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First demonstration and operation of a roller-driven timestamp mechanism for GRAINE 2023 balloon-borne experiment

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A multi-stage shifter allows timestamped measurements by emulsion films, which have a thin-medium and high resolution (< 1 μ m). Using multiple layers of emulsion films that move indifferent speeds like hands of an analog clock, the shifter can create a unique positional displacements with respect to the time track recorded. Time information of each tracks is obtained by reproducing each positional displacements by track reconstruction. The GRAINE project aims for precise observation of cosmic gamma rays (10 MeV - 100 GeV) using a balloon-borne telescope with nuclear emulsion films. The emulsion telescope mounts multi-stage shifter as time stamper. It has obtained sub-second time resolution in the 2018 balloon experiment, which realized the highest resolution imaging of the Vela pulsar(> 80 MeV). For scientific observation, the emulsion telescope needs scale up and expansion of driving time. So we developed a new model of shifter with lighter structure to enable a large aperture area and long-duration observation times by adding more layers. Operational test suggested that the new shifter has the sub-second time resolution, which allows emulsion gamma-ray telescope to obtain a imaging resolution within 1 degree like previous balloon experiment. We are preparing for the next balloon-borne experiment in Australia by JAXA Scientific Ballooning from March to May 2023. In this poster, we present the preparations and details involved in this experiment about the multi-stage shifter.

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1. Introduction

The GRAINE project aims for precise observation of cosmic gamma rays (10 MeV–100 GeV) using a balloon-borne telescope with nuclear emulsion films. Emulsion films are precise trackers that record charged particles in three dimensions with high spatial resolution($< 1\ \mu$m). The emulsion telescope consists of a converter that detects gamma-ray events, an attitude monitor, and a multi-stage shifter(timestamp mechanism)[1]. The arrival direction of gammma rays can be determined by combining the incident angle with information from the attitude monitor via the arrival time. The converter consists of a stack of emulsion films, which records the electrons and positrons resulting from pair-production by gamma rays. Given the thin medium and the precise position resolution, emulsion films can record the starting point and angle of pairs produced with small multiple Coulomb scattering. This allows determination of the incident angle with 0.1 degree resolution for 1 GeV gamma-rays[2] and detection of linear polarization[3], which is better than the Large Area Telescope on the Fermi Gamma-ray Space Telescope[4].

Although emulsion films accumulate tracks integrally until development, we can get each track's arrival time by a multi-stage shifter. Using multiple layers of emulsion films that move in different speeds like hands of an analog clock, the shifter can create a unique positional displacements with respect to the time track recorded. So after each track recorded in the films is positioned and angled by an automatic readout system[5], we can get time information of each track by reproducing each positional displacements by track reconstruction.

The multi-stage shifter has been operated in three balloon experiments and has obtained sub-second time resolution in the 2018 balloon experiment, which realized the highest resolution imaging of the Vela pulsar($>$ 80 MeV). Although future emulsion experiments will attempt to obtain large statistics with a large-area telescope, the conventional shifter becomes too heavy with large aperture areas. We developed a new model of the shifter with lighter structure to enable a large aperture area and long-duration observation times by adding more layers. This paper describes the development and operation of a new multi-stage shifter for the balloon experiment in Australia in 2023.

2. Multi-stage Shifter

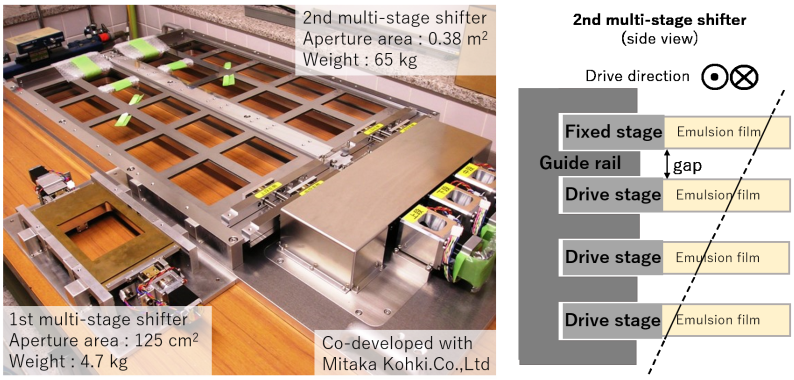

Figure 1: The conventional multi-stage shifter model. The left picture shows the first and second multi-stage shifters. The right picture schematically depicts the side view. The shifter consists of a fixed stage and three drive stages that follow metal guide rails.

