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Maximizing Scientific Exploitation of Raman Spectroscopy With A.C.M.E. (Atmospheric Chamber for Measurements in Environment)

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ABSTRACT

The Atmospheric Chamber for Measurements in Environment (A.C.M.E.) provides a versatile and highly controlled environment for simulating planetary conditions, supporting the testing and calibration of instruments for planetary exploration. In this study, we utilized A.C.M.E. to evaluate the performance of a novel hollow-core fiber (HCF) Raman gas sensor prototype developed by the ERICA research team. By integrating the HCF sensor with a dedicated spectrometer, we confirmed that Raman spectrometers, such as the Raman Laser Spectrometer (RLS), could be used for atmospheric gas analysis in future planetary missions, expanding their applications beyond mineralogical studies. By using the A.C.M.E. chamber to produce representative gas mixtures, this work analytically demonstrated that, once optimized, the HCF sensor prototype could be potentially used to investigate the atmosphere of both Mars and Venus in future planetary missions. These findings underscore the critical role of atmospheric chambers like A.C.M.E. in advancing technologies for future planetary exploration missions.

1 | Introduction

Novel planetary exploration missions increasingly rely on spectroscopic instruments to achieve their scientific goals. Spectrometers enable the in situ identification and characterization of planetary surface and subsurface materials, providing critical insights into the geological, chemical, and potential biological processes of extraterrestrial environments. Since NASA's Mars 2020 mission successfully landed on Mars in February 2021, SHERLOC [1] (Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals) and SuperCam [2–4] instruments, onboard the Perseverance rover, have pioneered the use of Raman spectroscopy beyond Earth. Looking ahead, further rover missions are being planned in which Raman spectroscopy will play a key role. These include the Raman Laser Spectrometer [5] (RLS) onboard the ExoMars/Rosalind Franklin rover (to be launched in 2028) and the RAX spectrometer [6] onboard the MMX mission to Phobos (to be launched in 2026).

To maximize the scientific exploitation of Raman spectrometers (to be) developed, validated, and operated in other planets, the ability to perform representative support science activities on Earth is of critical importance [7]. In recent years, an increasing number of representative studies have been carried out, in which terrestrial analogue materials (Planetary Terrestrial Analogues Library, PTAL [8–10]) or simulants [11, 12] have been characterized by using Raman simulators that are able to provide analytical results qualitatively equivalent to the instruments to be operated in space (e.g., SimulCam [13] and RLS-Sim [14], for SuperCam and RLS, respectively).

However, higher degrees of representativeness are reached when Raman analysis is performed under representative environmental conditions [15–17]. To do so, dedicated atmospheric chambers need to be employed, as they help bridge the gap between laboratory conditions and the realities of operating instruments on other planets, where environmental factors significantly influence spectroscopic outcomes. This is because environmental parameters—such as atmospheric pressure, temperature, and radiation levels—can induce measurable changes in the spectral properties of planetary materials. For instance, low pressures promote the dehydration of hydrated phases [18], especially in freshly exposed subsurface samples; temperature variations affect the shape and position of hydration bands as well as changes in hydration states [19]; and UV radiation, while having limited impact on minerals, critically influences the preservation of potential organic biosignatures [20].

Besides revealing the spectroscopic behavior of minerals exposed to planetary environmental conditions, atmospheric chambers are also used to test the potential analytical performance of instrument prototypes to be eventually developed and validated for future planetary exploration missions. For instance, the RLS made extensive use of atmospheric chambers to evaluate the analytical performance of the Raman instrument during the development process [5].

Although atmospheric chambers play a critical role in planetary science, none of the options currently available on the market are specifically designed to support planetary exploration research. As a result, commercially available chambers typically allow for the regulation of only a limited number of environmental variables (most often temperature and humidity), while omitting the control of critical parameters essential for simulating planetary conditions (e.g., ultraviolet [UV] radiation exposure, atmospheric pressure variations, and tailored gas compositions).

This limitation significantly reduces the applicability of commercial atmospheric chambers for planetary exploration research. To overcome this issue, researchers in planetary science must rely on the use of customized atmospheric chambers specifically designed to meet the demands of space research. Over the past few years, a wide variety of atmospheric chambers have been presented, including PASC [21], PEACh [22], SpaceQ [23], and MEC [24]. A detailed comparative review of tailored chambers used in planetary and space research has been recently published by Wipf et al. [25].

Being at the forefront of Raman spectrometer development for planetary exploration (contributing to the development of SuperCam [26], RLS [5], MMX [6], and PANGAEA [27] spectroscopic instruments), the scientific activities performed by the ERICA research group (University of Valladolid) also rely on the use of a tailored atmospheric chamber. The development of such a chamber began over 15 years ago [28], driven by the need to simulate Martian atmospheric conditions for the RLS instrument. Initial designs focused on reproducing temperature and pressure environments that closely mimic those of Mars, enabling accurate calibration and operational testing. Since then, the chamber has undergone continuous upgrades to accommodate the evolving analytical demands of the group, integrating features such as advanced gas composition controls, radiation modules, and in situ spectroscopic capabilities. This iterative development process has culminated in the Atmospheric Chamber for Measurements in Environment (A.C.M.E.). A.C.M.E. is designed to provide the versatility and modularity needed to create highly customizable environmental conditions; this is critical to support a wide variety of planetary-related scientific activities.

