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Laser Spectroscopy Multi-Gas Monitor: Results of a Year Long Technology Demonstration on ISS

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Tunable diode laser spectroscopy (TDLS) is an advanced trace and major gas monitoring technology with unmatched selectivity, range and stability. The technology demonstration of the TDLS based Multi-Gas Monitor (MGM), initially reported at the 2014 ICES conference, has been operating continuously on the International Space Station (ISS) for over 15 months as of this writing. The MGM is designed to measure oxygen, carbon dioxide, ammonia and water vapor in ambient cabin air in a low power, relatively compact device. While on board, the MGM experienced a number of challenges, planned and unplanned, including a test of the ammonia channel using a commercial medical ammonia inhalant and carbon dioxide spikes from thruster firings from another payload. Data from the unit was downlinked once per week and compared with other analytical resources on board, notably the Major Constituent Analyzer (MCA), a magnetic sector mass spectrometer. MGM spent the majority of the time installed in the Nanoracks Frame 2 payload facility in front breathing mode, sampling the ambient environment of the Japanese Experiment Module (JEM), but was also used to analyze recirculated rack cooling air. MGM can be operated in portable mode (via internal rechargeable lithium ion polymer batteries or by plugging into any Express Rack 28VDC connector). Results show excellent stability and agreement with MCA data for oxygen and carbon dioxide. The ammonia challenge (~ 75 ppm) was successful as well, showing very rapid response time in both directions. Water vapor results showed weekly spikes corresponding to dry out cycling of JEM condensing heat exchangers and good agreement with dew point measurements in Columbus module. None of the 4 sensor channels has degraded perceptibly to date. Work on expanding the capability in next generation devices has just begun. Target gases include combustion products, formaldehyde and hydrazine. Various hand-held and integrated laser spectroscopy based monitors are envisioned for use on ISS, Orion and Exploration missions.

Nomenclature

CO = Carbon monoxide
CO_2 = Carbon dioxide
ISS = International Space Station
JEM = Japanese Experiment Module
MCA = Major Constituents Analyzer
MGM = Multi-Gas Monitor
NH_3 = Ammonia gas
O_2 = Oxygen
ppm = parts-per-million concentration
RH = Relative humidity
TDLS = Tunable Diode Laser Spectroscopy

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I. Introduction

NASA has been following the advance of environmental tunable diode laser spectroscopy (TDLS) and has funded the application of TDLS to the challenge of spacecraft cabin air monitoring primarily via the Small Business Innovative Research (SBIR) program. One of the drivers has been frustration with the limitations of commercial electrochemical sensor based hand-held devices previously used for oxygen and still used for combustion product monitoring on ISS. Recent development of low power tunable laser diodes in the mid infrared wavelengths has put portable, battery powered TDLS based monitors within reach for many gases of interest. TDLS holds promise of unmatched selectivity—the ability to distinguish, for example, between different contaminant gases such as ammonia in parts-per-million (ppm) concentrations while also measuring percent levels of oxygen, carbon dioxide, and water vapor in the International Space Station (ISS) cabin atmosphere. Another potential advantage, which is being confirmed, is the ability to hold calibration for long periods (years). The Portable Oxygen Monitor was the very first environmental TDLS device deployed on ISS, and it is still in use for airlock operations[1]. In addition to SBIR efforts, the Jet Propulsion Laboratory in collaboration with Port City Instruments (Wilmington, NC) is developing a TDLS based gas sensor for combustion products[2]. In 2013, the Multi-Gas Monitor (MGM) was built and certified as a payload under the ISS Technology Demonstration project at NASA-JSC, with a primary motivation of developing continuous ammonia monitoring capability. The unit was calibrated in July 2013, and was launched on a Soyuz vehicle to ISS in November 2013. MGM was installed in the Nanoracks Frame 2 in the Japanese Experiment Module (JEM) and activated on February 3, 2014, making continuous measurements of ISS cabin air for over 15 months as of this writing. The history of the development of MGM, preparation, calibration, operation and early results from the ISS technology demonstration were reported at the 2014 ICES Conference[3]. MGM is pictured in Figure 1 and its performance specifications for the 4 gases MGM measures are provided in Table 1. The advantage for ammonia monitoring is the incredible dynamic range (5 to 20,000 ppm). The unit can be powered by multiple sources including 5VDC USB, 28VDC EXPRESS rack power or by internal rechargeable lithium ion polymer batteries, allowing considerable flexibility in deployment. This paper reports on the MGM flight results to date including intentional and unintentional inflight challenges, O_2 and CO_2 data comparisons with the central Major Constituents Analyzer (MCA) data, and humidity compared to Columbus module dew point data.

Figure 1. MGM being operated in battery powered mode in the JEM during Increment 42.

Table 1. Physical and analytical characteristics of Multi-Gas Monitor Tech Demo

Mass	2.6 kg		
Volume	4.4 L		
Power	2.5 W*		
Channel	*Precision*	*Target Concentration Range*	*Actual Concentration Range*
Ammonia	3 ppm	10 – 10,000 ppm	5 – 20, 000 ppm
Carbon Dioxide	20 ppm	500 – 25,000 ppm	250 – 30,000 ppm
Oxygen	0.05 %	14 – 32 %	4 – 36%
Water vapor	1 % RH	20 – 80% RH	2 – 90 % RH

*Power draw is higher (5W max) when internal batteries are recharging while the sensor is running.

