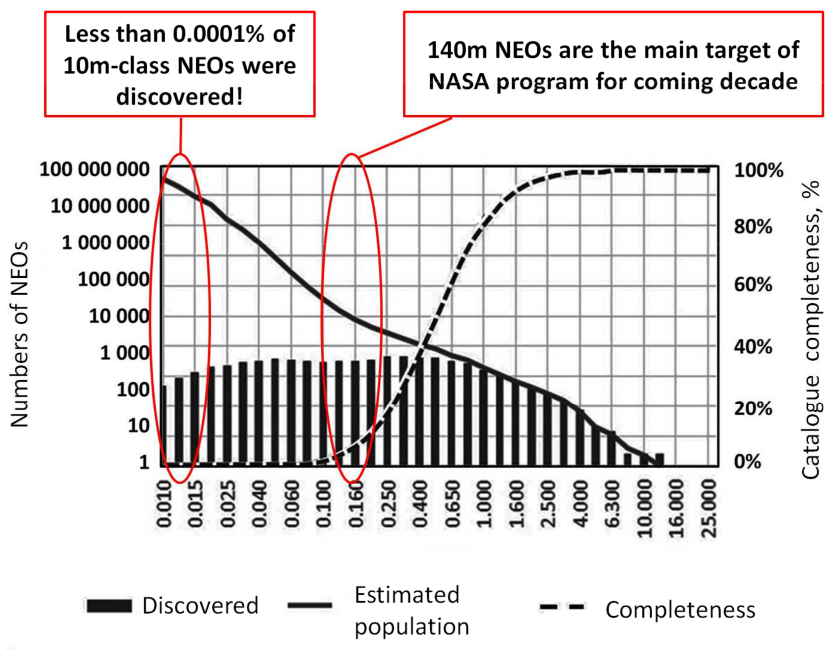

Fig. 1. Completeness of existing and future NEOs surveys (NASA).

SODA system goals

- To detect >90% of potential hazard bodies larger than 10 m coming from the Sun direction (day-time).
- To provide alert no later than 4 hour before possible collision.
- To predict the NEO atmosphere entry point with accuracy better than 10 km across orbit.
- To evaluate the size and mass of the observed NEO.
- The system should be low cost project.
- To collaborate with ground-based systems (e.g. ATLAS) that are focused on NEOs detection at night-sky.
- To be implemented in the international cooperation.

Day-time and night-time NEOs

Fig. 2 demonstrate the effectiveness of potential cooperation between full-scale ATLAS project and SODA project. It is possible to ensure all-sky detection of 10 m class NEOs at least for 11 hours before possible collision. Several hours of warning time provided by ATLAS and SODA projects is sufficient to decrease risks. Larger warning time implies dramatically larger cost.

We believe that combination of space-based (SODA) and ground-based (ATLAS) projects is a way to provide realistic all-sky protection of the Earth against 10 m class impactors.

