Panoptes-1AB and Solaris-5 unique wide field telescopes with sCMOS cameras

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ABSTRACT

There are several Polish entities carrying active research in SSA and contributing to the new Polish Space Situational Awareness Centre. One of them is the Baltic Institute of Technology (Baltech), a non-profit research foundation. As part of its core research area, Baltech is developing a new optical sensor, Panoptes-1AB. Panoptes-1AB is a double system composed of a unique TEC300VT-7DEG astrograph and a 0.5 m Planewave telescope. The astrograph is a unique instrument 0.3 m in diameter and f/1.44. The instrument will be equipped with a Kepler KL4040 sCMOS camera. Panoptes-1B will offer a staggering $5^\circ \times 5^\circ$ field of view with 4.4 seconds of arc per pixel. The Panoptes-1 telescope will be initially installed at the Pomeranian Science and Technology Park's area in Gdynia, Poland. It will be a temporary site for R&D purposes and first on sky test and later relocated to the southern hemisphere. On the other hand, the Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences has just secured funding for a new 1 m, wide field (f/1.3) survey telescope Solaris-5 as an extension of the existing Solaris network. Solaris-5 will be equipped with a Kepler KL6060 sCMOS camera. The telescope will offer a large for this aperture $2.7^\circ \times 2.7^\circ$ field of view with 1.59 seconds of arc per pixel and will be installed in the northern hemisphere. The telescopes which are expected to become operational in the first quarter of 2020 and the second quarter of 2021 respectively will be fully dedicated to SST and NEO and will employ the technique of synthetic tracking to help boost SST and NEO survey and tracking capabilities.

Keywords: optical sensors, astrographs, sCMOS cameras, synthetic tracking

1. INTRODUCTION

We present our strategy to survey the nearest space in order to boost the detection of yet unknown objects and improve tracking capabilities. The combined use of the wide field of view (FOV) telescopes equipped with a new generation of scientific CMOS (sCMOS) detectors and advanced data processing such a synthetic tracking will allow us to significantly increase sensitivity to dim and rapid objects' detection. We plan to implement the technique of synthetic tracking (ST) in a regular observational routine. The synthetic tracking is the enhancement of the popular "shift-and-add" method used in surveys for Kuiper Belt or Main Belt bodies. The idea behind this technique is to use a few consecutive images to detect an object typically invisible or barely visible in a single image. Successive frames should be shifted by the distance corresponding to the displacement of the object in time between the frames and then added. The procedure is used to strengthen the signal from the object. The detection is based on cumulative images obtained in postprocessing. The brief historical review of this method is presented in section 2. The synthetic tracking technique is based on the idea of previous methods of computer-aided searches but it stands out as a technique with short, high frame-rate exposures and significant complexity of data processing. Due to that, ST necessitates technologies recently developed, like sCMOS detectors (or at least fast CCD cameras) and computing power of modern computers. Thanks to these, synthetic tracking allows finding faster and fainter objects than it would be possible with previously used approaches or traditional observations. The technique is applicable to asteroids of Main Belt and near-Earth region, Kuiper Belt Objects as well as anthropogenic satellites and space debris. Its description is presented in section 3. Our strategy is to upgrade and set up our sensors in a way that allows us to apply the technique of synthetic tracking. We plan to equip the telescopes with modern commercial-off-the-shelf cameras with sCMOS detectors that offer fast frame rate and low readout noise. Those features are necessary to acquire sequences of images without losing the signal between consecutive frames. Two sensors with wide FOV are currently being developed by Polish institutions, Panoptes-1AB and Solaris-5. The telescopes characterised by wide FOV allow observing a big piece of the sky in a reasonably short period. It is crucial to speed up the survey rate and increase the number of new discoveries. The description of telescopes is in section 4. The specification of all sensors that are or will be used to implement the synthetic tracking method and their comparison with other survey telescopes is presented in section 5.