II. Experiment Operations on ISS

The Multi-Gas Monitor was launched to ISS on Soyuz 37 on November 25, 2013 and installed and activated on February 3, 2014 (Figure 2). The unit was designed specifically for a Nanoracks Frame, with its nose protruding from the locker front in order to “breathe” cabin air. Power and data are supplied via USB cables connecting MGM to the rack frame infrastructure. MGM remained installed in the frame for the majority of the tech demo period to simplify data downlink and minimize crew involvement. The MGM display updates every second and 30 second running averages are recorded on internal memory to duplicate distinct files created each day. A spectrum is saved once a day as well. The position in the spectrum of the targeted absorption feature for each detection channel is continuously monitored and automatically corrected, if required. The feed forward of that error signal is logged daily. In addition, the laser power is continuously monitored for long term degradation. The power supply voltage to the board is likewise monitored and logged. There is a pattern type designation logged for each detection channel on each data point that describes the pattern that the sensor has recognized and analyzed for that point. The sensor raises flags in the data set if the temperature or pressure is outside of defined bounds. Generally, compressed data files are downlinked once a week, and the data is immediately checked and plotted. Sensor health data and spectra are examined as well, looking for any sign of degradation or drift. Combined MGM and MCA data plots are updated about once per month, to check accuracy and look for any drift or trend. As reported in the previous paper, a crewmember breathed into the unit upon activation as an immediate test of operability (both CO_2 and water vapor increased as expected). The data is inspected for clues to dynamics taking place in the ISS atmosphere such as oxygen and nitrogen represses, control of carbon dioxide levels, and humidity and temperature changes in the JEM.

Figure 2. ISS crew member pointing to MGM just after installation in Nanoracks in the JEM.

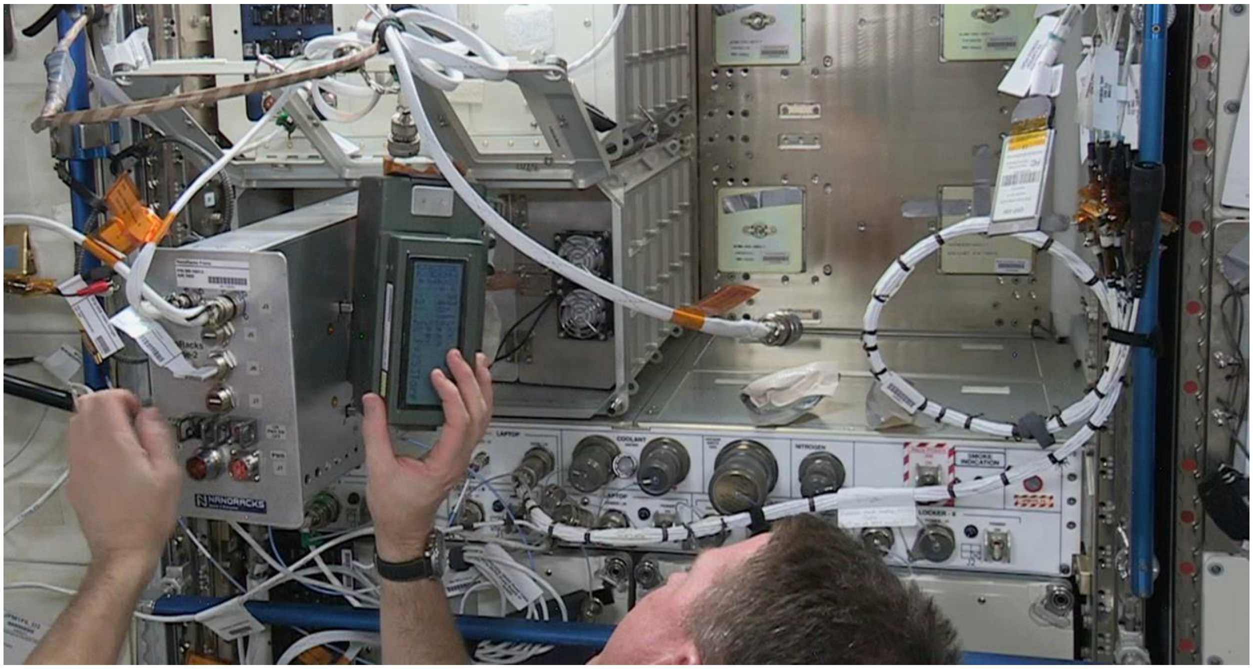

Figure 3. ISS crew member removing MGM from inside the locker where it monitored recirculated rack avionics air over a several month period, in support of the Fruit-Fly Lab that operated Jan 15-30, 2015.

Commercial ammonia inhalants[4] were supplied to the ISS for the express purpose of testing the ammonia channel, which was performed on July 25, 2014. In November, the MGM was moved to a position inside the rack frame (Fig. 3) in order to monitor recirculated avionics cooling air quality for a fruit-fly payload[5]. Over the yearlong technology demonstration, a few MGM data logger/data interface issues required intervention of ground controllers to cycle Nanoracks Frame power, and, on two occasions, crew intervention to manually reset the data logger inside the MGM by cycling the power via ON/OFF switch. The original duration of the technology demonstration was to be 6 months, to test long-term stability of TDLS based sensors, but since all was going well at the 6 month mark, and the unit was making useful measurements, the duration was extended. As of this writing MGM continues to operate in the JEM beyond 15 months. The extension potentially could allow deployments outside the rack. Recently, there has been increased interest in monitoring CO_2 due to reports of headaches[6] and concern about a possible (unconfirmed) link to vision degradation[7] with long term exposure to elevated CO_2. This has led to controlling CO_2 to lower set points, a challenge for the life support systems to meet consistently. One MGM deployment possibility is to log CO_2 in the crew quarters while occupied overnight. MGM is virtually silent, having a small quiet fan to draw air into unit across sensor and out, and would not disturb the crew sleep.

