Fiber Optics Sensing System (FOSS) deployment on Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)

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Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) is a technology demonstration of an inflatable aeroshell to slow down and protect heavy and valuable payloads when entering atmospheres such as those of the Earth and Mars. The ultimate project goal is to enable future payload deliveries to Mars. The LOFTID is based on more than a decade of development of the hypersonic inflatable aerodynamic decelerator (HIAD) technology, which consists of a stack of the inflatable concentric rings that make up the inflatable structure that is covered with a Flexible Thermal Protection System (FTPS) and, when combined, form the inflatable aeroshell. The goal of the LOFTID demonstration was to verify that a flexible heat shield, packed into a small-volume payload, can be inflated exoatmospherically to sizes much larger than that of the launch vehicle fairing and survive re-entry into the Earth atmosphere while withstanding a temperature excess of 1,600 °C. The LOFTID is part of Technology Demonstration Missions (TDM) under the National Aeronautics and Space Administration (NASA) Space Technology Mission Directorate (STMD).

The NASA Armstrong Flight Research Center (AFRC) (Edwards, California) is part of the LOFTID program, where a space-launch version of the fiber optic sensing system (FOSS) is integrated into the avionics bay of the re-entry vehicle to provide high-spatial-density temperature measurements in three strategic locations of the vehicle. The program is part of a partnership agreement between the NASA Launch Service Program (LSP) at Kennedy Space Center (KSC) (Merritt Island, Florida) and the main Center of the LOFTID program at NASA Langley Research Center (LaRC) (Hampton, Virginia). This paper will first give a

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brief introduction of the FOSS, then discuss how the FOSS was integrated into LOFTID, in terms of fiber sensor integration into various sections of the vehicle, as well as integration of the FOSS interrogator into the avionics bay. Finally, data analysis during the LOFTID re-entry will be discussed.

I. Introduction

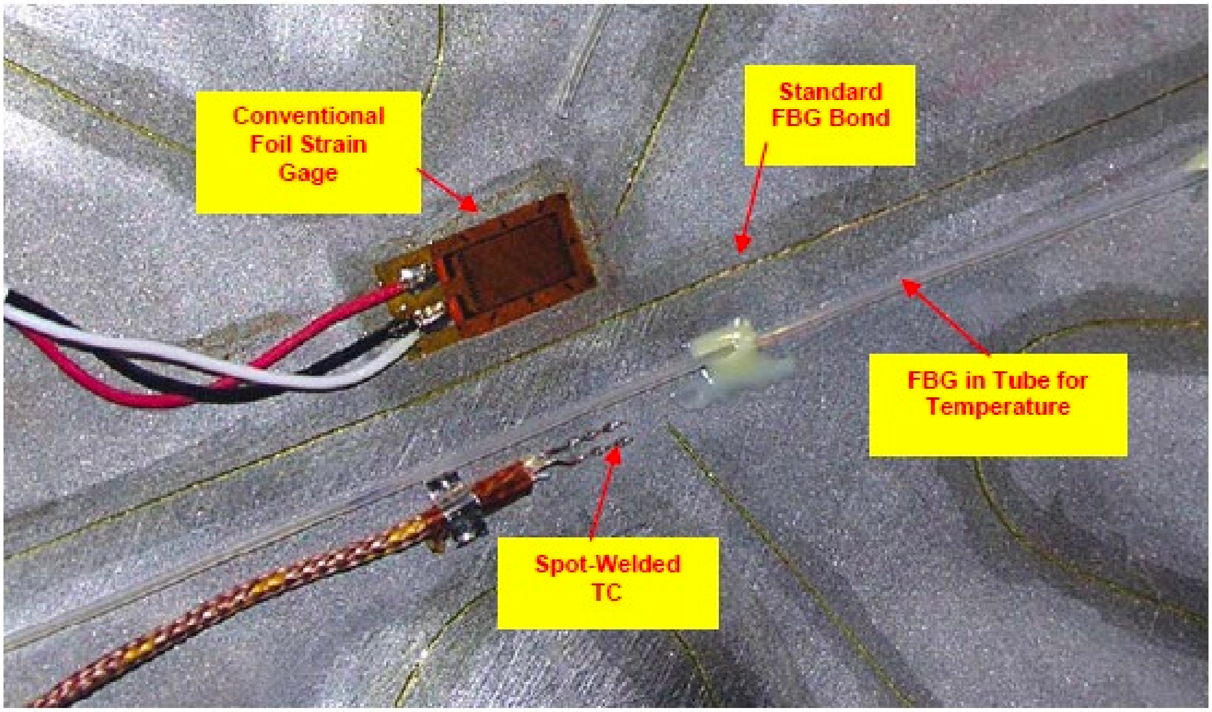
The goal of the Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) project is to test a new type of inflatable heat shield designed for safe re-entry of payloads into Earth or other atmospheres. The inflatable decelerator is made up of a flexible heat shield that can be folded up and stored inside a spacecraft during launch. Once the spacecraft reaches the atmosphere, the heat shield is inflated to slow down the vehicle and protect it from the intense heat of re-entry. The LOFTID is part of the Technology Demonstration Missions (TDM) under the Space Technology Mission Directorate (STMD) at the National Aeronautics and Space Administration (NASA).

On November 10, 2022, the LOFTID re-entry vehicle was launched at Vandenberg Space Force Base (previously Vandenberg Air Force Base, Santa Barbara, California) as a secondary payload with the Joint Polar Satellite System-2 (JPSS-2), which is a weather satellite in polar orbit that was launched using an Atlas V (Lockheed Martin, Bethesda, Maryland) rocket, now operated by the United Launch Alliance (ULA). Once JPSS-2 reached polar orbit, the LOFTID was put on a re-entry trajectory from low-Earth orbit to demonstrate the inflatable aeroshell capability that will decelerate and withstand re-entry temperatures. At a speed of 18,000 mph, the vehicle entered the Earth atmosphere, and the aeroshell was able to decelerate the vehicle to 80 mph at which point onboard parachutes were deployed, providing a smooth splashdown in the Pacific Ocean.

