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ARTIFICIAL SATELLITE OBSERVATIONS USING THE TELESCOPE COMPLEX OF RI «MAO»

Special methods, means and software for cosmic object observations and processing of obtained results have been developed. A combined method based on separated accumulation of images of reference stars and artificial objects has been mainly used for observations of artificial space objects. It applies to observations of artificial objects in all types of orbits.

Keywords: artificial satellites, telescopes, combined method of observation, time delay and integration.

The main problem in observation of artificial space objects (ASO) in the optical range is a problem of different speeds of apparent rate of reference stars and ASO. To observe the geosynchronous objects, the daily telescope tracking method is used. As a result, images of geosynchronous objects obtained as stroke against the dot image of stars. Or if observing on a stationary telescope, the ASO are imaged as dot pattern against the stars showed as strokes. Both methods require specialized software for processing of extracted images. The Research Institute «Mykolaiv Astronomical Observatory» (RI «MAO») has developed a combined observation method for ASO observations, which is based on the use of *time delay* and *integration* (TDI) with different rates for forming the images of ASO and reference stars. This approach enables obtaining dot images of both the object studied and the reference stars.

In addition, for the objects on low and medium orbits, there is the problem of formation of high-speed object images. For the time being, throughout the world, researchers are searching the optimal method for imaging the low-orbit ASO whose speed reaches 1.5 deg/sec. Fig. 1 shows images of low-orbit ASO obtained by different methods: *a*) image of Gravity Probe B received at the Korean Department of Astronomy and Space Physics using a telescope (D = 0.5 m, F = 1.5 m) equipped with CCD camera and obturator [1]; *b*) image of SL-26 RB received at the University of Rome using a telescope (D = 0.25 m, F = 0.075 m) equipped with CCD camera in the daily telescope tracking mode [2]; *c*) image of *Envisat* obtained at the Aerospace Agency's German Institute for Technical Physics using a telescope (D = 0.43 m, F = = 2.94 m) in daily telescope tracking mode [3].

DEVELOPMENT OF NEAR-EARTH SPACE RESEARCH AT RI «MAO»

Starting with 2000, RI «MAO» has begun the near-Earth space and the development of combined method for observations (*Shulga O.V., Kovalchuk O.M, and Pinigin, G.I.*). The first data of geostationary ASO observations were obtained in 2001 for multi-channel telescope (D = 0.160 m, F = = 2.044 m), manual mount. Frames with images of reference stars were obtained to calculate the ASO coordinates in TDI mode. The frames with ASO

Fig. 1. Images of low-orbit ASO obtained by different methods

images were got on a stationary telescope in the accumulation mode. The first ASO observations showed the necessity of developing special computerized telescopes and special methods of observation. In 2001—2010, RI «MAO» designed five computerized telescopes and two methods for ASO imaging. It was also modernized combined method of observation. The basic principle of the combined method is the separation of imaging the reference stars and the ASO. It enables obtaining dot images of both objects in modes and with exposures that are the most advantageous for achieving a high level of signal/noise ratio [4]. For observations using the full-frame CCD cameras the method of short charge transfer has been developed [5] (see example in Fig. 2, *b*). Prerequisites for the development were oversaturation of ASO images and uneven speed of low-orbit ASO, which led to stretching of images in the case of long exposures. For the observations using TV CCD camera the method of shift frame accumulation has been developed [6], which enables real-time summing of the frames bearing ASO image with shift that corresponds to velocity of its motion in sight of the telescope (see Fig. 2, *a*). To implement the methods RI «MAO» has designed and manufactured specialized telescopes. In parallel with the development of combined method, a modified reduction model has been elaborated, which enables to carry out an astrometric reduction of observations obtained by the combined method with interframe reference.

TELESCOPES DESIGNED AT RI «MAO» FOR ASO OBSERVATIONS

High-speed computerized telescope complex was designed and manufactured in 2004 and used in observations of near-Earth objects for up to 2011. The telescope consisted of two objectives: 1) D = 0.3 m, F = 0.15 m, FOV = (1.38 × 1.38)° for observing the geosynchronous ASO and 2) D = 0.057 m, F = = 0.085 m, FOV (3 × 4)° for observing the low-orbit ASO. The telescope was installed on parallactical mount. The target rate is 3 deg/s, the target error on both axes is 0.1°. The telescope was used for surveying the ASO having geosynchronous and low orbits; the accuracy of observations amounted to ±(0.26—0.91)" for $(12.5—14)^m$ ASO and (1.4—5.6)" for $(3—10)^m$ ASO, respectively.

