Jet Propulsion Laboratory
California Institute of Technology

The Technology Demonstration of the Spacecraft Atmosphere Monitor

International Conference on Environmental Systems 2019

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S.A.M. Team

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What is the Spacecraft Atmosphere Monitor?

- *Miniaturized Gas Chromatograph Mass Spectrometer (GC/MS)*
- *Slated for 21 July 2019 launch to ISS as a Technology Demonstration Unit*
- *Candidate for air monitor on future crewed spacecraft*

S.A.M.'s Duties on the ISS:

1. Continuously monitor N_2, O_2, CO_2, and humidity levels (MCA Mode)

2. On demand, detect trace contaminants that could pose a risk to astronaut health (TGA mode)

3. Deploy S.A.M. to regions throughout the ISS to analyze off-gassing of various astronaut activities

4. Expected lifetime 1-year

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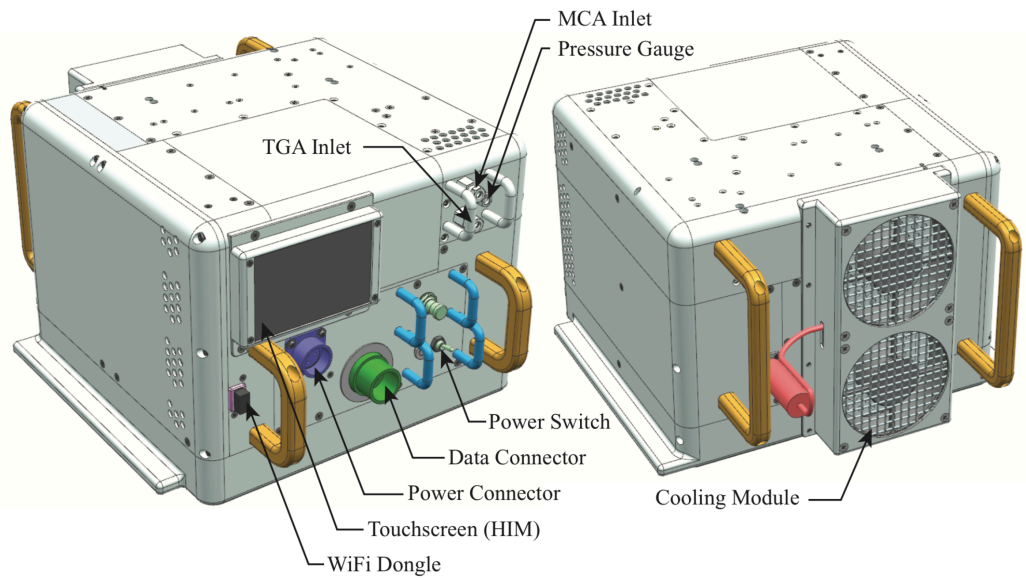
S.A.M. TDU-1 Instrument Overview



Technical Specifications	
Mass	9.55 kg
Dimensions	9.5” x 8.75” x 7.5”
Average Power	42 W (28 VDC, 1.5 A)
Startup Time	<2 min
Configuration	Rack-Mounted (EXPRESS), Aisle-Deployed
Communication	Wired or WiFi (aisle-deployed)
Compute Element	Xilinx Zynq FPGA (Red Pitaya)
Operating System	Linux
Operation Mode	MCA Only

MCA Mode		
Report Cadence	2 s	
Data Integration Time	30 s	
Leak Description	1.5” x 2 µm ID microcapillary	
Leak Rate	5×10^{-8} Torr L/s	
QITMS Pressure	10^{-9} – 10^{-8} Torr	
Species	Measurement Range	Measurement Precision (for 30 s)
Nitrogen (N_2)	360 – 600 Torr (47-79%)	±0.60 Torr (±0.078%abs)
Oxygen (O_2)	130 – 160 Torr (17-21%)	±0.54 Torr (±0.071%abs)
Carbon Dioxide (CO_2)	3 – 7 Torr (0.4 – 1.0%)	±0.05 Torr (±0.007%abs)
Methane (CH_4)	0 – 7 Torr (0 – 1.0%)	±0.07 Torr (±0.009%abs)

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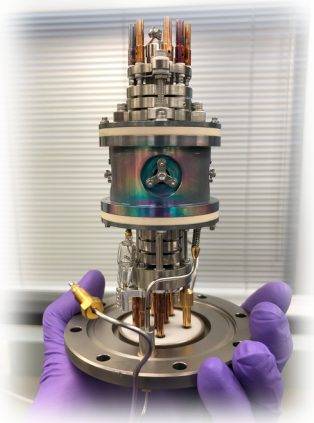
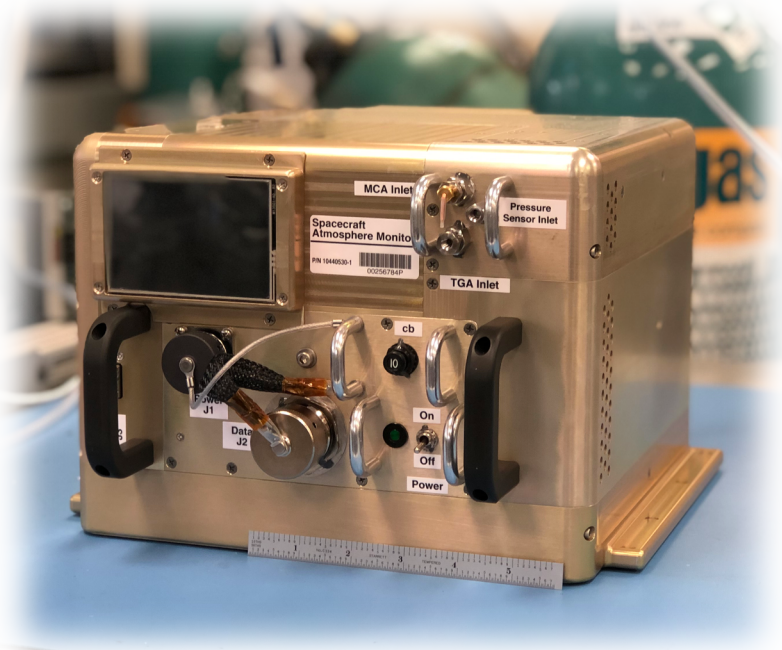
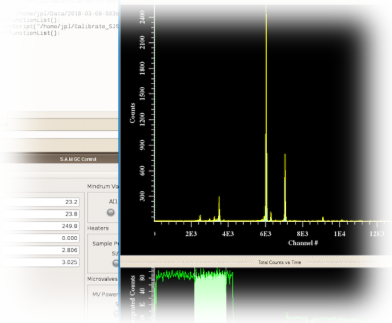
S.A.M. Subsystems

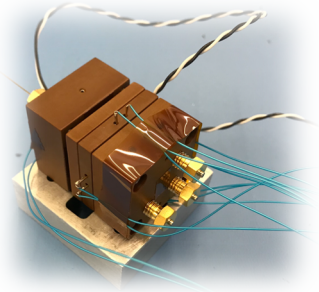


Sensor

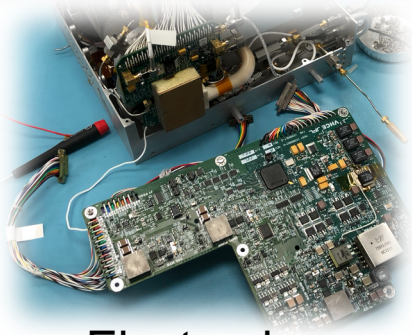




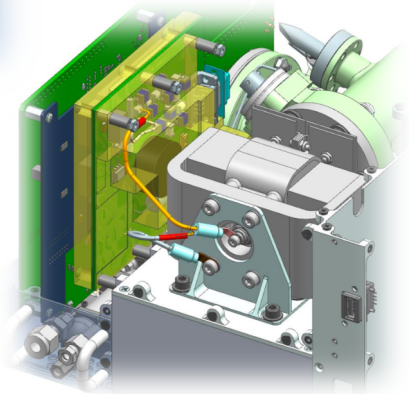
Software



Gas Chromatography



Electronics



Mechanical

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S.A.M. Talk Outline

1. *What is S.A.M.?*
   - *Technical Overview*
   - *Subsystems*
2. *QITMS Sensor Subassembly*
3. *MEMS PCGC Front-end Overview*
4. *Flight Electronics & Software*
5. *MCA Calibration & Performance*
6. *Next Steps for S.A.M.*

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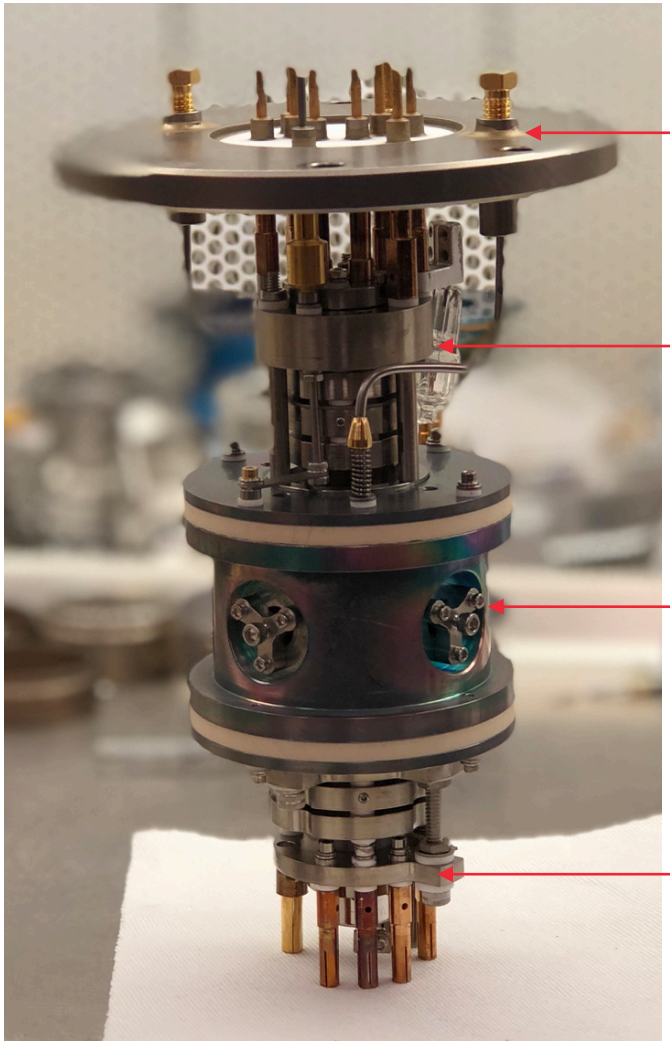
QITMS Sensor

The JPL Ion Trap



Gas Inlet System

Permits an inflow of sample gas from cabin atmosphere into the MS Sensor

Electron Gun

Ionizes injected gas to allow for ion trapping

Quadrupole Ion Trap (JPL Ion Trap)

Traps ionized air in a ponderomotive potential created by applied HV RF. As the RF amplitude is increased higher and higher mass ions are ejected axially.

Channel Electron Multiplier

Detects ions as they are ejected from the trap, and sends a current signal which ultimately creates a mass spectrum of the injected cabin air.

