Orion LAMS Laser Absorption Spectrometer for Human Spaceflight – Artemis 4 and 5 Design Updates and Flight Builds

Jason G. Pohly[1]
Romach Technologies, Inc., Huntsville, AL 35808, USA

David Roe[2], and Cody Erb[3]
Dynetics, Inc., Huntsville, AL, 35806, USA

and

Lance E. Christensen[4] and Kamjou Mansour[4]
Jet Propulsion Laboratory, Pasadena, CA, 91109, USA

The Orion Laser Air Monitor System (LAMS) is a tunable laser spectrometer that will monitor oxygen, carbon dioxide, and water vapor levels in the Orion Multipurpose Crew Vehicle (MPCV) cabin and in the space suit loop. LAMS, designed to be small, lightweight, and low power, can nonetheless accurately measure a wide dynamic range of analyte concentrations over relatively wide pressure and temperature ranges despite not using gas pumps, flow, or pressure controllers. Additionally, the LAMS hardware and electronics are capable of meeting stringent Crit-1R requirements for human life support. This paper is a follow-up to the 2020 and 2023 ICES papers which covered flight unit build and testing results for Artemis missions 2 and 3. This paper covers design updates, flight unit build, and test results for the Artemis missions 4 and 5.

Nomenclature

ADC = Analog-to-digital Converter
AR = Anti-reflective
ARS = Air Revitalization System
FAU = Fractional Absorption Units
JANS = Joint Army-Navy Nomenclature Systems
LAM(S) = Laser Air Monitor (System)
MPCV = Multi-purpose Crew Vehicle
PCBA = Printed Circuit Board Assembly
PBIT = Periodic Basic Internal Test
TEC = Thermoelectric Cooler

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[1] CEO, Romach Technologies, Inc. 4001 Market St SW STE 100, Huntsville, AL 35808.
[2] Chemical Engineer, Advanced Materials and Nanosystems, Leidos-Dynetics, 1004 Explorer Blvd, Huntsville, AL 35806.
[3] Optomechanical Design Engineer, Advanced Materials and Nanosystems, Leidos-Dynetics, 1004 Explorer Blvd, Huntsville, AL 35806.
[4] Scientist, Atmospheric Observations, Jet Propulsion Laboratory, Pasadena, California 91109.

I. Introduction

THIS paper is a follow-on to two previously submitted ICES papers[1, 2] about the Orion Laser Air Monitor System (LAMS). The LAMS is the primary atmosphere monitor for the Orion Multi-purpose Crew Vehicle (MPCV) that will return US astronauts to the moon for the first time since the Apollo missions. The first paper covered key system specifications and selection of a spectroscopic methodology. The second paper covered challenges encountered during acceptance and qualification testing of the Artemis 2 units and subsequent specification update, redesign, and testing of the Artemis 3 LAMS. At the time of this writing NASA has installed Artemis 2 and Artemis 3 LAMS units into their respective Orion MPCVs, and Leidos-Dynetics is in the process of building LAMS units for the Artemis 4 & 5 missions. This paper covers the status of the current LAMS flight unit build and development work, which includes software updates to improve laser reliability, updates to the optical assembly process that improve the oxygen accuracy, and development work to further improve oxygen measurement accuracy.

II. System Overview

As a point of review, the Orion Laser Air Monitor System (LAMS) is the primary atmosphere monitor for the Orion MPCV. A LAMS consists of four identical sensors, each individual sensor is referred to as a Laser Air Monitor (LAM). The LAMS monitors two air revitalization loops inside the Orion MPCV – the cabin air loop and the space-suit air loop. Two LAM units redundantly monitor the cabin air loop, and the other two LAM units redundantly monitor the space suit air loop. Each LAM unit is a tunable diode laser absorption spectrometer (TDLAS) that utilizes the direct fit (a.k.a. direct absorption) methodology. Each individual LAM monitors the total pressure of the air and the partial pressures of carbon dioxide (CO_2), oxygen (O_2), and water vapor (H_2O). The LAMS system is classified by NASA as Criticality- 1R (Crit-1R) and the firmware on the LAMS is rated Class A. The LAMs electronics are designed to be radiation tolerant. All active components (i.e. integrated circuits) are radiation tolerant or hardened components, and each of the individual components comply with Joint Army-Navy Nomenclature Systems (JANS) Class S or Class Q quality standards for spaceflight. The electronics are assembled to IPC J-STD-001FS with Space Addendum.