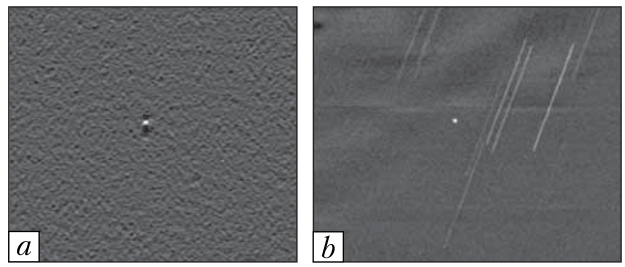

Fig. 2. Methods of image formation developed at RI «MAO»

The *Mobitel* telescope complex was developed in 2010. It includes three telescopes on a mobile platform [7]. Due to its maneuverability the telescope can be used under favorable astro-climate conditions. On the mobile platform there are the three telescopes:

1) KT-50 (D = 0.5 m, F = 3.0 m) equipped with a full-frame CCD camera (3 × 3)k having a field angle of (0.7 × 0.7)° and an optical resolving power of up to 18.5^m (at an exposure of 120 s); the telescope is used for observation of ASO on all types of orbits with an accuracy of ± 0.5";

2) TV telescope (D = 0.05 m, F = 0.14 m) equipped with a CCD television camera Watec 902h

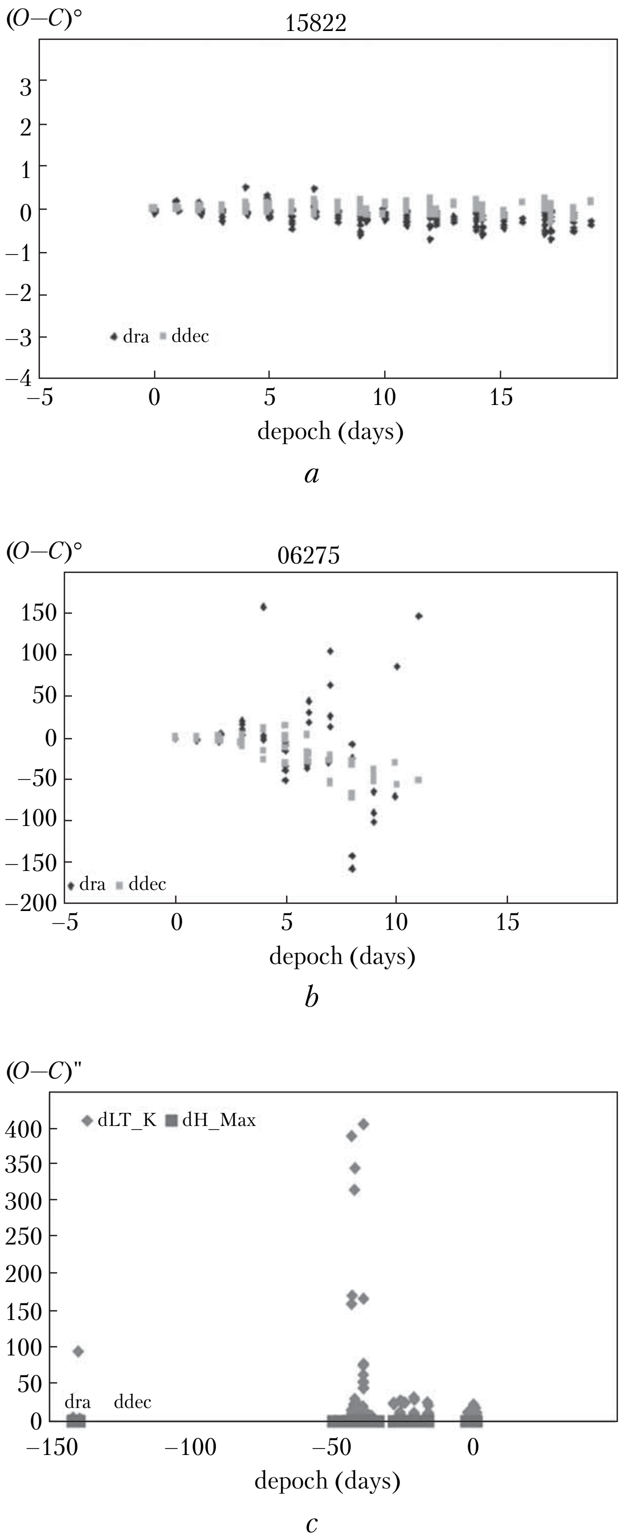

Fig. 3. Estimate of ephemeris calculation accuracy

having a field angle (2.8×2.1)° and an optical resolving power of up to a magnitude of 11; the telescope is used for observation of low-orbit ASO with an accuracy of ± 2.0";

3) Meson telescope (D = 0.23 m, F = 0.8 m) equipped with a full-frame CCD camera (3×3)k having a field angle of (2.7×2.7)° and limiting magnitude up to 16^m (at an exposure of 120 s); the telescope is used for observation of ASO on all types of orbits.

