PROCEEDINGS OF SCIENCE

Status of the DIMS project for macroscopic dark matter search using ultra-high sensitivity CMOS cameras at the Telescope Array UHECR observatory

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The nature of dark matter has been the subject of ongoing investigation in fields such as particle physics, cosmology, and astrophysics. One hypothetical form of dark matter is nuggets of strange quark matter, also known as nuclearites. They are characterized by a macroscopic mass with a high quark density. These nuclearites are believed to be bound to our galaxy and move at a similar speed of approximately 250 km s^{-1}, which is comparable to the galactic rotation near the Solar System. More commonly, such particles are now referred to as "macros". They can potentially be observed optically when they traverse the atmosphere, emitting light similar to a meteor. In the DIMS (Dark matter and Interstellar Meteoroid Study) project, our goal is to search for these dark matter particles by monitoring the night sky. We have employed ultra-high sensitivity CMOS cameras at the Telescope Array ultra-high energy cosmic ray observatory site. After conducting pilot observations in Japan, we began regular operations with two cameras at the TA site in August 2022. In March 2023, we relocated additional two cameras. The data is acquired using the UFOCapture software, widely used by meteor astronomers. The cameras have proven their functionality by detecting a large number of meteors. In this study, we present the current status of the DIMS operation at the TA site, preliminary analysis and the prospect for the analysis aiming to macro search.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1390

1. Introduction

The nature of dark matter has been the subject of ongoing investigation in fields such as cosmology, particle physics, and contemporary physics. One hypothetical form of dark matter is the nuggets of strange quark matter, also known as nuclearites [1]. These nuclearites are believed to be bound to our galaxy's gravity and move at a similar speed of approximately 250 km s^{-1}, which is comparable to the galactic rotation near the Solar System. More commonly, such particles are now referred to as "macros" [2, 3]. According to the model of Ref. [1], they can potentially be observed optically when they traverse the atmosphere, emitting light similar to a meteor. The luminosity is proportional to the power of 2/3 to the mass and is constant for a given mass. The apparent magnitude varies with distance. This model yields a magnitude of ∼ +1 for a 1 g nuclearite at 1 km away. Furthermore, such heavy nuclearites may even penetrate the Earth and be distinguished by detecting upward-moving events. As the meteors typically are bound to the Sun's gravitation, their speed is limited to the escape velocity of ∼ 42 km s^{-1}. Thus, the events from macros may be clearly distinct by recording as a video. Moreover, nuclearites that are heavier than ∼0.1 g can penetrate the Earth's diameter and thus events might be observed as upgoing from the ground that would be clearly distinct from the ordinary meteors.

In the DIMS (Dark matter and Interstellar Meteoroid Study) project [4, 5], our goal is to search for macros by monitoring the night sky. We have employed ultra high-sensitivity CMOS cameras at the Telescope Array (TA) ultra-high energy cosmic ray observatory site. After conducting pilot observations in Japan, we began regular operations with two cameras at the TA site in September 2022. In March 2023, we relocated an additional two cameras from Japan. The cameras have proven their functionality by detecting a large number of meteors. In this study, we present the current status of the DIMS operation at the TA site.

2. Apparatus

Telescope Array is located in the dry desert area near the city of Delta approximately 200 km south of Salt Lake City, USA. Over an ∼3000 km^2 area, about 750 particle detectors are deployed to form the TA and TA×4 air shower arrays [6, 7]. The DIMS detectors are hosted in two TA facility sites, namely of the Black Rock Mesa (BRM) fluorescence detector station [8] and of TARA (Telescope Array Radar) [9]. Seen from BRM (Lat.∼ 39.2°N and Long.∼ 113.7°W), TARA is located ∼16.7 km away on ∼3° east of the north. The altitude is ∼1400 m above sea level (asl.). Both sites permanently are powered with the grids.

