Development of lidar system based on nanosatellite for composition of 3D space debris map

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Abstract. A CubeSat mission is described in this paper, which deals with the space debris identification, classification and aggregation. The mission is responsible for debris observation close to the most populated orbit by on-board laser illuminator (lidar) system. An optical scheme of lidar was described. The energy balance and range of work were calculated. The architecture and properties of CubeSat are based on the multi-purpose block-modular platform «Synergy» [1].

1. Introduction

The problem of pollution of near-Earth space hors de spacecraft serious faced by the scientific community, as this may cause accidents and the impossibility of further space exploration [2]. The main reason for the formation of space debris (SD) is man-made, i.e. SD called all objects, including fragments and elements found in the Earth's orbit, which incapacitated. Increasing the amount of space debris in near-Earth orbits leads to an increased risk of collisions with spacecraft [3, 4]. In turn, such accidents in the future may be an additional significant cause of space debris. According to the European Space Agency [5], the SD is classified by size into three groups: large, more than 100 mm in diameter; medium, from 10 mm to 100 mm in diameter; small, less than 10 mm in diameter (see Table 1 «Distribution of space debris classified by size»).

| Size range          | Number of objects       | % of total mass  |
|---------------------|-------------------------|------------------|
| large (> 100 mm)    | >10000                  | > 99,5           |
| medium (1 mm - 100 mm) | tens of millions      | < 0,05           |
| small (< 1 mm)      | trillions               | < 0,01           |

Since most of the SD localized in low Earth orbit (LEO), then in the research and development of a miniature device lidar we will assume that the nano-satellite will be launched exactly into LEO.
Figure 1. Altitude distribution of the concentration of cataloged space objects [5].

In figure 1 shows the density of SD, distributed over altitudes, and as can be seen, most of SD is located at altitudes from 700 to 900 km, and the density peak is at an altitude of 775 kilometers. The other two peaks are at 425 and 1475 kilometers. Thus, in general, the range of heights useful for searching for space debris is from 400 to 1500 km. This range allows you to cover a significant part of the SD [6, 7].

At the moment, the main sources of space debris catalogs are studies conducted at radar stations with electronically controlled beam directivity and phased antenna arrays [9–11]. In 2014, more than 200 thousand objects of more than 10 mm in size and more than 330 million objects of more than 1 mm in size with a total mass of more than 5000 tons were in near-Earth space. Only about 10% of SD is detected, tracked and cataloged using ground-based radar and optical equipment. Thus, the development of a miniature lidar for the detection of space debris based on nanosatellite is highly relevant, since: 1) most of the SD is not cataloged 2) the main work on finding and cataloging the SD is done using ground-based radars [12].

2. Materials and methods

A laser remote sensing system, or lidar, is a contactless means for measuring the parameters of a remote target, in which laser radiation is directed through space to a target, and radiation scattered by a target from this sensing distance is collected on a photodetector [13]. A lidar consists of a laser transmitter and receiving telescope with a spectrum analyzer and a photodetector [14]. The lidar control and signal processing from the photodetector is carried out by a specialized electronic device [14]. Consider the main areas of application of lidar systems used on the basis of the spacecraft as a payload [15]:

1) Agriculture.
   ✓ Inventory of land: the allocation and identification of agricultural areas. For this kind of research, the panchromatic radiation range is used in the lidar system: 0.56; 0.6; 1.55-1.7; 10-12 micron.
   ✓ Identification of different types of agriculture: yield assessment, collection of information for planning of planting, assessment and forecast of the crop. Radiation ranges used: 0.478-0.508; 0.566-0.638; 0.725-0.920 microns.

2) Climatology.
   ✓ Detection of atmospheric gases causing an increase in average annual temperature, destruction of the ozone layer, formation of smog, for example, such gases as: CO2, CH4, N2O, CFM [11].
   ✓ Monitoring of atmospheric ozone: ozone depletion, increased tropospheric ozone.
   ✓ Observation of aerosols in the atmosphere of the Earth: determination of the concentration and density of aerosols in the atmosphere.

3) Mineral resources.
   ✓ Search areas suitable for wind energy: definition and structure of the atmospheric winds, temperature fields of data analysis.
Search for areas suitable for design of hydroelectric power plants: the detection of large precipitation zones, the determination of full-flowing rivers and other tasks related to the control of water resources.

Exploration tasks of various scales: detection of planetary cracks, tectonic anomalies, identification of areas of geological activity, oil and gas geological zoning and analysis of such processes.