In this manuscript, we present both a technical description of the A.C.M.E. chamber and a representative scientific application that demonstrates its experimental capabilities. To highlight the chamber's role in supporting the development of space instrumentation, we present a dedicated case study involving the testing of a novel Raman-based gas sensor prototype developed by the ERICA team. This sensor, based on hollow-core fiber (HCF) technology and operated with the RAD-1 Raman simulator, was evaluated under Mars- and Venus-like conditions generated within A.C.M.E. This case study thus serves to illustrate the scientific versatility of A.C.M.E. in enabling realistic and reliable testing of advanced spectroscopic technologies under representative planetary scenarios.

1.1 | Rationale of the Study

Mars 2020's SuperCam and SHERLOC instruments, along with the Raman Laser Spectrometer (RLS) on the ExoMars mission, represent the first Raman spectrometers validated for planetary exploration. Looking ahead, the application of Raman spectroscopy is being actively evaluated for a range of future planetary and astrobiology exploration missions to Phobos [29], Europa [30], and Enceladus [31].

While Raman spectroscopy in planetary research missions is primarily utilized for mineralogical investigations [32–35], its application to atmospheric and gas analysis has been largely limited due to the inherently low Raman scattering cross-section of gas molecules. This limitation poses significant challenges for detecting minor atmospheric components and even main constituents in low-pressure environments, such as those found on Mars. Despite this limitation, Raman-based gas sensors hold significant promise for future exploration missions due to their ability to simultaneously detect nearly all types of gas analytes, with the exception of noble gases, which lack a Raman signal due to their monoatomic nature.

On Earth, gas analysis using Raman spectroscopy has traditionally relied on dedicated gas probes, in which a mirror is added into the front of a conventional backscattering system, generating a theoretically four-fold intensified Raman signal [36].

In recent years, however, hollow-core fibers (HCF) have emerged as a highly promising alternative for gas probes in spectroscopic instruments.

Building on recent advances in Raman technology for space research, the ERICA team has recently developed the first gas probe based on the HCF technology that converts Raman spectrometers into extremely efficient gas analyzers. HCFs are a special type of optical fiber in which light is guided through a hollow core, allowing both the excitation laser and the target gas to be confined within the same optical path. This configuration significantly increases the interaction length between the laser and gas molecules, thereby amplifying the Raman scattering signal. These fibers not only demonstrate significant potential for improving Raman signal detection but also offer superior performance compared to conventional methods, making them an increasingly attractive solution for advanced gas analysis applications. Advancing in this line of research, the scope of this work is to explore the potential usability of the HCF sensor prototype in future planetary exploration missions to Mars and Venus.

Exploration rovers operating on Mars are systematically equipped with analytical instruments designed to study and characterize the Martian atmosphere. For instance, the Mars Environmental Dynamics Analyzer (MEDA) onboard Perseverance has demonstrated the periodic fluctuation of atmospheric pressure on Mars, with notable changes driven by CO_2 condensation and sublimation processes, as well as by the influence of airborne dust, which can amplify daily pressure cycles. These pressure fluctuations underscore the dynamic and complex nature of the Martian atmosphere [37]. As for future astrobiology missions to Mars, the use of gas sensors with enhanced sensing capabilities could play a pivotal role in detecting additional trace gases in the atmosphere, such as methane, whose formation on Mars has been often associated with biological activity.

On the other hand, Venus has an incredibly thick atmosphere, extending over 250 km in height, and is primarily composed of carbon dioxide (CO_2), with trace amounts of nitrogen and sulfur compounds. As the surface of the planet is approached, atmospheric pressure increases significantly, reaching a maximum of 92 bar. Venus' atmosphere is also characterized by the presence of dense, opaque clouds composed of sulfuric acid that shroud the entire planet, preventing optical observation of the surface from Earth or orbit [38]. These clouds form a thick deck extending from about 48–68 km above the surface, with thinner hazes reaching altitudes up to 90 km. Within the altitude range of these clouds, the atmospheric pressure varies between approximately 10 mbar and 1 bar.

2 | A.C.M.E. Technical Description

The Atmospheric Chamber for Measurements in Environment (A.C.M.E.) is a highly modular system, designed to accommodate a wide range of experimental setups for planetary exploration research. At the core of its design is a robust stainless-steel chamber, which serves as the primary environment for scientific experiments. This central chamber is equipped with multiple vacuum ports arranged radially, allowing for seamless integration of various auxiliary units and instruments required for diverse experimental configurations. This modularity ensures maximum flexibility, enabling researchers to easily adapt the chamber to the specific requirements of each study while maintaining precise control over environmental conditions. A general overview of the multiple units composing the A.C.M.E. system is provided in Figure 1.

2.1 | Vacuum Chamber

The vacuum chamber of the A.C.M.E. system is a custom-built unit fabricated from 304 stainless steel (304SS) to ensure durability and resistance to extreme conditions. It has a circular shape with a diameter of 40 cm and a height of 15 cm, providing an optimal volume for various experimental configurations. The chamber is equipped with multiple radially arranged vacuum ports (CF-DN40), allowing for the integration of auxiliary components and instrumentation tailored to specific experimental needs.

