PROCEEDINGS OF SCIENCE

GRAINE, balloon-borne emulsion telescope experiments for precise gamma-ray observations

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We are developing a GRAINE project, 10 MeV – 100 GeV cosmic gamma-ray observations with a precise (0.08 degree @ 1 – 2 GeV) and polarization sensitive large-aperture-area (~10 m^2) emulsion telescope repeated long duration balloon flights. We demonstrated a feasibility and performance of the balloon-borne emulsion gamma-ray telescope experiment with various test experiments and developments on the ground, and balloon-borne experiments in 2011, 2015 and 2018. In 2018, we performed the balloon-borne experiment with a 0.38 m^2 aperture area and 17.4 hour flight duration in Australia by JAXA Scientific Ballooning. By the flight data analysis, we achieved highest imaging of the Vela pulsar ever and established the emulsion gamma-ray telescope with the world's highest angular resolution in the gamma-ray telescopes in this energy regime. Based on the experiences and achievements, we aim to start scientific observations expanding an aperture area and flight duration repeated balloon flights. In 2023, we performed the balloon-borne experiment in Australia with a 2.5 m^2 aperture area and 27 hour flight duration, aiming e.g. to observe Galactic Centre region with the highest imaging resolution. An overview and status of the GRAINE project, especially the latest results on the 2018 balloon-borne experiment and status of the 2023/future balloon-borne experiments are presented.

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1. Introduction

Cosmic gamma-ray observations have a ripple effect on a wide range of scientific fields, including cosmic ray physics, high-energy astrophysics, cosmology, and fundamental physics. In addition, gamma-rays play a crucial role in recent multi-messenger astronomy, including neutrinos and gravitational waves. Currently, state-of-the-art gamma-ray telescopes such as the Fermi Gamma-ray Space Telescope are making great progress in observing cosmic gamma-rays in the high-energy band. On the other hand, the resolution of these gamma-rays is an order of magnitude lower than observations at other wavelengths due to the difficulty of observation, and there are still unexplored areas in this band. Qualitative improvement of observations is important to advance the observation of cosmic high-energy gamma-rays to a new level.

The emulsion film with excellent spatial resolution allows us to capture extremely precise images of high-energy gamma-ray interactions. By introducing ultra-fast automatic analysis technology and time information assignment technology, it can become an excellent gamma-ray telescope with the "world's highest angular resolution," "world's first polarization sensitivity," and the "world's largest aperture area." We have developed an emulsion gamma-ray telescope and are promoting the GRAINE project, which aims at precise observation of cosmic high-energy gamma-rays through repeated long-duration balloon flights. Figure 1 shows a schematic view of the emulsion gamma-ray telescope.

Through various R&D and test experiments on the ground, as well as the 2011 balloon-borne experiment, 2015 balloon-borne experiment, and 2018 balloon-borne experiment, we have pioneered the feasibility of cosmic high-energy gamma-ray observations in balloon flights with the Emulsion Telescope. In particular, in the 2018 balloon-borne experiment, we succeeded in imaging the world's highest resolution for the Vela pulsar, which is actually a known bright gamma-ray source, and established an emulsion telescope with the world's highest angular resolution. Based on these experiences and achievements, we will expand the aperture area and flight duration, and begin full-scale scientific observations through repeated balloon flights. A precursor balloon-borne experiment was conducted in Australia in 2023 (JAXA Australian Scientific Ballooning). The 2023 balloon-borne experiment aimed to realize a telescope with an aperture area of 2.5 m^2, 6.6 times larger than the previous experiment, and with a longer flight duration (>24 hours), to cover the Galactic Centre region. In addition to realizing the world's largest aperture gamma-ray telescope, we will start further observations of the Vela pulsar for the world's first high-energy gamma-ray polarization observations, high-resolution observations of Galactic Centre region where gamma-ray sources of unknown origin exist, and observations of transient gamma-ray sources that could also be sources of neutrinos and gravitational waves.