III. Artemis 4 & 5 Flight Build and Development Work

A. Software Updates to Improve Laser Reliability

A critical step during the assembly process for LAM units is what the team refers to as 'resistor selection.' During this step, gain resistors for the photodetector transimpedance amplifier circuits are selected such that they scale the laser ramp signal such that it utilizes approximately 80% of the range of the microcontrollers' analog-to-digital converters (ADCs). This step is necessary to optimize the resolution of the photodetector signal because each laser outputs a different optical power as a function of injection current.

During this resistor selection step for the flight builds of the Artemis 3 units, the team noticed that sometimes when the main LAMS printed circuit board assembly (PCBA) was powered up, the lasers would attempt to turn on but never fully power up. This behavior was unexpected and therefore warranted further investigation. The team discovered that this issue was due to updates to the laser control circuits and software that were implemented for the Artemis 3 design.

The design of the Artemis 2 system had an analog feedback control loop to keep the laser at a desired temperature setpoint. As part of the period basic internal test (PBIT) executed by the LAMS software, the software checked to make sure that the error signal of the feedback control loop stays near one volt, when this signal was at one volt, it meant that the feedback circuit was controlling the laser to the proper temperature. This was a useful metric to determine proper operation of the laser and TEC, whenever anomalies occurred within the system. After the Artemis 2 build, the team determined that it would be helpful to be able to measure the value of the laser thermistor directly in software since that temperature value would enable the software to automatically run additional PBITs and since that temperature could be reported out in system messaging and used by the team during diagnostics of issues. For the Artemis 3 design, the electronics and software were both updated to be able to read the laser thermistor temperature directly, instead on only reading the set-point voltage for the feedback loop.

The Artemis 3 software design updates included a new parameter in each LAM unit's calibration (or configurable) parameters called 'xxx_laser_max_safe,' where 'xxx' was either 'co2' or 'o2,' specific which laser that parameter was for. This value was typically set to be 5 °C above the operating temperature setpoint for that laser. The software used this parameter to shut down the laser if the laser temperature exceeded the 'xxx_laser_max_safe' value for two consecutive measurements, roughly one second apart. This was intended to keep the laser diode safe if the laser's TEC control loop was not able to keep it at the appropriate temperature (perhaps due to an anomalously high or low environmental temperature). If this safe temperature threshold was triggered, the software would shut off the lasers, and the LAMS would have to be power cycled to get the lasers to turn back on.

To identify the cause of the laser-shut off issue encountered during resistance selection, the team put a new Artemis 3 control board and flow cell (which houses all the lasers, photodetectors, and associated optics) into a thermal chamber and ran tests of starting up the LAMS system under various environmental temperatures, laser setpoints, and 'xxx_laser_max_safe' values. This testing revealed that the way the software sequenced turning on of the lasers and TEC control loops was not sufficient to allow the temperature of the lasers to settle to the correct temperature before tripping the laser-max-safe PBIT under certain conditions. Specifically, when the laser setpoint was low compared to the range of possible setpoint values and the ambient temperature was elevated to 50°C, the TEC could not cool the laser fast enough for the laser temperature to get below the laser-max-safe temperature before the software completed two laser temperature measurement cycles. Therefore, a design update that was intended to provide an additional layer of security for the laser diodes resulted in them not being powered on at all under elevated environmental temperatures. To fix this issue, the team updated the software to have a delay between powering on the TECs and powering on the laser diodes. The software now power on the TECs, waits for them to settle to the setpoint temperature, then powers the laser diodes on.