At the top of the chamber, a larger vacuum port (DN250) provides easy access to the chamber's interior for maintenance and sample placement. This top port features a vacuum viewport made of UV fused silica, capable of transmitting light across a wide wavelength range (195–2100 nm). The vacuum viewport serves a dual purpose: enabling operators to observe the chamber interior and allowing external light sources, such as those from a Raman spectroscopy unit or a UV irradiation unit, to reach the sample inside.

Depending on the experiment to be conducted, this chamber can be easily replaced with alternative chambers of different shapes and volumes, providing additional flexibility for various scientific applications. For example, the ERICA team also employs a second circular chamber with a diameter of 25 cm and a height of 10 cm. This smaller chamber is equipped with 8 radial vacuum ports and a larger top port (DN160) featuring a UV fused silica viewport. The performance tests with the HCF sensor presented in this paper have been performed using this smaller version to reduce the total volume.

The vacuum chambers come with a wide variety of fittings that further extend the versatility of the setup. These include fixed blank flanges used to cap off open ports when not required; tubulated adapters which transition from a CF flange to a KF mating flange to connect mismatched components; copper gaskets employed to create a vacuum seal between two flanges using bolts; connectors used to extend ports and pipework to a required length; and tees which increase the number of available ports as needed.

2.2 | XY Translation and Rotation Stage

Inside the conventional 40-cm-diameter chamber, a high-precision XY translation and rotation stage is installed to securely position the sample and enable precise remote control of its movement during experiments. This stage is constructed using commercial components from Thorlabs, combining the M30XY XY Stage and the DDR100 Rotation Stage mounted on top. The M30XY stage provides 30 mm of travel in both the X and Y axes, ensuring precise and stable motion with a bidirectional repeatability of ±1.0 μm and a minimum incremental movement of 2.5 μm. The platform, measuring

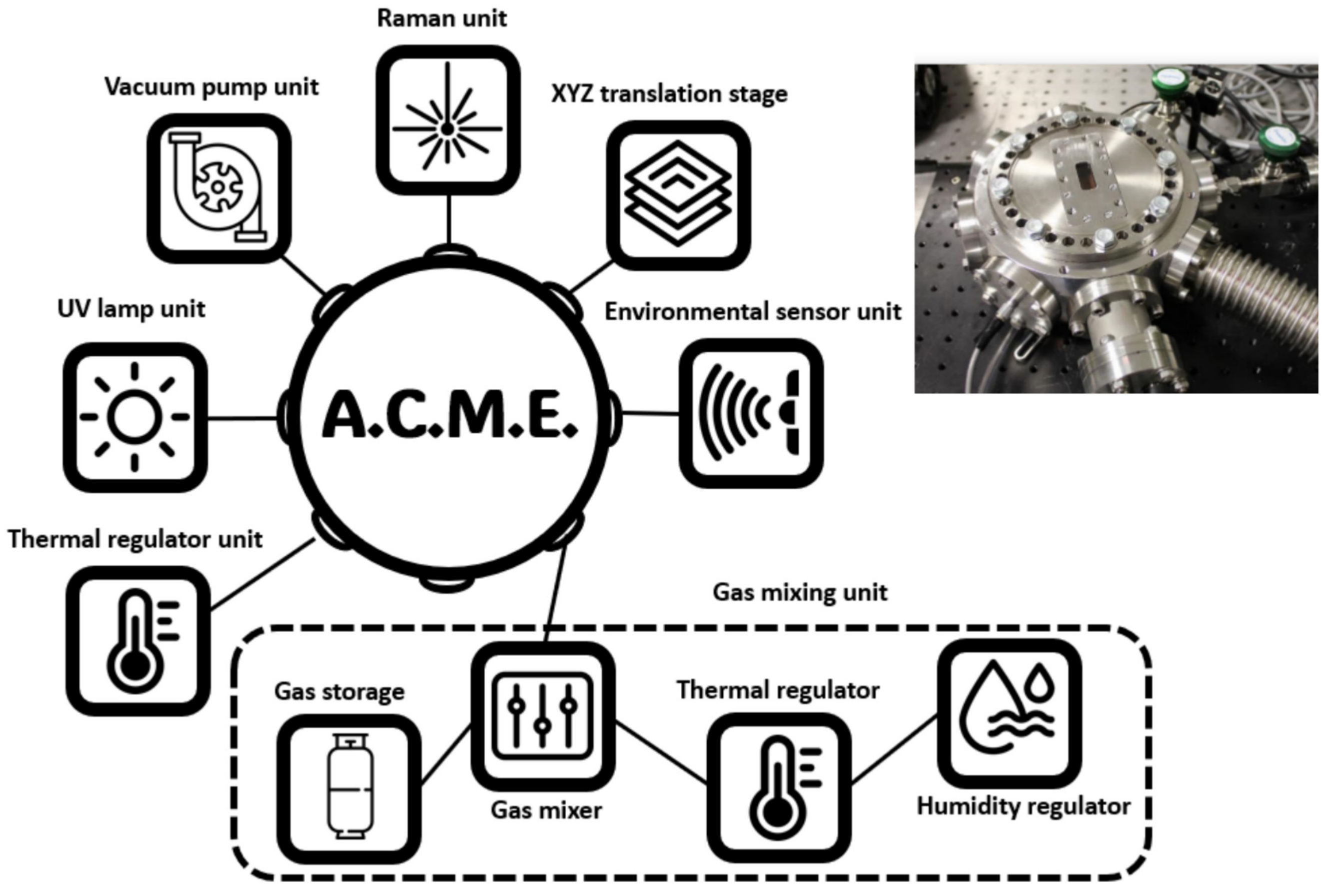

FIGURE 1 | General overview of the A.C.M.E system and its main modular units.