2. The 2023 balloon-borne experiment

We have been preparing for the 2023 balloon-borne experiment through a series of various developments and tests. In the production of emulsion film, we have achieved mass production of emulsion film by establishing a nuclear emulsion mass production facility and introducing machine coating (1670 kg of manufactured emulsion, 750 m^2 of coating area). In addition, the introduction of roller-driven multistage shifters for the time-assignment mechanism has realized a larger area

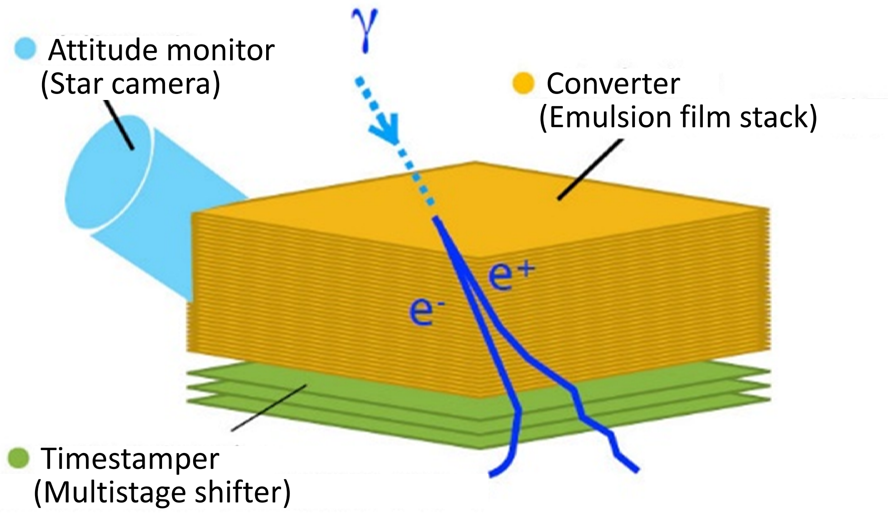

Figure 1: The emulsion gamma-ray telescope consists of a converter with emulsion film stacks, timestamper with multi-stage shifting emulsion films, and an attitude monitor with star cameras. By capturing a beginning of electron pair precisely at the converter, timestamping to detected events with the timestamper, and combining attitude monitor data based on the time, then the gamma-ray arrival direction can be determined on the celestial coordinates.

(total of four units, total aperture area of 5m^2), and a star camera system that is more resistant to low temperatures has been constructed for the attitude monitoring star camera. For pressure vessel gondola, we have developed large, lightweight membrane pressure vessel gondola. The gondola was shipped to Alice Springs, Australia in mid-December (by sea) with a multi-stage shifter, star camera, and balloon experiment system assembled to the gondola. The emulsion film was shipped to Alice Springs, Australia, at the end of January by refrigerated transport (by air) after pretreatment (refreshment, humidity control, and vacuum packing). Members arrived at the site on February 16 for final preparations, which were almost completed on March 14 (Figures 2 and 3). After a final engagement test with JAXA equipment and a communication radio sensitivity test, we waited for wind and other conditions to become favorable.

On April 30, wind and other conditions were favorable, and the balloon was launched at 6:32 a.m. local time (UTC+9.5) (Figure 4). The balloon continued to ascend, reaching an altitude of 36 km about 2 hours later, and began a level flight in an easterly wind. After flying to cover the entire period when the Vela pulsar and the Galactic Centre region crossed the field of view of the emulsion telescope (15:00 – 6:30 the next day), the entire emulsion telescope system was shut down at around 8:00 on May 1. After carefully estimating the landing site, the balloon was detached at

