
LEAH HULVERSHORN ‘28

ORIGINAL RESEARCH

AIRIS: Pushing the Boundaries of GRB Optical Afterglow Observation

WashU Satellite
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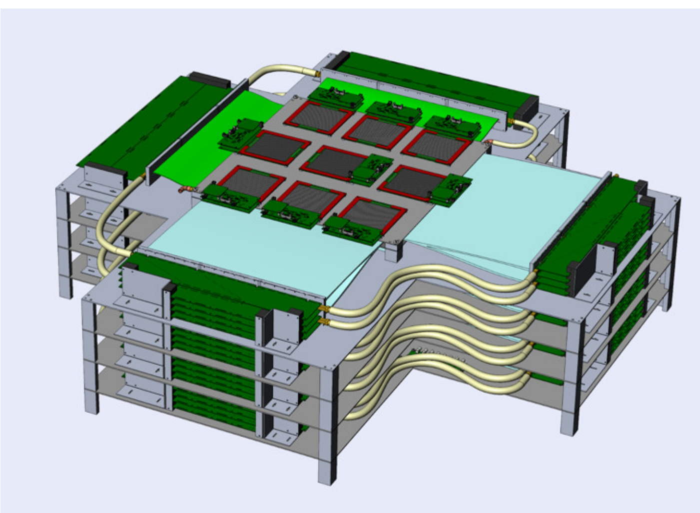
Gamma-ray bursts (GRBs) are the most energetic electromagnetic events in the universe, and although high-energy gamma-ray observations have provided significant insights, the mechanisms of GRB origins remain unclear. More study of their afterglows, the broad-spectrum radiation following a GRB, is required for further understanding. The Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT), a NASA mission led by James Buckley of the Washington University in St. Louis Physics Department, was developed to address this question. Using a high-altitude weather balloon over Antarctica, ADAPT is designed to demonstrate a Compton scattering detector for a future space-based gamma-ray and cosmic-ray observer. Planned for a December 2026 flight, ADAPT will provide unprecedented sensitivity and a wide field of view, producing localizations and polarization constraints on a few gamma-ray bursts (GRBs) in seconds. However, ADAPT alone cannot obtain precise GRB localization or capture optical afterglows, limiting its ability to fully capture these bursts. AIRIS (ADAPT Incidence Resolution & Imaging Subsystem) is an optical telescope mounted on the same platform as ADAPT with the ability to quickly reposition itself after a detection event. When ADAPT detects a gamma-ray burst (GRB), AIRIS quickly repositions itself, slewing at up to 30 degrees per second to refine the GRB's location and capture optical images of its afterglow. Due to the combination of ADAPT's rapid computing pipeline, the location of AIRIS on the same platform as ADAPT, and AIRIS' rapidly slewing mount, AIRIS is quickly able to observe the optical afterglows of GRBs. Furthermore, AIRIS' near-space vantage point, low-noise SONY CMOS sensor that produces clear, high-quality images, and large aperture 200mm f/1.8 lens, enables the observation of very faint signals. Through burst localization and time evolution tracking, AIRIS enables observations essential for studying GRBs' development. The data AIRIS gathers will feed into NASA's General Coordinates Network, guiding telescopes worldwide to observe GRB afterglows, contributing to multi-messenger astronomy.

Gamma-ray bursts (GRBs) are immensely energetic events in our universe, emitting intense gamma radiation. They are characterized into two types: short-duration GRBs, lasting less than two seconds; and long-duration GRBs, which can last from several seconds to a few minutes. Short-duration GRBs are thought to be the result of the merger of two neutron stars; long-duration GRBs are possibly associated with the collapse of massive stars into black holes. However, the true origin of GRBs remains uncertain [1]. Following the initial gamma-ray emission of a GRB, an afterglow is observed across the entire electromagnetic spectrum, including X-ray, ultraviolet, optical, infrared, and radio. The afterglow is a result of the interaction between the ejected material and the surrounding interstellar medium, which produces a shockwave that emits radiation. Studying GRB afterglows provides valuable insights into the characteristics of the burst, such as its energy, the environment surrounding the explosion, and the possible causes of these events [2].

