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RECONFIGURABLE OPTICAL SYSTEM FOR SPACE OBJECT TRACKING

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The growing quantity of space debris poses a serious hazard to functioning satellites. Mitigating space debris is critical to ensure the safe and sustainable use of space in Earth's orbit. Near-Earth objects such as asteroids can pose a serious threat to infrastructure and life on the ground. As space debris and near-Earth object observation communities use similar techniques and processes to measure space objects, the need for synergy is growing. This paper presents the ability of small sensors to detect and track such objects using the implemented technology – CCD image stacking in equatorial coordinates. The experimental optical system is intended for both positional astrometric and laser ranging observations – its optical scheme is reconfigurable. Here we provide the technical characteristics of the system and a description of its functionality using comprehensive control and analysis software. We propose a method of image stacking, which has several advantages in searching space objects by different optical systems and their combinations. This method enables increasing the brightness of space objects, visualizing their motion relative to stars, and stacking images obtained by optical systems with different technical parameters.

Keywords: *Charge-coupled device, near-Earth objects, optical sensors, space debris, tracking.*

1. INTRODUCTION

The rapid expansion of human space activities has significantly increased the quantity of space debris in Earth's orbital environment. This poses a serious threat to all space operations and exploration missions [1]. The development of automated algorithms for detecting space objects has become a subject of interest. The importance of these algorithms lies in their accuracy, speed, repeatability, and maximum objectivity and is apparent in many fields and large surveys.

The acquisition of space debris orbital data through observations is critical. Current ground-based tracking systems of space surveillance networks (SSN) include the use of radars and passive-optical and active-optical telescopes for cataloging and characterising space debris. Lasers are extremely precise but have limitations in terms of the energy of emitted pulses, which is important for targets without retroreflectors and a relatively small field of view [2], [3]. Passive-optical systems, which are used mainly to determine the astrometric position of an object, are of considerable importance in many applications [4]–[6]. Observation by such systems is a well-suited method for monitoring the geosynchronous protected region [7].

Progress in imaging technologies has changed the properties of the star position measurement process. Currently, CCD matrices provide high sensitivity and allow immediate astrometric processing, and the accuracy and number of star coordinates substantially increase. This ensures fast and efficient methods for the precise identification of space objects for different observation communities.

Here, we provide the technical characteristics of an experimental optical tracking system (OTS), which is designed as an alternative to custom-made systems. We propose a method of CCD image stacking implemented in equatorial coordinates, which increases the efficiency of capturing space debris and faint near-Earth objects (NEOs) via different optical systems and their combinations.

2. CONCEPTUAL AND EXPERIMENTAL PART

2.1. Concept and Design of OTS

The OTS includes twin receiving optical tube assemblies (OTAs), which are symmetrically set on an Alt-Alt mount (Fig. 1). This type of mount ensures continuous tracking of objects in different regions of the sky, unlike Alt-Az and equatorial mounts, which have 'blind spots' in the zenith and celestial pole, respectively. The system's optical scheme is reconfigurable. The design implies that one OTA is equipped with a CCD matrix and that the other OTA can be fitted with a laser collimator and a reflected light pulse detector for satellite laser ranging (SLR) purposes or with other instruments.

The following configurations of the OTS are most promising:

- one or both OTAs are equipped with a CCD for positional astrometric observations;

- one OTA with an analogue signal receiver (e.g., PMT – photomultiplier tube) for registration of reflected SLR pulses, another OTA with a digital receiver (CCD) for visual guidance;
- both OTAs are equipped with analogue signal receivers for registration of reflected SLR pulses in the coincidence scheme or the gate and window scheme (in noisy environments).

Fig. 1. Assembly of the optical tracking system.

Each OTA has an advanced coma-free (ACF) 0.41 m F/10 optic (focal length: 4 m) with a high transparency coating.

The drive of the mount has two stepper motors with wormwheel gearboxes and two incremental encoders. It is controlled by the FPGA. Technical parameters are summarised in Table 1.

