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Orion LAM Laser Absorption Spectrometer for Human Spaceflight – Flight Unit Build and Test Results

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The Orion Laser Air Monitor (LAM) is a tunable laser spectrometer that will monitor oxygen, carbon dioxide, and water vapor levels in the Orion Multipurpose Crew Vehicle (MPCV) cabin and space suit air loop. Four LAM instruments comprise the LAM System (LAMS). LAM, despite being small, lightweight, and lower power, can accurately measure a wide dynamic range of analyte concentrations over relatively wide pressure and temperature ranges without using gas pumps, flow, or pressure controllers. Additionally, the LAM hardware and electronics meet the stringent criticality requirements for human life support. This is the first time a tunable laser spectrometer is being used for atmosphere monitoring and feeback control for ECLSS hardware in a manned spaceflight environment.

Nomenclature

LAM = Laser Air Monitor
LAMS = Laser Air Monitor System
TLAS = Tunable Laser Absorption Spectroscopy
MPVC = Multi-Purpose Crew Vehicle
TEC = Thermoelectric Cooler
AR = Anti-reflective
ECLSS = Environmental Control and Life Support System
PSI = Pounds per square inch
PSIA = Pounds per square inch absolute
mmHg = millimeters mercury (pressure measure)
EDU = Engineering Development Unit
ADC = Analog to Digital Converter
MPCV = Multi-Purpose Crew Vehicle
Crit-1R = Criticality 1 Redundant
PCBA = Printed Circuit Board Assembly
HDLC = High-Level Data Link Control
Vpp = Voltage peak-to-peak
TEC = Thermal electric cooler

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I. Introduction

THE Orion Laser Air Monitor System (LAMS) is comprised of four LAM instruments, each of which is a tunable laser absorption spectroscopy (TLAS) instrument designed to monitor oxygen, carbon dioxide, water vapor and pressure in the cabin and space suit air loops of the Orion Multi-Purpose Crew Vehicle (MPCV). The Orion LAMS is classified as Criticality-1R (Crit-1R) hardware, which is one of NASA's highest criticality ratings. For context, the o-rings in the Space Shuttle solid rocket boosters were considered Crit-1.

Tunable semiconductor laser spectrometers have been an essential part of NASA Earth Science since the 1980s[1]. Early high-altitude aircraft spectrometers used cryogenically-cooled lead-salt lasers to measure chemical species at the parts-per-trillion level, enabling understanding of critical Earth systems. As tunable lasers matured towards room-temperature operation, synchronous miniaturization of tunable laser spectrometers permitted their integration into NASA Planetary Science platforms such as the Tunable Laser Spectrometer on the Mars Curiosity Rover to understand geochemical processes and possible life signatures on Mars[2]. NASA also invests in tunable laser spectrometer demonstrations for monitoring of gases important to human spaceflight on ISS[3].

LAMS is the first tunable laser spectrometer system being used for atmospheric monitoring and feedback control for Environmental Control and Life Support System (ECLSS) hardware in a manned spaceflight environment. Motivation and previous TLAS development towards this goal are described elsewhere[4].

II. System Specifications

The Orion LAMS is required to monitor pressure, oxygen, carbon dioxide, and water vapor levels in the Orion MPCV. The LAMS provides the primary pressure measurement for both the cabin air and space suit air loops, and it is the primary sensor used to monitor the three aforementioned analytes. The meauserment specifications for the system are listed in Table 1.

Table 1. LAMS Measurement Specifications

Parameter Monitored	Range	Accuracy	Precision
Total Pressure	2.1-24.2 psia	±0.3% Full scalue output	±0.02 psi
Partial Pressure H_2O	3.62 – 40.00 mmHg	±0.2 mmHg	N/A
Partial Pressure CO_2	0 – 7.76 mmHg	± 0.31 mmHg	N/A
Partial Pressure O_2 Range 1	1.90 – 7.40 psia In Total Pressure Range 2.1-7.4 psia	± 0.5 psia	N/A
Partial Pressure O_2 Range 2	1.90 – 5.50 psia In Total Pressure Range 7.5 – 15.5 psia	± 0.5 psia	N/A
Partial Pressure O_2 Range 3	1.9 – 24.2 psia In Total Pressure Range 15.6-24.2 psia	± 0.5 psia	N/A
Partial Pressure O_2 Range 4	1.90 – 5.50 psia In Total Pressure Range 7.5 – 15.5 psia	± 0.05 psia	N/A