115 mm × 115 mm, can handle loads up to 5.0 kg and achieve speeds of up to 2.4 mm/s. The stage is remotely controlled using Thorlabs' Kinesis software suite. The stage is generally used when a precise sample positioning is required (e.g., to select the micrometric spot on the sample to be investigated by the Raman unit).

Mounted atop the XY stage, the DDR100 rotation stage provides 360° continuous rotation with a resolution of 2 μrad. The rotation speed can reach up to 180 rpm, and the stage supports loads up to 5 kg. The DDR100 is equipped with an integrated brushless DC servo motor actuator, delivering smooth, high-speed operation.

Together, these components enable precise translation and rotation, ensuring accurate alignment of the sample with external light sources, such as Raman or UV units. For example, the M30XY stage is typically used for precise positioning of the sample under the UV silica viewport, such as selecting the micrometric spot on the sample to be investigated by the Raman unit. In contrast, the DDR100 is utilized when multiple samples need to be sequentially positioned under the viewport without breaking the vacuum.

2.3 | Vacuum Pump Unit

The A.C.M.E. chamber is equipped with a high-performance vacuum system to create and maintain the precise low-pressure environments required for planetary simulation studies. The pump unit used for this purpose is the HiCube 80 Pumping Station from Pfeiffer Vacuum. This portable, bench-top vacuum solution is specifically designed for high and ultra-high vacuum (UHV) applications, making it an excellent choice for supporting the A.C.M.E. chamber's diverse experimental needs.

The HiCube 80 integrates a turbopump from Pfeiffer's HiPace series, paired with a backing pump tailored to the specific requirements of the user. This combination allows the system to achieve an ultimate vacuum pressure of 1×10^{-7} mbar, ensuring the capability to replicate even the most extreme extraterrestrial atmospheric conditions. The HiCube 80 is connected to the A.C.M.E. chamber via a flexible vacuum hose, which allows for easy alignment and adaptability to the chamber's configuration while maintaining high-performance standards required for planetary simulation studies.

2.4 | Raman Unit

Raman spectroscopic analysis does not require a dedicated spectrometer integrated within the chamber. Instead, Raman measurements are performed directly from outside the chamber through the silica viewport placed on top of the A.C.M.E chamber. This setup allows flexibility in the choice of spectrometers, as any commercial or custom-made system equipped with a Raman probe can be used. The long-distance objective of the probe is positioned near the viewport to focus the laser beam onto the sample inside the chamber. To ensure optimal focus, the probe is mounted on a Z-stage outside the chamber, while precise alignment of the sample under the objective is achieved using the XY translation and rotation stage described earlier.

2.5 | UV Light Source Unit

On Mars, the thin atmosphere allows the Sun's ultraviolet (UV) radiation to reach the surface with much higher intensity than on Earth, resulting in a daily UV fluence approximately 10 times greater than that experienced on our planet. This intense UV radiation significantly affects materials exposed on the Martian surface. Therefore, to conduct representative studies of Martian conditions, it is crucial to consider the impact of UV radiation on the materials under investigation. To replicate Martian UV radiation within the A.C.M.E. chamber, we utilize the Sirius-300PU-H light source from Zolix Instruments.

The Sirius-300PU-H is equipped with a 300-W Xe lamp that provides a high-intensity output across a spectral range from ultraviolet to near-infrared, making it ideal for simulating the effects of UV radiation on materials exposed to the Martian surface. The outer power is 6.6 W in the UV range (< 390 nm), 16.6 W in the VIS range (390–770 nm), and 26.8 W in the IR range (> 770 nm).

The Sirius-300PU-H features a high-efficiency parabolic condenser to ensure well-collimated and high-energy output, which is crucial for uniform irradiation of samples. High-efficiency air cooling ensures an extended bulb life and stable operation (emission stability > 99%).

The UV unit also integrates a liquid filter to prevent most of the heat produced by the lamp from reaching the sample, ensuring the integrity of the experimental conditions [39]. For this purpose, the 6214 liquid filter commercialized by MKS Newport is used. This filter is constructed from aluminum and includes a cavity designed to hold distilled water between two silica windows (3-in. diameter). The inner cavity features a relief valve preset at 15 psi to prevent damage to the windows, offering both effective thermal management and durability during prolonged operation.