For the DIMS video camera, we employ three Canon ME20F-SH cameras and one ME20F-SHN camera [10]. The former cameras are monochromatic, while the latter is a color camera. These cameras utilize an ultra-high high-sensitivity 35 mm full-frame CMOS sensor that can achieve a maximum sensitivity equivalent to ISO $\sim 4,000,000$. Each camera is equipped with a 35 mm f/1.4 lens, providing a field of view (FOV) of $\sim 56^\circ \times 33^\circ$. The captured video has a resolution of 1920×1080 pixels. In the current configuration, the frame rate is set to 29.97 per second, while the maximum can be 59.97. The gain of the sensor is set to 66 dB that is equivalent to ISO ∼1,600,000. The output pixel values for luminance ranges 256 integer levels with no gamma correction. Infrared filter is disabled.

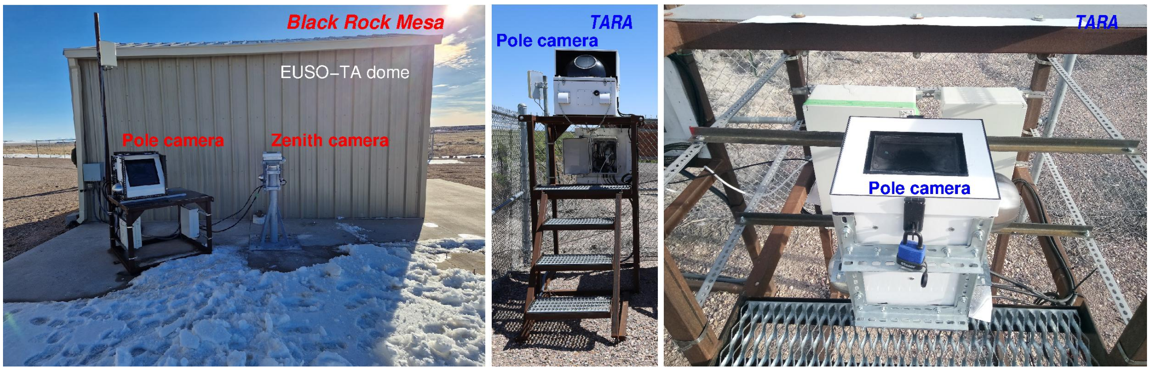

Figure 1: Installations of the DIMS cameras at the TA site. Left) Pole and zenith camera installed situated at the BRM site; Middle) Pole camera at TARA; Right) Zenith camera at TARA.

The video signal from the camera is readout through HDMI output by a PC using an Avermedia CV710 video capture device. System time for each data acquisition (DAQ) computer adjusted according to current GPS time using a GlobalSat BU-353S4 GPS receiver and NMEATime2 software. The DAQ is monitored remotely via Internet connection over 4G cellular network. A 4G router "Pepwave MAX BR1 Mini" is located at both locations and the connection is shared between the DAQ computers handling the capture of video streams from cameras.

The video is recorded by using the commercial software 'UFOCapture' [11]. It triggers by the moving events in the FOV, designed for the meteor observations. The parameters are configured in the internal units described in the manual to trigger by at least two continuous frames satisfying threshold criteria or at least 100 pixels changed in one frame. The threshold called "Detect Lev" is automatically adjusted to a level 110% of the background noise, while its minimum value is 4, its minimum difference and the noise level are set to 10. Scintillation mask is used to reduce the influence of the light of fixed starts. The minimum ratio of the brightness of starts compared to the background is 110%. The scintillation mask detection speed is 2 and the size parameter is 4 to the masked area around the stars. We also utilize the so-called "Dark Object Mask" and "Slow Object Mask". The former reduces the detection of the movement darker than the background and is set to the level of 2. The latter tracks the objects that move slowly and masks the area around them. The fastest speed on a masked object is 36 pixels per second, and the mask size is 36×36 pixels. Before and after the event, 30 frames are recorded for the background evaluation. The data is saved as an uncompressed video in YUYV422 pixel/color format. The operation starts automatically at 30 min after the sunset and terminates at 30 min before the sunrise.

Figure 1 displays photos of the DIMS camera installation at the TA site. The left panel shows a photo of two DIMS camera boxes at BRM. Middle and right panels exhibit camera boxes installed at TARA. Two camera boxes are installed on the concrete pad for the EUSO-TA dome at BRM [12], as seen in the background in the left photo. Two boxes are mounted on custom pedestals at TARA. Two modes of camera pointing are chosen to align near the Celestial North Pole and the zenith.

