Development of Onboard Image Processing Software for MONSTER on the HiZ-GUNDAM Satellite

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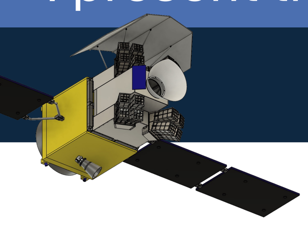
Abstract

HiZ-GUNDAM (High-z Gamma-ray bursts for Unraveling the Dark Ages Mission) is a future space mission whose primary goal is to detect high-redshift gamma-ray bursts. The satellite will carry two types of instrument. They are the wide-field X-ray monitors called EAGLE and the Multi-band Optical and Near-infrared Telescope called MONSTER. The satellite is designed to detect a Gamma-ray bursts(GRBs) with EAGLE and to autonomously maneuver MONSTER to point toward it. There should be ~1,000 stellar objects in the images obtained with MONSTER, but it is impossible to immediately downlink all that information to the ground via an alert system. Therefore, it is necessary to narrow down the candidate objects to dozens. In this poster, I present the current development status of the onboard image processing software.



1. HiZ-GUNDAM

Current Flow of GRB Observations

- A GRB is first detected by a Gamma-ray or X-ray space telescope, and an alert is immediately sent to the ground.
- However, large ground-based telescopes cannot begin follow-up observations immediately because the alert information does not include the distance (redshift), making it unclear whether the GRB is worth observing. Currently, we have no choice but to use small and medium-diameter telescopes to measure the distance. It typically takes about 1 day to obtain a photometric redshift and to prepare for observation with a large telescope.
- Although GRB afterglows exhibit significant diversity, their luminosity typically decays approximately as t^{-1}. Therefore, it has often been difficult to obtain statistically sufficient observations.

HiZ-GUNDAM Observation

EAGLE (0.4 – 4 keV, 0.53 sr) : Searching for GRBs

MPU : Determining whether each X-ray source is an X-ray transient or a known source by catalog matching (~several sec)

The satellite autonomously maneuvers MONSTER to point toward it.(~300s)

MONSTER : 5-band simultaneous follow-up observation (2 min × 5 frames)

MPU : Due to downlink limitations, images cannot be immediately downlinked, so onboard analysis is required to identify afterglow candidates and downlink their positions and magnitudes (~30 min).

Ground : Catalog matching and photometric redshift estimation; identify a single afterglow candidate and send alert with rough photometric redshifts to the GRB community (~1 h).

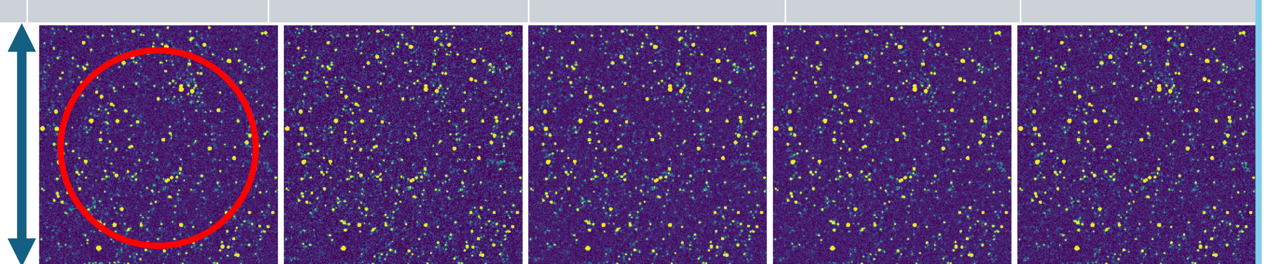
MONSTER specifications[1]

Aperture	30 cm diameter				
Field of View (un-vignetted)	12’ x 12’				
Pixel scale	2’’ x 2’’				
Wavelength (μm)	0.5-0.9	0.9-1.3	1.3-1.7	1.7 – 2.1	2.1-2.5
Limiting AB magnitude S/N=10	21.3	20.9	20.6	20.5	20.4

Location Accuracy of EAGLE : ±1.5 arcmin

3σ error circle

12’