2. REVIEW OF PAST WORK

Likely, the first case of computer-aided sky survey in order to find objects too dim to be observable in the traditional way was presented by Tyson et al. (1992) in [20]. Authors proposed to co-add many short exposures frames to enhance the chance to discover new Kuiper Belt Objects (KBOs). However, they did not find any objects. The first discovery and more detailed description were introduced by Cochran et al. (1995) in [5]. The Hubble Space Telescope (HST) survey was carried out, which resulted in detections of 29 very faint trans-Neptunian objects. The discoveries were reported to be the first detections of short-period comets in their native reservoir.

For simplicity, we will use the name "shift-and-add" for every former implementation of technique consisting of the acquisition of a large number of relatively short exposure time frames and their integration in order to synthesise longer effective exposure. The inquisitive reader will notice that such observation methods occur in the literature under many different names (e.g. "shift and stack", "stack and track", "track before detect", or like more sophisticated version presented in [12] "matched filtering"). The shift-and-add technique became a common procedure to improve asteroid detectability. It was used in order to search for KBOs and examine the population of objects in the outer Solar System. In general, the exposure time of a single frame was about several minutes, but combined frames could have an effective integration time of several hours. Employment of shorter exposure aimed to decrease trailing losses of moving objects, while combining frames together hugely improved a limiting magnitude. There followed several other campaigns in which many previously unknown KBOs were detected. Gladman & Kavelaars (1997) in [9] conducted a survey in order to determine more precise orbits for known KBOs and search for not yet discovered smaller objects. The 5 m Hale telescope (Palomar) was used. Instead of searching a big piece of the sky, they observed a single field for a longer time to obtain higher limiting magnitude by using combined frames of 4-6 hours effective integration time. Although they did not find new KBOs with a magnitude up to 25, they improved orbits of 18 objects beyond Neptune. Gladman et al. (1998) in [10] detected 5 new KBOs brighter than 26 magnitude using the Canada-France-Hawaii Telescope (CFHT, Mauna Kea) and the 5 m Hale telescope. Luu & Jewitt (1998) in [18] and Chiang & Brown (1999) in [4] used 10 m Keck telescope and found respectively 6 and 2 new trans-Neptunian objects. Gladman et al. (2001) in [11] used CFHT and 8 m VLT (Paranal) and discovered 17 new objects. Allen et al. (2001) in [1] conducted the survey of the population of small bodies within 50 AU of the Sun. They used 4m Blanco Telescope (CTIO). For the first time frames from more than one night had been combined, what became the proof of the feasibility of integrations spanned on many nights. It resulted in 24 new objects' detections. Bernstein et al. (2004) in [2] surveyed trans-Neptunian region using HST and, in result, they discovered 3 new objects. Gural et al. (2005) in [12] used archival data from the Spacewatch survey; typically, a few images of each field of view. They not only obtain a modest increase of sensitivity but also proved that a different approach allowed detection of previously undetected asteroids (compared to more traditional procedures). They pointed out the usefulness of the method to dense-star-fields.

A similar approach was presented by Kavelaars et al. (2004) in [16] and Holman et al. (2004) in [15] who took advantage of combined use of big telescopes, CFHT and 4m Blanco telescope, and computer-aided data processing in order to find new irregular satellites of Uranus and Neptune. All data originally acquired for [16] and [15] were used by Fraser et al. (2008) in [6] in order to search for KBOs. The search resulted in detection of 72 objects, from which only 2 were previously known. Fraser & Kavelaars (2009) in [7] used 8m Subaru telescope (Mauna Kea) and found 36 new KBOs. Fuentes et al. (2009) in [8] used the archival data from Subaru telescope to employ shift-and-add methods and found 20 previously unknown KBOs.