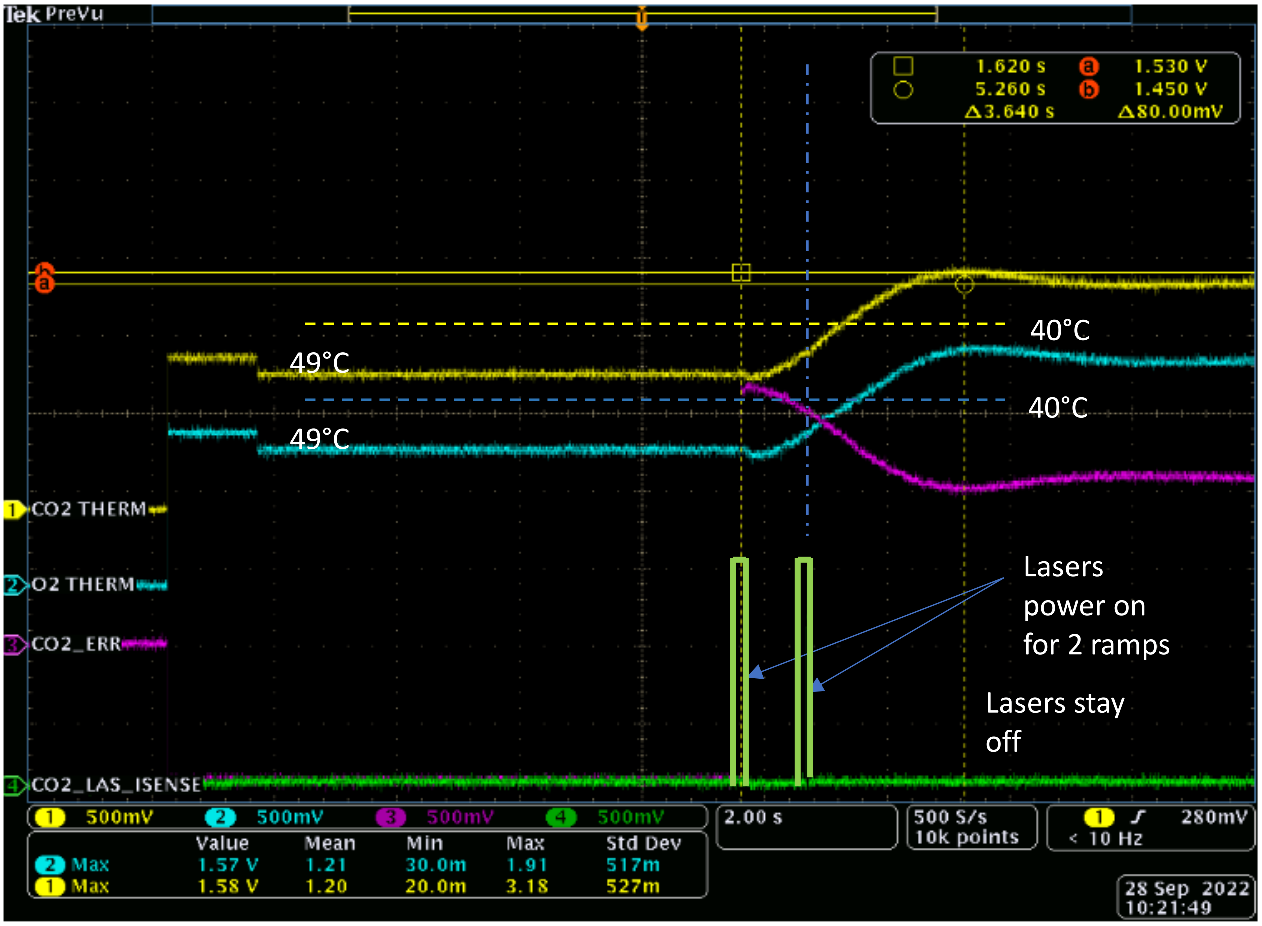

Figure 1. Oscilloscope Capture of Laser Temperatures When Powering on a LAM at 49°C Environmental Temperature

B. Improvements to Oxygen Measurement Accuracy - Background

In addition to improving the laser reliability, the main goal of development work for the Artemis 4 & 5 build was to reduce the total uncertainty (herein, 'total uncertainty' or simply 'uncertainty' is used to describe the combined error due to both in-accuracy and lack of precision) of the oxygen measurements. As mentioned in previous papers[1,2], there are two uncertainty ranges for the oxygen measurements. What the team refers to as the 'tight O_2' range applies to an oxygen partial pressure of 1.90-5.50 psia when the total pressure is 7.5-15.5 psia. In this range the desired total uncertainty is ±0.05 psia. Otherwise, when the oxygen partial pressure is 1.9 – 24.2 psia and the total pressure is 2.1-24.2 psia, the required uncertainty is ±0.5 psia. This latter range is referred to as the 'loose O_2' region since the accuracy requirement is an order of magnitude less stringent.

For both the Artemis 2 and the Artemis 3 builds, the LAM units were able to meet the loose-O_2 specification, but not the tight region specification. For Artemis 2, most LAMS units were approximately ±0.3 psia total uncertainty in the tight region. Improvements were made for the Artemis 3 design resulting in the best unit having a total uncertainty of ±0.1 psia, while the rest of the units were around ±0.2 psia.

