IDENTIFICATION OF DEBRIS OBJECTS AND DETERMINATION OF THE FRAGMENTATION NATURE BASED ON THE OPTICAL OBSERVATION RESULTS

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ABSTRACT

Analysis of space object optical observations is the investigation of the light curves, obtained by telescopes. Light curves give an opportunity to pick up a three-dimensional model of the observed object, its mass-inertial characteristics and parameters of motion around the center of mass.

Optical observation analysis was used for the investigation of properties and characteristics of space objects with high area-to-mass ratios (HAMR). It allows to make reasonable assumptions about the geometric shape and attitude of HAMR objects which improves the accuracy of the orbit's prediction.

Also optical observations in comparison with the simulation make it possible to determine the nature of satellites fragmentation and assess its negative effects. Thus, the results of observation analysis of the Russian upper stage "BREEZE-M" (international number of launch is 2012-044) after its explosion in October 2012 led us to the conclusion about the nature of the explosion.

Key words: optical observations; light curves.

1. INTRODUCTION

Optical observations are widely used for the investigation of space debris in various Earth orbits. In some cases (if some a priori information is known or the light curves behave specially) it's possible to estimate different physical properties of the space object by the results of optical measurements.

Two groups of space debris objects were selected to be analyzed by optical observations.

The first group includes the objects with high area-to-mass ratios (HAMR) in near-GEO orbits. These objects have quickly changing orbit parameters because of solar radiation pressure. Lack of information about size, shape and tumbling motion of such debris impairs the accuracy of orbit prediction, impedes the maintenance and re-identification of HAMR objects.

The second group includes some fragments of the recent spacecraft destructions. The study of objects in the "cloud" of fragments allows to draw conclusions about the nature of the destruction, the number of fragments, fragment shapes and size distribution.

TSNIIMASH and ISTP have been performing joint investigations of debris for several years. This involves the analysis of both the current and the "dead" satellites and unknown debris about which there is no a priori information. Since 2008 ISTP has performed periodic observations of HAMR objects. In late 2012 - early 2013 ISTP provided observations of "BREEZE-M" upper stage fragments.

The paper presents some results obtained from optical observations of the objects mentioned above.

2. ISTP - OBSERVATIONS

ISTP performs observations of satellites and space debris in Sayan Solar Observatory. The observatory is located in the mountains at an altitude of 2000 m. The equipment includes AZT-14A (automatic telescope, D = 480 mm, focal length — 2320 mm) and AZT-33IR (infrared telescope, D = 1600 mm, focal length — 30 m).

ISTP is able to acquire space object data of different types such as light curves (brightness variations of an object over time) in different spectral ranges, optical and thermal images (for large objects in LEO).[1,2] ISTP is capable of performing optical observations of various events in low orbits.

3. TSNIIMASH - DATA ANALYSIS

The investigation of light curves helps to determine the physical characteristics of the observed object. The time and the duration of the observation, the relative position

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of the object, the observer, the Earth and the Sun are taken into account. The next step is to consider the various options for the object's shape, orientation, rotation parameters and optical properties. For each case an optico-geometric model is formed. The object is represented as a set of polygons with a certain orientation. The flux in the direction of the observer is calculated. The main task is to determine the case that produces the best fit of the simulated light curve and the light curve obtained by optical observations.

4. HAMR OBJECTS

The analysis of the HAMR objects motion is hampered because of the lack of a priori information about their geometric shape and orientation. Solar radiation pressure causes the perturbing acceleration that is directly proportional to the instant cross-section of the object. That's why a rotating object of irregular shape has a complex evolving orbit. Solar radiation pressure results in periodic fluctuations of eccentricity and inclination. The lifespan of HAMR objects can last for tens of years.[3,4,5] A set of various factors, that has an influence on the evolution of HAMR objects orbit, was studied. The investigation confirmed that the satisfactory prediction of the orbit was feasible provided that the accurate data on the size, attitude, geometry, rotation axes position, direction and speed of the object rotation are known.[6] The availability of these data makes it possible to calculate the maximal area of section perpendicular to the direction to the Sun in every time point.

