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Development of an In Flight Non-intrusive Mass Capture System

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The demonstration of an in-flight Tunable Diode Laser Absorption Spectroscopy (TDLAS) system for the measurement of mass capture is being developed in the Hypersonic International Flight Research Experimentation (HIFiRE) Flight 1 (see Kimmel et al AIAA 2007-534 for full description). The key to integration into a flight payload is to make a system that will both fit into the flight system meaning weight, size and power requirements as well as being able to survive in the much harsher flight environment as compared to the laboratory. This document contains the design consideration and overview of the system as it progressed from bench type hardware to being a fully integrated flight payload.

I. Introduction

The HIFiRE flight programs goal is to conduct basic hypersonic research through in flight experimentation. This is an international partnership between both the United States Air Force Research Laboratory and the Australian Defence Science Technology Organization. The program will conduct

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multiple flight tests to explore many realms of hypersonic flight including, fundamental hypersonic flow characteristics, hypersonic vehicle aerodynamics, and supersonic combustion performance. The HIFiRE program follows the HyShot[1] and HYCAUSE[2] programs and aims to leverage much of the low cost flight test technique developed in those programs. Further, the effort includes the development and validation of novel instrumentation and high-resolution measurement techniques to hypersonic aerodynamic and aeropropulsion flowfields. The international team is completing final preparations for the first flight experiment to be launched from the Australian Woomera Protected Weapons Range in April 2009.

The U.S.-led HIFiRE Flight 1 payload is the first of up to10 that will provide a world-class data set for hypersonic vehicle development above Mach 5. Flight 1 is designed to evaluate boundary layer transition (smooth and rough body), aero-heating, shock-boundary-layer interaction and structural design data. The boundary-layer shock interaction experiment will help determine if unsteady phenomena seen in ground-based tests exist in flight environments. The Flight 1 payload also includes a laser-equipped optical mass capture channel that measures flow through a simulated hypersonic inlet. Other labatory based diode measurements have been made AFRL's Propulsion Directorate and small business team partners Zolo Technologies and Southwest Sciences have adapted and miniaturized laser-based telecommunications technologies to develop a unique Tunable Diode Laser Absorption Spectroscopy (TDLAS) platform, the first time this technology has been miniaturized to scales suitable for sounding rocket flight experiments (mass < 3 kg, power < 15 W). The TDLAS provides a novel approach to measure flow properties in flight (e.g. density, velocity, combustion efficiency) at kHz sampling rates.

II. Optical Mass Capture Overview

This experiment's ultimate goal is to develop first generation compact diode laser systems capable of measuring oxygen concentration and velocity in the inlet or isolator of a hypersonic vehicle mounted within a sounding rocket payload over an altitude range of 60,000-90,000 ft. Tunable diode laser absorption spectroscopy (TDLAS) employs single mode diode lasers that are temperature stabilized and current tuned over atomic and molecular absorption features. Molecular oxygen can be detected and quantified by tuning over selected transitions of the $b^1\Sigma_g^+ - X^3\Sigma_g^-$ (atmospheric) system at 760 nm. Scanning multiple transitions enables the oxygen concentration to be determined as well as the static temperature. By directing one laser beam upstream and another downstream, the oxygen transitions will be shifted in frequency due to the Doppler effect, thereby enabling the flow velocity to be determined from the separation of the two absorption features in frequency space. These data provide the flow density and velocity and provide a direct measurement of the mass capture.

The TDLAS system being developed would ultimately be used to measure the total mass capture of a hypersonic vehicle inlet in flight. Being able to determine the mass entering a supersonic engine has been identified as one of the largest parameters needed to accurately determine overall combustion performance[3]. Traditionally in ground based wind tunnels this measurement has been made with the use of probes to measure the core flow properties. The problem is that the very presence of the probe disturbs the flow negating the ability to make these measurements during an active combustor test. The mass capture system that is currently being designed for flight test uses a TDLAS system to make line averaged measurements of both oxygen concentration and velocity. These measurements along with wall pressure and the known flow field characteristics will be used to deduce the inlet air mass capture. The goals of TDLAS experiment on HF1 are to: Test the survival of diode laser driver card, detector electronics, and acquisition system; Test survivability of optical lens mounting; Measure the effectiveness of the laser operation over fight envelope, and measure the laser power and heath during flight; and Demonstrate ability to maintain optical alignment in flight.

