Status and Results of the Spacecraft Atmosphere Monitor Technology Demonstration Instrument

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The Spacecraft Atmosphere Monitor (S.A.M.) is a miniaturized gas chromatograph mass spectrometer (GC/MS) instrument that is being developed for monitoring the cabin atmosphere for human spaceflight missions. The first Technology Demonstration Unit (TDU1) operated successfully aboard the International Space Station (ISS) from August 2019 to July 2021, exceeding its 1 year planned operational lifetime. The TDU1 continuously monitored the ISS cabin atmosphere for the major constituents. In June 2020 the TDU1 was also reconfigured at the request of the ISS vehicle office and successfully determined that there was no benzene leaking into the ISS atmosphere. The technology demonstration unit #2 (TDU2) is scheduled to be deployed on the ISS in 2022. While on-station, TDU2 will continuously monitor the major atmospheric constituents as well as trace organic volatiles. The S.A.M. TDU2 uses the same quadrupole ion trap mass spectrometer (QITMS) sensor as in TDU1, but includes a MEMS preconcentrator, gas chromatograph, and microvalve system. Its miniature, ruggedized form factor allows the S.A.M. to be aisle-deployed to monitor the cabin in different locations and during activities such as exercise and sleep. The operational performance of TDU1 and the current status of TDU2 will be discussed

Nomenclature

DM = Development Model
FSW = flight software
GC = gas chromatograph
HOSC = Huntsville Operations Support Center
HIM = Human Interface Module
ISS = International Space Station
MCA = Major Constituents Analysis
MEMS = Micro Electro Mechanical System
MSFC = Marshall Space Flight Center
MS = mass spectrometer
MV = microvalves
NEG = Non Evaporaporable Getter
PC = preconcentrator
PCB = printed circuit board
QITMS = quadrupole ion trap mass spectrometer
S.A.M. = Spacecraft Atmosphere Monitor
TDU = Technology Demonstration Unit
TGA = Trace Gas Analysis
VCAM = Vehicle Cabin Atmosphere Monitor
VOC = volatile organic compound

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1. Introduction

THE Spacecraft Atmosphere Monitor (S.A.M.) is an instrument based upon a highly-compact gas chromatograph mass spectrometer (GC/MS), developed as a technology demonstration for measuring the major constituents and trace volatile organic compounds (VOCs) in the cabin-air of the International Space Station (ISS) and future crewed vehicles. The S.A.M. instrument has been under development since 2015 and has been matured, and delivered for spaceflight demonstration using a step-wise methodology. Previous reports discussing the progress towards the S.A.M. TDU can be found elsewhere[1,2,3]. Throughout the development of S.A.M., the environmental test facilities at Marshall Space Flight Center (MSFC) has been used to test the performance. Results from this testing have been used to inform the S.A.M. project through its maturation to the Technology Demonstration Unit (TDU).

