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THE OBSERVATIONS OF ARTIFICIAL SATELLITES AND SPACE DEBRIS USING KT-50 TELESCOPE IN THE ODESSA UNIVERSITY

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ABSTRACT. In paper the equipment, images analysis techniques in the frame and the method of the satellite brightness estimation in the standard photometric system are describes. Within two years, on the KT-50 telescope were obtained measurements of about two hundred objects in more than 2,000 passages. The results of statistical analysis of actual data observations array in 2015 and 2016 are given.

1. Introduction

The observation of celestial bodies in near-Earth space solves two main tasks:

1. The space control, ie tracking and monitoring of active and inactive satellites and space debris in order to ensure security and the possibility of space flight (as a component of "space situational awareness").
2. The development of a entirely scientific ideas about the motion of bodies in near-Earth space, that is the nature of the forces that determine the movement of these bodies. Accumulation of the high quality observations allows you to build better models of the motion of bodies and analyze the nature of motion of bodies and the factors influencing this movement.

To control the movement of bodies in near-Earth space are apply various methods for their observation. Co-processing of these observations may allow to improve significantly the results of the study of these objects despite the significantly different methods of monitoring the same space objects. However, for the successful integration of various observations it is very important to know the particularity and accuracy of this.

On Earth orbits there is a significant number of defunct satellites that can not be observed by laser ranging. In addition, most of the space objects are an different fragments of previously launched artificial bodies, which also can not be monitored by laser ranging means. Therefore, they can be observed by active radars and passive optical telescopes. The advantages of expensive radars is the mass character of observations, all-weather, the continuity and the ability to measure the distance to object. The advantages of the optical means are an lower energy consumption and lower cost of the observation complex, better angular resolution, and passivity (stealthy). This allows you to quickly deploy a large number of optical observation means (Shulga et al., 2015).

2. Objective

In the case of optical observations of space objects typically use two main strategies. The first is the satellite observation during short intervals, and accordingly the short arc (staring mode) (McGraw et al., 2015). The second strategy is the continuous tracking of the satellite along its apparent path (tracking mode) (Gasdia et al., 2016; Shakun & Koshkin, 2014). The first strategy provides significant savings in observation time for MEO and GEO objects which have a low apparent speed, at an equivalent the object orbit accuracy determination. For low-orbit objects whose apparent movement speed is high, the first strategy does not provide any significant advantages. Moreover the second strategy provides an opportunity to obtain long and continuous photometric observations and allows to obtain continuous series of pointing data, which in turn provides information on the standard deviation and local trends systematic differences between the model and satellite motion.

This paper discusses the observations of space objects received in the tracking mode. The observations were made during 2015-2016 in the Institute "Astronomical observatory" of the Odessa National Mechnikov University. This paper presents an overview of the astrometric and photometric observations, the method of obtaining and processing of observations, as well as statistics characteristics of the measurements.

3. Equipment

The KT-50 telescope (Fig. 1) is equipped with a digital angle encoders on axes and GPS-receiver for time measurements. In main focus of the telescope mounted CCD camera Watec-902H2 Sup, working in the TV standard mode of 25 frames/s interlaced (50 fields per second) to record a video file with the satellite image. For focal distance of 2.0 m field of view is about 12x9 arcmin. The scale of frame 768x576 is equal about 1 arcsec per pixel.

Figure 1: (Right) – Alt-azimuthal KT-50 telescope (photo); (Left) – Optical scheme of telescope.

The in-frame background stars are blurred when tracking the satellite. Therefore, the exposure accumulation can not be used to extract images of faint stars above the level of the sky background. To detect the faint stars over the noise level the low-pass filtering of the image is used.

This filter is constructed as a result of the convolution of two filters: low-pass Gaussian filter (with the width equal h and a standard deviation equal h/3) and the Π-shaped filter along the direction of the satellite motion (with the length equal to the anticipated shift of the satellite during frame exposure). After filtration, the standard deviation of the noise decreases by 2 times, which makes it possible to identify additional faint stars and a blur of the image stay moderate. Limiting magnitude of detected moving objects is equal to 11m in the V-band (at an average angular speed of the telescope motion).

To determine the time of the mid exposure we using an original technique. It consists in coding of second pulses of GPS-receiver and mixing them into a video stream (Dragomiretsky et al., 2013; Shakun & Koshkin, 2014).

In this case, the random error in the determination of registration time is less than 0.0001 seconds. To estimate the systematic shift between the time of the middle of frame exposure and the time of his transfer to the video stream, we use a comparison of the measured coordinates of the satellites and its ephemerides by ILRS – international laser ranging network (Kara, 2009/2010). An estimate of the systematic shift was about 0.01 seconds. This result agrees well with the analysis of the timing diagrams of video camera Watec-902H2 Sup (Dragomiretsky et al., 2015).

4. Processing of video sequences

All of the observations in this study were obtained in the video mode, the exposure duration 0.02 seconds. Method of determining the coordinates of objects in frame is described in early paper Shakun & Koshkin (2014). Estimation of the standard deviation of the object placement in the frame is in the range of 0.3 pixel for objects with high signal to noise ratio up to 0.9 pixel for objects with a signal to noise ratio of less than 3.