III. HIFiRE Flight 1 (HF 1)

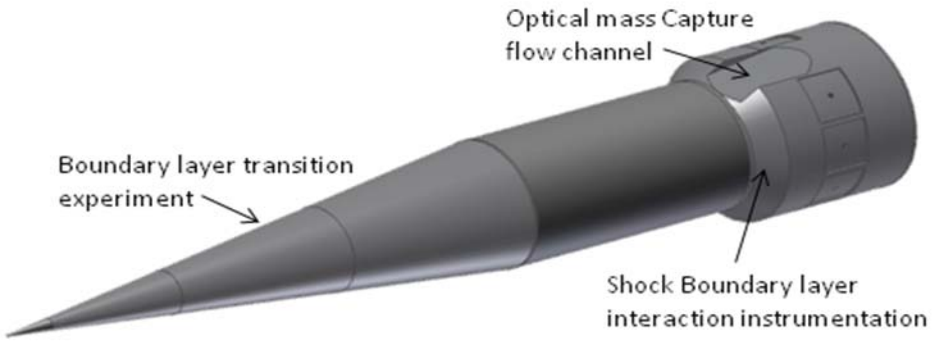

Figure1. HIFiRE Flight 1 Payload.

HIFiRE Flight 1 payload is shown in figure 1. The primary experiment is a boundary layer transition experiment. This experiment aims is to measure the natural transition of the boundary layer as it goes from laminar to turbulent on a flight vehicle. There is also a shock boundary layer interaction experiment on the flare region which is to measure the heating loads associated with a flight vehicle. The TDLAS experiment is also a secondary experiment meaning it needs to be integrated in such a way as to not interfere with the primary experiment. Since there is no engine or inlet on the first HIFiRE flight, see figure 1, a design was developed to measure flow velocity without interfering with the other flight experiments. This design was done by carving out an air passage in the flare region ninety degrees offset to the instrumentation of the shock boundary layer interaction experiment and far enough aft of the primary boundary layer transition experiment so that there will be no interaction.

IV. Ground Test

Multiple groups have worked on TDLAS in the laboratory environment[4, 5, 6, and 7] using standard optical hardware. Specifically ground tests on this TDLAS system were conducted at the Air Force Research Laboratory. The tests were to prove that a meaningful measurement of oxygen concentration and flow velocity could be made using the TDLAS hardware that would lend itself to a flight sized package. To perform the velocity determination, counter propagating paths are shown in a previous paper[8]. For this measurement, the two paths were made as symmetric as possible, with nominally-identical fibers, optics and path lengths. Light from both paths were sent through GIF50 fiber directly to detectors and both signal sizes were comparable. These tests provided the data that show that flow velocity is able to be discerned to an acceptable level compared to that of standard practices. The results are not reviewed here.

V. Electronics design

The experimental focus was not to prove that TDLAS is a viable diagnostic technique. That has been proven in the laboratory. The goal is to determine whether it is feasible to develop a TDLAS system that would provide useful data in a flight test. In this case, the largest challenges were to both miniaturize and ruggedize the electronics into a package that would be capable of fitting on a flight vehicle and surviving the harsh conditions encountered in a rocket launch.