III. Results & Discussion

Oxygen Channel

The MGM oxygen data over a 15 month period is plotted in Figure 4. The O_2 channel is calibrated in percent, but results are converted on the ground to partial pressure to conform with MCA output. Results confirm that O_2 is maintained in a fairly narrow range on ISS for crew health and safety, as expected. The saw tooth shape depicts both consumption of O_2 and resupply. Data from the MCA (JEM only) is plotted alongside the MGM results, and clearly show they track each other very closely (within 1% difference). The inset of Fig 4 shows detail for an arbitrary 3.5 month period. There are a few data gaps in MGM results, reflecting periods where there were connectivity issues between the USB data logger inside MGM and the Nanoracks Frame. It appears the MGM sensor continued to operate nominally during these episodes, but the data was not being recorded. On two occasions the crew was asked to perform a hard reset of MGM. Changes in how the rack Frame is operated from the ground have helped, but the root cause of the lockups is not known. Oxygen represses were directly observed in the MGM data along with pressure spikes (Fig 5), as recorded by an internal pressure sensor. The pressure plot follows the O_2 trends with temporary spikes occurring during repress events.

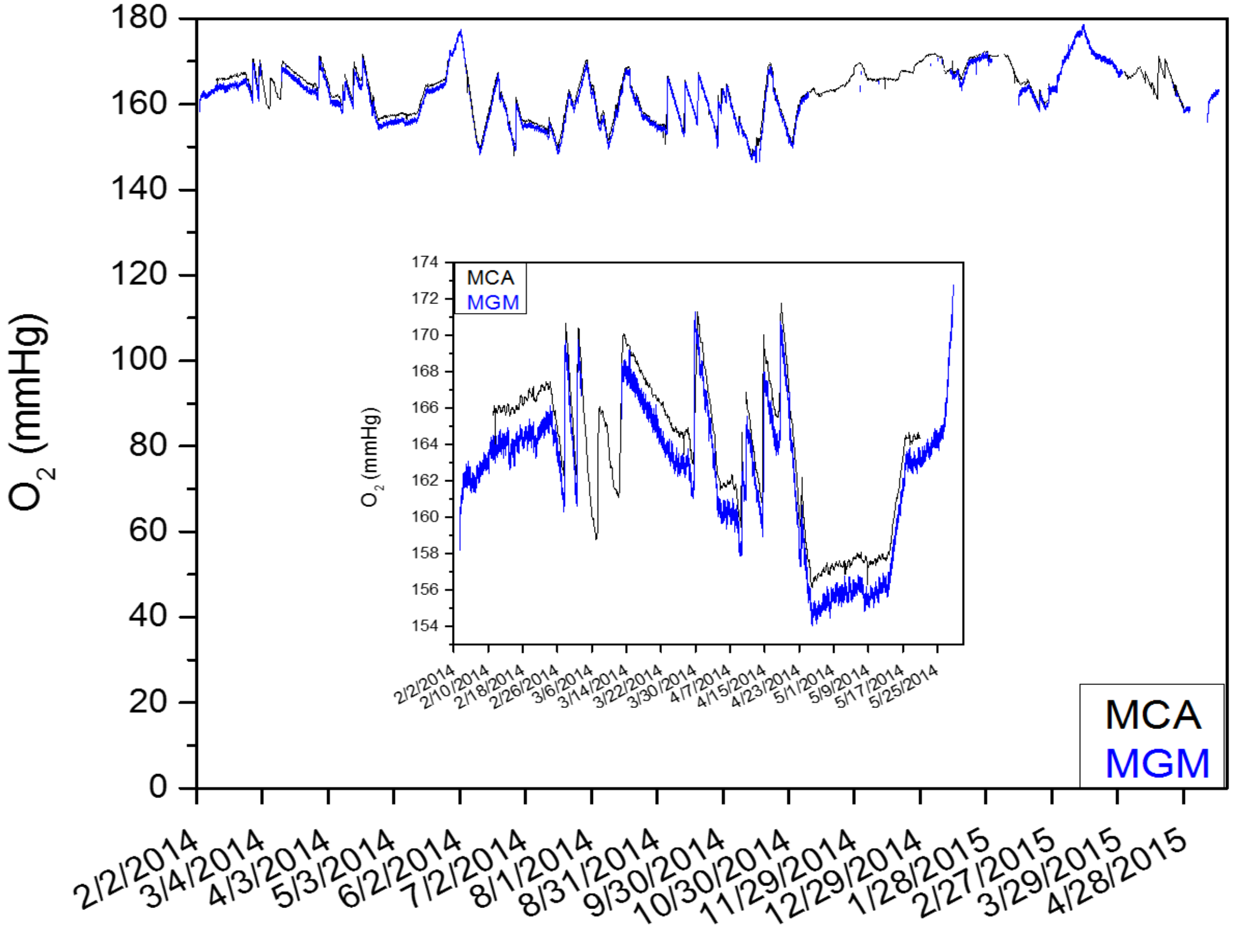

Figure 4. Fifteen months of MGM oxygen data plotted with Major Constituents Analyzer O2 data. The two analyzers track each other very closely, within 1% difference. Inset shows an arbitrary period with expanded scale to show detail.

