International Space Station (ISS) Environmental Control and Life Support System (ECLSS) vent flow reflection and detection by Robotic External Leak Locator (RELL)

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ABSTRACT

On-orbit Robotic External Leak Locator (RELL) (i.e., mass spectrometer and ion gauge) measurements on the International Space Station (ISS) are presented to show the detection of recurring Environmental Control and Life Support System (ECLSS) vents at multiple ISS locations and RELL pointing directions. The path of ECLSS effluents to the RELL detectors is not entirely obvious at some locations, but the data indicates that diffuse gas-surface reflection or scattering resulting from plume interaction with vehicle surfaces is responsible. RELL was also able to confirm the ISS ECLSS constituents and distinguish them from the ammonia leak based on the ion mass spectra and known venting times during its operation to locate a leak in the ISS port-side External Active Thermal Control System (EATCS) coolant loop.

Keywords: Gas/Surface Reflections or Scattering, Mass Spectrometers, International Space Station

I. INTRODUCTION

The United States External Active Thermal Control System (EATCS) on the International Space Station (ISS) uses liquid ammonia in closed loops to collect, transport, and reject heat.[1] The general locations of these external ammonia coolant loops on ISS are shown in Figure 1. Detection and location of small ammonia leaks (estimated to be < 50 lbm per day) from the EATCS was identified as a risk by the ISS program and a Robotic External Leak Locator (RELL) was commissioned to demonstrate the capability to locate these small leaks.[2] Leaks greater than 50 lbm per day are expected to be detected by visual inspection techniques in combination with system pressure monitoring. Integration of RELL to the ISS and robotics systems brought together teams from NASA's Goddard Space Flight Center (GSFC) and Johnson Space Center (JSC). RELL is connected, powered, and maneuvered by the Space Station Remote Manipulator System (SSRMS) and Special Purpose Dexterous Manipulator (SPDM) to locations of concern. RELL performed its first set of on-orbit operations in November-December 2016 in which it set out to measure the natural and induced environment around the ISS. These operations were successful and, additionally, detected a known, low-level ammonia leak.[3] At the time, the known ammonia leak rate was 20.2 lbm per year in the port-side EATCS coolant loop; however, the leak rate surged to 101 lbm per year in 2017. Due to an increasing leak rate, the ISS Program approved RELL for a second round of external operations in February 2017. After on-orbit operations in November-December 2016 and February 2017, RELL successfully detected and located a small ammonia leak in the radiator-side lines in the port-side EATCS coolant loop.

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The EATCS coolant lines were inspected by a crew member during an Extravehicular Activity (EVA) in March 2017, and the video from his high definition camera showed small flakes originating from the lines. The lines were then isolated from the port EATCS coolant loop in April 2017 and subsequent monitoring of the system pressures indicated that the leak has stopped. The radiator-side EATCS coolant line was retrieved via EVA in March 2018 for inspection on the ground. Prior to RELL, leaks could be detected through monitoring of the coolant system pressures and thereby isolated to specific sections.

In addition to leak locating operations, the Robotic External Leak Locator was employed to characterize the natural environment in Low Earth Orbit (LEO) (e.g., atomic oxygen characterization) and an environment induced by the ISS (e.g., Environmental Control and Life Support System [ECLSS] venting).[4] ISS ECLSS comprises of life support systems hardware on the Russian segment and the United States Operating Segment (USOS). The ECLSS performs several functions on ISS.[5] One of its functions is to monitor and control cabin air partial pressures of nitrogen, oxygen, carbon dioxide, hydrogen, methane, and water vapor. In order to control these levels, ECLSS vents primarily carbon dioxide, hydrogen, methane, and water vapor overboard into the space environment. RELL detected these gas effluents (with the exception of hydrogen) from ISS ECLSS vents at various locations and orientations. The present work provides observations of reflected gas phase molecules released from a recurring ECLSS vent and subsequently measured by the RELL during ISS on-orbit operations. The paths of reflected molecules reaching the RELL were not entirely obvious as the ISS is a large spacecraft, approximately the size of a football field. Because a number of propulsive devices (e.g., overboard vents, thrusters) are employed to operate and control any spacecraft, the understanding of plume flow and possible gas/surface reflections (or interactions with the spacecraft) is important when scientific instruments (e.g., mass spectrometers) are externally monitoring the environment.[6]

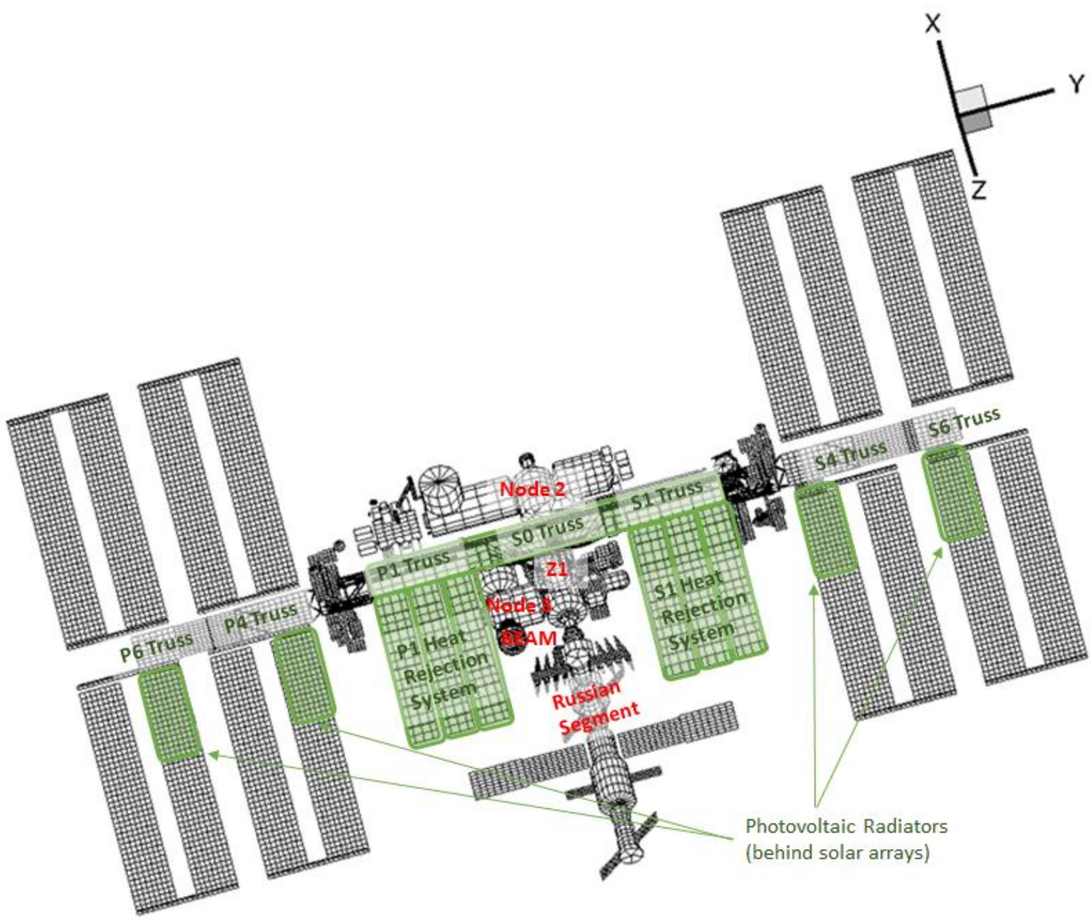

Figure 1. Locations of External Ammonia Coolant Loops (highlighted green) on ISS.