In 2011 ISTP observed about 30 HAMR objects with area-to-mass ratio of more than 1 m^2/kg. Photometric measurements in the visible range were obtained. The specific task was to identify the characteristics of the light curves, in particular, the presence or the absence of periodic brightness variations. The observations were performed in the mode of the object ephemeris tracking. The exposure level and duration of the series were selected individually for each series of observations. The stars from the catalog of Landolt photometric standards were used for calibration measurements. The mean value of the observed fragment light ranged from 15 to 18.5 magnitudes, light amplitude — from 0.2 to 2.5 magnitudes, rotation periods — from 13 to 68 seconds.

The light curves of the observed objects have different shapes — from 2 to 7 peaks for the period. A large number of peaks may indicate, that there are many reflective details on the surface of the object.

TSNIImash performed a detailed analysis of one of the observed objects. The selected object has the highest area-to-mass ratio value (in compliance with the ballistic calculations) and the most unstable orbit. The observations of this object have been conducted since 2008. Two orbit parameter data blocks were considered, relating to 2009 and 2011, respectively. In 2009 the average value of area-to-mass ratio was calculated to be about 12.7 m^2/kg,

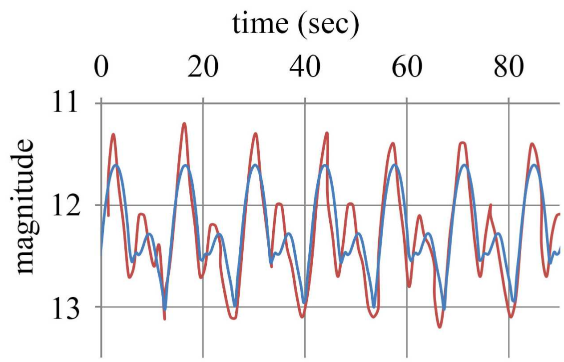

Figure 1. The simulated light curve (blue) and the light curve obtained by optical observations (red) for the observed HAMR object

Figure 2. The estimated shape of the HAMR object

as opposed to about 17.3 m^2/kg in 2011. This inequality may be explained by the suggestion that the object changed its orientation between these two observation periods. The observations of the object in 2011 revealed the object brightness oscillations with amplitude of 2.5 magnitudes. Mathematical simulation gives the best fit of the calculated and the observed light curves for the object with the shape of a truncated cone shell like "dish" with a radius of 2 meters. Figure 1 shows both the calculated light curve and the observed light curve, Figure 2 shows the estimated shape of the object.

5. "BREEZE-M" FRAGMENT ANALYSIS

The launch rocket "Proton-M" with the upper stage "BREEZE-M", the Russian satellite "Express-MD2" and the Indonesian satellite "Telkom-3" was launched on 6 August 2012 from the Baikonur Cosmodrome. The main engine of "BREEZE-M" cut off prematurely, the upper stage and the satellites were stranded in an elliptical orbit with parameters 260 km x 5030 km. The auxiliary propellant tank (APT) had not been separated, therefore more than 5 tons of propellant was left in the upper stage. In a few months the perigee altitude of "BREEZE-M" decreased, and it exploded on 16 October 2012, creating thousands of new debris.[7]

Figure 3. The general view of "BREEZE-M"

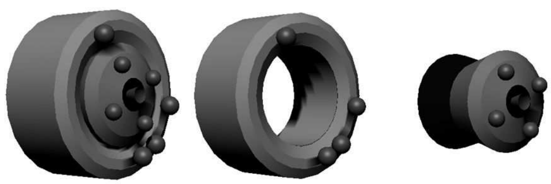

Figure 4. The developed optico-geometric model of "BREEZE-M" (assembled, APT and core section separately)

In November-December 2012 Sayan Observatory observed the basic part of the upper stage and its fragments. The following objects were measured: 2012-044C (basic part), 2012-044T, 2012-044AA, 2012-044AC, 2012-044AL, 2012-044BY (smaller fragments). For every object several light curves were acquired.

An optico-geometric model, applicable to the upper stage "BREEZE-M", was developed on the basis of information from open published papers. Figure 3 shows the general view of "BREEZE-M". The developed optico-geometric model is shown in Figure 4.

On 8 December 2012 the launch rocket "Proton-M" with the similar upper stage "BREEZE M" and the Russian satellite "Yamal-402" was launched. Sayan Observatory performed observations of the core section (2012-070B) and the APT (2012-070C). The obtained light curves were used for the verification of the developed optico-geometric model. The simulated light curve and the light curve obtained by the optical observations coincide rather precisely.

