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Multi-stage shifter for subsecond time resolution of emulsion gamma-ray telescopes

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ABSTRACT

To observe gamma-ray sources precisely, a balloon-borne experiment with a new type of detector, the emulsion gamma-ray telescope, is planned. A multi-stage shifter mechanism based on the concept of an analog clock serves as a time stamper with subsecond time resolution and uses multiple moving stages mounted on the emulsion chambers. This new technique was employed in a test experiment using a small-scale model in a short-duration balloon flight. Tracks recorded in nuclear emulsion were read by a fully automated scanning system, were reconstructed, and time information were assigned by analysis of their position displacements in the shifter layers. The estimated time resolution was 0.06–0.15 s. The number of tracks passing through the detector was counted every second, and hadron jets were detected as significant excesses observed in the counting rate. In future, the multi-stage shifter is greatly contributing to ongoing efforts to increase the effective area of emulsion gamma-ray telescopes.

1. Introduction

To observe the sky coordinates of cosmic gamma-ray sources precisely, we are developing a new gamma-ray telescope using nuclear emulsion [1]. Fig. 1 shows the general concept of the emulsion gamma-ray telescope. Gamma rays in the 10 MeV to 100 GeV energy range are detected in the converter by topological identification of the pair production vertex (gamma-like events start in the middle of the chamber, penetrate downstream, and are accompanied by a partner track). Nuclear emulsion, a powerful tracking detector, can clearly observe electron and positron tracks at their starting points and can also determine their three-dimensional positions and angles precisely in a thin detector medium with little multiple Coulomb scattering. The angular resolution (68% uncertainty cone) for emulsion gamma-ray telescopes is 1.4 mrad ($=0.08^\circ$) @$E_\gamma = 1-2$ GeV and 10 mrad ($=0.57^\circ$) @$E_\gamma = 100$ MeV, and is achieved by accurately measuring the angles of the initial electron and positron pair in an emulsion film. This performance is about one order of magnitude better than that of the Large Area Telescope on the Fermi Gamma-ray Space Telescope, which has observed cosmic gamma rays in the sub-GeV/GeV region above 100 MeV since 2008 [2].

We plan a large-scale program of balloon-borne emulsion gamma-ray telescope experiments, Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE). We will launch a large-area telescope (aperture ~ 3 m) in several long-duration flights (~ 200 h), like the JACEE or RUNJOB balloon-borne experiments [3,4]. The main goal of our project is to reveal the spatial positions and structures of gamma-ray sources by observing them with a high-angular-resolution telescope.

Nuclear emulsion is a time-integrating detector, so an emulsion gamma-ray telescope without additional equipment has no time resolution. A balloon-borne emulsion gamma-ray telescope constantly changes its attitude relative to celestial coordinates during flight. One component of the variation is the diurnal motion of the celestial sphere (angular velocity ~ 0.1 mrad/s), and the other dominant component is the rotation of the balloon (a few milliradians per second without active attitude controls). Therefore, to convert the coordinates on the detector to celestial coordinates with sub-milliradian accuracy, it is necessary to assign arrival-time information for gamma-ray events with subsecond accuracy.

We employed a multi-stage shifter to effectively time stamp each track recorded in the nuclear emulsion at various balloon altitudes. We describe an advanced method that reduces its time resolution to the subsecond level. This paper describes in detail the multi-stage shifter we developed and its time resolution, which was determined in a balloon-borne prototype experiment.

2. Time stamper for emulsion gamma-ray telescope: Multi-stage shifter

2.1. Principle

Since fully automated scanning systems were developed, we have been able to identify all the tracks in a nuclear emulsion

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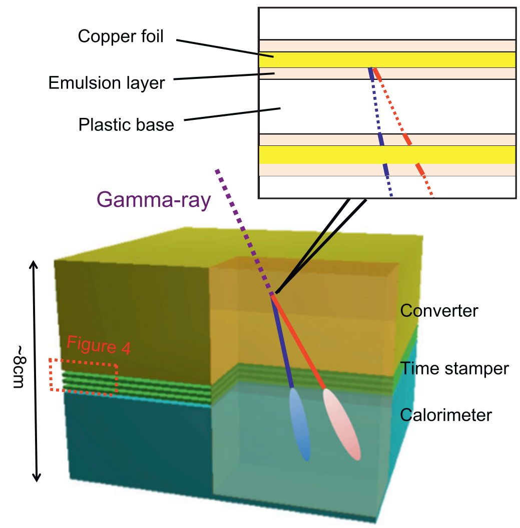

Fig. 1. General concept of emulsion gamma-ray telescope. It consists of the converter (100 sets of interleaved emulsion film and copper foil layers) for detecting gamma rays and determining their directions precisely, the time stamper for assigning event arrival time, and the calorimeter (several dozen sets of an emulsion film and Pb plates) for measuring energy by the shower counting or multiple Coulomb scattering method. Dotted area corresponds to the part described in Fig. 4.

plate within a given angular range [5,6]. All the identified tracks are reconstructed by the NETSCAN analysis method, which has been described in detail elsewhere [7]. These advances in nuclear emulsion techniques make it possible to build a multi-stage shifter that allows the determination of track arrival times with high resolution.