II. INSTRUMENTS

RELL, shown in Figure 2, utilizes a combination of a residual gas analyzer (RGA) and an ion pressure gauge to detect small ammonia leaks outside ISS. While both are Commercial Off The Shelf (COTS) instruments, additional design considerations included: 1) thermal management for widely varying environments, 2) structural support during launch, and 3) integration of RELL with ISS systems (e.g., electronics, data processing, and compatibility with ISS robotic arm operations).[2] The intent of the RGA is to measure partial pressures of interest. The ion pressure gauge measures total pressure and provides data near real time. The flight instrument underwent a full suite of tests for thermal vacuum, ionizing radiation, vibration, and electromagnetic interference environments. Leak simulation testing was also performed in a thermal vacuum chamber at GSFC.[7] Pressure data collected by the RGA was compared with analytical models for vent/round jet in a rarefied environment. The mass spectrometer was mounted on a translation/rotation stage and moved relative to fixed leak sources near the chamber wall. The testing simulated leak rates from 1 lbm per day to 1 lbm per year of a mixture of water and ammonia. The analysis results of the distance squared dependence and cosine relationships between the leak source and pointing vector of the RGA showed that the analytical models successfully predicted measured plume behavior.

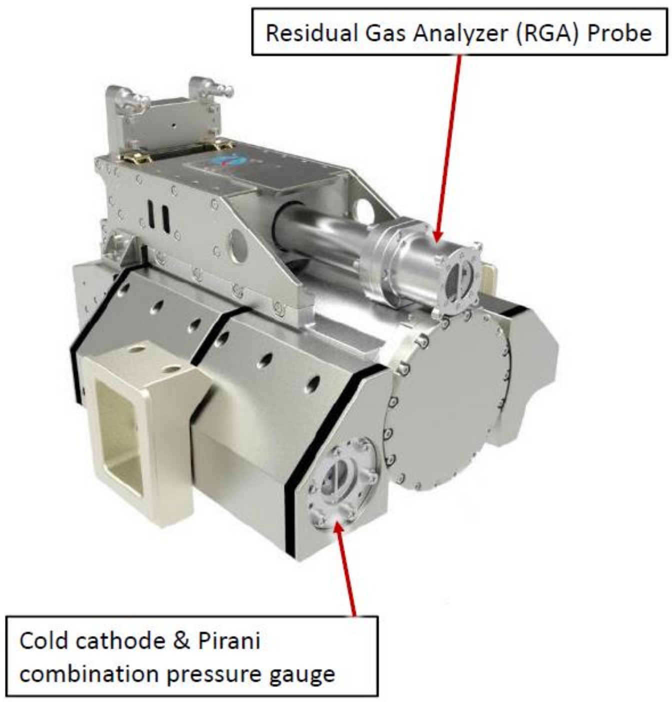

Figure 2. Robotic External Leak Locator.[2]

A. RGA-100

The RGA-100 from Stanford Research Systems (Sunnyvale, CA) is a typical quadrupole gas analyzer that measures for a mass range from 1 to 100 ion mass-to-charge ratios. The RGA has three main sections: 1) electron impact ion source, 2) quadrupole ion filter, and 3) an ion detector.[8-9] The ion source produces positive ions by bombarding gas molecules with electrons from a heated filament. The ions are directed toward the quadrupole filter where they are separated by their mass-to-charge ratio. A combination of Direct Current (DC) and Radio Frequency (RF) voltages are applied to the quadrupole rods increasing the probability of ions with certain mass-to-charge ratios traveling down the axis of the filter towards the detector. The probability of other ions reaching the detector is smaller. These ions are deflected to the cylindrical rods or surrounding structure. The Faraday Cup detector measures current directly and for increased sensitivity, an electron multiplier measures the electron current proportional to ion current. The Faraday Cup and the electron multiplier gives the RGA the capability of measuring pressures between 10^{-15} to 10^{-5} torr. Scan times can vary from several seconds to a minute based on the parameters (e.g., mass range).

B. PKR251 Ion Gauge

The PKR251 ion gauge from Pfeiffer Vacuum Inc. (Nashua, NH) is a combination of a Pirani gauge and a cold cathode system.[10] A tungsten filament in the PKR251 Pirani gauge is heated when a current flows through it. Gas molecules' collisions with the filament remove heat from it. The pressure of the surrounding environment can be determined from this heat dissipation rate. The cold cathode system utilizes orthogonal electric and magnetic fields to trap electrons. Electrons are drawn from the cathode by a potential field and deflected by the magnetic field, causing them to spiral around the anode. The spiraling increases the opportunity to collide and ionize gas molecules. The ions are captured by an ion collector generating a current proportional to the gas density. The measurement range for ion gauge is from 3.75×10^{-9} to 750 torr. Response times range from ~10 ms for pressures above 7.50×10^{-7} torr to ~1 s for pressures at the low end of the range. The ISS has previously flown this ion pressure gauge on the Materials Degradation and Exposure Experiment (MEDET) from February 2008 to September 2009 as part of the Columbus payload European Technology Exposure Facility (EuTEF).[11] Russian scientists also made various pressure measurements during thruster firings and vents for the ASTRA-II experiment on the MIR Space Station.[12]

III. ISS ECLSS

Life support systems are located both on the U.S. and Russian segments. There are two main Environmental Control and Life Support Systems operating on the U.S. segment: 1) in Node 3, and 2) in U.S. Laboratory. Node 3's Regenerative ECLSS comprises of the Carbon Dioxide Removal Assembly (CDRA), the Oxygen Generation Assembly (OGA), the Sabatier Assembly, and Water Recovery System. The ECLSS diagram, shown in Figure 3, details the primary gaseous byproducts (CO_2 and H_2) to be vented overboard.[5] The Sabatier assembly, which was removed in late 2017 and flown back to the ground, is not shown in the diagram. While in operation, the Sabatier on occasion converted carbon dioxide (from CDRA) and hydrogen (from the OGA) to methane and water. The CO_2 was held in the CDRA bed until the Sabatier made a demand for it. Node 3 has three single vent lines: 1) CO_2, 2) H_2, and 3) Air. When the Sabatier was operational, the system vented CO_2 and CH_4 from the CO_2 vent line and H_2 from the H_2 vent line. The air vent line was only used at the startup. Figure 4[13] is an on-orbit image showing the three Node 3 vent locations prior to Bigelow Expandable Activity Module (BEAM) installation on ISS. On April 16, 2016, BEAM was installed on the aft port of Node 3 and then inflated. Figure 5[13] shows the plumes from Node 3 CO_2 and H_2 vent lines directly impinge onto BEAM. Thus, the gas byproducts of the life support systems will reflect from BEAM upon exit of the vent line. The U.S. Laboratory also has all of the Node 3 ECLSS components except for the Sabatier. Both of the systems usually operate with a 144 minute cycle. The vent for the U.S. Laboratory CDRA is non-propulsive (i.e., T-vent), versus the propulsive Node 3 single vent lines. This study focuses primarily on the carbon dioxide vented from Node 3.