The determination of topocentric equatorial coordinates of the star in the reference catalogue system (J2000.0) is performed as follows.

1) In the frames containing three or more star-like objects is performed the identification with the objects configuration in catalogue (in the vicinity of the sight direction). If among the star-like objects in the frame SO can be isolated, its image is erased before the configuration identification.

2) For all frames, in which it possible to identify two or more objects with a reference stellar catalog are computed corrections to the sight direction of the telescope.

3) The slope of the frame coordinate system was specified always if identification by 3 to 5 stars. Are specified the coefficients of the transform of the frame to the celestial coordinate system in the plane if a more than 6 objects was identified.

4) The corrections to the telescope sight direction are smoothed by approximating high rigidity cubic spline.

5) Are specified the sight directions for all frames.

6) Re-procesed all frames. The SO' position in the current frame is predicted based on the information about the its places in several previous frames.

7) For frames in which is possible to identify at least one star-shaped object with a reference catalogue the estimate topocentric coordinates of the satellite was done based on the average of the coordinate system in the frame. (SO previously deleted on all frames).

All obtained topocentric coordinates of satellite was approximated with use Kepler or SGP4 orbit. Erroneous estimates of the satellite coordinates are rejected.

5. Method of photometric measurements processing

Method of initial processing of satellite photometric observations using analog CCD-camera thoroughly described in the (Shakun & Koshkin, 2014). The brightness of all star-like objects in images is estimated in terms of luminance volume. Transformation to the magnitudes is performed as follows.

The estimates of photometric characteristics of satellite based on comparison with measurements of catalog stars. The process can be divided into three stages. First – a linearization of the measured brightness scale. Second – a determination of the extra-atmospheric magnitude of all observed (measured) objects. Third – the transformation of the objects magnitude in the 'hardware' photometric system to the standard photometric system.

The measured brightness of all the stars in dependence on the catalog magnitudes is not linear, and to the scale correction are use the following formula:

$$m = a * \left(2.5\lg\frac{Vol}{const}\right)^2 + b * 2.5\lg\frac{Vol}{const} - c \ ,$$

where *Vol* – "volume" of point source image on the CCD frame, *m* is its instrumental magnitude obtained using constant: $a = -0.188001$, $b = 0.563329$, $c = 0.587$, $const = 280000$, which values obtained in advance.

The obtained instrumental magnitudes are distorted by absorption in the atmosphere and must be corrected by reduction to extra-atmospheric magnitudes. For this are determined a spectral extinction coefficient. For broadband photometric system, as our case, there is a dependence of the atmospheric extinction from the energy distribution in the spectrum of the star and its color-indeces.

Given these factors, the formula for atmospheric extinction is a complex function, which dependent also on the air mass *M(z)* and color-index *(B-V)* of the object and can be represented by the formula:

$$m = m^\circ + (K_0 + \gamma(B-V))M(z) + (K_1 + \tau(B-V))M^2(z),$$

where K_0 is the coefficient of extinction. To determine coefficients K_0, γ, K_1, τ we used the method of successive approximations. By usage these coefficients was calculated of the extra-atmospheric magnitudes of 275 stars that measured in our photometric system.

However, change the sensitivity of a detector, temperature and other factors are lead to change of photometric system. Even more it refers to measurements taken at different times in different observatories using different equipment. This requires to carry out the transformation of the our photometric system to some standard system. The relations between the photometric systems is generally regarded as a function of magnitude and color-indices C^i:

$$m_1 = f(m_2, C_2^1, C_2^2, ..C_2^n)\,.$$

In our case, photometric system is the wide not-standard band, so we will use conversion rates to standard V system. The measurements and calculations showed that relationship between the magnitudes of the standard photometric system (m_v) and magnitudes of our system (m^o) is close to the linear. Therefore we made the transformation using the following relationship:

$$m_v = Q_0 + Q_1 m^o + Q_b(B-V) + Q_r(V-R)\,.$$

The solution of system equations for all the stars having the extra-atmospheric magnitudes give us the transformation coefficients Q_0, Q_1, Q_b, Q_r. We find maximum spread of m_v is ± 0.1 mag, and standard deviation – 0.05 magnitude. These values are satisfactory for CCD photometer with sensor that works in TV-mode.

Thus, this relationship allows to determine of extra-atmospheric magnitude of artificial satellite in the standard photometric system V. For this as a color-indeces of satellite the solar color-indeces was used. The compelled assumption is accepted the satellite color are "gray" on average, which of course there is wrong, but distort the light curve of satellite unsignificantly.

