Tracking and Recovery of the LOFTID RV

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The LOFTID mission launched from Vandenberg on Nov 10, 2022, and successfully demonstrated the reentry of a 6m diameter inflatable aeroshell from low Earth orbit. This paper will cover the design features implemented to enable recovery of the flight vehicle, and will discuss the splashdown calculations, in-flight tracking, recovery from the ocean, and post-flight inspection of the flight vehicle.

I. Overview

The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) was the first reentry from orbit of NASA's stacked-torus Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology, and at 6m diameter was the largest blunt body aeroshell ever flown. It was a follow-on mission to several previous suborbital tests that demonstrated the ability to maintain the structure at the design pressure through reentry and descent, and aerodynamic stability across the flight regimes from hypersonic through subsonic and splashdown. LOFTID demonstrated HIAD's ability to survive reentry heating at levels relevant to Mars entry and Earth return flights.

LOFTID launched late on Nov 10, 2022, from Vandenberg Space Force Base, as a secondary payload on the Atlas V carrying the Joint Polar Satellite System 2 (JPSS-2) to orbit. After delivery of the weather satellite, the Centaur upper stage maneuvered to LOFTID's reentry trajectory, then jettisoned the structural adapter that had supported the primary payload, giving LOFTID room to inflate its reentry aeroshell. While still attached to the Centaur, LOFTID deployed from its stowed launch configuration and inflated to full size.

Centaur upper stages typically deorbit and burn up in the atmosphere, with any surviving debris splashing down in remote parts of the ocean. For LOFTID, this approach was modified slightly, with the Centaur deorbiting onto LOFTID's desired reentry trajectory, releasing the reentry vehicle (RV), then performing an additional divert maneuver. The divert maneuver was needed to remove the chance of a collision, since the RV with its low ballistic coefficient would slow significantly upon reaching the atmosphere while the Centaur would not.

Due to JPSS-2's required sun-synchronous orbit, the Centaur launched late in the evening to a near-polar orbit, and splashdown sites near the continental North America would not be available for several orbits. The team selected a splashdown location about 550 miles east of Hawaii, positioning the Centaur debris footprint in an acceptably remote location with the LOFTID footprint still being reachable from an American port. With approximately 2 hours 5 minutes flight time from launch to splashdown, the LOFTID RV would splash down several hours before dawn, causing RV recovery operations to occur in the dark.

The LOFTID RV carried two data recorders: one that stayed on the vehicle, and a second ejectable data recorder (EDR) that would be released from the RV after the end of reentry. The EDR was buoyant, bright yellow, hardened to survive splashdown, and equipped with a locator beacon that would transmit for at least 30 days to ensure that even if the sea state was so rough that the RV sank on splashdown the reentry performance data and video would still be recovered.

Recovery of the LOFTID hardware after splashdown was made possible by our partner United Launch Alliance (ULA), who rented the offshore supply vessel Kahana II from Honolulu's P&R Water Taxi for the mission. The 220' Kahana II had a flat cargo deck 138' long by 37' wide, giving us plenty of space for the 20x20' recovery stand that would support the RV once it was hoisted onto the ship. The onboard knuckle boom crane was rated for 6000 lbs, at a full extension of just over 40', giving us more than enough capacity to lift the RV unless it was totally waterlogged; the ship also had bow and stern station-keeping thrusters enabling it to maintain position near objects in the water during operations. The ship's 10-knot cruising speed meant that we would need over 2 days to travel between the port and the predicted splashdown site, so departure was planned for 2½ days before launch to provide sufficient time to get the ship on station.

Fig. 1 Kahana II

II. Monitoring LOFTID in Flight

ULA placed an additional video camera on the Centaur to monitor deployment of the primary payload; the camera's position would fortunately also allow it to monitor LOFTID's inflation and release. Available bandwidth was limited, but we were able to select coverage windows that allowed observation of all the planned LOFTID events on the Centaur. An estimated 15-minute downlink delay meant that the video would not be available in real-time, but it would still allow confirmation of RV inflation and separation before the start of active recovery operations.

After releasing the RV, the Centaur would transmit an Orbital Parameter Message (OPM) including the as-released trajectory of the RV. This would be used to update the predicted splashdown ellipse, removing launch uncertainties from the calculations and further reducing the ellipse size. This update would reach the recovery team while only shortly before splashdown, but every improvement in the predictions would be welcome.

