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COLOR-INDEX DETERMINATION OF LEO SATELLITES USING COLOR IP-CAMERAS

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ABSTRACT. The study is devoted to determining the color characteristics of the structural surfaces of artificial satellites. Observations of satellites were carried out in automatic mode using software for detection fast moving object, developed at RI "MAO". The satellite observations equipment consists of Canon EF 85mm f/1.8 USM photographic lens and professional VIVOTEK IP816A-HP network camera. The camera is directed to the zenith and has a field of view (4.9ºx2.8º). The camera has progressive CMOS sensor with Bayer color filter array for producing RGB color image. Coordinate and photometric processing of saved images is carried out using SExtractor and Astrometry.net software along with additional Python scripts. In this paper, we present first results of our LEO satellites observations using network IP-cameras with RGB Bayer filter. To convert the instrumental magnitudes from RGB Bayer system into standard *bp/rp* magnitudes of the Gaia EDR3 photometric system, a system of equations was solved, where the calculated magnitudes in the *bp/rp* photometric system were represented as functions of magnitudes and colors in the instrumental RGB system. The mean differences between the calculated magnitudes and the catalog magnitudes are $(0.03\pm0.15)^{mag}$ and $(0.01\pm0.16)^{mag}$ for *bp* and *rp* band, respectively. The calculated *Brjb_bp* and *Rrjb_rp* magnitudes using obtained transformation coefficients show a good linear correlation with the *bp* and *rp* Gaia EDR3 magnitudes. Only main sequence's stars in the range of $(5\text{-}13)^{mag}$ were used as reference stars for determining the transformation coefficients. The results of determining the color indexes (*Brjb_bp - Rrjb_rp*) for 8 LEO satellites with the obtained transformation coefficients were received. The average accuracy of the obtained values of color indexes is about 0.2^{mag}.

Keywords: RGB-cameras, Photometry Transformations, Gaia *bp/rp* photometric system, color index, LEO satellite.

АНОТАЦІЯ. Дослідження присвячене визначенню кольорових характеристик структурних поверхонь штучних супутників. Спостереження за супутниками проводилися в автоматичному режимі з використанням програмного забезпечення виявлення швидких об'єктів, розробленого в НДІ «МАО». Устаткування для супутникових спостережень складається з фотооб'єктиву Canon EF 85mm f/1.8 USM та професійної мережевої камери VIVOTEK IP816A-HP. Камера направлена в зеніт та має поле зору (4.9°x2.8°). Камера оснащена прогресивною матрицею CMOS із матрицею кольорових фільтрів Байєра для створення кольорового зображення RGB. Координатна та фотометрична обробка збережених зображень здійснюється за допомогою програмного забезпечення SExtractor та Astrometry.net разом із додатковими скриптами Python. У цій статті ми представляємо перші результати наших спостережень супутників LEO з використанням мережевих IP-камер із RGB-фільтром Байєра. Для перетворення інструментальних зоряних величин у системі RGB з фільтрами Байєра в стандартні зоряні величини фотометричної системи Gaia EDR3 *bp/rp* була вирішена система рівнянь, в якій обчислювані зоряні величини в фотометричній системі *bp/rp* були представлені як функції зоряних величин і кольорів в інструментальній системі RGB. Середні залишкові різниці між розрахованими зоряними величинами та величинами з каталогу становлять $(0.03\pm0.15)^{mag}$ та $(0.01\pm0.16)^{mag}$ для смуг *bp* та *rp* відповідно. Розраховані з використанням отриманих коефіцієнтів трансформації величини *Brjb_bp* та *Rrjb_rp* показують хорошу лінійну кореляцію з величинами *bp* та *rp* з каталогу Gaia EDR3. Тільки зорі головної послідовності в діапазоні $(5\text{-}13)^{mag}$ використовувалися як опорні зорі для визначення коефіцієнтів трансформації. Обчислено значення показників кольору *(Brjb_bp – Rrjb_rp)* для 8 супутників LEO з отриманими коефіцієнтами перетворення. Середня точність одержаних значень показників кольору становить близько 0.2^{mag}.