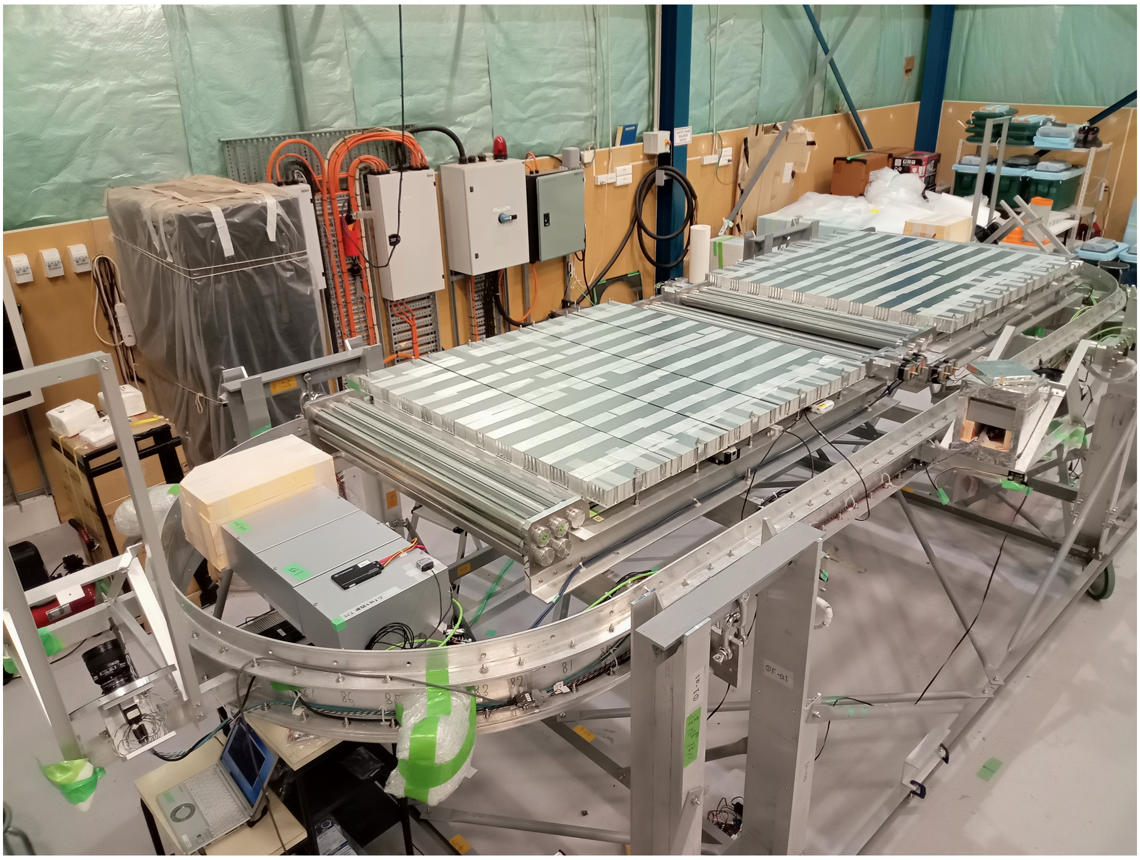

Figure 2: Upon completion of loading all equipment and emulsion film (before insulation is loaded and before closing the pressure vessel shell). Two roller-driven multistage shifters are mounted on the pressure vessel gondola, and all 20 converter packs are mounted there. The total sensitive area is 2.5 m^2 (1.25 m^2 × 2 sets). The controller, communication equipment, and batteries for each device are mounted in both semicircles. Star cameras facing in three directions are mounted on the outside of the arc and straight sections of the pressure vessel ring. Total length of 5.7 m in the longitudinal direction.

8:47 a.m. and parachuted into a slow descent, landing at about 9:25 a.m. at a point about 1100 km east-southeast of Alice Springs and 220 km south of Longreach (Figures 5 and 6). 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 (Figure 7). After confirming the safety of the gondola by helicopter around 3 pm on May 1 (storage data retrieved), the gondola was safely transported to Longreach by truck on May 2, and the removed emulsion film packs were shipped to Japan by refrigerated transport on May 4 (by air). Thus, the 2023 balloon-borne experiment was successfully accomplished.

Figure 3: After closing the pressure vessel shell, during final engagement, the silver cylinder facing in three directions is the stray light hood of the star camera.

3. Outlook

The emulsion films returned to Japan are developed at a large-scale developing facility of Gifu University. After the emulsion film has been developed and dried, the surface deposited silver is rubbed off, the film thickness is adjusted by swelling, and emulsion film tracks are read by an automatic scanning system at Nagoya University. A data processing system will then be established and flight data analysis will be performed.