All of the measurements listed in Table 1 are required to be accurate in a temperature environment from 2.2°C to 49.4°C (36°F - 121°F). The system was also required to provide all four measurements at a rate of one hertz. All of the electronic parts used in the system are required to be radiation tolerant and meet stringent reliability requirements due to the criticality of the system and mission requirements. All of the firmware written for the unit was classified as Class A, which is NASA's highest criticality rating for software. This meant that every line of code had to be written from scratch and every subroutine tested. The team had to develop unit and integration tests that provided

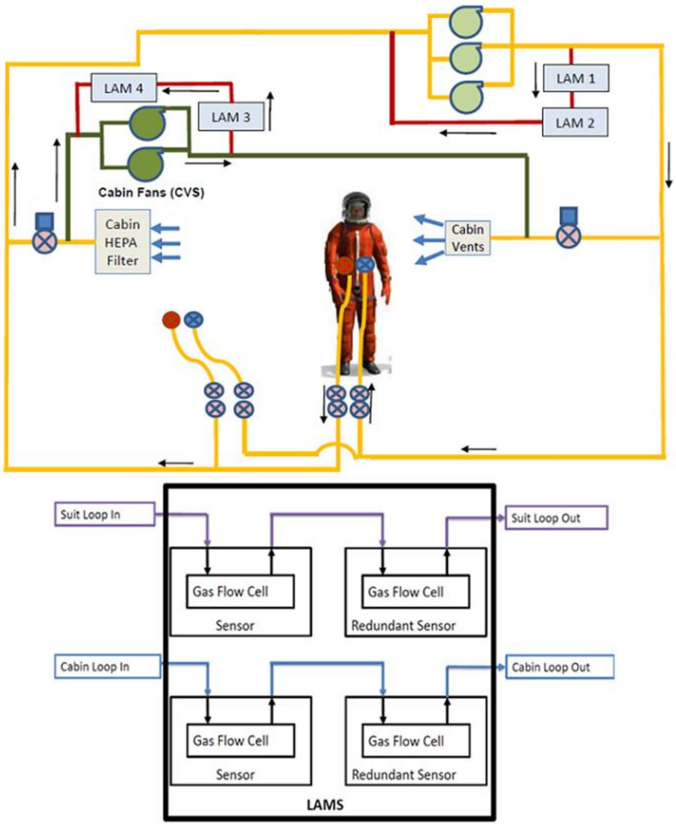

Figure 1. Role of LAMs for Orion. *Left:Schematic of LAM within Orion. Right: Close-up schematic of LAM*

100% code and branch coverage. Another challenging constraint was the tight schedule - the entire project was taken from inception to delivery in just under two years.

III. System Description

In the Orion MPCV, two LAM instruments will be plumbed in series to monitor the cabin air and the other two will be plumbed in series to monitor the space-suit air loop. This is shown in Figure 1. Fans induce the flow of analyte gas through each of the LAM instruments. There is no active pressure control.

A schematic of the analysis cell is shown in Figure 2. The measurement system consists of two commercial diode lasers in hybrid packages (Nanoplus GmbH, TO-5 packages) that define the two measurement channels. One channel uses a diode laser whose beam makes a single-pass (8.15 cm optical pathlength) through the measurement region with an emission wavelength of 2683.3 nm. This channel detects both CO_2 and H_2O. The second channel uses a diode laser with emission wavelength at 760.9 nm. This channel was coupled into a multi-pass Herriott cell configuration using spherical mirrors in order to get an optical depth with an sufficient signal-to-noise ratio (SNR) for detection of oxygen across the specified partial pressure ranges.

As part of this project, the team built five Engineering Development Units (EDUs) and eight flight units. Each of the units underwent full system shock and vibration, thermal testing at the NASA Johnshon Space Center (JSC) and KBR/Wyle and were re-tested after these tests to ensure full compliance with required measurement sensitivities as listed in Table 1.

The overall design of the system consists of four individual Laser Air Monitors (LAMs) that can be stacked together with each unit serving as the lid for the previous unit, and the last unit having a dedicated lid. All four units are bolted to a single mounting plate that attaches to the structure of the Orion MPCV. Figure 3 shows the LAMS in its flight configuration, with each of two set of units plumbed in serial.

