Detectability of Optical Transients with Timescales of Subseconds

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Abstract

We search for optical transient sources with durations of $\sim$0.1 to $\sim$1.3 s using a data set obtained in the Organized Autotelescopes for Serendipitous Event Survey (OASES) observation campaign. Since the OASES observations were carried out using two independent wide-field and high-cadence observation systems monitored the same field simultaneously, the obtained data set provides a unique opportunity to develop a robust detection method for subsecond optical transients. In the data set of a selected field around the ecliptic and the Galactic plane, we find no astronomical event candidate that satisfies our detection criteria. From the nondetection result, we derive an upper limit on the event rate of subsecond transients around the ecliptic and the Galactic plane for the first time, obtaining $\sim$0.090 and $\sim$0.38 hr$^{-1}$ deg$^{-2}$ for $m = 12$ and 13 Vmag, respectively. In addition, future prospects of the subsecond-scale transient event surveys are discussed.

Unified Astronomy Thesaurus concepts: Time domain astronomy (2109); Transient sources (1851); Astronomical methods (1043)

1. Introduction

Optical astronomical transients with timescales of days to minutes have been recognized and studied over the past several centuries. On the other hand, there are only a few previous coordinated surveys exploring transients occurring over shorter, especially subsecond timescales. For example, Schaefer et al. (1987) present one of the earliest survey studies that explores 1–0.01 s scale optical transients using two telescopes equipped with a single photometer pointed at a random sky region. They found 49 flash-like transient event candidates, 29 of which are those detected by both telescopes simultaneously. These candidates are possibly caused by meteors and satellites passing through the observed sky region. A survey concept of very short-timescale transients is proposed by Griffin (2012) using photometer arrays onboard telescopes primarily designed for observations of optical Cerenkov flashes in the atmosphere. Tingay (2020) demonstrates a drift scan technique for detections of optical transients with timescales much shorter than the integration time of charge coupled device (CCD) cameras.

Recently, observations with large-formatted and low-noise complementary metal oxide semiconductor (CMOS) cameras provide opportunities for wide-field and unprecedented high-cadence observations. Early explorations of subsecond transients using CMOS cameras have been carried out by the Mini-MegaTORTORA survey (Karpov et al. 2016), which uses nine independent small observation systems. Each system consists of an 85 mm camera lens and a CMOS detector covering $10^6 \times 10^6$. In 2.5 years of the Mini-MegaTORTORA survey, detections of optical transient candidates with durations of 0.4–1.0 s and typical peak magnitudes of 4–10 were reported (Karpov et al. 2017). However, all of these candidate events are thought to be flashes caused by the reflection of sunlight from artificial satellites and space debris. Recently, the Tomo-e gozen camera (Sako et al. 2018), consisting of 84 CMOS sensors covering 20 deg$^2$ in total and offering a 2 Hz sequential shooting mode, was installed on the prime focus of the 105 cm Schmidt Telescope at Kiso Observatory. Tomo-e gozen provides opportunities for not only high-cadence observations of known short-timescale astronomical events (e.g., Arimatsu et al. 2019a) but also serendipitous surveys for unknown faint sources that emit only for a few seconds (Richmond et al. 2020). However, the time resolution offered by Tomo-e gozen is slightly insufficient for explorations of optical transients with timescales comparable to or less than a second.

As of 2021, no clear evidence for nonrepeating astronomical optical transients in the background with timescales less than $\sim$1 s has been reported. Furthermore, there is no observational constraint on the occurrence rate of these transient events. The lack of previous detections of short-timescale astronomical events is primarily due to insufficient optical surveys, unlike previous surveys covering other wavelength ranges that led to historical discoveries of gamma-ray bursts (GRBs; Klebesadel et al. 1973) and fast radio bursts (FRBs; Lorimer et al. 2007). This in turn means that there is a vast and unexplored parameter space of observational time-domain astronomy. For example, Yang et al. (2019) predict optical counterpart emissions from a small fraction of FRBs, which would reveal physical conditions in the FRB environments. Recent superflare studies suggest that brightnesses of extremely powerful superflares on short timescales could reach approximately 100 times the quiescent emission (Howard et al. 2018). Thus the high-cadence monitoring of stellar fields should provide fruitful information on the occurrence rate of such extreme superflare activity. Furthermore, especially in the sky close to the ecliptic, optical light flashes produced by mutual collisions of small asteroids would be observed like lunar impact flashes (e.g., Yanagisawa & Kisaichi 2002). Direct observations of these impact flashes should give a new insight into the production rate of interplanetary dust particles in the solar system. Surveys...
with monitoring timescales less than a second are required to detect and investigate these possible transients.

Serendipitous surveys for optical subsecond transients face several challenges. First, one must observe with a cadence faster than 10 Hz to acquire multiple measurements of emitting events with timescales of less than a second. Second, one must monitor using instruments covering a large field of view (FOV) since these events are expected to be rare. Third, one must achieve detections of nonrepeating events that are robust concerning false-positive events, such as detector noises, atmospheric events including sporadic meteors, and optical flashes due to the reflection of sunlight from artificial satellites and space debris. There are thus few previous wide-field monitoring observations for subsecond optical transients reported. Developing detection methods for subsecond transients and obtaining observational constraints for their occurrence rate should provide guidance to observations in the future.