Ключові слова: RGB-камери, фотометричні перетворення, фотометрична система Gaia *bp/rp*, показник кольору, супутник LEO.

1. Introduction

Optical observations of artificial satellites play significant roles in obtaining orbital characteristics, monitoring and catalogization but for object classes identification surface materials, rotation and shape models development, besides the orbits, additional information like physical properties is required. Photometric colors are an important tool in the identification of satellites manufacturers (Vananti et al., 2017) and bus configuration, that includes size and shape of the object, antennae, solar arrays etc. (Zhao et al., 2022) Different photometric systems have also been used for physical characterization of space debris, such as the (BVRI) Johnson-Cousins, the SDSS/Sloan and the infrared bands. In this paper we present first results of the LEO satellites color determination based on data obtained with consumer-level RGB cameras. Such cameras are typically not used in professional astronomy because of the systematic errors present in the data as a result of the strong intra- and interpixel variations associated with each of the three different colors (RGB) of the Bayer color filter array (Gee et al., 2021). Nevertheless, because the cost of such cameras compared with traditional astronomical CCDs is so much lower, the use of such cameras is, in our opinion, very promising for obtaining mass photometric data. Also, recent works have made strong efforts to produce standard photometry in RGB bands based on high-precision photometry of the EDR3 Gaia catalog. A new set of spectral sensitivity curves, computed as the median of 28 sets of empirical sensitivity curves from the literature, that can be used to establish a standard RGB photometric system was presented in (Cardiel et al., 2021a). This work led to creation of the new catalogs with RGB photometric calibration of Gaia stars (Cardiel et al., 2021b; Carrasco et al., 2023).

2. Observational facilities and technique

The satellite observations equipment consists of Canon EF 85mm f/1.8 USM photographic lens and professional VIVOTEK IP816A-HP network camera, which provides a shooting speed of up to 60 frames per second, a field size of 2 megapixels (1920x1080), a sensitivity of 0.03 lux (color mode), 3D noise suppression in low light conditions, RBF (Radial Basis Function) system for precise focus adjustment, EIS (electronic image stabilization) to control image stability. The camera is directed to the zenith and has a field of view (4.9ºx2.8º), pixel size – 9 arcsec. The RGB Bayer filter system consists of a mosaic of R, G, and B filters on the grid of the photo sensors which cameras are equipped with. Observations of satellites are carried out with frame rate 5 fps in automatic mode using software for detection of the fast moving object, developed at RI “MAO”.

The algorithm for detection of moving objects is similar to algorithm for detection of meteors but modified for processing of video stream from different kind of sources and devices (Kulichenko et al., 2019). Another feature of the algorithm is saving color images in standard raster-graphics file formats (such as png) so that the data of each color (R, G, and B) could be processed separately during further photometric reduction.

Average duration of observations for night was 6 hours. During 15 nights 1362 objects were detected. Total number of frames is 41680.

3. Processing

Coordinate and photometric processing of saved images is carried out using SExtractor (Bertin & Arnouts, 1996) and Astrometry.net software (Lang et al., 2010) along with additional Python scripts. Reference stars are obtained using “track-and-stack” technique. Processing of obtained observations included next steps:

1) Frames filtering using software for processing of the CCD images developed in RI “MAO”;

2) Extracting stars and cross-match with catalog Tycho-2 for obtaining reduction coefficients using Astrometry.net software. Flux of extracted stars in ADU with subtracted background also saved in result files. Flux values for each color of RGB-image are obtained separately;

3) Obtaining a summary csv-table for all detected stars with measured celestial coordinates and streams from all processed frames using a Python script. The table also includes coordinates and magnitudes from Tycho-2 catalogs for all cross-matching stars.

3.1. Astrometry

Cross-matching procedures with Gaia EDR3 catalog were made by CDS Cross-Match service by TOPCAT software (Taylor M., 2005). The cross-match results are shown in Tab. 1. (O – C) differences and their standard deviations in right ascension and declination are given in column 2, 3, N1- number of common stars with Gaia EDR3 catalog. As you can see from the table, there are no significant systematic differences between obtained coordinates and Gaia EDR3 catalog. The accuracy is almost the same for both coordinates in the B, G, R ranges.