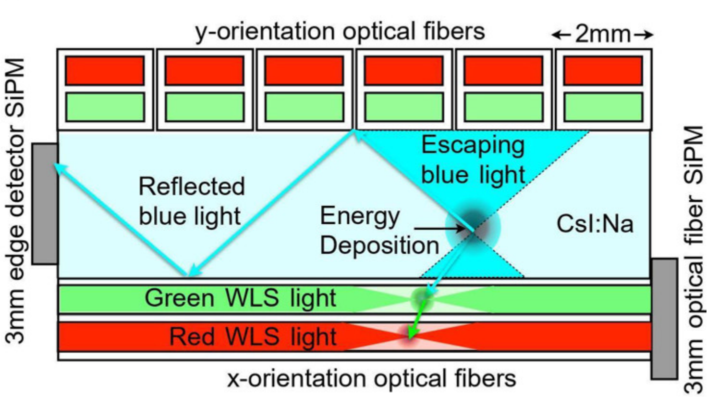
Scientists use multi-messenger astronomy to analyze transient events like GRBs. Multi-messenger astronomy is an approach that combines many observations from the same astronomical event. Astronomical events can have a variety of phenomena produced, each with categorically different kinds of "signals." For instance, a single astronomical event can produce light in wavelengths from radio to gamma rays, neutrinos, and gravitational waves. Each of these messengers requires an observational system dedicated to the detection of particular messengers, such as LIGO (Laser Interferometer Gravitational-Wave Observatory) for gravitational waves or VLA (Karl G. Jansky Very Large Array) for radio waves. GRBs are thought to produce light in all wavelengths from gamma to radio, typically in afterglow emission. By integrating data from diverse sources, scientists can study complex events, like GRBs, in greater detail.

ROTSE (Robotic Optical Transient Search Experiment) was designed to detect optical counterparts of GRBs in real-time. It gained prominence by capturing the first real-time optical afterglow of a GRB (GRB990123). The first system, ROTSE-I, consisted of a ground-based four-camera array using Canon 200mm f/1.8 lenses - the same lens used for AIRIS (ADAPT Incidence Resolution & Imaging Subsystem). Later, ROTSE-III systems were deployed globally with improved optics. Working with gamma-ray burst detection instruments such as Swift, ROTSE was able to react to hundreds of GCN (General Coordinates Network) notices and contribute key findings to astronomical research, helping to prove GRBs are of extragalactic origin [3].

ADAPT (Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope) is a multi-university NASA mission, led by Professor James Buckley of the Washington University Department of Physics, which plans to fly on a balloon over Antarctica in December 2026 to demonstrate technologies for the proposed future APT (Advanced Particle-astrophysics Telescope). Its detector is built from four layers of CsI:Na scintillating tiles with wavelength-shifting fibers in the x- and y-directions, which are read out by SiPMs (Silicon PhotoMultipliers) on a nanosecond time scale, as seen in Fig 1. The signals are amplified by ASICs (Application-Specific Integrated Circuits) and fed a set of FPGAs (Field-Programmable Gate Arrays), which preprocess the data, turning streams of detection counts into an "event" containing a set of information associated with a single gamma ray photon. This information is fed into a CPU (Central Processing Unit), which produces a maximum likelihood vector and a likelihood map. The vector will be calculated within 300ms of the burst occurring, with the full map estimated to take 1-2 seconds. This represents a major step forward from previous missions such as Fermi, which took 20 seconds to localize a GRB burst and transmit the signal to the ground. [4] However, due to the relatively small detector size and the location in the upper atmosphere, the 95% error box will be fairly large, ranging from 16° to 2°, for bursts of 0.5 and 4 MeV/cm2, respectively. These localizations will be fed into the NASA General Coordinates Network (GCN), which distributes them to ground-based telescopes for afterglow imaging, presenting an opportunity to study the afterglows at an unprecedented low latency [5].



(a) ADAPT detector overview [5, Figure 1]



(b) Cross-section of ADAPT detector tile [6, Figure 4]

Fig. 1 | The ADAPT instrument sensor

WashU Satellite, an undergraduate-led design team building space missions to solve research questions, has been working closely with the physics department to contribute AIRIS to the ADAPT mission. Founded a year ago, it has grown to a forty-five-person team including students from every undergraduate school at the university, as well as Masters and PhD students. The group is assembling and tuning a large 70 cm radio ground station to communicate with satellites; has two satellites in the proposal stage; and is spearheading the design, build, and testing of the AIRIS project.