The final step to obtain the standard light curve of satellite, regardless of the distance to it, is "ranging" to a standard distance of 1000 km

$$m_V^{1000} = m_v - 5 * \lg R + 15\,.$$

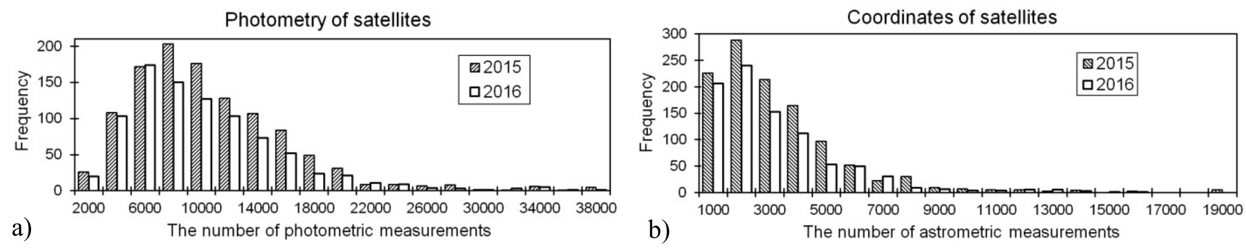

Figure 2: (a) – The frequency distribution of the photometric measurements number during single pass.
(b) – The frequency distribution of the number of pointing measurements of satellite during single pass (in 2015-2016).

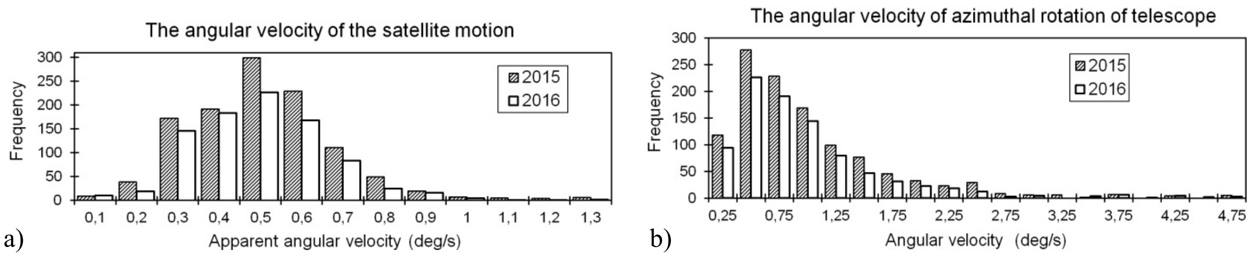

Figure 3: (a) – The frequency distribution of the maximum angular velocity of targets in the culmination.
(b) – The frequency distribution of the maximum angular velocity of telescope in the azimuth movement.

6. Overview observations in 2015-2016

Below, are provide a brief general information about SO observations received in the past two years. In 2015, on the KT-50 telescope the observations of 182 targets in 1133 passages were obtained. Among them, 136 targets is a different payloads observed in 929 passages, and 46 is the last stages of vehicles (r/b), observed in 204 passages. In 2016, the observations of 157 objects were obtained in 974 passages during 65 nights.

To characterize the observation process, we consider some statistical parameters of the total array of the measurements in the 2015 and 2016. Fig. 2,a shows the frequency distribution versus the length of the brightness' arrays obtained in one pass. That is, the length of the photometric arrays ranged from zero to 2000 measuring in approximately 25 passages. But more often (in 195 passages) the number of measurements of the brightness during one passage was from 6000 to 8000 in 2015, and from 4000 to 6000 measurements in the 174 passages in 2016. Fig. 2,b shows the frequency distribution versus the number of astrometric measurements in the one pass. Since the background stars can not be measured in every frame of the video sequence, the number of SO coordinate measurement is substantially smaller than the photometric measurement, and the maximum of distribution is in the range from 1000 to 2000 measurements for both periods.

The KT-50 telescope is the specialized high-speed device, accordingly are observed among us to many objects moving at low altitudes above the Earth's surface. The distribution of the maximum of apparent speeds for passage to characterize the satellite speed in Fig. 3,a shown. As can see, most of the apparent angular velocity in the culmination is between 0.4 to 0.5 degrees per second, and in extreme cases exceed 1.2°/sec. However, for a biaxial mounting important characteristic is the maximum speed of telescope movement on one of the coordinates. Fig. 3,b shows the observed frequency distribution of maximum angular velocity of azimuthal telescope movement. In most cases (nearly 250 passages per year) in our observations this rate ranged from 0.25 to 0.5 degrees per second. But in many passages of the rotational speed of the telescope reaches 2.5 degrees per second, and in rare cases – 4.75 degrees per second. This index shows the limiting capabilities of the telescope for tracking of lowest LEO.

7. Conclusion

Tracking mode does not involve mass monitoring of many LEO space objects. The purpose of these observations to obtain very precise measurements of the position of the satellite (space debris) and its brightness throughout the visible arc over the observation point. These measurements can be used later to refine the orbit of the satellite and to development of movement theory considering their own rotation. The precise measurement of time is an important component of the high-quality measurements of the position and brightness of satellite. In this paper, images analysis techniques in the frame and the method of the satellite brightness estimation in the standard photometric system were describe. Within one year on the KT-50 telescope are always obtained a measurements of about two hundred objects in more than 1,000 passages. The results of statistical analysis of actual data observations array in 2015 and 2016 are given. This project was supported by the Ministry of Education of Ukraine, and, in part, with the support of the Main astronomical observatory of NAS of Ukraine.

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