To eliminate any possible electrical or electromagnetic interference with the delivery of the primary payload, LOFTID remained powered off until after the primary payload was released and the subsequent Centaur maneuvers and deorbit were complete. Even once powered on, LOFTID made no transmissions until 10 sec after release from the Centaur. At that point, LOFTID's Real-Time Beacon (RTB) began transmitting position & velocity data, along with a limited amount of engineering and flight performance data, approximately every 20 seconds. The RTB used the Iridium Short Burst Data protocol, which transmitted a limited data volume through the Iridium satellite network to stations on the ground. The Iridium system had a reported lag of up to 5 minutes depending on satellite position, but the data would provide trajectory information as the RV coasted from separation to atmospheric interface, through reentry and descent.

To ensure that the recovery team could safely approach the RV after splashdown, the inflation system's pressurized nitrogen tanks would be vented once reentry was complete. Confirmation of the vent command and the resulting pressure drop in the inflation tanks, along with firing confirmation for the RV's pyrotechnic devices and the release of the EDR, were included in the RTB data steam. Additional confirmation of the pyrotechnics' activation would be obtained visually: aeroshell inflation would indicate that the launch restraint cutters had fired, parachute deployment would indicate that the parachute gas generator had fired, and the absence of the EDR from its launch tube would indicate its spring energy was no longer a concern. Hang-fires of redundant pyro cutters on the launch restraint could still occur but would only be a danger to items that could fit into 1/8" diameter cutter hole; the possibility of a cutter failure, where the cutting blade shoots out the end of the cutter, was dealt with by pointing the end of the cutter at a solid metal mounting block. Hang-fire of the redundant parachute initiator were handled by having the recovery team avoid the path outward from the pilot mortar, where the exhaust of any late-firing initiator would exit.

Shortly after sending the confirmation data, the RTB would be powered off and a self-contained Locator Beacon (LB) derived from the EDR would be powered on in its place. While this transmitter change removed our real-time access to vehicle performance during descent, it was necessary to permit location of the RV after splashdown, when the RTB and other RV electronics were expected to be disabled by submersion in salt water. The full set of vehicle performance data would be available in the RV's internal data recorder in any case.

Additional monitoring of the RV's reentry would be provided by the SCIFLI LOFTID Imaging Mission (SLIM), which deployed several of SCIFLI's radiometers & spectrometers on a NASA Gulfstream IV aircraft to observe the LOFTID reentry. (Detailed in appendix.)

III. Splashdown Ellipse

The predicted two-sigma splashdown ellipse for the RV was long and narrow at approximately 57 miles by 11 miles, with the long axis tilted to the northeast. The footprint for the Centaur debris would fall further north, almost entirely outside the LOFTID footprint. However, the predicted amount of overlap varied, with less overlap at the start & end of the launch window, and slightly more overlap if the Atlas launched toward the middle of the launch window. Given the small size of the recovery ship compared to the splashdown ellipse, calculations indicated that the odds of debris or the RV impacting the ship would be acceptably low (under one in a million) at the start or end of the launch window, even with the ship positioned in the center of the ellipse. With the Atlas launch nominally planned for the start of the launch window, it was agreed that we would initially position the ship at the center of the ellipse for speed of recovery after splashdown. If the Atlas launch occurred toward the middle of the window, we would have just over two hours to move the ship outside the ellipse, returning for recovery after a brief period to allow the debris to splash down.

The splashdown calculations for LOFTID were updated regularly as the launch date approached. The atmospheric model uncertainties shrunk as the number of days to launch steadily decreased, causing the predicted footprint to decrease slightly as well.

IV. Additional Recovery Aids

The parachute onboard the LOFTID RV was designed to slow the vehicle's splashdown speed to approximately 13 miles per hour, minimizing splashdown damage to the RV so that it would stay afloat longer for recovery. The parachute system also included a saltwater release device that would activate upon submersion, preventing the main parachute from dragging the RV through the water if it got caught in an ocean current. The saltwater release device would detach the parachute canopy and most of the riser line length from the vehicle, leaving four 20-foot parachute riser legs attached to the top of the RV centerbody. The riser legs each had a loop at the end to connect to the ship's crane, and would be used to hoist the RV onto the recovery ship.