As a risk reduction maneuver flight 1 has on board two sets of electronics and optics. They are completely independent systems that have been manufactured by two separate contractors. One system was made by Zolo technologies and the other was created by Southwest Sciences. Each of these systems will be routed to a separate flow channel further reducing the risk by keeping them completely independent. Each contractor came with a different skill set that made have the two on board very beneficial to both this flight and future opportunities. They were experts in the design of optics and had previous experience with practical TDLAS systems that they have based their commercial sector on making systems to monitor and provide control inputs to coal fired power plants to help reduce harmful emissions. Southwest was the second contractor to be selected. The brought with them expertise in miniaturized electronics they had already designed electronics board for the use of a handheld methane detector. Not only did the two companies come with a different set of qualifications they also had different approaches to their design. Zolo used a direct scan method for measuring this would be an ideal way to measure water in later flights. While Southwest sciences used wavelength modulation which will be beneficial to making the much more difficult oxygen measurement because of its ability to help reject more of the noise that can be of the same magnitude of the oxygen measurement. They also used different methods to get the laser light from the Vertical cavity surface emitting laser (VCSEL) into the fiber. Zolo used a mechanical restraint that was aimed to focus the light into the fiber while Southwest Sciences used a high temperature epoxy to butt couple the laser directly to the fiber. The used of different techniques let us evaluate the merits of each in a flight test environment. Their individual efforts are outline in their companion papers[9,10].

Both contractors delivered electronic packages that exceeded program expectations. On the final flight vehicle both electronic laser packages were able to be integrated into a 5.75 inches long by 13.5 inches diameter section of the payload with enough room for all the communications cables to also run through. Figure 2. The final weight and power requirements were also below requirements with Zolo's electronics weighing 3.5 kilograms and consuming 20 Watts of total power and Southwest Sciences weighing 1.8 Kilograms and consuming 2 Watts of power. Each unit is able to run off of a 28 volt nominal power supply that could be as high as 32 volts and as low as 22 volts.

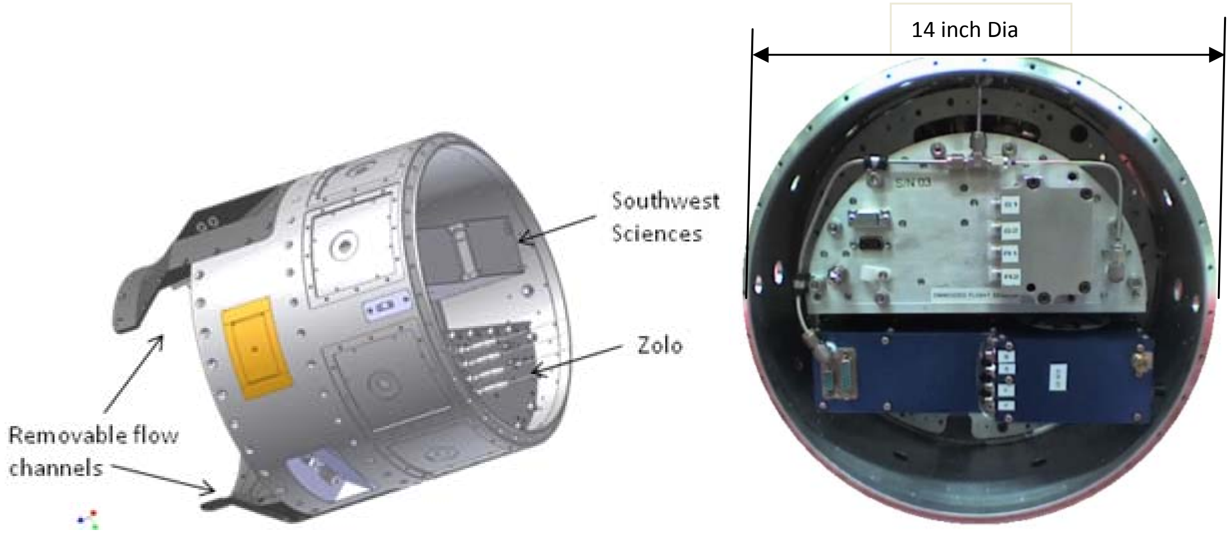

Figure 2. Aft section of HIFiRE flight 1 payload.