This paper describes a survey for transient sources with durations of 0.2-2 s using a data set obtained with two small observation systems named the Organized Autotelescopes for Serendipitous Event Survey (OASES; Arimatsu et al. 2017). Though the OASES project was originally carried out for detecting stellar occultations of small-sized trans-Neptunian objects (Arimatsu et al. 2019b), they also provide a unique opportunity for understanding optical transients lasting less than a few seconds. Based on the survey strategy described by Richmond et al. (2020), we searched the data set obtained during an observation campaign in 2016–2017 with the OASES systems for short-timescale transient events. The present results provide upper limits for astronomical transient events with timescales down to \( \sim 0.1 \) s, which is approximately an order of magnitude shorter than recent studies by Richmond et al. (2020). Section 2 describes the outline of the data sets obtained by the OASES observations. In Section 3, a survey method developed for the present study including criteria of the transient detection and the survey results are presented. Upper limits on the occurrence rate of transient events derived from our survey results are presented in Section 4. Finally, we summarize the results and future prospects in Section 5.

2. Outline of the OASES Data Set

The OASES monitoring observation campaign was carried out on a total of 23 nights between 2016 June 25 and 2017 August 1 UT. The OASES project uses two identical observation systems (OASES-01 and OASES-02) primarily designed for detections of stellar occultation events by trans-Neptunian objects. Each system consists of a 279 mm Celestron \( f = 2.2 \) Rowe–Ackermann Schmidt Astrograph (RASA) equipped with a single ZWO ASI1600 MM-C CMOS camera and a Metabones Speed Booster SPEF-M43-BT4 focal reducer. The effective focal ratio and angular pixel scale of the observation systems are \( f/1.558 \) and \( 1^\circ 96 \), respectively. The OASES observation systems are capable of monitoring up to \( \sim 2000 \) stars with apparent brightnesses down to \( V \sim 13.0 \) in a \( 23^\circ 3 \times 1^\circ 8 \) FOV simultaneously, providing signal-to-noise ratios comparable to or greater than 3–4 with a sampling cadence of 15.4 Hz at an extremely low cost (\( \sim 16,000 \) USD per single system). Details of the OASES observation systems have been described in Arimatsu et al. (2017).

| Date (UT)  | Hours  |
|-----------|--------|
| 2016 Jun 28 | 0.77   |
| 2016 Jun 29 | 0.95   |
| 2016 Jun 30 | 0.77   |
| 2016 Jul 2  | 1.61   |
| 2017 Jun 23 | 2.86   |
| 2017 Jun 27 | 0.71   |
| 2017 Jun 28 | 2.38   |

During the observation campaign, the two systems were installed in different positions on the rooftop of the Miyako open-air school (Miyako Shonen Shizen no Ie) on Miyako Island, Miyakojima-shi, Okinawa Prefecture, Japan, with a separation of 39 m (2016 to 2017 June) or 52 m (2017 July to 2017 August). For the monitoring observations, we selected a monitoring observation field with central equatorial, ecliptic, and galactic coordinates of (R.A., decl.) = (18:30:00, \(-22:30:00\)), \((\lambda, \beta) \sim (276^\circ 9, +0^\circ 8)\), and \((l, b) \sim (10^\circ 5, -5^\circ 6)\), respectively, to increase the detectability of stellar occultations of solar system objects. Since the selected field is close to the ecliptic and the galactic plane, transients occurring in the solar system’s ecliptic plane and in the Galactic disk are expected to be detected in the OASES monitoring observations with higher sensitivities relative to randomly selected fields. During the observations, images of the selected field are obtained with each observation system for a 2 × 2 binned sequential shooting mode of 15.4 frames per second. The exposure time is 65.0 ms for each frame. An individual single data set consists of 3300 sequential frames. The data set obtained with the OASES monitoring observations in good weather conditions corresponds to 60 hr of imaging data in total. Details of the OASES monitoring observations have been described in Arimatsu et al. (2019b).

3. Data Reduction and Transient Detection Method

As noted by previous studies of high-cadence observations (Karpov et al. 2017; Richmond et al. 2020), optical flashes due to the reflection of sunlight from artificial satellites and space debris cause false detections of real astronomical transients. To reduce these false detections, we have to use the data observed when the selected field was within Earth’s shadow. We thus select the image data of the selected field obtained when its Sun-observer-target angle was larger than 175° and the Sun’s elevation above the horizon was lower than \(-25^\circ\). The selected data set is summarized in Table 1. The total data set that passes this criterion amounts to 10.1 hr of data runs.