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Figure 4: The balloon at the time of launch (about 6:30 a.m. local time). The balloon is approximately 130 meters from the head to the tail (mid-light point) (volume of 300,000 cubic meters when fully inflated in the sky). The gondola weighs about 1.1 tons (ballast about 0.4 tons), and the total weight including the balloon is about 1.9 tons.

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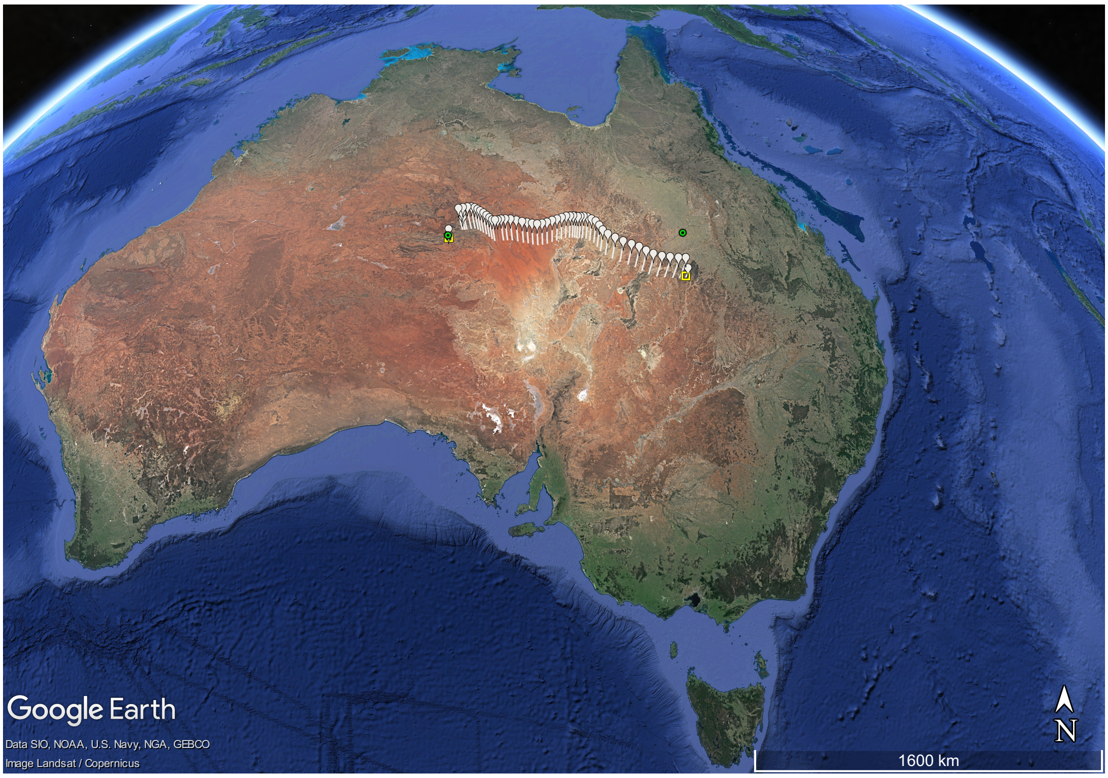

Figure 5: Flight path is shown with the white icons every 30 minutes. The open-squares (yellow) indicate the launch (left) and landing (right) points. The dotted-circles (light green) indicate Alice Springs (left) and Longreach (right). (Latitude, longitude, altitude, and time taken by JAXA)