Table 1. Technical Specifications of the Mount

Description	Technical parameters
Stepper motor drive	200 steps/rev, up to 256 mkstep/step
1:85 wormwheel gearboxes	with about 10–15 arcsec backlash
Drive resolution	up to 0.32 arcsec/mkstep
18 000 division (72 arcsec) relative encoders	with up to 100 x interpolation
Encoder pulse resolution	up to 0.36 arcsec, accuracy 2–3 arcsec
Slewing speed	up to 5–10 dg/s
Tracking speed	up to 2 dg/s
Mount control software: Windows PC via FPGA	up to 1000 control cycles/sec

The OTS design outline and its control parts are shown in Fig. 2. Descriptions of all numbered components are given in Table 2.

One of the principal design goals for

the system is laser ranging capability. The laser ranging in automatic (blind) mode requires a pointing accuracy exceeding the divergence of the transmitted beam. As subarcminute beam divergence is a common choice for ranging distant objects, the pointing accuracy should be within a few arcseconds. Therefore, an error model must be applied in the control software to introduce the necessary pointing corrections.

The system is now equipped with two CCD matrices for astrometric observations: 8.3 Mpix (3326 × 2504) and 16.8 Mpix (4096 × 4096) CCD matrices. A more advanced model ensures a field of view of 0.5° × 0.5° with a minimum pixel size of 0.46 arcseconds.

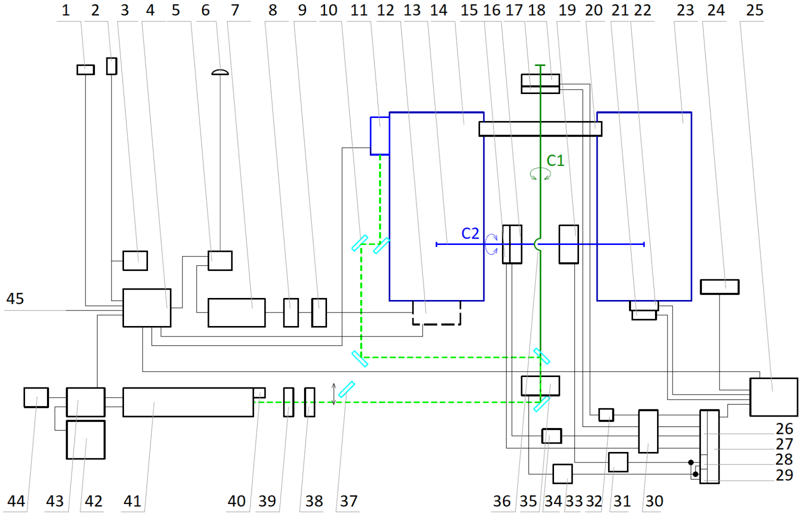


Fig. 2. OTS design scheme. The primary rotation Axis C1 is shown in green, and the secondary rotation Axis C2 is shown in blue. The Coudé path for the transmitted laser beam enters along C1. The transmitting collimator is attached to the side of the receiving OTA. Descriptions are given in Table 2.