Scientific and Engineering Goals of AIRIS

AIRIS is a fast-slewing optical telescope mounted on the same platform as ADAPT. AIRIS is designed to refine GRB localization sent by ADAPT and provide optical images of their afterglows. Consequently, AIRIS has several scientific goals.

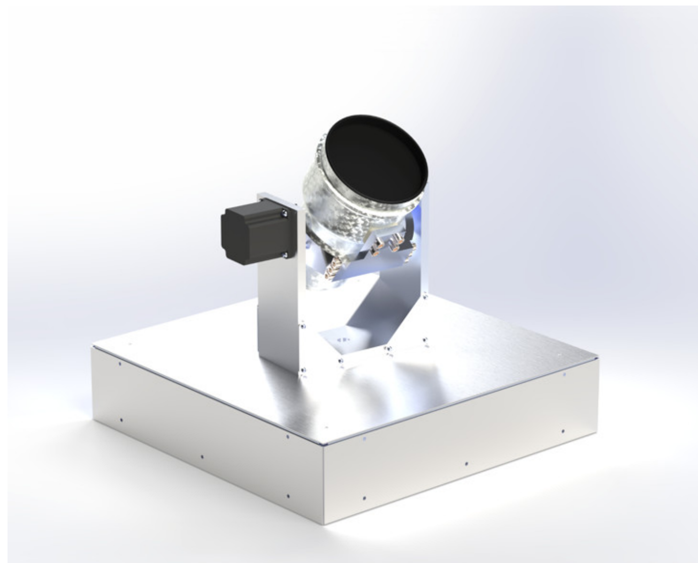


Fig. 2 | AIRIS preliminary structure CAD

Rapid GRB Afterglow Imaging

AIRIS aims to capture the optical afterglow of GRBs within 30 seconds, enabling early-time imaging that can reveal details about the GRB's energy, environment, and evolution. AIRIS can help fill observational gaps in the early phases of GRB afterglows.

Localization Refinement

AIRIS aims to improve the positional accuracy of the GRB detected by ADAPT. By comparing real-time sky images to its own star map, AIRIS can improve the positional accuracy of GRB events. AIRIS will then upload that location to NASA's General Coordinates Network to support multi-wavelength follow-ups by other telescopes.

Observation of Other Transients

While AIRIS is designed to imagine GRB afterglows, it is capable of observing other astronomical objects of interest, like active galactic nuclei (AGNs) or fast radio bursts (FRBs) visible in the southern hemisphere (i.e. blazar PKS 2155-304).

In addition to the astrophysics mission, AIRIS will demonstrate optimal search and control strategies vital to multi-messenger astronomy, in collaboration with postdoctoral fellow Marion