Analysis of the light curves of the upper stage basic part 2012-044C indicated that the simulated light curve and the light curve obtained by the optical observations correspond to each other only if we assume the end face of the upper stage to be completely black. Therefore, the optico-geometrical model without bottom shells of core section and APT was selected for the detailed analysis. Figure 5 shows the selected mode of the optico geometrical model. Figures 6, 7, 8, 9, 10, 11 shows the simulated light curves in comparison with the light curves obtained by the observations for the basic part 2012-044C.

Figure 5. The optico-geometrical model of "BREEZE-M" selected for the detailed analysis (without bottom shells)

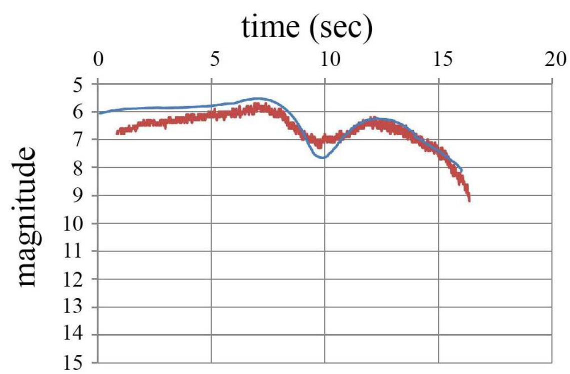

Figure 6. The simulated (blue) and obtained (red) light curves for the basic part of "BREEZE-M" 2012-044C 22.11.2012 22:49

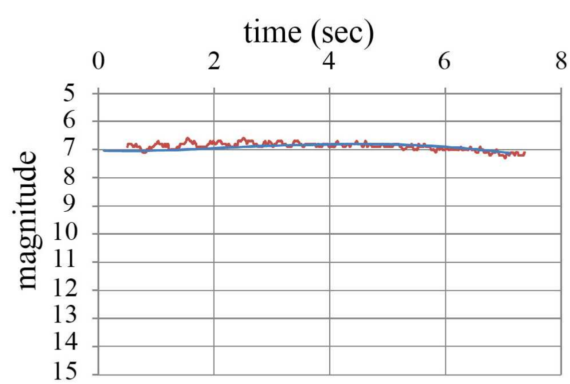

Figure 7. The simulated (blue) and obtained (red) light curves for the basic part of "BREEZE-M" 2012-044C 28.11.2012 21:30

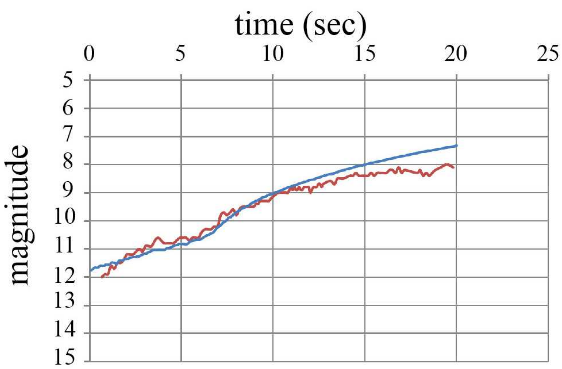

Figure 8. The simulated (blue) and obtained (red) light curves for the basic part of "BREEZE-M" 2012-044C 04.12.2012 14:29

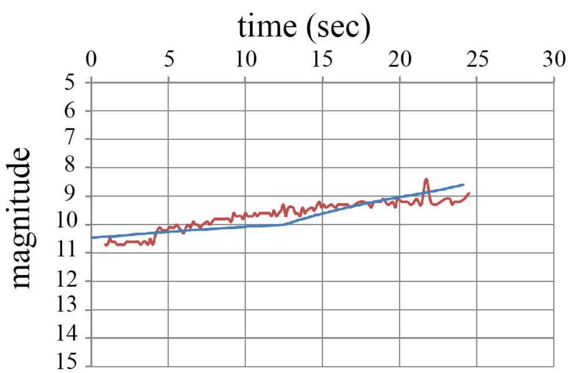

Figure 9. The simulated (blue) and obtained (red) light curves for the basic part of "BREEZE-M" 2012-044C 15.12.2012 11:44