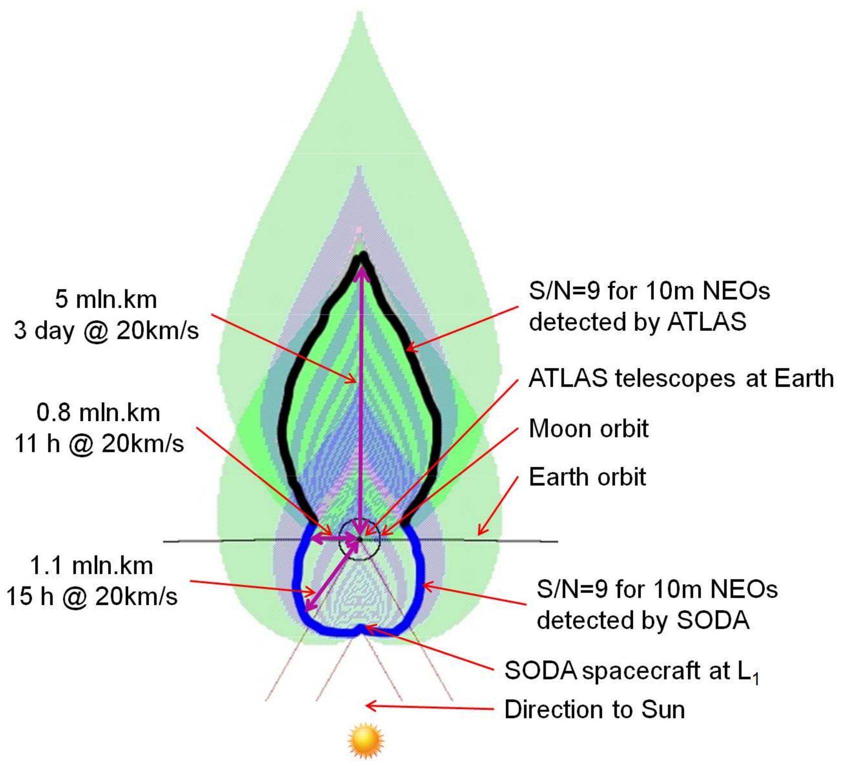

Fig. 2. Combination of visibility zones of 10 m NEOs for space-based (SODA , L_1 point) and ground-based (ATLAS) projects.

Estimates of system performance

Visibility zones

Detection zones for space telescope located at L_1 with given S/N ratio are shown in fig. 3 for following parameters:

size of the NEO	10 m
albedo	0.13
telescope	30 cm aperture, 2 arcsec resolution
detector	2e⁻ readout noise, 85% QE
exposure time	4 s

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.

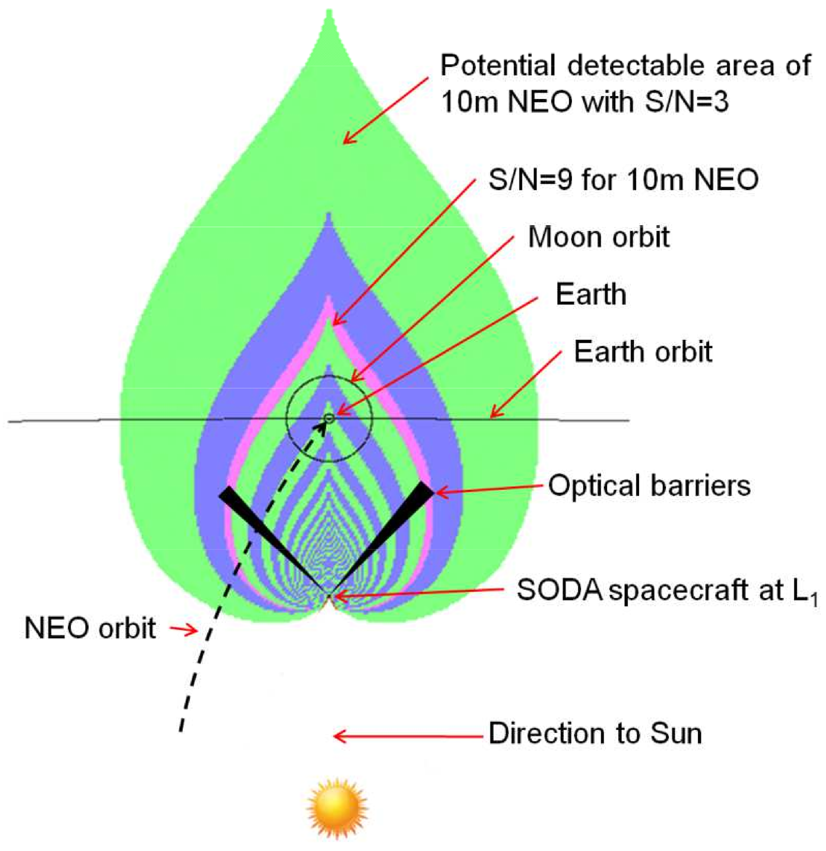

Fig. 3. Visibility zone of 10 m NEOs from L_1.

Numbers of detections and alerts

The SODA project is to discover about 3000 NEOs larger than 10 m coming into near Earth space in 5 year life time. It is expected to have one impactor in this period.