2.6 | Thermal Regulator Unit

The average recorded temperature on Mars is approximately −63°C, with seasonal variations ranging from a maximum of 20°C during equatorial summers to a minimum of −140°C in polar winters. To simulate these conditions, the A.C.M.E. chamber is equipped with a custom-designed liquid nitrogen (LN2) storage and delivery system inspired by the design of the system used in the PEACh chamber [20]. This unit provides active temperature control within the chamber over a range of 21°C to −100°C. The LN2 is stored in a Dewar located outside the A.C.M.E. chamber. A resistor immersed in the LN2 reservoir heats the liquid nitrogen, causing it to evaporate into nitrogen gas (NG) at near-LN2 temperatures. This cold NG is then delivered into the chamber via a feedthrough, where it circulates through a toroid-shaped, double-walled copper block referred to as the cold plate (CP). Positioned inside the chamber, the CP ensures uniform heat exchange and precise temperature control. A separate feedthrough evacuates the NG after it has passed through the CP. The temperature of the CP is monitored and controlled by an electronic autotune controller. This controller uses a resistive thermal device (RTD) sensor to measure the CP's temperature in real time and adjusts the flow of cold NG entering the CP to maintain the desired thermal conditions.

2.7 | Gas Delivery Unit

Many of the experiments conducted in the A.C.M.E. chamber by the ERICA team, both space-related and non-space-related, are performed under carefully controlled atmospheric conditions. These tailored environments are achieved using the advanced gas delivery unit, a system designed to provide precise control over the gas composition and pressure within the chamber.

The pure gases stored in the bottles are mixed to the desired concentrations using a high-performance gas mixing unit. This unit allows the ERICA team to create specific atmospheric conditions tailored to the requirements of each experiment. At the core of this unit is the GMS_4CH_HP (from Qcal), a compact and versatile system capable of mixing up to four different gases simultaneously. The mixing system is connected to 50 L bottles of pure (4×) compressed gases such as O_2, N_2, CO_2, and H_2 (housed in a G-ULTIMATE-90 safety cabinet), ensuring compliance with safety regulations. Each of the four channels is able to handle flow ranges from 0.1 to 100 mL/min, with a dynamic control range of 1:1000 and a maximum error of ±0.8% of the setpoint. The system operates through user-friendly software that ensures precise mixing of gases in the desired ratios, enabling simulations of complex planetary atmospheres. In addition to mixing, the gas delivery unit also controls the temperature and humidity of the gas mixture to be then delivered to the vacuum chamber. The integrated humidity module allows for precise humidity control, achieving up to 95% relative humidity (RH) at 90 °C.

2.8 | Environmental Sensor Unit

To ensure precise monitoring and control of the experimental conditions inside the A.C.M.E. chamber, environmental sensors are used to measure temperature, humidity, and pressure. In detail, temperature and humidity levels are measured using the HMM170 Humidity and Temperature Module (from Vaisala), a robust sensor specifically designed to provide accurate measurements across a wide temperature range of −70°C to +180°C and a relative humidity range of 0%–100%, even in high-humidity and vacuum conditions. On the other hand, the pressure inside the A.C.M.E. chamber is monitored by a digital vacuum gauge that provides real-time measurement of pressure, ensuring high accuracy and reliability across a wide range of vacuum conditions. For this purpose, the Digiline CCT 36× digital gauge (from Pfeiffer) is used.

3 | Case of Study: Testing a Novel Technology for Gas Monitoring Under Representative Environmental Conditions

3.1 | Materials and Methods

In this work, the analytical performance of the HCF gas sensor developed by the ERICA research team was investigated. As presented in Figure 2, the HCF prototype has a length of 150 mm, a diameter of 25 mm, and a total weight below 100 g. The technical specifications of the HCF probe cannot be disclosed at this time, as the design and technology are patent pending; however, further details will be provided in a dedicated manuscript following the release of the patent.

Using this analytical setup, Raman analyses of gas analytes were conducted under representative environmental conditions using the A.C.M.E. chamber.

For this purpose, the A.C.M.E setup was configured by integrating the vacuum chamber to the vacuum pump unit to create a vacuum inside the chamber, where the HCF sensor prototype was installed and connected to the Raman unit (in this case, the RAD-1 unit). The gas mixer subunit was utilized to produce gas mixtures emulating the composition of Earth (78% N_2, 21% O_2, and 1% Ar), Mars (95% CO_2, 3% N_2, and 2% Ar), and Venus (96% CO_2, 3% N_2, and 1% other gases) atmospheres. The gas mixtures were sequentially introduced into the chamber through a controlled valve, while the resulting gas pressure within the chamber was continuously monitored by the pressure gauge to ensure precise regulation of the experimental conditions. The configuration of A.C.M.E. for the proposed experiment is presented in Figure 3.

FIGURE 2 | Image of the HCF-based prototype developed by the ERICA team.

In this work, the spectrometer used as a Raman unit was the RAD-1 (Raman Demonstrator 1) [7], which is a portable emulator of the Raman Laser Spectrometer (RLS) onboard the ExoMars rover, designed by the RLS team to conduct in situ analyses at terrestrial analog sites. This instrument enables highly representative ExoMars-like analyses of Martian analog materials. The RAD-1 shares several key characteristics with the RLS instrument, making it an ideal tool for predictive studies. It has a spectral range of 70–4200 cm^{-1}, a laser wavelength of 532 nm, a maximum power output of 100 mW, and an average spectral resolution of 6 cm^{-1}. During the tests, the emission power of the Raman unit was set to the max. For each step of the experiment, between 50 and 100 spectra were then collected by setting an acquisition time of 15 s. Data sets were then visualized using the SpectPro software [40] and analyzed by means of dedicated Matlab routines.

