DETECTION AND REGISTRATION OF ORBITAL "SPACE JUNK" WITH OPTICAL INSTRUMENTS ON SMALL SPACE PLATFORMS

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Abstract: *The launch of the first artificial satellite of the Earth in 1957 marked the beginning of the space age. At the same time, the appearance in the near space of a large number of objects of artificial origin that had exhausted their technological resource created a large number of non-working satellites and their small or large fragments. Thus, the extremely serious problem associated with the so-called space debris gradually appears. The number of these objects has increased significantly in recent years, especially in orbits up to about 2500 km. This makes their existence and the lack of technologies for their disposal an increasingly big problem for the international space community. Currently, space agencies of various countries are working on projects to search for, catalog and remove space debris from orbit. However, a significant part of such projects is aimed at searching for and removing from orbit large objects with dimensions larger than 10 cm. Objects below this size are much less studied, mainly due to the difficulties in observing such objects from the Earth's surface. One way to solve this problem is to develop space-based observation technologies using small optical devices deployed on nanosatellite platforms.*

Debris with sizes of about 10–1 cm can be effectively observed with optical instruments. The report presents the fundamental possibility of such registration, based on observations of debris in reflected sunlight. The possibility of determining the main orbital characteristics of debris, including from a single observing session, is also shown. The possibility of implementing an observational research program for space debris observations on board a specially designed nanosatellite is discussed. The characteristics of the scientific equipment are examined in detail, taking into account the dimensions and other limitations, as well as the capabilities of the equipment in terms of the distance to the observed objects, their size and physical characteristics.

ОТКРИВАНЕ И РЕГИСТРАЦИЯ НА ОРБИТАЛЕН „КОСМИЧЕСКИ БОКЛУК" С ОПТИЧЕСКИ ПРИБОРИ ВЪРХУ МАЛКИ КОСМИЧЕСКИ ПЛАТФОРМИ

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Резюме: *Изстрелването на първия изкуствен спътник на Земята през 1957 г. отбеляза началото на космическата епоха. Заедно с това, появата в близкия Космос на голям брой обекти от изкуствен произход, които са отработили своя технологичен ресурс създаде изобилие от неработещи спътници и техни малки или големи фрагменти. Така постепенно се появява изключително сериозния проблем, свързан с т. н. космически отпадъци. Броят на тези обекти се е увеличил значително през последните години, особено на орбити до около 2500 km. Това превръща тяхното съществуване и липсата на технологии за утилизация във все по-голям проблем за международната космическа общност. В момента космическите агенции на различни страни работят по проекти за търсене, каталогизиране и отстраняване на космически отпадъци от орбита. Значителна част от подобни проекти обаче са насочени към търсене и отстраняване от орбита на големи обекти с размери над 10 cm. Обектите под този размер са много по-слабо проучени, най-вече поради трудностите при наблюдението им от земната повърхност. Един от начините за решаване на този проблем е свързан с разработване на технологии за космически наблюдения с помощта на малки оптични устройства, разположени на наносателитни платформи.*

В доклада е представена фундаменталната възможност за ефективна регистрация на отломки с размери от 1 до 10 cm, базирана на наблюдения на отразената от тях слънчева светлина с оптични прибори. Показана е и възможността за определяне на основните орбитални характеристики на отломки, включително и от един наблюдателен сеанс. Обсъдена е възможността за прилагане на изследователска програма за наблюдения на космически отпадъци на борда на специално конструиран наносателит. Подробно са разгледани характеристиките на научното оборудване, съобразени с ограничените обеми, разстоянието до наблюдаваните обекти, техния размер и физически характеристики.

Introduction

A CubeSat is a small artificial satellite (nanosatel, picosatel), designed according to the "CubeSat Design Specification" standard. This standard defines several sizes of satellites, the smallest (and most commonly used) being designated 1U (from unit – "unit") and having the shape of a cube with an edge of 10 cm and a weight of 1.33 kg. The center of mass of the CubeSat must not deviate more than 2 cm from its geometric center for the 1U size. The standard and the multilateral cooperation program were created in 1999 by the California Polytechnic State University in cooperation with Stanford University with the aim of unifying and reducing the costs of launching small satellites into orbit (Fig.1a, b). Many universities and scientific institutes benefit from this, for whose limited budgets this is the only way to gain practical experience with real satellites and small instruments mounted on them [1]. The cost of constructing and launching one such satellite is in the range of \$65,000 – \$80,000. To date (2025) about 2,500 CubeSats have been manufactured and launched into space in the world. Most of them are 3U - 4U in size [2], [3]. There are no generally accepted specifications for the internal equipment of CubeSats, but in general, many manufacturers and organizations use compatible sets of standard equipment, which allows for a relatively short time to assemble a working satellite with a specific purpose [4, 5].

