

# Determination of Space Debris Coordinates by Means of a Space Service Vehicle

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**Abstract** – The problem of space debris utilization is quite relevant nowadays and has a global character. The space industry experts from all over the world are working on the task of removing space debris. This article proposes the method of determining space debris coordinates by means of the airborne equipment of a space service vehicle. The set of airborne equipment includes a global navigation satellite system receiver, an inertial navigation system and a laser radar. To study the accuracy characteristics of the proposed method under different initial conditions a series of simulations was performed. They showed that the accuracy of determining space debris coordinates becomes higher with the reduction of the distance between the debris and space service vehicle. Stringent requirements for the accuracy of determining the orientation of the coordinate frame of the space vehicle are essential for providing the accuracy characteristics of the method.

**Keywords** – Accuracy estimation, global navigation satellite systems (GNSS), inertial navigation system (INS), satellite, space debris, space junk, space service vehicle.

## I. INTRODUCTION

The problem of space debris utilization has become so acute that nowadays it is necessary to wait for years to get a place for a satellite on an orbit. The main problem is space pollution which has a global character. Space industry experts from all over the world are working on the space debris removal task. As of September 2015, NASA officials estimated there were more than 500 000 pieces of debris the size of a marble or larger orbiting Earth. According to NASA officials, more than 23 000 pieces of space junk are larger than a softball, but there are millions more that are too small to track. There are around 7000 tonnes of space junk circling our planet, and this figure is rising exponentially [1].

Upper stages of launch vehicles, defunct satellites, flecks of paint and other pieces of fast-moving space junk can all threaten active spacecraft. Cases of satellite death as a result of collisions with space debris are already known, and after such space collisions the number of space debris grows in geometrical progression. For example, in 1996, a French satellite was damaged by debris from a rocket that exploded 10 years earlier, and a 2007 anti-satellite test launched by China introduced more than 3000 pieces of debris to space, according to NASA. In 2009, the US satellite Iridium 33 collided with the defunct Russian satellite Kosmos 225 in an event that destroyed them both [2].

For the moment, Russian, American and other scientists all over the world are developing different methods and systems of space debris monitoring and utilization, but for today all the offered options are either too expensive or impossible to realize.

The task of space debris utilization is complex and multidisciplinary. One of the questions here is navigation of a space service vehicle (SSV) and determination of space debris coordinates for the solution of the approach task.

## II. ANALYSIS OF THE LATEST RESEARCHES AND PUBLICATIONS

There are a number of publications on the methods of space debris utilization. Among them there are crushing by laser, capture by network and withdrawal to a safe orbit. Let us consider some of them.

The Japanese Aerospace Exploration Agency proposes to use an electrodynamic tether whose current would slow down the speed of satellites or space debris, according to an early 2014 report from Agence France Presse. Slowing the satellite speed would make it gradually fall closer to Earth, where it will burn up. A satellite using a part of the system was expected to be launched on Feb. 28 (without the capturing a satellite) with a tether test proposed for 2015 [3]. But at the moment there is no any news about this experiment.

A Switzerland-based spaceflight company is finalizing plans with Canada over a potential launch site for a new private space plane, which is slated to launch a satellite to clean up space junk by 2018. Swiss Space Systems (S3) Company is planning to launch the new Clean Space One satellite using the European Suborbital Reusable Shuttle, a small space plane the firm is developing for low-cost launches off the back of a modified Airbus A300 jumbo jet. Clean Space One's first satellite target for a de-orbit demonstration will be Switzerland's SwissCube nanosat to avoid potential legal issues or other concerns surrounding the de-orbiting of a satellite owned by a party from another country. A satellite that can dock with and deorbit a spacecraft could potentially be used as a sort of anti-satellite weapon [4].

Greater attention is paid to space debris monitoring.