3.2 | Experimental Results

3.2.1 | Analysis of Relevant Gas Analytes and Their Mixtures

To assess the sensor's ability to detect and distinguish various gas analytes, the HCF gas sensor was installed inside the A.C.M.E. chamber, and a series of Raman spectroscopic measurements of varied gas analytes were conducted. Initially,

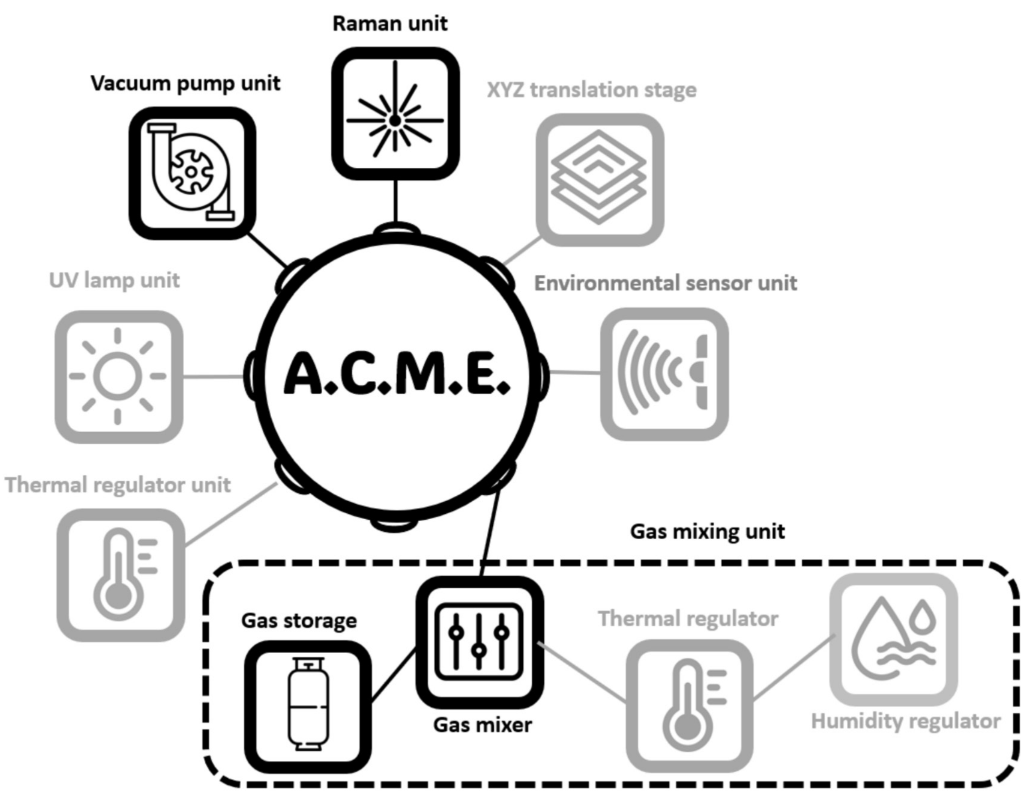

FIGURE 3 | A.C.M.E. modular configuration selected for the proposed experiment.

analyses were performed under vacuum conditions to capture the background spectral response of the sensor. This reference spectrum (Figure 4, black line) served as a baseline to remove the spectral contribution of the sensor from all the raw spectra (Figure 4 top), thus isolating the spectral emission of the analyzed gases (Figure 4 bottom).

After establishing the baseline, pure gas analytes were sequentially introduced into the chamber at a pressure of 1 bar. The aim was to capture their characteristic Raman spectra to evaluate the sensor's response to each gas as well as to collect spectral standards to be used during data processing and interpretation.

As shown in Figure 4, the analysis of pure CO_2 (red spectrum) resulted in the detection of the characteristic Fermi doublet bands located at 1285 and 1388 cm^{-1}. Similarly, the analysis of pure N_2 (yellow spectrum) revealed its characteristic Raman band at 2329 cm^{-1}, while the pure O_2 (green spectrum) exhibited its signature Raman shift at 1555 cm^{-1}.