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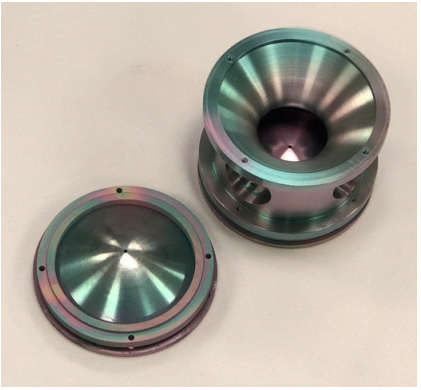
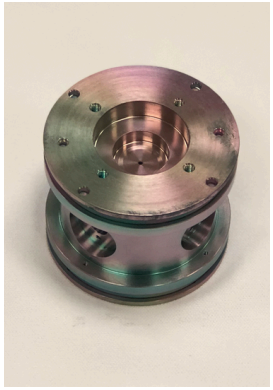
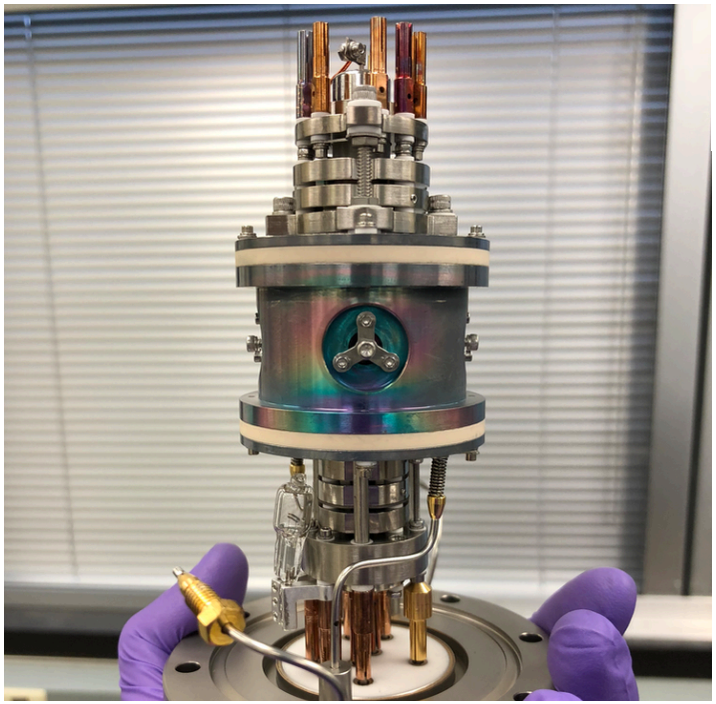
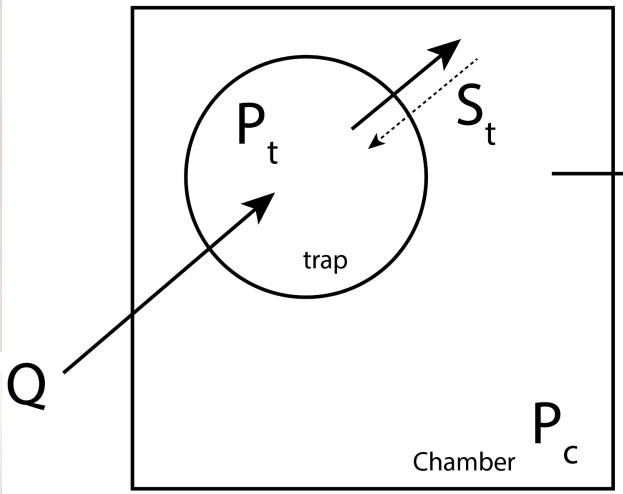
Differentially-Pumped QIT Design









$P_t S_t = P_c S_{ig}$

therefore, $P_t = P_c(S_{ig}/S_t)$

$(S_{ig}/S_t) = 100\text{-}1000$

- Closed off QIT from surrounding chamber volume
- Gas is inserted directly into the QIT
- Differential pumping leads to 100-1000 increase in signal

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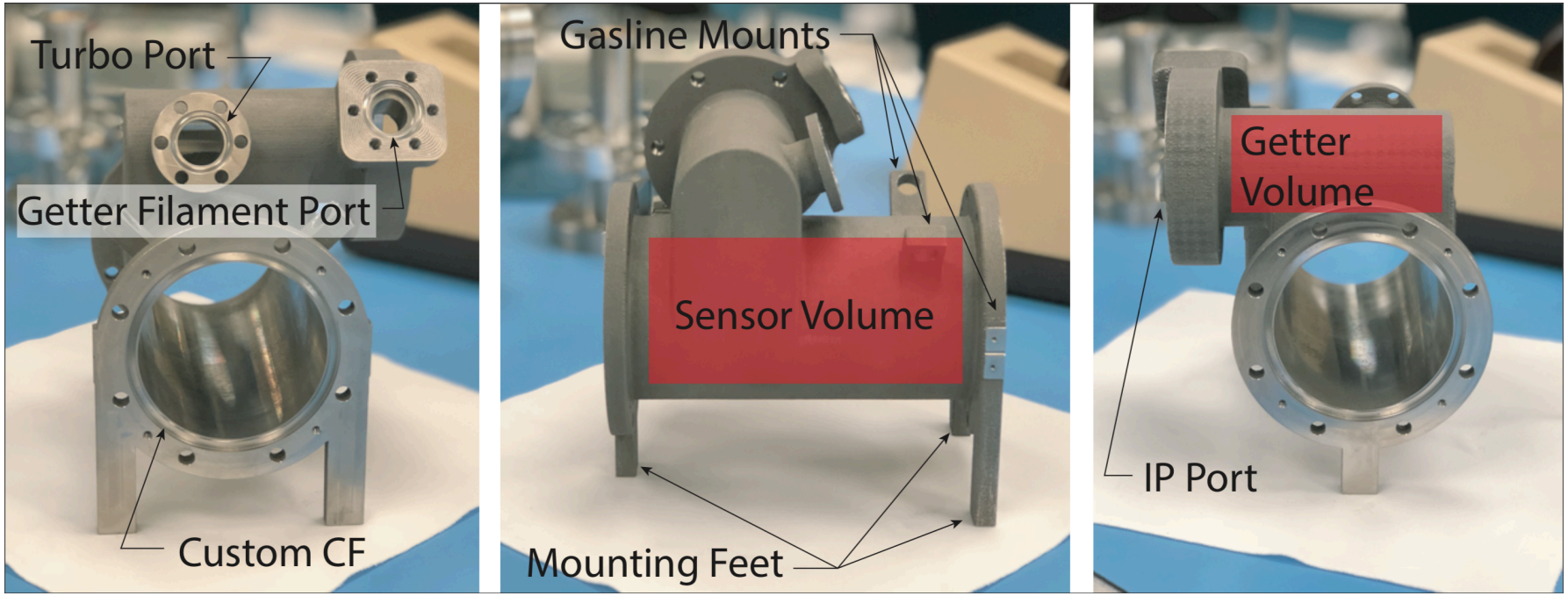
S.A.M. Custom Mini-Chamber Design



- 3D Printed Titanium Body
  - Laser sintering
- Hot Isostatic Pressing (HIP)
- Post Machining

- Performance
  - High-G Load (60 G)
  - Random Vibe (6 G)
  - Leak tight (<10^{-10} Torr L/s)

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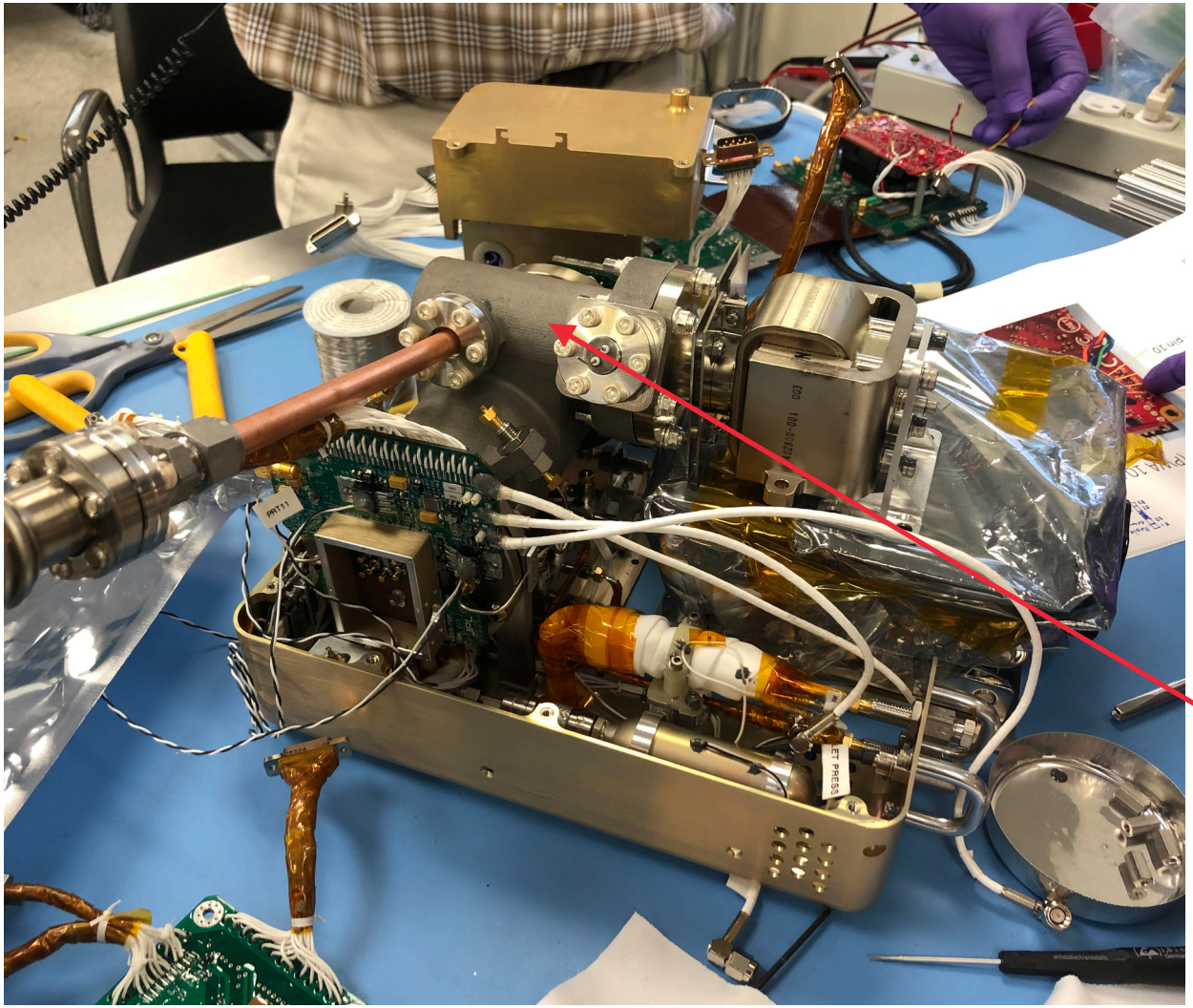
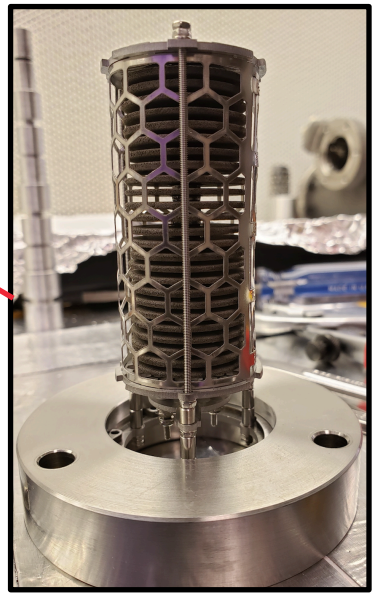
QITMS Pumping System