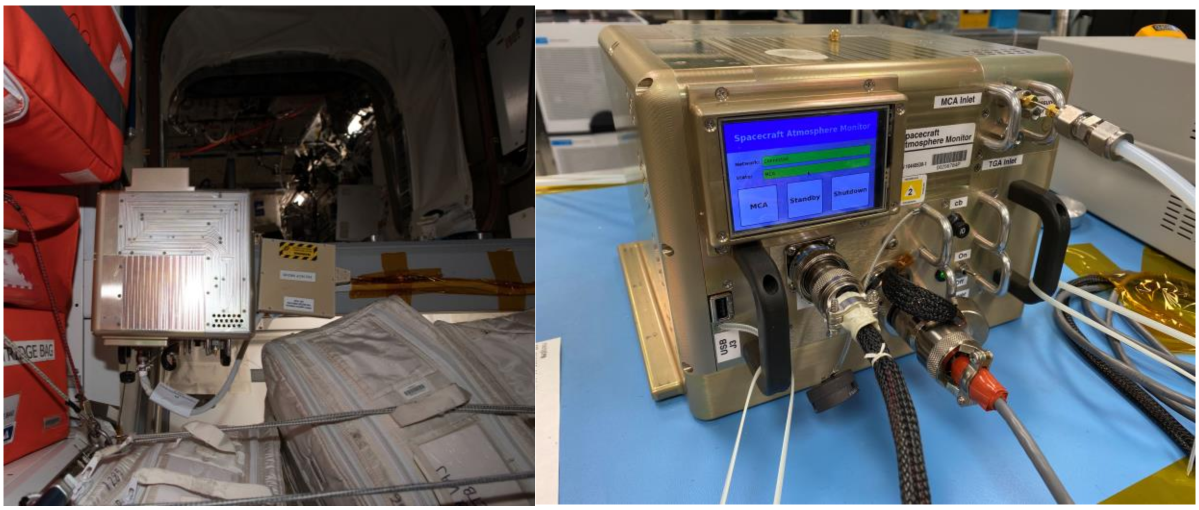


Figure 1. The S.A.M TDU1. *Photographs of the S.A.M. TDU1 isle-deployed at Node-2 on May 20, 2020 (left) and at JPL on Feb. 20, 2022 (right) after two years of continuous operations on ISS. TDU1 returned to earth aboard SpaceX-24 on January 24, 2022 and was received at JPL on February 15, 2022. After replacement of a corrupted flash-memory card, checkout of TDU1 at JPL confirmed that the instrument is still operating within required specifications. The TDU aluminum chassis is 9.5" x 8.75" x 7.5" in volume with a mass of 9.5 kg. The S.A.M. handles and small form factor allows for the instrument to be easily transported to perform cabin-air monitoring anywhere within ISS. It is planned for TDU1 to be upgraded with trace gas analysis (TGA) capabilities and reflown to ISS in 2023.*

2. TDU Instrument Overview

The S.A.M. TDU shown in Figure 1 is a direct successor of the VCAM instrument4,5,6 which operated for two years onboard the ISS. Although VCAM and S.A.M. provide similar functionality, the S.A.M. TDU incorporates several key technological advances including 1) the use of a passive pumping system (an ion/getter pump) rather than turbo and roughing pumps; 2) nominal operation under high vacuum conditions; 3) and the introduction of MEMS components. These advances enable the S.A.M. instrument to operate at less than one half of the VCAM power consumption (approximately 110 Wpeak) in a compact form factor one third of VCAM mass and volume.

The front panel of S.A.M. includes the power, data, and wireless connectors, the power switch, and various inlets for cabin-air monitoring. Although the S.A.M. TDU is predominantly autonomous, the front panel also includes a touchscreen, or Human Interface Module (HIM), enabling astronaut control of low-level operations such as initiating different operational modes such as Standby, MCA, or TGA. In total the instrument weighs 10 kg and has an average power draw of 45 W. Located inside the S.A.M. mechanical structure are the quadrupole ion trap mass spectrometer (QITMS) assembly, the preconcentrator gas chromatograph (PCGC) assembly, and printed circuit boards (PCBs) which make up the electronics assembly. The PCGC sub-assembly holds pressurized gas lines, vacuum valves, and filters that feed sampled air and hydrogen carrier gas into the MEMS PCGC subassembly and ultimately into the QITMS assembly. The sensor assembly consists of the QITMS and ion/getter pump. The QITMS is a 3D Paul Trap with a 10 mm field radius and effective capacitance of 85 pF, operated using an 800 kHz rf voltage up to 2 kV amplitude. The top and bottom endcaps are nominally kept at ground potential. At the center of both endcaps are two 1 mm OD x 2.5 mm long holes: one for the introduction of the electron beam and the second for the ejection of ions into the detector assembly. The nominal sensitivity of the QITMS is approximately 2-3x10^{12} counts/torr/sec, with a maximum of 10^{14} counts/torr/sec possible under certain operating conditions. To prevent the creation of patch potentials due to the adhesion of trace organics on trap surfaces, the QITMS is also coated with Silcoguard. To further maintain the cleanliness of trap surfaces, the QITMS is equipped with a 20 W halogen bulb which nominally heats the trap to above 200 ºC.