Table 2. Descriptions of the Numbered Components of the OTS Design Scheme

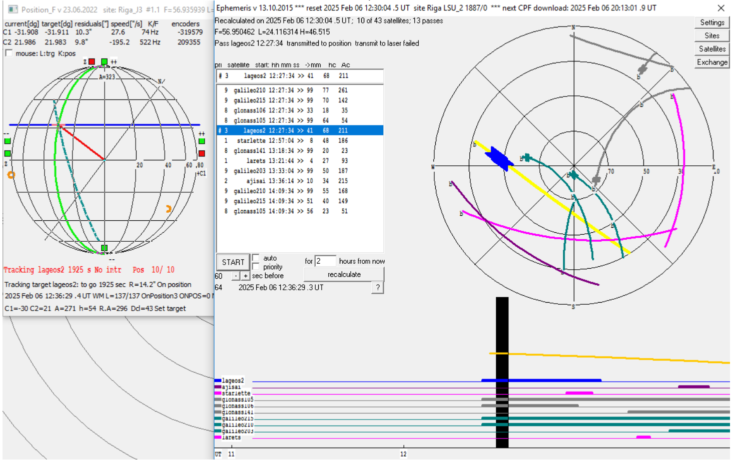
No	Item	No	Item	No	Item
1	All sky camera	16	Encoder II	31	Power unit II
2	Meteo sensor	17	Limit and zenith switch I	32	IBV 102 I
3	Digital barometer	18	Encoder I	33	Power unit I
4	PC I	19	Drive II	34	IBV 102 II
5	GNSS receiver	20	Tie	35	Drive I
6	GNSS antenna	21	CCD sensor	36	Rotation Axis I (C1)
7	Event timer	22	Microfocuser	37	Adjustment mirror
8	CFD	23	OTA II	38	Filter set
9	Filter set	24	Dome control	39	SHG
10	Laser beam path	25	PC II	40	Infrared detector
11	Optical transmitter	26	Slot CN4 CN6	41	Laser
12	Analog receiver	27	PC extension board	42	Cooling unit I
13	Rotation Axis II (C2)	28	Slot CN3	43	Cooling unit II
14	OTA I	29	Slot CN5	44	Manual control keyboard
15	Limit and zenith switch II	30	TTL/LVTTL board	45	Internet

2.2. Control and Analysis Software

The control software is developed using MS VisualStudio C++ and C#. This software consists of several semiautonomous modules supporting positioning, astrometry, ephemeris, and SLR functionality.

The positioning (mount control) module uses angular encoders to determine the current positions of the OTS; it calculates the step frequency needed to track the object and controls mount motor step pulse generation. GNSS event timing can be used for tracking purposes and acquisition of the CCD image exposure time. The object tracking process uses a motion model, which is based on a precalculated (by the ephemeris module for satellites or by the astrometry module for stellar objects) polynomial approximation of the topocentric horizontal rectangular coordinate dependency on time. The values of the target coordinates are calculated and corrected by the mount error model in real time.

a)



b)

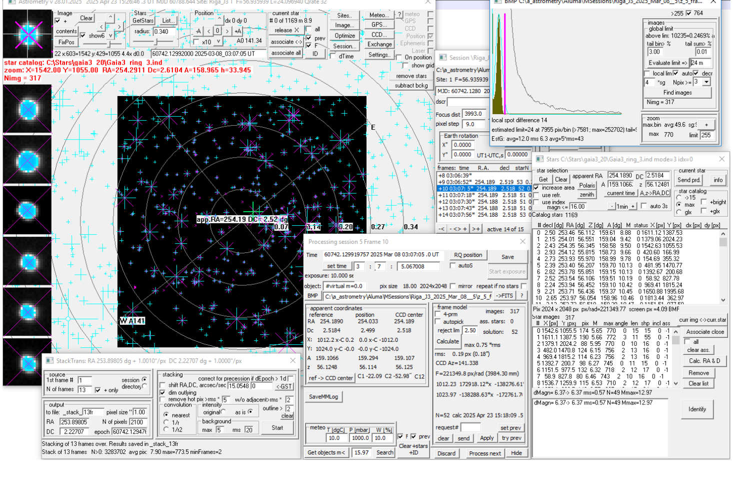


Fig. 3. Software interfaces: a) positioning and ephemeris modules; b) astrometry module.

Ephemeris is a separate module (see Fig. 3a) for satellite prediction data acquisition and management, tracking model generation, situation visualization, and providing current pass prediction to the positioning module. The module uses the consolidated prediction format (CPF) as a data source. Other data sources and formats, e.g., the two-line element set (TLE) format, can also be implemented.