- Ion Pump (UTAS)
  - 2 L/s
  - Noble Diode
- NEG Pump (SAES D200)
  - 10-200 L/s (H_2)
  - 280 Torr L H2 capacity
  - ~400 TGA runs
- Turbo pump-out port



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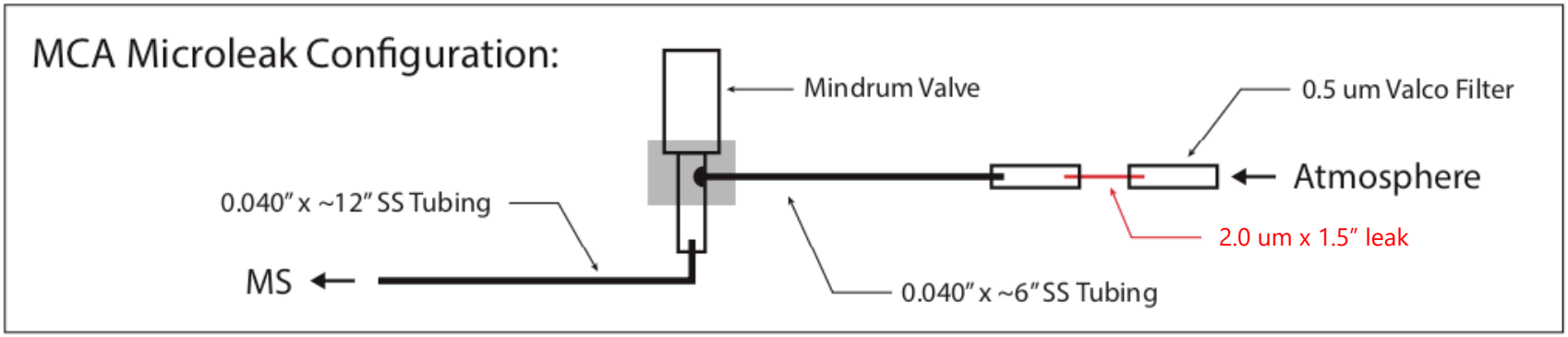
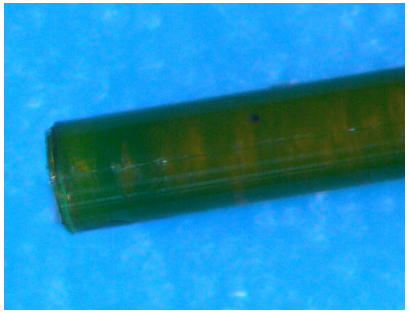
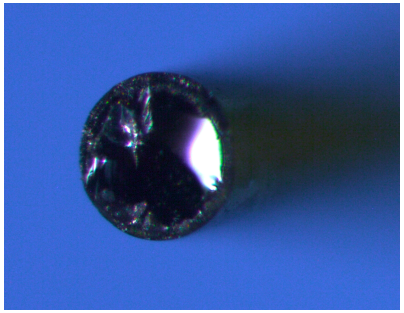
MCA Microleak Inlet Design







- Glass capillary microleak
- Dims: 1.5"L x 2 um ID x 360 um OD
- Leak rate = 5.0E-8 Torr L/s
- ~20E3 cts/s @ 1E-9 Torr (chamber)
  - N2 ~ 10E3 cts/s

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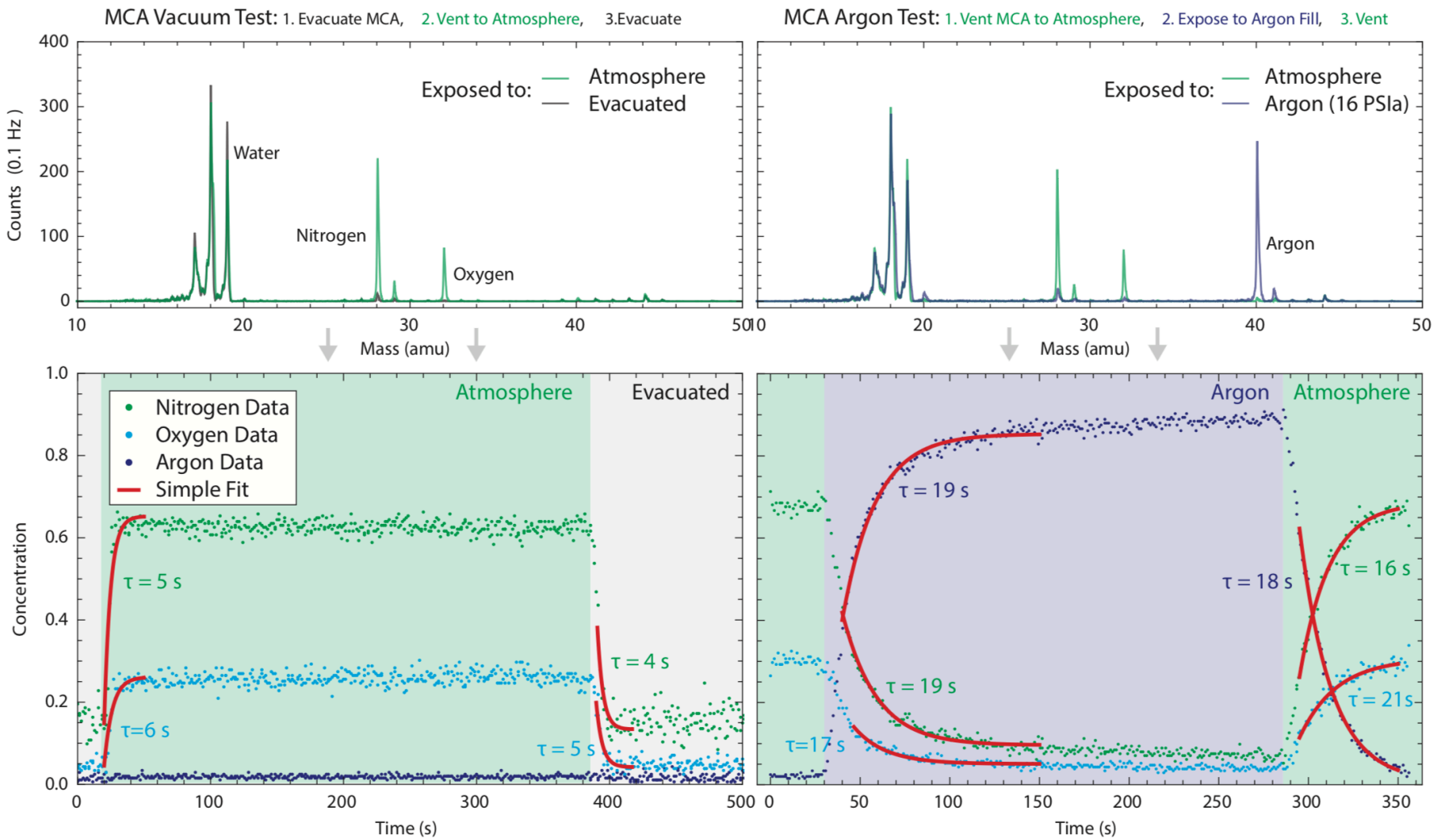
MCA Microleak Inlet Design



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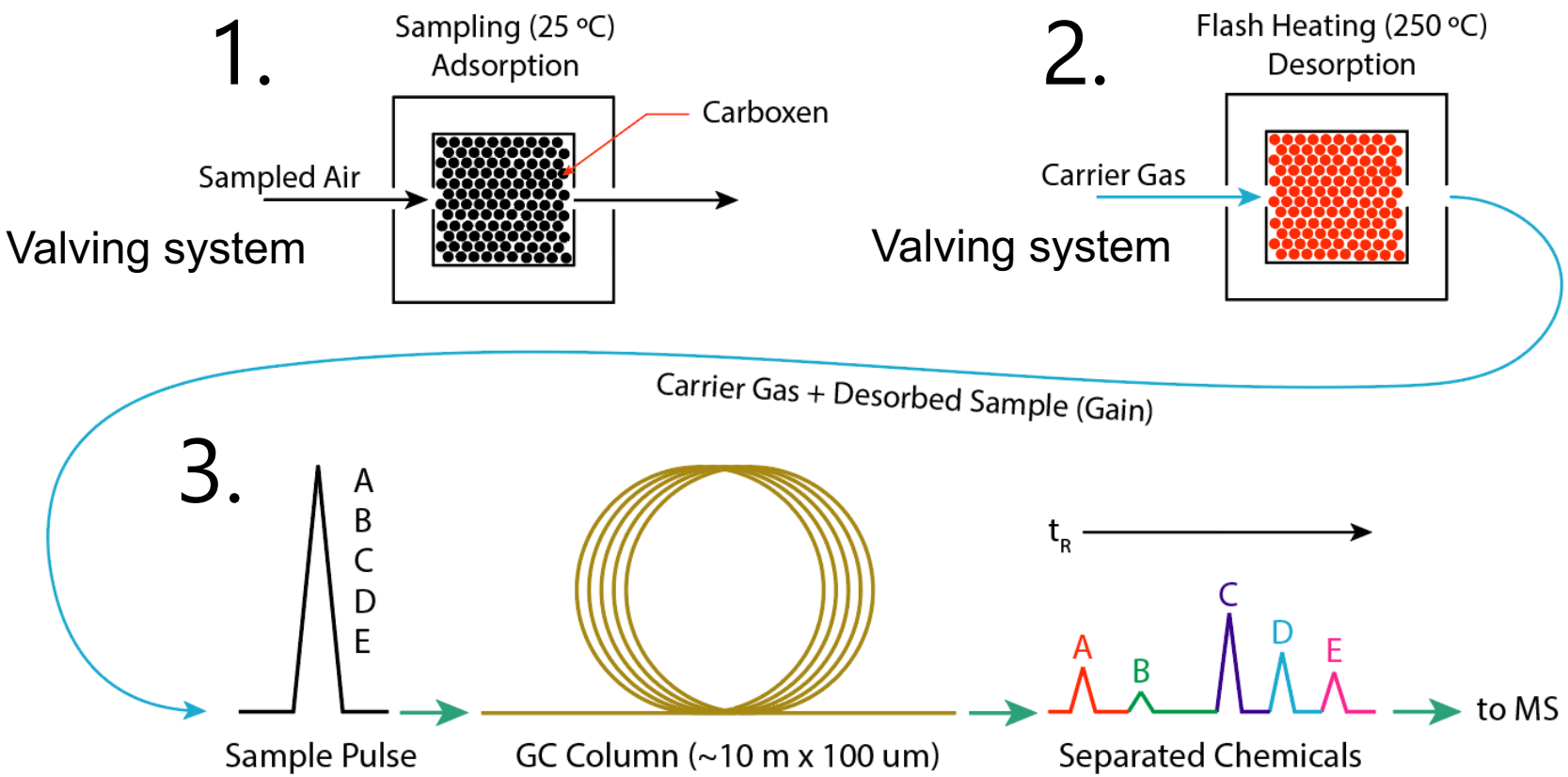
Preconcentrator Gas Chromatography