The multi-stage shifters used in previous experiments were stage-driven models (Figure 1). This model has emulsion films mounted on a metal stage, which is driven following metal guide rails. In the 2018 balloon experiments, we operated the second multi-stage shifter. It has an aperture area of 0.38 m^2, weighs 65 kg, and consists of a fixed stage and three drive stages.

Although it has demonstrated the sub-second time resolution and reliable time stamping necessary for imaging celestial objects, the stage-driven model is highly unsuitable for use with large aperture areas. For example, if it is used for the 10 m^2 large-area telescope that is GRAINE's future goal, it would weigh 1700 kg and thus significantly affect the weight limits of other components. Therefore, scientific observations would require a major change of model for the multi-stage shifter.

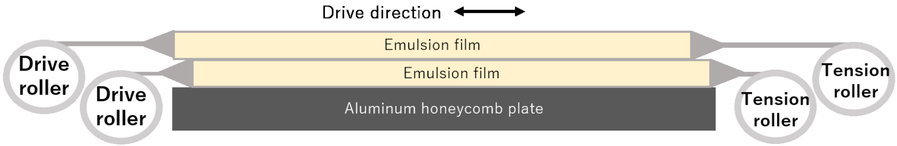

Figure 2: Schematic depiction of the roller-driven model. Both ends of the film pack are fixed to a pair of rollers; i.e., a drive and tension roller. The drive roller is connected to the motor via gears. A winding spring is built into the tension roller.

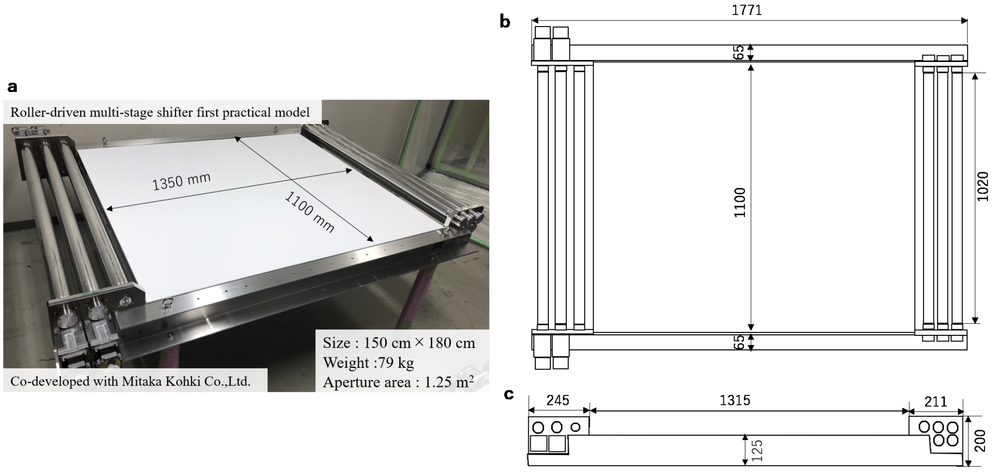

Figure 3: (a) Photograph of the first practical model of a roller-driven shifter and diagrams of the (b) top and (c) side view. It has five pairs of drive and tension rollers, and topmost drive roller is a fixed roller without a motor

The new shifter is a roller-driven model[6]. Both ends of its film pack are pulled by a drive roller and tension roller pair (Figure 2); the drive roller is connected to the motor via gears. A winding spring is built into the tension roller to keep a certain tension. Eliminating stages and guide rails should significantly reduce the weight. This would allow the model to be made larger, and more positional states coud be achieved by adding stages. As the film packs contact each other, the gap between films is significantly reduced compared with conventional models; this improves spatial resolutions in track (reconstruction accuracy). The resolution of arrival time (σ_t) is determined by the driving speed of the fastest moving film($v_{fastest}$) and the reconstruction accuracy of the positional displacement of the tracks (σ_{dx}) (eq1):

$$\sigma_t = \frac{\sigma_{dx}}{v_{fastest}}. \tag{1}$$

The uncertainty of the shift velocity is smaller than reconstruction accuracy. Therefore, a reduction in gap improves the time resolution. Figure 3 shows the first practical model of the roller-driven shifter. It has an aperture area of 1.25 m^2 and a mass of 80 kg. The weight per unit area is approximately 1/3 that of the conventional model. It has five pairs of drive and tension rollers, and the topmost drive roller is a fixed roller without a motor.

3. Operation Testing

We demonstrated that the roller-driven shifter has the sub-second time resolution in operation test[7]. So additional operation test was conducted in a flight environment using Temperature/Altitude/Humidity Icing Test Chamber in Minami-Shinshu/Iida Industry Center. We observed secondary cosmic rays (muons) using emulsion films and evaluated the shifter's time resolution.