The QITMS assembly is housed in a 3D-printed titanium vacuum chamber, intentionally designed to minimize the mass and footprint of the MS Sensor assembly. The additive manufacturing process (CalRAM[8]) includes a state-of-the-art laser sintering procedure followed by hot isostatic pressing to reduce the porosity of the titanium to minimize outgassing and increase its durability. After printing, the chamber undergoes traditional machining to clean out the internal volume as well as to create the knife edges for conflat flange seals. Ultimately these custom QITMS chambers exhibit external leak rates less than 10^{-11} Torr L/s and base pressures less than 10^{-10} Torr following a typical 24-hour bakeout at 150ºC. High vacuum for QITMS operation is provided by a nonevaporable getter (NEG) pump coupled with a noble diode ion pump, which are used in tandem to achieve chamber pressures 10^{-9} to 10^{-8} Torr during MCA and 10^{-6} to 10^{-5} Torr during TGA. The noble diode ion pump was custom manufactured by Collins Aerospace Systems[10] for spaceflight applications with a 2 L/s pumping speed over a wide range of pressures (10^{-9} to 10^{-4} Torr). The NEG pump is custom design, constructed from 25 stacked ZrVFe discs[9] which have a cumulative mass and surface area of 28 g and 238 cm^2, respectively. The NEG pump's large hydrogen sorption capacity (280 Torr L) and pumping speed (200 L/s), permits the use of relatively high flow rates of GC hydrogen carrier gas (0.1 sccm) into the QITMS chamber while performing TGA of the cabin atmosphere. This design enables S.A.M. to have a lifetime of approximately 700 trace gas analysis runs. Cabin air is admitted into the instrument for MCA and TGA analysis through two independent gas inlets mounted on the front panel. For MCA analysis, the cabin air is transferred into the S.A.M. QITMS via a hydrophobic passivated air leak with a conductance of approximately 5x10^{-9} Torr liter/sec, resulting in a constant pressure inside the QITMS chamber of 8x10^{-9} Torr. This design enables S.A.M. to have an approximate 5 years lifetime for continuously cabin atmosphere MCA analysis.

The S.A.M. PCGC subassembly is shown schematically in Figure 2. The preconcentrator (PC), microvalves (MV) and gas chromatograph (GC) are all micromachined (MEMS) chips. Employing MEMS technology yields an extremely small footprint in terms of space and power consumption. In the PCGC, a single small assembly contains

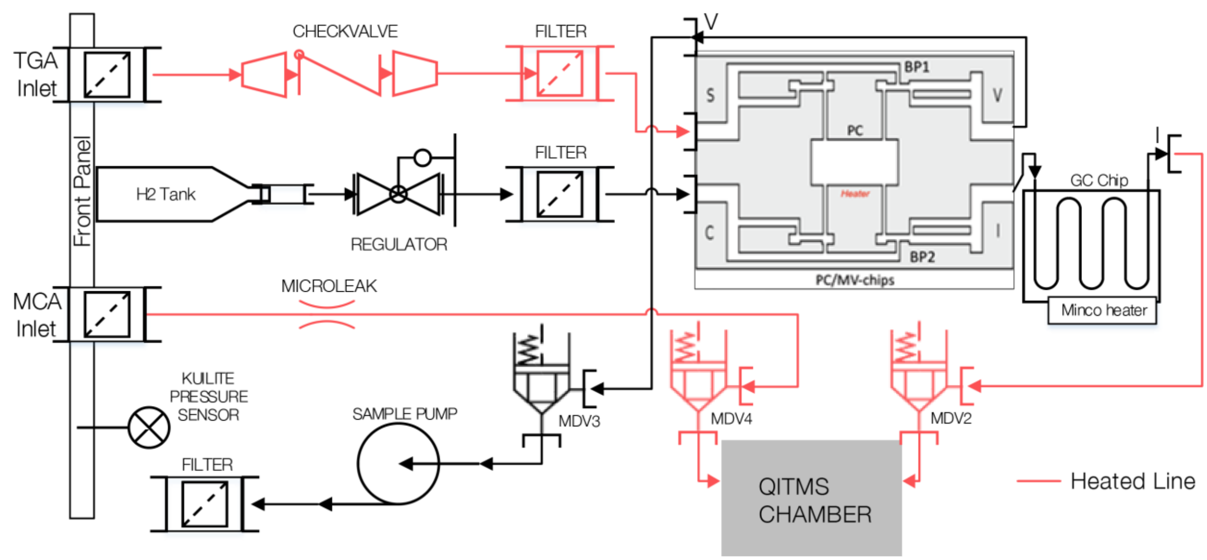


Figure 2. PCGC assembly plumbing diagram. *This schematic shows the components including filters, valves, heaters, and plumbing used in the PCGC assembly. The main paths, starting from the left side, are the sample, carrier, and MCA flow paths. Two Mindrum valves, MDV2 and MDV4, control the gas flow from the GC chip and MCA microleak to the QITMS chamber. A simplified 2-D model of the MV chip shows the various flow paths combining the input from the H2 tank and the TGA inlet during TGA runs.*

the PC, GC, MV chips – each approximately 15 mm x 15 mm x 4 mm. The PC is a 250 nL chemical trap filled with 80-100 mesh Carboxen 1000 spheres (Sigma-Aldrich[11]) heated by a silicon heater. During TGA, cabin air is drawn through the PC by a downstream sample pump and the VOCs adsorb to the Carboxen. After as set sampling time, the PC is flash-heated by applying ~20 W of power to the heater for 7-12 s resulting in nominal temperatures of 250-300 ºC (measured by monitoring the resistance of the heater element). This heating quickly drives off the adsorbed VOCs which are then injected into the GC microcolumn and ultimately into the QITMS. The S.A.M. PC has demonstrated chemical gains on the order of 1000, making ppb concentration relatively straightforward to detect[12].