Traditional Approach



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Preconcentrator Gas Chromatography

Traditional Approach

2 ft

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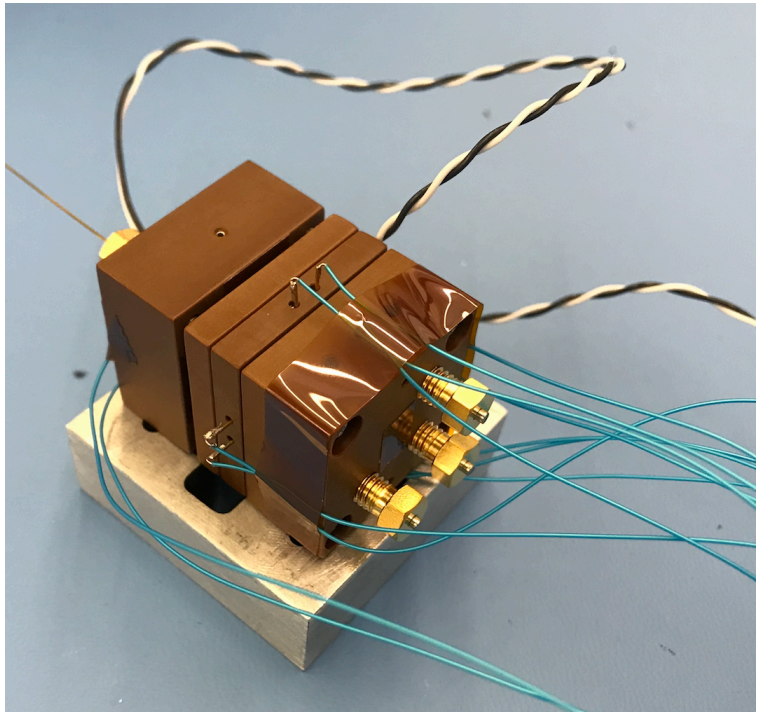
Preconcentrator Gas Chromatography

MEMS Approach

2 in



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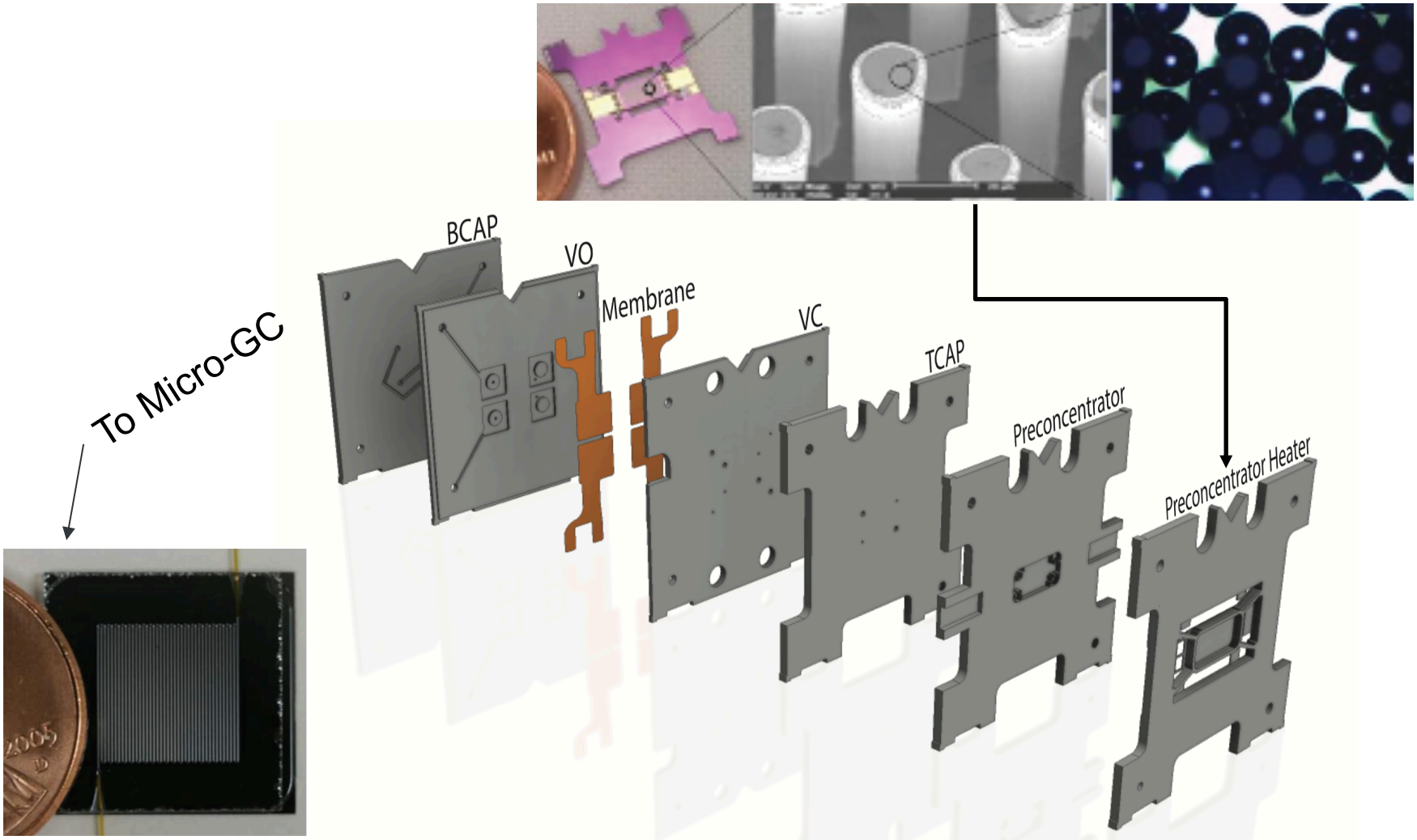
Preconcentrator Gas Chromatography

MEMS Approach



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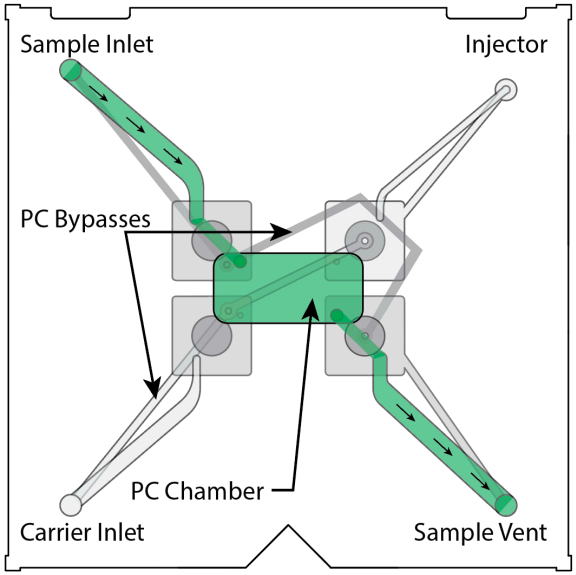
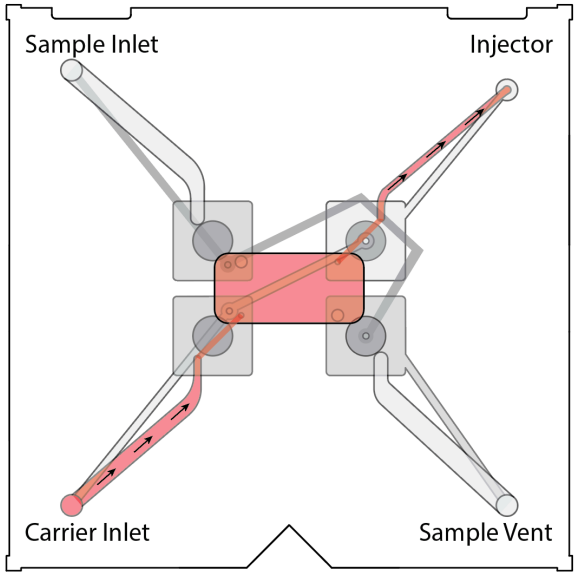
Preconcentrator Gas Chromatography