The LAMS units monitor two separate air revitalization systems (ARSs) in Orion – the suit ARS (or 'suit loop') and the cabin ARS (or 'cabin loop'). A set of four LAMs are flown in Orion so that sets of two can redundantly monitor the two separate ARSs. The suit loop air is composed of almost 100% oxygen, with the balance being CO_2 and H_2O exhaled by the astronauts. The cabin air is meant to mimic more closely the earth atmosphere, being made of approximately 80% N_2, 20% O_2, with the amount of humidity and CO_2 fluctuating based on crew activities. For instance, the CO_2 and H_2O levels increase when the astronauts exercise. The total pressure at the cabin will be around 14.7 psia, but it will also be kept around 10.2 psia for long periods of time.

The tight O_2 uncertainty specification is driven by keeping the O_2 around 2.8-3.0 O_2 partial pressure when the cabin air is at a total pressure of 10.2. Therefore, the tight O_2 uncertainty specification, only applies to the LAM units that will monitor the cabin ARS, while the LAMS units that monitor the suit ARS only need to meet the loose O_2 uncertainty specification. The LAMS that needs to monitor the cabin loop need to meet the ±0.05 psia uncertainty specification because the measurements from those units are used to determine how often to cycle certain valves and other mechanisms that control the release of oxygen into the cabin. If the LAMS units cannot meet this accuracy, then the valves must be cycled more often, thus chipping away more quickly at the lifetime of those devices.

For the Artemis 4 & 5 build contract, an effort was undertaken to reduce the oxygen measurement uncertainty by removing the sapphire windows from the laser-side O2 optical train. This effort was executed in parallel to making additional units that were 'build-to-print' (BTP) of the Artemis 3 design. While the LAMS team was assembling the BTP units, they discovered an optimization to the collimation procedure that greatly reduced the uncertainty of the oxygen measurements.

C. Improvements to Oxygen Measurement Accuracy by Adjusting Collimation Procedure

During the Artemis 3 assembly process, the team noticed that the way the O2 lasers were collimated had a significant impact on the level of fringing, which is the main source of measurement uncertainty in this system. At the time, the lasers were collimated, then the collimation lens were adjusted up and down. As the lenses were adjusted, the team used custom software to analyze the level of fringing in the optical system. A lens to laser distance was chosen that minimized the level of fringing.

At that time, it was assumed the optimal lens-to-laser spacing that minimized fringing was somewhat random for each unit. Prior to stating the collimation process for the Artemis 4-5 BTP units, the team conducted a study of past, Artemis 3 units, collimation versus fringing levels, and a trend was discovered. That trend showed that, within a certain range, as the collimation lens was moved closer to the laser, the fringing levels were reduced. Based on this realization, a more thorough study of lens-to-laser spacing versus fringing levels was conducted. This study confirmed the trend seen in the Artemis 3 units and provided an optimal lens-to-laser spacing to target for the next series of laser collimation.

This discovery proved to be extremely valuable because it resulted in a significant reduction in fringing levels. Modeling conducted by JPL team members predicts that to meet a total uncertainty of ±0.05 psia the fringing levels need to be 5e-4 fractional absorbance units (FAU) or lower. For the Artemis 4-5 BTP effort, five LAMS Herriott cells were assembled. All the Artemis 4-5 Herriott cells had fringing levels between 5.15e-4 and 7.09e-4 FAU. This is a significant improvement over the Artemis 3 units where the best unit, and the only one that was fully certified for cabin air measurements on the Artemis 3 mission, had a fringing level of 1.04e-3 FAU, and all the other units had fringing levels that ranged from 2.11e-3 to 2.35e-3 FAU. Thus, by adjusting the collimation of the lasers in this manner, the fringing levels were reduced by a factor of three.

