Exploration Research and Technology Programs

Capacitive Mass Gauging for Cryogenic Fluids in Micro-g (CAPMAG)

8/3/2022

Chris Biagi

KSC Applied Physics Lab





OUTLINE

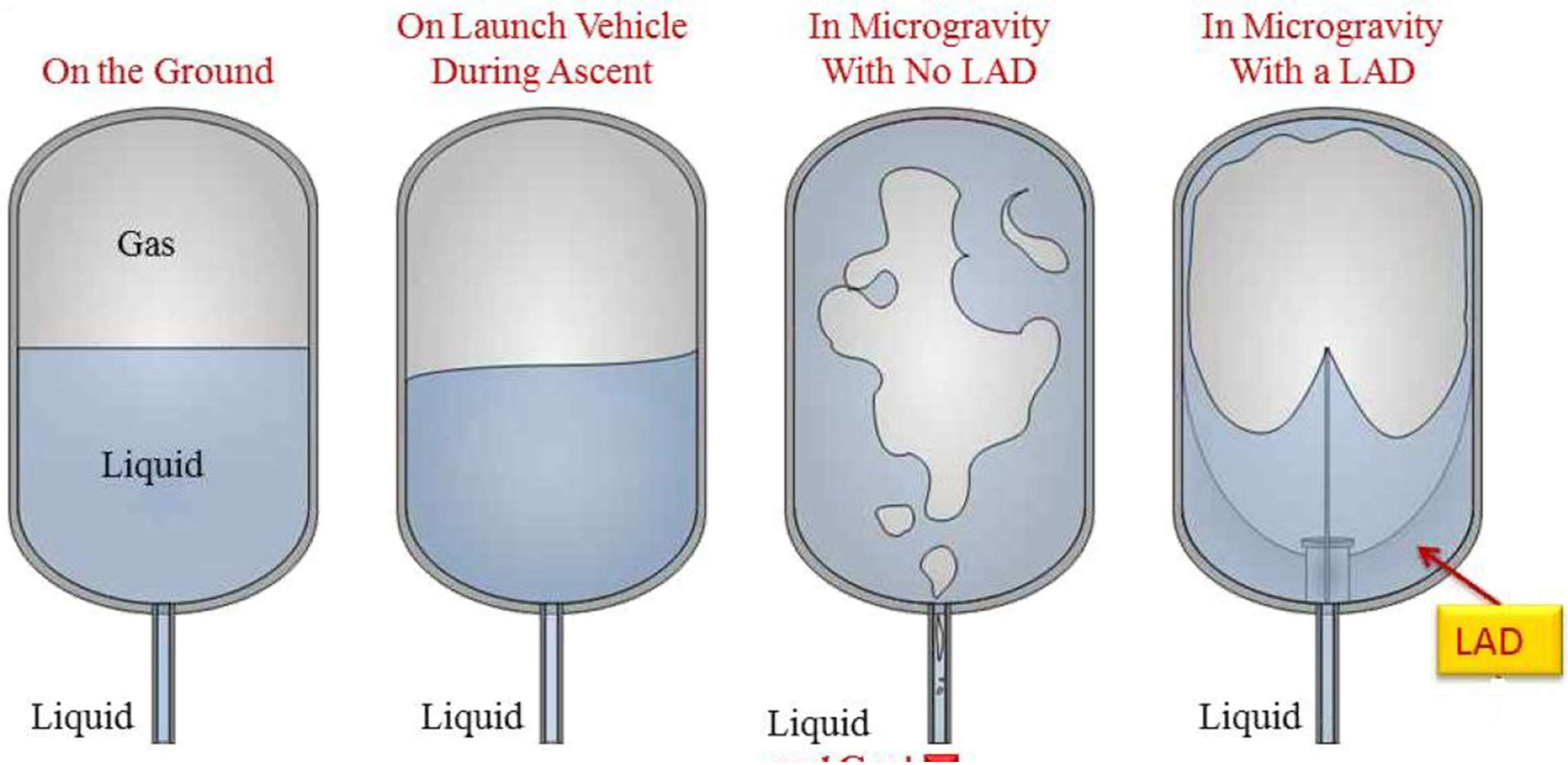
- Fluids in micro-g
- Capacitive Sensing
- Development Approach
- Project Goals
- Benefit to NASA and the Project Team

BACKGROUND

- B.S. in Physics, M.S Atmospheric Science - University of Arizona
- Ph.D. in Electrical Engineering - University of Florida
- Consultation, design, testing work related to aircraft EMI and lightning interaction
- Work developing capacitive sensors for a government contractor and in academia
- Broad experience in sensors and instrumentation, particularly capacitive sensing.
- Joined the NASA Applied Physics Laboratory at KSC in September 2020