The functions of the module responsible for SLR functionality include control of the event timer and collimator's divergence, as well as control of the receiver's diaphragm and filter wheel. It ensures the collection, analysis, and storage of calibration data and laser ranging data, as well as the generation and export of normal point data.

The astrometry module supports image acquisition and near-real-time analysis (see Fig. 3b). It controls the CCD camera settings, contrast enhancement, and object image recognition, ensures reference star selection and identification, and determines the object coordinates. The module includes the vector astrometry software package NOVAS for calculating the apparent places of stars [8]. A subset of the Gaia star catalog (data release EDR3), consisting of astrometry and star magnitude data for stars brighter than magnitude 21, is used.

2.3. Image Stacking Method

Astronomical images are usually stacked to detect moving space objects or to produce a single image of a faint object with a superior signal-to-noise ratio. As all the summed pixel intensities contain a random noise component, stacking leads to a relative decrease in the noise level (up to a factor of $1/\sqrt{N}$) [9], resulting in better contrast of the target object. In common practice, image stacking is performed by comparing patterns on frames or directly overlaying images, and it requires images obtained using the same optics and under similar circumstances.

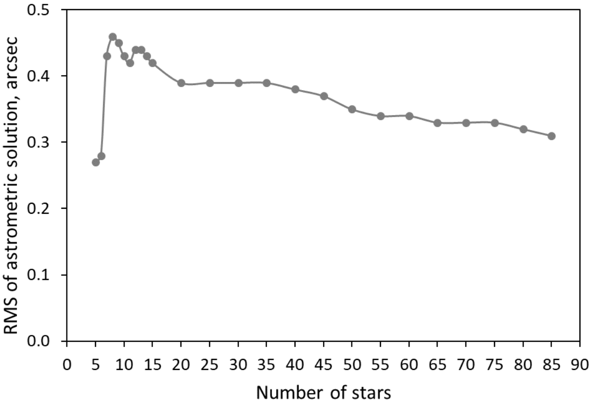
We propose a method of CCD image stacking implemented in equatorial coordinates. This allows stack images, which have different scales, distortions, framing and epochs. The method requires an astrometric solution for all involved images, i.e., transformation from image (pixel) coordinates to equatorial coordinates. The stacking mechanism is based on the calculation of coinciding positions on source images via a frame astrometric model. The stacked image is generated in a rectangular coordinate system, with coordinates of right ascension and declination.

3. TEST RESULTS AND DISCUSSION

To ensure correctness of star identities and sufficient accuracy of the astrometric solution, several tens or more stars are beneficial (see Fig. 4a). For the used set of instrumentation typical RMS of astrometric solution is 0.2–0.4 arcseconds at pixel size close to 1 arcsecond. Figure 4b shows the effect of the number of reference stars used within various solutions (from 6 up to 85 stars were used) on the position of a test star selected close to the centre of the frame.

According to Fig. 4a, RMS of astrometric solution slowly decreases with an increasing number of reference stars starting from 20 stars. For less than 20 reference stars considerable wandering of RMS values is observed; low RMS values in the case of 6–7 stars are caused by partial absorption of random measurement errors in astrometric model parameters. This is also reflected in more pronounced wandering of the test star's position in Fig. 4b. However, the wandering does not exceed 0.1 arcseconds even for the case of 6 reference stars. Similar results, with wandering up to 0.2 arcseconds, were obtained also for locations of test stars on the edges of the frame. Such accuracy is quite satisfactory for the purposes of image stacking.

a)



b)

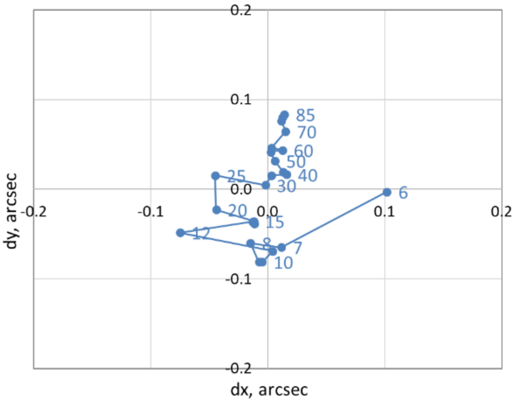


Fig. 4. a) RMS of astrometric solutions using increasing number of reference stars on the frame; b) Positions of selected star on the frame within different astrometric solutions with reference stars from 6 up to 85 (number of stars is indicated).