The NASA Armstrong Flight Research Center (AFRC) was tasked to provide a ruggedized Fiber Optic Sensing System (FOSS) to instrument and record high-spatial-density temperature measurements in three strategic locations on the vehicle. The FOSS provided 1,110 measurands just behind the nose cone, 114 measurands along the midsection of the payload section of the vehicle, and 193 measurands on the aft section of the payload. The main measurement of interest for the LOFTID project was located just behind the nose cone. At this location, The AFRC FOSS technology successfully measured temperature data in a decaying spiral pattern, spanning a length of 23 ft. This measurement was achieved with a spatial density of 0.25 in, and the data were captured at a rate of 20 samples per second. These data were recorded locally onboard the AFRC system as well as transmitted to the LOFTID avionics data recorder via Ethernet protocol. The FOSS successfully captured data throughout the entire re-entry profile, splashdown, and during vehicle recovery. This paper details the fiber installation, which will be documented along with operational results. An accompanying, planned to be published, paper will elaborate on the operational concept and will present the results of environmental testing for FOSS [1].

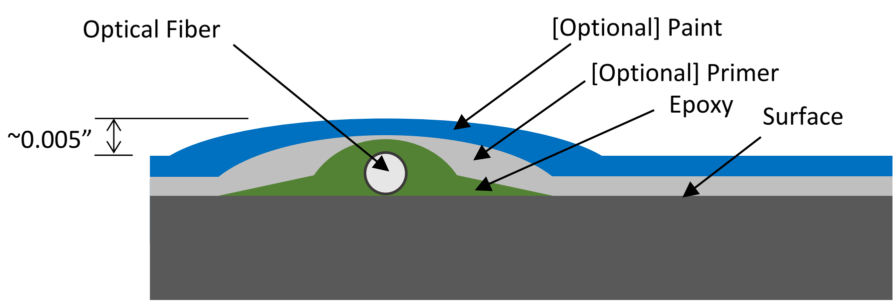
II. Installation and Testing of Fiber Bragg Grating (FBG) Temperature Sensors on the LOFTID

Fiber Bragg gratings can detect environmental perturbation either through mechanical strain or thermal expansion [2]. To measure temperature exclusively without incurring apparent strain, a polytetrafluoroethylene (PTFE)-based carrier tubing, with its inner diameter being larger than the outer diameter of the fiber sensor itself, allows for the fiber to be freely moved without incurring apparent strain from the surface of the structure. Figures 1a), 1b), and 1c) show the installation between strain sensing and temperature sensing for a resistive gage versus a fiber sensor counterpart.



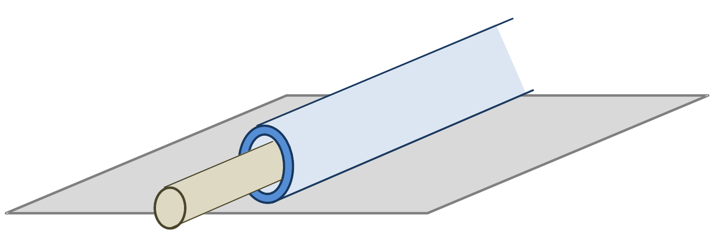
a)

Fig. 1a) Typical installation of a conventional foil strain gage and spot-welded thermocouple (TC); an optical fiber-based standard strain bond of an FBG; and an FBG residing inside PTFE tubing for temperature measurement.



b)

Fig. 1b) Layers of optical fibers for strain bonding.