In addition to the camera lights, which would be left on through splashdown, four blinking aircraft collision avoidance lights were added to the RV to help the recovery team spot it during descent, and several optical reflectors in case we needed to locate the RV via spotlight from the recovery ship.

As the RV and EDR locator beacons each transmitted their location via both Iridium and the line-of-sight LoRa protocol, the recovery team also brought several LoRa radio relays on board the recovery ship, along with weather balloons and the helium to inflate them. LoRa relays would be released on balloons as we approached splashdown, allowing location of the RV and EDR further away (over the horizon) than our receiver onboard ship; the LoRa system would also bypass the Iridium system's time lag.

ULA also funded the deployment of an infrared camera system from Kennedy Space Center (KSC) onto the recovery ship. The IR camera team brought along a Starlink high-speed internet connection, which made communication with the team on land much easier than the limited network access normally available on the ship.

V. Handling Off-Nominal Conditions

In addition to adding the EDR to allow data recovery even if bad weather or other events sank the RV before it could be reached, the recovery team also planned for several other off-nominal conditions. If the RV was rapidly taking on water as we approached it, flotation buoys included in the recovery gear could be connected to the parachute riser legs and would support the RV until we could connect the recovery ship's crane. If the RV was full of water, making it too heavy for the ship's crane, we planned to lift the RV by two adjacent parachute riser legs instead of all four; this would bring it out at an angle, allowing most of the water to drain and the crane lift to be completed. If rough seas or an off-nominal splashdown caused the RV to float nose-up, so that the parachute riser legs were hanging inaccessibly underneath, we had 30-foot hooked poles allowing us to reach under the RV to retrieve the parachute riser legs; we would again attach two adjacent parachute riser legs to the ship's crane, and lift until the RV flipped nose down, after which we would connect the other two lines for the lift onto the recovery ship.

VI. Recovery Operations

Two and a half days before the initial launch date of Nov 1, 2022, the recovery ship left Honolulu for the splashdown site, with the recovery stand that would support the RV secured on the aft end of the deck near the crane, and our shipping container of recovery equipment secured amidship. However, on the morning of our second day out of port, the launch was scrubbed due to a battery issue on the Atlas, and we returned to port. We took the opportunity during the return trip to again practice recovery of the EDR, releasing an EDR engineering unit into the ocean, motoring away, then tracking it down by GPS and scooping it from the water. Upon return to port, half the recovery team flew home to await the new launch date, while the other half stayed with the recovery hardware, as it was unclear whether we'd need to transfer to a new ship to support the new launch date. Several days later it was confirmed we'd be able to stay on the Kahana II for the new launch date, and the recovery team gathered again in Honolulu.

Fig. 2 Recovery equipment on deck of the Kahana II.

Two and a half days before the updated launch date of Nov 10, 2022, the recovery ship again left port for the splashdown site, reaching the desired location at the center of the predicted ellipse with several hours margin remaining. The weather thankfully cooperated once we were on station, with clear skies and the calmest seas we'd seen while on ship. Thanks to the KSC camera team's Starlink internet connection, the recovery team was able to watch video coverage of the Atlas V countdown and launch. The launch occurred toward the center of the window rather than at the start, so we repositioned the ship a few miles west to be outside the splashdown ellipse and safer from descending debris.

While the LOFTID team expected to begin receiving data from the RTB soon after the RV's scheduled separation from the Centaur, none initially arrived, raising concerns about whether release from the Centaur had been successful. After several uncomfortable minutes of uncertainty, video from the Centaur showed that the RV had inflated and separated cleanly. Later analysis showed that, with the new launch date and time, the RV's trajectory had kept it out of contact with the Iridium network until after atmospheric reentry. In comparison, the locator beacons on both the RV and EDR connected as intended, since they only operated close to the Earth's surface.

When the splashdown ellipse update based on the Centaur's as-released trajectory for the RV reached the recovery team, there was some additional confusion. While all previous trajectory updates had agreed on the location of the ellipse and had only tweaked its size, the in-flight update indicated that splashdown would occur approximately 200 miles south of the earlier predictions. The trajectory group was surprised enough by this change that they had re-confirmed the input numbers and ran the calculations a second time. However, given that it would take about 20 hours for the ship to reach the new estimated location, and we were expecting splashdown to occur within the next 10 minutes, the recovery team decided to wait at the current location in hopes of receiving a position update from the RV's RTB or LB. A few minutes later, data received from the RTB confirmed that the RV was descending nearby. Later investigations discovered a typo in the script that calculated the footprint from the OPM update; while a discrepancy had been noted in earlier practice runs, the error had been written off as arising from input trajectory differences until it recurred during recovery of the flight hardware.