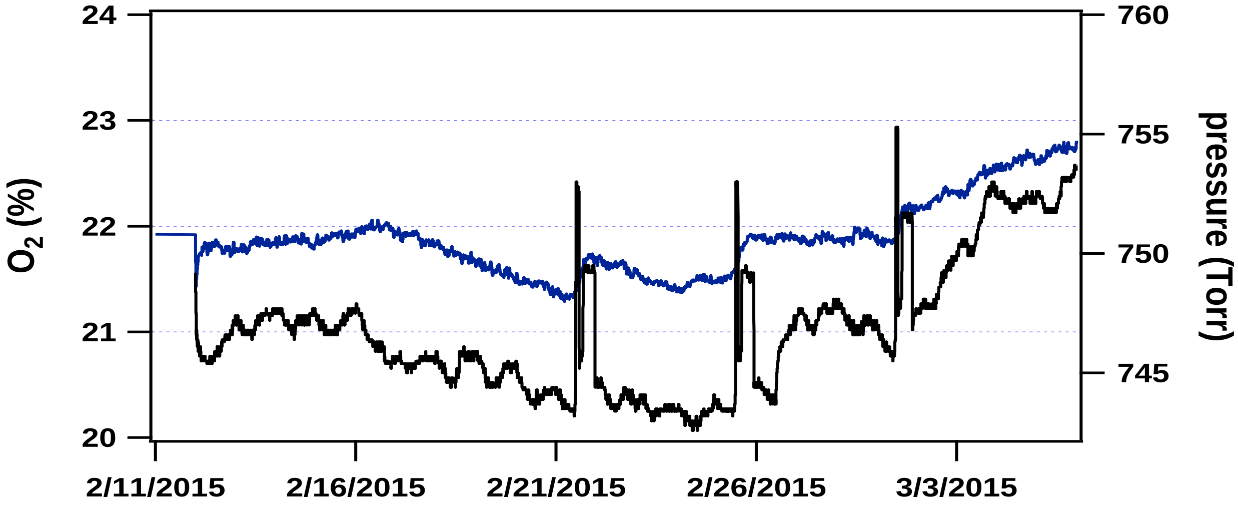

Figure 5. MGM oxygen data (upper, blue) plotted for an arbitrary 1 month period with its internal pressure sensor data (lower, black). The linear O_2 decreases correspond to crew consumption (and leak rate) and the positive step functions show when O_2 or air is added (ISS "repressurized") from storage tanks.

Carbon Dioxide Channel

Figure 6 shows the MGM results for CO_2 converted to partial pressure in mmHg and plotted with MCA data over the 15 month duration. The inset figure details an arbitrary period to show the difference. Note that results from MGM and MCA track quite closely (within 5%). As the plot shows, CO_2 behavior is much more variable than O_2, but is generally controlled below 4 mmHg (5300 ppm). The average during 2014 is roughly 3 mmHg (4000 ppm), whereas the current long term Spacecraft Maximum Allowable Concentration is 7000 ppm (5.3 mmHg). In order to protect against potential symptoms for sensitive individuals, however, ISS mission action requests ("chits") have regulated CO_2 at 4 mmHg with temporary excursions allowed. More recently, at the request of flight surgeons, that control target level has further decreased to 2.7 mmHg (3600 ppm) CO_2 as a goal. Figure 7, the most recently downlinked MGM CO_2 data (in ppm), shows that the reduced control target is achievable, at least over the short term, with the CO_2 removal equipment on the US and Russian segments functioning properly.

