LLNL-CONF-865429

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Deep Purple Payload Qualifies for NASA Launch, Could Provide New Method for Real-Time Space-Domain Awareness

J. Smilo, F. Ravizza, J. Ganino, J. Karburn, L. Simms, D. Carter, P. Corral, M. Wong, A. Godfrey, B. Bauman, C. Houldin Hatala, R. Fellini, L. Hagler, W. De Vries, A. Pertica, B. Bahney

June 10, 2024

Small Satellite Conference - SmallSat
Logan, UT, United States
August 3, 2024 through August 8, 2024

SSC24-III-08

Deep Purple Payload Qualifies for NASA Launch, Could Provide New Method for Real-Time Space-Domain Awareness

Jordan Smilo, Frank Ravizza, John Ganino, Jordan Karburn, Lance Simms, Darrell Carter, Princess Corral, Michael Wong, Aaron Godfrey, Brian Bauman, Cohl Houldin Hatala, Ryan Fellini, Lisle Hagler, Wim De Vries, Alex Pertica, and Ben Bahney
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550; 1-925-424-4833
smilo1@llnl.gov

ABSTRACT

In January 2024, the Lawrence Livermore National Laboratory (LLNL) Space Program fully assembled and qualified its Deep Purple payload. It will be on board NASA's Pathfinder Technology Demonstrator-R (PTD-R), scheduled to launch on the SpaceX Transporter 11 in July 2024.

The Livermore team designed, developed, qualified, and delivered the Deep Purple payload in approximately one year and has now been integrated into the PTD-R satellite, a 6U (36 cm x 23 cm x 10 cm) bus constructed by a Laboratory Collaborative Research and Development Agreement (CRADA) partner Terran Orbital.

NASA's Small Spacecraft Technology Programs' PTD-R space vehicle containing the Deep Purple payload was developed to replace an earlier NASA technological demonstration (PTD-2). LLNL utilized this opportunity to rapidly prototype a payload utilizing a new design for LLNL-developed ultra-violet (UV, 230nm – 310nm) and short-wave infrared (SWIR, 1000nm – 1700nm) monolithic Cassegrain telescopes.

Deep Purple will demonstrate LLNL's monolithic UV and SWIR optical sensing platforms from space for the first time via two co-boresighted, 85mm aperture telescopes. A new compact electronics module and a novel, lightweight, carbon-composite optical housing and radiator save considerable weight, cost, and lead time while boosting optical performance. The dual optical module and the electronics are contained in a 23 cm x 15 cm x 10 cm package (about the size of a loaf of bread).

The Deep Purple payload showcases the rapid development, test, and build cycles needed for responsive space missions. The modular optical housing developed for PTD-R allows future missions to rapidly integrate and gang telescopes for an even quicker time-to-flight. What traditionally takes years can now be accomplished in just a few months.

Once operational, Deep Purple will perform simultaneous UV and SWIR observations from high-UV stars and the Milky Way's galactic bulge. Furthermore, it will attempt to capture time-domain galactic and extra-galactic events as well as demonstrate real-time space domain awareness using these unique sensing bands. The Space Program at LLNL continues to demonstrate its leadership in developing and delivering small satellite tools and capabilities.

RESPONSIVE SPACE

Lawrence Livermore National Laboratory (LLNL) has designed and deployed a wide range of space systems throughout the decades. In the last ten years, the LLNL Space Program focused on hardware development for rapid time-to-flight optical payloads. Furthermore, these advancements inherently reduce payload volume, relative mass, and cost. What used to take three to five years for development and flight can now be accomplished in as little as one year.

NASA's Pathfinder Technology Demonstrator (PTD), led by the Small Spacecraft Technology Program located at NASA's Ames Research Center, is a series of missions that offer the opportunity to rapidly test new concepts with a dedicated bus. Each mission in the PTD series will use a Terran Orbital 6-unit (6U) Trestles bus to greatly reduce the spacecraft design time.[1]

LLNL was approached to rapidly develop a technology demonstration mission as a replacement for PTD-2. PTD-R is in perfect alignment with the core competencies of the LLNL Space Program – to deliver responsive and innovative optical payloads for small satellites.

HARDWARE DEMONSTRATION

Several technologies were developed or demonstrated specifically for the Deep Purple mission. These include the SWIR and UV telescope variants, the SWIR and UV sensors, the compact onboard electronics, a modular carbon fiber telescope housing, and a carbon fiber radiator panel.