4) Water resources.

The study of individual ice floes: the study of individual ice blocks (information about their fracture, thickness, etc.).

Groundwater detection, depth, flood monitoring, water quality monitoring.

The problem of detecting and cataloging of space debris by using systems based on nanosatellites, based on the base «https://nanosats.eu» service data is reflected in the projects and ARMADILLO REMOVEDEBRIS.

Next, we define the characteristics of the lidar, taking into account the fact that the task of the optical system is to detect the SD and present the final data in the form of a three-dimensional map of the SD. There are several ways to accomplish such a task. In one of the above missions detection SD for three-dimensional image used flash lidar, by which one can recover from the parameters determining the size and distance to the object of studying the individual parts of the output image of the investigated object depth map [16]. Another option for obtaining a three-dimensional SD map is the use in the optical scheme of MEMS-mirrors, which are micro-dimensional mirrors mounted on a chip. MEMS-mirrors are miniature microscanners. Their significant advantage is miniature and low energy consumption. However, the disadvantages of MEMS-mirrors do not allow them to be used in the receiving optical scheme within the framework of this work: the mechanical angle of inclination of the MEMS-mirrors is very small and usually amounts to several degrees (a single-axis MEMS-mirror with an aperture of 1.7 mm has a maximum scanning angle equal to 8 degrees [17]).

Another way to get a three-dimensional image is to use a laser range finder and a CCD matrix as a radiation receiver, while the lidar should work in the signal accumulation mode (multiple repetition of the target sounding, summing the stored results and their subsequent computer processing, thus obtaining a cloud of points object image [18]). However, the three-dimensional image in this case can be obtained only with the help of mechanical movement of the lidar system, which is undesirable in the conditions of use on nanosatellite [19–21].

Based on this, the optimal solution seems to be the construction of an optical scheme based on a flash lidar, since in such a lidar, a single laser pulse is used, highlighting the entire necessary scene to obtain a three-dimensional image of moving targets, and the lidar system itself may be in motion [19].

In flash lidars photodiode arrays are used as radiation detectors. To ensure the shooting of large scenes and to achieve high resolution, it is necessary that each pixel has its own scheme for measuring the time intervals between the moment of radiation of a laser pulse and the moment of receiving radiation reflected from an object. Based on [23], resolution accuracy of a flash lidar is limited by several factors, including laser pulse width, receiver bandwidth, counting circuit resolution, receiver shot noise, etc. In one study [24] published in the journal «Applied Physics B», the authors showed developed flash LIDAR using the Pockels cells (PC is a crystal, located between the two prisms Nicolas, which do not transmit light in the absence of an electric field) and a photodiode. The PCs change the polarization state of the radiation passing through it as a time function, thus allowing the photodiode, together with micro-polarizers, to measure the polarization state, obtaining information about the distance to the reflection object.

However, the photodiode is capable of measuring the range of only one point at a time, therefore, to obtain a three-dimensional image, this system requires a scanning part. Another variant of the implementation of three-dimensional scanning in this case consists in the use of a micro-polarization CCD matrix with high resolution in conjunction with a polarization-modulated PC. The high resolution of the micro-polarization CCD matrix, for example, 1024x1024 pixels, will allow to obtain three-dimensional images with high resolution accuracy up to several millimeters.
3. Results

Light and energy calculation involves determining the maximum measured range for a given parameter: the laser pulse power, the detection characteristics of the radiation receiver, the conditions for using the lidar system. Assume a number of assumptions for determining characteristics of the lidar system: suppose that the diagram backlight is adopted as a flat cone angle $\gamma$ at the apex, wherein the probe radiation is uniformly distributed.

\[ \gamma = \sqrt{\frac{4 \cdot \Omega_p}{\pi}}. \]  (1)

Moreover, if the diverging laser beam is a cone, then there is a relationship between the flat divergence angle $\omega$ and solid $\Omega_p$:

\[ \Omega_p = 2\pi \cdot (1 - \cos \left(\frac{\omega}{2}\right)). \]  (2)

The source of laser radiation with radiation power $P_l$ passing through the optical system with transmission $\tau_p$ creates a probe beam with the energy of light:

\[ I = \frac{P_l \cdot \tau_p}{\Omega_p}. \]  (3)

And at a distance $R$ an energy illumination will be created:

\[ B = \frac{P_l \cdot \tau_p}{\Omega_p \cdot R^2}. \]  (4)

Taking the SD as an object diffusely scattering radiation of the backlight, it is assumed that its surface reflects the radiation according to Lambert's law:

\[ P(\psi) = P_0 \cdot \cos(\psi), \]  (5)

where $P_0$ – power illumination beam incident on the reflecting surface, and $\psi$ – angle relative to the normal to the reflecting surface.