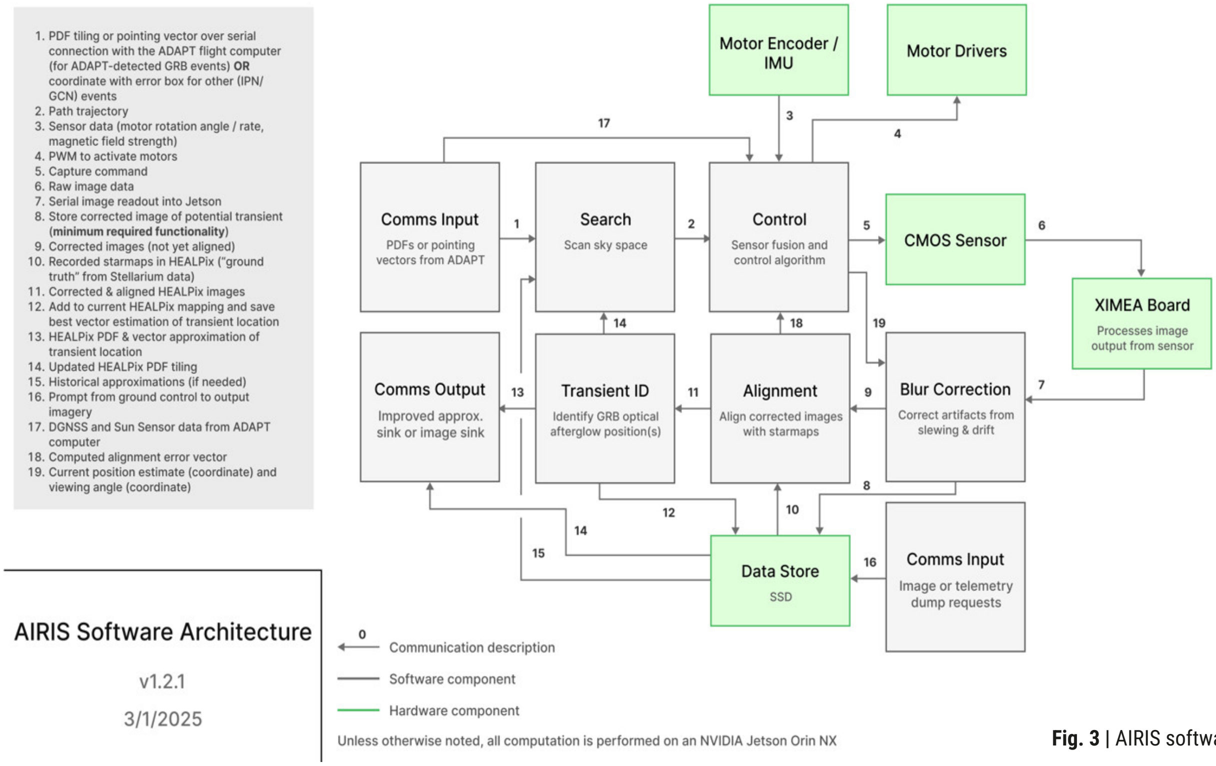


Fig. 3 | AIRIS software architecture

Sudvarg and Professor Andrew Clark of Electrical and Systems Engineering. For optimal performance, a search algorithm must plot a path to search through the probability density function given the expected event magnitude, imaging performance (noise, sensitivity, field-of-view, and resolution), and control system performance. This is a highly probabilistic problem that, if solved for a general case, could improve the performance of multi-messenger follow-on instruments. AIRIS will provide a real-world testing platform for these strategies.

Imaging

The AIRIS imaging system is designed around a Canon 200m f/1.8 lens graciously donated by Professor Buckley, which has excellent light gathering and low aberration, and has heritage from the first observation of GRB afterglow in the ROTSE experiment. [3] A band-pass filter is used to block imaging wavelengths outside of 645-675 nm. The high frequency cut blocks out blue/green colors, which are still bright in the arctic atmosphere and would reduce the image contrast. The low frequency cut blocks out near-IR and IR wavelengths, which do not focus properly through the lens and blur the images. The SONY IMX455 monochromatic CMOS sensor was selected for its high quantum efficiency, space heritage, large size, and single electron read noise, which is key to stacking many short-exposure images.

We aim to characterize GRBs occurring at magnitudes 12-20. Astronomical magnitude is a logarithmic scale where higher magnitudes signify lower luminosities and a difference of five in magnitude equates to a scale of 100x in luminosity. While GRBs are some of the most energetic events in the universe, they occur in extremely distant galaxies (z ~ 0.008 - 9.06 [7], corresponding to distances of 100 million - 20 billion light years). The extreme distances of these events cause GRB afterglows to have large redshift and low brightness, resulting in their high magnitude.

To calculate the limiting magnitude (the highest magnitude events detectable with our optical system), we rely on physically accurate Python simulations, to be confirmed with empirical measurements made with the sensor and lens at a later date. Simulating CMOS sensor data involves generating a star map with a random distribution of magnitudes and locations, gaussian point-spread functions, Poisson photon shot noise, and readout and thermal noise. Additionally, the script offers support for 3x3 pixel binning, moving exposures, cosmic ray sims, background sky signals from Rayleigh scattering, and SNR (Signal-to-Noise Ratio) calculations. An SNR of 2-3 is considered minimal for detection, and current simulations support SNR > 3 for signals of magnitudes > 15 at or above 10 seconds of exposure.