Further development of the shift-and-add method was not possible without a technological progress. There were needed two enhancements to improve the processes of data acquisition and processing. First, cameras which enable fast imaging with low read-out noise. Second, the computational power that could handle large data volume and associated more demanding computations. Improved version of shift-and-add technique, which took advantage of newly developed technologies like modern GPUs and sCMOS cameras, was proposed by Shao et al. (2014) in [19]. The new approach is called synthetic tracking and allows the detection of dim and fast-moving objects, like NEOs. The idea of synthetic tracking is analogous to shift-and-add technique and consists of acquiring a large number of short-exposure frames and then shifting them according to hypothesised NEO's velocity and integrating to obtain image equivalent to the telescope tracking on the target. The differences between the shift-and-add and synthetic tracking are that in synthetic tracking exposures times are below single second and numbers of co-added frames can range from several dozens to several hundred. In [19] the first results of the implementation of ST were presented. They used the Palomar 200 inch telescope and CHIMERA instrument with two Andor iXon 888 EMCCD's allowing high-speed imaging with very low read noise. They observed two known NEOs and proved the possibilities of the new method. Soon after that, Zhai et al. (2014) in [21] announced the discovery of faint near-Earth asteroid during the blind observation conducted on the same instrument.

A similar approach, called digital tracking, was presented by Heinze et al. (2015) in [14] and resulted in the discovery of 156 new asteroids and 59 known objects. These results were obtained using 0.9 m WIYN telescope on Kitt Peak and large-format CCD imager in a single field. They stated that computer-aided searches improve the detectability of asteroids ranging from Kuiper Belts through Main Belt and near-Earth objects and allow to detect object even ten times fainter than traditional methods. Gural et al. (2018) in [13] proposed a methodology in case of observations in which a moving object could induce a non-linear track in an acquired sequence of images. This problem can be significant for near-Earth objects observed from space-based sensors in high inclinations and low Earth orbits. The new procedure was developed to enhance the matched filtering algorithm presented earlier by Gural in [12], but it could be applied to synthetic tracking as well. Zhai et al. (2018) in [22] demonstrated that synthetic tracking boosts the astrometry precision level to 10 mas in contrast to 100 mas level of astrometry for the traditional approach of detection with streaked images. Accurate astrometry is crucial in the orbit determination of moving objects and therefore improves risk assessment and prevents losing them. They obtain better astrometric precision for 12 near-Earth asteroids using the Pomona College 40 inch telescope (Table Mountain Facility).

3. SYNTHETIC TRACKING

An object is discoverable only if a sufficient number of photons is accumulated above a certain noise threshold. In general, for a given optical system, sensitivity for the faint star detection is proportional to the square root of the exposure time, $\sqrt{t}$, in background-limited case. This means that the sensitivity increases with the exposure time. In the case of imaging of the moving object, sensitivity increases until it reaches value $\sqrt{\tau_M}$, where τ_M is maximum useful exposure time. τ_M is the time an object takes to move an angular distance corresponding to the resolution of the system being used to detect it or size of point-spread-function. If the exposure time is bigger than the maximum useful exposure time the image of the object blurs out into streak which covers a larger area of the detector. As a consequence, it contains more noise and may become harder to distinguish from the background. The signal losses resulted from the blurring of the signal are called trailing losses. One could try to reduce them by shortening the exposure time of every acquired frame but single short exposure is not long enough to detect a faint object, though. The solution is to acquire numerous frames fast enough to avoid streaks in a single frame, shift subsequent frames by a value corresponding to the object proper motion and then integrate them to synthesise the long exposure. The procedure results in freezing the moving object and improving its signal-to-noise ratio and hence enhancing the sensitivity for objects' detection.

Such a procedure is the essence of the synthetic tracking technique proposed in [19] and [21]. It simulates the object's tracking of the telescope to mitigate the trailing loss caused by smearing fast-moving objects image through a field of view (FOV) during a long exposure (fig. 1). Observations could only be conducted with use of modern low readout noise and fast frame rate cameras. The value of the shift corresponding to object proper motion is unknown. It is necessary to find appropriate value by searching the data over a two-dimensional velocity grid (e.g. 1000 different velocities). For every velocity, the synthetic long exposure frame is created, and then the image is surveyed in order to find an object moving with examined velocity. If the object is detected the created image is equivalent to the image as if the telescope were tracking the object (images of the stationary background stars are streaked and the image of moving object is a single spot). The motion of the object can be approximated as linear motion in the plane of the sky. This fact simplifies calculations and hence speeds up processing, but even though sophisticated data preprocessing and parallel computation are needed. The linear approximation, however, is not always the case and this problem was undertaken in [13].