In evaluating the performance of the lidar on a diffusely reflecting surface, it is made extrapolation Lambertian surface [25]. The part of SD with the area $S_{km}$ and reflection coefficient $\rho_{km}$ illuminated by the probe beam, will have the energy intensity of light:

\[ I = \frac{P_l \cdot S_{km} \cdot \rho_{km} \cdot \tau_p}{\Omega_p \cdot \Omega_{otp} \cdot R^2}, \]  (6)

where $\Omega_{otp}$ is the solid angle of propagation of radiation reflected by an object, equal to $\pi$ radians, since The reflected radiation is considered to be distributed uniformly in a solid angle forming a cone.

In the plane of the lidar, the energy illumination will be created by the radiation reflected from the object:

\[ B = \frac{P_l \cdot S_{km} \cdot \rho_{km} \cdot \tau_p}{\Omega_p \cdot \Omega_{otp} \cdot R^4}. \]  (7)

Receiving lens diameter $d_0$ will collect the power of the reflected signal is equal to:

\[ P_{pr} = \frac{P_l \cdot S_{km} \cdot \rho_{km} \cdot d_0^2 \cdot \tau_p}{\gamma^2 \cdot \Omega_{otp} \cdot R^4}. \]  (8)

Given the transmittance $\tau_{pr}$ receiving optical system on the photoreceiving device, namely on the CCD matrix, the power will flow equal to:

\[ P_{FP} = \frac{P_l \cdot S_{km} \cdot \rho_{km} \cdot d_0^2 \cdot \tau_p \cdot \tau_{pr}}{\gamma^2 \cdot \Omega_{otp} \cdot R^4}. \]  (9)

Taking into account [26], we consider the minimum acceptable value of the signal-to-noise ratio $\mu$ to be 1.5.

Using the data presented in Table 2, determine the current strength $I_f$, which occurs when the calculated power $P_l$ arrives at the photodetector:
Thus, to determine the signal-to-noise value for a given distance:

\[ \mu = \frac{I_f}{I_{\text{noise}}} \]  

Table 2. Initial data for calculating the range of the flash lidar.

| Name of value                        | Value   | Units of measure |
|-------------------------------------|---------|------------------|
| Laser pulse power, \( P_1 \)        | 100 W   |                  |
| Coefficient of the optical transmission system, \( \tau_p \) | 0.92    | dimensionless    |
| Angle of divergence of the laser, \( \omega \) | 0.34907 | rad              |
| Solid angle of radiation, \( \Omega_p \) | 0.095   | steradian        |
| Area of the object being probed, \( S_{\text{km}} \) | 0.005 m² |                  |
| Reflection coefficient, \( n_{\text{km}} \) | 0.82    | dimensionless    |
| Solid angle of reflected radiation, \( \Omega_{\text{abp}} \) | \( \pi \) | rad              |
| Diameter of the receiving lens, \( d_{\text{pr}} \) | 0.041 m |                  |
| Noise Current CCD matrix, \( I_{\text{noise}} \) | \( 2.4 \cdot 10^{-19} \) A |                  |
| A/W ratio for laser wavelength \( \lambda_l = 850 \) nm | 0.6 | \( B^{-1} \) |

Table 3. The results of calculating the value of the power \( P_1 \) incident on the photodetector and the signal-to-noise value \( \mu \) for different object ranges with linear dimensions \( l = 10 \) mm and \( l = 100 \) mm at a constant reflection coefficient.