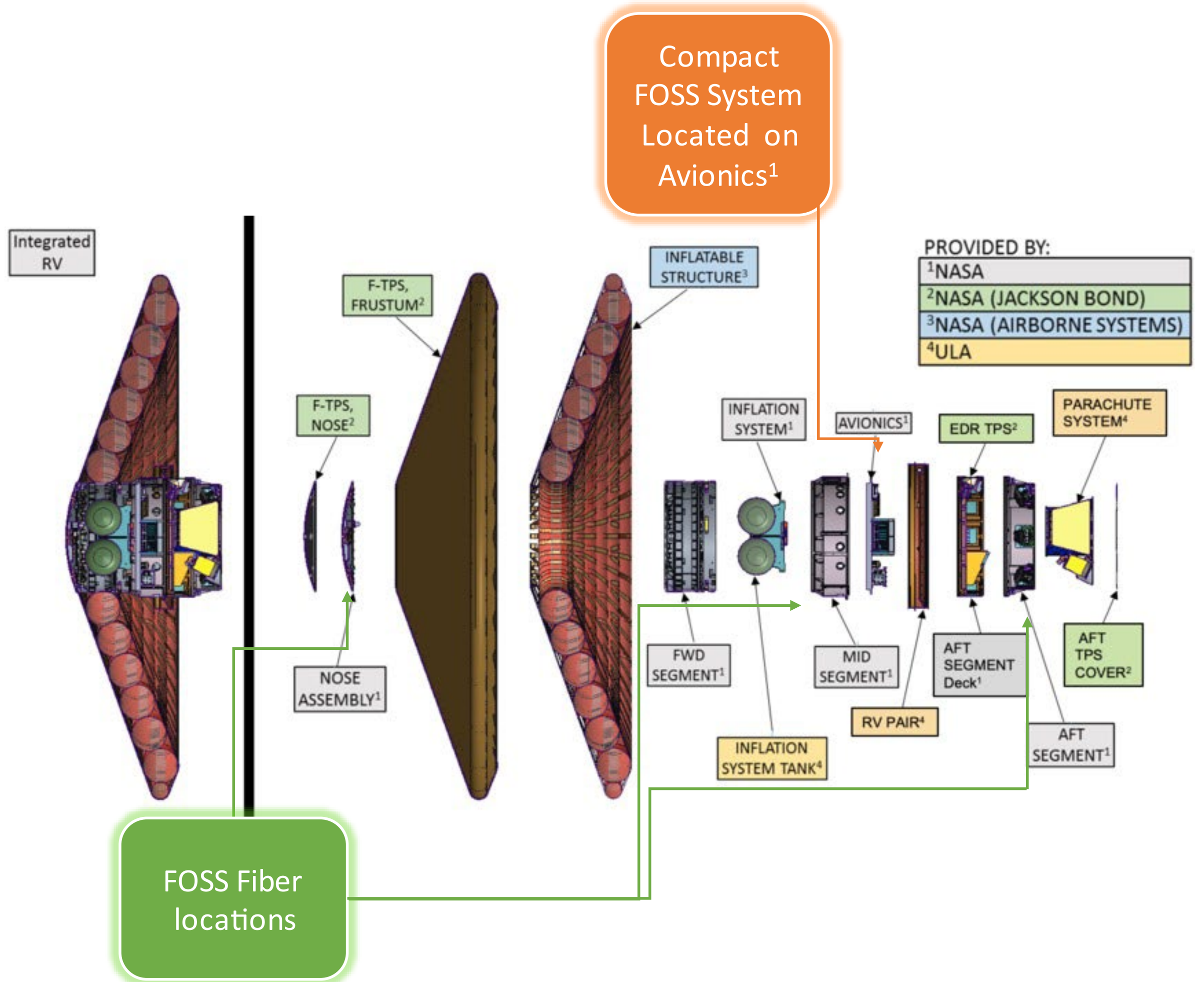


c)

Fig. 1c) An FBG being loosely coupled to measure temperature without measuring mechanical strain generated from the surface.

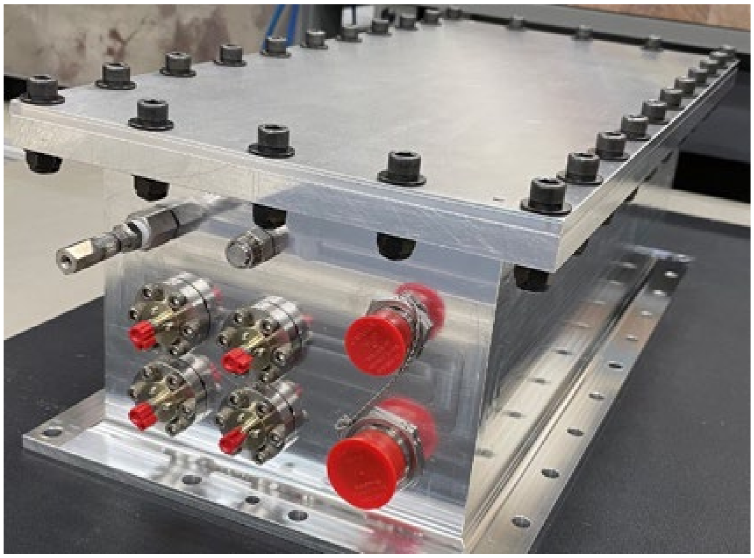
Fiber Bragg gratings are fabricated via inducing periodic change of index of refraction to the core of the fiber [3], these changes of index of refraction are caused by a concentration of Germanium (Ge) dopant to the silica fiber on the core. By exposing FBGs to long-term high heat, there is tendency for the excited Ge-dopant to be diffused away; thus, causing the effect of the resonant wavelength reflection of the FBG to be minimized. In other words, the sensor could be "washed out" under long exposure of elevated temperature. The FBG used in this application was coated with a 10-µm thick polyimide coating, which can endure continuous temperatures of up to 300 °C and short-term temperatures as high as 400 °C [4].

Figure 2a) and Fig. 2b) show the overview of the location of fiber sensors as well as the ruggedized compact FOSS system. The main fiber sensor array was installed on the back side of the nose assembly of the aeroshell, which was integrated in 2018 at Jackson Bond Enterprises (JBE) (Jackson Bond Enterprises, LLC) (Dover, New Hampshire). Before laying down the fiber pattern, a preconfigured stencil mapped out the pattern of the 23-ft fiber. The fiber sensors have a spatial resolution of one-quarter inch (1/4"), which translates to over 1,100 sensors. The fiber layout is sandwiched between multiple layers of a flexible thermal protection system (FTPS), manufactured by JBE. To prevent apparent strain that would affect temperature reading, these fiber sensors are carefully stitched between the FTPS layer, shown in Fig. 3, such that the fibers are held relatively in place without being impinged. The final fiber layout is shown in Fig. 4 and represents the nose cone section. Figure 5 shows the size difference between the hard aeroshell (nose cone) versus the FTPS frustum, which are supported by multiple tori from the inflatable structure. In addition, four thermocouples are installed on the subsequent layer of the FTPS, just above the FOSS.



a)

Fig. 2a) The LOFTID segment view, and FOSS avionics and fiber sensor locations.



b)

Fig. 2b) Space-rated FOSS interrogator that was on-board LOFTID.

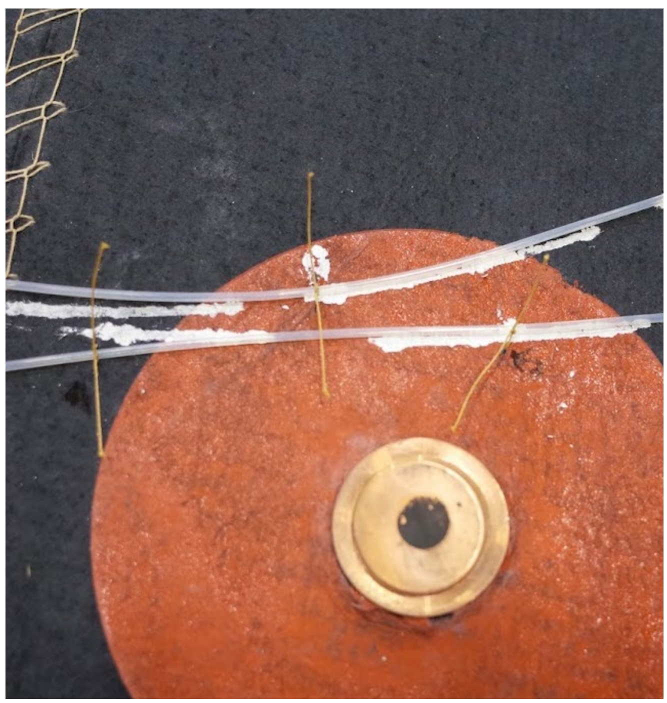


Fig. 3 Loose PTFE sleeve containing temperature sensing FBGs, being held in place by loose threading, which is located between the FTPS layers.