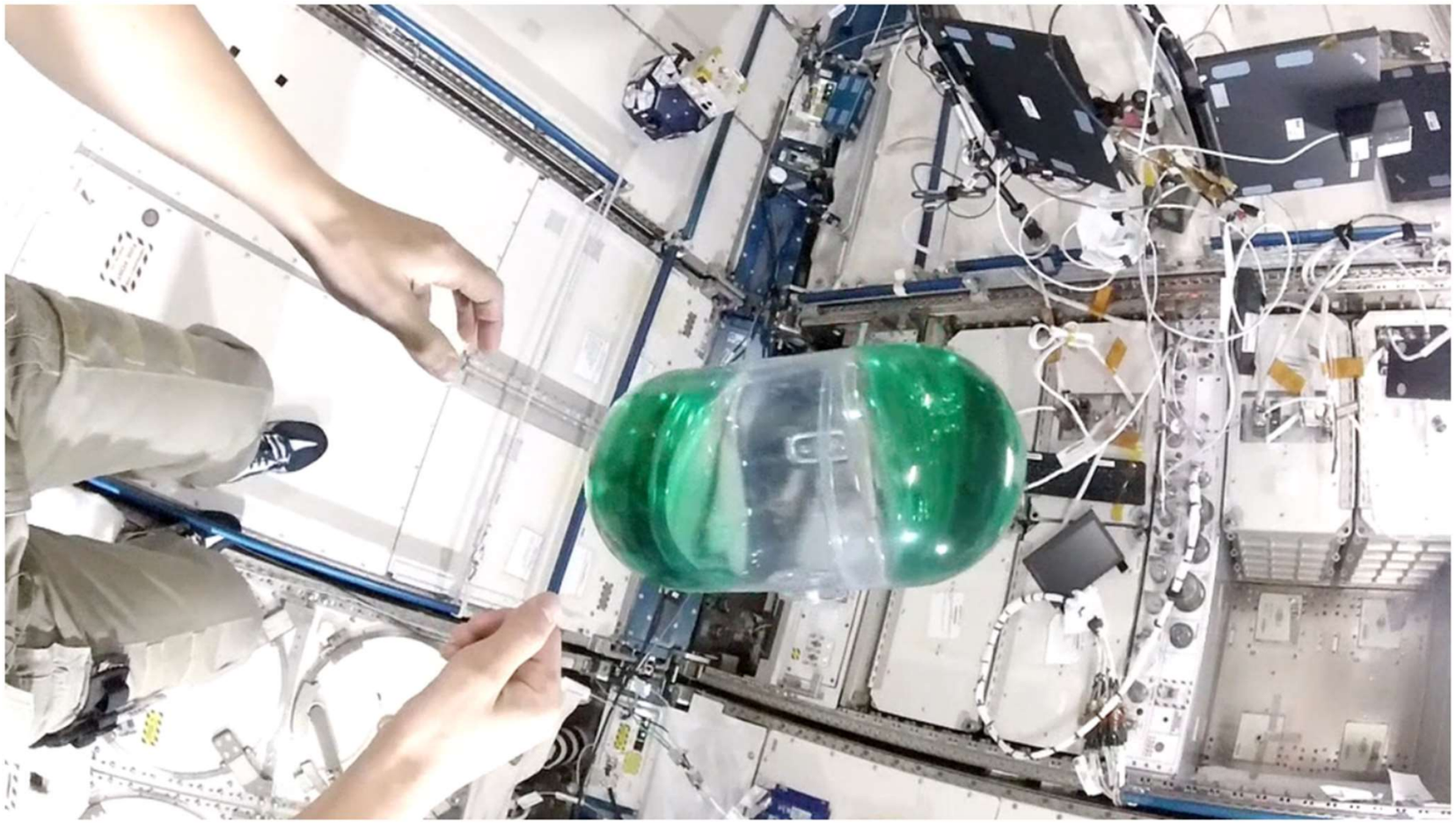
CRYOGENIC FLUIDS IN MICRO-G



Hartwig 2008 https://ntrs.nasa.gov/citations/20170000667

FLUIDS IN MICRO-G

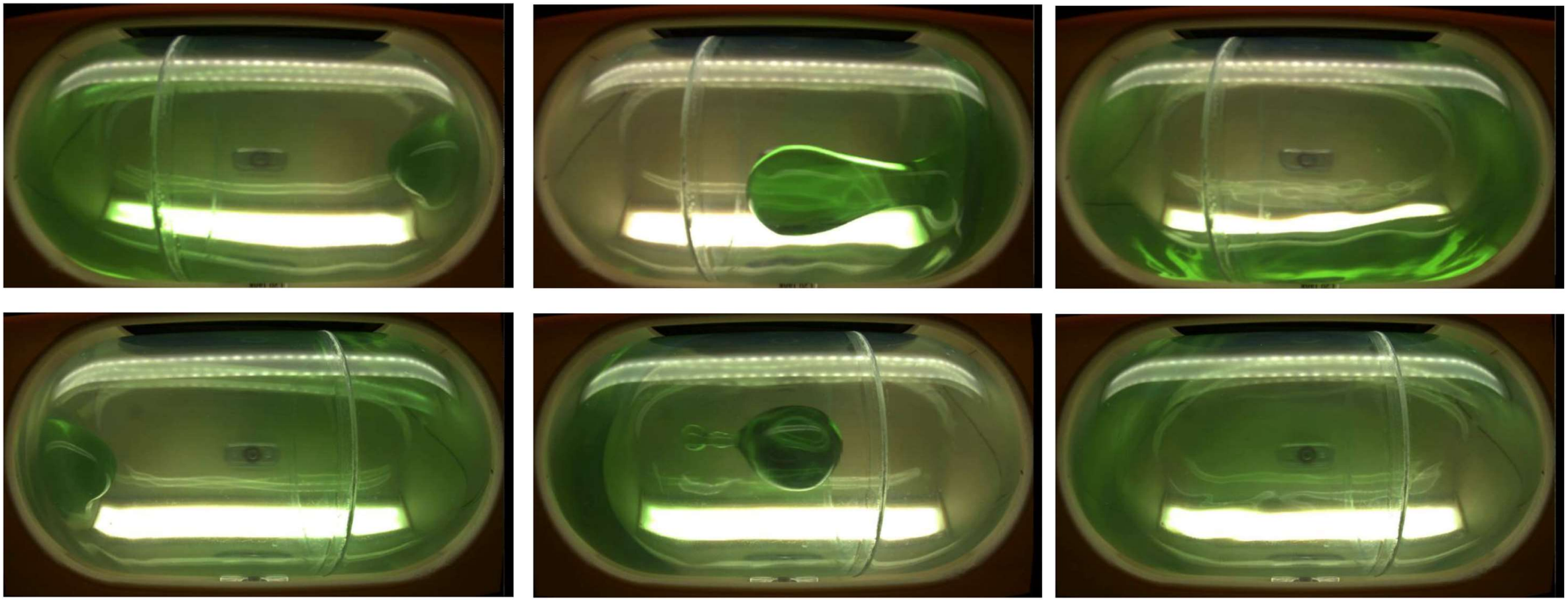
FIT/NASA SPHERES-SLOSH Experiment
Storey et al. 2020 https://ntrs.nasa.gov/citations/20180001518