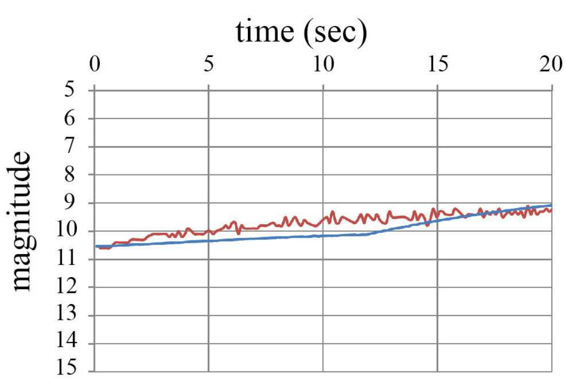

Figure 10. The simulated (blue) and obtained (red) light curves for the basic part of "BREEZE-M" 2012-044C 16.12.2012 11:30

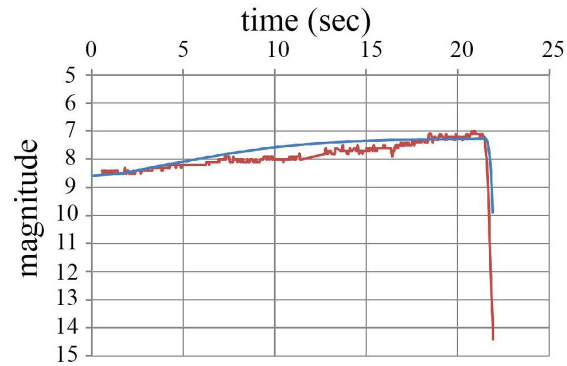

Figure 11. The simulated (blue) and obtained (red) light curves for the basic part of "BREEZE-M" 2012-044C 19.12.2012 13:34

The analysis of the "BREEZE-M" fragments was performed to make assumptions about their sizes and geometrical shapes.

To estimate the sizes, the fragments were simulated as spheres with As = 0.4. Using the values of observed brightness their characteristic sizes were estimated as follows: 2012-044T — R = 0.07 m, 2012-044AA — R = 0.24 m, 2012-044AC — R = 0.15 m, 2012-044AL — R = 0.40 m, 2012-044BY — R = 0.11 m.

The shape of space object significantly affects the shape of its light curve. For instance, if the object is flat (pieces of MLI), its light curve is expected to have periodical sharp peaks related with the chaotic rotation of the object. On the contrary, spherical objects (spherical tanks, gas bottles) have rather smooth light curve. Conical and cylindrical objects (jet nozzles, pipelines) have light curves with smooth peaks. But this shape estimation is very approximate and inaccurate.

The objects 2012-044AC and 2012-044AL are estimated to be flat, 2012-044AA — spherical. The objects 2012-044T and 2012-044BY are supposed to be cylindrical and conical, respectively, but were simulated as spheres to estimate the sizes.

The objects 2012-044AC and 2012-044AL are supposed to be MLI pieces, 2012-044T and 2012-044BY — fragments of engines or pipelines. The object 2012-044AA is the most interesting, because its estimated size and light curve behavior agree with the characteristics of a spherical gas bottle.

Figures 12, 13, 14, 15, 16 show the simulated light curves in comparison with the light curves obtained by the observations for the objects 2012-044AA, 2012-044T, 2012-044BY and 2012-044AL. For the object 2012-044AL two alternatives are given to confirm the shape estimations (the object was simulated as a sphere and as flat square).

It should be noted that the upper stage "BREEZE-M"

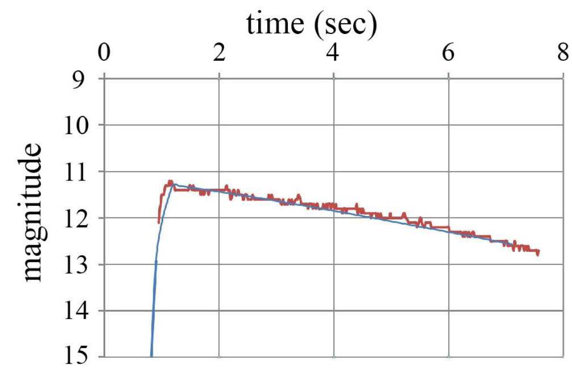

Figure 12. The simulated light curve (blue) in comparison with the light curve obtained by the observations (red) for the fragment 2012-044AA simulated as a sphere r = 0.24 m, 18.11.2012 18:19