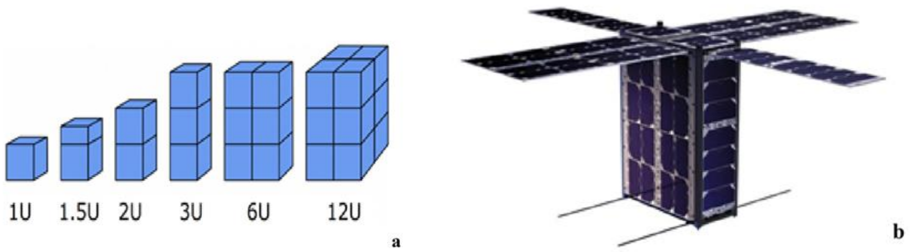

Fig. 1 a, b. Standard “CubeSat Design Specification” in geometric progression (a) and in orbital version with solar panels deployed (b)

This article considers the possibility of providing part of the tasks for optical registration of Space Debris (SD) to CubeSat technology. Space debris in the article should be understood as objects of artificial origin that no longer serve their original purposes and have uncontrolled movements and orbital parameters in near-Earth space. The sizes of these objects range from fractions of a millimeter to one meter or more [6]. Space debris larger than 10 cm are observed from Earth using radar technology [7]. At the submillimeter scale, their population can be studied by direct detection, for example, using piezoelectric dust detectors, including those mounted on CubeSat satellites [8, 9]. For those with a size of 1 mm to 10 cm, both methods are not applicable, the most effective being the search and registration of these objects using equipment located directly in space. The same can work in the optical range, i.e. to observe space debris based on the white light coming from the Sun reflected by them.

It must be said that man-made debris of this size is of the greatest interest from the point of view of ensuring the safety of space flights. This is due to the fact that although space debris larger than 10 cm are dangerous, they are few in number. Objects smaller than 1 mm are a large number, but they do not pose a fatal threat to satellites. However, those whose sizes range from 1 mm to 10 cm are, first of all, a large number of objects, as their mass and speed are large enough in kinetic impacts to cause fatal consequences [10, 11].

The article consists of four sections. The first presents the results of space debris research at the current stage. The second describes a conceptual design for creating optical observation equipment for CubeSat. The third describes the most suitable CubeSat orbits, where this equipment would be most effective for detecting, tracking and precise localization of space debris with sizes from 1 mm to 10 cm. The last section contains brief conclusions and inferences on the topic.

Materials and Methods

A. The problem of Space Debris

The main negative effect of the efforts of Mankind in the exploration of Space is its progressive pollution with man-made products accompanying space activities. The following fact is indicative. For almost 70 years of the space age, more than 5500 launches of Artificial Earth Satellites (AES) have been carried out. A small part of them fall into the Catalog of space objects that are observed by ground observatories. Many of them have an exhausted resource and form the list of so-called space debris [12]. This problem has become especially relevant in the last 20 years, in connection with a number of man-made disasters in space and the increase in the number of countries launching satellites [13], [14]. A huge number of scientific articles and books have been written about the causes and consequences of pollution of near-Earth space [15], [16]. The spent large satellites and their groups have been observed and cataloged as space debris, but the danger of small-sized SD is often ignored, and they are associated with the biggest problems for the space invasion of civilization (Fig. 2). Obtaining a more complete understanding of space debris (their quantity, composition, distribution in space, dynamics and potential danger) is hindered by at least two factors: a clear underestimation of the real danger of small debris and the shortage of appropriate observational measurements, which is a direct consequence of the lack of instruments capable of observing them [17].