Each inidivual LAM consists of an enclosure, a flow cell, and an electronic control

Figure 2. LAM Schematic *Curved surfaces are mirrors. On the left side is the 2683 nm laser which emits a single pass beam (blue) to a room-temperature mercury cadmium telluride detector on the opposide side. On the right side is the 760 nm laser which emits a multi-pass beam (red) with several meters optical pathlength which impinges on a silicon detector on the opposite side. For scale, the distance between mirrors is around 8.15 cm.*

printed circuit board assembly (PCBA). The flow cell houses all of the components that are critical for gas analysis. The flow cell consists of a Herriott cell assembly, a pressure transducer, a thermistor, and a housing to which everything mounts and that provides a hermetic seal. The Herriott cell assembly consists of two spherical concave mirrors that multi-pass the 760.9nm laser. Each mirror attaches to a spacer that tight controls the lateral spacing and parallelism of the the mirrors. A laser diode and collimation assembly, a photodetector, and a thermistor are mounted to each mirror. One mirror holds the 760.9nm laser and a Mercury, Cadmium, Telluride (HgCdTe) detector. The other mirror holds the 2683.3nm laser and a silicon photodetector. The laser collimation assemblies both consist of a single aspheric collimation lens with anti-relective coatings for the wavelengths of their respective lasers. The lenses are mounted into a threaded barrel that is screwed into a threaded ring that gets bonded to the laser can. The lasers were collimated using a custom laser collimation fixture that was designed and built during the course of this project. Each laser is a Distributed Feedback (DFB) Tunnable Diode Laser (TDL) in a TO-5 can. Each laser package has an internal thermoelectric cooler and thermistor that provide temperature control of the laser diode. The laser collimation assemblies, photodetectors, and thermistors are epoxied and potted into the back of the mirrors. The Herriott cell assemblies also include sapphire windows in front of each laser and detector that provides a pressure barrier between those electro-optical components and the gas being analyzed. Each set of two windows is placed a 3° angle and coated with an anti-reflective (AR) coating, appropriate to the respective wavelengths of the lasers, in order to prevent standing optical waves, which produce noise, or ‘fringes’ in the final analytical detector signals.

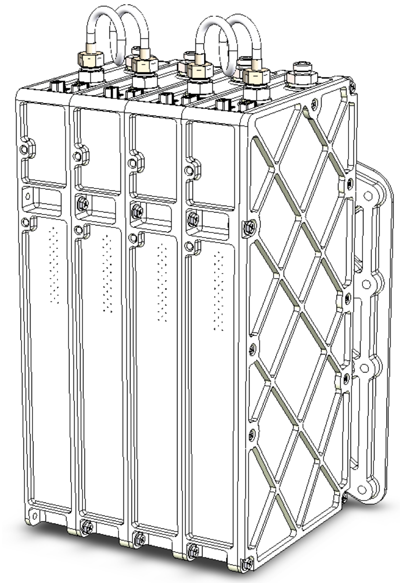

Figure 3. LAMS Physical Structure. *Four LAM units. Two are in series for the suit loop, two are in series for the cabin loop. Overall dimensions are 10.0×16.6×7.5 inches. Mass is 22 lbs.*

Each LAM has a single PCBA that holds all of the necessary electronics to control the system, condition and provide power to the electronic subsystems, make measurements, calculate partial pressure levels of the analytes, and communicate with the Orion MPCV flight computer. The electronic subsytems include a microcontroller, a communication subsystem, a current control circuit for each laser, a thermoelectric cooler (TEC) control circuit for each laser, and necessary filters and analog-to-digital converters (ADCs) for getting the signals from the thermistors, pressure transducer, and photodetectors to the microcontroller. One thermistor, extending out from the analysis cell wall, measures the gas temperature in the analysis region. Other thermistors are embedded near both lasers. At the gas flow rates used for LAM measurements, these thermistors agree to within 0.2 K and the cell metal temperature dictates the temperature of the analyte. Error analysis shows that ±0.1 K uncertainty in temperature measurement translates into < 0.1 % uncertainty in reduced concentration measurement. The pressure transducer is a GP:50 Model 7100 with the following specifications: ±0.3% full-scale accuracy; full-scale is 2 bar.