The GC microcolumn, provides sufficient chemical separation to simplify trace VOC identification and quantification by the QITMS, is 6m x of 86 µm (channel width) with a OV-5 stationary phase, prepared using a custom in-house procedure. To reduce retention times for nonpolar VOCs, the GC chip is equipped with a foil heater which is heated to 100 ºC during the latter half of the chromatogram. Nominal hydrogen carrier head pressures are between 16 and 18 PSIa resulting in the flow rates of ~0.1 sccm and total elution times of up to 20 min for siloxanes.

Carrier and sample flow directions within the PCGC package are controlled by the MV chip which has *five* independently controlled electrostatic membrane microvalves – one for the sample inlet, carrier inlet, sample outlet, carrier/injector outlet and carrier gas bypass. The source of hydrogen carrier gas is a custom 4" metal hydride canister (HCI) which holds 10 Torr·liters of hydrogen with a head pressure of ~50 PSIg when full. An inline regulator reduces the hydrogen carrier pressure to the nominal 16 to 18 PSIa carrier pressure for chromatography (0.1 sccm). The steady-state flow of hydrogen, when not in TGA mode, is measured to be much less than 0.01 sccm, such that after 1 year of operation it consumes at most 2.7 Torr·liter of hydrogen. The hydrogen mass volume used during the 365 TGA runs (0.1 sccm flow) is approximately 1.0 Torr·liter of hydrogen. As such, a conservative estimate of total hydrogen consumption over one year of expected operations is no more than 3 Torr·liters, enabling S.A.M. have an expected 3 year lifetime, exceeding its goal of 1 year of on-orbit operations. Shown in Table 1 are the technical and performance specifications for the S.A.M. instrument.

3. S.A.M. Performance

A. TDU1 Delivery, Operations, and Return

The S.A.M. TDU1 was delivered to Johnson Spaceflight Center (JSC) on June 6, 2019. On July 25, 2019, aboard SpaceX-18, it was delivered to the ISS. The TDU1 was installed in the EXPRESS locker 8 in the US Laboratory module on August 7, 2019 and commenced checkout and commissioning operations the next day. On August 17, 2019, after completing these operations without anomaly the TDU1 commenced continuous MCA mode operations. TDU1 ceased operations on July 23, 2021, after nearly two years of continuous operation, exceeding it's 1-year lifetime goal. Shown in Figure 1 is the TDU1 that was returned to earth on January 24, 2022 aboard SpaceX-24 and delivered to JPL on February 15, 2022. Examination of TDU1 confirmed that the instrument ceased operations due to a corrupted flash-memory card. The corruption was due to the two years of continuous operations exceeding the flash-memory card's specifications for the maximum number of read/write cycles. A software patch has been developed and preclude this error mode in future S.A.M. units by limiting the number of read/write cycles and by buffering S.A.M. run-time data in the memory storage available on-board ISS. Future embodiments of S.A.M. would likely use memory storage hardware (e.g. rad-hard random access memory (RAM)) that is not susceptible to this type of failure mechanism.

B. TDU1 Major Constituent Analysis of ISS Cabin Atmosphere

For almost two years S.A.M. TDU1 continuously monitored the N_2, O_2, CO_2, and CH_4 partial pressures in the ISS cabin atmosphere. The continuous MCA monitoring was interrupted occasionally for events such as software updates and when was TDU1 relocated between the EXPRESS Rack mounting, and remote isle-deployment in either Node-1 or Node-2. One significant two month gap in the MCA work worth noting however started on June 5, 2020, where at the request of the ISS Vehicle Office TDU1 QITMS was re-tuned to detect if the ISS cabin atmosphere had concentrations of benzene that exceeded the Spacecraft Maximum Allowable Concentrations. Although TDU1 did not have trace gas capability, the TDU1 within two weeks was able to categorically state that no benzene was present at levels greater than 0.1 parts-per-million. This was confirmed in September 2020 by analysis of grab samples of