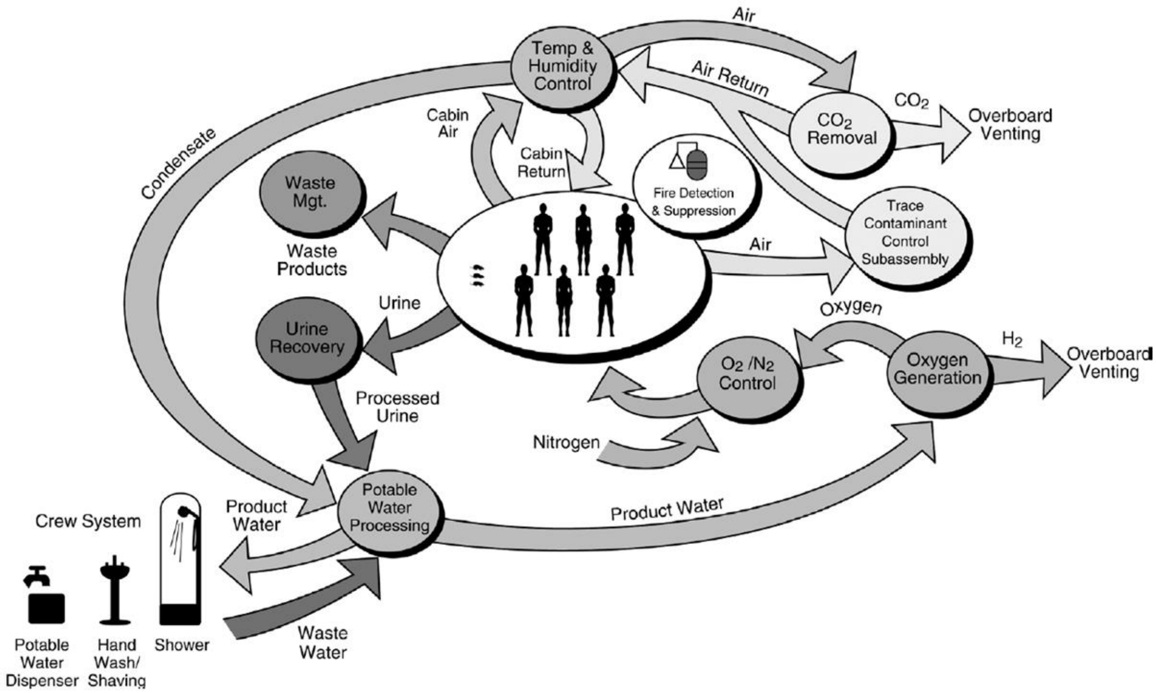

Figure 3. Environmental Control and Life Support System Diagram.[5]

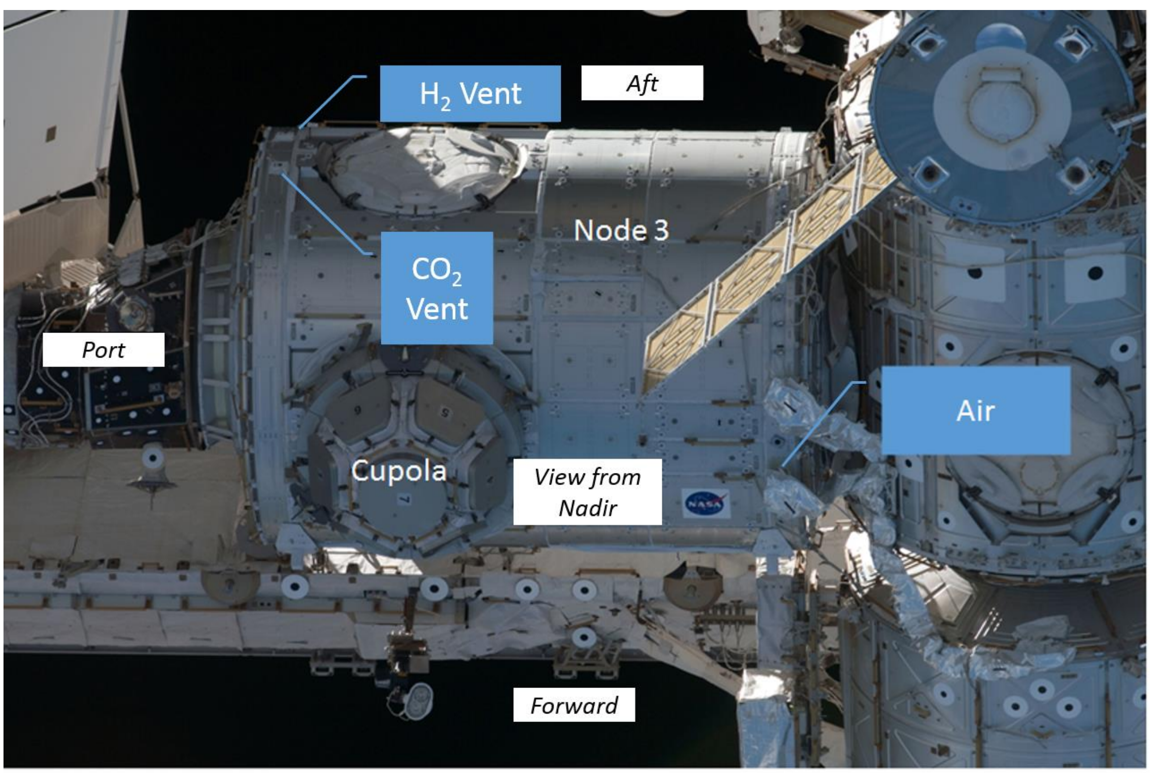

Figure 4. Node 3 Vent Locations prior to Bigelow Expandable Activity Module Installation on ISS.[13]