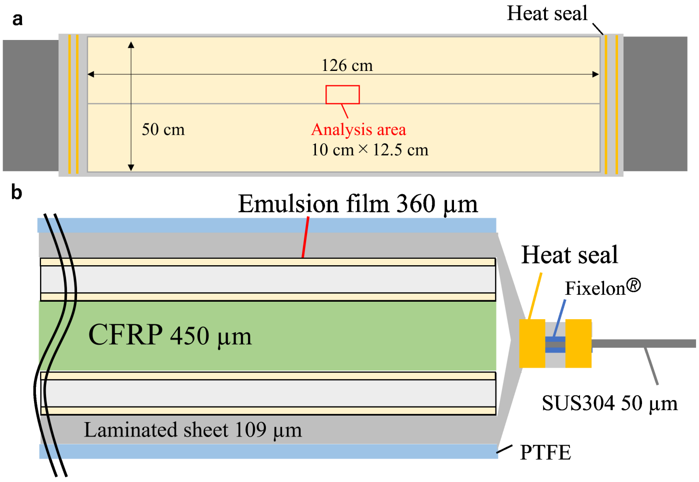

Figure 4: Composition of film packs: (a) top and (b) side view.

We prepared the emulsion films at Nagoya University, in August 2022. The film had a base thickness of 210 μm and an emulsion thickness of 75 μm. The film pack was made on September 17, 2022, using a vacuum packaging machine. Figure 4 shows the film pack used in this test. A highly rigid, low-mass backplate of carbon fiber reinforced plastic (CFRP) was sandwiched between emulsion films and packed with laminated sheets. One pack measured 50 cm × 126 cm, more than six times larger than the film pack used in the 2018 experiment. To make the ends of the packs rigid, 50 μm-thick stainless foil (SUS304) was used, which was thermally bonded to the laminated sheets using Fixelon ® (Aicello Co.,Ltd.). Two film packs were pulled by each roller pair and one film measured 25 cm × 126 cm. Therefore, a total of 40 films were used. To reduce friction during driving, 50 μm-thick polytetrafluoroethylene(PTFE) sheet with good sliding properties was inserted between the packs. After completing the operation test, the film packs were immediately unpacked and small pieces of film(10 cm × 12.5 cm) cut out as analysis area. All small films were developed the next day.

Table 1 lists the operations in this test. The rollers are labeled 0 (the fixed roller), 1, 2, 3 and 4 from top to bottom. This oeration aimed for the 0.1 s time resolution required for 0.1 degree resolution imaging. Rollers 1 were driven in steps of 500 μm, and rollers 2 and 3 were driven in steps of 200 μm. Roller 4 was driven continuously at 100 μm/s for 1.5 mm. The shifter made a reciprocating motion, with a period of movement in one direction defined as one stroke. The upper roller moved one step every time the lower roller finished one stroke. Position displacemant of tracks found between the roller3 and 4 can provide a 0.1 s time resolution with 10 μm reconstruction accuracy. To simulate a flight environment, we controlled tempreture and pressure of inside the chamber. Based on the temperature changes measured in the 2018 experiment, we cool -4 °C/hour from 20 °C to -40 °C and kept 300 hPa.

Table 1: Operation details

Roller	Operation	Track accumulation time per step
Roller1	500 μm/step	about 2 hours
Roller2	200 μm/step and 20 step/stroke	about 6 minutes
Roller3	200 μm/step and 20 step/stroke	about 15 seconds
Roller4	1.5 mm/stroke 100 μm/s continuous drive	-

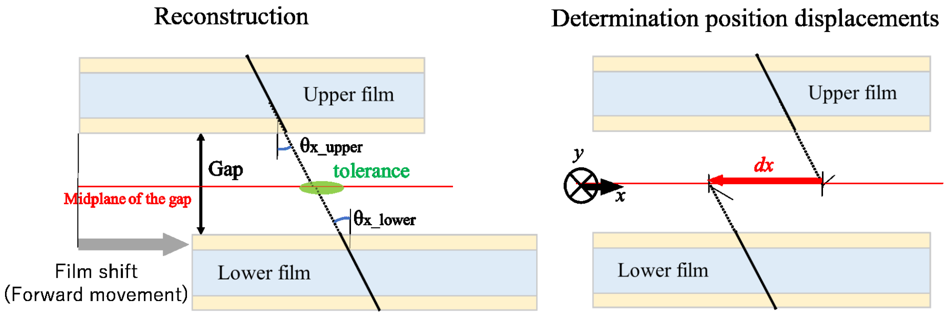

Figure 5: Definition of position displacement. On the midplane of the gap, the position displacemant is defined as (the position of the lower film track) − (the position of the upper film track) , and it is represented by dx in the direction of film shift and dy vertically