Amazing view of the Slosh Tank recorded by crew member Kjell Lindgren
Credits: NASA Ames

FLUIDS IN MICRO-G

FIT/NASA SPHERES-SLOSH Experiment
Storey et al. 2020 https://ntrs.nasa.gov/citations/20180001518



WHAT ARE WE DOING?

Develop a new technology for micro-g cryogenic mass gauging based on whole-tank capacitive sensing

- Accurate and reliable micro-g mass gauging is essential for future space missions and operations
  - Identified by NASA as an enabling technology for deep-space exploration
    - Tier 1 technology gap (STMD-CFM-015)
  - Long-duration missions (e.g., cis-Lunar and Mars transit)
  - Orbital refueling
  - NEP and NTP
- Impacts
  - Propellant margin (uncertainty and settling burns), total burn time
  - Performance characteristics
- Tier 1 technology gap, STMD-CFM-015
- Current TRL 3, increase to TRL 6

TECHNOLOGY HISTORY

- Capacitive sensors have a history of use as settled level gauges
  - S-IVB stage of Saturn V (LOX and LH2)
  - Apollo Service Propulsion System (UMDH and NTO)
  - Lunar Excursion Module (Aerozine 50 and NTO)
  - CENTAUR Upper Stage (LOX and LH2)
  - Shuttle Orbital Maneuvering System Tanks (MMH and NTO)

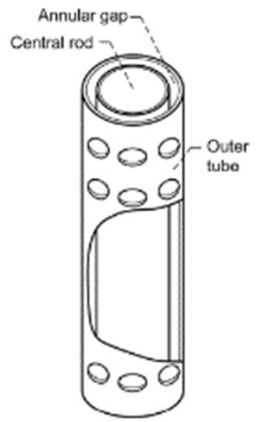
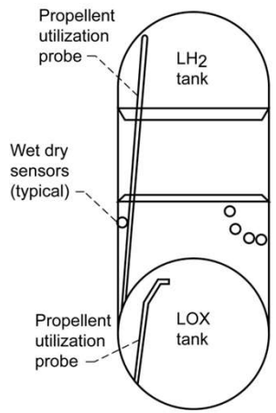


Figure 2.2 Schematic of cylindrical capacitance probe with perforations.



Schematic of S-IVB stage in orbital experiment configuration.