Table 1: Results of cross matching between observational arrays and Gaia EDR3 catalog

Band	(O – C), arcsec		N
	RA	DE	
B	-1.8 ± 7.4	2.1 ± 6.9	175
G	1.2 ± 7.0	-1.1 ± 7.9	272
R	1.2 ±7.3	-0.7 ± 6.7	270

3.2. Photometric transformation and color index determination

The counts from the stars with the subtracted background were converted to the scale of instrumental magnitudes according to the known ratio: $mag = -2.5 * log(FLUX)$.

Differential photometry is achieved by comparing the flux from a target star (within a given radius or aperture) with the flux of the reference stars. The flux measurements of stars were calculated using isophotal mode of SExtractor software. The photometric measure errors for B, G, R files are shown in Fig. 1.

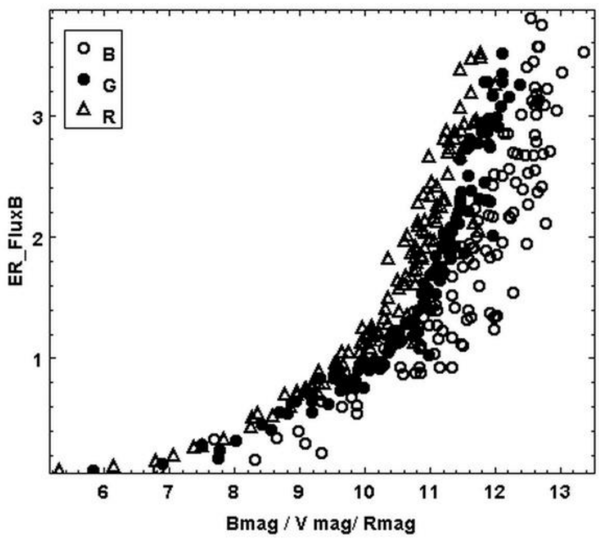

Figure 1: Flux errors for B, G, R bands

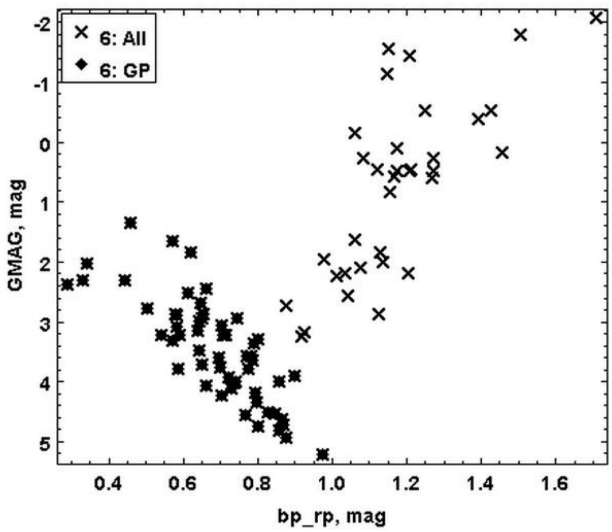

Figure: 2 Hertzsprung-Russell Diagram

To derive the conversion formula that describes the transformation between the instrumental RGB and Gaia *bp_rp* photometric systems only main-sequence stars are selected. The Hertzsprung-Russell diagram plotted using Gaia EDR3 Supplement data provides a way to distinguish stars. As is clear from Fig. 2 main sequence stars are easy visualized as strip from left to right of a HR diagram.