Figure 2 illustrates the projections of the FOVs of four DIMS cameras. The left panel displays projections on the geographical coordinates at an altitude of 100 km asl. The right shows schematic projections of FOVs on the vertical cross section on the baseline.

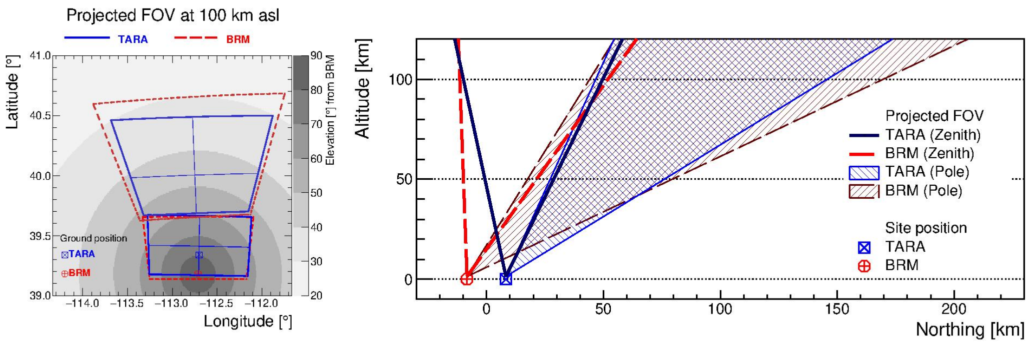

Figure 2: Left) FOVs of DIMS cameras projected at an altitude of 100 km asl. The gray scale indicates the elevation seen from BRM. Right) Schematic projection of FOVs on the vertical plane above the baseline.

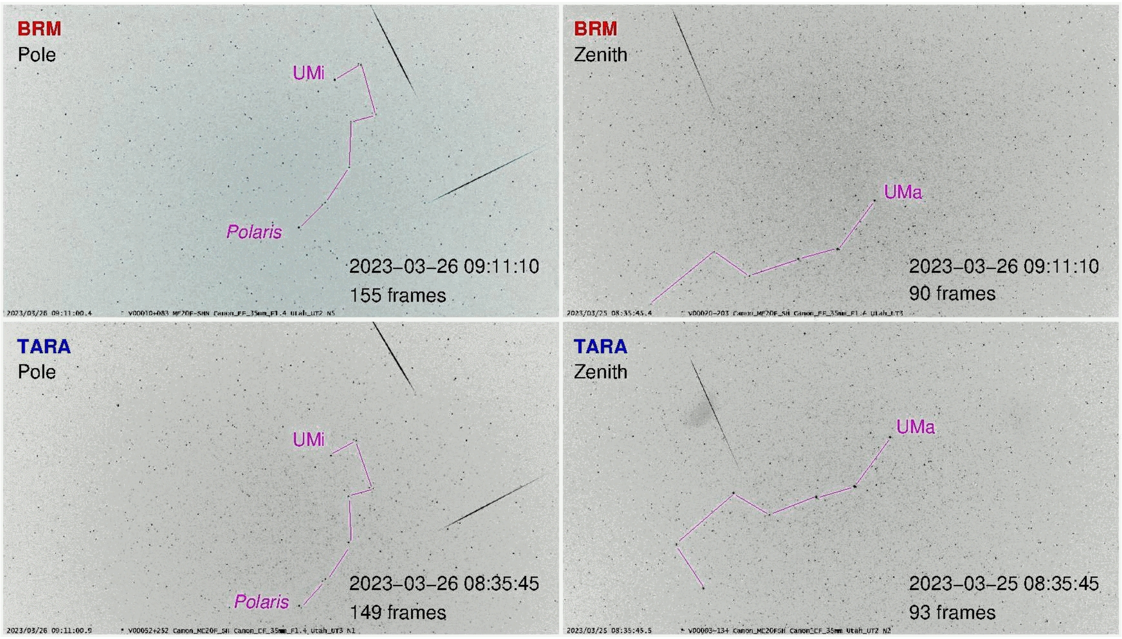

Figure 3: Left) examples of the meteor events simultaneously captured by Pole cameras at BRM (top) and TARA (bottom). Right) an example of a meteor event for Zenith cameras. The number of frames include ~30 frames each before and after the trigger events. Constellations lines are partly drawn for Ursa Minor (UMi) and Ursa Major (UMa). The images are peak-hold and the color scale is inverted and modified for the representation purpose.