The microcontroller is a 300 MHz, radiation tolerant, SAMV71 made by Microchip (formerly Atmel). For the reliability requirements of this project, the microcontroller was clocked back to 240 MHz. The microcontroller provides current control of the lasers via a digital-to-analog function interfaced to an external current driver; takes in measurements from the thermistors, pressure transducer, and photodetectors; uses that data to calculate analyte partial pressure; and sends and receives messages to the Orion flight computer through the communication subsystem. This microcontroller has a radiation hardened version that is expected to be available in 2020 that states immunity to 70 MeV cm^2 mg^{-1}. However, this needs to be verified. Radiation qualification at the system level is expected to occur in the latter half of 2020.

Key to the success of flight-qualified LAM and any flight-qualified human exploration tunable laser spectrometer are obtaining lasers that can pass Criticality 1 level requirements. While the technology exists to produce mW or higher levels of single-wavelength emitted light from semiconductor laser chips at room temperature at almost any wavelength through the mid-IR, flight qualifying semiconductor lasers remains in its infancy. There is data on the radiation performance of GaSb diode lasers[6] but extrapolating that to other laser materials and internal structures (interband- or quantum- cascade) is not straight-forward. Almost all of what is referred to as ‘lasers’ is actually a hybrid package of components such as thermoelectric coolers, package material, solder joints, thermistors, windows, internal coatings, internal bath gas. Generally, these materials, as well as the laser chips themselves, are sourced from foreign vendors with little flight experience. Working in tandem with laser material growers, fabricators, packagers, and testers to generate a consistent, reliable source of this essential component is a paramount importance. Radiation testing for total ionizing dose (TID) and proton displacement damage (DD) for the opto-electronics (both types of lasers and both types of detectors) has already been done and will be reported elsewhere. For the LAM application, the lasers were tested to greater than 100 krad total ionization dose in silicon and greater than 5×10^{11} cm^{-2} proton dosage for both types of lasers.

The communication subsystem consists of an FPGA and RS-422 tranceivers. This system takes serial communication messages from the microcontroller, converts them to the Orion High-Level Data Link Control (HDLC) data protocol, and then passes them to the Orion flight computer. A reverse series of operations is carried out when receiving messages from the Orion flight computer and passing them along to the microcontroller.

IV. Spectroscopic Methodology Design and Selection

The first step in the design of LAM was to select the absorption features from which to make measurements and the second step was to select diode lasers whose tunning ranges encompassed the selected absorption features.

For oxygen, a single absorption peak centered at 13142.58 cm^{-1}, with a linestrength of 8.847E-24 $cm^{-1}/(molec\times cm^{-2})$ was selected. It was then determined that a pathlength of 235 cm would be used in order to provide absorption depths that give high signal-to-noise ratio for the specified range of oxygen concentrations. The selected lines are shown in Figure 4.

For carbon dioxide and water vapor, spectroscopic absorption features in the range of 3726.4 – 3727.2 cm^{-1} were selected. Spectral modeling for this wavelength is shown in Figure 5. Both molecules have multiple absorption peaks in this range with the most significant CO_2 peak being located at 3727.08 cm^{-1} with a linestrength of 5.93E-20 $cm^{-1}/(molec\times cm^{-2})$, and the most significant H_2O peak