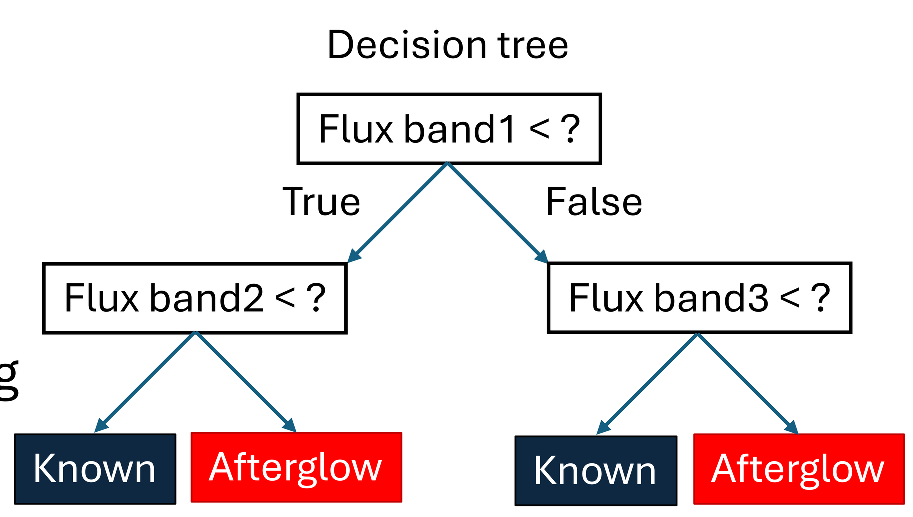
2. Image Processing

1. Image registration → Image stacking → Source detection → Aperture photometry (There are less than 1000 sources brighter than limiting magnitude)
2. From detected sources, the MPU selects dozens of GRB afterglow candidates, and their information is immediately downlinked.

I develop a selection method to identify GRB afterglow candidates.

The processing speed of satellite CPUs is limited (e.g., LEON4: ~200 MHz).

I consider to construct a simple decision tree using machine learning and to implement the derived branching conditions onboard the satellite.



3. Constructing Decision Tree

To construct the decision tree, it is necessary to simulate the flux observed by MONSTER.

Known sources, Cosmos catalog(2 deg^2 wide survey)

- Cross-matched with Subaru and Ultra-VISTA (covered 0.5 – 2.5 μm)
- Limiting magnitude is deeper than MONSTER

About 960,000 sources in the catalog —Brighter than limiting mag→ about 56,000 sources

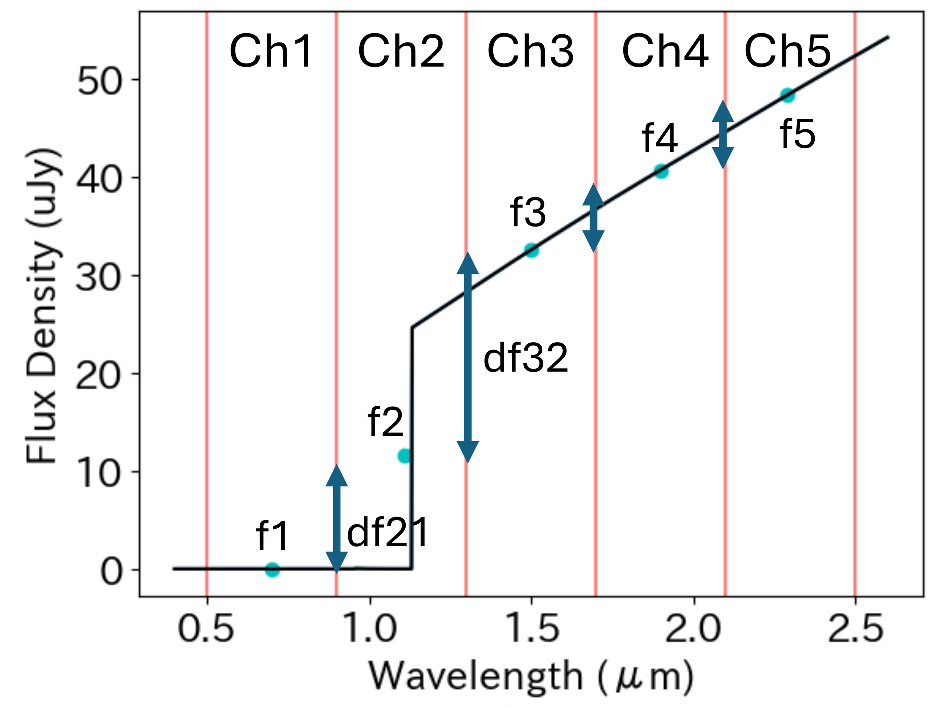
Model SED fitting → Simulated fluxes in each MONSTER band

Afterglow : I used the afterglow SED simulation code Phozzy[2], developed by the Gamow Explorer team.

- Redshift **z**: randomly sampled in the range 3.1 – 19.6
- Power-law index β: drawn from a normal distribution (μ = 0.7, σ = 0.04)
- **Flux**: drawn from a normal distribution (μ = 6.18 μJy, σ = 2.65 μJy) at z = 10 and scaled depending on redshift.

These three parameters were varied to generate 50,000 afterglow SEDs, and the expected fluxes in each MONSTER band were calculated using the corresponding filter transmission curves.

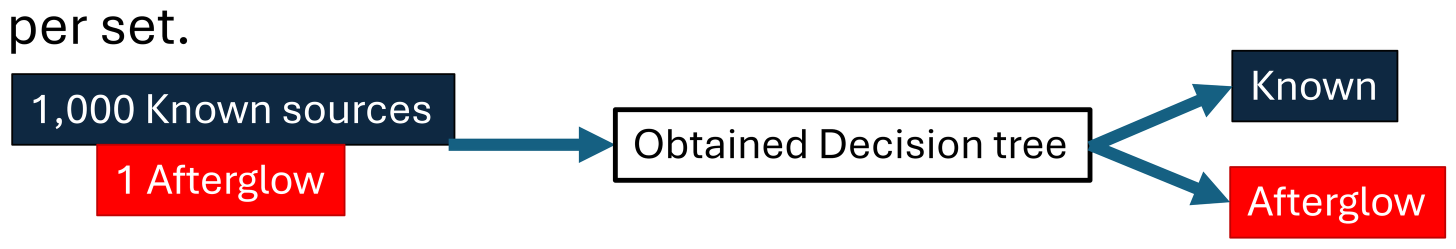
Note that the predicted fluxes of both known sources and afterglows are ideal values without noise.