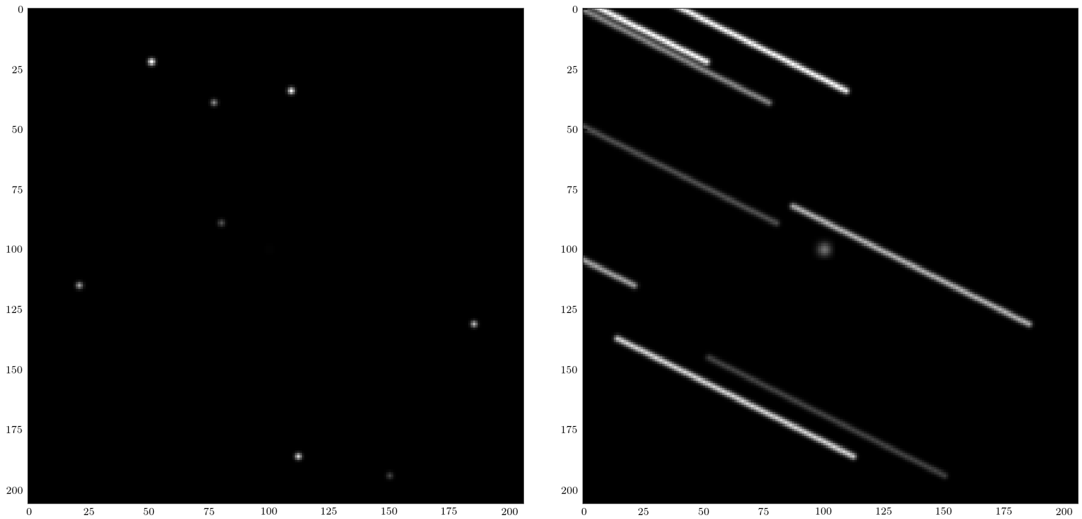

Fig. 1: The idea of the synthetic tracking technique – integration of 50 frames. On the left: simulation of the conventional long exposure frame, a dim, fast-moving object in the middle of the figure is invisible. On the right: simulation of the synthetic tracking successful detection, short exposure frames after shifting and adding, the object becomes visible and stars are streaked. This approach gives results similar to tracking on object in the sky.

The method is applicable for diverse objects: asteroids and comets (from Kuiper Belt, Main Belt, and near-Earth region) as well as anthropogenic satellites and space debris. The technique allows to carry out wide blind surveys and multiple detections of objects moving with different velocities in a single field of view. In addition, usage of synthetic tracking technique results in better astrometry, because of reduction related to the inhomogeneous shape of the streak caused by distortion in the atmosphere. More precise astrometry implies better orbit determination and prevents losing discovered objects.

4. TELESCOPES

The sCMOS camera allows acquiring a series of data with no intermission between consecutive frames because the readout time of this electronic device is negligible. The conducting measurements almost continuously, though, has become possible, so the signal from the astronomical object will not be lost between consecutive frames. Furthermore, the high frame rate provided by sCMOS camera is very valuable because of the possibility to carry out fast photometric observation for the bright object and e.g. offers information about the object's rotation (in case of e.g. space debris). Employment of the technique of synthetic tracking is possible thanks to abilities of such detectors.