VI. Optics Design

The original intent was to design a system that would work with what is a current conventional design for a scramjet engine. The two examples that were looked at were the X-43 and the X-51 both are rectangular designs with the engine slung under the body with all the electronics and support equipment in the body directly above. This was a tough design to accommodate because the optics need a line of sight across the flow to be able to make a useful measurement and fitting the optics into the limited space available required a significant design change. Because of the under slung design the optics package needed to be able to contain a collimator, a turning prism and some sort of alignment feature in a space that would be able to fit between the cooling channels of the scramjet combustor. Zolo technologies were able to design such a package which is illustrated in figure 3

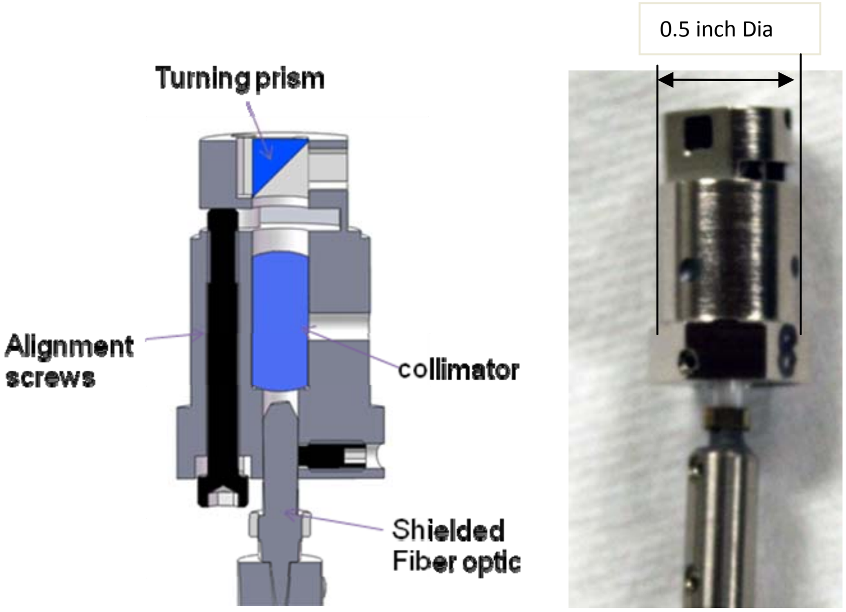

Figure 3 TDLAS flight optic.

This design has a collimator reflecting onto a turning prism which is in a flexing head. The horizontal alignment is set by rotating the entire optic package in the fixture and the vertical alignment is done with three counter tensioning alignment screws. The benefits of this design are that it includes alignment features into a package that is 0.5 inches in diameter. This reduces the machining cost by not making the machinist conform to unreasonable tolerances and they can use the standard 0.005 inches with any errors being accounted for with the alignment features.

VII. Channel Design

HIFiRE flight 1 does not have a scramjet isolator, inlet, or combustor therefore a representative mass capture measurement was not proposed. However at this point in the program the goal is only to develop and evaluate flight hardware and future flights will be used to fine tune the actual measurement and analysis techniques. The design that was achieved was to make a flow passage into the flange section of the payload. This section already exists for the shock boundary layer interaction experiment. Originally the flow passage was more of a duct but after some thermal analysis was completed it was determined that the design would have to move to an open channel. A cylindrical section was also added to prevent the shock boundary layer interaction experiment from interacting with the boundary layer transition experiment. These design changes can be seen in figure 4.