Dodge 2008
https://ntrs.nasa.gov/citations/20080034885

https://ntrs.nasa.gov/citations/19680027035

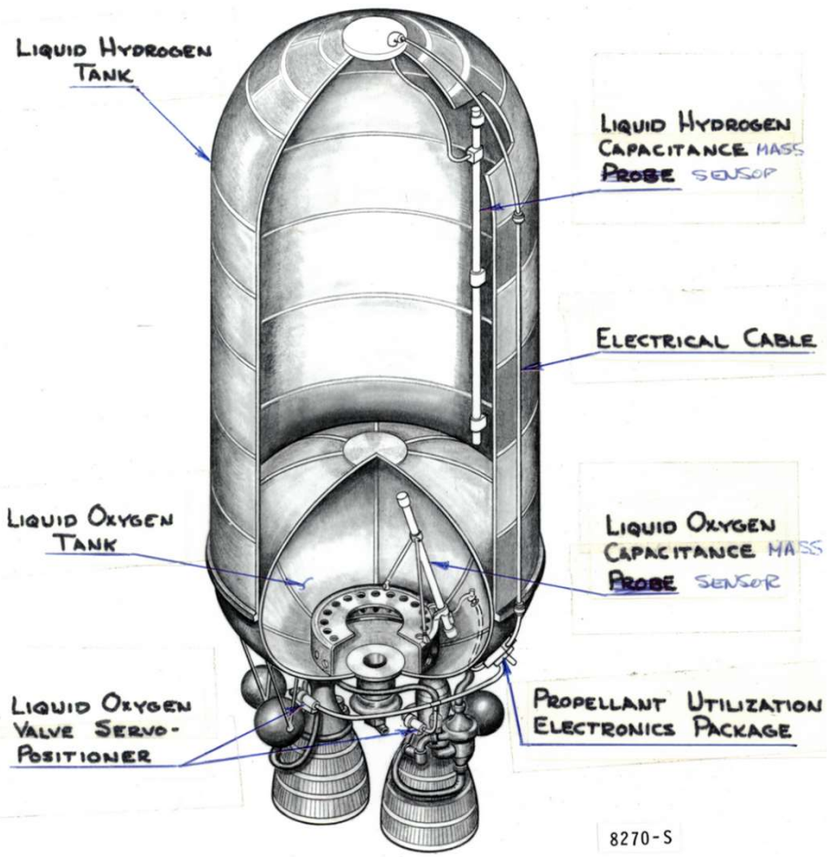
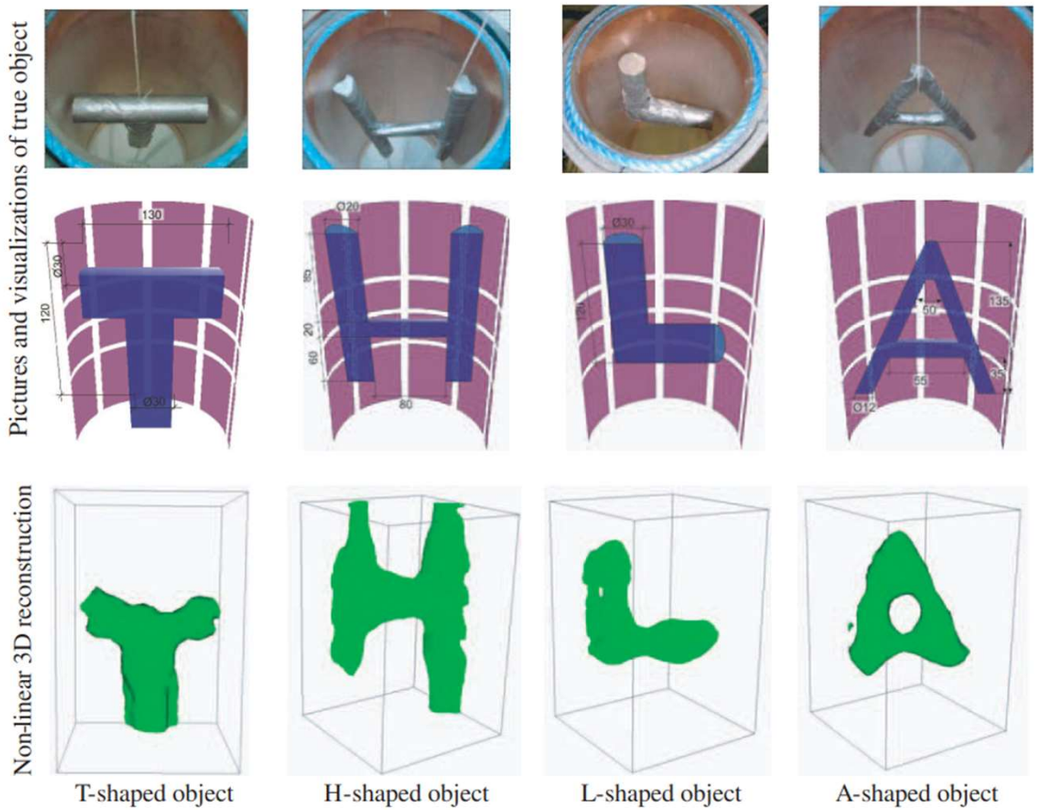


FIGURE 4 CENTAUR PROPELLANT UTILIZATION SYSTEM

- APL (KSC) has a history of developing capacitive level sensors
  - Nurge et al. 2003 - *'Capacitance based mass metering for cryogenic fluids'*
    https://www.sciencedirect.com/science/article/pii/S0011227503001279

TECHNOLOGY HISTORY

- Can we use the entire tank as capacitor volume?
  Promising results from previous efforts
- What level of mass fraction accuracy can be achieved for arbitrary fluid configurations?
- How does the sensor function with internal fluid management surfaces?
- What are the requirements of the sensor?



Banasiak et al. 2010

Reproduced courtesy of The Electromagnetics Academy

http://dx.doi.org/10.2528/PIER09111201

TECHNICAL APPROACH

Capacitive Sensing

- Permittivity is a measure of the polarizability of a dielectric due to external electric field

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

ε_0 vacuum permittivity
ε_r relative permittivity

- Capacitance is defined by electrode geometry and permittivity between electrodes
- The permittivity of cryogenic dielectrics is greater in liquid phase than gaseous phase

ε_r, relative permittivity for typical cryogenic dielectrics

	Liquid	Gas
LH2	**1.23** (T=20K)	**1.004** (T=21K)
LO2	**1.49** (T=90K)	**1.002** (T=91K)
LCH4	**1.63** (T=111K)	**1.002** (T=112K)
LN2	**1.43** (T=77K)	**1.002** (T=78K)

Because differences in ε_r for liquid and gas are small , we call these *low-contrast* dielectrics

