THE SET OF METHODS AND ALGORITHMS FOR THE REMOTE PHOTOMETRIC AND COORDINATE MONITORING OF COSMIC OBJECTS

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ABSTRACT. The paper is devoted to elaboration of the new optimized methods, algorithms and programs for the solution of problems of the remote control of near-earth space (CS), which are related to investigation of cosmic objects (CO) based on the photometric and coordinate measurements. It is shown, that for these determination of satellite's rotation period around center of mass, the orientation of rotation axis, and also its color, polarization and others characteristics can be used. The main principles of a system of the CO identification based on their light curves are elaborated. A new algorithm of CO orbit determination using the network station data is created. Its accuracy is by 3-4 orders at magnitude higher than that of algorithms based on the well-known methods of celestial mechanics.

Keywords: Earth's artificial satellite, cosmic object, remote control of space, light curve, orbit determination.

The intensive use of the space by the world community has resulted that now at different near-earth orbits there is a huge quantity of the fulfilled satellites, rockets, their fragments and waste (named by "Space debris"), representing real danger to working CO, of orbital stations and is potentially dangerous to the inhabitants of the Earth.

In presented conditions the further development of near-earth space is impossible without the objective analysis of a condition of "pollution", sources of "space debris" and laws of its evolution. For the decision of these tasks the continuous *control of space* (Problem of pollution of space, 1993) is necessary, which provides observation of the greatest possible number of cosmic objects with the purpose of reception of the most full and operatively updated multi-parametric information on current conditions in near-earth space is necessary for the decision of these problems. The volume of the information should allow to determine various characteristics CO, to draw conclusions on their form, size, status, etc. And as CO are also some kind of "trial bodies" the received information also enables to determine and specify physical parameters and state of environment of CO and to predict the further development of interaction CO with environment. I.e., the decision of CS problems is reduced to versatile research observable CO for the forecast of their flight and, probably, direction by the flight. The network of stations of the observation equipped with means of reception, processing and the analysis of the observant data is necessary for the successful decision of CS problems.

Experience shows, that most effectively problems of CS can be solved on the basis of complex use of the coordinate and not coordinate information received from observations of CO. As optical earth-based observations receive both kinds of these information about CO, the basic and the most developed now are following kinds of CS:

1. *The coordinate control* - the control of near-earth space by means of positional observations of CO with use of methods of satellite astrometry, radio ranging, laser ranging, etc. The coordinate control is primary and is based on comparison and the analysis of positions CO, that are observable and are calculated on the basis of the theory of movement, on comparison of orbital elements and their changes.

2. *The photometric control* - the control of a space by means of the analysis of the light-stream reflected by a CO-surface and measured with use photometric, spectral, polarimetric and other methods of research, widely used in astrophysics. Thus characteristic features of change of brightness of CO can be revealed, parameters and the criteria are found, allowing to estimate of grade of conformity received photometric data to properties real CO. Thus the photometric control promotes improvement of quality and reliability of identification of CO, made on a basis only the coordinate information.

It is known, that observable brightness of CO depends on many different factors. The account of influence of some geometrical and atmospheric factors on the value of observable brightness of CO is well fulfilled, approved and stated in many papers of different authors. For the take into account of influence of some other factors it is necessary to know optical properties of CO-surface, its form, orientation, etc.

The large influence on the value of observable brightness of the artificial satellite renders absorption of light in the atmosphere of Earth, dependent besides from length of a wave. Methods of the account of distinction of instrumental and standard photometric systems are well fulfilled for stars and generalized for the artificial satellites in V.B.Nikonov's papers. Used methods of definition of extra-atmospheric brightness and color of CO are fair for all CO, taking place outside atmosphere of Earth. However, strictly speaking, application of these methods for CO moving in atmosphere, will result in overestimate of determined the values of extra-atmospheric brightness of CO.

After the account of the changing distance up to CO and the atmospheric amendments, it is possible to explain the staying observable changes of brightness by the following factors:

1) by movement of CO on the orbit and change of conditions of its illumination and the observation, owed, for example, to change of phase angle (an angle the Sun-CO-observer);

2) by CO rotation around center of mass and precession move of rotation axis;

3) by change during some time optical characteristics of a material of CO surface under action of space factors.

Besides, brightness of the some CO can contain a small-amplitude component which can be caused by the vibrations, accompanying maneuvering CO or discrete change of its form. Action of factors 2 and 3, determining CO "behavior" in the orbit and its "state", enables to carry out passive remote photometric sounding and diagnostics (or the remote control) of CO in the orbit.

The researches specify, that photometric control of CO in orbit should be based on continuous monitoring and be carried out by the following parameters:

1. By change of the period of variations of CO brightness. Angular speed of CO rotation can vary under action of atmospheric influence, pressure of the sunlight, the leak of fuel, and also at the short-term directed external influence (impact) or by a command.

2. By change of orientation in space of the axis of CO rotation, which can occur for the same reasons, as change of the period of variations of brightness.

3. By change of color, spectral and polarizing characteristics of reflected light. Their change gives the information on state of CO in the orbit and about influence on its surface of factors of near-earth space.