| \( R \), m | \( l = 10 \) mm, \( n_{\text{km}} = 0.9 \) | \( l = 100 \) mm, \( n_{\text{km}} = 0.9 \) |
|------------|-------------------------------------------|-------------------------------------------|
| \( P_1 \), W | \( I, \) A | \( \mu \) | \( P_1 \), W | \( I, \) A | \( \mu \) |
| 1 | \( 3.22 \cdot 10^{-5} \) | \( 2.90 \cdot 10^{-5} \) | \( 1.21 \cdot 10^{14} \) | \( 3.22 \cdot 10^{-3} \) | \( 2.90 \cdot 10^{-3} \) | \( 1.21 \cdot 10^{16} \) |
| 100 | \( 3.22 \cdot 10^{-13} \) | \( 2.90 \cdot 10^{-13} \) | \( 1.21 \cdot 10^{6} \) | \( 3.22 \cdot 10^{-11} \) | \( 2.90 \cdot 10^{-11} \) | \( 1.21 \cdot 10^{8} \) |
| 500 | \( 5.16 \cdot 10^{-16} \) | \( 4.64 \cdot 10^{-16} \) | \( 1.93 \cdot 10^{3} \) | \( 5.16 \cdot 10^{-14} \) | \( 4.64 \cdot 10^{-14} \) | \( 1.93 \cdot 10^{5} \) |
| 1000 | \( 3.22 \cdot 10^{-17} \) | \( 2.90 \cdot 10^{-17} \) | \( 1.21 \cdot 10^{2} \) | \( 3.22 \cdot 10^{-15} \) | \( 2.90 \cdot 10^{-15} \) | \( 1.21 \cdot 10^{4} \) |
| 2000 | \( 2.02 \cdot 10^{-18} \) | \( 1.81 \cdot 10^{-18} \) | \( 7.55 \) | \( 2.02 \cdot 10^{-16} \) | \( 1.81 \cdot 10^{-16} \) | \( 7.55 \cdot 10^{2} \) |
| 3000 | \( 3.98 \cdot 10^{-19} \) | \( 3.58 \cdot 10^{-19} \) | \( 1.56 \) | \( 3.98 \cdot 10^{-17} \) | \( 3.58 \cdot 10^{-17} \) | \( 1.56 \cdot 10^{2} \) |
| 4000 | \( 1.26 \cdot 10^{-19} \) | \( 1.13 \cdot 10^{-19} \) | \( 0.472 \) | \( 1.26 \cdot 10^{-17} \) | \( 1.13 \cdot 10^{-17} \) | \( 47.2 \) |
| 5000 | \( 5.16 \cdot 10^{-20} \) | \( 4.64 \cdot 10^{-20} \) | \( 0.193 \) | \( 5.16 \cdot 10^{-18} \) | \( 4.64 \cdot 10^{-18} \) | \( 19.3 \) |
| 6000 | \( 2.49 \cdot 10^{-20} \) | \( 2.24 \cdot 10^{-20} \) | \( 9.32 \cdot 10^{-2} \) | \( 2.49 \cdot 10^{-18} \) | \( 2.24 \cdot 10^{-18} \) | \( 9.32 \) |
| 7000 | \( 1.34 \cdot 10^{-20} \) | \( 1.21 \cdot 10^{-20} \) | \( 5.03 \cdot 10^{-2} \) | \( 1.34 \cdot 10^{-18} \) | \( 1.21 \cdot 10^{-18} \) | \( 5.03 \) |
| 8000 | \( 7.87 \cdot 10^{-21} \) | \( 7.09 \cdot 10^{-21} \) | \( 2.95 \cdot 10^{-2} \) | \( 7.87 \cdot 10^{-19} \) | \( 7.09 \cdot 10^{-19} \) | \( 2.95 \) |
| 9000 | \( 4.92 \cdot 10^{-21} \) | \( 4.42 \cdot 10^{-21} \) | \( 1.84 \cdot 10^{-2} \) | \( 4.92 \cdot 10^{-19} \) | \( 4.42 \cdot 10^{-19} \) | \( 1.84 \) |

From the results of table 3 it can be seen that the maximum range of a lidar system when operating on a point diffuse object is 3 km with a laser pulse power of 100 watts. The graph of the signal-to-noise value versus the object distance, taking into account its linear dimensions, and hence the area, is shown in figure 2. In consequence of the fact that SD may be composed of different materials should analyze the signal-to-noise ratio as a function of object distance at different reflection coefficients of the material. The calculated values are presented in table 4.

For a qualitative assessment of the possible number of detected parts of the SD, we turn to [27]. So, the author of this paper offers the following version of a simple estimate of the number of particles:

\[ \Delta N = S \cdot \rho \cdot V \cdot \Delta t, \]  

where \( \rho \) – density of particles at a predetermined orbit SD, \( V \) – velocity of the incident particles, \( \Delta t \) – time interval, and \( S \) - cone area through which the particles equal to:

\[ S = \frac{l^2 \cdot \omega}{2} \]
where \( L \) – distance lidar action, and \( \omega \) – angle divergence of laser radiation.