MEMS Approach

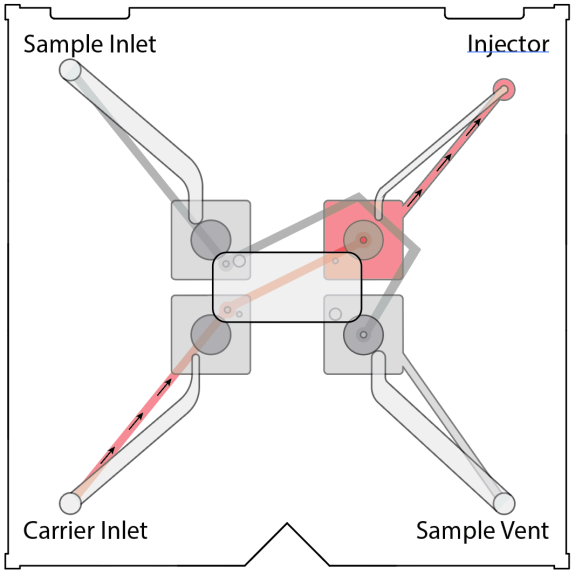
To Micro-GC



Sampling



Injecting



Chromatography

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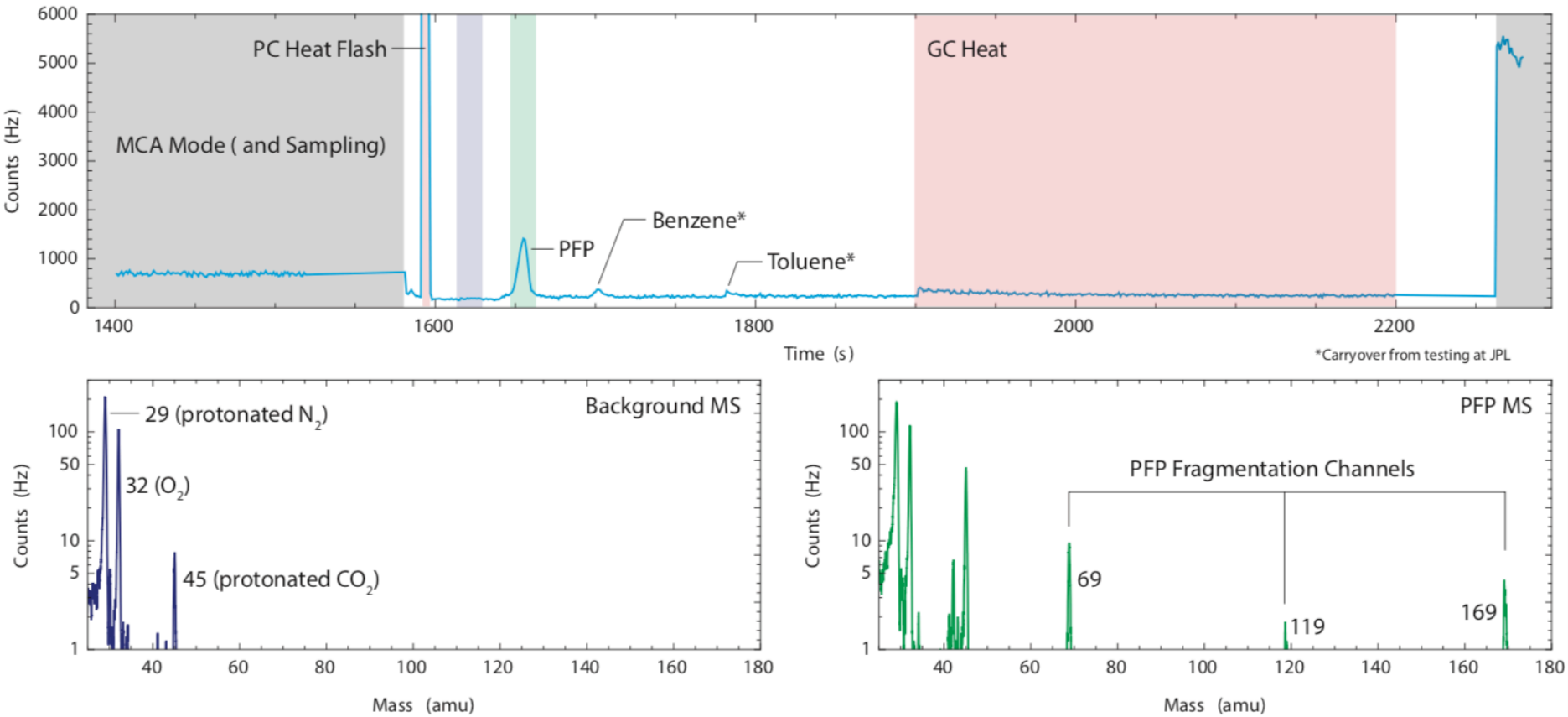
Preliminary TGA Testing at MSFC (DM1 & DM2)

TGA Sequence using PFP Environments



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TGA Capabilities for TDU-2

TGA Mode					
Frequency			1 per day (or on-demand)		
Run Time			10 – 20 minutes		
GC Carrier			H_2 (10 L metal hydride tank)		
GC Column			6 m x 86 µm ID microcolumn		
GC Flow rate			0.10 sccm H2		
PC Description			250 nL Carboxen 1000		
PC Heating			250 ºC for 5 s		
QITMS Pressure			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	Propylene glycol	TBD	TBD
o,m,p-Xylene	0.02	0.2	Trimethylsilanol	0.05	1

- Current PCGC Status
  - MV fabrication process being optimized
  - PCGC Testing TGA sequence optimization at JPL and MSFC
  - Implementation in TDU-2 in late 2019

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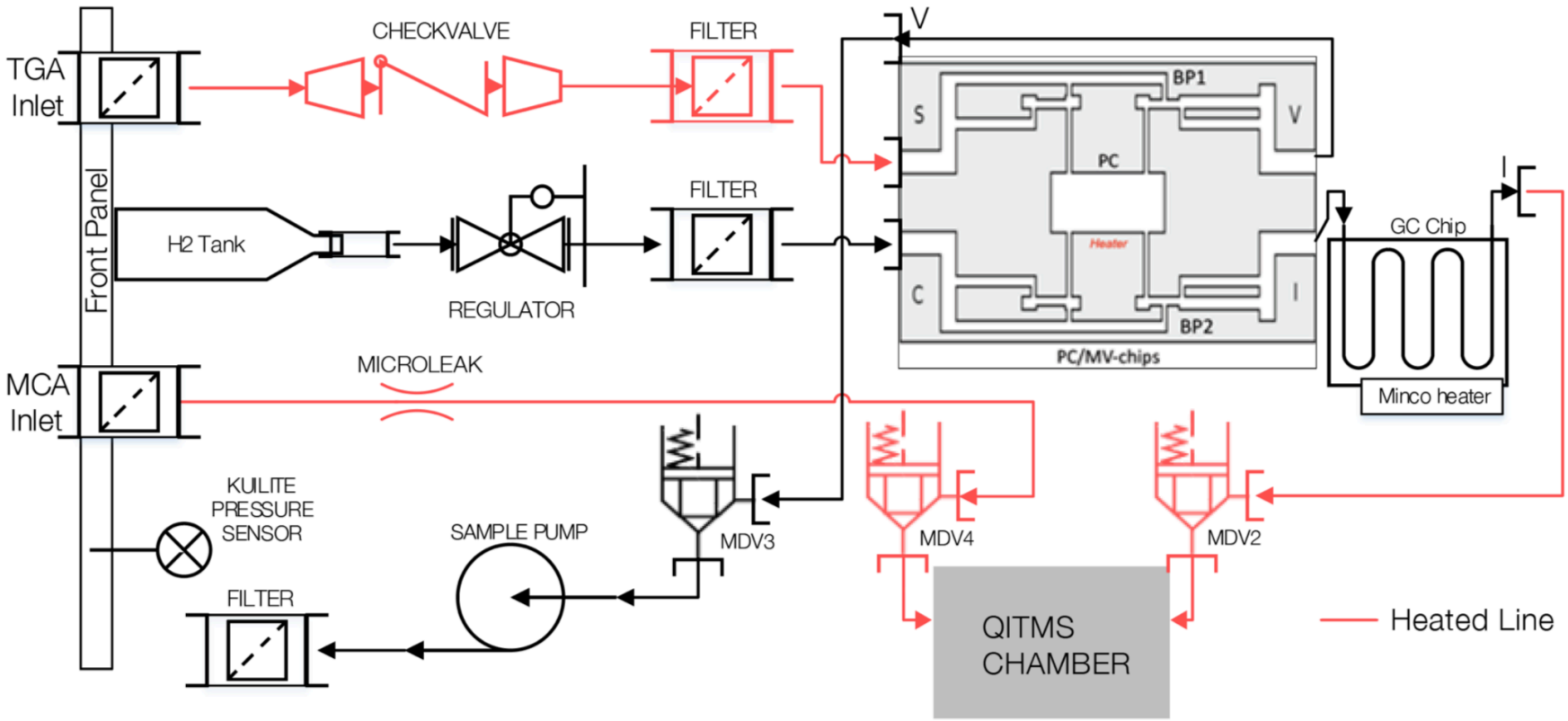
Preconcentrator Gas Chromatography

Subassembly Plumbing



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Preconcentrator Gas Chromatography

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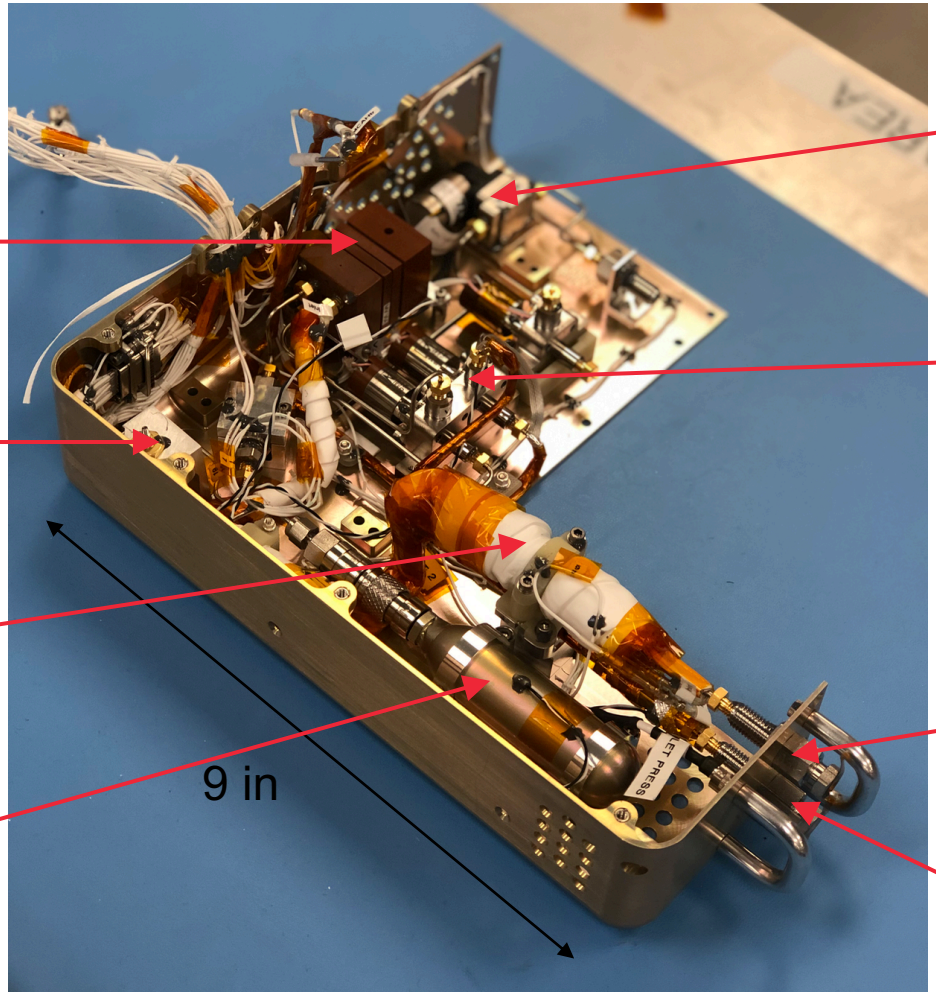