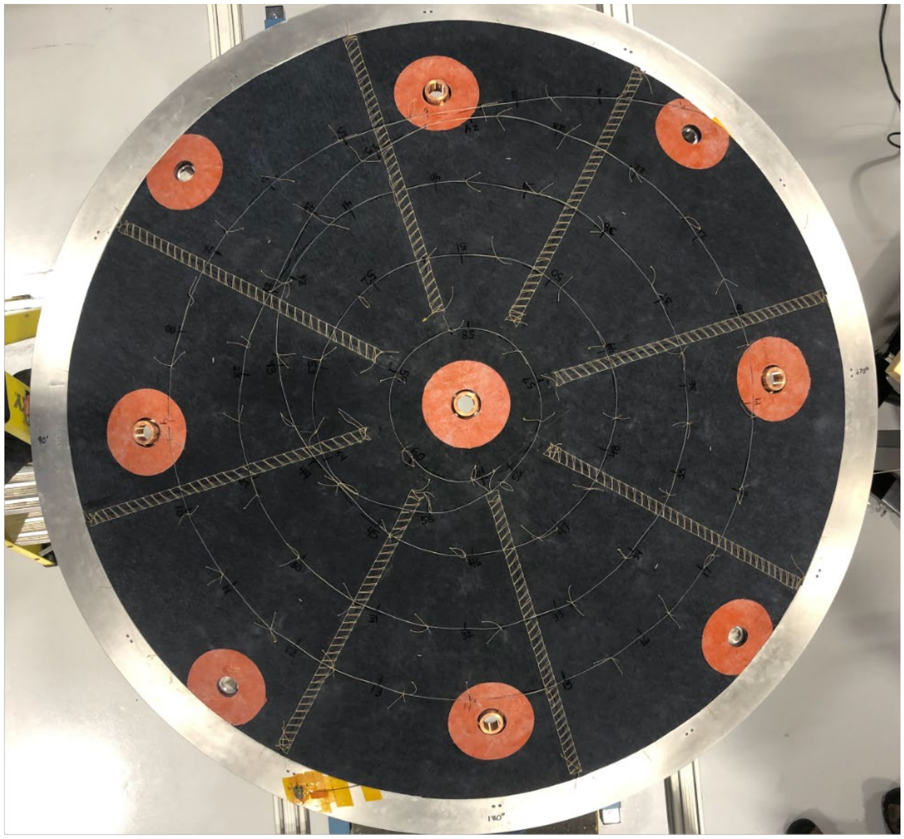


Fig. 4 Final fiber sensor layout on the rigid aeroshell.

Fig. 5 Relative size of the rigid aeroshell that is covered with FTPS, compared to the inflatable aeroshell on the LOFTID.

To map the location of the fiber sensor relative to the aeroshell accurately, once the fiber has been placed on top of the FTPS, a bench-top FOSS interrogator is used to identify and validate the location of each specific sensor; this method is accomplished via generated heat (from a heat gun source) directed at the sensor in question. The location of every 10th FBG was identified and, subsequently, marked on the nose. With this information, an X-Y coordinate of the fiber position is located, within ±¼-in accuracy. The relative location FBG sensors, behind the four thermocouples, are also identified and are shown in Fig. 6.