After identify the same stars in B, G, R images, we compared B magnitude with bp Gaia EDR3 magnitude and R magnitude with rp Gaia EDR3 magnitude for individual stars. The relationship between magnitudes can be represented in the form taking into account color differences between Bayer filters:

$$bp\_G = B_0 + C_1B_{rgb} + C_2(B_{rgb} - G_{rgb}) + C_3(G_{rgb} - R_{rgb})$$
$$rp\_G = R_0 + C_4R_{rgb} + C_5(B_{rgb} - G_{rgb}) + C_6(G_{rgb} - R_{rgb}),$$

where *bp_G, rp_G* – Gaia EDR3 photometric magnitude, B_{rgb}, G_{rgb}, R_{rgb} – Bayer B, G, and R magnitudes; B_0, R_0 – the zero-points for the Bayer filters. The transformation coefficients were derived by the iterative least square fitting algorithm with 3-sigma clipping method. The calculated values of transformation star coefficients and their errors are presented in Tab. 2 As could be seen from table 2 the accuracy of link between the two systems is 0.15^{mag} for *bp* band and 0.16^{mag} for *rp* band. The *Brjb_bp* and *Rrjb_rp* magnitudes calculated with usage transformation coefficients show a good linear correlation with the *bp* and *rp* Gaia EDR3 magnitudes.

The Fig. 3 presents residual differences between RGB and Gaia *bp* and *rp* photometric magnitudes. As is observable from the Fig. 3 there is no significant systematic differences in magnitudes in the observational range. The random error is determined by the errors of the least squares method solution and mean residual differences between the calculated magnitudes and original catalog magnitudes, are $(0.03\pm0.15)^{mag}$ and $(0.01\pm0.16)^{mag}$ for *bp* and *rp* band respectively.

The Fig. 4 presents residual differences between (*bp_rp)* Gaia color index and calculated color index (*Brgb_bp – Rrgb_rp)* The mean value of the color differences is $(0.02 \pm0.12)^{mag}$.

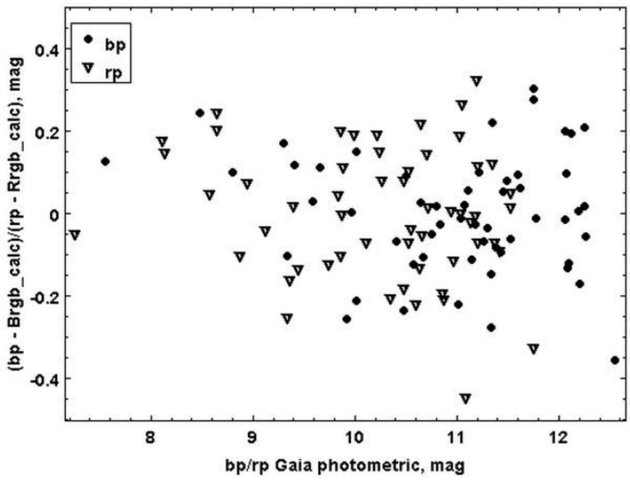

Figure 3: Residuals in magnitude plots for the bp and rp Gaia photometric bands

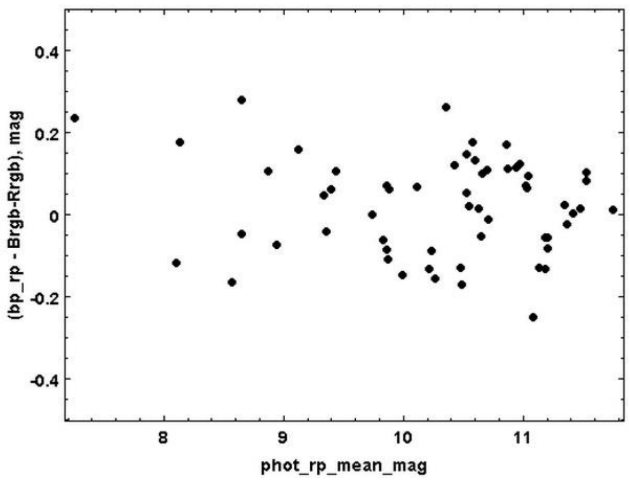

Figure 4: Residuals in color index vs rp band Gaia magnitude

We applied obtained transformation coefficients to the RGB magnitudes of some satellites, whose images were present in the fields with reference stars. Results of the color index determination and identification for selected satellites are shown in Tab. 3. It would be mentioned that 6 satellites were identified by NORAD catalog number. Satellite light-curves for N99005 and N99008 satellites are shown in the Fig. 5.