The Monolithic Telescope

The monolithic telescope is a Cassegrain design where the primary and secondary mirrors are contained within a single piece of fused silica. This completely removes the difficulty in designing, producing, and maintaining the precise alignment of a metering structure. This design affords significantly reduced tolerances and when coupled with a proven manufacturing process, diffraction-limited performance is achieved. Once the telescope is produced, the alignment of all mirror and optical surfaces are preserved indefinitely and are considered "shelf stable". Additionally, since both mirror surface coatings face inwards to the solid telescope, the cleanliness of the mirrors also remains pristine.

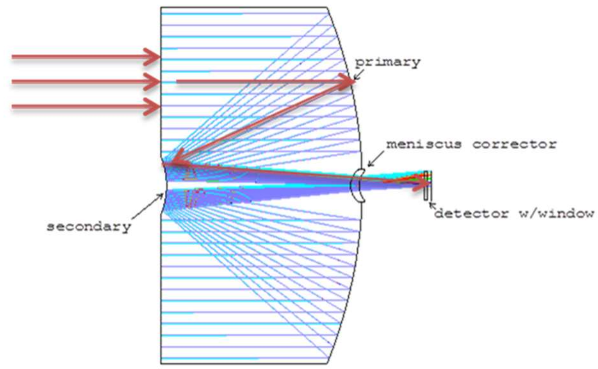

Figure 1: Ray Tracing Diagram of a Monolithic Telescope

This technology was invented at LLNL[2,3] and has been utilized on a host of missions including GEOStare SV2[4], Tactically Responsive Launch-2 (TacRL-2)[5], and the Stellar Occultation Hypertemporal Imaging Payload (SOHIP)[6] to name a few.

The PTD-R mission advanced the monolithic telescope from the visible spectrum into the ultraviolet (UV) and short-wave infrared (SWIR) and sets to prove their capabilities for use in space. Based on specific mission interests, the 230 – 310 nm band was selected for the UV telescope and 1000 – 1700 nm for the SWIR telescope. Due to the UV sensitivity deep into the electromagnetic spectrum, the optical payload was fondly named Deep Purple.

The achromatic design of the telescope allows both the UV and SWIR telescopes to share an identical prescription to their visible counterpart. Therefore, the telescope design time was greatly reduced and only mirror coatings and anti-reflective coatings required updates.

Further details can be found in Table 1 below.

Table 1: Deep Purple UV and SWIR Telescope Properties

PAYLOAD PROPERTIES	UV	SWIR
Telescope	**V3U**	**V3S**
Clear Aperture (mm)	85	85
Focal Ratio (f-number)	f/3.6	f/3.6
Focal Length (mm)	306	306
Obscuration by Area (%)	12.5	12.5
Light collection area (cm^2)	50	50
Focal Plane Array	**IMX487**	**IMX990**
Type	CMOS	InGaAs
Pixel Pitch (micron)	2.7	5.0
X Pixels	2848	1096
Y Pixels	2848	1032
Camera	**Alvium Custom**	**Alvium 1800 U-130**
Shutter Type	Global	Global
Max Bits	12 bits	12 bits
Interface	USB 3.0	USB 3.0
Dimensions, L x W x H (mm)	30x27x14	30x27x14
Mass (g)	65	65
Imaging		
IFOV (urad)	8.8	16.3
GSD (m) @ 500km	4.4	8.2
X Field of View (degrees)	1.44	1.03
Y Field of View (degrees)	1.44	0.97

First-to-Flight Sensors

Traditionally, UV and SWIR sensors have been exceedingly expensive and perhaps prohibitive for smaller missions. The recent developments and ubiquity of CMOS sensor technology reduces the cost, increases availability, and enhances performance in the visible and UV bands. LLNL was able to purchase a Sony IMX487 prototype sensor which is a CMOS sensor with enhanced sensitivity in the UV spectrum. This sensor has significant sensitivity in the visible spectrum so filter selection is critical. To ensure only UV light is measured, a filter with a bandpass of 230 – 310nm and an optical density of 4 in the visible spectrum was selected.

Infrared sensors typically require a cryocooler which adds significant complexity, weight, and cost. The IMX990 sensor small pixel sensor uses indium gallium arsenide (InGaAs) photodiode technology to offer high sensitivity in the SWIR wavelength without the need of a cryocooler.

Deep Purple is set to be the first payload to demonstrate the IMX487 and IMX990 sensors on a space vehicle.