The first in Russia optical-electronic system of outer space monitoring started its work in Altai, as it was reported by Yuriy Roy, CEO of scientific-production corporation "Systems of precision instrument making". This system is served simultaneously by civilian and military staff and allows to detect space vehicles, nano-satellites and space debris. Similar systems are planned to be opened later in Kaliningrad, the Far East and Crimea [5]. This system uses the precision digital electro drives of the rotary support devices of different trajectory measurement telescopes developed by ITMO University engineers. The leading constructor, Valentin Tomasov, also noted that his colleagues were going to test two digital electrical drivers. There will be precision electric drivers of laser distance measurement system for artificial earth satellites. Thanks to technologies developed at ITMO University it is possible detect any object located on the Earth and determine its position with a measurement error of 5 cm [6].

According to the National Scientific and Technical Space Program of Ukraine for 2013–2017 approved by the Law of Ukraine on September 5, 2013 No. 439-VII [7], one of the tasks was to create an integrated multifunctional monitoring system for the analysis of situation in outer space that will ensure the monitoring of space objects by using radio-location, quantum-optical and other means (with the purpose of searching and monitoring the fragments of space debris). As reported in the news [8], the Cabinet of Ministers of Ukraine distributed almost 224 million of hryvnas for the fulfilment of tasks according to the Program.

Odessa Research Institute "Astronomical Observatory" contributes to the solution of Ukrainian national security problems. The employees of the observatory analyse the characteristics of foreign geostationary satellites and carry out the monitoring of the movement of so-called "space debris". This subdivision is a part of the team for the national network monitoring and analysis of space situation in Ukraine [9], [10].

The Space Based Space Surveillance (SBSS) system is a planned constellation of satellites and supporting ground infrastructure that will improve the ability of the United States Department of Defense (DoD) to detect and track space objects in orbit around the Earth. The primary SBSS contractor, Boeing, characterizes some orbiting space objects as "potential future threats to the United States' space assets". The first "pathfinder" satellite of the SBSS system was successfully placed into orbit on board a Minotaur IV rocket on September 25, 2010. It is designed to examine every spacecraft in geosynchronous orbit at least once a day. The SBSS pathfinder satellite has a 30 cm telescope on a two axis gimbal with a 2.4 megapixel image sensor and has a projected mission duration of five and a half years [11]. For 2016, Congress appropriated about \$ 27 million for activities related to space situational awareness systems, of which nearly all the money was set aside for the SBSS follow-on program. The launch of the follow-on system remains targeted for 2021 [11].

All the above mentioned ways of space debris monitoring imply data acquisition on the Earth surface.

The question of determining space debris coordinates with the help of a space service vehicle is scarcely described in the available literature.

### III. PROBLEM STATEMENT

The purpose of this work is to develop the method of determining space debris coordinates by means of the airborne equipment of a space service vehicle and to conduct the study of accuracy characteristics through mathematical simulation.

### IV. METHOD OF DETERMINING SPACE DEBRIS COORDINATES

The device synthesis for attitude determination in Earth Centred Earth Fixed coordinate system, which is based on GNSS receiver and fixed to its own coordinate system (body-fixed) carrier of antenna array, is described in the monograph [12].

It is proposed to modify the above mentioned method in the following way. First, it is necessary to introduce the additional hardware, namely, a laser radar and an inertial navigation system (INS) in this complex. Then we fix their coordinates in a body-fixed coordinate system of the carrier. Then it becomes possible to solve the inverse task: to define the orientation of laser radar beam and to define space debris coordinates using the measured range from the carrier to the space debris object. In such a way there is no need in the antenna array and phase measurement.

For the illustrative purpose, let us assume that the laser radar is located in the centre of the body-fixed coordinate system with its beam directed along the longitudinal axis. The vector of laser beam coordinates in the body-fixed coordinate system has the following form (1):

$$\mathbf{I}_s^T = [R, 0, 0], \quad (1)$$

where  $R$  is a distance between the space service vehicle and space debris object.

Then, after the rotation of  $\mathbf{I}_s$  vector on the Euler angles measured by INS, we obtain the  $\mathbf{I}_0$  (2) vector of space debris coordinates in the topocentric coordinate system [13] with the origin in the centre of the mass of SSV:

$$\mathbf{I}_0^T(r_x, r_y, r_z) = \mathbf{MM}(\alpha, \beta, \gamma) \cdot \mathbf{I}_s, \quad (2)$$

where  $\mathbf{MM}(\alpha, \beta, \gamma)$  is a rotation matrix.