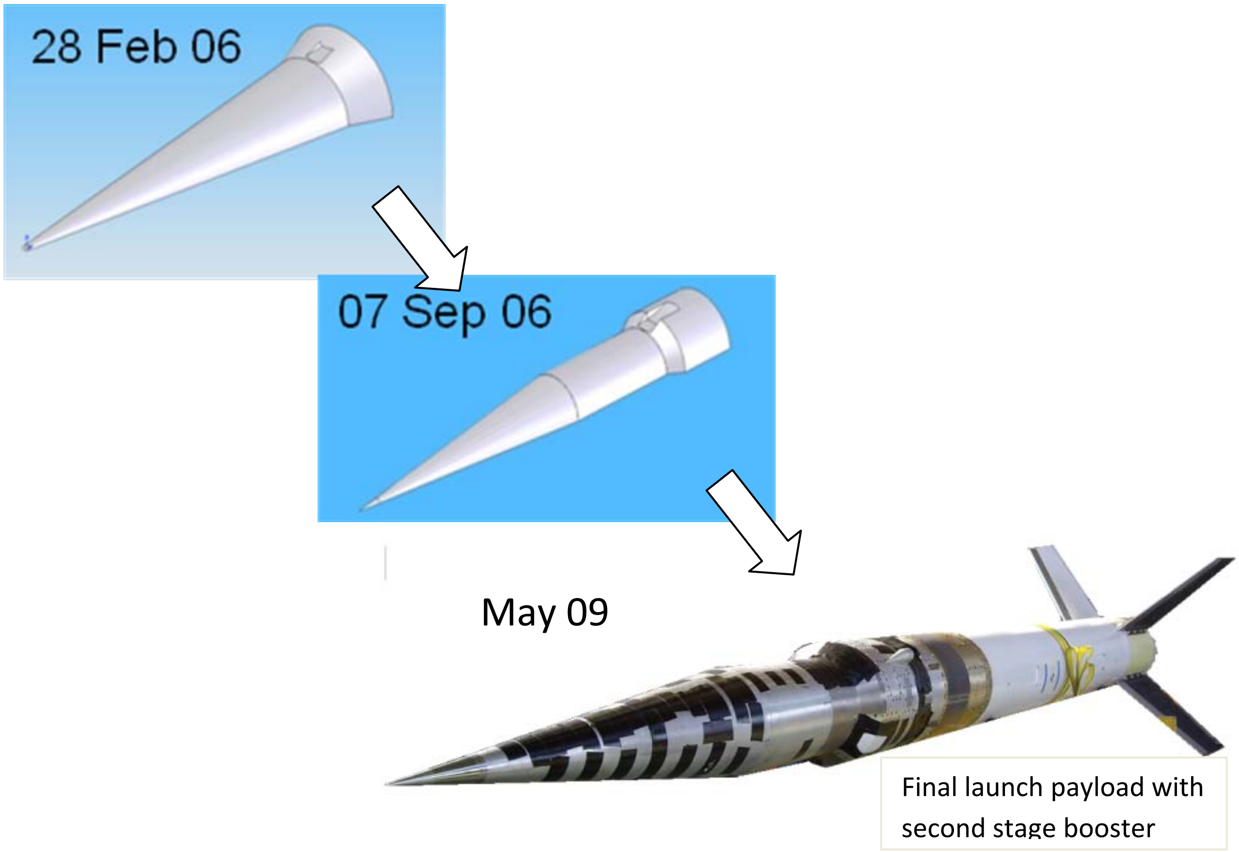

Figure 4 Payload design changes.

Since the goal of this project is to ultimately make velocity measurements a design was needed that would allow for counter propagating laser beam paths. One beam path would be going with the flow and one going against the flow to be able to provide the Doppler shift. The included angle between the beam was performed by the window optics. There is a 20° angle of the back face of the window compared to the flow face. The window design allows the alignment optics with an included angle of 24.12 to be placed almost directly behind the windows and since the angle is in opposite directions on opposing sides any misalignment due to the change in refraction of the window optic due to temperature variations is canceled out. All of these factors added to the complexity and due to size constraints limited us to two beam paths per channel. The final design can be seen in figure 5. There are two identical channels located at 0° and 180° of the flight vehicle and each electronic package had its own flight channel.