Images will be streamed from the CMOS sensor, through a carrier board, and into an NVIDIA Jetson GPU, which will execute the image processing. Each image will be taken with a short exposure to allow for rapid traversal of the sky space, and, once passed to the Jetson, will have motion blur removed and its alignment calculated relative to a stored star map. Star maps and accumulated imagery of the current observation period will be formatted with HEALPix, an equal-area spherical coordinate transform commonly used for similar imaging applications. The updated map will be compared to the stored star map and the ADAPT PDF (Probability Density Function) at each capture stage, searching for the optical GRB afterglow. Once a highly likely transient is identified, AIRIS will continue to observe the afterglow and send an alert to the General Coordinates Network for further observation.

Control

AIRIS will operate under a structured Concept of Operations (CONOPS), supporting multiple operational modes to optimize transient detection and follow-up observations. These modes will include idling, communication, fixed-target observation, observing a fixed target, and transient searching. The fixed-target mode will be primarily used for observing sources identified by ADAPT and other General Coordinates Network (GCN) notifications with small error boxes, ensuring rapid and precise follow-up of transients. Transient search mode will be used for real-time scanning of PDFs of potential locations. This mode will also serve as a testbed for detection algorithms. The choice between these modes will be adjusted based on mission priorities, with transient search serving as the default reaction to ADAPT alerts when no fixed targets are specified.

To ensure pointing and tracking performance, AIRIS will implement a path planning framework that governs slewing, stabilization, and targeting. The control system will optimize for three parameters: (1) slew rate, the rate at which AIRIS can reorient itself to capture afterglows within the required response time (30 seconds or less); (2) settle time, the time required for AIRIS to stabilize after slewing, minimizing jitter; and (3) pointing knowledge and accuracy, the ability to maintain sub-arcsecond precision in localization, allowing for refined position of bursts.

AIRIS will use a combination of positioning sensors for attitude determination and control. Coarse pointing determination sensors include, (1) two internal measurement units (IMUs) to provide data to support attitude control and stabilization; (2) two magnetometers to measure Earth's magnetic field for attitude determination; and (3) motor encoders to provide feedback on actuator positions. Fine pointing knowledge will be determined from the alignment data of the image processing pipeline. Furthermore, the ADAPT gondola is equipped with a sun spotter and a Differential Global Navigation Satellite System (DGNSS) that AIRIS can access to gain information for the platform's location and orientation.

AIRIS will use vacuum-rated stepper motors for telescope pointing and reaction wheels for counter-torque mechanisms, ensuring rapid and accurate pointing while minimizing disturbance to the ADAPT platform. The AIRIS optical system is designed for azimuth and elevation rotation, allowing full sky coverage. Due to cabling constraints, the lens assembly will not spin continuously but remains capable of covering all necessary orientations. AIRIS is designed to operate without a gearing system, minimizing the complexity and mechanical play in the control system.

Support Systems

The ADAPT platform will provide AIRIS with power, communications, a thermal sink, and mounting points. AIRIS will include a power distribution network to regulate and step down voltage levels for the various mission systems. Communications, including OTA software updates, debug and status information, GCN likelihood updates, and science data downloads will be sent over TCP/IP through the ADAPT Starlink connection when AIRIS gets communication bandwidth.

The AIRIS structure provides mechanical support for the imaging and computational missions by creating a thermally regulated electronics enclosure section for all stationary components and a moving frame for the lens to allow for full sky coverage. Both sections are designed to maintain component functionality in ADAPT's high-altitude near-vacuum conditions, stay within the 20 kg mass limit, and integrate seamlessly with the larger ADAPT gondola structure. Currently most all structural components will be made of 6061 aluminum, a high strength-to-weight ratio alloy with significant spaceflight heritage. Finite element analyses of all structural components are conducted in SolidWorks to ensure proper factors of safety to avoid any mechanical failure under static or slewing conditions. Vibration damping systems are also under consideration to protect AIRIS and its imaging system from disturbances to the ADAPT gondola such as vibrations from ADAPT's fluid cooling pumps.