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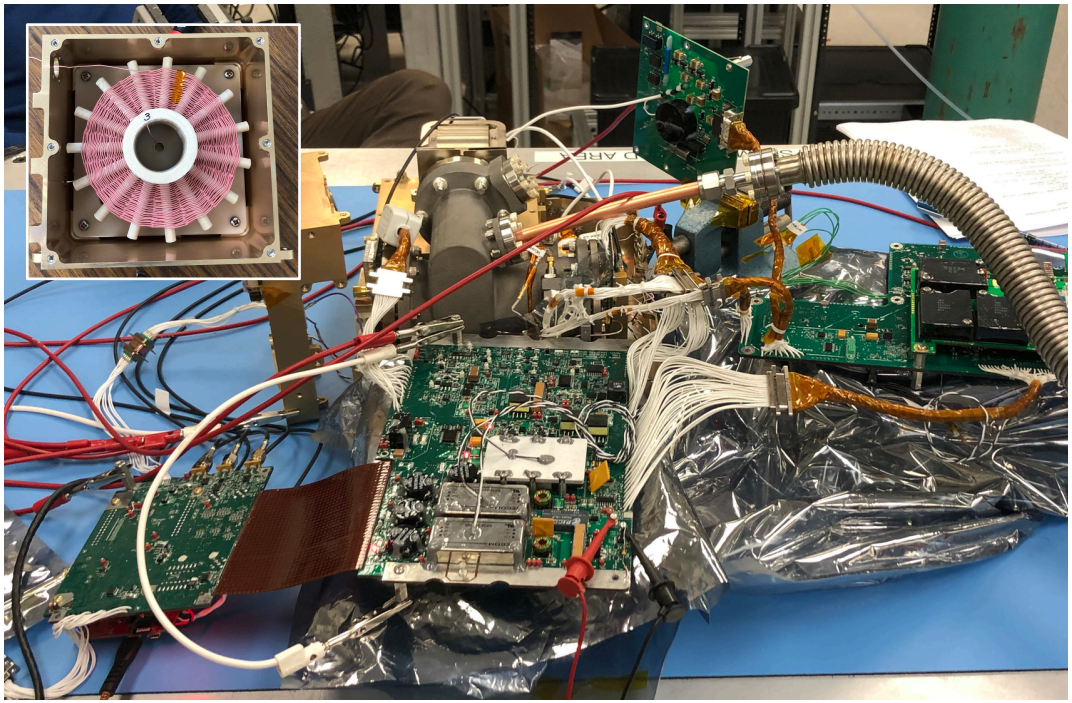
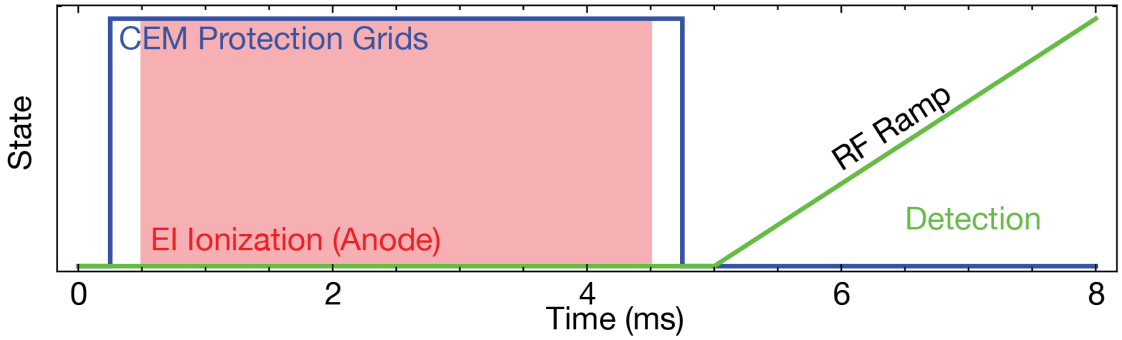
Electronics Overview

- FPGA-Controlled
  - Red Pitaya (Xilinix Zynq)
- HV Electronics
  - CEM and Ion Pump
- Pulsers
  - QITMS Duty Cycle
- HV RF generation
  - 850 kHz q-Scan
  - Resonant Circuit (Q~200)
- Valve & Heater Control
  - Fault Handling
- Touchscreen (H.I.M.)





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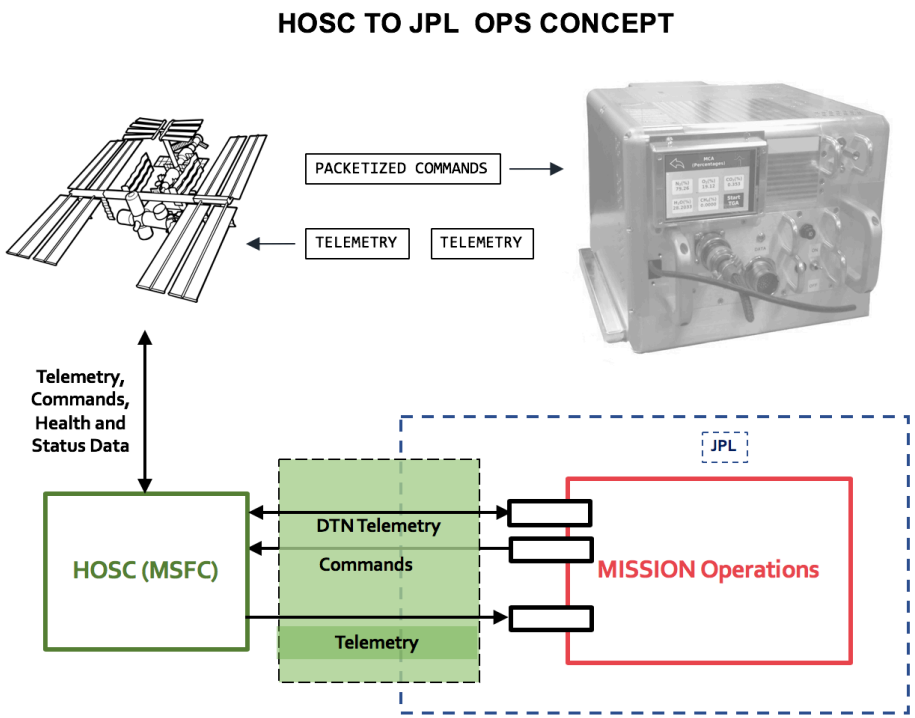
Software Overview

- C++ with QT Libraries
- Software Duties
  - Command & Control
    - Local: H.I.M. GUI
    - Remote: JPL EOMOC
  - MS Recognition Algorithm
    - Internal, autonoumous
  - Telemetry Monitoring
  - Science Reporting
- 2 GB/day (Telemetry + Science)
- Communication Scheme
  - Data
    - TCP/IP: Commands & Telemetry
    - UDP: Science Data
  - Ku Band via TDRSS to HOSC to EOMOC
    - Telemetry, Science, Commands
  - S-Band (non-nominal) to HOSC
    - Payload Health & Status, critical commands



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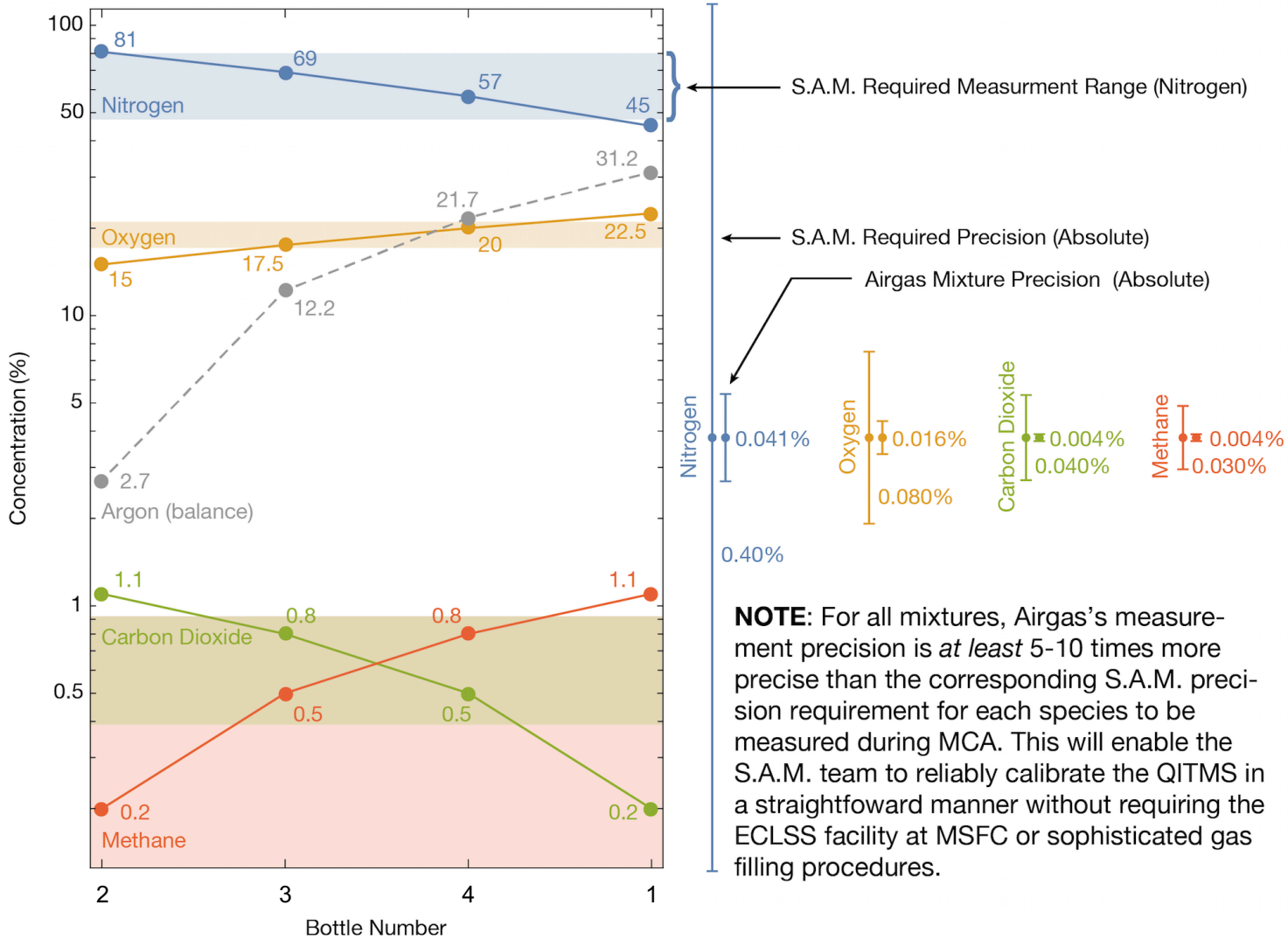
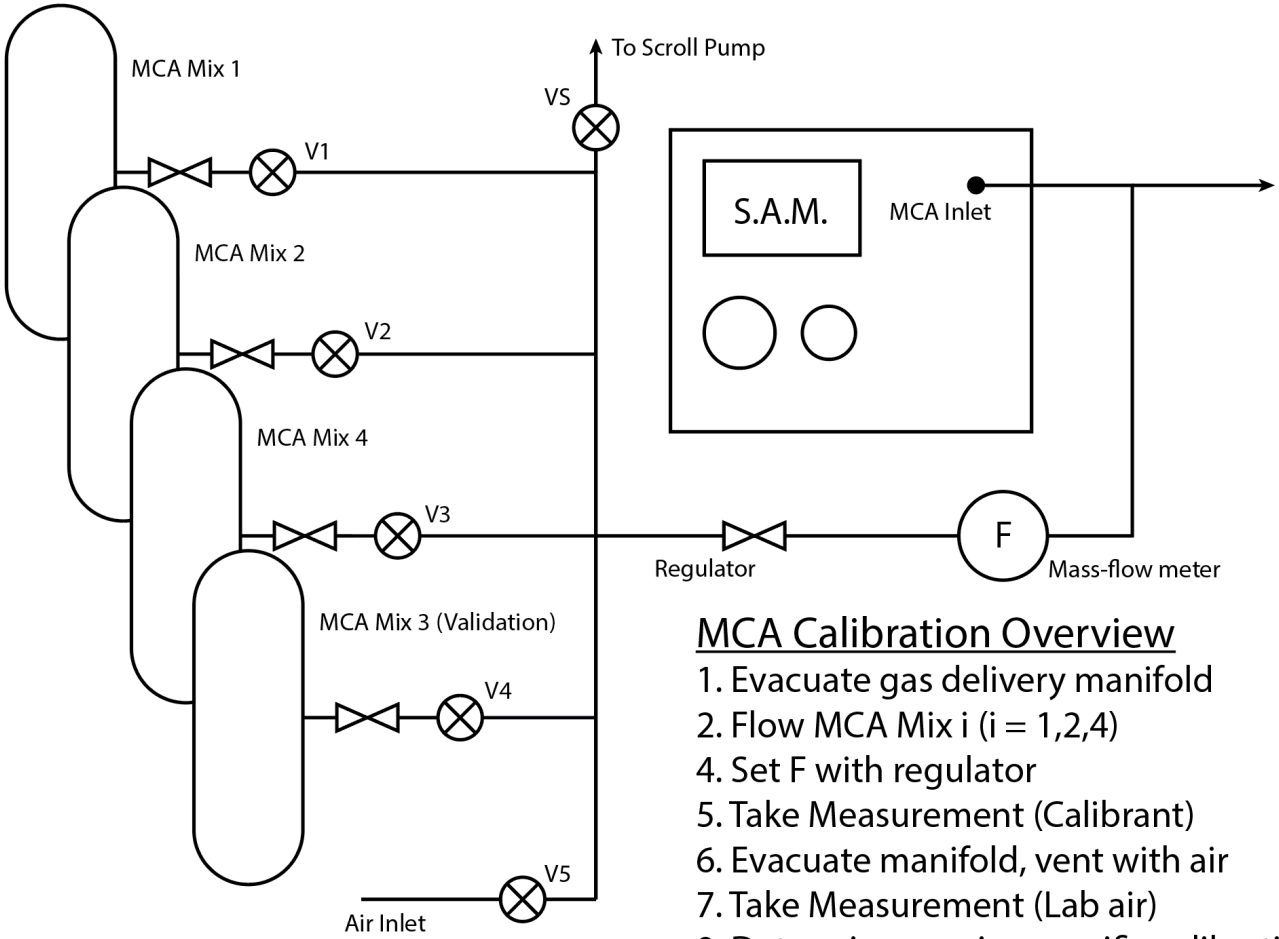
MCA Gas Calibrants (Airgas)