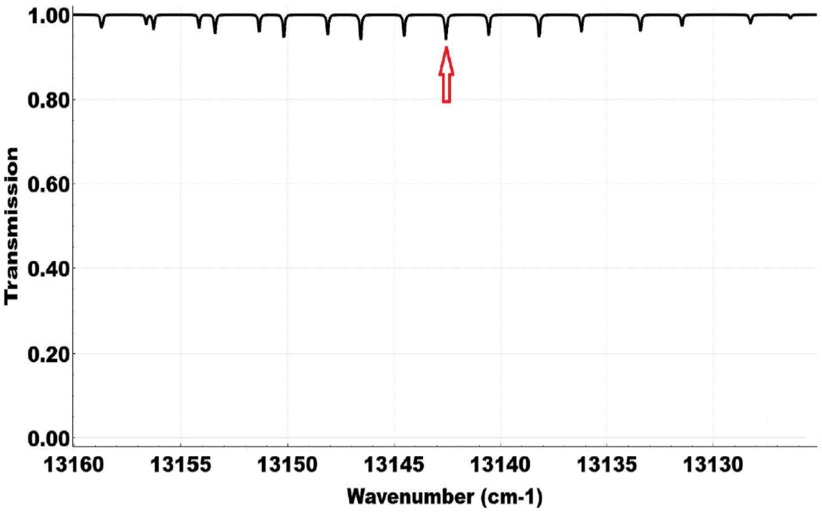

Figure 4. Modeled Spectra of Oxygen *Model spectra of 20% O_2 for 230 cm optical pathlength, 980 mbar, 298K. Arrow points to target spectral feature.*

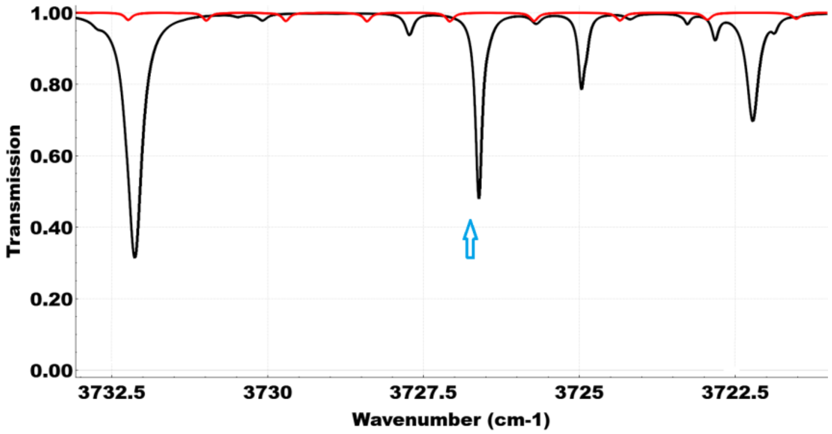

Figure 5. Modeled Spectra of Water and Carbon Dioxide *Model spectra of 1.5% water vapor (black) and 500 ppm CO_2 (red) for an 8-cm optical pathlength at 980 mbar, 298 K. Arrow points to central target wavelength.*

located at 3726.62 cm^{-1}, having a linestrength of 3.18E-20 cm^{-1}/(molec×cm^{-2}). These absorption features were selected because they were close enough together to be scanned by a single laser, but far enough apart, even under the largest collisional broadening conditions, to identify absorption of each species individually. The optical path for the 2683.3 nm laser used to scan across these features is 8.15 cm. This optical pathlength, along with the linestrength of each molecule provided adequate signal-to-noise ratio for resolving partial pressures in the specified range.

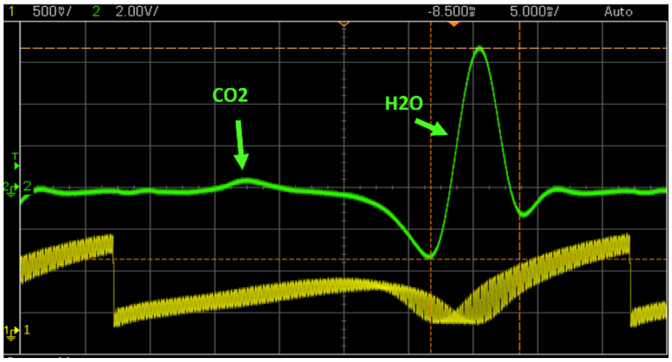

Figure 6. LAMS measurements of CO_2 and H_2O. *The green trace is the WMS-2f signal. The yellow trace is the DC signal. These data were obtained at 295 K and 1 atm with ambient CO_2 (around 450 ppm) and H_2O (1%).*

The first spectroscopic method evaluated for LAMs was second harmonic detection wavelength modulation spectroscopy[5] (WMS-2f). This method consists applying a high frequency sine modulation to the laser injection current. Since the TLD's used for LAMs change wavelength as a function of the laser current, this results in modulating the laser wavelength around an operating point. The modulated signal is then subsequently demodulated at a harmonic of the input signal. It is common to use the second harmonic of the input signal, since the resulting signal has the greatest peak-to-peak height, and therefore, the highest signal-to-noise ratio, for a given amount of analyte concentration. Figure 6 shows an example of the WMS-2f signal for CO_2 and H_2O for the 2683 nm laser channel.