3.1. Geostationary Satellite Detection and Tracking

Figure 5 shows an example of an image stacking application for satellite observations in the geostationary Earth orbit (GEO). The frames are taken in static mode with 0.8 s exposures. Notably, the northern geographical location of the OTS means that the geostationary arc is only approximately 25° above the horizon and that an arc of approximately 50° is observable. In this case, the advantage of the method is the improved RMS value of the astrometric fit compared to that of single-frame solutions.

However, limitations may be related to the exposure time. Long streaks of star images make the identification process less accurate [10].

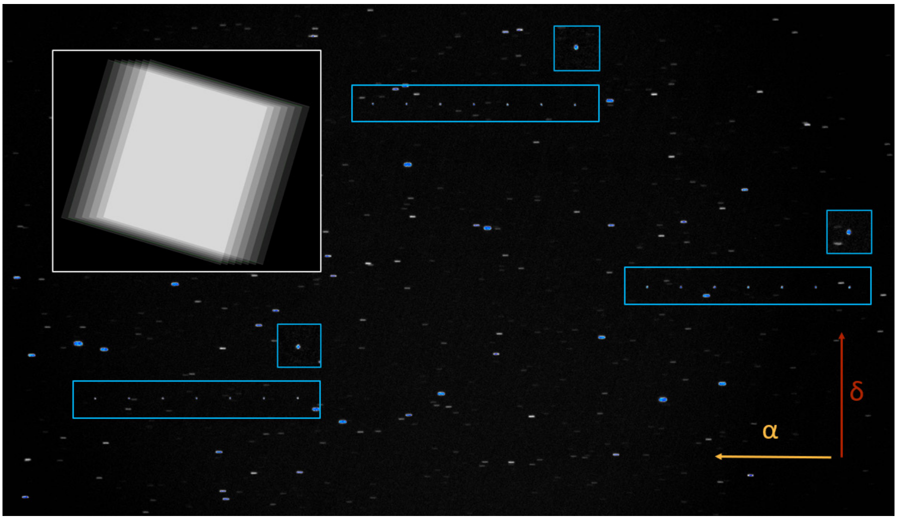


Fig. 5. Stack of 7 0.8-s frames in the region of the geostationary arc (31.5° E point) with three captured satellites; the image in the blue square is a stacked image (the scale is the same) of 7 single images of each GEO satellite.

To increase the brightness of small objects, e.g., pieces of GEO debris, stacking should be combined with the method of image shifting. Here, this is realised via the known rate of Earth rotation. Figure 5 shows the image in the blue square, which is a stacked image (the scale is the same) of 7 single images of each satellite applying the shifting technique. This allows increasing the brightness of an object. Thus, it is possible to detect space debris, which is not visible on a single CCD frame.

According to past and ongoing GEO surveys, in most cases, optical telescopes with diameters of 1 m or less were used, with sensitivity limits in the magnitude range of 15–20, corresponding to objects larger than 15 cm [11]. Using such systems for observation and applying methods of image stacking and shifting could increase the brightness of fainter GEO objects and detect their positions.

3.2. NEO Detection and Tracking

Current NEO survey programs such as Pan-STARRS and CSS (Catalina Sky Survey) usually conduct observations via the same strategy and data analysis process; several CCD images with exposure times of up to a few minutes are taken and compared to detect moving NEOs. The proposed method of image stacking has advantages over such an observation strategy: it increases the brightness of the asteroid during one session with a set of consequent images with relatively short exposure, i.e., it prolongs the "effective exposure time" of the object, and representatively shows the trajectory of its movement during the entire observation period.