The camera pointing elevations are optimized to ensure that the projected FOV areas of the TARA cameras are entirely within those of BRM at a 100 km altitude. The pole cameras point to elevations of ~ 51° at TARA and ~ 45° at BRM, while the zenith cameras point to ~ 85° and ~ 75°, respectively. These arrangements enable simultaneous measurements to determine the geometry and kinematics of the same meteors. As macros are expected to emit light at lower altitudes near the ground, certain events may pass through the FOVs of multiple cameras.

Figure 3 shows an example of meteor events captured by DIMS cameras. In the example for

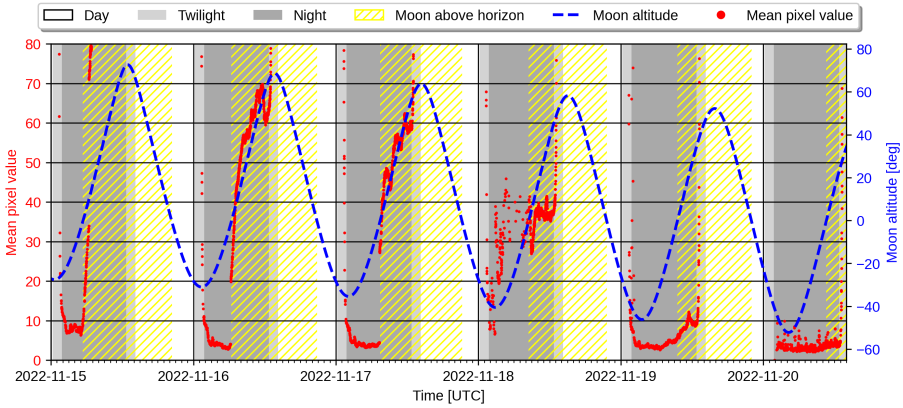

Figure 4: An example of the mean background level shown by the marker for the Pole camera of TARA between November 15 and 20, 2022 represented by mean pixel values in 120×120 pixel region at the center of the camera FOV. The values scale on the left of the vertical axis. The elevation of the Moon is shown by the dashed line to the scale on the right. Bands indicate the prevailing astronomical conditions.

the Pole cameras, two meteors were captured within $\sim$ 90 frames or $\sim$3 s, while in that for the Zenith camera, one meteor that lasted $\sim$1 s triggered.

In general, most of the recorded videos last a few seconds that are triggered by the meteors. UFOCapture may be triggered by airplanes and satellites that slowly cross the FOV, resulting in videos that can last tens of seconds or even minutes. During this time, one or multiple meteors may appear. These videos, along with their metadata, are stored locally on the hard disks. During the operations period, $\sim 221,000$ videos were recorded accounting for $\sim$ 90 TB data for four cameras.

3. Preliminary analysis

So far the analysis of the data has been oriented to one of two main objectives of DIMS, namely, the meteor astronomy to search for the interstellar meteoroids (ISM) with extra-Solar System origin. For this purpose, the videos are analyzed using the UFOAnalyzer software [11] as well as the pipeline developed for the PRISMA network that aims at monitoring fireball and retrieval of associated meteorites [13, 14]. The analysis has been made for the data obtained in the pilot operation in the TA site and in Japan that identified several ISM events by reconstructing the orbit in the Solar System [4].

The full analysis towards macro search is the underway. The preliminary analysis in this work has focused on estimation of the running time for the observations. The brightness of the night sky background matters to the detection sensitivity and observation time. The background level is primarily characterized by the output values. In this work, it is simply evaluated by the mean of those values over time and pixels in a limited region in the FOV.