Table 1. Artemis 4 Optical Assembly Fringing Levels

Artemis 4 LAMS Serial Number	Fringing Levels, FAU
001	6.97E-4
002	7.39E-4
003	5.73E-4
004	4.70E-4
005	5.57E-4

D. Improvements to Oxygen Measurement Accuracy by Removing Sapphire Windows

Prior to starting the Artemis 4-5 LAM assemblies, fringing data from the Artemis 3 was analyzed to determine potential sources of fringing that could be targeted for re-design. The method used to analyze the data is called free spectral range (FSR) analysis. This is done by filling the Herriott cell with nitrogen so that no absorption peaks are visible in the spectra, and only a linear ramp remains in the signal. A line (or in some cases a second-order polynomial) is fit to the spectra with a linear regression algorithm. The residuals of the fit are then put through a Fast Fourier Transfer (FFT) algorithm to get the frequency components of the residuals. Since fringing manifests in the spectral signal as a sign wave over-laid on the normal spectral ramp signal, the FFT of the residuals yields the frequencies of various cavity modes that cause fringing. The results of the FFT yield the frequency of all standing waves in the optical train, from which the actual cavity length can be calculated. Figure 2, below, shows an example plot of the FSR analysis for an Artemis 3 O_2 channel under 100% N_2. This figure shows that the largest amplitude fringe is generated by a cavity with approximately 1 cm optical path length.

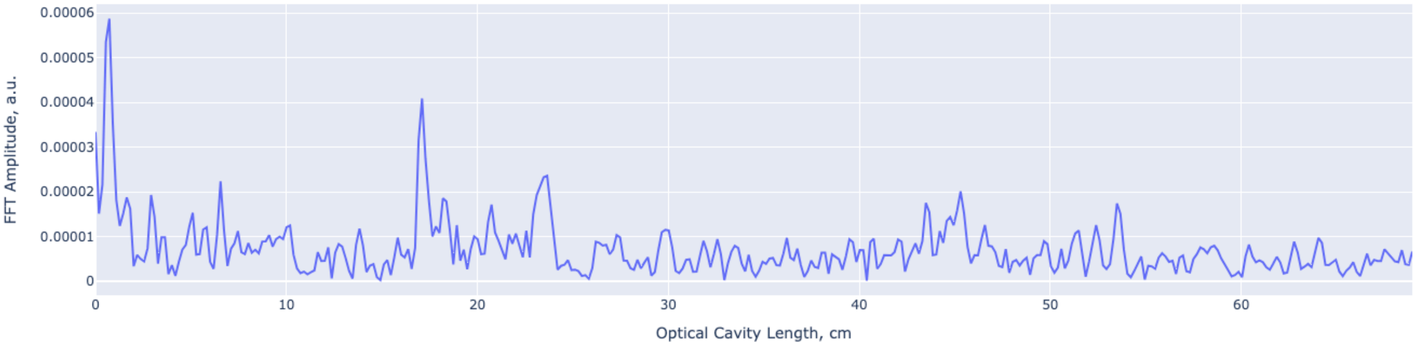

Figure 2. Example Free Spectral Range Plot. Large peaks correlates to a larger fringe amplitude caused by a cavity of the length specified on the X-axis.

Free spectral range analysis for this system is only accuracy to approximately ±20% of the optical cavity length, making it hard to identify the specific cavity in the optical train that is causing the fringe. Based on analyzing the physical spacing of components within the optical train, the sapphire window that sits between the O_2 channel collimation lens and the gas sample cell was identified as one of the most likely sources of fringing. Based on this analysis, the team undertook and effort to redesign the O_2 laser-side fore-optics to exclude the sapphire window.

The sapphire window was originally included in the design to meet the fracture criticality rating levied on all components that make up the suit ARS. This rating applies to the suit ARS for the contingency scenario when the pressure hull of the Orion capsule develops a leak (perhaps caused by a micro-meteorite or some other emergency), in which case, the astronauts will don their space suits and helmets, and hook up to the space suit ARS for the entire return to earth. Sapphire windows were selected to serve as the pressure barrier between the LAM flow cell, through which the sample air circulates, and the laser and detector optics. Sapphire was specifically selected because its fracture mechanics are well known and can therefore be analyzed against fracture specifications.

Since the fracture criticality rating is only needed for the LAMS units utilized to monitor the suit ARS, NASA preferred to have one set of specifications for all the LAMS units, not a separate set of specifications for suit ARS vs.

cabin ARS LAM units. NASA decided that is more desirable to have LAM units that can meet the tight O_2 uncertainty specification than to have only one set of specifications for both ARS's. Based on this direction from NASA, the team undertook an effort to investigate how much the measurement uncertainty could be reduced by removing the laser-side sapphire window for LAM units used on the suit ARS.