After dark subtraction, flat-fielding, and subtraction of a constant sky background level, stationary features (field stars, see Figures 1(a) and (b)) are subtracted and masked from each frame to produce difference images (Figures 1(c) and (d)). As a reference frame, a median combined image is produced using 100 reduced images in every data group (Figures 1(e) and (f)). To detect flash-like transients, we first run Source Extractor (SExtractor, v2.5.0; Bertin & Arnouts 1996) on each difference image using a detection threshold of \((\text{DETECT\_THRESH}) = 4.5\). We then manually run selection tests for detected point-like sources in the difference images according to the following criterion partially based on the previous second-scale transient survey by Richmond et al. (2020).
1. An event candidate must be detected between 2 and 20 times within a single data set of 3300 frames obtained with OASES-02. This window size range corresponds to durations of $\sim0.1$ to $\sim1.3$ s. In the present study, we exclude single-frame detections that can result in real transients with durations shorter than $\sim0.1$ s. We found that single-frame detection candidates are highly contaminated with false detections such as short-timescale flashes of artificial satellites and space debris, detector noise spikes, and cosmic-ray hitting. Since the durations and the angular moving speeds of these candidates are unknown, it is difficult to select real astronomical event candidates from the contaminations. Specific tests are thus required to select and investigate the single detections, which are beyond the scope of the present study.

2. All detections of a single-event candidate must appear in a window of $(N + 2)$ consecutive frames, where $N$ is the total number of detections. In other words, events that appear once and then disappear once (i.e., nonrepeating events) pass this criterion in general. However, this criterion accepts up to two nondetection frames that are possibly caused by temporal variations in atmospheric transparency or a scintillation effect.
3. An event candidate detected with OASES-02 must be detected more than one time simultaneously with OASES-01. The angular distance between the candidates observed with individual systems must be smaller than 4′. We note that the detection performance for faint objects of OASES-01 was slightly inferior to that of OASES-02 due to imperfect adjustment of its optical instrument.

After running the selection tests above, we found three candidate events that satisfy these criteria. An example of the candidate events is shown in Figure 1. We investigate the candidate events that satisfy these criteria. An example of the where

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\lambda \sim 0.1 \text{ s}
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\text{Upper Limit of the Subsecond Astronomical Transients}
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4. Upper Limits of the Subsecond Astronomical Transients

We estimate \( \varepsilon(m) \) by recovering artificial point sources implemented in randomly selected actual images obtained in the present data set. For this purpose, a point-spread function for each image was constructed by stars detected in the same image. The V-band apparent magnitudes of the artificial stars range from 11.75 to 13.0 with a 0.25 mag step. For example, the estimated \( \varepsilon(m) \) values for Vmag = 11.75, 12.5, and 13.0 are 0.87, 0.59, and 0.19, respectively. Figure 2(a) shows the estimated \( \Omega(m) \) for the present selected data set as a function of m.

The upper limit to the transient event rate \( \lambda(m) \) at 95% confidence level as a function of m is shown in Figure 2(b) and is also presented in Table 2. \( \lambda(m) \) is derived with a technique developed by Richmond et al. (2020), assuming a Poisson distribution of \( N_{\text{exp}}(m) \). The obtained upper limit is placed approximately 0.1–0.4 hr⁻¹ deg⁻² for the estimated magnitude range (Vmag = 11.75–13.0). Since the selected field monitored in the present observations is close to the ecliptic and the

Galactic plane, the real occurrence rates of transients occurring around the solar system’s ecliptic plane and Galactic disk averaged over the entire sky are expected to be lower than the obtained upper limit. On the other hand, typical amplitudes of the Galactic interstellar extinction toward the selected field are not significant but non-negligible (A_V ~ 0.9 mag; Schlafly & Finkbeiner 2011). The occurrence rate of the extragalactic event could be higher than the obtained upper limit.

5. Summary and Future Prospects

With the data set of a selected field around the ecliptic and the Galactic plane obtained with the OASES two observation systems simultaneously, a detection method for optical transient events with a timescale range of 0.1–1.3 s is developed. In the present data set, we found no astronomical transient event candidates that satisfy our criteria. From the nondetection results, an upper limit of the occurring rate of transient events was derived. We should note that the present
upper limit ($\sim$0.090 and $\sim$0.38 hr$^{-1}$ deg$^{-2}$ for $m = 12$ and 13 Vmag, respectively) is larger than the occurrence rates of observable GRBs ($\sim 2 \times 10^{-5}$ hr$^{-1}$ deg$^{-2}$; von Kienlin et al. 2020) and that of FRBs ($\sim 10^{-2}$ hr$^{-1}$ deg$^{-2}$; Thornton et al. 2013). However, it is the first obtained observationally and provides guidance to observations in the future.

As already noted in Section 2, the previous OASES campaign only monitored the selected fields close to the ecliptic and Galactic plane. Future OASES campaigns plan to carry out monitoring of several fields to derive the ecliptic latitude and Galactic latitude dependences of the event rate. As of 2021, a future upgrade of OASES observation systems is planned that will extend its current 2°.3 × 1°.8 FOV since the prime focus of the RASA optical tube offers a circular FOV with an angular diameter of $\sim$4°. Instead of the current front-illuminated sensor, a larger-sized back-illuminated CMOS sensor will be installed that offers a significantly larger (approximately 3°.3 × 2°.5) FOV and higher sensitivity high-cadence imaging. Monitoring observations of the upgraded OASES systems will provide an unprecedented opportunity of revealing faint and rare transient events with timescales of less than a second.

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