The relative positions of the main emulsion chamber and a secondary emulsion chamber can be reconstructed with sub-micrometer accuracy by aligning tracks that penetrate plates in both chambers. Thus, if the relative positions are controlled by intentionally shifting the secondary chamber(s) according to time, we can measure the position displacements of tracks reconstructed between the main chamber and the shifted chamber during the analysis phase, and thus assign time information to tracks using the observed amounts of position displacement. Simple shifter mechanisms have long been used in emulsion chamber cosmic ray experiments as two-state track taggers; a single large displacement of the secondary emulsion chamber is used to distinguish tracks recorded while the balloon was at float altitude from those recorded during ascent and descent [3,8]. The newly developed multi-stage shifter has multiple chambers that are shifted in different cycles, allowing many more independent combinations of relative positions of each chamber. (This idea is based on the principle of an analog clock, which cyclically identifies the time of day from a combination of an hour hand, a minute hand, and a second hand.) A multi-stage shifter permits fine-scale time resolution even in a long-duration balloon flight. We have already shown that this technique yielded time information for cosmic ray tracks with high efficiency and high reliability in a ground-based experiment [9]. The multi-stage shifter system meets the requirements for a balloon-borne experiment: light weight, compactness, simple design, low power consumption, and absence of high-voltage devices.

2.2. Flight model for test experiment

We developed and built the first flight version of a multi-stage shifter for a balloon-borne experiment. Fig. 2 shows a picture and schematics of the first flight model. It has three 1-mm thick brass stages. Emulsion films are mounted on an empty frame in each stage. The first and second stages are guided by bearings and slide with a 10-mm stroke. The third stage is guided by parallel blade springs and slides with a 6-mm stroke. The gaps between stages are 1 mm (the pitches are 2 mm). The multi-stage shifter is designed to minimize sliding friction, to avoid clearance in the stages, and to work in low-temperature and low-air-pressure conditions. Each stage is driven by a fine-scale pulsed stepping motor. The motor controller consists of PC/104 boards, including a CPU, which operate each stage with an open-loop system and record the time and position (the number of sent pulses) for each step. Each stage performs a one-way shift (back or forth) to avoid backlash in the shift direction. The position reproducibility of each stage is $\sim 1\ \mu m$ in standard deviation. The dimensions and mass of the first flight model are $220\ mm \times 440\ mm \times 60\ mm$ and 5 kg, respectively. The power consumption is 7 W (typical value, while driving one stage) or 20 W (maximum value, while driving all stages at once) and is supplied by a battery at balloon altitudes.

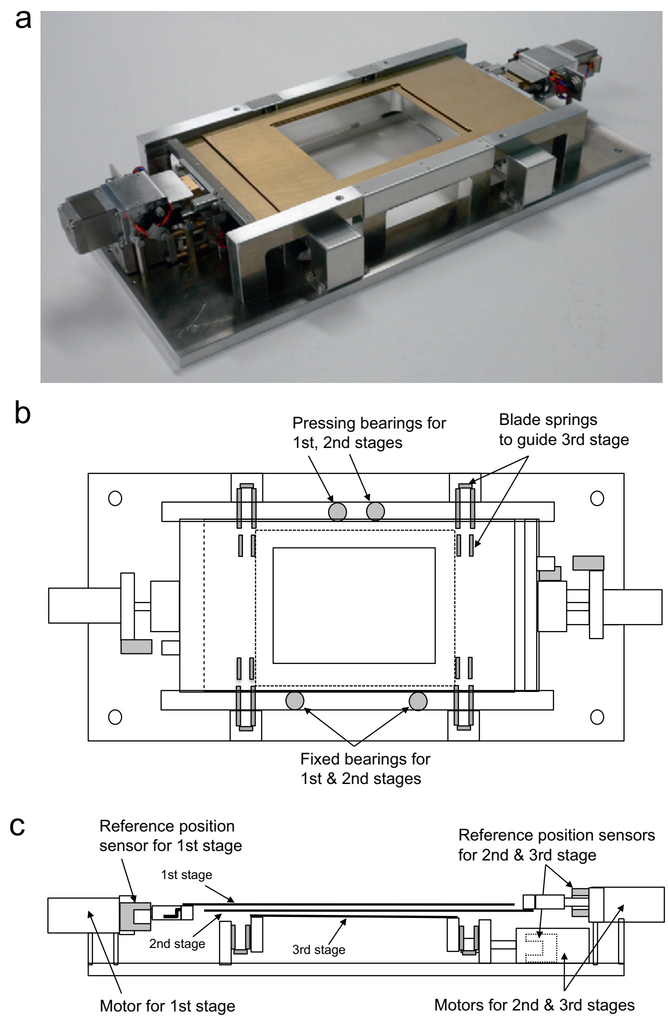

Fig. 2. (a) Picture of first flight model of multi-stage shifter and schematics showing (b) top and (c) side views. The first and second stages are guided by two fixed bearings and a pressure bearing. The third stage, which is shifted in a more frequent cycle, has parallel blade spring mechanisms to ensure highly reproducible motion. Each stage has a reference position sensor. The performance is monitored by counting pulses sent to the motor (according to the difference between clockwise and counterclockwise pulses) in each cycle.