- The dataset was split into **80% training** and **20% testing** for both afterglows and known sources.
- I constructed a decision tree using training data consisting of nine features.
  - 5 normalized fluxes(f1, f2, f3, f4, f5)
  - 4 flux differences between adjacent bands(df21, df32, df43, df45)

The test data were used to evaluate the tree’s performance

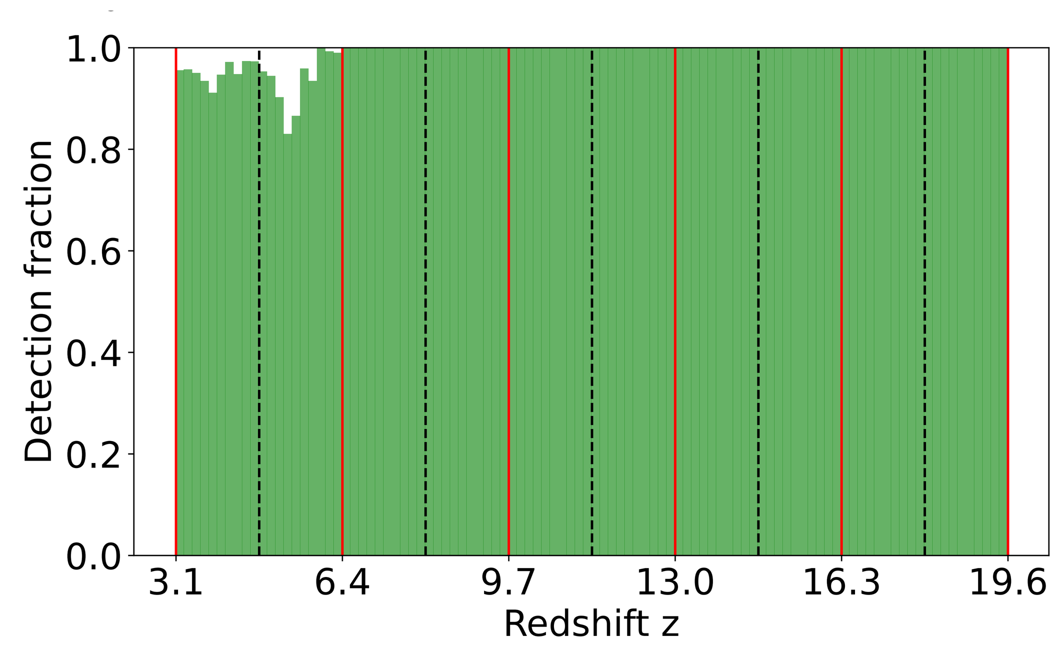
Each test set was constructed by pairing **one afterglow** (taken sequentially from the test-afterglow sample) **with 1,000 known sources** randomly selected from the test known-source sample, yielding a total of 1,001 objects per set.



From the point of view of on-board implementation, if the afterglow is selected correctly, it will not be a big problem even if some known sources are mistakenly selected as afterglow. However, in case that too many sources would be selected as afterglow, there will be a problem.

I first tested whether the afterglow was correctly extracted as an afterglow. As a result, I found that the prediction accuracy depends on the redshift of Afterglows, as shown in the figure below. The horizontal axis represents the redshift of the test afterglows, and the vertical axis represents the detection fraction, that is, the fraction of afterglows that were correctly selected as afterglows by the decision tree.

- The number of trials at each redshift is approximately 100.
- It was found that the method works effectively for z > 6.4.
- This is because the flux in Channel 1 (f1) is nearly zero in this redshift range.
- Note that these results correspond to an ideal case without considering noise.



Next, I investigated how many sources were selected as afterglows when 1,001 sources were input into the decision tree. The number was found to be 19 ± 4, which is considered to satisfy the constraints of the alert system.

4. Future Task

- Improving the detection fraction of GRB afterglows at 3.1 < z < 6.4.
- Implement the obtained decision tree in C to measure its execution time.
- Astronomical and systematic noise will be added to the fluxes to evaluate how the accuracy of the decision tree changes.

5. References

[1] Tsumura, Kohji, et al. "Concept of the MONSTER onboard the HiZ-GUNDAM satellite." Journal of Astronomical Telescopes, Instruments, and Systems 11.3 (2025): 034002-034002.

[2] H.M. Fausey et al. Photometric redshift estimation for gamma-ray bursts from the early Universe. Monthly Notices of the Royal Astronomical Society, Vol. 526, No. 3, pp. 4599–4612, December 2023