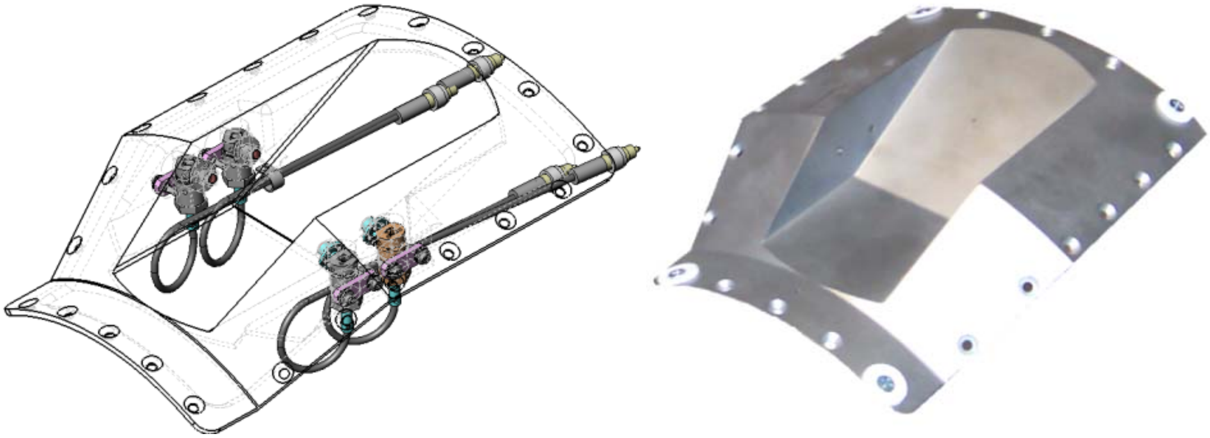

Figure 5 Flow channel with optics.

VIII. Environmental requirements

The environmental requirements for a flight vehicle are much different than those in of a laboratory environment. The design of the flight electronics now have to take into account thermal dissipation, thermal growth, alignment, and surviving the 60g impact load on rocket take off. The program had clearly defined environmental requirements vibration and thermal testing that had to be completed in order to optimize chances of success in flight. Chiefly among them were the temperature and vibration requirements as laid out in the NASA sounding rocket handbook. The design had to withstand sinusoidal vibration of 7.6cm/s from 10-144 Hz and 7.0g from 144-2000Hz in the thrust profile while the Lateral Axis sustained 3.0in/s from 10-35 Hz, 7.0 g from 35-105 Hz and 5.0 g from 105-2000Hz. It also had to withstand random vibration of 10.0 grms at 0.052 g^2/Hz from 20-2000 Hz in the thrust axis and 7.6 grms at 0.029/Hz from 20-2000 Hz in the rest of the axis for 20 seconds. The thermal requirements were that all the electronics had to survive and function from +61º C to -24ºC for duration of 3 hours. During the course of design it was determined that to save power the requirement to function below 0º C would be waived to permit the removal of a laser heating device which would have added considerable strain to the batteries. Another design feature that was added in was the requirement for a continuous nitrogen purge while the payload was on the launch pad. This was done to prevent moisture from condensing on the thermal electric cooler but it had another benefit of cooling the electronics so the internal heat generation would not become a problem with an extended launch delay on the pad. There were also other design issues that arose that are not in formal design documents. Such as the metal clad shielding on the fiber optic cables, this was done for manufacturing to reduce the risk of damage during integration and flight. Also because the goal is to ultimately integrate the optics into a scramjet flow path the temperature rating on the items in contact with the flow path were increased to 800K (~1000ºF). Another set of tests was conducted to gauge the thermal survivability of the optics. An insert for the optics was made to integrate into the RC 18 isolator (see Figure 6). Readings were taken during a combustor run and minimal (<20%) performance loss was recorded over the entire run night. Thermocouple measurements were made at two different depths into the side wall material and are plotted in figure 6, one measurement located in the sidewall material closer to the flow surface and one is farther from the flow surface close to the optics.