Table 1. S.A.M. Technical Specifications for Major Constituents Analysis (MCA) and Trace Gas Analysis (TGA). *Key parameters regarding science performance of the S.A.M. TDU1 and TDU2 instruments. TDU1 was delivered with MCA only capabilities. TDU2 will be delivered with both MCA and TGA capabilities. Note that values marked with * are expected TDU values. All low and high levels for trace gas detection are based on S.A.M. requirements.*

MCA Mode	
Report Cadence	2 s
Data Integration Time	10 s
Major Constituents Leak - Type	1.5” x 2 µm ID passivated microcapillary or crimped gold tube
Leak Rate	5 x 10^{-8} Torr L/s
QITMS Pressure	10^{-9} – 10^{-8} Torr

Species	Measurement Range	Measurement Precision (for 10 s)
Nitrogen (N_2)	360 – 600 Torr (47-79%)*	±0.5 Torr (±0.07%)
Oxygen (O_2)	130 – 160 Torr (17-21%) *	±0.5 Torr (±0.07%)
Carbon Dioxide (CO_2)	3 – 7 Torr (0.4 – 1.0%)	±0.1 Torr (±0.01%)
Water (H2O)	4-12 Torr	±20%
Methane (CH_4)	0 – 7 Torr (0 – 1.0%)*	<±0.5 Torr (±0.03%)*

TGA Mode	
Frequency	Nominally once per day (or on-demand)
Run Time	10 – 20 minutes
GC Carrier	H_2 (supplied by 10 torr liter capacity metal hydride tank)
GC Column	6 m x 86 µm ID microcolumn with OV-5 stationary phase
GC Flow rate	0.10 sccm H_2
PC Description	250 nL Carboxen 1000
PC Heating	Adjustable 250 ºC - 350ºC for 1 to 5 s
QITMS Pressure during TGA mode operations	10^{-6} – 10^{-5} Torr
TGA Measurement Precision	40% relative

Species	Low (PPM)*	High (PPM)*	Species	Low (PPM)*	High (PPM) *
Hexane	0.014	1.4	Dichloromethane	0.01	0.1
Propenal	0.004	0.04	Acetaldehyde	0.06	1.1
Ethanol	0.5	11	Perfluoropropane	13	130
2-Propanol	0.04	4	Methanol	0.1	4
1-Butanol	0.02	0.7	Octamethylcyclotetrasiloxane	0.02	0.2
Acetone	0.04	1.3	Hexamethylcyclotrisiloxane	0.02	0.2
Benzene	0.01	0.2	Decamethylcyclopentasiloxane	0.01	0.1
Toluene	0.03	0.3	Trimethylsilanol	0.05	1
o,m,p-Xylene	0.02	0.2			

cabin air that were returned to earth and analyzed by the JSC Toxicology group. TDU1 returned to continuous MCA monitoring on August 21, 2020.

The TDU1 instrument did not have the capability to measure the partial pressure of H_2O due to the MCA microleak being constructed of un-passivated silica tubing. The un-passivated tubing effectively acts as a sponge to the strongly polar molecule and as such water is not transferred to the QITMS. As such, during ISS operations the TDU1 MCA analysis assumed a H_2O partial pressure of 9 mmHg, equivalent to the nominal value reported by the ISS Major Constituents Analyzer. In TDU2 the MCA inlet is passivated enabling H_2O monitoring. TDU1 also detected a persistent quantity of argon is present in the ISS cabin atmosphere. Unfortunately the TDU1 instrument did not have a requirement for argon and as such was not calibrated for argon. To compensate for this, the detected ISS argon pressure was evaluated based on detected TDU1 argon signal, the relative argon ionization cross sections, and the QITMS ion trapping and detection efficiencies. This analysis yielded an argon level of approximately 2 mmHg. As part of the TDU2 verification and validation process, the instrument will be calibrated for argon response.

Onboard operations have been compared to both analyzed grab samples of ISS atmosphere and the ISS MCA instrument. Throughout operations TDU1 has measured MCA partial measures with consistent offsets from those reported by the ISS MCA. It is worth noting a number of cautionary factors when making direct analytical comparisons or conclusions about TDU1 performance. Specifically: (1) the ISS MCA has experienced numerous outages and difficulties during TDU1 operations, (2) ISS MCA measures only the ion signals from N_2, O_2, CO_2, H_2O, and CH_4 and then converts to partial pressures by multiplying the ratio of these ion signals by the cabin pressure retrieved off of the ISS 1553 data bus, (3) the ISS MCA instrument is not calibrated for H_2O, (4) the ISS MCA instrument does not measure argon, which is present in the ISS atmosphere at approximately 2 mmHg, (5) TDU1 and ISS MCA instruments were not co-located within the ISS.