Figure 4 shows an example of variation of the background level during the DAQ by the closed circles. See the caption for the details. These values are closely related to the background level during the DAQ. Stably low background conditions are seen most of the night periods when the Moon is below the horizon. In the example of this figure, the moon age was $\sim$22 days, the Third

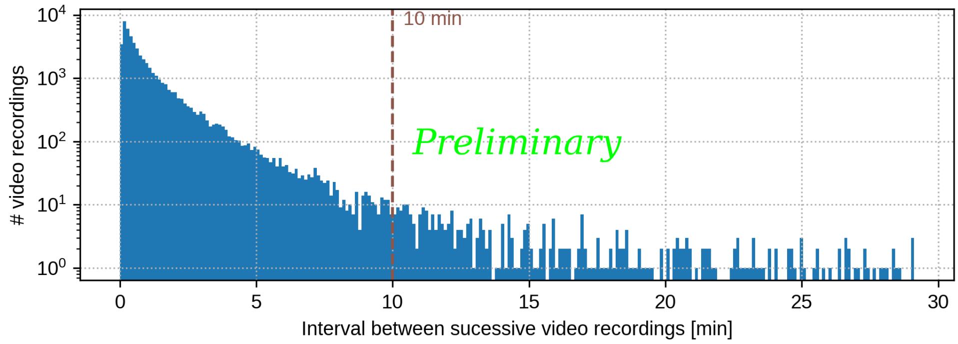

Figure 5: Distribution of time intervals between successive video recordings' start times for the Pole camera of TARA. All the videos captured during the dark night time were used.

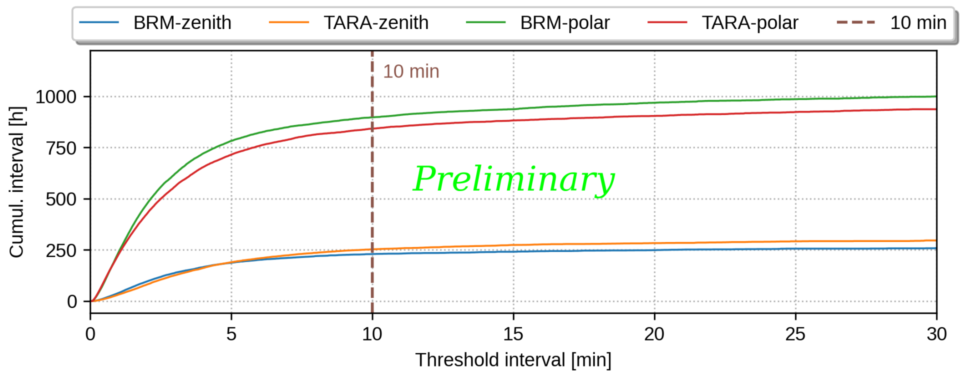

Figure 6: Cumulative time over the intervals between successive video recordings based on Figure 5 for four DIMS cameras at the TA site.The functions represent estimated operation time by integrating the interval time multiplied by its distribution up to the threshold interval time on the horizontal axis.

Quarter, on November 17. Rapid increase of the background level is recognized at the moonrise. This level is well correlated with the elevation of the Moon.

Limiting the data to the subset obtained in the low background improves the detection sensitivity of the macro search particularly for ones with lighter mass even though the effective time for the DAQ is reduced. For this analysis, we consider only the 'dark night' time defined by rejecting astronomical twilight when Sun is above an $-18°$ elevation as well as moonlight when the Moon is above the horizon. The operation time is assumed to be a sum of the time either when the video is recorded or when UFOCapture is the status of "active" to trigger.

Figure 5 illustrates the distribution of time intervals between successive recordings of the videos' start times. This time interval implies the operation time of the instrument for the monitoring when the trigger system is active. A 10 min threshold is a referential threshold that contains $\sim 99\%$, assuming that the observation conditions do not significantly vary within this time scale.