Figure 6 presents an example of an image stacking application for asteroid observation. This is a stack of 25 5-s frames obtained in star-tracking mode during a 5-hour period in five batches.

Fig. 6. Stack of 25 5-s images with moving asteroid during a 5-h period. The orientations and overlaps of the images are shown.

The resulting stacked image allows for the detection of faint NEOs and the determination of their coordinates. Additionally, it is possible to combine images obtained by several telescopes simultaneously to increase the brightness of small and fast-moving NEOs, which cannot be detected via common observation strategies.

3.3. A Combination of Frames from a Set of Sensors

Figure 7 shows an example of stacking using images obtained by two CCD cameras simultaneously. The streak is a satellite observed by the OTS in static (not tracking) mode. This proves that the use of equatorial coordinates enables the processing and stacking of optical frames of various origins, with different orientations of the CCD matrices and different scales and distortions of images.

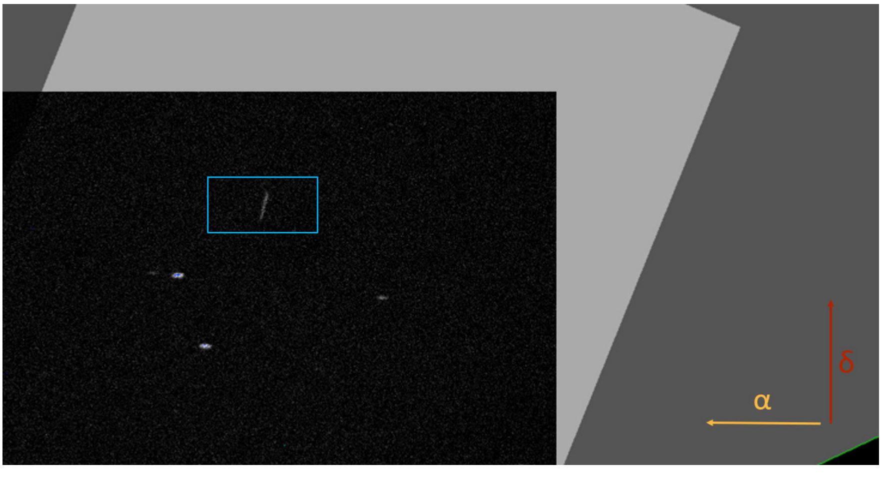


Fig. 7. Stack of 2 1-s images obtained by both cameras of OTS simultaneously, with a satellite streak.

If input frames have different source parameters, the question of differentiating their weights in the stacked frame arises. In this case, an estimate of the effective light flux (product of the exposure time, telescope aperture area, and sensitivity factor) can be used. This is implemented in our software, but other options are possible. More experimental results obtained by different optical systems are needed to evaluate this choice.

Stacking images from a set of sensors could be useful for detecting and tracking objects in low Earth orbit (LEO), which results in increased risks of collisions due to the high density of orbital debris [6], [12]. Combining images from multiple sensors simultaneously can increase the brightness of faint streaks of debris.

4. CONCLUSIONS

In this paper, the design of a combined active and passive optical measurement system has been presented with experimental results obtained via the new method for astronomical imaging, i.e., the method of CCD image stacking in equatorial coordinates.

We have shown that it has several advantages in tracking and detecting space objects and can be adapted for various observation strategies: in star or target tracking mode or in static mode. The main strengths are the ability to increase the brightness of faint objects via small sensors and the ability to combine images obtained by multiple optical systems, ensuring the detection of small and fast-moving objects. As such stacking requires the presence of astrometric solution for all source frames, an effect of small number of reference stars on accuracy of stacking was evaluated. We have found that for stacking purposes accuracy is quite satisfactory even for very few (10–20) reference stars per frame. More results obtained via different optical systems and their combinations are needed to fully evaluate the effectiveness of the proposed method.

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