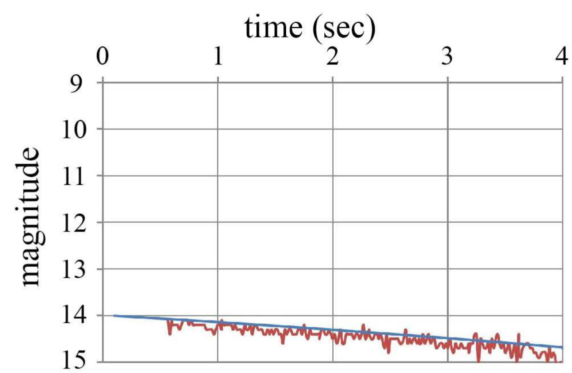

Figure 13. The simulated light curve (blue) in comparison with the light curve obtained by the observations (red) for the fragment 2012-044T simulated as a sphere r = 0.07 m, 17.11.2012 17:32

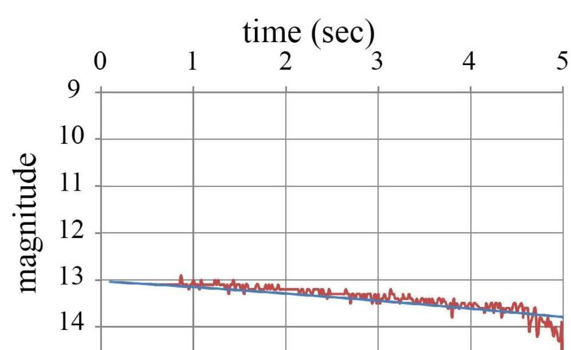

Figure 14. The simulated light curve (blue) in comparison with the light curve obtained by the observations (red) for the fragment 2012-044BY simulated as a sphere r = 0.11 m, 17.11.2012 17:23

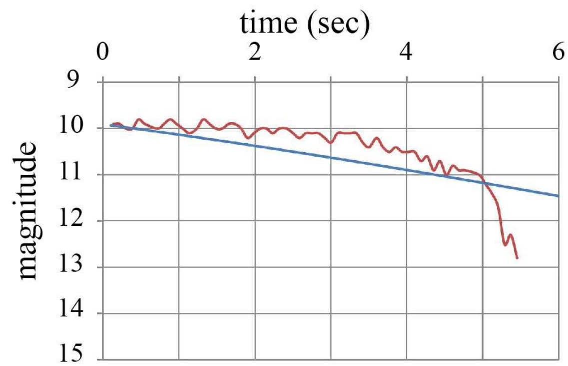

Figure 15. The simulated light curve (blue) in comparison with the light curve obtained by the observations (red) for the fragment 2012-044AL simulated as a sphere r = 0.4 m 18.11.2012 18:12

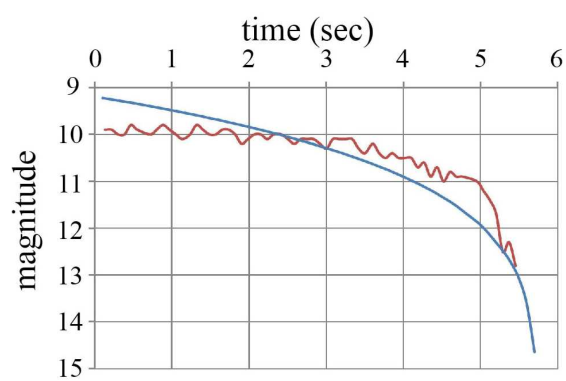

Figure 16. The simulated light curve (blue) in comparison with the light curve obtained by the observations (red) for the fragment 2012-044AL simulated as flat square 18.11.2012 18:12

2012-044 destruction had a number of features. The destruction is supposed to be partial: the upper stage wasn't entirely crushed, but a number of pieces were thrown out. Apogee and perigee altitudes of most fragments are below the altitude of the basic part, therefore, the explosion was directed against the flight course. The estimated sizes and the shapes of the observed fragments agree with the characteristics of the elements at the bottom of the upper stage. The great number of fragments confirms the assumption that the explosion occurred at the bottom of the upper stage and destroyed the propulsion system.

6. CONCLUSIONS

In the paper the results of TSNIIMASH and ISTP joint investigations are described. Two classes of space debris were considered. The light curves of several objects were obtained. The optico-geometrical models applicable to these objects were developed. The simulated light curves were compared with the light curves obtained by optical observations. The results confirm that some physical characteristics of space objects can be defined by light curve investigation under certain conditions. Thus, this method may be used for increasing orbit prediction accuracy or making assumptions, related to the destructions in space.

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