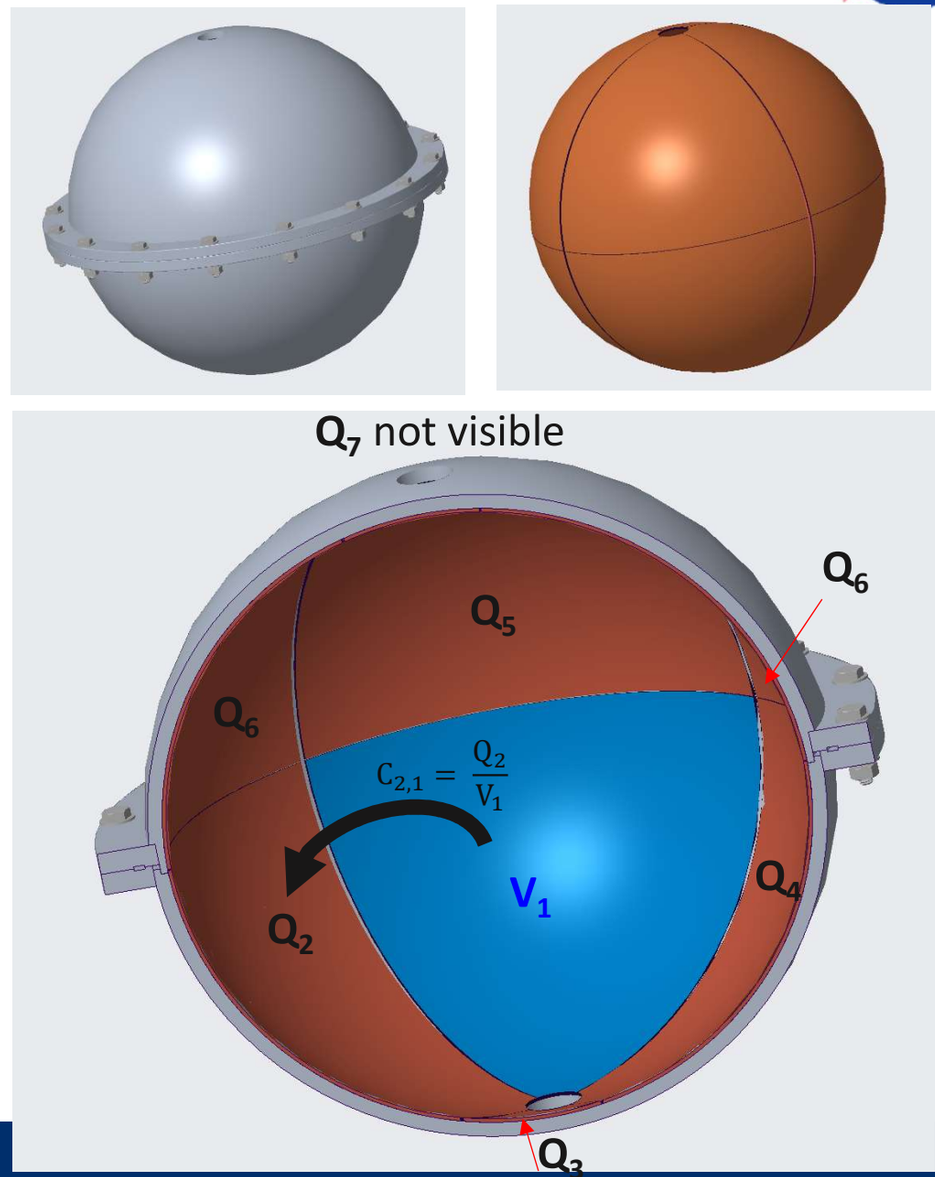
- Increasing liquid-to-gas ratio (fill fraction) leads to increasing permittivity and increasing capacitance of tank volume
- Suitable for cryogenic tanks: extremely low power (< 100 uW), fast operation (1 ms scans), and no moving parts

SENSOR DESCRIPTION

- Surround the 3D tank volume with a set of electrodes lining the inner tank wall surface
- Measure all the unique pairs of capacitances

$$C_{i,j} = \frac{Q_i}{V_j}$$

- For n electrodes, there are $\frac{n(n-1)}{2}$ unique pairs
- Process the capacitance measurements with some algorithm to yield information about the permittivity (i.e., propellant) distribution
- More electrodes generally provides greater accuracy