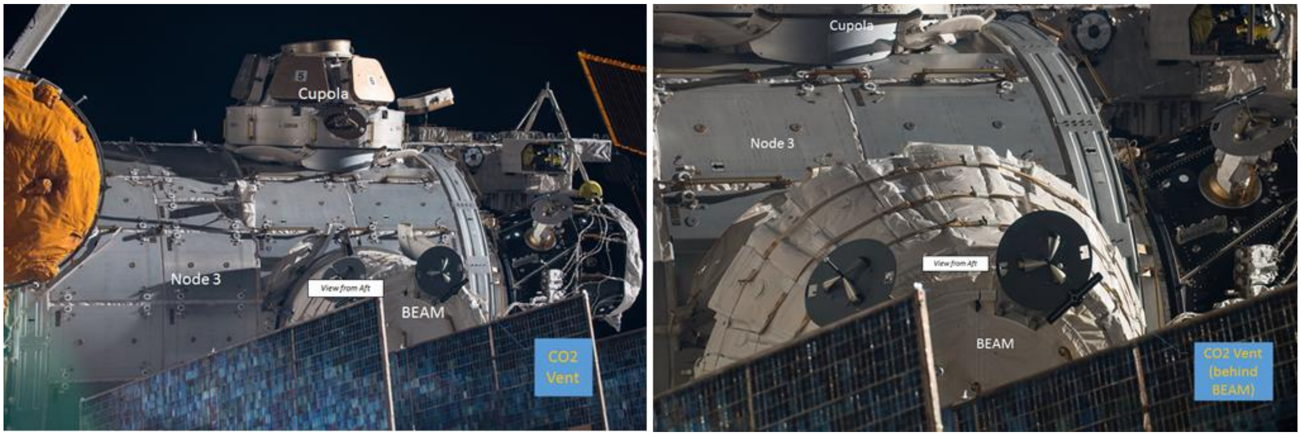

Figure 5. Installation and Expansion of BEAM in relation to Node 3 CO_2 Vent Line.[13]

On the Russian segment, there are two continuous vents, Vozdukh and Elektron, both located on the Service Module. Similar gas byproducts are generated except for water which is recovered in the USOS. The Vozdukh has six exit holes comprising the vent and the Elektron has four exit holes. The Vozdukh releases primarily carbon dioxide in conjunction with air and water. The Elektron provides oxygen to the ISS and vents H_2 in addition to H_2O as the system on the Russian segment does not recover the water. Depending on the operating mode, the cycle time may be 10, 20, or 30 minutes. The relative locations of the Vozdukh and Node 3 CDRA vents on ISS are shown in Figure 6.

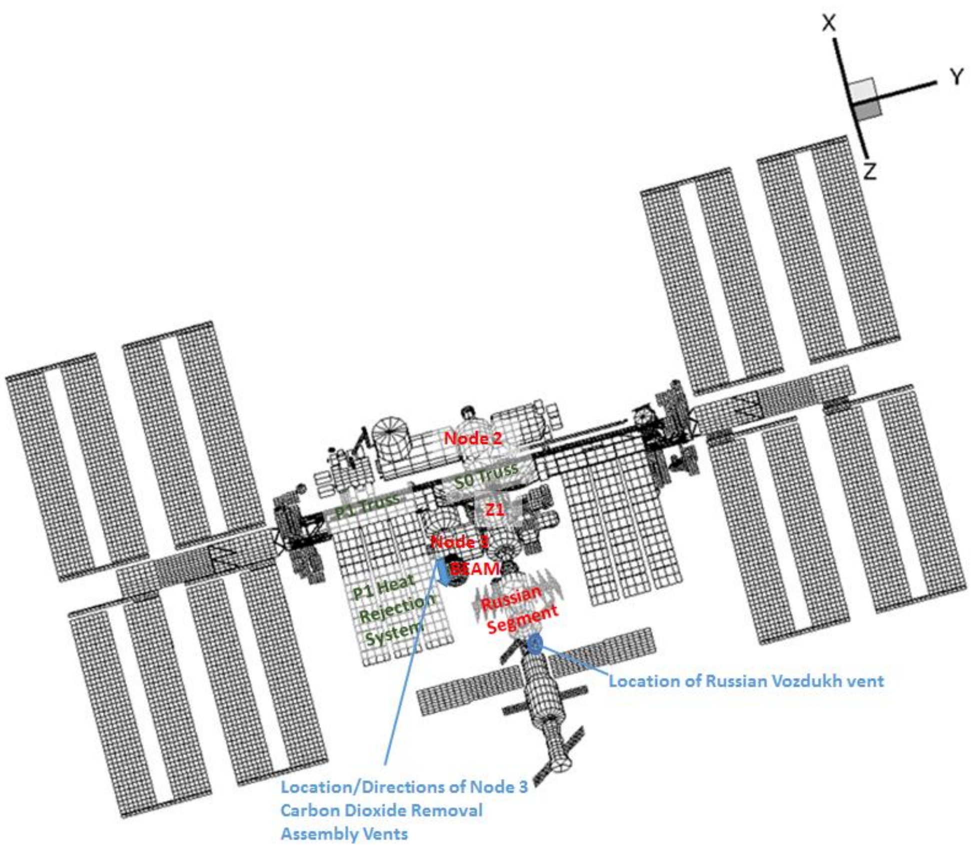

Figure 6. Locations of the Russian Vozdukh and Node 3 CO_2 Vents.

IV. RESULTS AND DISCUSSION

A. Node 3 Carbon Dioxide Removal Assembly Venting

While searching for a leak source on the port-side of the ISS, periodic pressure spikes were detected with the ion gauge real time and, subsequently, also measured with the RGA. Figure 7 shows a majority of the RELL locations and pointing directions while in operation on-orbit. RELL spent most of its time near the P1 Truss around the six Radiator Beam Valve Modules (RBVMs). In addition, the SSRMS also moved RELL to the following areas: 1) the three panels of the P1 center Heat Rejection System radiator, 2) Z1 Truss, 3) S0 Truss, and 4) Node 2/Japanese Exposure Module area. Red arrows denote that there was no obvious total pressure increase measured while the orange arrows indicate a jump in the total pressure was observed. Figure 7 also shows the reflections are rather diffuse and not specular. A specular reflection occurs when an incident molecule collides with the molecular structure of a solid surface and bounces elastically as if hitting a flat surface. The angle of reflection would be the same as the angle of incidence. For a diffuse reflection, the incident molecules collide with the molecular structure of the solid surface, attain thermal equilibrium with the surface, and then evaporate off at the surface temperature in all directions.

In the case of the Node 3 CDRA vent, the gas molecules are not colliding with a solid surface but the external fabric layer of BEAM. Figure 8 shows an example of an obvious pressure spike compared to measurements in the ram direction, where not as much ISS hardware is in the view of the RELL. In the figure, the Node 3 CDRA vent time is centered at the 20 minute mark. There were no obvious pressure increases measured when RELL is in the ram facing locations, viewing space. Figure 9 shows the views from RELL at the locations of the six positions represented in Figure 8. As RELL gets closer to the vent source, the measured reflected pressure, in turn, becomes greater. The ISS ECLSS team provided Node 3 and U.S. Laboratory CDRA vent times to space and examples of the Node 3 CDRA valve operation and bed pressure telemetry data. As stated earlier, the life support systems on the USOS operate on 144 minute cycles. This information, in combination with the mass spectrum data from the RGA, confirmed that these spikes were not ammonia, but the effluents of ECLSS venting.