4. Conclusion

First results of the LEO satellites color index determination from original observations obtained with network RGB color IP-cameras are presented. Derived transformation equations between the RGB instrumental system and the photometric *bp* and *rp* Gaia EDR3 magnitudes are given. The calculated *Brjb_bp* and *Rrjb_rp* magnitudes from the transformation equations has shown a good linear correlation with the *bp* and *rp* magnitudes from

Table2: Transformation coefficients

Band	B_0/R_0	C_1/C_4	C_2/C_5	C_2/C_5	RMS
bp	18.60±0.16	1.12±0.03	-0.77±0.12	-0.03±0.12	0.15
rp	17.39±0.17	1.05±0.03	0.41±0.14	1.01±0.14	0.16

Table3: Results of the color index determination and identification for selected satellites

UTC start 2023-07-	TMP ID	NORAD ID	Period, min	Incl, deg	Apo, km	Peri, km	RCS*	N	*bp*, mag	(*bp*-*rp*), mag	Std (*bp*-*rp*)
12 19:10:54	99001	51654	109.89	87.88	1223	1220	L	88	6.96	−0.3	0.2
12 19:13:32	99003	-	-	-	-	-	U-	194	6.85	−0.17	0.14
12 21:59:55	99004	52790	96.94	50.01	617	608	M	39	5.22	−0.24	0.07
12 23:01:45	99005	45767	95.59	53.05	548	546	L	25	4.93	−0.22	0.07
13 20:24:57	99006	54214	100.78	60.00	816	776	L	133	6.77	−0.31	0.12
13 21:06:51	99007	10730	103.30	114.98	999	830	L	39	7.09	−0.43	0.19
14 19:01:00	99008	-	-	-	-	-	U	36	5.13	−0.48	0.09
14 19:55:34	99009	31571	114.08	51.99	1414	1413	L	50	6.86	−0.26	0.45

* L -large, M – Medium, U – Unknown

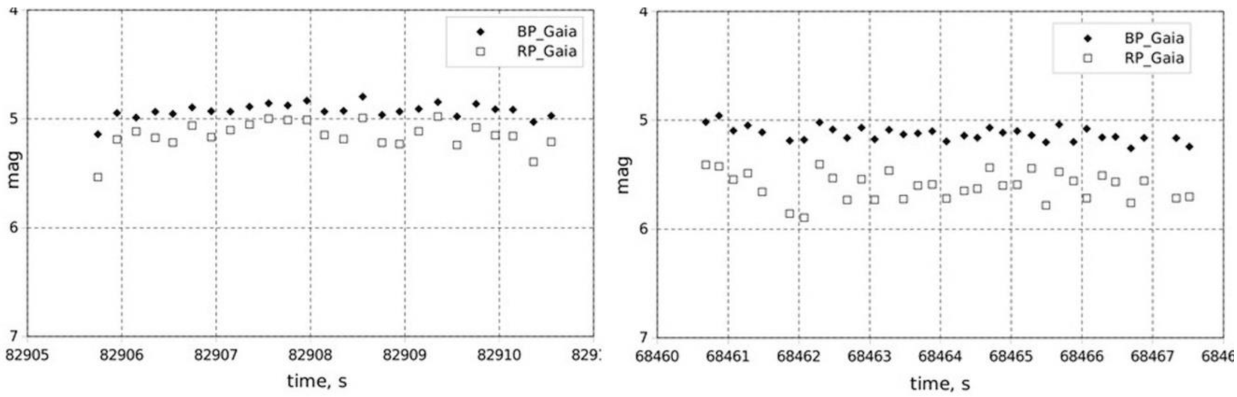

Figure 5: Light-curves for N99005 (right) and N99008 (left) satellites

Gaia EDR3 catalog. The average accuracy of the obtained values of color indexes for LEO satellites is about 0.2 ^{mag}.

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