The relationship between the orientation of  $\mathbf{I}_0$  coordinates in topocentric  $(r_x, r_y, r_z)$  (3) and earth centred earth fixed (ECEF) coordinate  $(g_x, g_y, g_z)$  systems with an origin shifted to the centre of the mass of SSV is determined by the system of equations [13]:

$$\begin{aligned} r_x &= \sin(\theta) \cdot \cos(\lambda) \cdot g_x + \sin(\theta) \cdot \sin(\lambda) \cdot g_y - \cos(\theta) \cdot g_z; \\ r_y &= -\sin(\lambda) \cdot g_x + \cos(\lambda) \cdot g_y; \\ r_z &= \cos(\theta) \cdot \cos(\lambda) \cdot g_x + \cos(\theta) \cdot \sin(\lambda) \cdot g_y + \sin(\theta) \cdot g_z, \end{aligned} \quad (3)$$

where  $\theta, \lambda$  are the latitude and longitude of SSV position determined by the GNSS receiver.

Solving the system of equations (1) we determine coordinates  $(g_x, g_y, g_z)$ . The transition to the non-shifted ECEF coordinate system is performed using the following equations (4):

$$\begin{aligned} X_c &= g_x + X_n; \\ Y_c &= g_y + Y_n; \\ Z_c &= g_z + Z_n, \end{aligned} \tag{4}$$

where  $X_n, Y_n, Z_n$  are SSV coordinates measured by the GNSS receiver in ECEF and  $X_c, Y_c, Z_c$  are the calculated coordinates of space debris.

To study the accuracy characteristics of this method, mathematical simulations were performed.

### V. RESULTS OF MATHEMATICAL MODELLING

The model is represented as software in the MatLab environment. It allows to calculate space debris coordinates at exact input data, and also to perform the statistical studies of calculation errors with the specified random errors of navigation parameters (coordinates) and INS errors (angles).

Errors are specified as normally distributed random numbers with the following parameters  $(\mu_D, \sigma_D)$  for the GNSS and  $(\mu_U, \sigma_U)$  for INS. The statistics was determined by means of data averaging for 10 000 cases.

The following input data were chosen:  $R = 500$  m;  $X_n = Y_n = 0$  m,  $Z_n = 6356$  km;  $\theta = 90^\circ, \lambda = 0^\circ$ . The calculated space debris coordinates are:  $X_c = 438.94$  m,  $Y_c = 239.24$  m,  $Z_c = 6356.098$  km. The research shows that the dependence of root-mean-square errors of space debris Cartesian coordinates determination on the root-mean-square errors of navigation parameters is directly proportional. It follows from the presented algorithm of calculations.

The dependence of mean values  $m_x, m_y, m_z$  and mean squares  $(D_x, D_y, D_z)$ , errors of space debris coordinate determination from  $\sigma_U$  are presented in Table I.

TABLE I

DEPENDENCE OF SPACE DEBRIS COORDINATE DETERMINATION ERRORS ON ORIENTATION ERRORS

$\sigma_U, \text{rad}$	0.0005	0.001	0.0015
$m_x, \text{m}$	1.35	-0.64	-0.76
$m_y, \text{m}$	2.6	-1	-1.1
$m_z, \text{m}$	-0.14	0.65	0.77
$D_x, \text{m}^2$	11	18.7	28.6
$D_y, \text{m}^2$	38	64.5	95.6
$D_z, \text{m}^2$	2	4.8	9.2

As it is seen from the data in the table, the errors of space debris coordinate determination are very sensible to the errors of Euler angle measurements.

Now let us study the nature of spherical error change. For this purpose, we will create a histogram of error distribution, the envelope curve of which is presented in Fig. 1.