Onboard Electronics

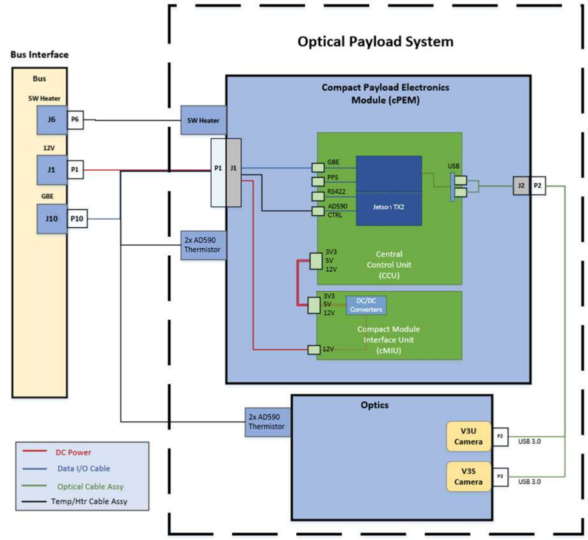

Figure 2: Deep Purple Payload System Block Diagram

The Deep Purple Optical payload utilizes a customized Compact Payload Electronic Module (cPEM) specifically designed to provide control and image processing for the SWIR and UV sensors within the 2U footprint allowed by the mission. The cPEM is based on LLNL's heritage Payload Electronics Module, but efficiently matched the functionality needed for the payload (shown in Figure 2) with the 4cm x 10cm footprint available.

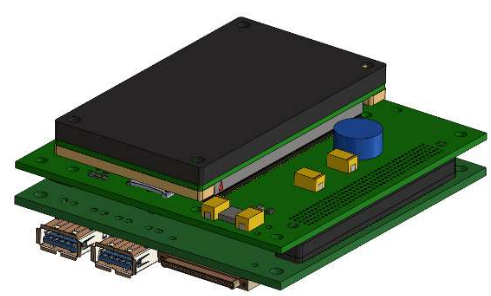

Figure 3: cPEM with Structure Hidden

The cPEM (shown above in Figure 3) is composed of two board-level units:

Central Control Unit (CCU): Designed and fabricated by a partner vendor. Hosts Nvidia TX2i system-on-module controller with 28 GB of internal storage for images. The cPEM communicates with the Bus over gigabit ethernet (GBE) while the Cameras operate over USB 3.0.

Compact Module Interface Unit (cMIU): This unit hosts the connectors for inter-module harnesses between the CCU, cameras, and thermal sensors.

The cPEM has a peak power of 15W and averages 9W during normal operations. Figure 4 below demonstrates the power usage over a typical two-camera imaging operation.

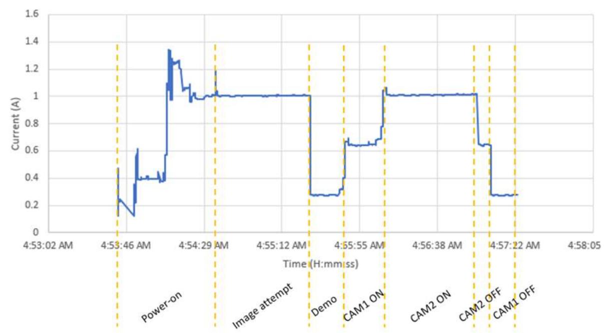

Figure 4: cPEM Current Profile, UV & SWIR Cameras

Modular Carbon Fiber Housings

A key sensitivity to optical systems is in the alignment of the mirror surfaces and sensor. Using the monolithic telescope design fixes the alignment between the mirror surfaces so only the relative position of the sensor face needs to be precisely set and maintained. Traditionally, a large structure made from a high stiffness and low coefficient of thermal expansion (CTE) material is required. Invar 36, a 36% nickel-iron alloy, has a near-zero CTE and is a common choice for optomechanical designers. Unfortunately, a very high temperature heat treatment is required to anneal the material to gain dimensional and temporal stability. Furthermore, additional heat treatments are required throughout the machining process to remove the induced stress of machining. This adds significant cost and time.

LLNL partnered with Patz Materials and Technologies (PMT) to replace the Invar 36 parts with their high strength carbon fiber[7]. Their PMT-F16 HM63+CNT material uses a carbon nanotube loaded resin and high strength carbon fiber to make a unidirectional prepreg sheet. LLNL and PMT have developed several optical housing designs which reduce lead time, weight, and cost while maintaining strength and stiffness. Such intentional design is demonstrated on the modular Deep Purple telescope housings.

The unidirectional prepreg sheet is chopped into confetti and placed in random orientations within the mold to optimize for low CTE along the direction of the fibers. The top and bottom half of the mold joins to the bottom half under high heat and pressure to spread the confetti and cure the part. This compression mold forms half of the final telescope housing. Two identical halves are molded, the mating faces machined to fit flush, then the two halves are joined, and all final machining is performed. These steps can be seen in Figure 5.