Astrometry accuracy

The accuracy of NEO orbit determination is related to astrometric accuracy and possibility to use triangulation method (two satellites option).

For the Chelyabinsk body the dispersion box of entry point into Earth atmosphere is 10×50 km under the following conditions (see fig. 4):

- Two spacecrafts in opposite location at halo orbit around L_1
- Observations are started 20 h before impact and are completed 4 h before impact
- Astrometric accuracy of single observation is 1.4"

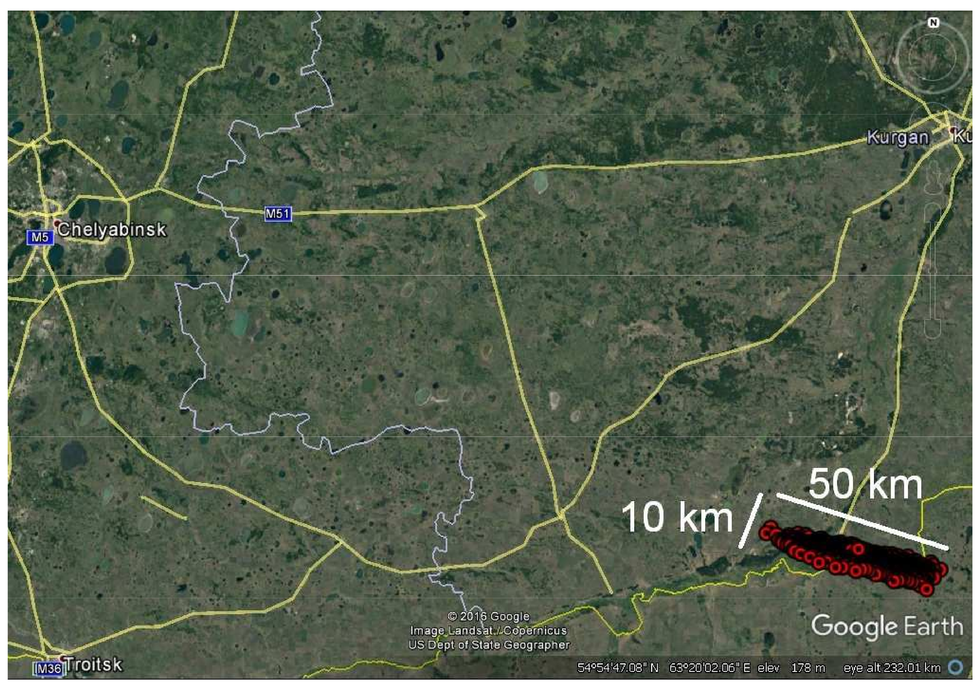

Fig. 4. SODA project simulation of the dispersion box for Chelyabinsk body atmospheric entry for two spacecrafts.

SODA spacecraft

The conceptual layout of the spacecraft with three 30 cm telescopes was shown in fig. 5. Parabolic high-gain antenna rigidly fixed on spacecraft with its axis coincides with the axis of the barrier cone. In front of the telescopes at distance of about 3 m the shamrock-shape mask is installed to screen the Earth light. While flying around L_1 point the SODA spacecraft axis is always pointed to the Earth.

Propulsion system should able to insert the spacecraft to L_1 vicinity point and ensure navigation around L_1 for 5+5 years.

Requirements to spacecraft are as follows:

Scientific payload mass	100-150 kg
Power consumption	100 W
Spacecraft angular stabilization	2 arcsec @ 5 s
Downlink channel rate	250 kbps