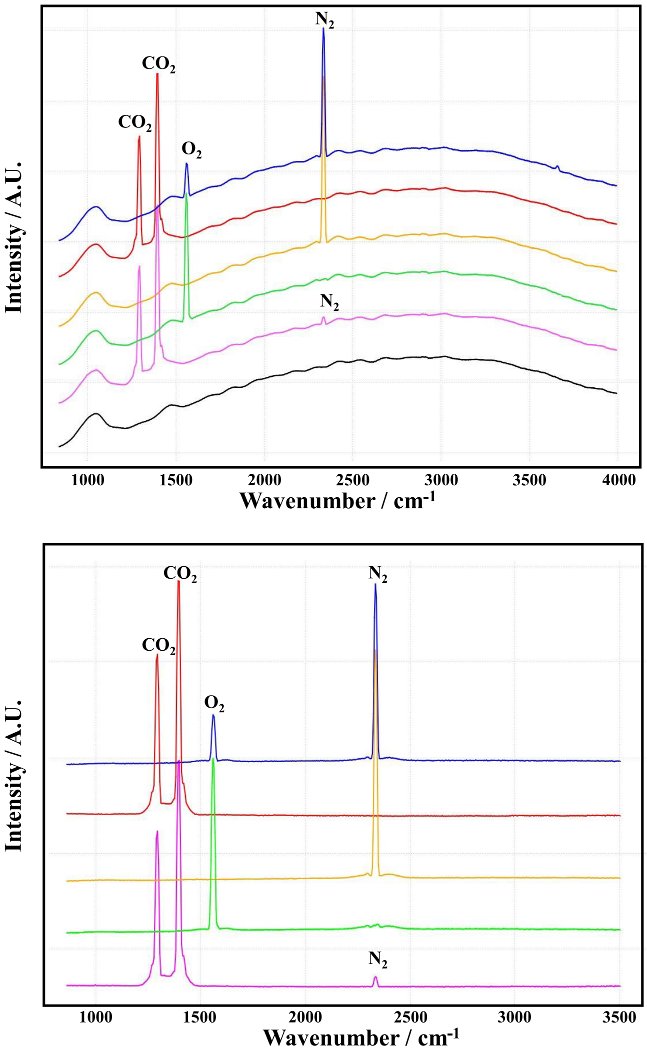

FIGURE 4 | Raman spectra of gas analytes collected by means of the HCF sensor prototype, before (top) and after (bottom) removing the spectral contribution of the sensor from all the raw spectra. Blue: Earth-like atmosphere; red: pure CO_2; yellow: pure N_2; green: pure O_2; purple: Mars- and Venus-like atmosphere. All analysis has been performed setting at ambient temperature and by setting a pressure of 900 mbar.

Afterwards, the gas mixing module of the A.C.M.E. chamber was employed to prepare two binary gas mixtures. The first mixture, composed of 21% O_2 and 79% N_2, was designed to replicate the composition of Earth's atmosphere (Ar was omitted as spectroscopic gas sensors are only able to detect molecular gases). The second mixture, consisting of 97% CO_2 and 3% N_2, was prepared to closely mimic the atmospheric composition found on both Mars and Venus. Using the HCF-based gas sensor, the Raman spectra of these two gas mixtures were analyzed. The characteristic spectrum of the Earth-like mixture is shown in blue, while the spectrum of the Mars/Venus-like mixture is depicted in purple.

The analysis of the two gas mixtures demonstrated the gas sensor's ability to simultaneously detect the presence of both gas analytes within each mixture. The sensor successfully resolved the characteristic bands corresponding to O_2 and N_2 in the Earth-like mixture, and CO_2 and N_2 in the Mars/Venus-like mixture. It is noteworthy that, although the spectra presented in Figure 4 are averages of 50 consecutive measurements, the characteristic bands of the gas analytes were also clearly identified when only a single spectrum was evaluated. This indicates that a successful characterization of the gas mixtures was achieved within just 15 s of measurement. It is also important to note that, during the described tests, the gas sensor was operated at only 1/5 of its maximum power (500 mW). Given that the sensitivity of the gas sensor increases linearly with the emission power of the excitation source, it can be inferred that the acquisition time could potentially be reduced by a factor of 5. This result highlights the rapid response and efficiency of the HCF-based sensor for real-time atmospheric analysis.

3.2.2 | Simulating the Application of the HCF Sensor on Mars

When testing a gas sensor for potential Mars applications, it must be considered that the atmospheric pressure on the red planet is much lower than on Earth. As this has a strong influence on the detection capabilities of gas sensors, the A.C.M.E. chamber was used to simulate Martian conditions and assess the HCF sensor's performance at lower pressures. To do so, the pressure of the Mars-like gas mixture inside the chamber was reduced to 11 mbar, representative of Hellas Planitia (the region with the highest pressure on Mars), and to 6 mbar, which approximates the average pressure on Mars. Under these low-pressure conditions, Raman spectra were then collected by setting the same acquisition parameters detailed above. The collected data (see Figure 5) clearly demonstrate that, although the average intensity of the spectra is much lower than that recorded at 900 mbar (see Figure 4), the characteristic CO_2 bands were still easily distinguished from the spectral background. The signal-to-noise ratio (SNR) was calculated by dividing the maximum intensity of each band by the standard deviation of a nearby background region without signal. Specifically, the analysis at 11 mbar revealed SNR values of 64 (1285 cm^{-1}) and 102 (1388 cm^{-1}) for the CO_2 doublet. When the pressure was further reduced to 6 mbar, the SNR decreased to 9 and 12, respectively. Since an effective detection of a Raman band is ensured when the measured SNR is above

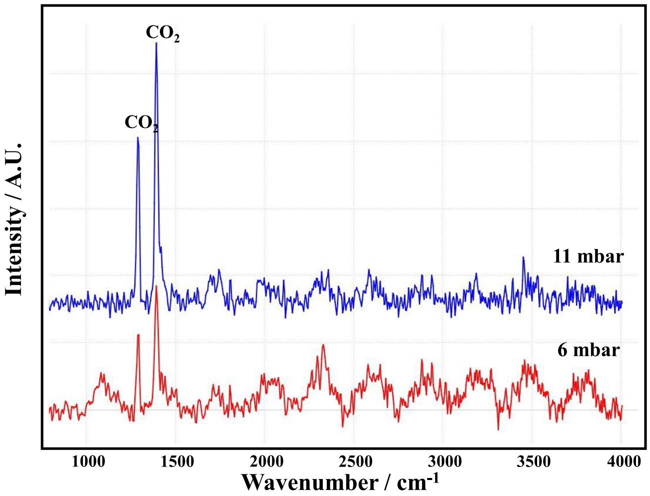

FIGURE 5 | Raman spectra of Mars-like atmosphere collected at 6 and 11 mbar by means of the HCF sensor prototype.