The two housing halves are fastened together using #4 flathead screws. The female threads use a helical insert within the carbon part. Ideally, threads should not be tapped into carbon fiber parts since the fibers are cut in the process. However, these fasteners are used strictly for alignment during telescope and payload assembly. Once the payload is fully assembled, the payload structure keeps the telescope housing under compression and the fasteners are no longer structural. The carbon fiber housing was vibration-tested using aluminum mass surrogates for the optic as well as the forward and aft components which attach to the housing. A peak level of 20.0 Grms (+3 dB) was selected to provide sufficient margin beyond the 14.1 Grms test level of the NASA General Environmental Verification Standard (GEVS)[8] qualification spectrum. The housing survived all three axes with no signs of wear.

When compared to the Invar 36 housing (406g), the carbon fiber housing (135g) ends up saving a total 542g for the payload. The Terran Orbital Trestles bus affords a generous 5 kg payload mass budget but fitting two monolithic telescopes and the associated electronics proved to be a difficult target to meet. The carbon fiber housings provided the necessary margin to proceed with the design.

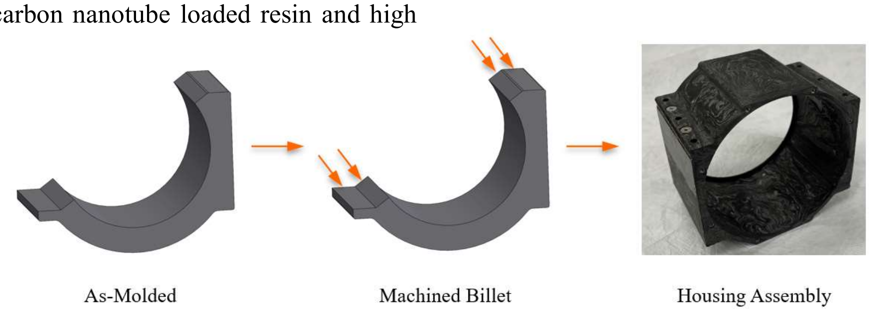

Figure 5: Carbon Fiber Optical Housing Manufacturing Process

Carbon Fiber Radiator Panel

PMT has also developed a high thermal conductivity fiber using a pitch-based carbon fiber and a higher concentration of carbon nanotubes. This novel use of carbon fiber afforded another area to reduce weight and boost performance. The electronics have a few components which need to reject heat including the onboard processor, the NVIDIA Jetson TX2i.

The baseline design used an aluminum radiator panel which is bonded directly to the processor's housing. Our lab testing showed that carbon fiber can be used as a drop-in replacement which cuts the weight in half, saving an additional 73g. This high thermal conductivity material is also high strength and low CTE. The demonstration of this carbon fiber radiator, shown in Figure 6, may lead to a multifunctional (structural and thermal) structure which stands to further save weight, complexity, cost, and lead time for future missions.

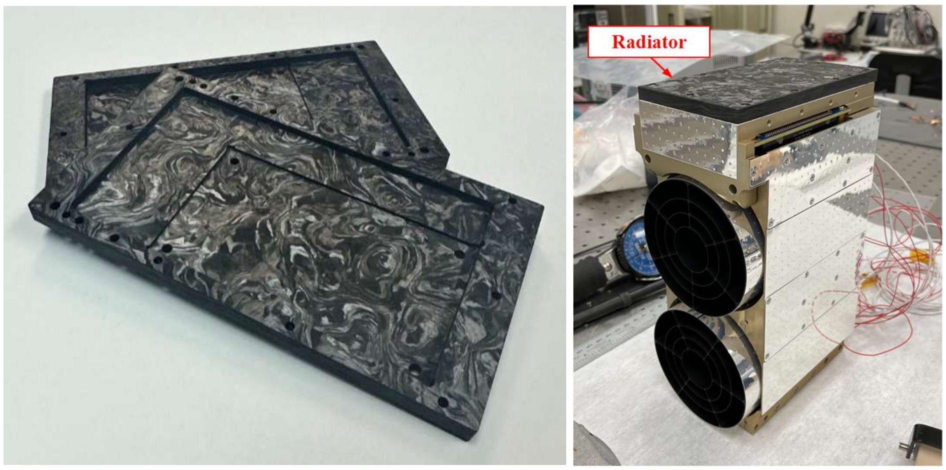

Figure 6: Left - Carbon Fiber Radiator, Right – Radiator Installed On Deep Purple Payload

MISSION DEMONSTRATION

UV and SWIR capabilities onboard a single spacecraft offer great utility. This mission utilizes several modes of operation which may use either telescope or both simultaneously. Capturing simultaneous imagery affords the a like-for-like comparison between a known SWIR response to a potentially unknown UV response.