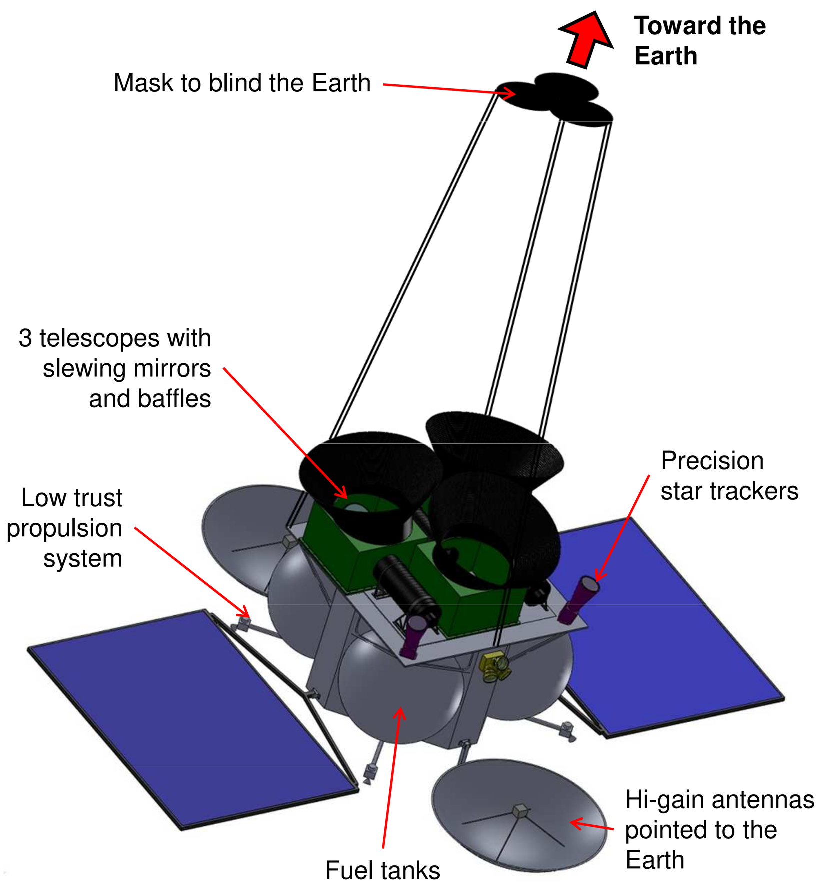

Fig. 5. SODA spacecraft concept.

Additional scientific goals

To increase the scientific outcome from the SODA mission we suggest to install additional scientific payload for:

- Sun observation on Sun-side of spacecraft
- Earth-observation on Earth-side of the spacecraft

On SODA spacecraft we can install additional 30 cm telescope with 0.6° field of view similar to EPIC of DSCOVR mission. With 4k×4k detector and 25% of radio link capacity for Earth observation program we have up to 5-10 images per hour with 4 km/pixel spatial resolution.

SODA project current status

- The SODA project is in Phase 0 (Mission Analysis/Identification)
- The request for funding for Phase A (Feasibility) was submitted to ROSCOSMOS
- International collaboration are welcome for the project as well as cooperation with other ground-based projects focused on detection of 10 m class NEOs.

SODA project video from television studio of Roscosmos https://youtu.be/m1Hw-sEB3UI

SODA project major features

The SODA project was based on several principal ideas and technical solutions that simplify the mission and reduce its cost.

- **To put spacecraft at L_1 point of Sun-Earth system**
  At this point small aperture telescope (25-30 cm) is efficient in detecting 10 m NEOs in optical wavelength.
- **To use barrier mode detection instead of all-sky survey**
  Barrier mode detection strategy significantly reduces requirements to survey rate, telescope field of view, detector size, etc.
- **To use slewing mirror for quick telescope repointing**
  This implies very flexible observation program, tight duty-cycle, redundancy.
- **Special mode of observation (target mode) for NEOs of special interest**
- **To put the mask in from of telescopes to blind the Earth**
  It helps to reduce scattered light in the telescope to observe NEOs at angular distance from the Earth down to 5°.
- **To use two spacecrafts located around L_1 in triangulation mode**
  - To increases accuracy of orbit determination.
  - Helps to eliminate the blind zones close to spacecraft.
  - To improve reliability of the system in case of one spacecraft completely fails.
- **To make data processing onboard**
  Helps to fit into realistic downlink channel of 0.25 Mbps.
- **To use dedicated network of ground radio link station to provide 24h bi-directional control**
  - Ensures fast response due to short warning time scale (several hours).
  - Ensures target mode of operation for dangerous NEOs.