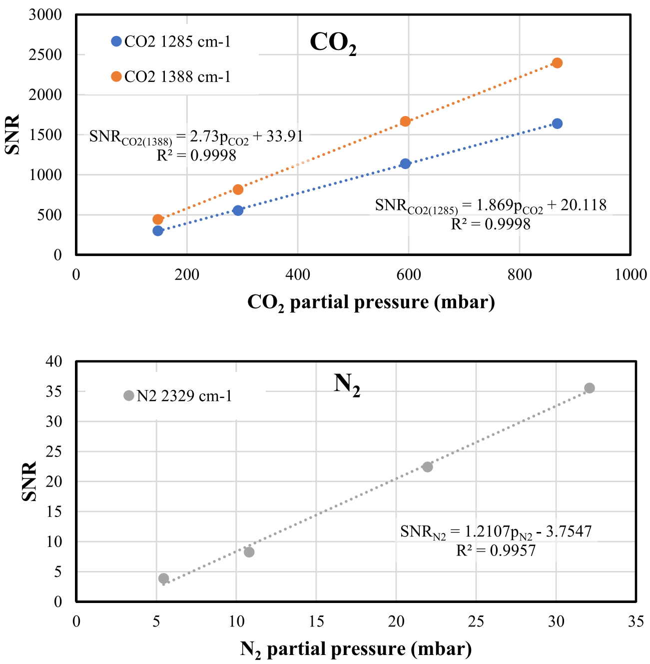

FIGURE 6 | Plots showing the linearity between the SNR value of CO_2 and N_2 bands and gas pressure.

3, these results confirm that CO_2 can potentially be detected at pressures down to 2.45 mbar. As explained in the previous section, this limit can be theoretically lower by a factor of 5 if the HCF gas sensor is operated to its maximum power (500 mW).

3.2.3 | Simulating the Application of the HCF Sensor on Venus

The A.C.M.E chamber was used to test the potential scientific response of the HCF sensor when measuring the evolution of Venus atmospheric pressure and composition along its vertical profile. As the current version of the sensor cannot sustain high pressures as those found at the Venus surface, the experiment was focused on simulating the descent down to the lower clouds level (900 mbar). To do so, the pressure of the Venus-like atmosphere was initially set to 150 mbar, and then gradually increased up to 900 mbar. At each step, at least 50 spectra were collected using the acquisition parameters detailed above. After data acquisition, the collected spectra were averaged, and the intensity and SNR values of the characteristic CO_2 and N_2 bands were measured. As presented in Figure 6a, the measured SNR value of the CO_2 doublet linearly increased with the gas pressure, delivering regression models with a linear coefficient of determination of 0.9998 (in both cases). Even though the intensity of the measured N_2 band was less intense than the CO_2 one (due to the different concentration ratio), this gas analyte was successfully detected down to 150 mbar. Furthermore, the measured SNR values also displayed a clear linearity with gas pressure, resulting in a regression model with a linear coefficient of determination of 0.9957.

Besides demonstrating that the sensor could be used to measure the evolution of Venus' atmosphere, the linear correlation between band SNR and gas content further proved that the HCF sensor could potentially be employed for quantitative estimations of the detected gas analytes.

4 | Conclusions

The development and testing of advanced spectroscopic instruments for planetary exploration requires highly controlled environments that replicate extraterrestrial conditions. The A.C.M.E. chamber represents a significant step forward in this field, providing a versatile platform for simulating diverse planetary scenarios. This study demonstrates the utility of A.C.M.E. in supporting the evaluation of novel gas sensing technologies, such as the hollow-core fiber (HCF) Raman probe.

The ability to perform these measurements under a wide range of environmental conditions was made possible by the versatility of the A.C.M.E. simulation chamber. Its capability to reproduce planetary atmospheres—in both gas composition and pressure—was essential for evaluating the HCF-based Raman sensor under realistic Mars- and Venus-like scenarios. Simulating low-pressure Martian conditions down to 6 mbar enabled us to test the sensor's detection limits in a way not achievable with standard lab setups. Additionally, the controlled generation of custom gas mixtures allowed clear spectral identification of gases like N_2 and CO_2 in planetary-relevant ratios. Without this level of environmental control, the results would have lacked the representativeness needed for planetary applications. A.C.M.E. thus proved to be a key enabler for validating the sensor's performance under mission-relevant conditions.

By integrating the HCF sensor with the RAD-1 Raman simulator, we confirmed that Raman spectrometers, such as the Raman Laser Spectrometer (RLS), could be effectively employed for atmospheric gas analysis in future planetary missions, expanding their scope beyond mineralogical studies. These findings underscore the importance of simulation chambers like A.C.M.E. in bridging the gap between laboratory testing and real-world planetary exploration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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