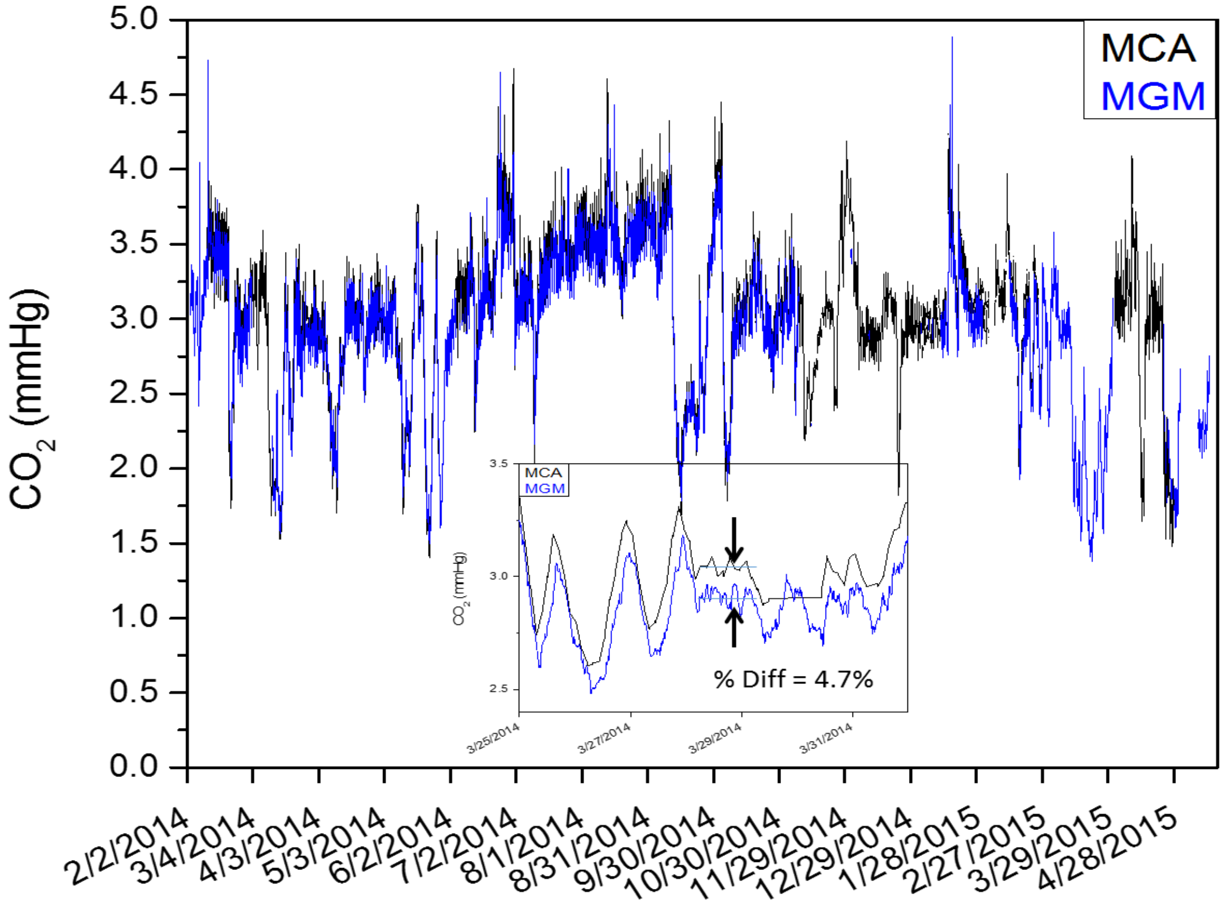

Figure 6. Fifteen months of MGM carbon dioxide data plotted with MCA CO_2 data for JEM. Inset shows detail for an arbitrary 1 week period including day-night cyclical behavior and percent difference of 4.7%.

As reported previously, MGM detected CO_2 thruster firings from the Synchronized Position, Hold, Engage, Reorient, Experimental Satellites (SPHERES) payload[8] that is typically operated in JEM. The most recent sessions in January 2015 were detected in the spikes of Fig 8, which are well above the nominal 4000 ppm CO_2 baseline. This data was corroborated with payload timelines to confirm the source of the CO_2 spikes. At the end of the experiment, the average CO_2 was roughly 1000 ppm higher in JEM. Based on the plot, recovery to the ~ 4000 ppm baseline required about 2 days.

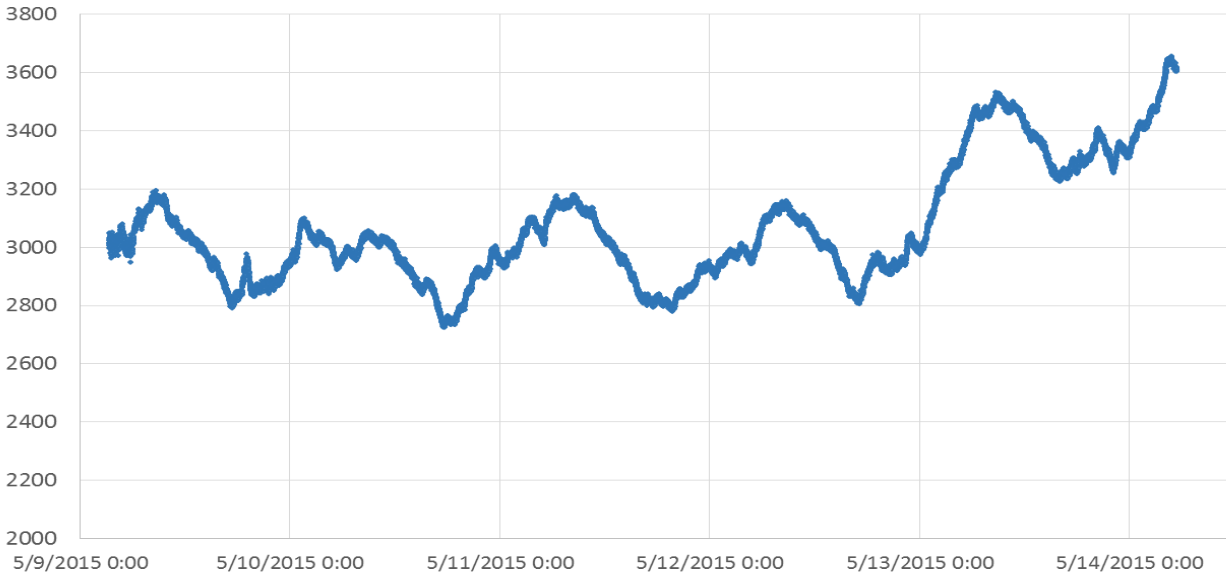

Figure 7. As of this writing, the most recently downlinked MGM CO_2 data in ppm, demonstrate ECLS control of CO_2 at or near the new operational target of 2.7 mm Hg (3600 ppm). Note the clear diurnal variations as well.