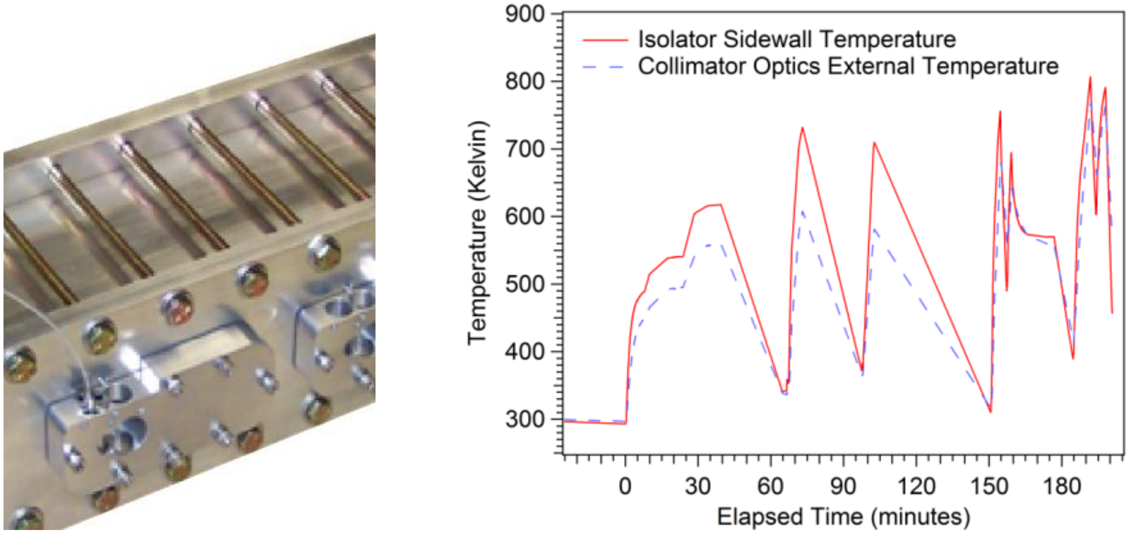

Figure 6. Thermal cycles test in RC 18. Left original optics holder, Right Thermal data.

IX. Design changes

During the course of design evaluation and testing many small problems were discovered. Notably changes had to be made to take into account thermal growth and misalignment due to vibration induced slipping of the optics. The first change that was made was to the channel flow side. It was determined that as a rectangular channel on the exterior of a cylindrical rocket was heated that the walls would splay outwards and they would no longer be parallel. This effect was minimized by giving the walls an angle to begin with such that side walls would point in toward the radius of the cylinder meaning that as the channel grew from heating the walls would stay at the same relative angle helping to keep the lasers aligned. See figure 7

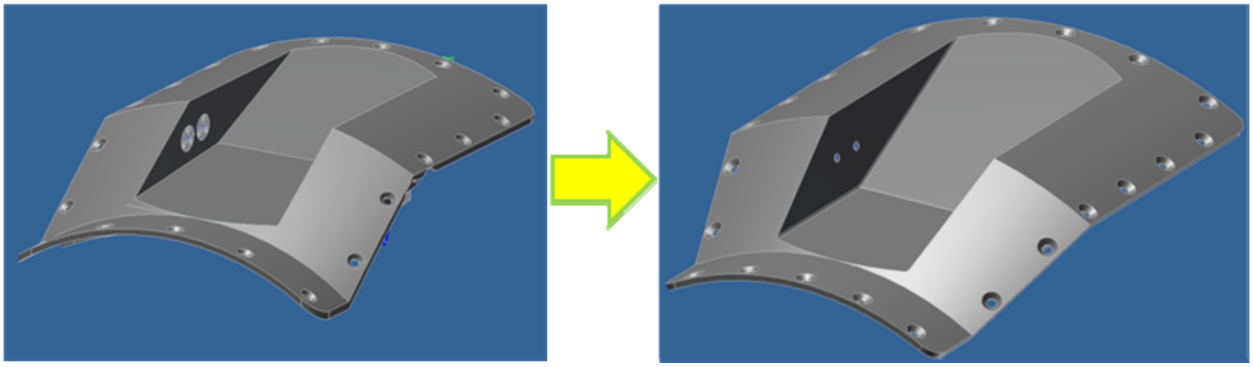

Figure 7 Channel design progression.