Figure 6 shows the estimated operation time below the interval threshold, assuming that the system records the video or stays active to trigger with this threshold. For both sites, the cameras

Table 1: Estimated operation time for each camera until June 24, 2023 from the start date. Dark night represents the sum of the duration without astronomical twilight and moonlight in the corresponding period. Recording represents the sum of duration that all the video is recorded by the trigger. Active represents the estimated operation time by assuming the trigger was fully ready between successive video recordings. The cases when two videos are separated over 10 min are eliminated. The values here are preliminary.

Mode	Site	Start date	Dark night [h]	#.videos	Recording [h]	Active [h]
Pole	BRM	Sept. 5, 2022	1282	51,495	43.5	1050
	TARA	Sept. 1, 2022	1306	49,812	46.8	1028
Zenith	BRM	Mar. 12, 2023	723	9053	9.5	232
	TARA	Feb. 22, 2023	880	9898	7.7	253
Total			–	120,258	107.5	–

exhibit a similar trend in the same mode.

Table 1 summarizes the DIMS operations at the TA site. For a threshold of 10 min within the dark night periods, the estimated 'active' operation times correspond to $\sim$ 13% and $\sim$ 9% duty cycles for the pole and zenith modes, respectively. The hourly trigger rates for these modes are $\sim$39 triggers per hour and $\sim$30 triggers on average, respectively. These trigger rates tend to increase from dusk to dawn due to the properties of meteor rates. About 3% of the dark night time is recorded on average that requires $\sim$110–170 GB disk space per hour depending on the cameras.

The next step that should be applied to the data analysis will be rejection of the video captured in the high background conditions. Such situations may be derived from the clouds for example high background levels seen on the night of November 18 in Figure 4. The trigger rates tend to decrease as the meteors and other moving events take place above the cloud altitudes.

For the meteor studies, we use the data when two cameras of the same mode were active. Same meteors are identified by matching the times from the offline analysis. Detection limit for meteors are determined by the sensitivity of the camera at BRM that is situated further from the meteor, while the detection aperture in terms of the area is determined by the FOV of the camera at TARA. Science analysis is motivated for the ISM search in a manner of astronomy using aforementioned analysis tools. This analysis includes photometry and astrometry, which are well-established techniques in astronomy used for the calibration of the sensors and corrections of the optics' distortions. Key performance parameters, such as the limiting magnitude, are also verified based on this analysis.

The work on the macro search is currently in progress. The fundamental concept is summarized as the following. Macros events are suppose to be very fast moving light emission that occurs close to the ground. As a result, these events appear as long line-like track of light, typically observable within a single video frame from one camera. However, depending on the geometry of the event, it may move within the FOV across a few frames and eventually transition to that of another camera. Such multi-camera event could serve as strong evidence for macro candidates.

At present, we aim to develop and apply the several algorithms on all the recorded videos as in Table 1 to search for the candidate events of macros. Science analysis is motivated in a manner of cosmic ray physics based on the simulations. The signals from the macros will be modeled by the literature together with the information of detector performance obtained by the meteor analysis. For each event, 60 frames of the video that are supposed to present the background are available

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on which the simulated macro signals are superimposed to evaluate the efficiencies of the trigger of the DIMS camera and subsequent search algorithms.

4. Summary

In this work, we report the status of the DIMS project focusing on the operation of the ultra-high sensitivity CMOS cameras at the TA site. Four cameras were installed to operate to cover the huge detection volume. While the analysis tools for the meteors that are also responsible for the characterization of the detector are available, the development of macro search algorithms and simulations are in progress. Throughout the operations, ~120,000 videos were recorded under the dark night. The functionality of the cameras has been well verified by the detection and analysis of a huge number of meteors. We plan to continue the operation in the same configuration for at least another half year to aim at detection of macros or setting an upper limit on their fluxes.

Acknowledgments

This work is supported by by National Science Centre, Poland grant 2020/37/B/ST9/01821, by JSPS KAKENHI Grant Number JP19H01910 and by the Joint Research Program of the Institute for Cosmic Ray Research, the University of Tokyo. We thank the Telescope Array collaboration for its help to achieve the observation, and also Appex Corporation and Canon Marketing Japan Inc., Canon Poland, and Canon Europe for their great help related to the ultra-high sensitivity cameras.

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