With the GPS data from the RTB providing a direction vector, the recovery team was able to spot the lights on the RV, descending slowly under parachute. The IR camera team was soon tracking the RV as well. As sufficient time had passed for any Centaur debris to have splashed down, the recovery ship headed back into the ellipse to recover the RV. "Steer for the light in the sky" worked well until the RV dropped below the horizon, after which the ship maintained the same vector until the RV became visible again. As the ship approached the RV it became clear that the vehicle was in great shape, floating high in the water, nose-down. While later inspection showed some localized melting of exposed Kapton tape and Tygon tubing, to initial appearances the RV looked as if it had been moved from the assembly facility directly into the ocean, with no apparent change from flight, reentry, and splashdown.

Fig. 3 IR view of LOFTID RV floating before recovery.

The ship reached the RV about an hour after splashdown; evaluation of the LB data indicated that the RV had splashed down about 10 miles away from the ship, roughly 6 miles from the center of the original predicted ellipse. The ship's crew used the crane to lower a rigid-hull inflatable boat (RHIB) into the water, then pull it alongside the ship to load personnel and some recovery equipment; we brought along some flotation buoys in case the aeroshell began taking on water, but thankfully did not need to use them. Robert Dillman, Steve Hughes, and Greg Swanson boarded the RHIB along with a pilot from the ship's crew, and motored over to the floating RV. We retrieved the four parachute riser legs and connected them to a lifting ring for easy attachment to the ship's crane, and connected tag lines to the RV structural straps, then pulled the RV behind us back to the ship. With the crane extended laterally from the ship, we connected the crane hook to the slack parachute riser lines, after which the RHIB backed off and the RV was hoisted onto the ship. With the ship rocking on the ocean waves, the tag lines were very much needed to stabilize the RV during the lift. After the RV was lowered into the recovery stand on the ship's deck, the parachute riser legs were detached from the crane, and connected to the legs of the stand to secure the RV in position. The tag lines were then removed from the perimeter of the aeroshell, wrapped around the RV centerbody, and likewise secured to the stand as backups. The RHIB pulled alongside the ship and was connected to the crane; the RHIB personnel climbed aboard the ship, and the RHIB was craned back to its cradle on the ship's deck. Shop air was connected to the aeroshell through a pressure regulator to maintain inflation for the trip back to port.

The ship then motored toward the GPS location of the EDR, waiting an additional hour for sunrise before approaching closely. The EDR was bright yellow for visibility, but there were concerns about running over it in the dark. After sunrise we deployed observers around the perimeter of the ship, including several with binoculars, and approached the EDR's GPS coordinates. While we had been able to spot the engineering unit EDR on our first approach during the earlier practice recoveries, it somehow took several passes before we spotted the flight EDR in the water. However, once it was spotted, the crew's excellent ship handling abilities made it a simple matter to come alongside the EDR and scoop it from the water with a fishing net on the end of a 30' recovery pole. With both pieces of LOFTID hardware successfully recovered, the ship returned to port.

Fig. 4 LOFTID RV on the Kahana II.

Once in port we craned the RV off the ship onto the shore-side recovery stand, then removed the rest of our equipment from the ship as well. We removed the internal data recorder from the RV, along with the up-look camera and the camera pods (which had recorded uncompressed video), and downloaded their data along with the EDR data. The flight data was then uploaded to network storage back at Langley. We also removed the RV battery pack, as there were concerns about shipping it after exposure to salt water; it was instead disassembled, and the lithium-ion battery cells were taken to a nearby recycler. After inspection and photography of the RV aeroshell, it was deflated and secured around the centerbody, then loaded in one of the shipping containers that we'd used to bring recovery equipment to Hawaii. After the remaining recovery equipment was loaded, and shipping of the containers back to Langley Research Center was arranged, the recovery team flew home.

Fig. 5 LOFTID RV back at LaRC.