Another area where that went through design iterations as testing and analysis was completed was in the area that held the optics into the flight channel. Originally the optic assemblies were held in by 3 set screws. The optics were aligned and three screws were tightened to hold it into place. This design encountered problems when it came to vibration and thermal testing. It was found that as the channel would heat up the hole containing the optics would grow and the set screws would loosen and it would lose alignment. It was also found that even without heat addition the design just did not have enough holding force to keep the optics in place. To give the holder more holding force it was then decided to try to increase the surface area holding the optic in place. This was done by carving out a retaining pocket into the cylindrical holder and pressing it into place with a restraining bar that is spring loaded with Belleville washers to be able to continue to apply pressure even as the hole grows due to thermal expansion. See Figure 8. The results of this design indicated vibration survivability in room temperature tests and required performance at high temperature conditions, data shown in Figure 6.

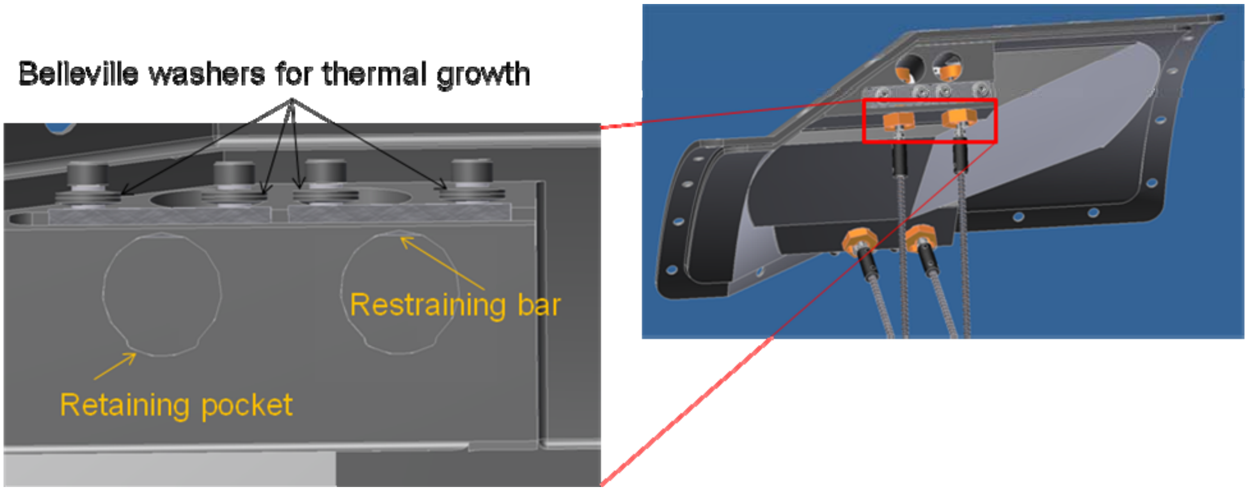

Figure 8 Optics holder redesign.

X. Conclusions

The Tunable Diode Laser Absorption System was successfully transitioned from the laboratory environment into a flight payload. Not only were the lasers and electronics ruggedized to be able to survive the harsh vibration and temperature environments encountered in a rocket payload but an entirely new miniaturized optic strategy was developed to that can maintain alignment with in 3 miliradians, hold that alignment during the flight and was designed in such a way to help transition it into future scramjet designs. With a little bit more development these systems will be able to greatly add to the available options for in-flight diagnostics hardware. The flight payload was completed and fully integrated into the HF1 flight vehicle during the May 2009 flight campaign unfortunately due to technical issues with the telemetry system the flight has been delayed until the spring of 2010.

XI. Future Flights

The TDLAS system is scheduled to be included on two future HIFiRE flights. Both of the flights will have an actual combusting scramjet engine. These flights will be flight 2 and flight 6. In flight 2 TDLAS will be configured to have 8 paths in the exit plane of the combustor. It will measure water and employ tomographic reconstruction to recreate the exit plan of the combustor, yeilding water concentration, static pressure, and static temperature. On flight 6 the TDLAS system will be used to once again measure oxygen but this time it will be in the isolator of the engine and will be used to measure the mass flux to within 10%.

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