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Proposal of optical sky monitoring with subsecond cadence

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Abstract. Sky monitoring needs to trade-off time resolution against limiting magnitude, usually leading to exposure times of some seconds or tens of seconds. Consequently, photometric information in the range below seconds remains largely undetected. We propose a scheme of sky monitoring using CMOS cameras to improve cadence aiming at exploring the sky in the subsecond region without relinquishing fainter stars. Optical systems could even be operated without any mechanical drives reducing costs and processed in a way similar to TDI mode. Data handling would be a challenge of processing and storage. We sketch the benefits of such a monitoring from meteors to high energy events.
Key words: Surveys – Stars: variables – Meteors – Gamma-ray burst: general – Techniques: photometric – Techniques: image processing

1. Introduction

Sky monitorings aims at detecting the unexpected, such as meteors, Cherenkov flashes or optical transients from gamma-rays bursts (GRBs) or fast radio bursts (FRBs), flaring stars, cataclysmic events and others. As these events happen to appear at any position on the sky at any time, sky monitoring requires either large-field-of-view optical systems or batteries of telescopes to cover as much sky area as possible.

The approach to permanent sky monitoring is not new, mostly driven by searches for optical transients of possibly different astrophysical origins. It was unknown for many years if bursts detected in the gamma-ray region of the electromagnetic spectrum would have optical counterparts at all or if there are optical flashes without high-energy counterpart, see e.g. Schaefer et al. (1987). Since a couple of years fast radio bursts propose a similar conundrum, in this case at the weaker side of the electromagnetic spectrum (Tingay, 2020; Tingay & Joubert, 2021).

The motivation is high to detect transient events in the optical as instruments and detectors are available at comparably low costs. As we see later, detectors of CMOS type are exceptionally suitable for this task owing to their high sensitivity and low noise even for subsecond exposure times. They have therefore been used since a couple of years in different projects (Biryukov et al., 2015; Beskin et al., 2017; Sako et al., 2018; Arimatsu et al., 2021).

Table 1. Some large currently active or coming digital sky monitoring programme.

Program	Site(s)	Cadence	Reference
OGLE	Las Campanas	20 min	OGLE (2023)
ASAS-SN	World-wide network	1 day	ASAS-SN (2023)
Las Cumbres O.	world-wide network	5 min	LCO (2023)
Argus Pathfinder	PARI	1 s – 30 s	AP (2023)
NGTS	Cerro Paranal	13 s	NGTS (2023)
ODNet, eVScope		0.2 – 0.3 s	Cazeneuve et al. 2023

2. Classical photographic sky patrol

Historically, sky monitoring started by means of photographic plates at different places in the world roughly one hundred years ago. Resulting from the relatively poor sensitivity of the emulsions of those days, typical exposure times were in the order of several hours. Exposures of the same field on the sky could be repeated only within days or weeks between them. Also, covering the whole sky was virtually impossible.

With the improvement of sensitivity of photographic emulsions the exposure time could be reduced reaching the same limiting magnitude, and thus the cadence of repeated exposures could be shortened to hours. Batteries of short-focal telescopes allowed to cover large areas on the sky simultaneously, such as the Sky Patrol installation at Sonneberg Observatory with 14 cameras of 55/250 mm lenses operated in parallel in the red-yellow (photovisual) und blue (photographic) color band between 1950ies and 2010.

Photographic plates of different monitoring programs are stored at several places in the world. A comprehensive overview about plate archives is given by Hudec (2019).

Generally speaking, the cadence of photographic monitoring is in the order of days to years, at best some hours.

3. Digital sky monitoring

The invention of digital solid state detectors such as CCDs (charge-coupled devices) improved sky monitoring in manifold ways. While the quantum efficiency of photographic plates is in the order of a very few percent, back-side illuminated CCDs are sensitive of up to 95% or even better. This feature allowed to dramatically reduce exposure time and, in combination with comparably short download times, improves the cadence of monitoring down to minutes or seconds.

Table 1 lists a representative but non-exhaustive subset of large currently active or coming digital sky monitoring programme.

4. Digital meteor monitoring

In the recent years a number of automatic meteor surveillence networks have emerged, such as FRIPON (2023) and AllSky7 (2023), see also Hankey et al. (2020), to mention a few, with impressive results of several thousands of meteor detections anually and frequent fireball registrations. In case of AllSky7 network, seven CMOS (complementary metal-oxide-semiconductor) sensors of SONY STARVIS IMX291 type are used in combination with 4 mm f/1.0 lenses. All cameras are 24/7 operated and read-out with 25 images per seconds in HD (high definition) and SD (standard definition) streams in parallel.

Although the image analysis software of AllSky7 is optimised to detect meteors, the images do also show stars down to magnitude 4.5 roughly, which is amazing with respect to the very short exposure time of 40 milliseconds and the small aperture.

This very feature of AllSky7 network cameras led us to the idea of this paper's subject, namely to exploit CMOS detectors with short exposure times, thus high cadence, to explore any other celestial events of subsecond duration or photometric variations shorter than seconds which are completely or partly missed by traditional monitoring programme like those listed in table 1.