VII. Conclusion

The recovery team was able to successfully retrieve the LOFTID RV and EDR from the Pacific after splashdown. Our experience during this effort illustrates the necessity of having multiple independent methods to track vehicles in flight. While we had also pursued deployment of a portable tracking radar from Wallops Flight Facility onto the recovery ship, LOFTID was unable to afford the additional cost; however, a tracking radar would still be a worthy addition to future missions.

Appendix: SCIFLI LOFTID Imagery Mission (SLIM)

The Scientifically Calibrated In-Flight Imagery (SCIFLI) team is comprised of engineers, scientists, and subject matter experts with a proven track record of delivering flight-truth data sets to government, DoD, commercial, and international partners since 2003. Born out of the Shuttle Return to Flight effort after the Columbia accident, the team's founder, Tom Horvath, employed his years of wind tunnel aerothermodynamics expertise to develop a novel method of acquiring infrared thermographic measurements of a hypersonic vehicle in flight. SCIFLI is a success-oriented team that provides unique engineering datasets to help investigators truly understand the behavior of vehicles under extreme conditions. The SCIFLI mission portfolio includes over 60 observations ranging in complexity across all flight regimes.

The mission to provide airborne imagery of the LOFTID test article, SCIFLI LOFTID Imaging Mission (SLIM), was developed and executed in approximately one month. The effort was executed in conjunction with partners Opto-Knowledge Systems, Inc. (OKSI) and MARS Scientific. NASA Langley's Gulfstream IV airplane, NASA 522, was outfitted with two 4-axis gimbals featuring seven different science instruments provided by MARS Scientific.

Fig. 6 SLIM Airborne Observation Team in Kona, HI

Fig. 7 SLIM imaging payload configuration. Two SkyShow-A gimbals are depicted here, with the custom UV-Acryllic windows in view.

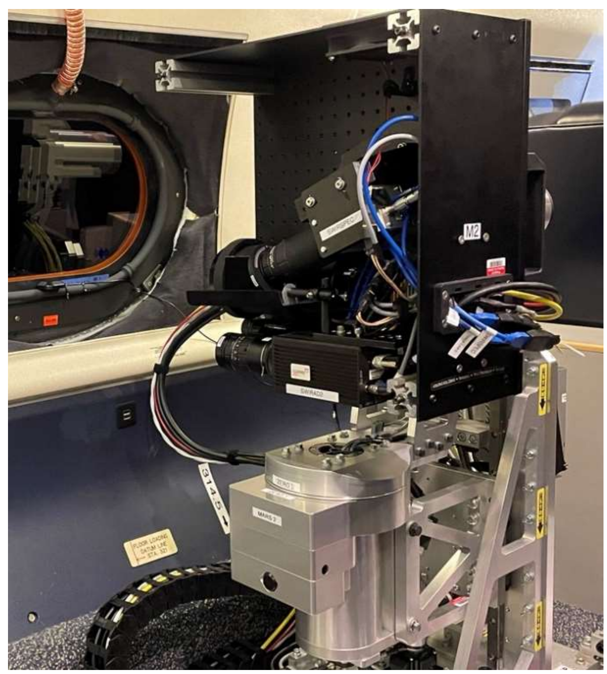

Fig. 8 Payload configuration for the SWIRSPEC spectrometer.

The primary science goals of the SLIM observation campaign were to remotely measure LOFTID Thermal Protection System (TPS) performance in flight and demonstrate SCIFLI capability for relevant HIAD vehicle designs. There was specific interest in measurements of the vehicle's peak heating temperature, laminar-to-turbulent transition, shock-layer species, and the identification of any ablation species if present. The imagery objectives based on the science goals were to obtain time-resolved temperature history and spatially resolved thermal imagery of the LOFTID TPS on reentry. Additionally, SCIFLI airborne imagery provided risk reduction in the case of any anomaly analysis.

To accomplish these complex goals, SCIFLI optimized the imagery flight path for early target acquisition, high signal-to-noise ratio (SNR), low aspect angle to TPS near the maximum dynamic pressure (Max Q) event, and collection of TPS temperature data from Entry Interface through Mach 12. The aircraft was equipped with single-pane, large-aperture optical windows to increase the quality and quantity of the data collected from the Gulfstream aircraft. The optical windows, made of Poly-II UV-transmissive acrylic, met the strict operational waveband requirements for the imaging goals as well as the material strength to withstand the mechanical loads from the aircraft in flight.