Fig. 2. Distribution and concentration of the main clusters of space debris located in Earth orbits

When assessing the degree of danger from space debris, it is necessary to know not so much their mass as the number and speed of individual particles. Unlike small-sized debris, many spent spacecraft are launched into suitable low orbits and directed to descend into the dense layers of the atmosphere, in which they burn up. However, this is impossible for those of them that are in relatively high orbits [18], [19]. A very clear and indicative comparison is the determination of the growth of small space debris (with a size of 1 mm to 10 cm) for three years in one of the most "populated" orbital regions (at altitudes of 800 to 900 km) according to real observations with Haystack and HEX radars made in 2006 and 2009. This increase then averaged 20...30% (ibid.: [18]). Today (as of February 2025) it reaches dangerous levels of 45%, which threatens the existence and functioning of a number of satellite constellations in these regions of near-Earth space [20, 21, 22].

B. Various types of danger from space debris:

1) When controlling artificial satellites of the Earth and manned missions, carrying the threat of a potential collision with them;
2) For the population of the Earth and ground structures (especially for nuclear facilities and facilities for storing chemical and bacteriological weapons) as a result of falling large fragments of space debris;
3) On the ecology of the Earth and near-Earth space, reducing the transparency of near-Earth space and the atmosphere (which disrupts the exchange of light and heat that has developed over billions of years between the Earth and Space, and also creates interference in astronomical observations - mainly in the optical range;

4) On the degree of pollution of near-Earth space, provoking and accelerating a cascade effect as a result of collisions not only with existing space debris, which leads to its rapid increase.
As for large-sized space debris, the most immediate danger is posed by those falling into the 1st, 2nd and 4th categories. From the point of view of the danger to space activities in orbit around the Earth, the difference between small-sized space debris and large-sized ones is as follows:
1) Small-sized space debris is not catalogued and does not have sufficiently accurate data on its motion vectors, therefore collisions with it are unpredictable and cannot be avoided;
2) The amount of small orbital debris is at least several orders of magnitude greater than that of large ones, and this difference is progressively increasing;
3) The spatial distribution of small orbital debris clusters and their kinetic parameters change faster than the distribution and motion parameters of large ones, due to the larger surface area to mass ratio;
4) The real danger of a collision with small space debris (even in the submillimeter range) for operating spacecraft cannot be ignored;
5) A decrease in the transparency of near-Earth space and the atmosphere, which occurs mainly due to the accumulation of fine particles of small space debris, increases or decreases the flux of solar radiation in the wavelength ranges that dissociate molecular oxygen and ozone at altitudes of 15 – 30 km, and this will lead to significant changes in the Earth's ozone layer;
6) The nature and degree of danger from small debris varies significantly and depends on the parameters of the collision (angle, vector of the particle's velocity to the surface of the spacecraft, vulnerability of the impact site, etc.);
7) Due to significant difficulties in observing small-sized space debris, there is very little data on the quantity, composition, concentration and orbital elements individual particles and its dynamics [23].

Results and Discussion

A. Conceptual design for optical observation equipment for CubeSat

When Many authors have reported on experiments related to orbital optical observations of small-sized space debris [24]. Our experience in optical ground-based observations of artificial satellites of the Earth and space debris shows that for this purpose, high-aperture lenses in combination with fast-acting CCD cameras are particularly suitable, which allow observing relatively faint satellites and fragments thereof (up to 12–14 magnitude) [25]. In this sense, our main idea for using them as optical observation equipment for CubeSat, which we present in this article, is also.

The CubeSat satellite that we propose to use has dimensions of 6U [26]. It is equipped with four side solar panels that can be opened in a *2 x 2* scheme. Inside it is a module with standard equipment for cubesats, occupying a size of 2U and two individually developed modules (Fig. 3). The first is two optical cameras with a size of 1.5 U, and the second is a module for solar orientation and stabilization with a size of 0.5 U. The orientation and stabilization module includes a slot, a solar sensor and six actuators [27]. The solar sensor works on the principle of a camera with an aperture and a small lens, which projects a focused image of the Sun onto four diodes. The diodes are placed at the edges of the solar image so that the solar disk only partially covers them.