In order to survey the whole sky during one night, one needs to cover roughly ten thousand degrees squared of the sky. This area is smaller than the entire hemisphere visible above the horizon so as it is free of light pollution and obstacles like trees or buildings at large zenith angles. To illustrate the difficulty of an all-sky survey, one could consider the optical system with FOV of 21'×21' which was historically considered to be a relatively wide angle. In order to cover the whole sky, one needs to take approximately 80,000 images. Assuming that one can observe through 8 hours a night time, the process of acquiring a single frame cannot exceed 0.35 seconds which makes a survey fruitless. It shows the clear need to employ genuinely wide FOV telescopes.

Fig. 2: The Panoptes-1AB telescope before shipment at the premises of Baader Planetarium GmbH in Mammendorf, Germany. On the left: TEC300VT7DEG astrograph, on the right: 0.5 m Planewave telescope.

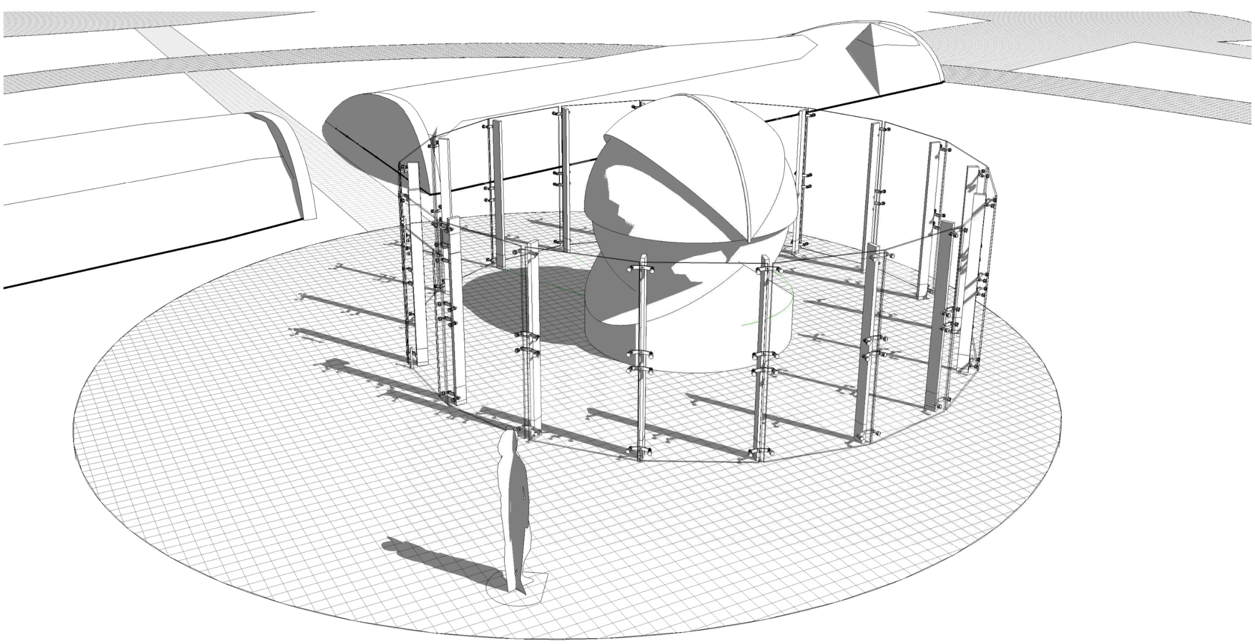

Fig. 3: Architectural concept of the Panoptes-1AB observatory and its neighborhood at the premises of the Pomeranian Science and Technology Park in Gdynia, Poland.