PTD-R Mission Concept of Operations

UV Star Survey – This mode initiates an inertial pointing submode on the spacecraft to allow long exposure imagery. Though this mode is intended mostly for the UV telescope, the SWIR telescope or both may be selected. Primary targets include several within the Galactic Bulge (M3, NGC 2808).

Earth Imaging – This mode points to a specified ground target and keeps the spacecraft aimed at it as long as commanded. The SWIR telescope will be the primary tool in this mode since UV is entirely scattered or absorbed in the atmosphere. Still, the SWIR telescope has significantly improved performance when looking through atmospheric turbulence and light cloud cover compared to a visible counterpart.

Nadir Tracking – This mode points the telescopes directly "downwards" towards Earth's center and maintains this alignment. A series of pictures when stitched together would offer a low distortion swath of Earth's surface.

Satellite Tracking – This mode processes a Two-Line Element set (TLE) and employs a Resident Space Object (RSO) tracking submode to track a known satellite's location. In doing so, the satellite of interest will appear in the same relative spot in the series of pictures. Both UV and SWIR telescopes may be used for this mode.

CONCLUSION

The LLNL Space Hardware Team designed, built, and delivered the Deep Purple payload in approximately one year and under $1M. It was seamlessly integrated on Terran Orbital's 6U bus, and it's set to launch in July, 2024. The larger PTD-R team at NASA, Terran Orbital, and LLNL all eagerly await the commissioning and mission demonstration which will lower the cost and schedule barrier to UV and SWIR scientific observations and space domain awareness. True to the spirit of the NASA Pathfinder Technology Demonstration mission objective, the PTD-R spacecraft stands to be the most technologically advanced CubeSat to launch to date.

Figure 7: The Deep Purple Team and Payload

Team members: (left to right) Princess Corral, Collin Averill, Peter Heatwole, Noemi Fortes, Ryan McRae, Ryan Fellini, Frank Ravizza, Michael Wong, Cohl Houldin Hatala, Benjamin Bahney, Lance Simms, John Ganino, Jordan Smilo, Darrell Carter, Brian Bauman, and Aaron Godfrey; Not shown – Wim De Vries, Lisle Hagler, Owen Alford, Christian Tolfa, Tiffany Yslas, Connie Ruvalcaba-Olson, and Erika Lopez

ACKNOWLEDGEMNETS

Great thanks are owed to the NASA Ames PTD project team led by David Mayer for their technical oversight and eagerness to ensure a successful mission. Further gratitude is due to the NASA Small Spacecraft Technology Program (SSTP) for making this opportunity a reality for LLNL.

Terran Orbital has a long history of working with LLNL as a CRADA and mission partner. The Terran Orbital PTD team, led by Christopher Laurent and Kyle Kung, exemplifies a successful partnership which is reflected in the high quality of the PTD-R spacecraft. The LLNL space program extends their gratitude and looks forward to the continued success in the PTD-R mission operations and future missions to come.

A special thanks goes out to Nick Patz, Tom Doolittle, and Jessie Bernhard at Patz Materials and Technologies who have all been instrumental in the development and success in the use of space-qualified carbon composite materials.

REFERENCES

1. S. Caldwell and A. Bowman, "Pathfinder Technology Demonstrator (PTD)" https://www.nasa.gov/mission/pathfinder-technology-demonstrator-ptd/, accessed 11/2023.
2. V. Riot, B. Bauman, et. al., "Integrated Telescope Assembly," U.S. Patent 9,720,223, Aug. 1, 2017
3. B. Bauman, A. Pertica, "Integrated Telescope for Imaging Applications," U.S. Patent 10,935,780, Mar. 2, 2021.
4. Terran Orbital Corporation, "GEOSTARE SV2" https://terranorbital.com/missions/geostaresv2/, accessed 6/2023.
5. S. Wampler, "LLNL's Tactically Responsive Launch-2 payload launched into orbit" https://www.llnl.gov/article/47746/llnls-tactically-responsive-launch-2-payload-launched-orbit, accessed 7/2021.

6. S. Wampler, “LLNL’s prototype telescope now fully operational aboard the International Space Station” https://www.llnl.gov/article/50081/llnls-prototype-telescope-now-fully-operational-aboard-international-space-station, accessed 8/2023.
7. G. Gardiner, “Composite molding compound replaces Invar for lightweight small satellite structures” https://www.compositesworld.com/articles/composites-molding-compound-replaces-invar-for-lightweight-small-satellite-structures, accessed 10/2023.
8. NASA Standard, “General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects”, GSFC-STD-7000 Ver. B.