When the observation tract deviates from the direction to the Sun, its image shifts, which leads to a change in the signal of the diodes. The corresponding changes are converted into an error signal, according to which the satellite returns to its original orientation with the help of three gyroscopic flywheels. The orientation of the device is towards the Sun. This orientation provides maximum illumination of the solar panels (maximum power about 20 W),

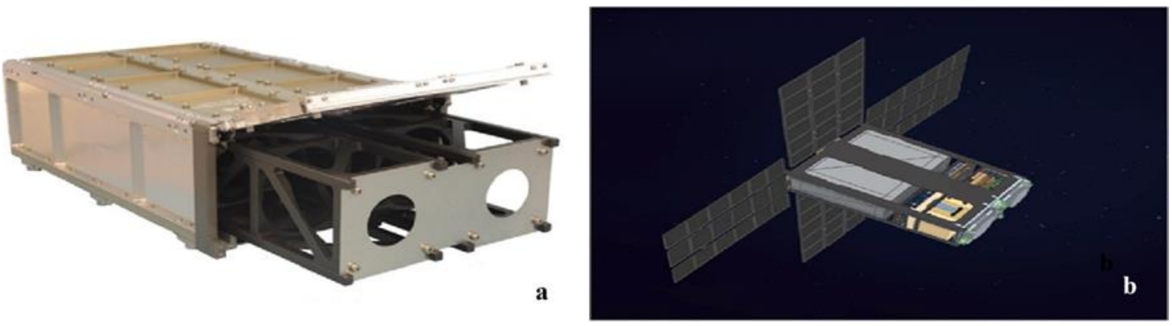

Fig. 3 a, b. Standard 6U CubeSat module with the internal framework
supporting the optical unit with two lenses (a), as well as four side solar panels (b)

While at the same time providing maximum illumination of the space debris from the sun's rays for the optics. The optical camera module includes two sunshades, two lenses, two CCD detectors, as well as four boards, a detector and a processor for built-in image processing. The aperture of the cameras is 80 mm. The dimensions of the CCD detectors are 1024 x 1024 pixels.

It is expected that when registering space debris from the CubeSat satellite, the specific object will be visible as an elongated, clearly distinguishable trail against the background of fixed stars. It is planned that both sensors will look in the same direction, and the trail of the object will be visible on both detectors. Such simultaneous observations allow, among other things, to distinguish situations when we have a real registration of space debris fragments as registrations are also possible because events occur when a charged particle hits the detector. In this case, a trace is also formed, but it is only visible to the one detector with which the particle interacts [28]. It should be noted that these two cases can be distinguished working with a single sensor equipped with a high-speed electronic shutter, which allows two consecutive images to be obtained in less time than the flight time of the specific fragment in the sensor's field of view. However, this introduces additional requirements for the design and control of the satellite in observational mode. The satellite is intended to perform primary processing of observations on board. Such processing is an analysis of the images in order to detect and record traces of space debris against the background of fixed stars. The presence of primary processing significantly reduces the requirements for the volume of information that must be transmitted by telemetry at a later stage. The size of the images from both cameras is about 4 MB. After the primary analysis, the information that must be recorded for tranmission to Earth for specific tracks of space debris on the images is small and 16–18 bytes are sufficient (these are only the coordinates of the end points of the specific tracks). This saves about 106 times the target data that would otherwise have to be transmitted.

The sensitivity of each of the cameras can be determined, in this case using formula (1), taken from the article [24], where D is the camera aperture (80 mm); F-focal length (80 mm); R is the distance to the object; α is the albedo of the object (we assumed it to be equal to 0.1); υ is the speed of space debris. The remaining parameters are characteristics specific to each CCD matrix, as well as the flux of solar radiation: h is Planck's constant $h = 6.63 \cdot 10^{-34}$ J·s; c – speed of light $c = 3 \cdot 10^{8}$ m/s; λ – wavelength of electromagnetic waves λ = 500 nm; η – quantum efficiency η = 0.4; q is the ADC conversion coefficient q = 0.1; μ – size of the individual pixel of the CCD matrix μ = 13.5 μm; σ is the detector noise (approximately 20).

The calculated value of the minimum size of space debris that can be observed by the satellite is denoted by a:

(1) a = √(4hcσRFυ)/(qηdλπD2Pμ)

The sizes of space debris that can be recorded by the cameras, depending on the speed of the object and the distance to it, are given in Table 1.

Table 1. Sizes of space debris that can be recorded by the cameras, depending on the speed of the object and the distance to it.