EXAMPLE ECVT RESULTS

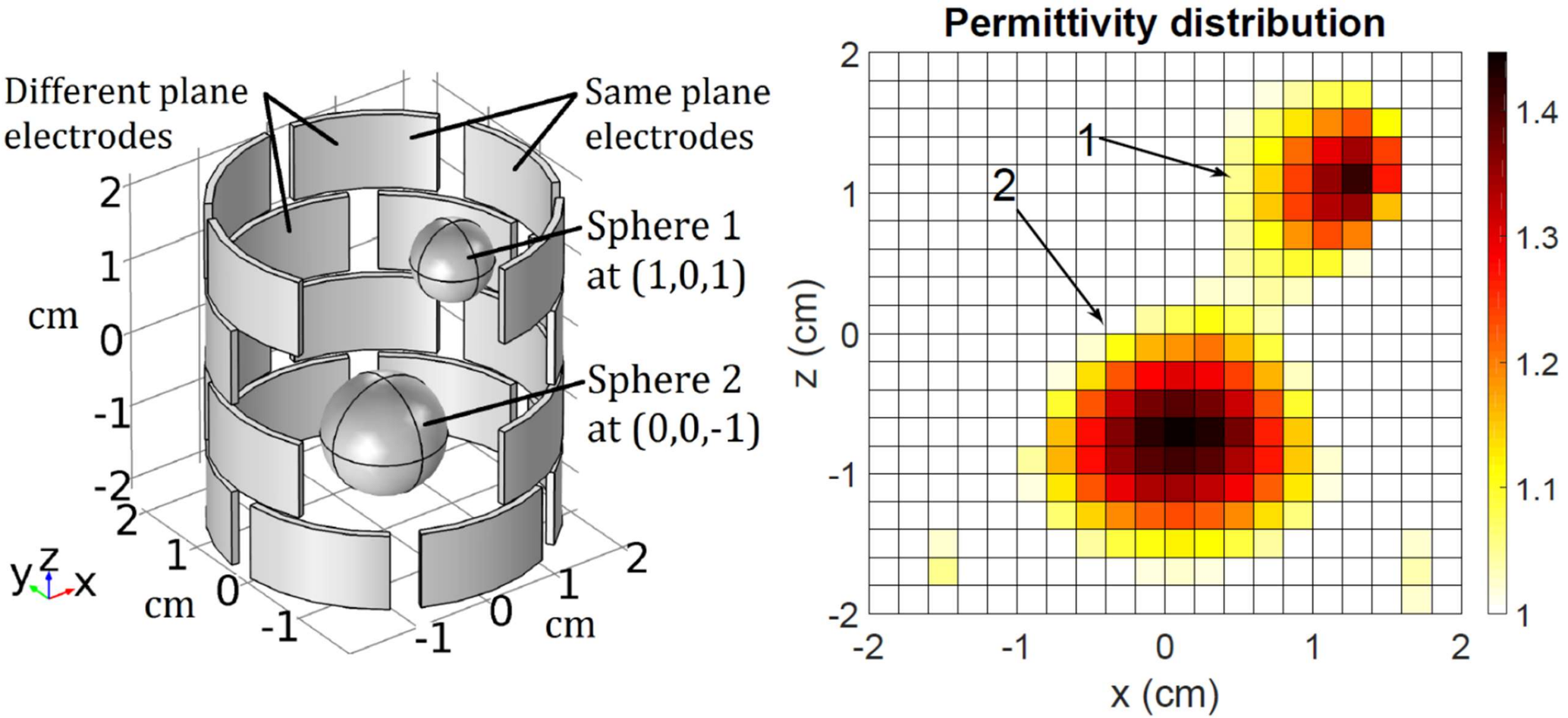


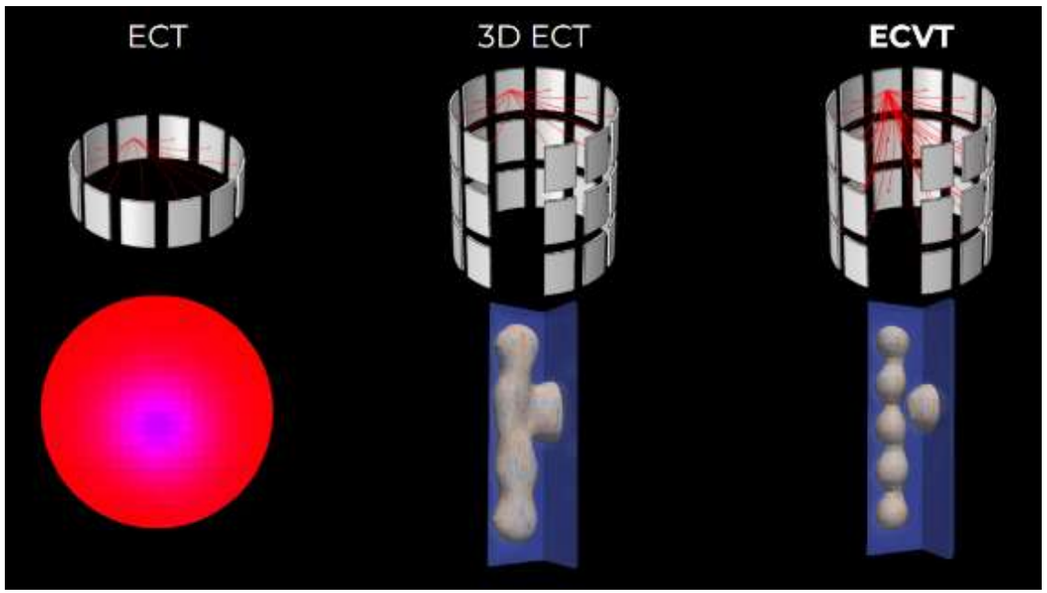
Image reconstruction in ECVT (a) an ECVT sensor enclosing two dielectric spheres (), (b) reconstructed permittivity distribution using Landweber iteration (Qussai Mareshdeh, Tech4Imaging)

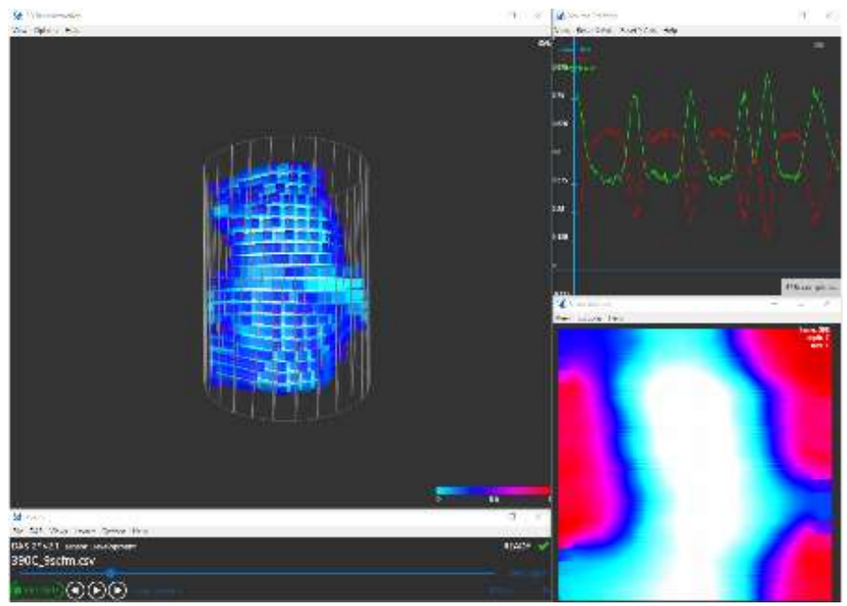
COMMERCIAL PARTNER - TECH4IMAGING

www.tech4imaging.com

Dr. Qussai Marashdeh (T4I) - President and CEO
Ben Straiton (T4I) - Product Manager
Matt Charleston - Product Development Engineer