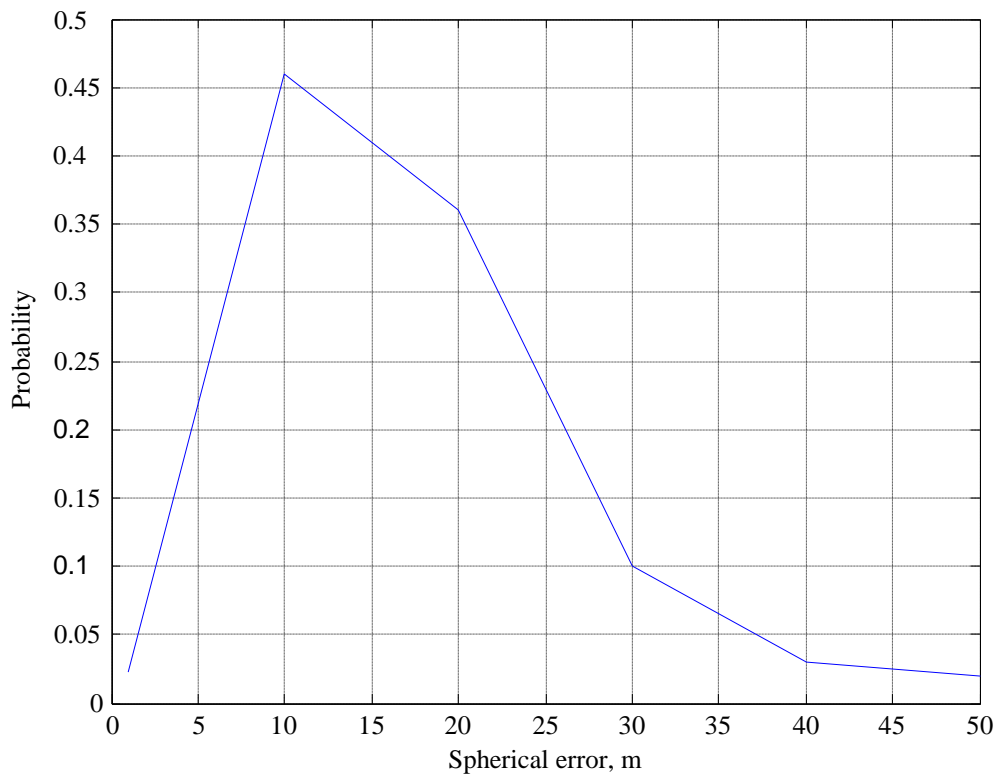


Fig. 1. The histogram envelope curve of coordinate determination, spherical error distribution.

As it is seen from Fig. 1, the distribution of spherical errors of space debris coordinate determination at presence of the Gaussian error in the measured Euler angles differs from normal, which follows from non-linearity of transformations (3). The results of study of the dependence of spherical error on the distance between the space debris and space service vehicle under  $\sigma_U = 0.001$  rad are presented in Table II.

TABLE II

DEPENDENCE OF SPHERICAL ERROR ON THE DISTANCE BETWEEN THE SPACE DEBRIS AND SPACE SERVICE VEHICLE

$R, m$	50	100	200	300	400	500
$D_s, m$	1.47	2.8	5.5	8.7	11.2	13.9

As it is seen from the data presented in Table II, the spherical error of space debris coordinate determination decreases linearly with the reduction of the distance between the space debris and space service vehicle. It is substantial at the approach of the vehicles.

## VI. HARDWARE EXAMPLES

At the international market there is a wide variety of GNSS receivers, inertial navigation systems, laser range-finders. The above mentioned equipment is produced in Ukraine as well. In particular, GNSS receivers are manufactured by state enterprise “Orizon-navigation” (Smila city) [14] and strapdown inertial navigation systems are produced by state enterprise ARSENAL [15]. It is also worth mentioning that the National Scientific Centre “Institute of Metrology” (Kharkiv) is developing a laser range-finder for the automatic docking of space vehicles [16].

## VII. CONCLUSION

The performed simulations show that the proposed method allows to determine the coordinates of space debris in the inertial geocentric frame. The accuracy of determination becomes higher with the reduction of the distance between the object and space service vehicle. The stringent requirements for the accuracy of determining the orientation of space vehicle coordinate frame are essential for providing the accuracy characteristics of the method. The tendency to improve the characteristics of the equipment of satellite, inertial navigation and laser technique mean the real possibility of implementing this method when the task of space debris utilization is to be solved in practice.

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