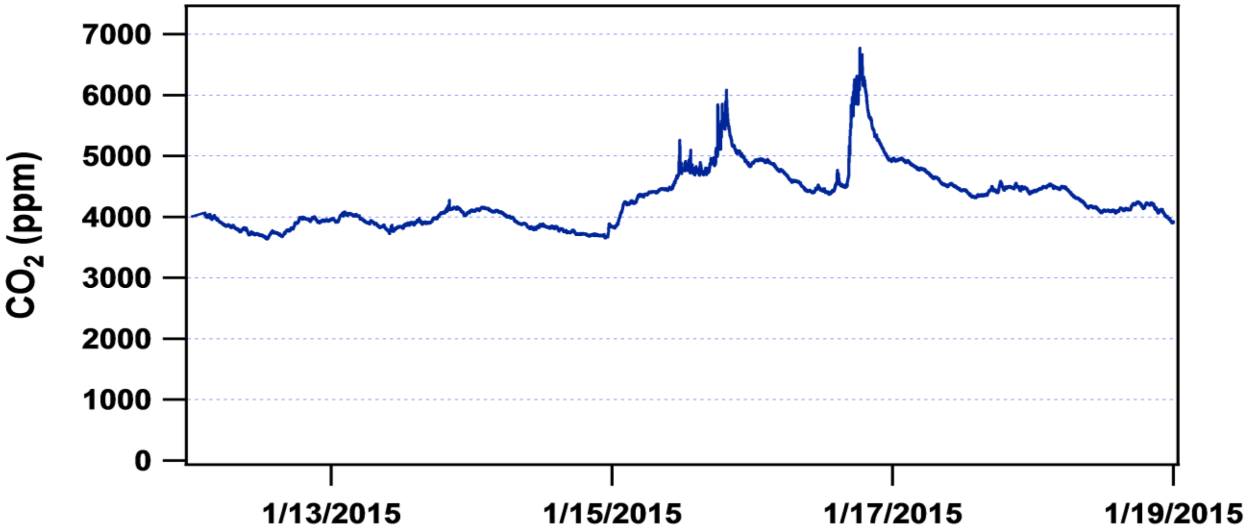

Figure 8. MGM again detected CO_2 increases as direct result of thruster firings from SPHERES Zero Robotics payload being operated in the JEM, the Dry Run on Jan 15, and the Competition on Jan 16, 2015.

Water Channel

Water vapor is measured directly by the MGM in ppm, which is then converted using temperature and pressure to percent relative humidity. Humidity in %RH is then displayed on the unit. An example plot of water vapor in ppm is given in Figure 9. Note the curious spikes occurring about once a week. These sharp peaks were determined to be routine switching and dry out cycles of the JEM condensing heat exchangers[9]. Overall, disregarding the spikes, water vapor remains in a fairly narrow range centered around 12,000 ppm. This corresponds to about 38% relative humidity at 25°C and 1 atmosphere. The MCA does not currently provide humidity data, but dew point sensors in Columbus Module[10] showed an average of 48F during 2014, a value that corresponds to 36% relative humidity at 25°C and 1 atmosphere, which is in excellent agreement with MGM findings in the JEM. Based on these data, humidity is well controlled on ISS in a comfortable range for the crew.

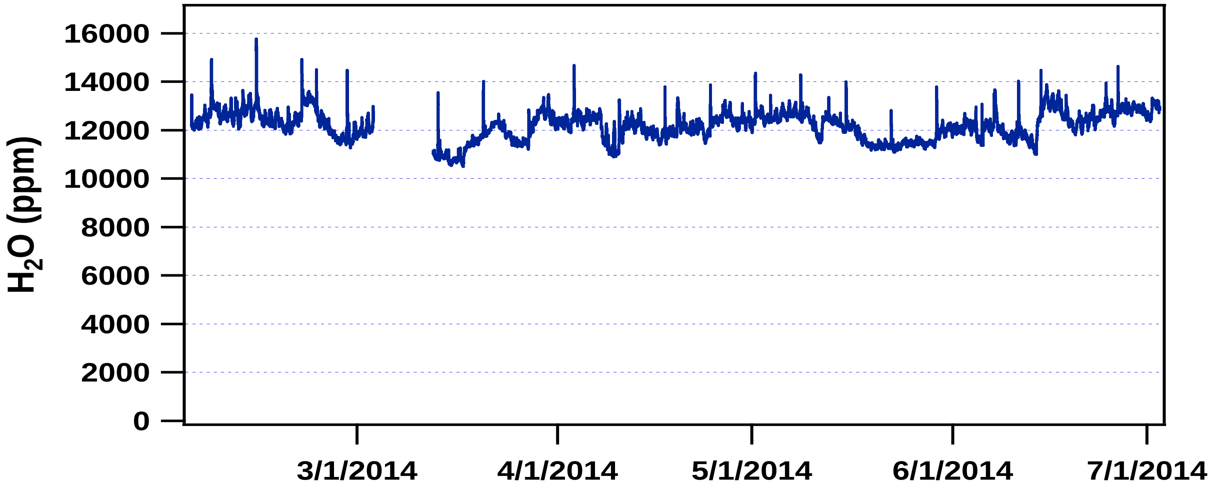

Figure 8. Plot of water concentration in JEM for a 5 month period showing the roughly once per week spikes associated with dry out cycling of JEM condensing heat exchangers.