The AFU-75 telescope developed in 2010 (D = = 0.23 m, F = 0.75 m) equipped with a full-frame CCD camera (3×3) k, having a field angle of (2.7×2.7)° and an optical resolving power of up to 16m (at an exposure of 120 s); the telescope is used for observation of ASO on all types of orbits [8], the standard deviation of low-orbit ASO positions with respect to International Laser Ranging Service ephemeris is (0.5—2)". The telescope was used in joint Ukrainian-Chinese project *Centralized Control of Optical Telescope Network* [9], as a result of which a catalogue of 1000 positions of 15 ASO has been created and the ASO orbit elements have been calculated.

The Celestron telescope was upgraded at RI «MAO» in 2015. It was used to observe low-orbit ASO and enabled to obtain the coordinates with a mismatch (*O—C*) (*observed—calculated*) of ±3.1" regarding the initial orbit. In 2016, the telescope was installed in Slovakia at the branch of Vihorlat Observatory on Kolonica Saddle at a height above sea level of 400 m. The telescope location in the mountains enabled to increase its limit magnitude.

In 2011, the Ukrainian optical station network (UOSN) was organized with RI «MAO» involved [10]. Based on UOSN observations the catalog of ASO orbit coordinates is regularly formed and updated. As of today, the electronic catalog at UOSN site [11] contains the 1,906 sets of orbital elements for 514 ASO obtained from observations of the network in 2011—2016, including 1,747 sets of orbital elements for low-orbit and 160 sets for geosynchronous ASO elements. All elements of the orbits have been calculated using software developed at the Research Institute «Astronomical Observatory» of the Mechnikov Odesa National University [12]. The program incorporates a numerical model for calculating the ASO orbit elements in which differential equations are integrated by classic 19th order Everhart method with a variable step. The model takes into account the perturbations from the gravitational potential of the Earth, the effect of the Moon, the Sun, Jupiter, and Venus (based on DE/LE 405 model), and the tides in the Earth's crust (based on the Wahr model). Based on results of observations, the accuracy of ephemeris prediction has been calculated. With respect to actual observations it has been estimated as ±1° for the low-orbit ASO with an orbit height over 1000 km for a period of up to 20 days (Fig. 3, *a*) and up to ±1° for an orbit height under 1000 km for a period of up to 3 days (Fig. 3, *b*). A rapid increase in the ephemeris error for the ASO with an orbit height under 1000 km for more than three days can be explained by neglect of perturbations when calculating the orbit. For the geosynchronous ASO the ephemeris errors have been estimated as 18" along the orbit and 1" across the orbit for a period of up to 140 days (Fig. 3, *c*) where *depoch* is the difference between the epoch of orbit elements and the epoch of observations.

CONCLUSIONS

Starting with 2000, RI «MAO» has been actively developing the near-Earth space studies. Within 2000—2016, RI «MAO» researchers have designed special methods and telescopes for ASO observations. UNOS has been established under support of RI «MAO» and software has been developed for calculating the ASO orbit elements and ephemeris. A catalog of orbit elements and positions in 2011—2016 has been obtained. ASO ephemeris ($O-C$) has been estimated with respect to the position catalog. The accuracy has been estimated as ±1° for the low-orbit ASO with an orbit height over 1000 km for a period of up to 20 days and up to ±1° for an orbit height under 1000 km for a period of up to 3 days. For the geosynchronous ASO the ephemeris errors have been estimated as 18" along the orbit and 1" across the orbit for a period of up to 140 days.

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СПОСТЕРЕЖЕННЯ ШТУЧНИХ СУПУТНИКІВ ЗЕМЛІ З ВИКОРИСТАННЯМ КОМПЛЕКСУ ТЕЛЕСКОПІВ НДІ «МАО»

Розроблено спеціальні методи, засоби та програмне забезпечення для спостережень та обробки результатів спостережень космічних об'єктів. Основним методом, який використовується для спостережень штучних космічних об'єктів, є комбінований метод, який полягає в роздільному накопиченні зображень з опорними зірками та штучними об'єктами. Метод використовується для спостережень штучних об'єктів на всіх типах орбіт.

Ключові слова: штучні супутники, телескопи, комбінований метод спостережень, режим вкороченого синхронного переносу заряду.

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НАБЛЮДЕНИЯ ИСКУССТВЕННЫХ СПУТНИКОВ ЗЕМЛИ С ИСПОЛЬЗОВАНИЕМ КОМПЛЕКСА ТЕЛЕСКОПОВ НИИ «НАО»

Разработаны и используются специальные методы, средства и программное обеспечение для наблюдений и обработки результатов наблюдений космических объектов. Основным методом, который используется для наблюдений искусственных космических объектов, является комбинированный метод, который заключается в раздельном накоплении изображений с опорными звездами и искусственными объектами. Метод используется для наблюдений искусственных спутников на всех типах орбит.

Ключевые слова: искусственные спутники, телескопы, комбинированный метод наблюдений, режим укороченного синхронного переноса заряда.