The thermal management system is responsible for keeping the AIRIS enclosure at the desired temperature range, preventing electronics from freezing in the harsh Antarctic conditions or overheating from their own heat generation. Due to the low density of the air encountered by high-altitude atmospheric balloons, the heat transfer apparatus will make use of conduction as its sole means of exchanging thermal loads. The system was modeled to take advantage of ADAPT's rotation, which keeps one of the gondola's sides permanently facing the sun, allowing the enclosure to be modeled with a hot sun facing side and a cold shaded side. The hot side will use solar radiation and Antarctic albedo as a heat source, while the cold side will be insulated to diminish the thermal gradient inside the enclosure, ensuring that the system does fall below any component's minimum operable temperature. The heat inside the structure will be conducted out by heat pipes that use the ADAPT frame as a heat sink, keeping the assembly within the required range for optimal operation. Flexible heat straps are used on the AIRIS-ADAPT connection to diminish vibration and mechanical stresses on the heat transfer apparatus. High fidelity thermal simulations will be performed to accurately choose the absorptivity of the sun side coating material and properly dimension the heat pipe system.

Risks & Development Plan

AIRIS's most critical risk is the potential to disrupt the primary ADAPT mission. Since AIRIS shares the same balloon platform, power, and communication systems as ADAPT, any malfunction that consumes excess power, uses too much bandwidth, or competes for the platform's limited resources could interfere with ADAPT's primary objectives. To mitigate this risk, ADAPT will have the ability to power down and/or sever the communications link to AIRIS if any anomalous behavior occurs. Furthermore, current limits, bandwidth allocations, and operational protocols will be established to minimize risk and clearly define anomalous behavior. Additionally, an analysis has confirmed that the momentum shift of the rotating telescope will not cause excessive oscillations on the main ADAPT platform.

A second major category of risk involves internal AIRIS malfunctions, including but not limited to thermal failure, mechanical failure, electrical component failure, imaging system failure, and software failure. These risks will be mitigated through rigorous simulation, prototyping, and a test campaign including component- and system-level thermal vacuum testing. Based on previous balloon flights with consumer lenses, key risks to the imaging system include: dust/moisture contamination, the off-gassing and recondensation of materials and coatings onto the lens or camera sensor surface, and the rapid expansion of gas trapped within the lens, leading to catastrophic failure of the optical elements and/or lens housing [8]. To mitigate these risks, the optical system will undergo rigorous vacuum testing, include onboard brushes for dust mitigation, and use carefully selected materials across the payload to minimize off-gassing.Through these strategies, AIRIS aims to maintain its own primary mission while ultimately protecting the primary mission of ADAPT.

Primary AIRIS development timeline began in October 2024 with preliminary design and trade studies, where the team made key architecture decisions and defined module-level requirements. Preliminary design reviews (PDR), where engineers responsible for each component and module present their ideas before having them reviewed by peers and the executive team, occurred in December 2024 and February 2025. After passing the PDR, the team begins prototyping each module. This phase includes developing a fully functional prototype payload, which will undergo component- and system-level performance and environmental testing, followed by a final design review (FDR) in May 2025. After the FDR, an updated prototype will be built and tested, culminating in a full thermal vacuum integration test alongside the ADAPT payload in October 2025. Following this phase, final flight hardware will be manufactured, and software will be implemented for a Flight Readiness Review (FRR) in Spring 2026 in preparation for full integration in Summer 2026. In December 2026, AIRIS will enter the launch and operations phase. Before ascent, it will undergo final checkouts and over-the-air (OTA) software updates, after which it will begin its primary mission. During the flight, telemetry and science data will be downlinked via Starlink, while the engineering team monitors the payload's health based on the data. If necessary, software updates will be transmitted over the air to optimize performance or troubleshoot malfunctions. Localization data will be sent to the NASA GCN. Post-flight, scientific analysis of the experiment data and performance assessment of the payload will be conducted in collaboration with the ADAPT team.

Conclusion

AIRIS presents a unique opportunity to observe GRBs and other high-energy phenomena, while also building knowledge about transient multi-messenger astronomy. AIRIS offers unprecedented rapid optical afterglow observation as a result of its proximity to ADAPT, ADAPT's fast computing pipeline, and its rapidly slewing mount design. The near-space vantage point and high performance sensor and optics on AIRIS enable observation of very faint signals. Much development work remains, including imaging, search, and control algorithms, communications and command software, power and structural support systems, and a detailed test campaign to ensure the system meets performance and longevity requirements in a near-space environment without endangering the primary ADAPT mission. Overcoming these challenges will allow for an exciting collaboration between the WashU Satellite team and the ADAPT mission, led by Professor James Buckley of the WashU Department of Physics.

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