On November 18, all tracks were read using an emulsion scanning system (Hyper Track Selector, HTS) at Nagoya University. The scanned tracks were reconstructed between two films at a time by using NETSCAN[8]. Each track was extrapolated to the midplane of the gap between films, and they are reconstructed if the deviation of angle and position is within a certain tolerance (Figure 5). First, we determined the alignment between two films by using tracks accumulated within a certain time. Starting from the design value, we adjusted the alignment by iterating so that the number of reconstructed tracks is maximized. After that, we reconstructed tracks accumulated during all operation by allowing position displacement in the direction of film shift. On the midplane, position displacement is defined as (the position of the lower film track) − (the position of the upper film track), which is represented by dx in the direction of film shift and dy in the direction perpendicular to dx on the film plane. The direction in which the film moves forward takes positive, so dx is negative. Tracks can be classified into different time periods by using the distribution of these position displacements.

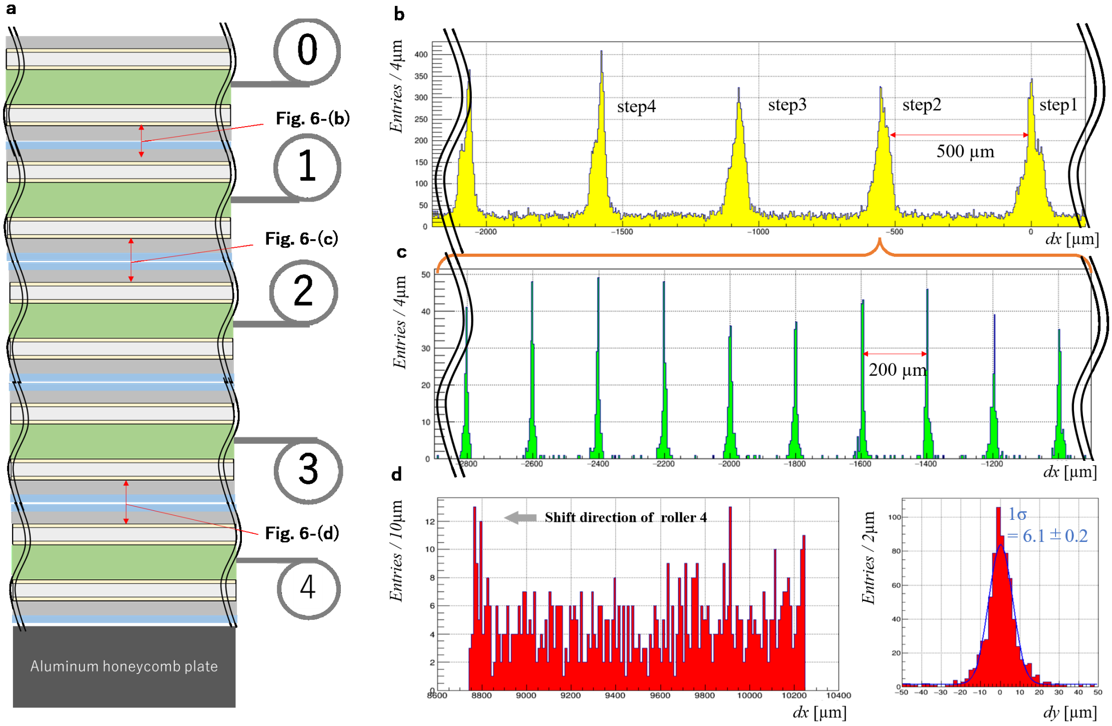

Figure 6: Distribution of position displacement for tracks reconstructed between rollers 0 and 1 (b), between rollers 1 and 2 (c) and between rollers 3 and 4(d). Figure(a) shows the side view of the shifter

Figure 6-(b) shows the distribution of roller 1's position displacement relative to roller 0. There are clusters at intervals of about 500 μm which correspond to the step spacing of roller 1. Therefore, tracks in each cluster were recorded during about 2 hours of rest time at each step of roller 1. Each cluster was assigned to each step by the logical position displacements calculated from the operation. So we can extract each certain clusters and reconstruct each lower films. Figure 6-(c) shows the distribution of roller 2's position displacement relative to roller 1 about the tracks which belong the second cluster from the right in Figure 6-(b). There are clusters at intervals of about 200 μm which correspond to the step spacing of roller 2. Therefore, tracks in each cluster were recorded during about 6 minutes of rest time at each step of roller 2. Figure 6-(d) shows the distribution of roller 4's position displacement relative to roller 3. There is a banded cluster about 1.5 mm long, consistent with the continuous driving of roller 4. (Only the case where rollers 3 and 4 were both in the forward movement stroke is shown.)