**Figure 2.** Graph of the ratio of the signal-to-noise ratio of the distance for different linear dimensions of the particles SD.

**Table 4.** The results of calculating the value of the power of \( P_f \) reflected from the object and the signal-to-noise value \( \mu \) for different object ranges with reflection coefficients \( \rho_{lm} = 0.6 \) and \( \rho_{lm} = 0.9 \) at a constant size.

| \( R, m \) | \( I = 10 \text{ mm}, \rho = 0.6 \) | \( I = 10 \text{ mm}, \rho = 0.9 \) |
| --- | --- | --- |
| \( P_f, W \) | \( I, A \) | \( \mu \) | \( P_f, W \) | \( I, A \) | \( \mu \) |
| 1 | 2,14\(\cdot10^{-6}\) | 1,93\(\cdot10^{-3}\) | 8,05\(\cdot10^{13}\) | 0,0032 | 0,0029 | 1,21\(\cdot10^{16}\) |
| 100 | 2,15\(\cdot10^{-11}\) | 1,93\(\cdot10^{-13}\) | 8,05\(\cdot10^{5}\) | 3,22\(\cdot10^{11}\) | 2,90\(\cdot10^{11}\) | 1,21\(\cdot10^{8}\) |
| 500 | 3,44\(\cdot10^{-16}\) | 3,10\(\cdot10^{-16}\) | 1,29\(\cdot10^{5}\) | 5,16\(\cdot10^{14}\) | 4,64\(\cdot10^{14}\) | 1,93\(\cdot10^{9}\) |
| 1000 | 2,15\(\cdot10^{-17}\) | 1,93\(\cdot10^{-17}\) | 8,05\(\cdot10^{1}\) | 3,22\(\cdot10^{-15}\) | 2,90\(\cdot10^{-15}\) | 1,21\(\cdot10^{4}\) |
| 2000 | 1,34\(\cdot10^{-18}\) | 1,21\(\cdot10^{-18}\) | 5,03\(\cdot10^{-1}\) | 2,02\(\cdot10^{-16}\) | 1,81\(\cdot10^{-16}\) | 754,8 |
| 3000 | 2,65\(\cdot10^{-19}\) | 2,39\(\cdot10^{-19}\) | 0,99 | 3,98\(\cdot10^{-17}\) | 3,58\(\cdot10^{-17}\) | 149,1 |
| 4000 | 8,40\(\cdot10^{-20}\) | 7,56\(\cdot10^{-20}\) | 0,32 | 1,26\(\cdot10^{-17}\) | 1,13\(\cdot10^{-17}\) | 47,2 |
| 5000 | 3,44\(\cdot10^{-20}\) | 3,10\(\cdot10^{-20}\) | 0,13 | 5,16\(\cdot10^{-18}\) | 4,64\(\cdot10^{-18}\) | 19,3 |
| 6000 | 1,66\(\cdot10^{-20}\) | 1,49\(\cdot10^{-20}\) | 6,21\(\cdot10^{-2}\) | 2,49\(\cdot10^{-18}\) | 2,24\(\cdot10^{-18}\) | 9,3 |
| 7000 | 8,95\(\cdot10^{-21}\) | 8,06\(\cdot10^{-21}\) | 3,35\(\cdot10^{-2}\) | 1,34\(\cdot10^{-18}\) | 1,21\(\cdot10^{-18}\) | 5 |
| 8000 | 5,25\(\cdot10^{-21}\) | 4,72\(\cdot10^{-21}\) | 1,97\(\cdot10^{-2}\) | 7,87\(\cdot10^{-19}\) | 7,09\(\cdot10^{-19}\) | 2,9 |
| 9000 | 3,28\(\cdot10^{-21}\) | 2,95\(\cdot10^{-21}\) | 1,23\(\cdot10^{-2}\) | 4,92\(\cdot10^{-19}\) | 4,42\(\cdot10^{-19}\) | 1,84 |

**Figure 3.** Graph of the ratio of the signal-to-noise ratio of the distance for different reflection coefficients of particles SD.
4. Conclusion
Using the data available in [27, p. 159], we obtain that in 1 second about 3 objects with a size greater than 10 mm will pass through the light cone formed by the lidar system. If it is necessary to increase the range of the proposed lidar system [28], a more powerful nanosecond laser with a pulse power of several kW should be used.

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