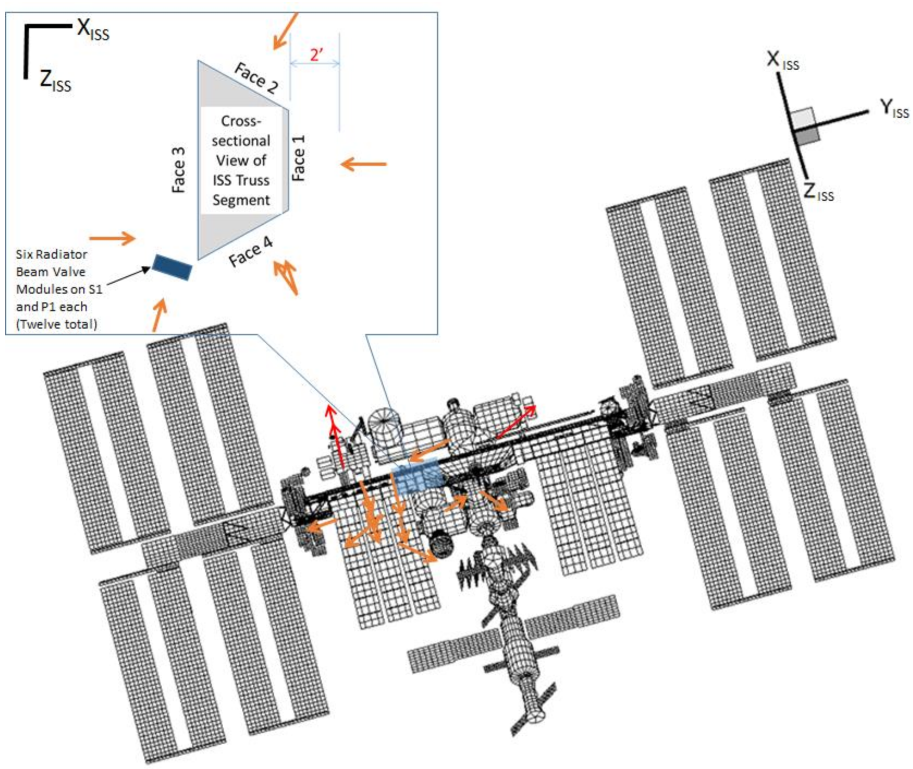

Figure 7. RELL Locations and Pointing Directions on ISS. Orange arrows denote there was an obvious increase in the total pressure during cyclic Node 3 CDRA vents while red arrows indicate no obvious increase in total pressure was observed.

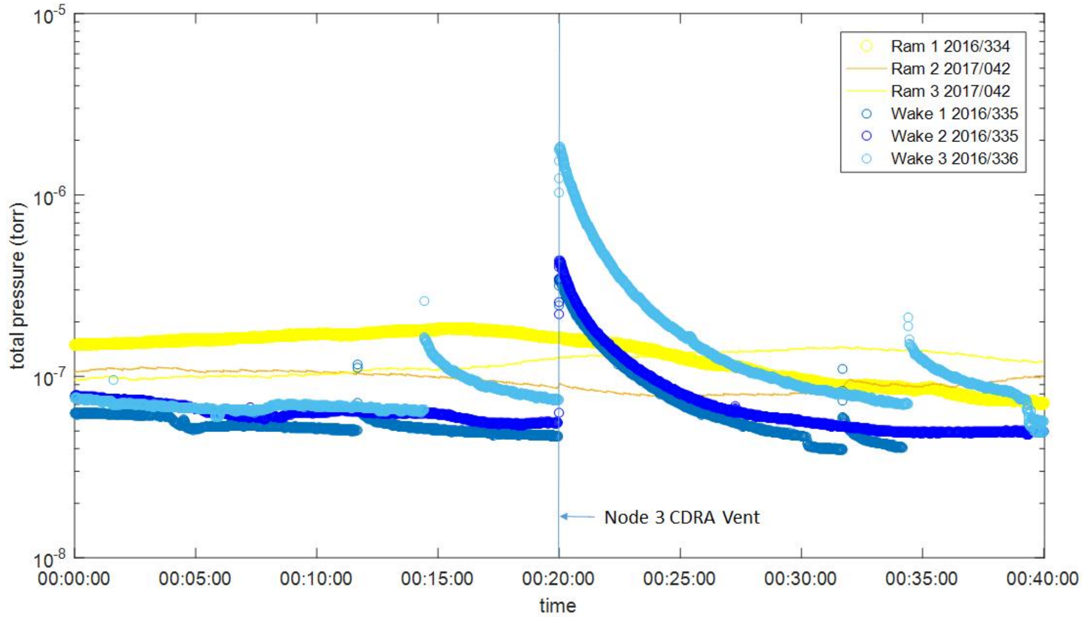

Figure 8. Total Pressure Spikes Observed with RELL Viewing ISS Hardware compared to Viewing Space.

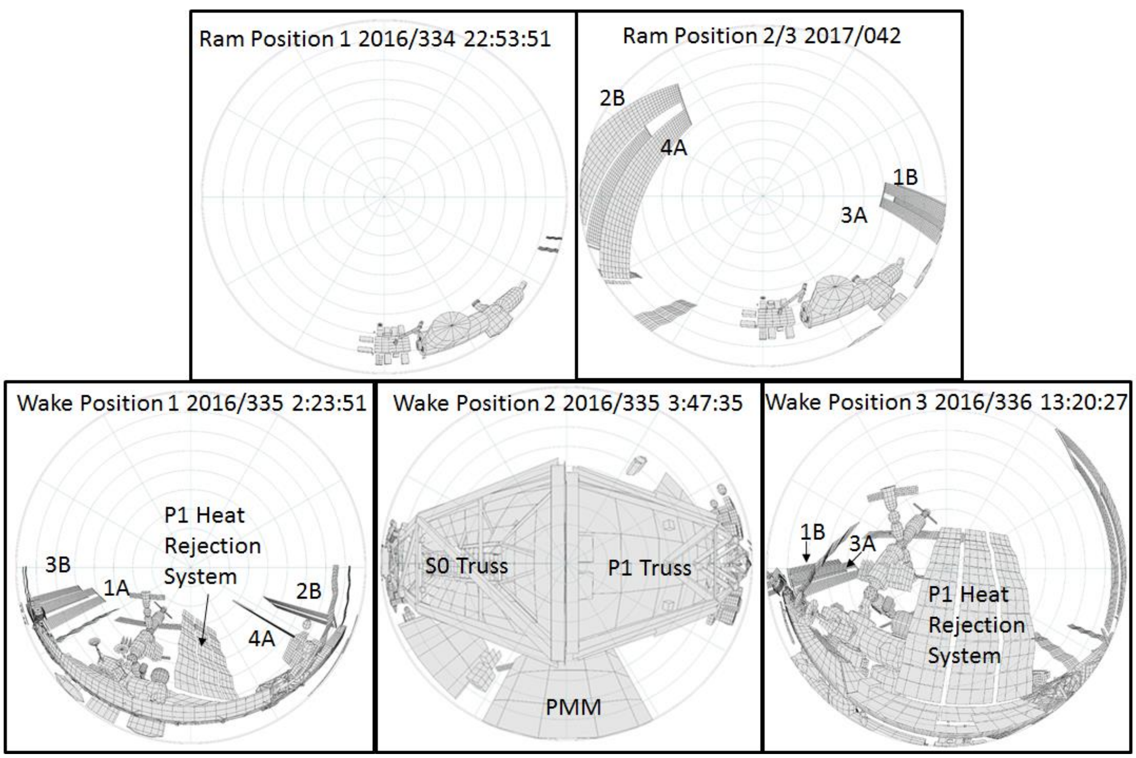

Figure 9. Views from the RELL at the Ram and Wake Locations shown in Figure 8. The Space Station Remote Manipulator System is not shown in the views.