We then evaluated the reconstruction accuracy for each cluster. We made Gaussian fitting dy distribution for $|\tan\theta_y| < 1.0$; 1σ was defined as the accuracy of the track reconstruction σ_{dy}.

Table 2 lists the σ_{dy} for each clusters, classified by the shift direction. All operations obtained reconstruction accuracies of ~7 μm . As roller 4 was continuously driven at 100 μm/s, the time resolution σ_t was less than 0.1 s from eq. 1. Therefore, the roller-driven shifter demonstrated sub-second time resolution.

Table 2: Reconstruction accuracy $\sigma_d y$ of tracks reconstructed between rollers 3 and 4

step	1		2		3		4	
Direction of roller4	Forward	Back	Forward	Back	Forward	Back	Forward	Back
$\sigma_{dy}[\mu$m]	6.5	6.1	6.1	6.1	6.0	5.4	5.8	6.5

4. GRAINE2023 balloon-borne experiment

We performed the 4th balloon experiment in Australia on April 30, 2023, which we call GRAINE2023. We began assembling the emulsion telescope in September, and the gondola was shipped to Alice Springs in mid-December with the two roller-driven multi-stage shifters and three star cameras installed. Emulsion film packs for shifter were made after that, then shipped to Alice Springs the end of January by refrigerated transport (by air). Members arrived at the site on February 16 for final preparations. Installation of the shifter film was completed on March 1, then installation of the converter film was completed on March 1(Figure7). After closing the pressure vessel shell and some test with JAXA equipment, we completed the emulsion telescope and waited for the flight opportunity.

Figure 7: Emulsion telescope after installation of the converter films. Two roller-driven multistage shifters are mounted on the pressure vessel gondola, and all 20 converter packs are mounted there. The total sensitive area is 2.5 m^2 (1.25 m^2 × 2 sets). The controller, communication equipment, and batteries for each device are mounted in both semicircles.

As soon as the balloon was launched at 6:32 a.m. local time (UTC+9.5) on April 30, two multi-stage shifters started observation operation at 1/10 speed(Roller 4 was driven at 10 μm/s(Table1)).

Before the Vela pulsar came into the field of view of the emulsion telescope, the drive speed of Roller4 were changed to 100 μm/s. The shifters finished the operation and was shut down at around 8:00 on May 1. Total flight duration was 27 hours, including an altitude of 35.4 - 37.2 km and a level flight of 24 hours and 17 minutes, making it the longest balloon flight in the Emulsion Telescope balloon-borne experiment to date, while the Emulsion Telescope was operated stably over night. After retrieving the gondola around 3 pm on May 1, the removed emulsion film packs were shipped to Japan by refrigerated transport on May 4 (by air). The emulsion films returned to Japan are developed at a large-scale developing facility of Gifu University on end of June, 2023.

5. Conclusion

By changing the drive mechanism from the conventional model, the roller-driven model is 1/3 lighter per unit area, allowing it to have a large aperture area and the lighter structure also enable longer observations by adding more layers. Operation testing with emulsion films suggested this model can achieve sub-second time resolution in flight environment. The roller-driven shifter was introduced in GRAINE2023 balloon experiments, and it realized large-area observations with emulsion telescopes for the longest durations to date. We will proceed with the scan and reconstruction of the tracks recorded in flight films and aim to form an image of Vela and the galactic center.

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References

[1] S.Takahashi et al,*Nucl.Instrum.Meth.A* **620**(2010)pp192-195.

[2] S.Aoki et al, *Nucl.Phys B Proc.Suppl.***196**(2009)pp 50-53

[3] K.Ozaki et al, *Nucl.Instr.Meth.A* **833**(2016)165.

[4] W.B.Atwood, et al., *Astrophys.J.***697**(2009) 1071.

[5] M.Yoshimoto, et al., *Prog. Theor. Exp. Phys.* (2017)103H01

[6] S. Takahashi, et al.,*Adv. Sp. Res.***62**(2018) 2945.

[7] M.Oda, et al., *Prog. Theor. Exp. Phys.*(2022)113H03

[8] K.Kodama, et al., *Nucl.Instrum.Meth.A***493**(2002)45.

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