Ammonia Channel

Under normal circumstances, the ammonia concentration in air in the ISS is well below 1 ppm, based on Henry's Law calculations using ground chemical analysis data for ISS humidity condensate samples. With the current sensor configuration, MGM cannot detect sub ppm levels. The ammonia lower detection limit of the MGM was estimated in preflight testing using an EPA method to be 5 ppm, and the display shows "< 5 ppm" to reflect that, when no ammonia is introducted. The baseline noise in Figure 9 is what MGM routinely shows on ISS, generally < 5 ppm NH_3. In order to check the ammonia channel, a commercial inhalant[4] packet (modern smelling salts) was supplied to the crew to introduce a low level of ammonia in a safe manner into MGM. The inhalant packet was torn open and held briefly at the inlet screen of the MGM. The packet was then placed back into its zip lock bag and discarded. Figure 9 shows the resulting 75 ppm peak, which was also called down by the crew. This was a qualitative challenge yet served as a positive control—evidence the ammonia channel is working as designed. The MCA cannot measure ammonia. Note the sharp peak of Figure 9, a rapid increase and decrease, showing that this optical sensor configuration gives a near instantaneous response (within a few seconds of introduction) with no hysteresis. Rapid response with no hysteresis is an essential quality of a contingency gas monitor.

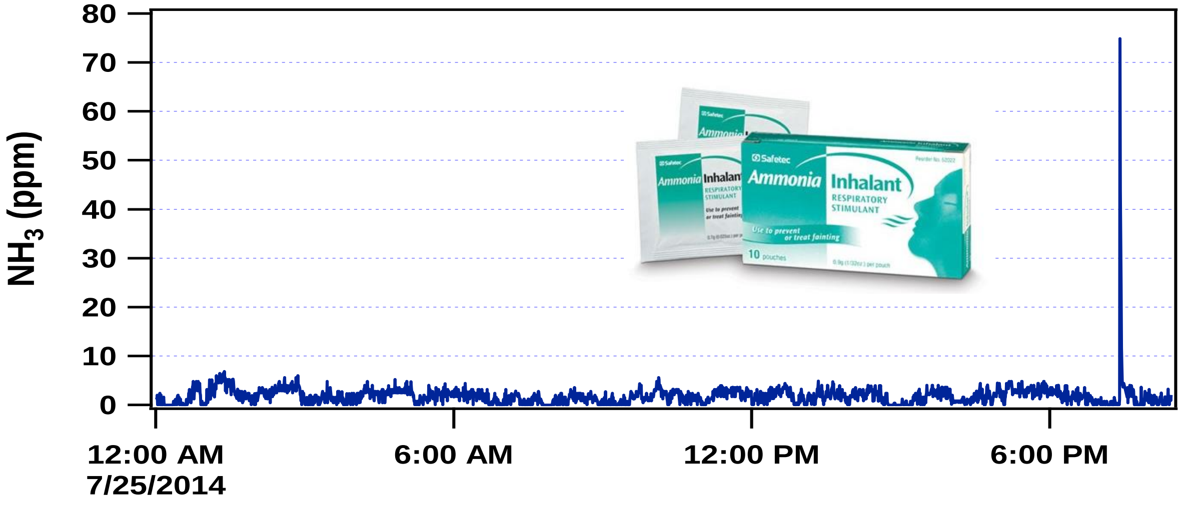

Figure 9. ISS crewmember challenged the MGM with a commercial ammonia inhalant (pictured) on July 25, 2014 and called down the maximum value displayed of 75 ppm. This exactly matched the peak in the downlinked data which is plotted here.

On January 14, 2015, ISS experienced an ammonia release alarm based on a minute quantity increase in an accumulator in the internal thermal control system. If ammonia leaks from the external system into the internal water based cooling system, it would manifest in this manner. The crew donned masks, evacuated to the Russian segment and closed the hatches per the established emergency procedures. Later they confirmed there was no ammonia release (false alarm) by using Draeger tubes just inside the hatch. Although experimental hardware cannot be used to make operational decisions in contingencies, the MGM did provide useful information on the day of the release that showed no hint of an increase in ammonia. A plot of data leading up to, during and after the ammonia alarm is given in Figure 10. Note there is no change in baseline noise during this time, suggesting no significant ammonia leak. Other on-board assets, notably the ISS Air Quality Monitor[11], a Gas Chromatograph/Differential Mobility Spectrometer, which is qualitatively quite sensitive to ammonia, corroborated these results, confirming no actual leak has occurred.