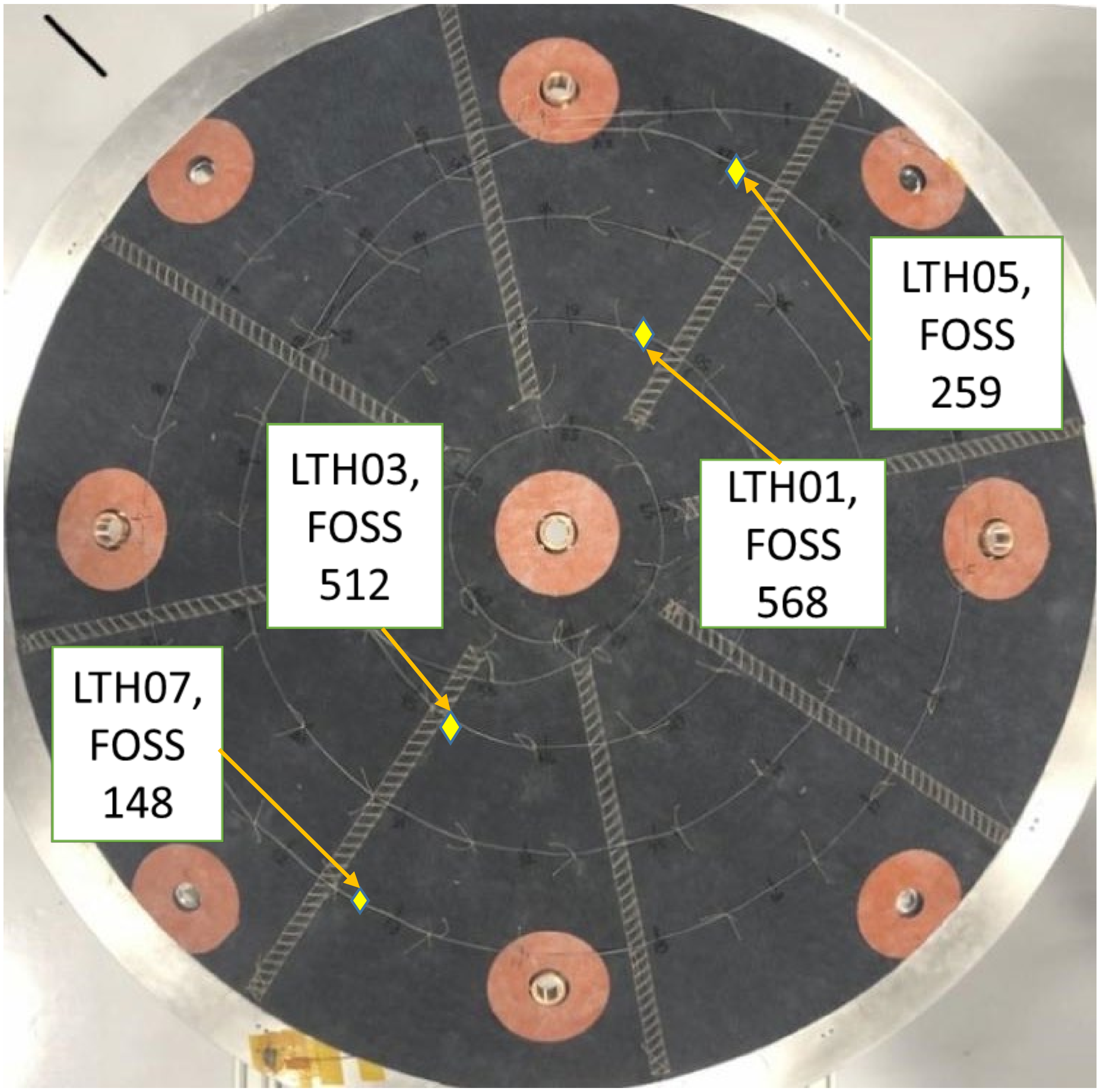
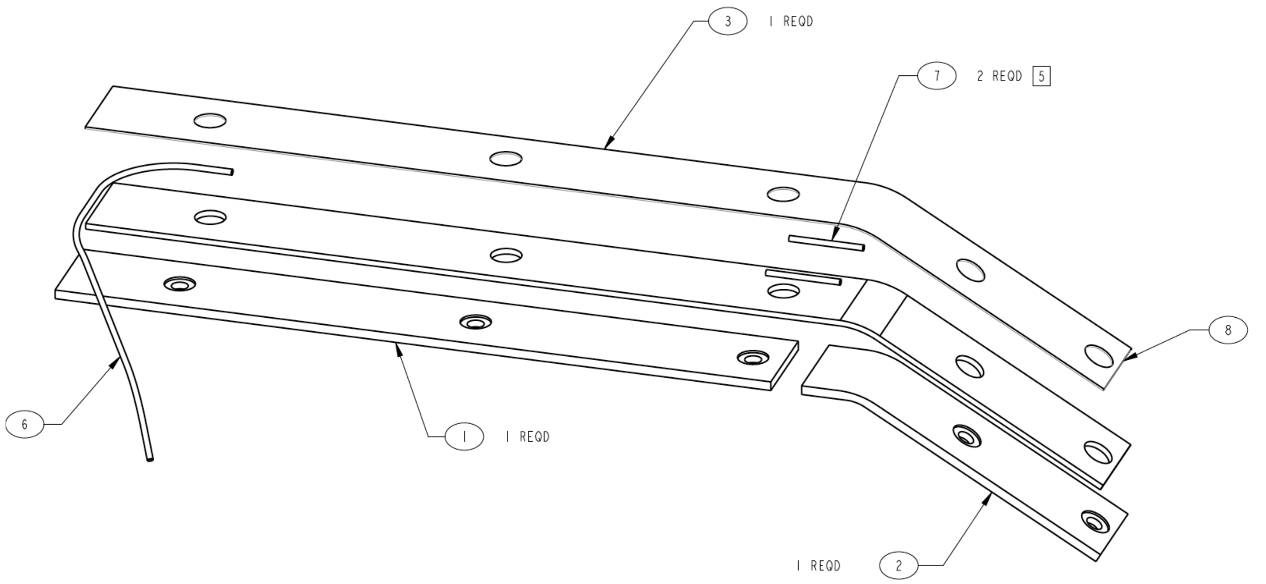


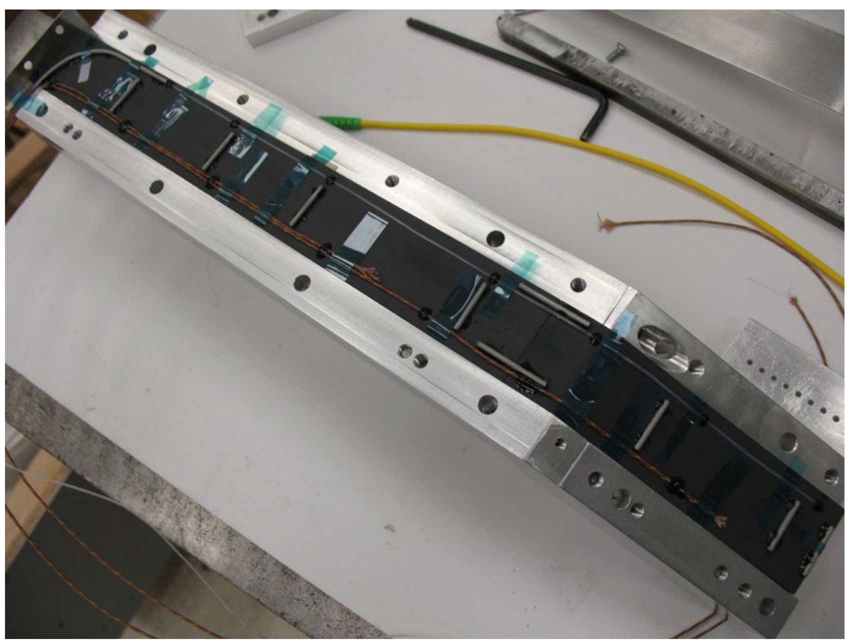
Fig. 6 Relative location of the thermocouples to the unique identification (ID) of the FBG sensors on FOSS.