The great representative of such instruments is Panoptes-1AB telescope owned by Research Foundation Baltic Institute of Technology (Baltech). Panoptes-1AB (fig. 2) is a double system composed of a TEC300VT-7DEG astrograph, Panoptes-1B, and 0.5 m Planewave telescope, Panoptes-1A. The astrograph is a unique instrument 0.3 m in diameter and f/1.44. The instrument will be equipped with a Kepler KL4040 sCMOS camera. It has high resolution 4096×4096, the pixel size of 9 μm, readout noise of 3.7 e^- and max. frame-rate of 7 fps. The optical system will offer a staggering $5^\circ \times 5^\circ$ FOV with 4.4 seconds of arc per pixel. As it could catch 25 degrees squared piece of the sky during a single exposition, only 400 frames are necessary to cover the all-sky and that gives 72 seconds for the whole single frame acquisition process. This time allows detecting an object with an apparent magnitude of 19.5. At the moment, the purchased telescope is stored at the lab of Baltech and waits for fulfilling all formal procedures (a construction permit, expected early October). The installation and the first light are expected later Q1 2020. It will be initially installed at the Pomeranian Science and Technology Park's area in Gdynia, Poland (fig. 3). It will be a temporary site for R&D purposes and the first on-sky test. Later on, the telescope will be relocated to the southern hemisphere. The telescope will be fully dedicated to SSA, especially to NEO detection.

Fig. 4: A possible configuration of 1 m wide FOV telescope Solaris-5. Courtesy of ASA Astrosysteme Austria.

Moreover, the Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences will extend the existing Solaris network by a new survey telescope, Solaris-5. The entity has just secured funding for it. Solaris is a global network of four autonomous telescopes located in the southern hemisphere. The new telescope will be 1 m in diameter and f/1.3 (fig. 4) and will be equipped with a Kepler KL6060 sCMOS camera. The detector features with high resolution of 6144×6144, 10 μm pixel size, readout noise up to 12 e^- and frame rate 5 fps. The optical system will offer a large for this aperture $2.7^\circ \times 2.7^\circ$ FOV with 1.59 seconds of arc per pixel. The telescope will be installed in the northern hemisphere and is expected to become operational in the second quarter of 2021 and will be dedicated to NEOs searches.

5. COMPARISON OF SURVEY TELESCOPES

In tab. 1 we present the basic parameters of our telescopes that are or will be soon equipped with sCMOS cameras. This includes two which are under construction – Panoptes-1AB and Solaris-5. These two are also wide field of view instruments that will be, as already mentioned, dedicated to surveys. It is interesting to compare them with other telescopes known from being used for surveys in the SSA domain. Tab. 2 contains such a comparison, [3], [17], [23]. It is worth noting that according to the internal nomenclature of the European Union Space Surveillance and Tracking Consortium (EU SST), the telescopes 1-m ESA OGS and 1.3-m NASA MCAT would not be considered survey sensors as their field of view is below 1 by 1 deg. Nevertheless, thanks to their aperture sizes they are capable of detecting small debris in the GEO belt.

Table 1: Specifications of the Polish telescopes dedicated to synthetic tracking.

	Solaris-3B	**Solaris-2**	**Panoptes-1B**	**Solaris-5**
Aperture (m)	0.2	0.5	0.3	1.0
Effective aperture (m)	0.17	0.46	0.25	0.89
Focal ratio	f/2.8	f/15	f/1.44	f/1.3
FOV (deg^2)	1.7×1.4	0.28×0.28	5×5	2.7×2.7
Camera	Andor Zyla 5.5	Kepler KL4040	Kepler KL4040	Kepler KL6060
Resolution	2560×2160	4096×4096	4096×4096	6144×6144
Pixel size (μm)	6	9	9	10
Pixel scale (arc sec per pixel)	2.40	0.25	4.40	1.59
Frame rate (fps)	30	7	7	5
Peak QE (%)	60	74	74	72
Site	SSO, Australia	SAAO, South Africa	Gdynia, Poland (future relocation to the southern hemisphere)	northen hemisphere
Availability	available	Q1 2020	Q1 2020	Q2 2021

One of the parameters commonly associated with astronomy with survey telescopes is the so-called etendue which is essentially a product of the observed sky area and the effective collecting area of the telescope and quantifies a speed of a survey with a given telescope. In the comparison, we used the literature data to obtain among others the sizes of the central obscurations of the telescopes to compute the effective unobstructed diameter of a telescope. One result that clearly stands out in this comparison is that a 0.3-m Panoptes-1B has higher etendue than a 1.3-m MCAT. In other words, Panoptes-1B is faster in surveys. This due to a large FOV of Panoptes-1B, more than 50 times larger than the FOV of the NASA MCAT. Such difference in the FOVs is not compensated by the obvious difference in the aperture sizes of the two facilities.