NOTE: For all mixtures, Airgas's measurement precision is *at least* 5-10 times more precise than the corresponding S.A.M. precision requirement for each species to be measured during MCA. This will enable the S.A.M. team to reliably calibrate the QITMS in a straightfoward manner without requiring the ECLSS facility at MSFC or sophisticated gas filling procedures.

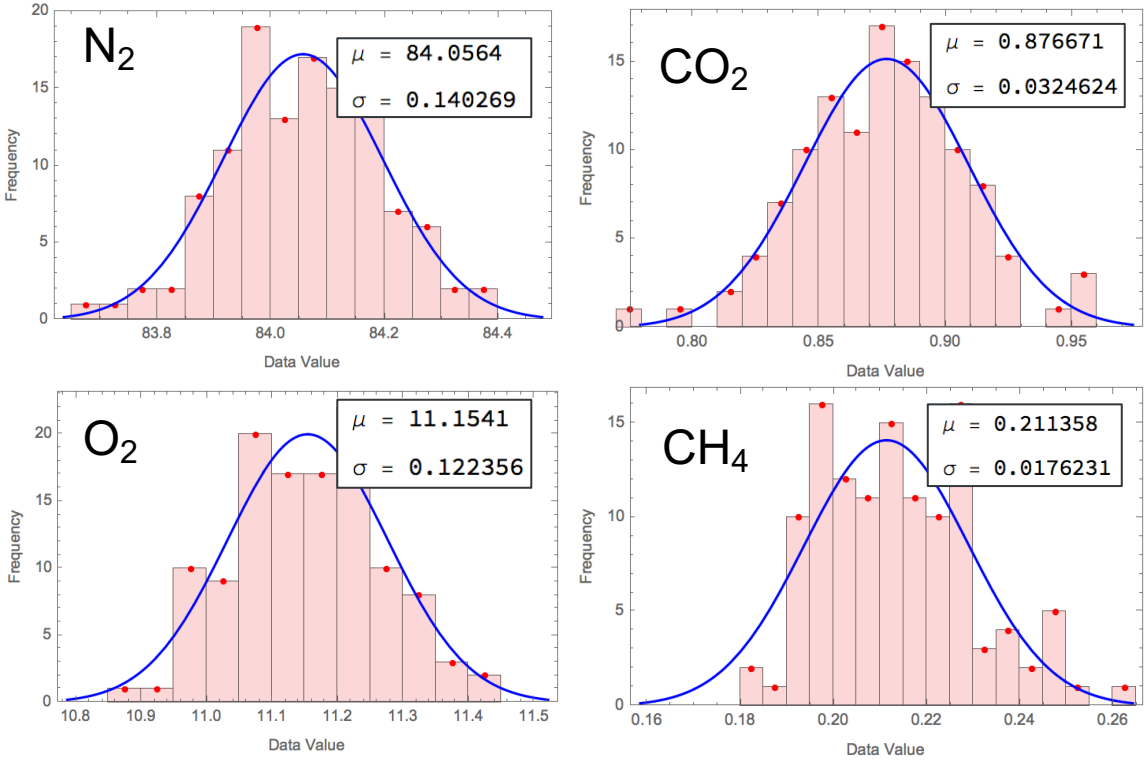
MCA Calibration G.S.E. Schematic



MCA Calibration Overview

1. Evacuate gas delivery manifold
2. Flow MCA Mix i (i = 1,2,4)
4. Set F with regulator
5. Take Measurement (Calibrant)
6. Evacuate manifold, vent with air
7. Take Measurement (Lab air)
9. Determine species-specific calibration coefficients
10. Validate calibration using MCA Mix 3

Step 1: Measure Calibrant Bottles (Training Set)

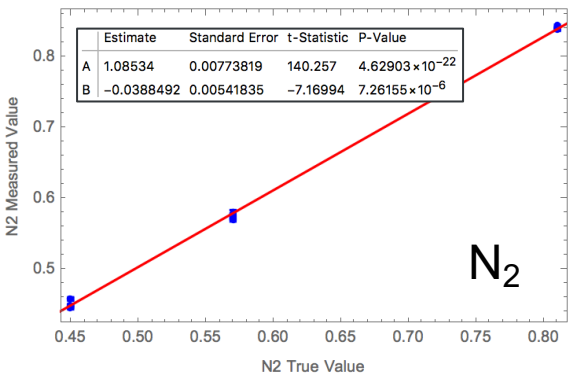


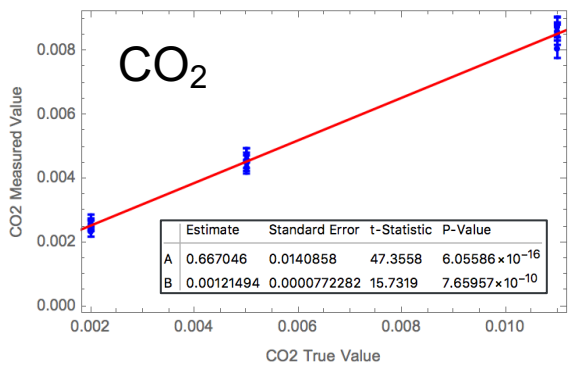
- (Shown) Single 10 min Bottle 2 measurement
- 1-Sigma defines measurement error bar
- Measurement repeated 5 times for the 3 Calibrant Bottles

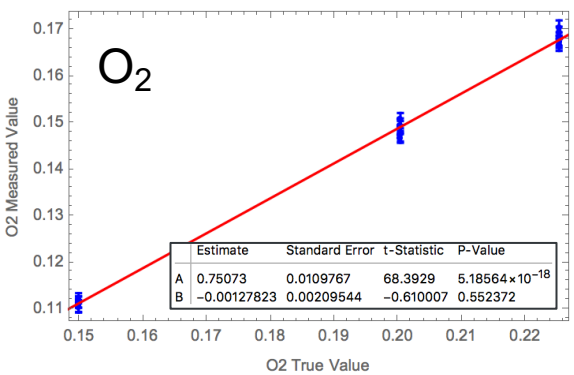
Component	Requested Concentration	Reported Mole %	Process Accuracy (% relative)
NITROGEN	81.00 %	81.01 %	± 0.02 %
OXYGEN	15.00 %	14.99 %	± 0.04 %
CARBON DIOXIDE	1.10 %	1.101 %	± 0.09 %
METHANE	0.20 %	0.1997 %	± 0.18 %
ARGON	2.70 %	2.697 %	± 0.06 %

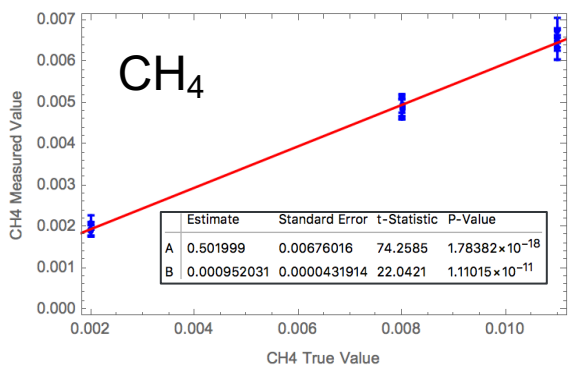
Step 2: Calibration Coefficients

- Five 10-min measurements for 3 Calibrant Bottles are used to determine calibration coefficients for the 4 species (+ argon, not shown)
- Chi-squared minimization ($1/\sigma^2$-weighted) used to A,B coefficients for model exp = A (true) + B
- Associated standard errors taken as systematic error



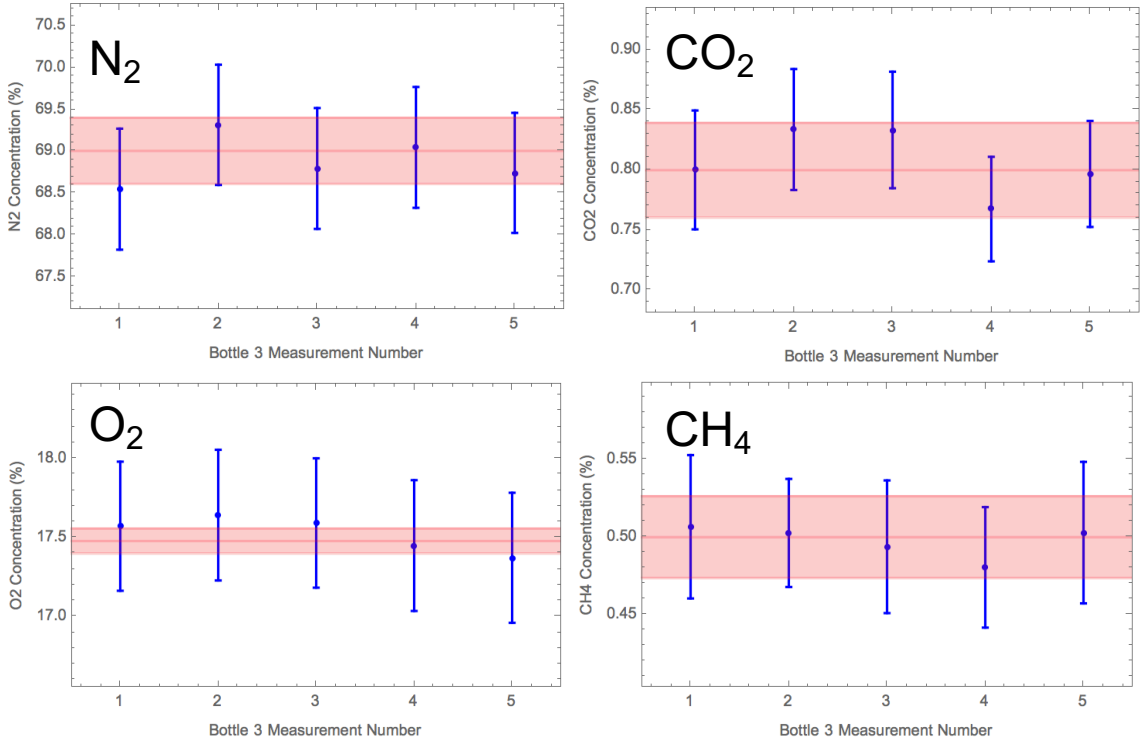






Step 3: Validation of MCA Calibration

Using Calibration coefficients, measure Bottle 3 Concentration (shown)