This study was conducted by redesigning the O_2 channel lens-and-window mounts to exclude the window and to include a 360° bond line for the O_2 collimation lens. The new design was manufactured, and fringe testing was conducted for replicates of the new design and replicates of the Artemis 3 design to get a side-by-side comparison of the fringing levels of the new design. These designs were tested by placing collimated laser and lens assemblies into a Herriott cell, filling the Herriott cell with N_2, then using a heater-chiller unit to ramp the Herriott cell through an 11°C temperature ramp, as this amount of temperature change is necessary manifest a full phase change of fringing. While the system was undergoing the temperature ramp, spectra were continuously record and fit, and the residuals were recorded. Once the temperature ramp was complete all the recorded residuals were analyzed by custom software that determined the fringing levels of the test. The same Herriott cell and photodetector assembly were used for all tests, only the laser assemblies were swapped out to isolate any variation to just the laser assemblies.

The results of this study, listed in Table 2 below, showed an average reduction of fringing levels by approximately one order of magnitude as compared to the Artemis 3 design, which included the sapphire windows. In addition to the order of magnitude reduction in fringing levels, the fringing levels were also much more consistent for the windowless units as compared to the units that include windows. This study shows that removing the sapphire windows from the laser-side fore-optics results in significantly lower and more repeatable fringing levels.

Table 2. Comparison of Fringing Levels Between Windowed and Windowless Subassemblies

O2 Channel Configuration	Avg Fringe Level, FAU	Std. Dev. of Fringe Level, FAU
Units with widows	1.05E-03	4.35E-04
Windowless units	6.39E-04	6.37E-05

Since this testing was only conducted at the sub-assembly level, the next step was to build engineering development units (EDUs) of entire LAM sensors with without windows included in the laser fore-optics. The EDUs would be used to take continuous partial pressure measurements of known gas concentrations while varying the temperature of the EDUs. This testing would show the impact of fringes on partial pressure measurements, allowing the team to assess if the fringing levels were low enough to meet the accuracy specification. When the windowless EDUs were built, their fringing levels were higher than the windowless subassemblies. Instead of being around the 6.4E-4 FAU level like the subassemblies above, on average, they were around 1.0E-3 FAU, see Table 3 below for unit-specific fringing levels. This suggested that the laser-side sapphire window was not the primary source of large fringes, but that the sapphire window in the photodetector subassembly was a more likely candidate. Another potential source of the higher fringe levels is that the laser alignment was somewhat negatively impacted from all the repeated use of the hardware during subassembly testing. Despite the higher-than-desired fringe levels, actual measurement variance testing showed that the windowless units produced less measurement variance than anticipated.

Table 3. Windowless EDU Fringing Levels

Windowless EDU Serial Number	Fringing Levels, FAU
001	1.0E-3
002	8.0E-4
003	1.5E-4

Ultimately, since the windowed units with the modified beam collimation produced lower fringing levels than the windowless subassemblies and windowless EDUs the NASA team decided to continue using the windowed design with the modified collimation instead of utilizing the windowless design. At the time of writing this article, final calibration and accuracy testing is has not yet been completed. Despite final accuracy testing not being completed, based on the fringing levels achieved, the windowed units are expected to closely meet the tight-O_2 accuracy specification.

IV. Conclusion

Leidos-Dynetics has continued to successfully manufacture Criticality-1R tunable diode laser absorption spectrometers for use as the primary atmosphere monitor for NASA's Artemis missions. While building the LAMS units for the Artemis 4 and 5 missions, the LAMS team was able to improve the overall system reliability by updating the laser and TEC power sequencing in the LAMS flight firmware. The team investigated a new design that did not include a sapphire window in the laser fore-optics subassembly. The new design was tested to see if fringing levels were reduced as compared to the existing design that includes the sapphire window. Since the windowless design did not show significant reduction in fringing levels, the team decided to stick with the pervieous design. The modification that was added to the laser collimation procedure resulted in fringing levels in the upper 5.0E-4 range for multiple. units, which is expected to closely meet the tight oxygen accuracy specification.

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References

[1] Pohly JG, et al. “Orion LAM Laser Absorption Spectrometer for Human Spaceflight – Flight Unit Build and Test Results” ICES 2020-360, 2020.

[2] Pohly JG, et al. “Orion LAM Laser Absorption Spectrometer for Human Spaceflight – Artemis 3 Flight Unit Build and Test Results” ICES 2023-302.