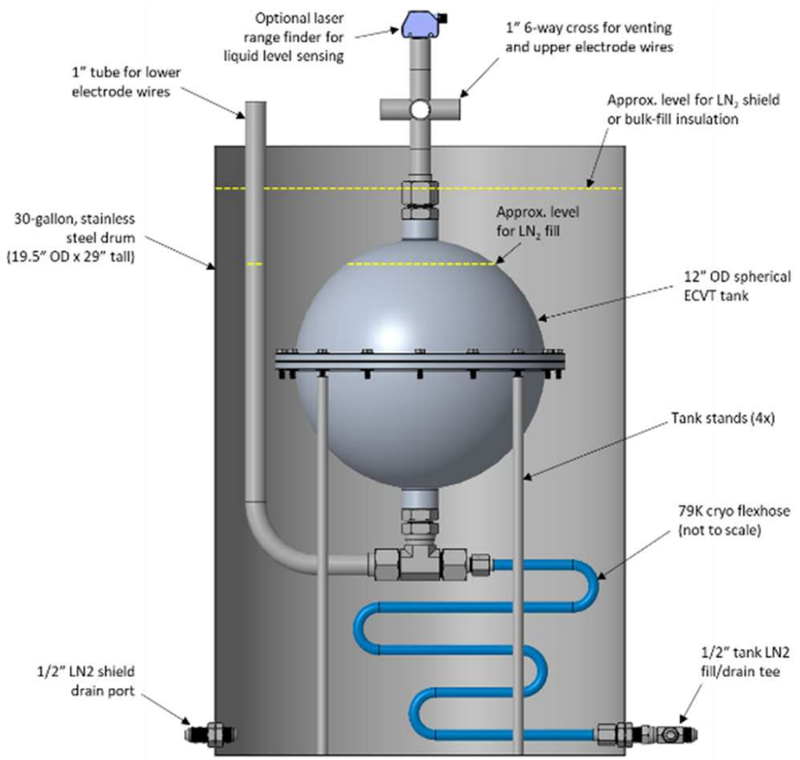


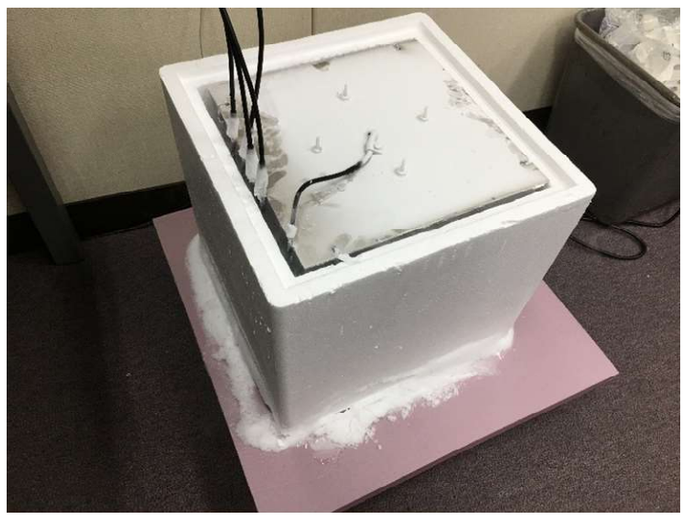


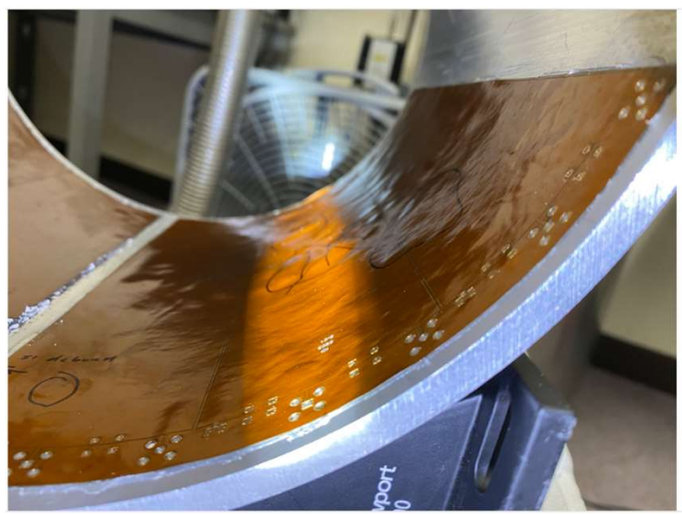
DEVELOPMENT PLAN

- Test capacitive sensor systems in three tank geometries
  - Cubical, Cylindrical, and Spherical
- Ground testing with LN2
  - Settled fluid - insulate tanks by submerging them in LN2 baths
  - ‘Unsettled’ fluid
    - allow boil-off
    - induce some slosh with gentle rocking motion