Figures 10 and 11 show semi-log plots of the partial pressure data from the RGA at the Wake 2 and 3 positions. The partial pressure measurements indicate that the gases are carbon dioxide and methane, which correspond to Node 3 CDRA effluents. Figure 10 shows a release of methane approximately twelve minutes before the start of the CDRA cycle. This indicates that the Sabatier reactor was running. Figure 12 provides the National Institute of Standards and Technology (NIST) mass spectra for carbon dioxide and methane. The spectrum of CO_2 from the NIST Chemistry WebBook has three major mass-to-charge ratios of 16, 28, and 44 in increasing order.[14] The two major mass-to-charge ratios for methane are 15 and 16. The expected ratios of the ion masses of 44 to 28 and 44 to 16 are 10.2 and 10.4, respectively. The relative intensity ratios of 44 to 28 and 44 to 16 measured by the RGA in Figures 10 and 11 were in the range from 8 to 12 and 3 to 4, respectively, indicating there is more ion mass of 16 from another source than CO_2. The most plausible source is methane from the Sabatier reactor, and thus confirming that the Sabatier is in operation. There are two small pressure spikes observed at the Wake 1 position on GMT2016/335 and also at the Wake 3 position on GMT2016/336, both twenty minutes apart. The RGA data shows the addition of carbon dioxide and water at those times. After coordination with ISS Space Environments Russian counterparts, it was confirmed that these effluents were from the Vozdukh vent on the Service Module, which operates on 20 minute cycles.

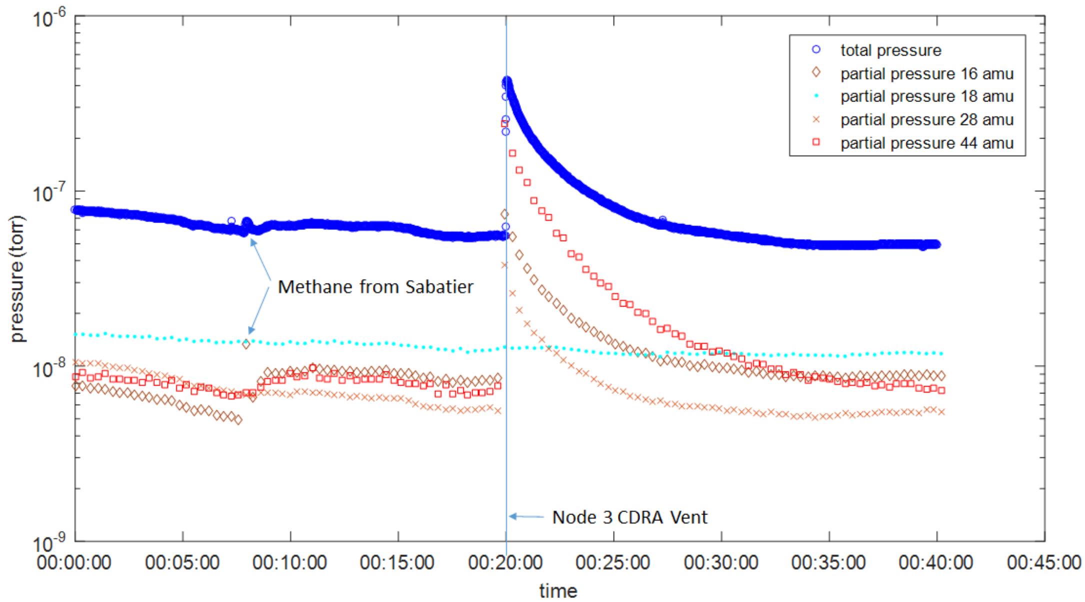

Figure 10. Total Pressure in combination with RGA Partial Pressures for RELL (Wake 2 position) pointing wake on GMT2016/335.

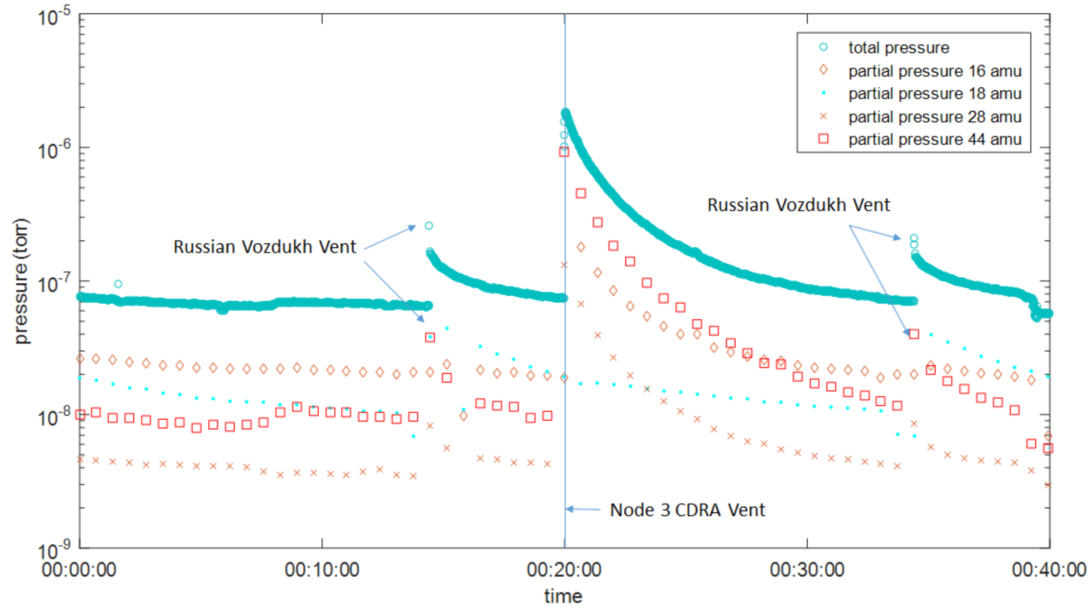

Figure 11. Total Pressure in combination with RGA Partial Pressures for RELL (Wake 3 position) pointing wake and nadir at Russian Segment on GMT2016/336.