In tab. 2 we also present the magnitude limits of the telescopes. They were computed in a somewhat simplified way to see how the telescopes compare to each other rather than to compute absolute magnitude limits. In the calculations, we made the following assumptions. The observations are done without a filter, the dark current is negligible, the readout noise is ignored, the peak QE is assumed as the quantum efficiency of an entire detector, light loses due to the optics correcting the images are ignored, the seeing is 1.5 arcsec and the sky is 21.5 mag/sq-arcsec. The magnitude limits follow the aperture sizes as expected.

Table 2: Comparison of the Polish telescopes with other, international telescopes to sky surveillance.

	Panoptes-1B	Solaris-5	ESA OGS	GEODSS	NASA MCAT
Aperture (m)	0.3	1.0	1.016	1.0	1.3
Effective aperture (m)	0.24	0.89	0.96	0.89	1.13
Focal ratio	f/1.44	f/1.3	f/4.4	f/2.15	f/4
FOV (deg)	5×5	2.7×2.7	0.71×0.71	1.23×1.61	0.68×0.68
Camera	Kepler KL4040	Kepler KL6060	custom, mosaic	Sarnoff Corp MIT/LL CCID-16	Specinst 1100S
Resolution	4096×4096	6144×6144	4096×4096	1960×2560	4096×4096
Pixel size (μm)	9	10	13.5	24	15
Pixel scale (arc sec per pixel)	4.4	1.59	0.62	2.27	0.6
Peak QE (%)	74	72	40	86	90
Etendue (deg^2 m^2)	1.13	4.54	0.36	1.23	0.46
Mag. limit [30 sec, SNR 5]	20.65	22.54	22.30	22.64	22.93
Mag. limit synthetic tracking [SNR 5]	20.65	22.54	20.97	21.95	22.28
Exp. time /pixel size (sec/arc sec)	0.29/4.4	0.106/1.59	0.165/2.48	0.151/2.27	0.16/2.4
Readout time [binning] (sec)	0	0	12.0 [1×1] 1.5 [4×4]	0.37	3.0 [1×1] 0.36 [4×4]
Total single exp. (sec) / **Number of frames in 30 sec** / **Total on target** (sec)			1.665/18/2.97	0.521/58/8.76	0.52/58/9.28

However, such a magnitude limit reflects a telescope's range in the detection of stationary targets which is typically not the case in the SSA domain. Moving targets streak out and their detection is limited by the time it takes for a target to cross a point-spread-function (PSF) of a given system. For the sake of the discussion let us assume that we are searching for debris via the stare mode for targets with an angular speed of 15 arcsec/sec ($\sim$GEO belt) and that PSF corresponds to the assumed seeing of 1.5 arcsec. In the case of Panoptes-1B, Solaris-5, and GEODSS such PSF is smaller than the size of a pixel so the maximum exposure time is set by the time it takes to cross the pixel's size. In the other two cases, ESA OGS and NASA MCAT, we assumed binning 4 x 4 that results in binned pixels of 2.48 and 2.4 arcsec respectively. These were used to compute the maximum exposure time for each telescope. In the case of Panoptes-1B and Solaris-5, the sCMOS cameras allow for a practically lossless combination of a series of images via the synthetic tracking technique and hence their magnitude limits should be approximately the same as in the case of stationary targets. For the other CCD based systems, synthetic tracking is visibly less efficient due to the read-out time. Effectively, e.g. 1-m Solaris-5 outperforms 1.3-m NASA MCAT. Clearly, the synthetic tracking technique based on the sCMOS cameras and wide FOV telescopes will have a lot to offer.

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