R, km	**Size, cm at υ = 1km/s**	**Size, cm at υ = 5km/s**	**Size, cm at υ = 10km/s**	**Size, cm at υ = 20km/s**
1	0,2	0,6	0,8	1,1
10	0,8	1,7	2,5	3,5
100	2,5	5,6	7,8	11,0
500	5,5	12,3	17,4	24,7
1 000	12,2	25,5	35,6	62,2

Taking into account the above, a preliminary program can be made for the CubeSat satellite for observing space debris of different size. The planned field of view of the cameras is 8o. This provides a full sky overview with the realization of approximately 440 images, which corresponds to approximately one observing day of the CubeSat satellite's life (Fig. 4).

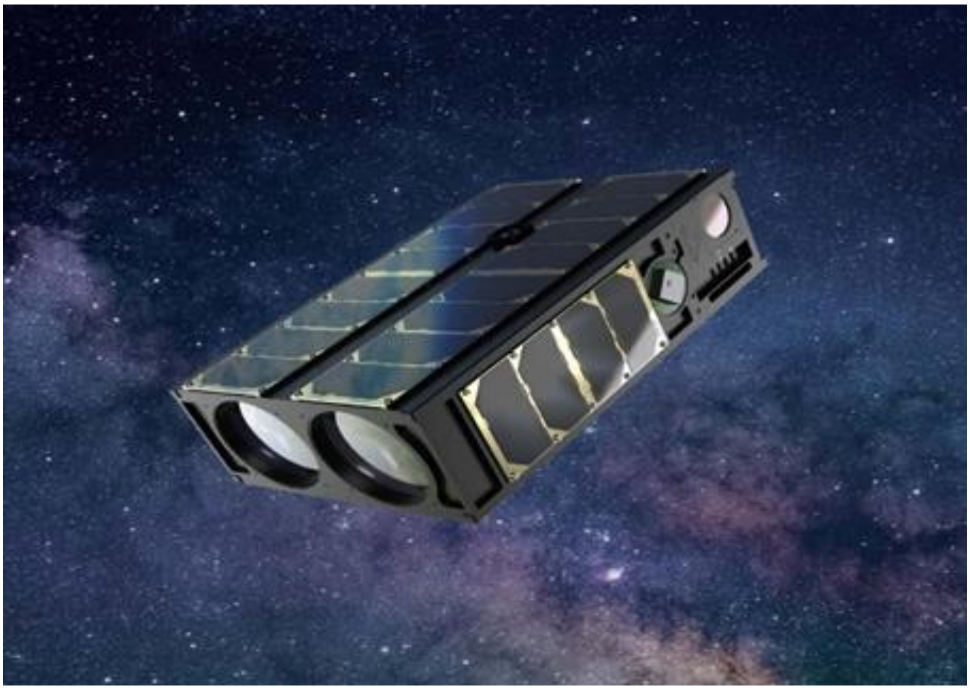

Fig. 4. General view of the CubeSat satellite for orbital registration of space debris in the operating position without open solar panels

The visibility range is from 10 km to 1000 km. In 120 days (the probable life of the cubesat) about 45,000 images can be obtained and a spatial volume of near-Earth space of 200 × 200 km for centimeter objects and approximately 20,000 × 20,000 km for 10-centimeter objects can be seen. The average probability of registering specific fragments is estimated as one event (track) per 100–200 images. Therefore, the total number of registrations could be 300–600 events, which can serve as a statistical estimate of the space debris population and its distribution by velocity at specific orbits.

Conclusions

In practical implementation and commissioning, the project for optical observation equipment for CubeSat can solve the following tasks:

- continuous observation in a certain time interval of space debris, the fragments of which are located in low-Earth orbit space;
- observation of space debris with a given rate and duration of tracking;
- generation of coordinate information for objects from the space orbital debris cloud, determination of the effective scattering area of individual fragments, the fact of possible rotation of the object;
- calculation of the orbital parameters of the movement of space orbital debris based on the accumulated measurements and determination of the dynamics and evolution of their movement.

Automation of data exchange between the telemetry of the CubeSat satellite and the ground center allows for effective use of the resources of the observation equipment and rapid receipt of information from it about the most important objects in the space debris cloud. The duration of the individual observation sessions was chosen as a compromise between achieving a relatively high accuracy in determining the motion parameters of individual fragments and saving energy and time resources of the satellite. The average duration of satellite observation by CubeSat is sufficient for reliable determination of orbital parameters of space debris in the range of 1 – 10 cm and is about 1 to 2 minutes.

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