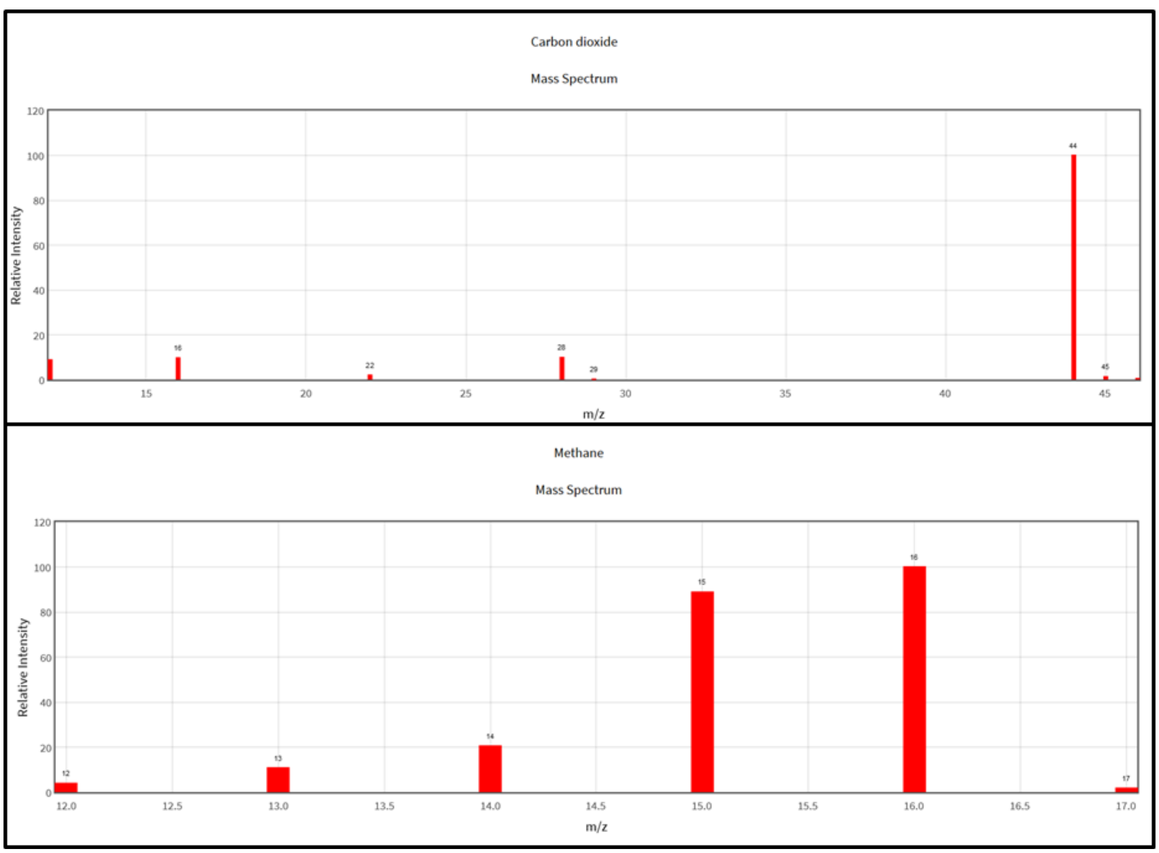

Figure 12. NIST Mass Spectra for Carbon Dioxide and Methane.[14]

While there were no obvious total pressure spikes observed when the RELL was in the ram facing positions, additional data, including the more sensitive RGA partial pressure data collected during the February 2017 operations, was examined. RELL was parked overnight in the Ram 2 position as shown in Figure 9. The SSRMS is not shown in the view, but a section of the robotics arm is in the view of RELL. Unfortunately, a full calibration among the ion gauge, Faraday Cup, and electron multiplier was not completed during the February 2017 operations primarily due to water that had condensed on the RGA while the RELL was stowed inside the ISS between 2016 and 2017 operations. The water had to be baked out in space for at least twelve hours.[2] Thus, the February 2017 RGA data can't be reduced to provide absolute partial pressure values, but it can still provide relative pressure changes.

First, the total pressure scans for five consecutive Node 3 CDRA vent cycles are shown in Figure 13. There is an additional ISS effect that needs to be considered when taking measurements in the ram direction - the ISS floating potential. Three of the five scans show an almost instantaneous bump which does not correspond to any vent. The increase corresponds to times when the ISS is at eclipse exit (i.e., the ISS and its solar arrays are insolated). The filament in the RGA or ion gauge only ionizes a small fraction of the neutrals that enter the aperture and make it to the collector or detector. Because ~1% of the gas at the ISS altitude is ionized (i.e., electrons and protons), this can lead to a significant but incorrect increase to the measured currents as the ISS floating potential is enhanced (i.e., becomes more negative). The electrons are much more mobile than the ions and are attracted toward the solar arrays. The charge of the ISS is driven negative until the current from the ions and the electrons are equal. The largest charging is generally seen at eclipse exit. The shape of Floating Potential Measurement Unit (FPMU) voltage measurements on ISS also matches that of the partial pressure measurements for the mass-to-charge ratio of 16 (i.e., the main ion at ISS altitude, atomic oxygen) showing that there is an effect. The total pressure data in Figure 13 is inconclusive regarding whether there is an increase at the Node 3 CDRA vent time. However, the more sensitive RGA measurements were also examined. Figure 14 presents the partial pressure for the primary mass-to-charge ratio, 44, of carbon dioxide in the Ram 2 position on GMT2017/042. For each scan, there seems to be a local maximum at the start of the Node 3 CDRA vent time indicating that the RGA is detecting the reflected CO_2 gas.

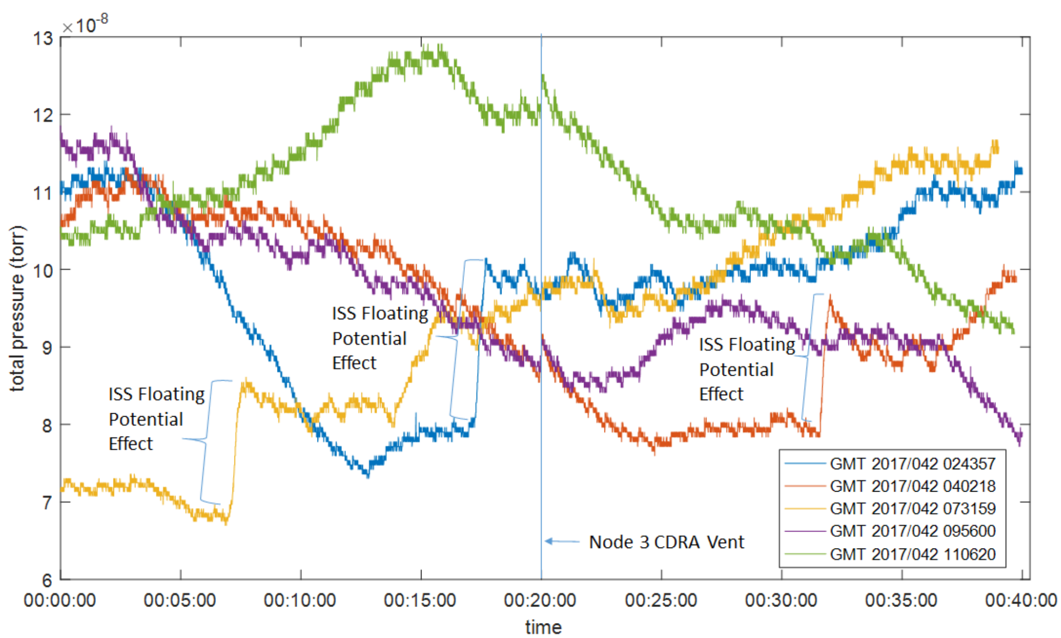

Figure 13. Total Pressure measurements in the Ram 2 position on GMT2017/042.