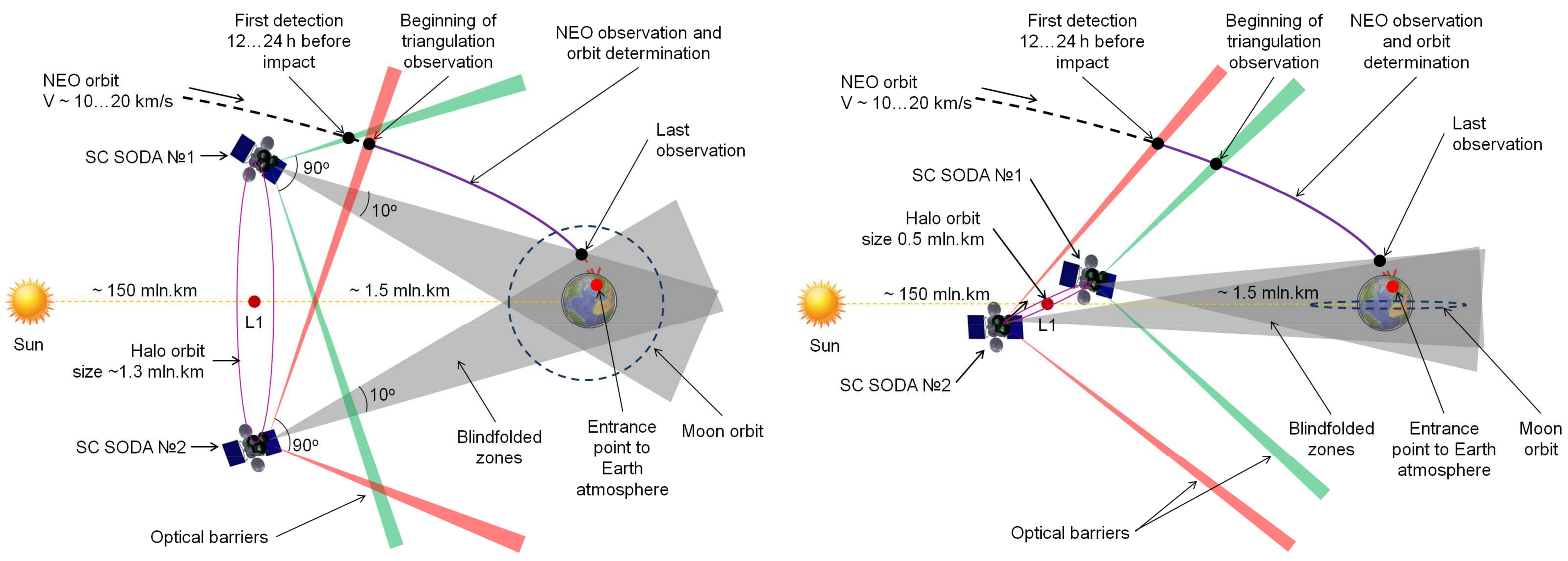

Fig. 6. Scheme of observation with SODA project. Left panel: X-Y projection, looking from ecliptic pole; right panel: X-Z projection, in the ecliptic plane.

In fig. 6 scheme of observation with SODA project for two spacecraft option is shown. The NEO flying from the Sun crosses the first optical barrier approximately one day before it closest approach to the Earth. The period of barrier observation is 3.5 minute. Typical NEO will be observed 8 times when crossing the barrier. This is not sufficient for accurate orbit determination, but quite sufficient to classify object as dangerous or not. The data are transmitted to the ground center where preliminary orbit was calculated. If the NEO is classified as object of special interest ground center sends a command to SODA to observe the object in target mode (observation cycle 3 min).

For impactors the observation was prolong as long as possible to determine the orbit with maximum possible accuracy. The last observation can be done at angular distance between NEO and the Earth about 5°, approximately 4 hours before impact.