Summary of the TDU1 MCA analysis during two years of operations

1. The partial pressures of N_2 as determined by S.A.M. TDU1 were about 2 mmHg lower than those reported by the ISS MCA instrument. Transitory and ephemeral events are seen by both instruments at the same time and magnitude.

2. The partial pressures of O_2, as determined by S.A.M. TDU1 were uniformly about 2 mmHg lower than those reported by the ISS MCA instrument, corresponding to a deviation of approximately -2%. Transitory and ephemeral events are seen by both instruments at the same time and magnitude.

4. The partial pressures of CO_2, as determined by S.A.M. TDU1 were uniformly about 0.9 mmHg higher than those reported by the ISS MCA instrument. Both S.A.M. and ISS MCA reported a rich time evolution in CO_2 abundances. Both instruments were in almost exact agreement with the timing and magnitude of these events. Returned grab sample containers of the ISS atmosphere were analyzed by the JSC toxicology group which report only on the partial pressure of CO_2. Comparison of S.A.M. TDU1 MCA and ISS MCA are shown in Table 2.

Table 2. Comparison of ISS Grab Samples to both ISS MCA and S.A.M. Reported CO_2 Concentrations. Three grab samples of ISS atmosphere were analyzed for CO2 concentration by the JSC Toxicology group. The results are compared to CO2 partial pressures reported at the same time from both ISS MCA and S.A.M. TDU1. Both ISS MCA and S.A.M. TDU1 are offset from the lab result by approximately the same amount, where ISS MCA under-reports and S.A.M. TDU1 over-reports.

Time stamp	Grab Sample CO_2		ISS MCA CO_2		TDU1 CO_2	
(GMT)	mg/M3	mmHg	mmHg	difference	mmHg	difference
2019_240:13:46:18	5500	3.17	2.71	-0.46	3.41	0.23
2019_317:08:20:15	5200	3.01	2.28	-0.72	4.10	1.09
2019_324:08:19:18	6100	3.50	2.60	-0.40	3.98	0.47

5. The partial pressures of CH_4, as determined by S.A.M. TDU1 were uniformly about 1 mmHg higher than those reported by the ISS MCA instrument. Both the TDU1 or the ISS MCA typically report a monotonic CH_4 time history, without any transitory events.

6. Overall there continues to be good agreement between the ISS MCA and S.A.M. TDU1 instruments. General trends and discrete events are seen by both instruments, at the identical time and in almost exactly the same magnitude.

C. TDU2 MCA Performance

All fabrications for the QITMS, PCGC, electronics, and mechanical subassemblies are complete and the sub-assemblies are under integration and test. On TDU2 the cabin-air inlet has been changed from that used on TDU1 to meet the MCA humidity monitoring requirements. This inlet is shown schematically in Figure 2. It is comprised of a 0.125" VALCO bulkhead connector with a 0.1 µm frit, installed on the TDU2 front-panel, leading to a flow conductance restrictor (microleak) composed of a GLACO coated tube (10cm x 1.5 µm I.D.). After the microleak there is 0.125" SilcoTek stainless steel tubing leading to the QITMS. A MINDRUM valve is installed in the stainless steel tubing to provide positive shutoff of the flow of cabin air during long term storage of the instrument. Shown in Figure 3 is the S.A.M. TDU2 instrument response to varying humidity. In order to completely understand the absolute MCA performance of the TDU2 and its relative performance to the ISS MCA, it is planned to acquire a number of