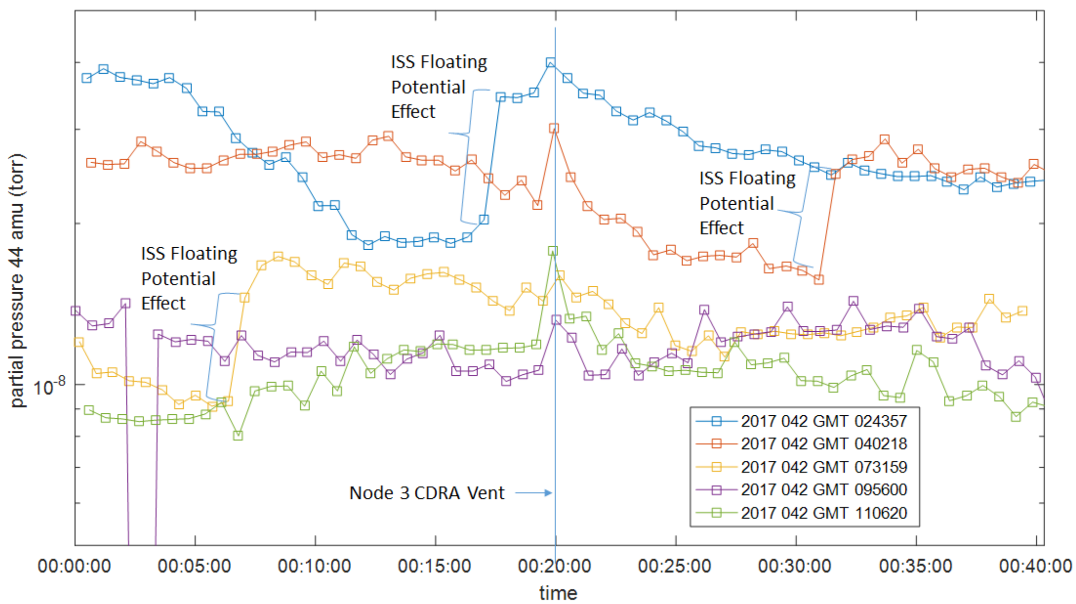

Figure 14. Partial Pressure measurements for an ion mass of 44 in the Ram 2 position on GMT2017/042.

B. U.S. Laboratory Carbon Dioxide Removal Assembly Vent

Following the blowdown of the Node 3 CDRA vent that occurred on GMT2016/336 13:20:27, shown in Figure 11, a U.S. Laboratory CDRA vent undergoing its own 144 minute cycle occurred at 13:54:10. The U.S. Laboratory is the module between Node 2 and Node 1/Z1 in Figure 1, and its CDRA vent is a non-propulsive vent on the nadir facing side. The RELL, parked and viewing the Russian Segment, was able to detect both vents. Figure 15 shows the detection of the U.S. Laboratory CDRA vent and a Sabatier operation in which it runs out of carbon dioxide and holds onto the carbon dioxide coming from CDRA (resulting in a drop in total pressure) before venting one of its by-products, methane, similar to the methane release observed in Figure 10. RELL was also able to detect argon from the Columbus Vacuum and Venting Assembly on GMT2016/336 to 337 in addition to USOS and Russian segment ECLSS vents.

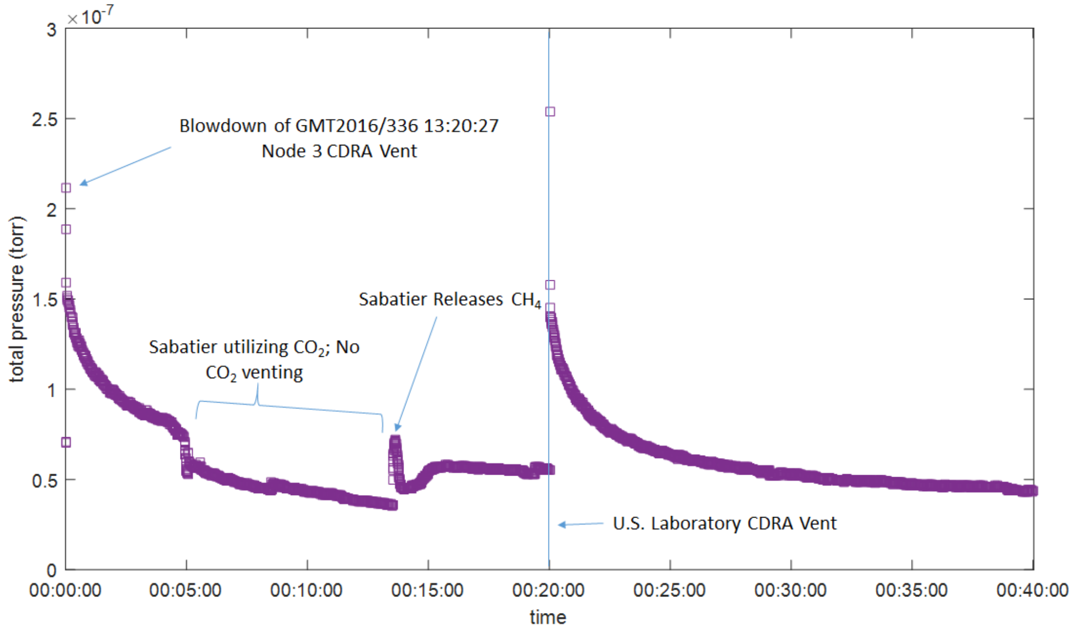

Figure 15. Detection of a U.S. Laboratory Carbon Dioxide Removal Assembly (CDRA) Vent Following a Node 3 CDRA Vent.

V. CONCLUSIONS

During the operation of ISS ECLSS and propulsion systems, liquid and gaseous materials will be produced and disposed through various vents and thrusters. Understanding of plume flow and possible gas/surface reflections (or interactions with the spacecraft) is critical when scientific instruments (e.g., mass spectrometers) are monitoring the external environment. The detection of multiple recurring ISS ECLSS vents during RELL's on-orbit operations to locate an ammonia leak demonstrate that a sensitive mass spectrometer or ion gauge can pick up gas molecules via diffuse reflection or scattering. The path to the detector that the gas molecules travel is not always obvious. In support of the leak locating operations, RELL was able to confirm the expected ISS ECLSS effluents and distinguish those from ammonia based on the ion mass spectra and known venting times.

VI. ACKNOWLEDGEMENTS

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