The short summary of typical parameters and scenario of SODA operation are as follows:

Optical barriers	80 individual fields
Exposition on each field	4 s
Repointing time between adjacent fields	3 s
Barrier observation with 3 telescope	3.5 minute
Average NEO speed	15 km/s
Average distance (telescope-NEO)	0.4 mln.km
Time of crossing the barriers	30 minutes
Number of observation on barrier	8
Number of observation in target mode	up to 300, every 3 min

Critical technology of SODA project

Slewing mirror

One of the challenge of SODA project is the problem of very frequently repointing of the telescope (every few seconds) and accordingly frequently reading of the detector. We suggest to put full-aperture slewing mirror in front of each telescopes for quick repointing.

One of the successful demonstration of slewing mirror technology for telescope repointing in space are series of new-generation meteorological satellites Electro-L developed by Lavochkin Association (Russia). The satellites operates in geostationary orbit. The main spacecraft payload is MSU-GS - the imaging system that take images of the Earth every 30 minutes with resolution up to 1 km per pixel in visible and IR bands.

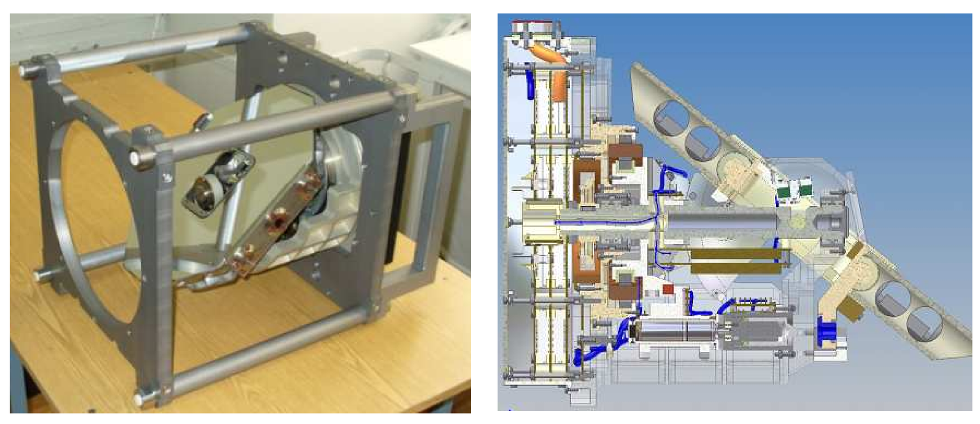

Fig. 7. 30 cm slewing mirror of MSU-GS, spacecraft “Electro-L”.

MSU-GS has an optical-mechanical scanner (flat slewing mirror) in front of telescope that moves continuously to provide frame and line scan to get two-dimensional image of the Earth using single-pixel detector. The size of the slewing mirror is about 30 cm, the mirror swing angle is ±5°, the final image size (angular field of view) is 20°×20°. MSU-GS mass is 88 kg, design lifetime – 7 years. Slewing mirror was developed by SKB SP IKI RAS.

Another example of the slewing mirror technology is UFFO instrument of spacecraft "Lomonosov". It has 10 cm telescope and 20 cm mirror. The movable mirror provides the tilting range of 70° with repointing time less than 1s. This system can be scale up for 25 cm telescope.

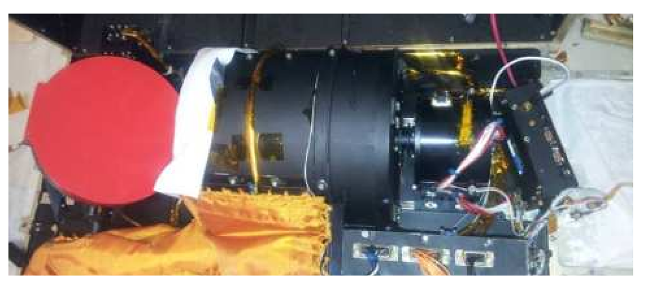

Fig. 8. 10 cm space telescope with 20 cm slewing mirror, UFFO, spacecraft "Lomonosov".

Two-dimensional gimbal with flat mirror to track the objects successfully used in the Moon-based Ultraviolet Telescope (MUVT) on Chang'e-3 (CE-3) lunar lander. Telescope aperture is 15 cm, field of view is 1.27°×1.27°.