Because the nose cone section is the main temperature fiber sensor that was monitored, fiber sensors were also installed straight down the side of the mid and aft sections of the LOFTID payload, as part of the embedment experiment. The mid and aft sections were integrated via an experiential process, where the temperature sensing fiber was sandwiched between two pieces of aluminum plates to provide structural support, as shown in Figs. 7a) and 7b). Stainless-steel reinforcement tubing with an outer diameter of 0.075 in (or 75 mils), which is approximately 1,900 µm, is designed to provide lift support to the PTFE tubing, which has a 28 American Wire Gage (AWG) rating, with an outer diameter of 33 mils (or 838 µm). The sandwich layer was fabricated via a NASA low outgassing approved epoxy, suitable for bonding, to hold the PTFE tubing to the stainless-steel tubing and set the bond line. The mounting hole patterns were drilled after the sandwich materials were fabricated. Post encapsulation installation, the sensing fibers were verified to be functional, confirming that they were not being crushed by compression from the top and bottom plates.



a)

Fig. 7a) Engineering drawing of experiential design of embedment of fiber temperature tubing encapsulated on the midsection of the payload.



b)

Fig. 7b) Fiber and TC placement just prior to encapsulation.

Multiple systemwide testing was performed to ensure that the installed fiber was operational. In addition, multiple FOSS units (both space-flight ready and benchtop equivalent versions) were built via rapid prototyping and sent to the LOFTID team to aid in software integration, as shown in Fig. 8. The most comprehensive testing occurred during the complete system testing, performed at NASA Langley Research Center (LaRC) (Hampton, Virginia) in May 2022. Table 1 displays the measurements in each fiber.

Table 1 Fiber number and number of measurements for each fiber.

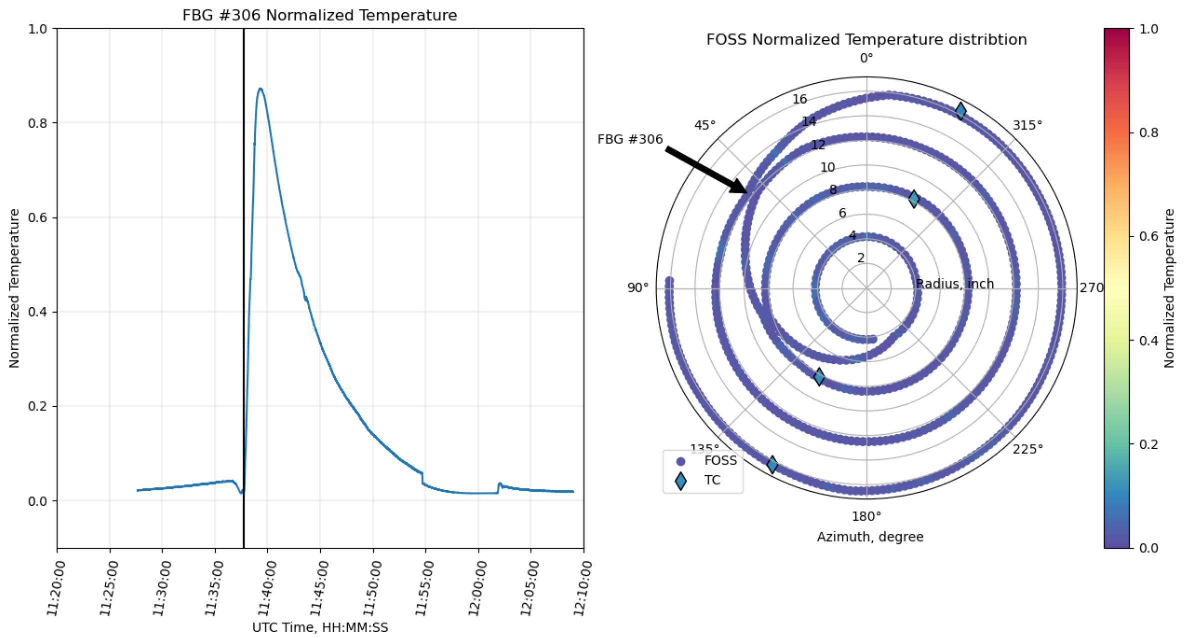
Fiber Number	Number of Measurements
1	1,110
2	114
3	193

These data were recorded at 20 Hz and stored along with internal temperature and pressure measurements of the FOSS unit. These data were stored both internally within FOSS and transmitted as telemetry to the LOFTID avionics, concurrently.

Fig. 8 (left) Relative size of the ruggedized compact FOSS unit that was on the LOFTID; and (right) a benchtop equivalent compact FOSS unit that was used by the LOFTID team for system familiarization and troubleshooting prior to integration.

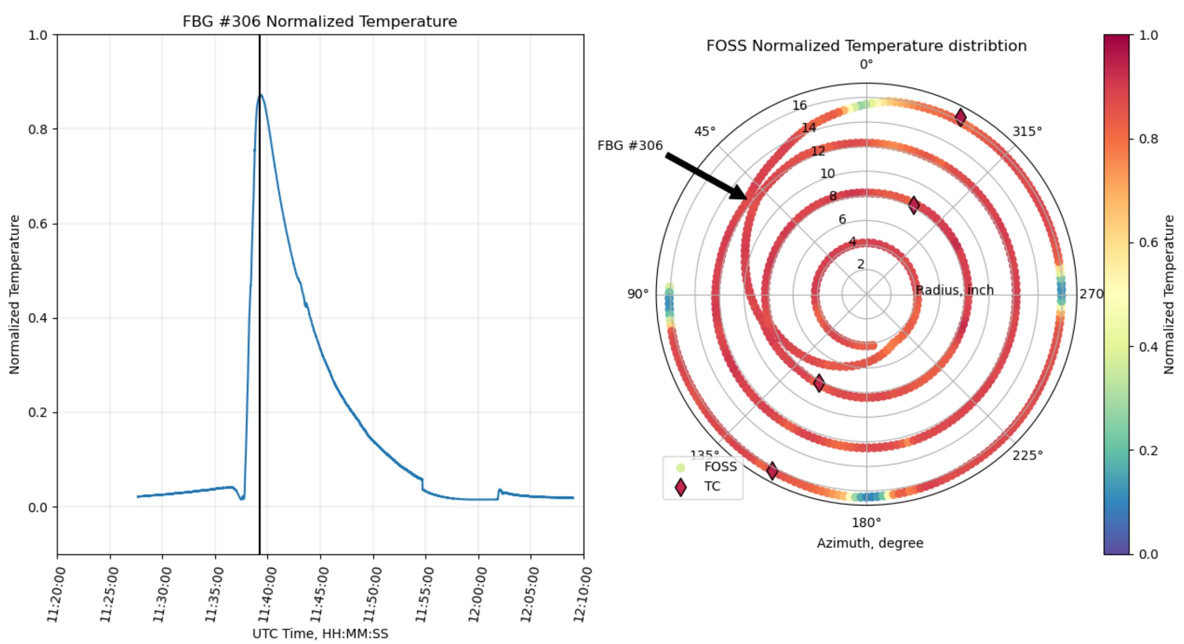
III. Data Analysis of the FOSS on the LOFTID Re-entry