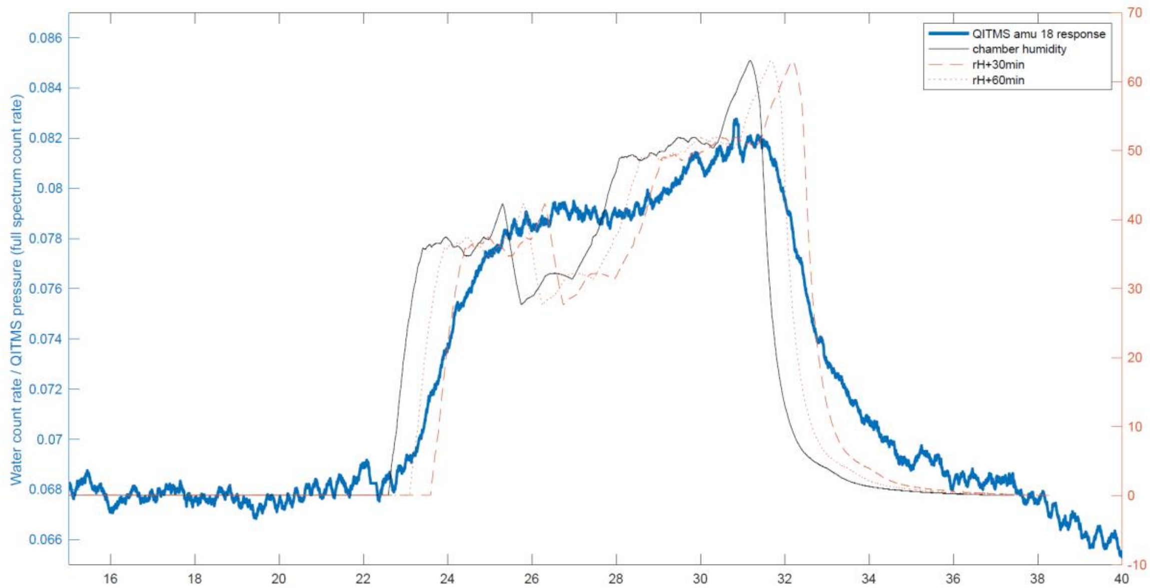


Figure 3. TDU2 Humidity Response. *This figure shows the amu 18 response of TDU over a long time holding the chamber humidity at 35% and 50%. TDU2 initially responds within 15 minutes to a 0-35% change in chamber humidity, and stabilizes after 2-3h. A smaller 15% change from 35% to 50% takes 30mins for initial response, and 1.5h to stabilize. There is at least a 3:1 SNR margin for these measurements. The MCA inlet water surface effects cause a time lag in the response, but that is still acceptable. As was seen during TDU1 flight operation[3], the TDU2 background levels of water in the QITMS will very likely constantly drop during long term operations. As such, TDU2 humidity response might improve further during ISS operations.*

grab samples during TDU2 operations that will be taken adjacent to the ISS MCA while the ISS MCA is operating. A complete analysis of these samples will then be performed on the ground for all MCA constituents. Unfortunately the JSC Toxicology Lab can only measure the CO_2 concentration, so that an alternate qualified laboratory will be chosen.

D. TDU2 TGA Performance

The TDU2 PCGC testing including measurement sequences, and the detection and quantification algorithms are performed on a Testbed unit consisting of a flight-quality sensor subassembly (QITMS + NEG/ion pump or turbomolecular pump), a flight spare of the Valve Heater and Control Electronics (VHCE) and a PCGC subassembly comprised of flight-quality PC, MV, and GC with an optional COTS Agilent 6-port chromographic valve. The COTS valve enables the independent testing of the adsorption and desorption properties of the PC together with the chromographic separations of the GC. All operational parameters learned during TB work is impressed upon the PCGC flight subassembly. Shown in Figure 4 are the GC elution times for the required trace species.

Mass spectra obtained on the QITMS are fed through the random-walk identification and quantification algorithms[13,14]. The TDU2 TGA identification algorithms employ both National Institute of Standards (NIST) mass spectra and mass spectra obtained by the QITMS obtained during laboratory testing. Shown in Figure 5 is the variation of the TDU2 PC gain for benzene as a function of applied PC power (voltage and duration). The current sensitivity of the TB instrument is approximately 10 ppb with a 5 min PC adsorption, PC desorption temp = 250ºC and a PC injection onto GC = 1.5 seconds.