The concept of SODA telescope with slewing mirror was presented in fig. 9. The main features of telescope with slewing mirror are as follows:

Telescope aperture	25-30 cm
Field of view	3.5°
Image area	~ 60×60 mm
Spectral range	400-700 nm
Image quality	1.5 arcsec
Limiting magnitude	17^m @ 4 s exp
Slewing mirror tilt angle	± 23° two axis
Mirror size	~ 55×40 cm
Moving and settling time	< 1 s @ 3°
Number of movements in 5 years	10^7

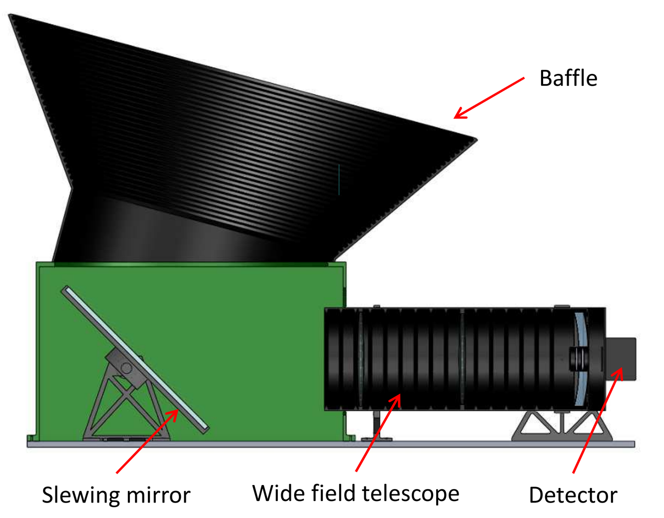

Fig. 9. The concept of SODA wide field telescope with slewing mirror.

Large format radiation tolerant detector with electronic shutter

For SODA telescope we need large format detector with fast readout and electronic shutter because of the short exposure (4 s) and huge amount of frames (10^7) during mission lifetime. The requirements to detector are as follows:

Image area	~ 60×60 mm
Format	~ 4k×4k
Spectral range	400-700 nm
QE	> 80 %
Readout time	< 2 s
Readout noise	< 8 e⁻ rms
Electronic shutter	Global electronic shutter was preferred

The best choice for SODA project are modern CMOS detectors with electronic shutter like e2v CIS 113 (2k×4.5k, two chips required) or GSENSE6060BSI (6k×6k). Extra large frame transfer e2v CCD 282 (4k×4k) also can be used.

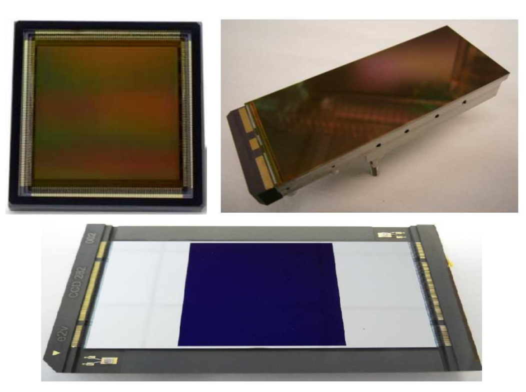

Fig. 10. GSENSE6060, E2V CIS 113 3-side CMOS, E2V CCD 282 frame transfer CCD.

Onboard data processing and radio link

One of the challenge of the SODA project is a big raw data flow from detectors (150Mbps) and requirement to have almost continuous transfer of scientific data from L_1 to ground processing center due to short warning time (several hours). From L_1 point typical downlink data rate provided with existing equipment is about 250 kbps using high gain parabolic X-band antenna of 1.3 m in diameter, 5 W-board transmitter (8.2 GHz) and 6-meter ground-based antenna. This implies necessity of onboard real time processing. Downlink channel capacity is sufficient to:

- Transfer of numerical information about the objects (coordinates, intensity)
- Transfer of small cropped image around the selected object(s) in target observation mode

It is necessary to organize SODA's own network of ground stations based on 6-m class antennas distributed longitudinally. Each time at least one (two for reliability) of the stations should be on the sunny side of the Earth.