Red-Shaded Region:
S.A.M. L2-1.1

- N_2 ± 0.395%abs
- O_2 ± 0.079%abs
- CO_2 ± 0.039%abs
- CH_4 ± 0.026%abs

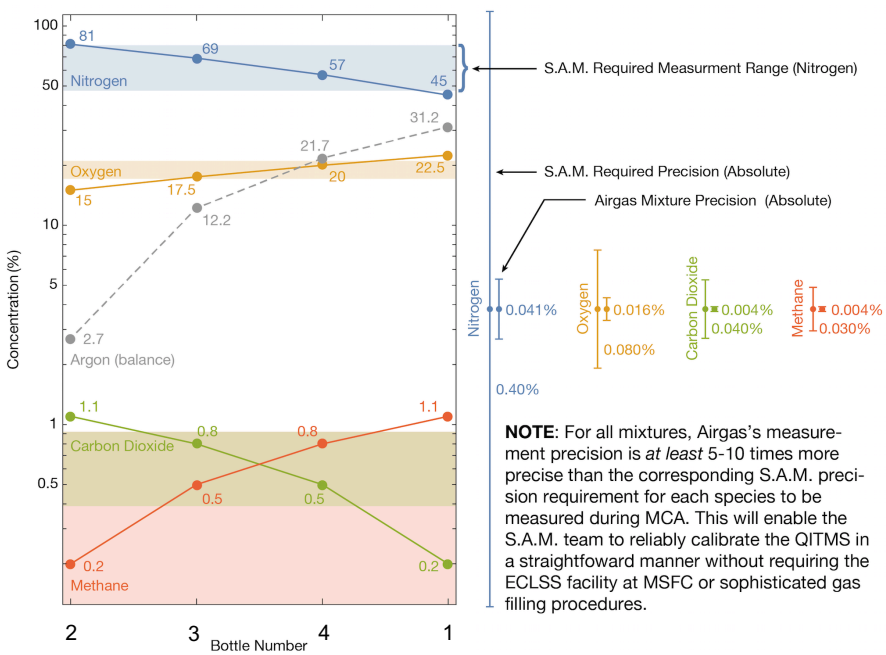
Blue error bars include:

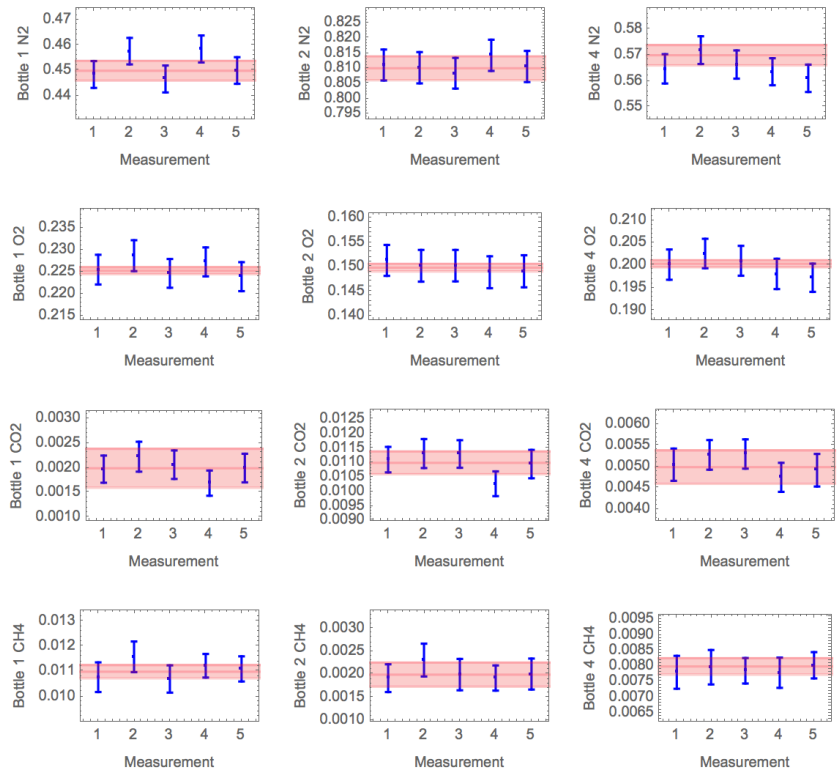
- Shot-noise (statistical)
- Systematic error

Component	Requested Concentration	Reported Mole %	Process Accuracy (% relative)
NITROGEN	69.00 %	69.01 %	± 0.02 %
OXYGEN	17.50 %	17.48 %	± 0.04 %
CARBON DIOXIDE	0.80 %	0.8012 %	± 0.11 %
METHANE	0.50 %	0.4997 %	± 0.12 %
ARGON	12.20 %	12.21 %	± 0.04 %

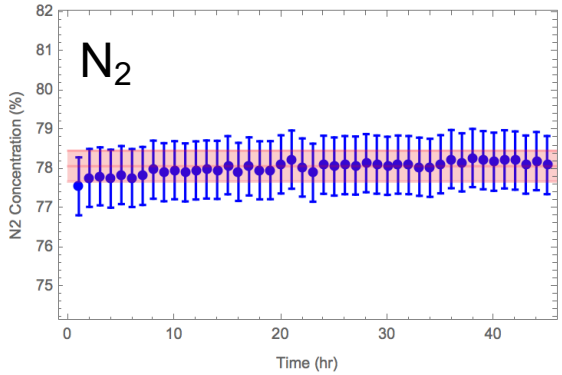
Assessing MCA Performance (Species' Ranges)

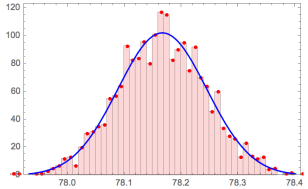
- Bottles 1, 2, and 4 concentrations span the required S.A.M. L2-8,9 ranges for each species (left, shaded regions)
- Red-shaded regions (right) represent true calibrant gas concentrations with the required S.A.M. L2-1.1 accuracy bounds
- Blue Error bars represent S.A.M. statistical and systematic error



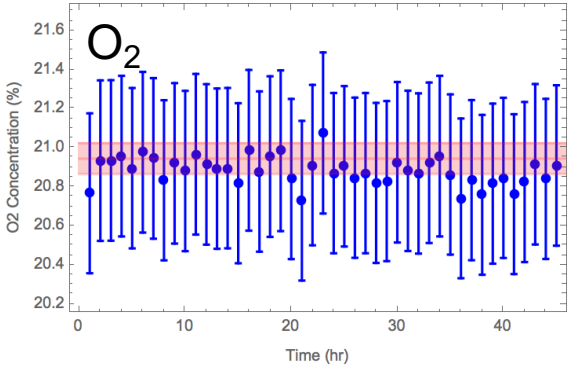


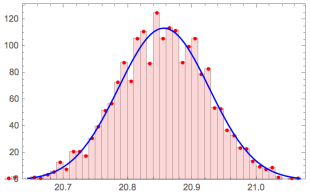
Assessing MCA Performance (Lab Air)



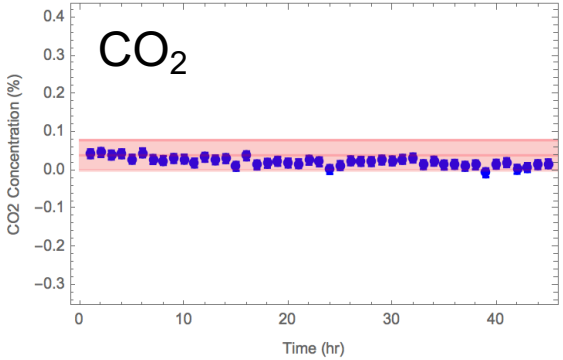


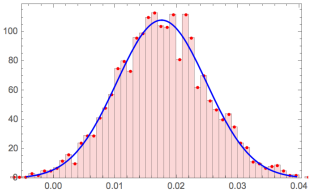
78.167%abs
±0.078%abs (statistical)
±0.741%abs (systematic)





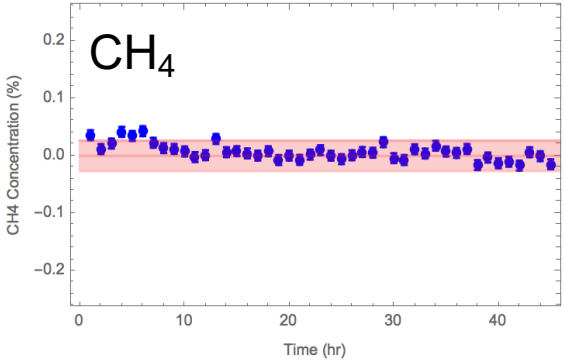
20.865%abs
±0.071%abs (statistical)
±0.410%abs (systematic)

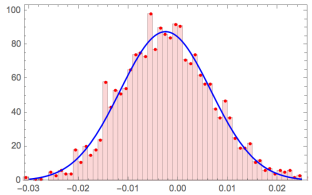




0.018%abs
±0.007%abs (statistical)
±0.011%abs (systematic)

- 48 Hour Lab Air Measurement
- Red-shaded regions: sea-level earth atmosphere with SAM L2-1.1 accuracy bounds
- Blue points: calibrated concentration (30 s integration)
- Blue error bars: calibration error (listed as systematic error)
- Histogram: 2000, 30 s measurements (1-Sigma listed as statistical error)





-0.002%abs
±0.009%abs (statistical)
±0.008%abs (systematic)

S.A.M. Talk Outline

1. *What is S.A.M.?*
   - *Technical Overview*
   - *Subsystems*
2. *QITMS Sensor Subassembly*
3. *MEMS PCGC Front-end Overview*
4. *Flight Electronics & Software*
5. *MCA Calibration & Performance*
6. *Next Steps for S.A.M.*

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SAM ISS Operations

- Launch: 21 July (SpaceX)
- Operations Begin: 30 July
- MCA Testing for 6-12 months

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Back on Earth

- MV Fabrication
- TGA Testing & Calibration
- TDU-2 I&T has begun

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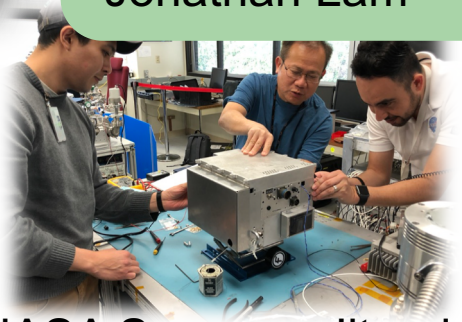

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Thanks for your attention!

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Questions?