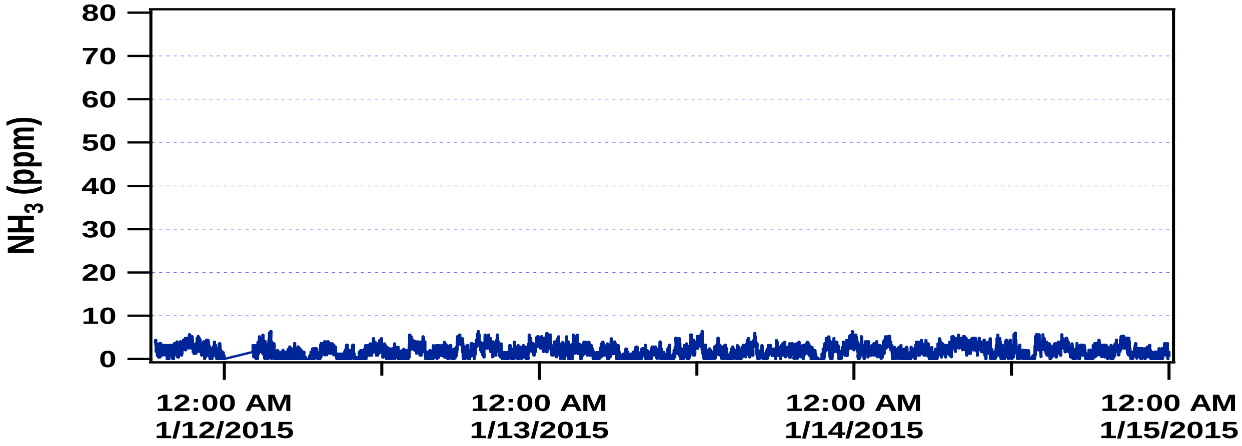

Figure 10. Ammonia data for several days including the day of the false NH_3 release alarm on ISS (January 14, 2015). Note no hint of an increase, no change in the typical baseline noise showing no detectable release.

Sensor Health

One of the primary measures of sensor health is power of each of the 4 lasers. Laser power is closely monitored and plotted (Fig 11) as it directly corresponds to long term stability and longevity of the sensor. The plot shows no perceptible decrease in laser power across all channels. Other measures include the quality of the spectra (recorded daily) and the power supply voltage, which is also recorded and downlinked. The sensor has performed remarkably well during the 15 months on board to date, and these results indicate a TDLS based sensor can be built, calibrated once on the ground and deployed operationally on orbit for years without maintenance. The only issues with the MGM tech demo have been associated with the previously mentioned internal data logger, not with the sensor itself.

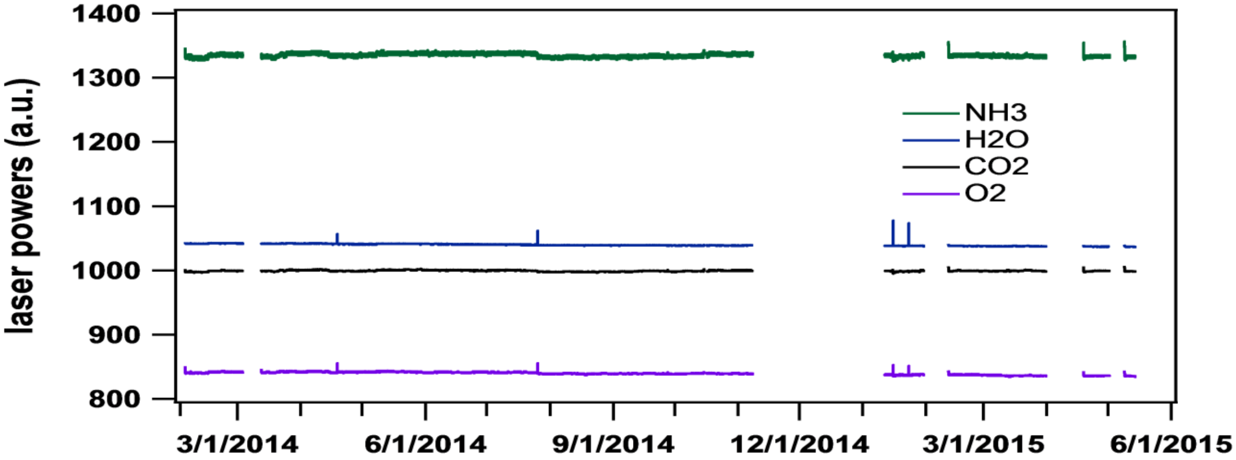

Figure 11. Plot of the DC power for each of the 4 laser lines monitored showing no perceptible degradation over 15 months for any of the lasers.

IV. Conclusions & Future Directions

The year plus flight demonstration of the Multi-Gas Monitor has shown that tunable diode laser spectroscopy (TDLS) is a viable new technology for long-term major and minor atmospheric constituent monitoring, both in nominal and contingency situations. Having been calibrated on the ground in July 2013, the flight experiment shows MGM is remarkably stable showing no drift for O_2 and CO_2 as compared with MCA data even to the present (May 2015). The water vapor results show that humidity is controlled in a comfortable narrow range, and agree with Columbus module dew point data. The ammonia channel was successfully tested on board using an inhalant packet. With its huge dynamic range, MGM can be considered a stop gap ammonia monitor while a permanent full-time NH_3 monitor is developed to replace or augment the manual Draeger tubes. The advantage of MGM is in having full-time insight on the potentially contaminated side of the hatch without exposing the crew. For the moment, MGM continues to operate in the JEM Nanoracks Frame facility, with nose out for sampling cabin air. NASA is in the process of expanding the capability of environmental TDLS for gases including combustion products like carbon monoxide (CO). Orion requires both an ammonia monitor for landing scenario as well as a combustion product monitor for inflight. ISS will need to replace the current (obsolete) hand-held combustion products monitor and the handheld CO_2 monitor within the next few years. A TDLS based formaldehyde monitor is also envisioned to replace the passive formaldehyde monitors deployed periodically and returned to the ground for analysis. Tunable diode laser spectroscopy has come of age and is making important contributions to spacecraft cabin air monitoring.

Acknowledgments

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