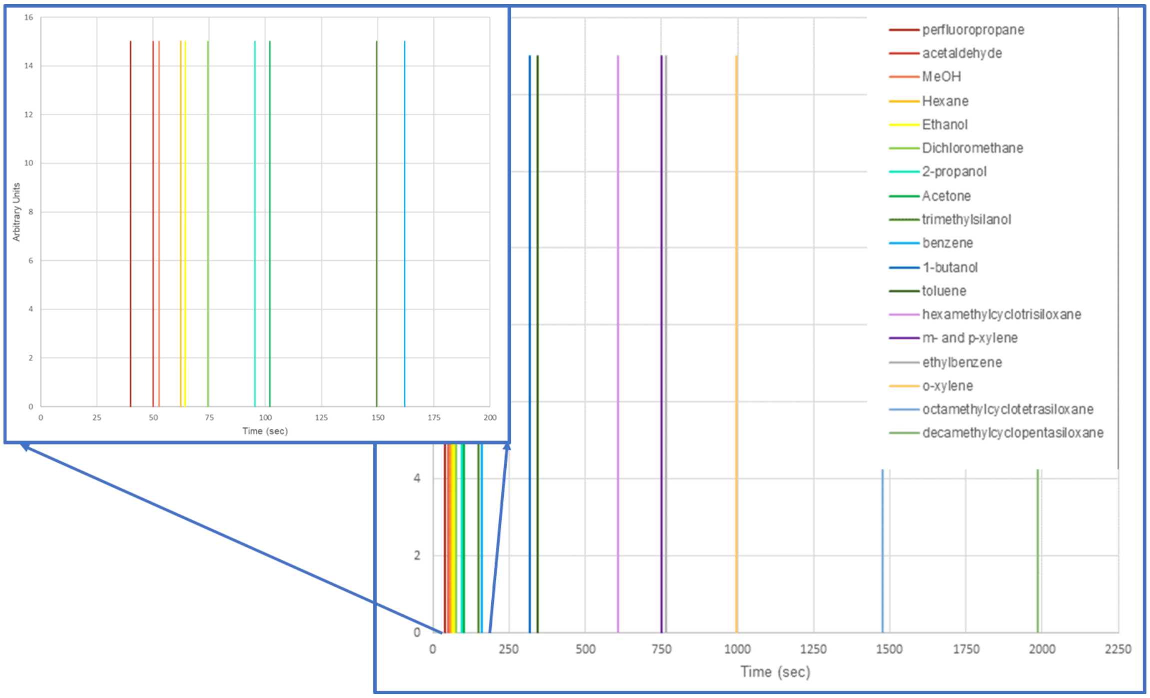
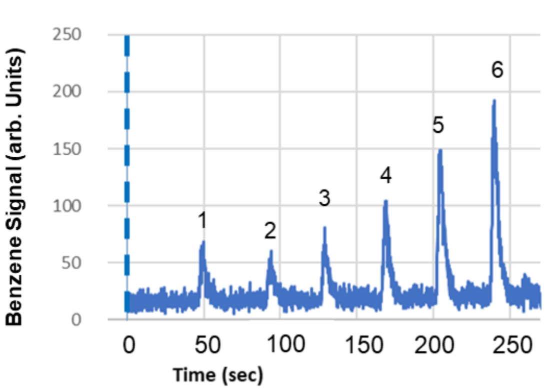


Figure 4. GC Elution Peak Timing. *Shown are the elution times of the TDU2 GC during TGA analysis. The inset in upper right shows a magnified view of the elutions times between 0-200 sec. The GC temperature was 26°C and hydrogen carrier gas was 2 psig with 0.1 sccm flow. Elution peak widths are approximately 10 sec. In-flight operations heats the GC to approximately 100 °C at t=600 sec to shorten the elution time of the siloxane and other later-arriving species. On TDU2 this heating is adjustable in-flight.*



PC Heating Cycle	PC Power (volts/time)	Energy (J)	PC gain	S/N (≥ 10 required)
1	*60V/7sec*	106.70	651	3.4
2	*49V/11sec*	135.45	457	3
3	*52V/11sec*	143.19	733	4.05
4	*55V/11sec*	151.85	1196	5.2
5	*58V/11sec*	159.41	1954	7.45
6	*60V/11sec*	163.47	2457	9.7

Figure 5. PC Gain as a Function of Applied Power. *Shown are the variation of the benzene elution peaks (left) as the power applied to the PC is varied. The PC temperature for heating cycle #2 and heating cycle #6 were approximately 200°C and 275°C, respectively. The TDU2 GC 25°C and the hydrogen carrier gas was 2 psig with 0.1 sccm flow. The resultant sensitivity of the S.A.M. TDU2 instrument is 10ppb.*

7. Plan Forward

The S.A.M. TDU2 is scheduled for delivery in late 2022 to JSC and subsequent launch to the ISS. After docking with the ISS, the S.A.M. payload (which includes the TDU and its stowage locker) will be installed by the astronauts into the ISS EXPRESS rack. It is planned that the TDU1, now at JPL, will be refurbished and upgraded with TGA capabilities and re-flown to ISS in 2023. Two instruments capable of both MCA and TGA on-board ISS will provide excellent analysis of the cabin atmosphere and experiments to study the spatial and temporal variation will be performed. While the S.A.M. TDU1 and TDU2 are fully autonomous and do not require data processing for issuing reports of major constituents and trace gases, JPL scientists will have the ability closely analyze the data for the occurrence of interesting or anomalous findings.

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