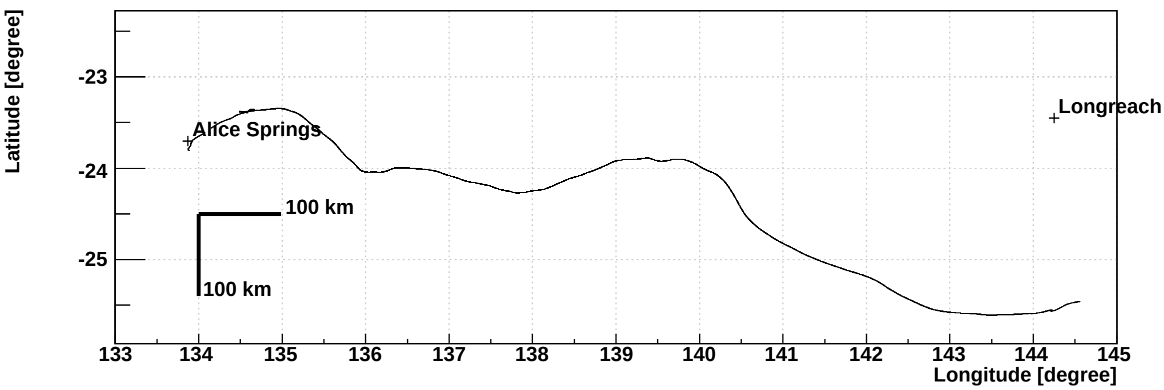

Figure 6: The flight path is shown from launch to landing in longitude (horizontal axis) and latitude (vertical axis). The distance from Alice Springs to Longreach is 1060 km. (Latitude and longitude taken by JAXA)

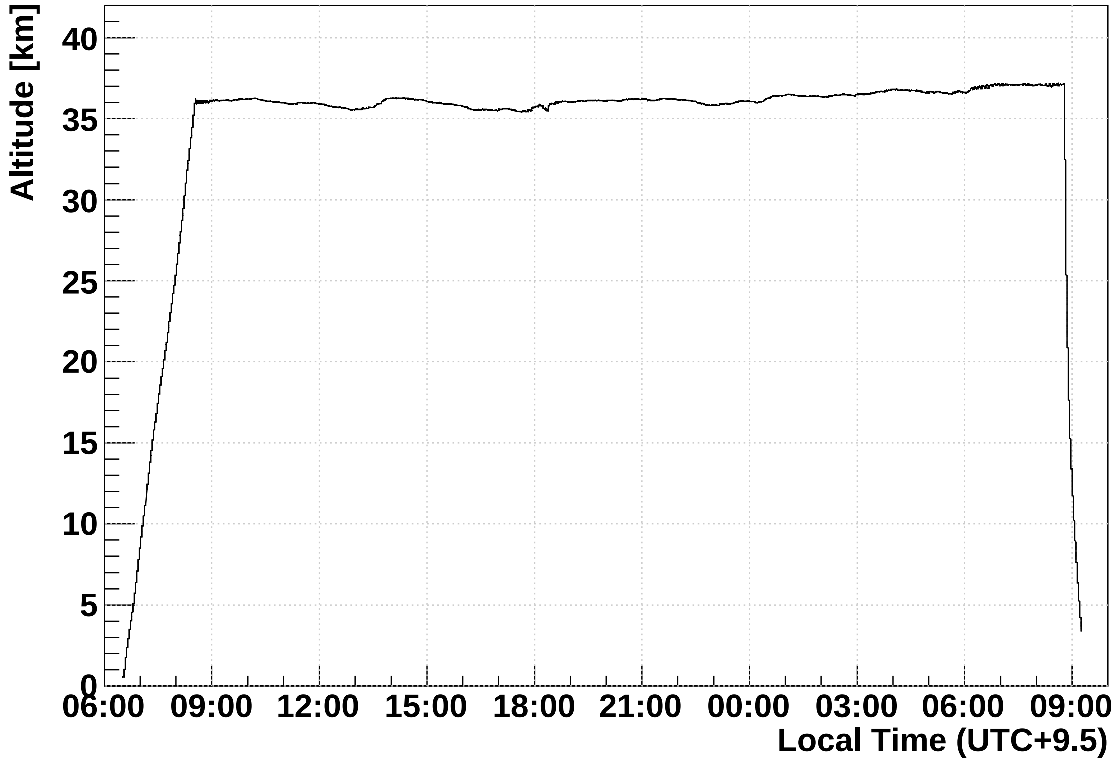

Figure 7: Altitude of the gondola as a function of time. (Altitude and time taken by JAXA)

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