5. Proposal: high-cadence optical sky monitoring

5.1. Scientific goals

High-cadence sky monitoring may follow two different strategies: follow-up observations of optical events, and detection of transient events by chance by means of continuously scanning large portions of the sky.

5.1.1. Follow-up observations

High-cadence observations are important for the following targets, which are possibly detected beforehand by other monitoring programme:

- Flare events of red dwarf stars.
- Outbursts of dwarf novae, novae, and supernovae.
- Optical transients of GRBs. Such counterparts of GRBs were detected in past, of which the brightest event GRB 080319B flared up to an optical magnitude of 5.7 (Bloom et al., 2009; Beskin et al., 2010). Although this particular GRB was observed with 0.13 seconds exposures, which is of comparably high cadence, it is unknown if bursts in general show structures at even shorter timescales or might be brighter for a very short period of time in some cases.

– Optical transients of FRBs. Optical counterparts are unknown so far. As the duration of radio bursts is in the order of a few milliseconds, one might expect similar time scales in the optical.

5.1.2. Detection by chance

Astronomical events on short time scales may appear at any position on the sky at any time. Therefore, permanent monitoring large field of views – virtually the whole sky –, promise to reveal lots of hitherto undetected objects:

– All types of events already listed in the previous sub section of follow-up observations.

– Transits of extrasolar planets and moons.

– Occulation events of asteroidal and cometary bodies in the main and Kuiper belts and the Oort cloud. These events may not only reveal the bodies themselves but also moons or rings around them.

– Meteors of solar system origin.

– Sub-relativistic meteors. The existence of this interesting phenomenon was proposed by Siraj and Loeb, 2020. It is unknown, if such type of meteors exist, but they could be detected by monitoring in the milli-second and micro-second range.

As a byproduct of sub-second cadence monitoring, tens of thousands of artificial satellites are monitored and need to be distinguished from real astronomical events. As these objects also flare, they cause lots of false events. Surveillance of satellite fleets and space debris, which both will grow in future dramatically, might become important also for other branches of observational astronomy. It this way, the proposed type of sky monitoring is able to yield data for different aims in parallel.

5.2. Instrumentation

In principle, any telescope can be used for monitoring, just by pointing it to the sky, equipping it with a camera and repeating readout.

For follow-up observations, slow optics (focal ratios 1:5 or less) can be used, as the target is already known.

In contrast, to cover large fields fast short-focal instruments (focal ratios 1:0. . .1:5) are preferable for monitoring to detect events of all types mentioned above.

In combination with the advantages of CMOS cameras, which is sketched in the next section, an interesting and simple approach emerges. As optical transients and other events occur non-predictable at any time and everywhere on the sky, it is equal where to look at. This offers the use of pure OTAs (optical tube assembly) without any astronomical mounting. The OTA has only to be mechanically fixed for stable pointing upwards. A battery of such OTAs may scan the sky by simply passing the stars through the field of view (scan mode). As CMOS cameras can be exposed and read out very quickly within milliseconds the effect of Earth's rotation is negligible. In this way, a sky monitoring program can be set up for moderate prices and may be very robust and reliable as no mechanical components are involved (except dome or movable roof).

This approach offers also a new life for old, non-computerized telescopes. These instruments are available at many places in the world, but they are frequently not used any more as mechanical parts are broken or got stuck, or it is too expensive to upgrade the mounting to modern GOTO-functionality. Mostly, the pure optical system is still working (possibly needs some cleaning) and thus ready for monitoring in the proposed way.

5.3. Camera and hardware and software requirements

To achieve sub-second cadence cameras with CMOS detector type are recommended. Exposure time can be very short and even for chips with tens of millions of pixels the read-out times are below seconds. By binning technique read-out time can be further reduced. In this way, very short-living astronomical events can be detected in single images and in series of consecutive images which were lost or too faint to be detected in long-time exposures.

Another advantage of CMOS detectors is the very low read-out signal and noise. This offers the possibility of adding up images to increase limiting magnitude, of course at the expense of temporal resolution.

For the case of fixed OTAs as proposed in the previous section, adding up images is more complicated as the drift speed of all objects across the chip decreases from equator to the poles. However, as long as the exposure time of a single image is short enough that stars appear as points, the declination dependent adding-up of images can be processed by software by separating parts of the images. In a certain sense this mode resembles the TDI (time delayed integration) mode of CCD cameras, which would here completely be made by software.

It is obvious that, by operating CMOS cameras in the proposed way a lot of data will be produced even for short operation times. This requires powerful computer hardware for storing the data stream from camera to disk, and also for analysing all the images. There are efficient software packages available today for astronomical image processing such as Astropy (2023) in Python language to set up a complete processing pipeline from raw images to object databases. Nevertheless, it remains a challenging task.

Other open questions concern networking with many stations world-wide, setting-up a kind of central database or making the software publicly available.

6. Concluding remarks

Apart from adaptive optics techniques for large telescopes or lucky imaging methods to compensate the influence of atmospheric turbulences, until now sub-second optical astronomy is poorly studied. Entering unexplored terrain usually leads to unexpected results and discoveries, or as Hermann Bondi with respect to short-time constant astronomy mentioned in 1970: "... but I think it is sometimes overlooked that perhaps we are missing a whole continent."

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