If observable change of CO brightness occurs because of its rotation around of the center of mass it will be periodic (quasi-periodic) and the period of CO rotation can be defined. From many methods of period search of time-series (in this case the period of CO rotation) one of the most powerful is method Lafler-Kinman (Pelt, 1980; Lafler & Kinman, 1965) and its modifications (Kholopov).

The construction of dependence of CO brightness versus the value of a phase angle does not represent difficulty if exact place of CO are known, however the kind of this dependence is determined by the CO form, and the calculation of real contribution of geometrical conditions of illumination into varying of brightness demands knowledge both form, optical properties, and CO orientation.

The orientation of CO is closely connected to installation of necessary operating mode of CO and its devices. Change of orientation affects on orbital drag and movement of CO, and, hence, on duration of its existence. Therefore methods of determination of CO orientation are very urgent. One's of the first papers devoted to determination of axis of rotation of rockets-carriers (RC) by means of the photometric data were the works by V.P.Tsesevich, V.M.Grigorevsky, M.Hansburg et al. (Davis et al., 1975; Grigorevsky, 1959; Hunsburg, 1967; Kolesnik et al., 1981; Epishev, 1985).

Modern methods of determination of orientation of the rotation axis of CO, that specular reflect the light from cylindrical, conic or flat surfaces, are stated in papers of Kolesnik (1981), of Epishev (1985), et al. These methods also allow to draw the certain conclusions concerning design features of CO. Thus, accuracy of determination of CO orientation very much depends on accuracy of determination of parameters of its orbital movement.

More difficult problem is a determination of orientation of complicated CO, which diffusely reflects (scatter) the light. Reliable algorithms of the common decision of such problem are not present. Therefore search of its decision carry out in several directions. In first, obviously simplified model of CO is considered and the problem is reduced to minimization of residuals of "calculate minus observable" brightness of CO at trial orientations of the rotation axis and sizes of model (Koshkin et al., 2003). Reliability of such decisions is for the present not so great.

On the basis of long-term experience of reception, processing and the analysis of great volume of the photometric data the system of classification of the light curves of CO is developed, allowing to automate the analysis and interpretation of the photometric data (Dobrovolsky et al., 1999; Korobko et al., 1999). On this system all light curves of CO, on presence or absence at them a periodic component, are shared into 3 classes:

- the nonperiodic light curves;
- the periodic smooth light curves;
- the periodic light curves with features.

In each of these classes, in view of specific features of the light curves, subclasses are allocated. Classification of the researched light curve to any of subclasses is carried out by its comparison with typical light curve of this subclass.

The light curves of different classes have different information content concerning characteristics of CO (dynamics of movement, features of their form, heterogeneity of covering, etc.), which cause the class of light curves and promote to identification of these CO. The most informative are light curves of 3-rd class. The light curves of 1-st class are least informative.

The developed system of classification of the light curves of CO is the important stage on the way of the decision of a inverse problem of photometry - to data acquisition about movement, the form and optical characteristics of the unknown CO. In the working catalogue over 1500 light curves concerning to more than two hundred CO is classified. These light curves are the basis of the informative data bank about CO, included in the Odessa catalogue of CO.

The opportunity of any kind of the remote control of CO depends on accuracy of the forecast of its movement, which, in turn, depends on accuracy of elements of orbits used for it. Algorithms of calculation of CO orbits based on methods of classical celestial mechanics have the essential lack and cannot satisfy the requirements of CS to accuracy of forecast of the CO positions. The analysis of movement of artificial satellite pointed, that the perturbed movement of satellite is the sum of movement of satellite occur in the plane of osculate orbit, and movement of these orbit plane that is not taken into account at all in classical methods of determination of orbits (Paltsev & Kolesnik, 2001). It requires development and creation of new reliable algorithm of determination of the CO orbit, which satisfy the requirements to accuracy of forecast of CO positions and use plenty of the coordinate information received from observation.

New algorithm of determination of CO orbit was created, admitting use of measurements received in one or several ($2 \div 5$) close passages of CO, received by one or network of observant stations. It includes the following stages:

a) determination of primary circular (or elliptic) orbit calculated on the basis of two (three) positions of CO or according to laser measurements;

b) calculation of "Functional" - the weighed sum of squares of deviations of calculated and observed positions of CO in all arc - on the basis of algorithm of calculation of ephemeris, which take account of evolution of elements of the CO orbit;

c) minimization of "Functional" on coordinates and speed of CO in the moment t ;

d) calculation of Kepler's orbit elements of satellite on the basis coordinates and speed in the moment t.

The use of "superfluous" sets of the measurements, which were received on the long arc, results to essential reduction of influence of random errors of the primary measurements and to increase of stability and reliability of determination of the orbit by this method. Due to this there was possible use of the positional measurements of average and small accuracy. The estimations have pointed, that by use of the primary data of low accuracy ($\sim 0.1^\circ$), accuracy of semi-major axis of the orbit δa determined by this algorithm on several passages approximately on three order is higher than according to one passage, and approximately on four order is higher than by use of classical algorithms of celestial mechanics (Paltsev & Kolesnik, 2001). Such accuracy of determination of semi-major axis of the orbit was confirmed on observations of artificial satellites in 1993-2003 and on calculations of their orbits by soft "Orbita-M" (Sheptoon et al., 1997) created on the basis of this algorithm.

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