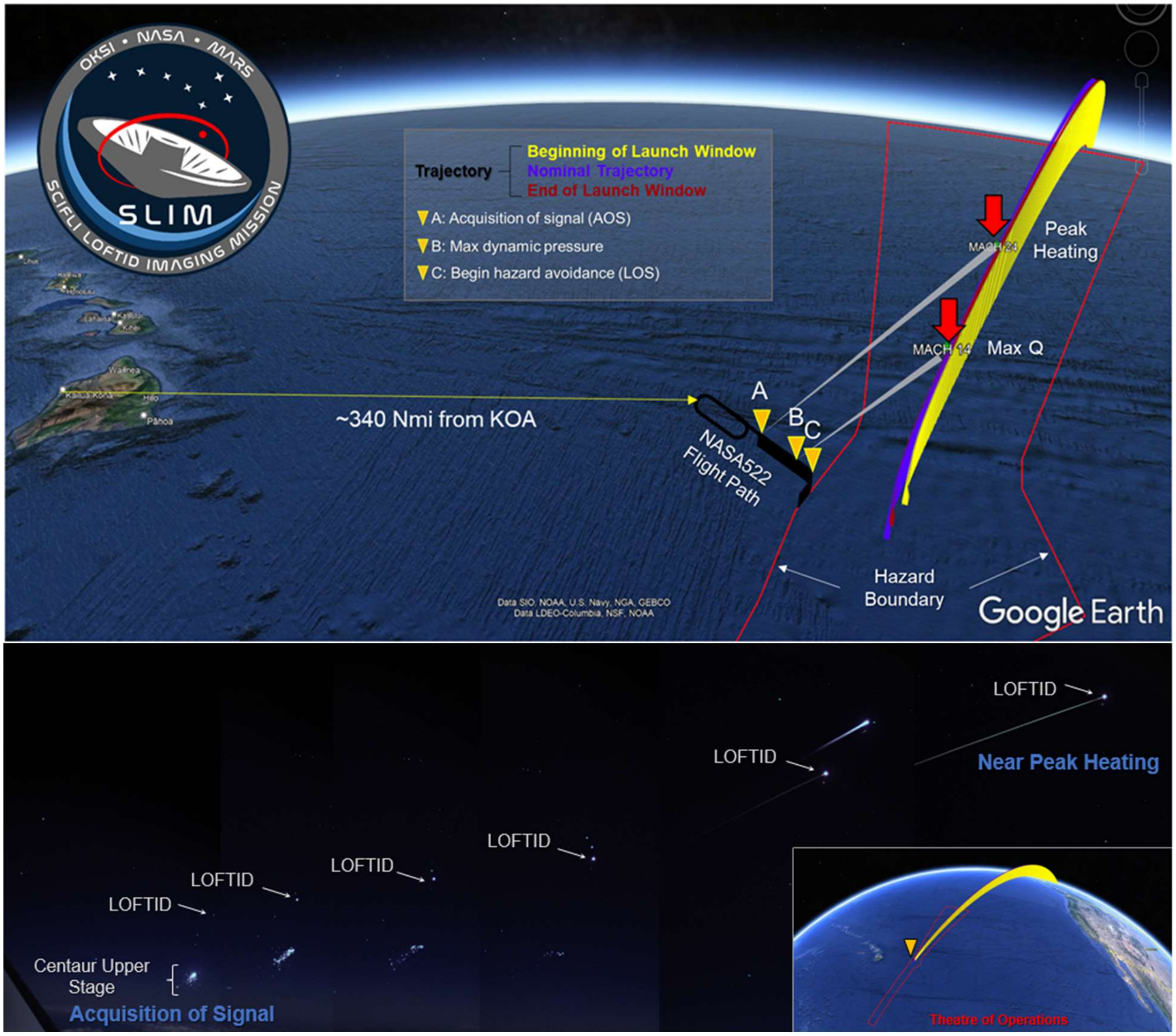

Fig. 9 (Top) SLIM Concept of Operations. (Bottom) Image Sequence of LOFTID flight.

In the weeks leading up to the reentry, the SLIM team integrated all the instruments onto the aircraft at NASA Langley Research Center and meticulously tested to ensure functionality on the ground. Then, the aircraft participated in a local instrument check flight (ICF) to continue system checkouts using stars to compare with the ground tests. Approximately one week out from the LOFTID reentry, the SLIM airborne team deployed to Kona, Hawaii and based their mission operations out of the Kona International Airport (KOA). Once in place, the team participated two mission dress rehearsals, flying in the intended mission airspace off the east coast of the Big Island, to finalize configurations, procedures, and protocols in preparation for the mission.