The LAMS team first developed the data reduction code to us the WMS-2f technique first because this method required the least amount of software development work. Since every line of code and every possible branch of code had to be thoroughly tested and scrutinized, and because schedule was the major driver of the project, the team determined that this method would be the quickest to implement and test. The software required to test this method consisted of laser drive functionality that was responsible for outputting a ramp current signal that ramped the laser current across the targeted absorption features. It also had to generate a high frequency sine modulation current in the range of 1-10 kHz. These two signals were output by the microcontroller, then summed together with analog electronics. Upon receiving the signals from the photodetector, the software demodulated the high-frequency ramp, producing a WMS-2f signal. The software then located each peak and calculated the peak-to-trough height, here designated as Vpp.

In order to calculate the analyte partial pressures, calibration curves had to be developed that correlated Vpp, pressure, and temperature to the partial pressure of each analyte. In order to do this, a calibration system was developed that provided independent control of those three parameters. Vpp values were recorded across a range of known pressures, temperatures, and analyte concentrations. During testing with this 2f WMS-2f data reduction methodolgy, it was observed there was a lot of cross-correlation between the CO_2 and H_2O signals for the 2683 nm channel. While this was expected because modulation causes the wavelength convolution on the order of hundreds of MHz (the modulation amplitude of the WMS-2f) and could be modeled, the modeling did not capture the entirety of all contributions to the WMS signal. For example, the WMS signal is affected by the low-pass filtering in the circuitry which was difficult to model and made deconvolving the CO_2 and H_2O signals difficult. Because of this this cross-talk and the issues in attaining robust calibration, we changed from WMS-2f to direct absorption fitting.

V. Direct Absorption Fitting

The use of direct absorption fitting for TLAS instruments is very common. In comparison with 2f-WMS, there is less spectral mixing of CO_2 and H_2O absorption signals in the 2683 nm measurement channel which makes measurements more accurate. Direct absorption fitting also, in theory, does not require calibration of the signal chain. For example, the 2f WMS signal is directly related to the gain of the 2f signal chain and is affected by any filtering. In contrast, the direct absorption signal is ratiometric - concentration information from data reduction is derived from the Beer-Lambert law. Further, direct absorption signals usually have a much higher dynamic range. At higher conentrations of analyte, the information that contains the concentration information moves to the wings of the direction absorption profile in a predictable way which can be modeled and fitted. This cannot be done for 2f-WMS where at high concentrations, it is difficult to predict the behavior of the waveform.

The cost of using direct absorption spectroscopy is that the data reduction is much more processor intensive. Most implementations of 2f-WMS data reduction basically determine the minimum and maximum signal from the digitized waveform. For the direct absorption spectroscopy data reduction used for LAM, a Levenberg-Marquardt non-linear fitting algorithm was developled. All firmware for the sensor is rated Class A, which is NASA's most stringent software classification. The software requires a high level of scrutiny, to the point where every line of code, every single subroutine, has to be either written and verified from scratch or evaluated and tested line-by-line.

VI. Future Planning and Development

The Orion Laser Air Monitor LAM is being built for delivery and integration into the vehicle for initial flight on the Orion Exploration Mission 2 flight currently scheduled for 2023. Nominally, this system will prove to be robust, reliable, and functionaly capable of meeting all objectives for a Criticality 1 human spaceflight system. Once successfully field proven, TLAS sensors may reach additional applications in human spaceflight, as well as in industry, military applications, and other highly demanding environments where human safety is critical and therefore accuracy, reliability, and operational ruggedness are paramount. While there will remain many applications for traditional mass spectrometry type systems, TLDAS sensor offer multiple advantages for SWAP vs systems currently in use, namely small form factor, relatively low power requirements, stability vs need for calibration, and hardware robustness.

VII. Conclusion

TLDAS remains a relatively young technology, and one that has seen a significant boost in recent years due to the availability of small, robust lasers. The implementation of TLDAS into Criticality 1 systems for human spaceflight offers a progressive step toward the verification and qualification of the technology for a wide range of applications, while simultaneously adding a useful new option to the engineering toolkit available to support human spaceflight.

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