For temperature data recordings that were obtained from the FOSS during the LOFTID re-entry, a successful cold boot of the FOSS unit was performed, which allowed for the successful recording of data, starting at approximately 11:28 Coordinated Universal Time (UTC) time. The fiber (located behind the rigid nose section, where recording of temperatures occurred) proved to be most interesting because it contained 1,100 measurement points. The temperature of the nose section had a steady temperature; however, the temperature then elevated exponentially between 11:36 UTC to 11:38 UTC, as shown in Figs. 9a) and 9b). The four co-located thermocouples were also plotted, where temperature profile increased at a normalized temperature rate of 0.8 temperature units per minute. Then, once peak temperature was reached, the temperature of the aeroshell steadily decreased until the aeroshell splashed down at around 11:55 UTC. Comparing the temperature recorded from the FOSS to the co-located thermocouples, located one FTPS layer above, showed that the temperature change profile matched well. In addition, the fiber location identified cold spots from copper heat sink, which housed additional instrumentation, as shown in Fig. 10.



a)

Fig. 9a) (left) Temperature profile experienced by FBG #306 throughout the re-entry process; and (right) a complete system mapping of 1,100 FBG measurements with respect to four co-locating thermocouples (diamond shapes) at 11:36 UTC, when the aeroshell first experienced a temperature increase.



b)

Fig. 9b) (left) Max temperature experienced by FBG #306 at 11:38 UTC; and (right) max temperature experienced by FBG #306, and system mapping of all FBGs, respectively.

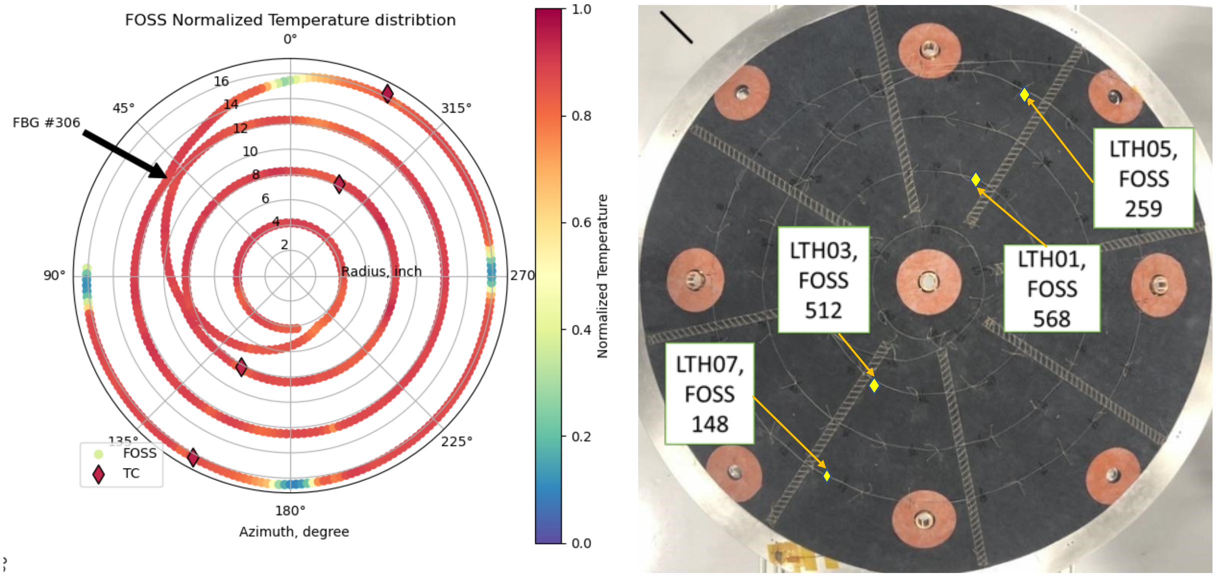


Fig 10. Cold spots recorded on the FOSS are directly correlated to the metallic cold sink that is adjacent to the fiber sensors.

Figure 11 shows the comparative temperature curve for the thermocouple versus a comparative FBG sensor. The peak temperature shown on the thermocouple is higher, as expected, because these thermocouples are closer to the surface heat than the fibers. The FOSS fibers were installed behind several layers of the FTPS with the thermocouples installed through the thickness of the FTPS layers. Another effect of the FTPS is that the cool-down rate for the representative fibers is more rapid versus the co-located thermal couples.