The Atlas V rocket with both the Joint Polar Satellite System (JPSS-2) and LOFTID payload launched from Vandenburg Space Force Base on November 10 at 9:49 UTC. Following the deployment of JPSS-2, the LOFTID heat shield re-entered Earth's atmosphere. The SLIM team successfully tracked the LOFTID test article from entry interface to Mach 12. Imaging data were successfully captured from all seven science instruments, including spectral emissions from the inflatable heatshield surface, shock layer, and wake in the visible, near-infrared, and short-wave infrared spectrum over approximately 200 seconds.

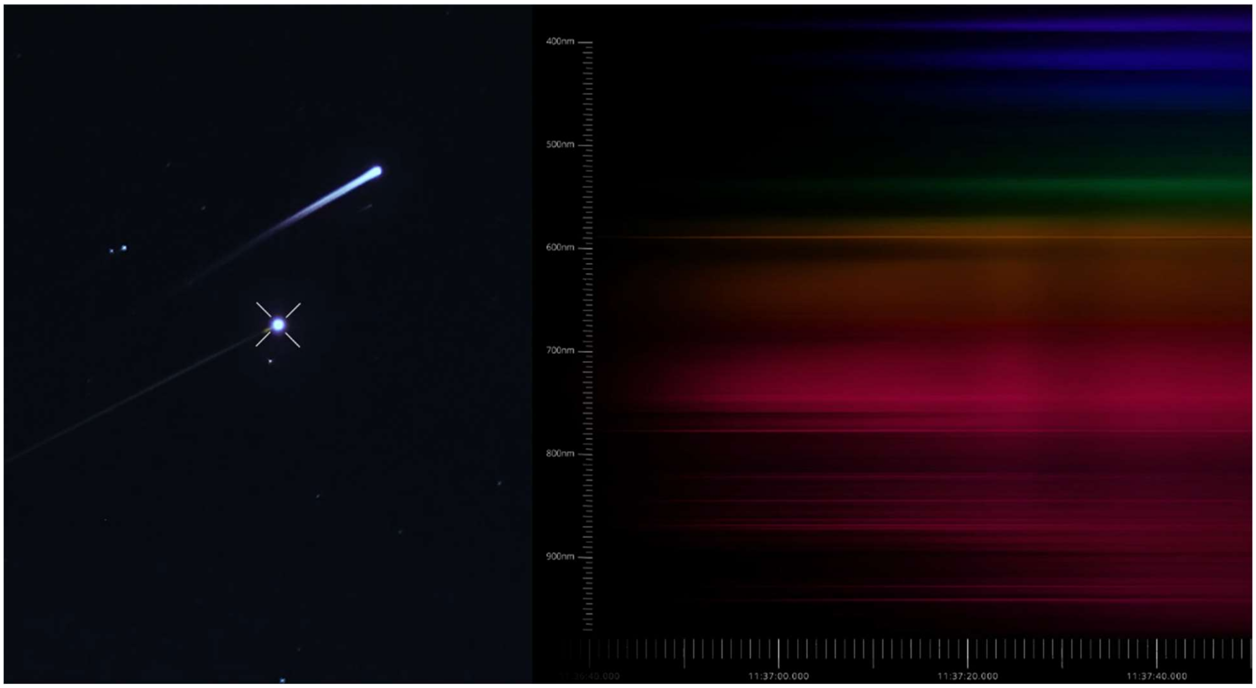

Fig. 10 Spectral data visualization of the LOFTID vehicle in flight.

The data collected by the SCIFLI team will be used for assessing the LOFTID TPS performance and design. Additionally, the success of the rapid-response effort demonstrated SCIFLI's ability to stand-up a mission in a short timeframe. This rapid-response capability may be useful for late-stage imaging efforts required for other flight tests or unscheduled returns. The future of HIADs for enabling the safe return of reusable spacecraft components, sustained LEO architectures, and other planetary entry system designs is very promising. Airborne imaging of future HIAD flight testing is recommended for future designs, especially since the data acquired from remote sensing systems is decoupled from the same failure modes associated with integrated instrumentation.

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