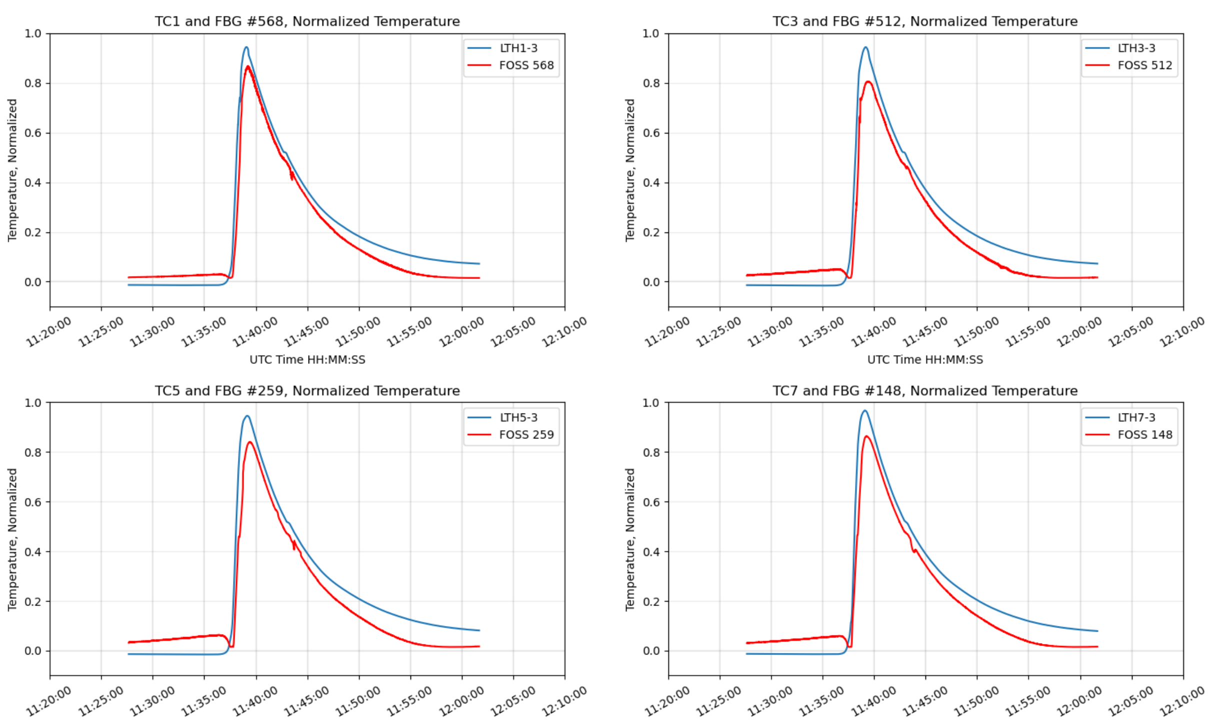
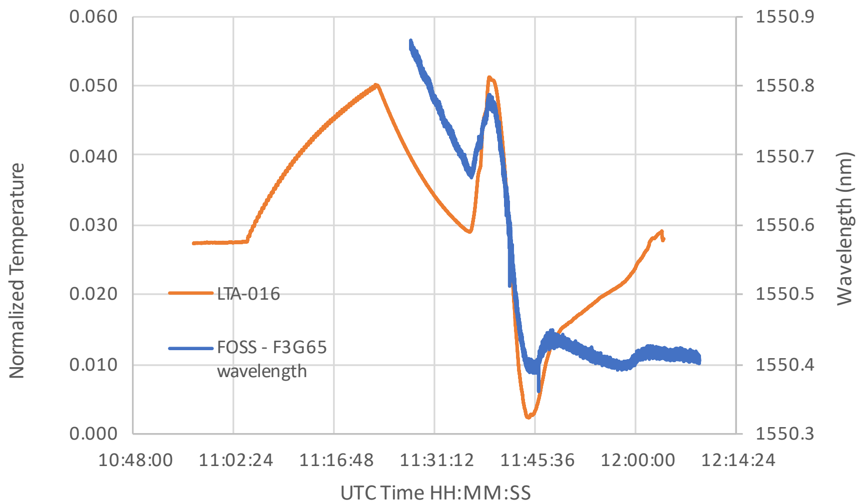


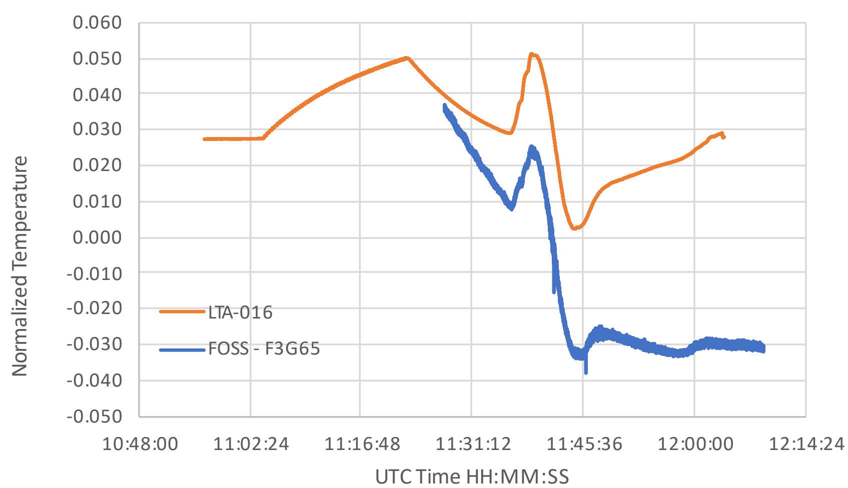
Fig. 11 Co-located FBG versus TC comparison.

As an experiential demonstration, Figs. 12a) and 12b) collected and compared FOSS sensor data from the aft section of the payload section versus represented thermocouple data during re-entry. In terms of overall slope of the data, the recorded data matched well between the TC versus representative FOSS data. The data shows that the payload does not experience any elevated temperature, suggesting the effectiveness of the inflatable heatshield. There is discrepancy, however, between the fiber data recorded versus the thermocouple data (where apparent strain from compression of the sandwiched aluminum panel is recorded), which results in the fiber data showing a negative temperature from the uncoupled strain component, even after landing.



a)

Fig 12a) Comparison of a TC on the aft section versus a co-locating fiber sensor measured in wavelength, nm.



b)

Fig. 12b) Comparison of the calculated temperature from initial wavelength shift.

IV. Conclusion

A compact Fiber Optic Sensing System (FOSS) system was successfully integrated with the Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) mission, where temperature measurements at 20 samples per second were acquired, and finite element-like resolution of temperature data fidelity from the rigid aeroshell were provided. The co-located FOSS fiber Bragg gratings (FBGs) and thermocouple agreed with reasonable tolerances for differences in locational protections. After the LOFTID splashed down, the FOSS avionics unit was retrieved from the payload bay.

The system proved to be fully operational because of its hermetic design, despite being tainted with saltwater. Overall, the FOSS has provided temperature data to supplement the LOFTID mission and has given confidence to the LOFTID team that an inflatable heat shield can be utilized for future missions.

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