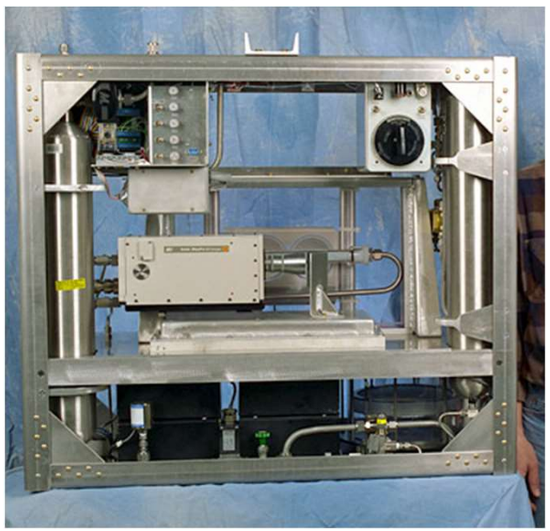




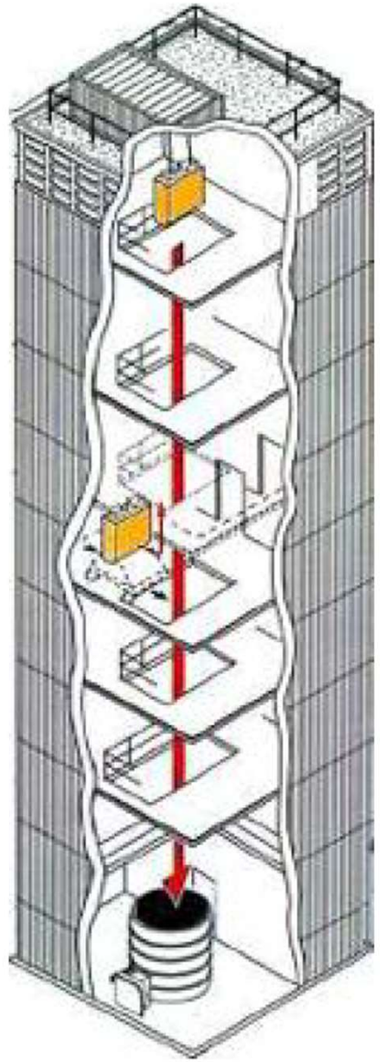
DEVELOPMENT PLAN

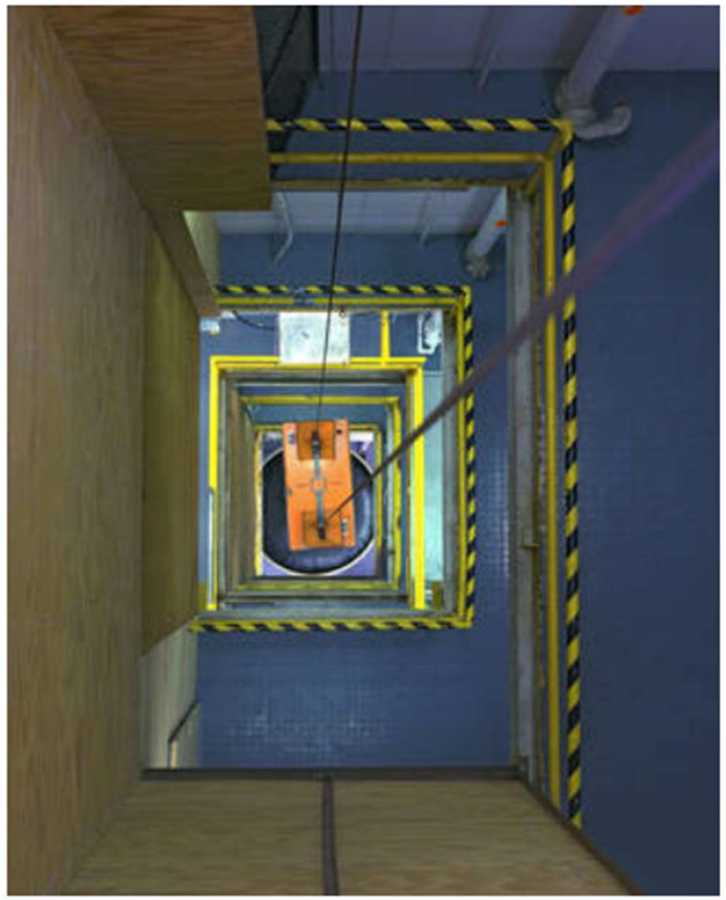
- 2.2-s Drop tower testing with simulant fluid
  - Spherical tank
  - 2 weeks of testing
  - roughly 140 drops

Images from NASA website https://www1.grc.nasa.gov/facilities/drop/









The 2.2 Second Drop Tower allows experiment packages to free fall a distance of 79 feet (24 m).
Credits: NASA

PROJECT GOALS AND OBJECTIVES

Objective 1: Demonstrate performance of ECVT for cryogenic mass gauging in a laboratory environment.
- with and without internal vane surfaces

Objective 2: Develop and test new ‘whole-tank capacitance’ techniques for cryogenic mass gauging (e.g., averaging algorithm)

Objective 3: Demonstrate performance of ECVT for cryogenic mass gauging in a relevant (micro-g) environment using the 2.2-second drop tower at GRC

Objective 4: Design a flight experiment to build following the project.

Key Performance Parameters (KPPs)	Threshold	Goal
KPP 1: Settled Measurement Accuracy	3%	1%
KPP 2: Unsettled Measurement Accuracy	5%	1%
KPP 3: Scanning Time	10 ms	1 ms
KPP 4: In-Tank Power Dissipation	1 mW	≤ 100 µW

BENEFIT TO NASA AND COMMERCIAL SPACE

Reliable, accurate micro-g liquid mass gauging is one of many technologies required enable and/or simplify the types of missions and space activities NASA and commercial space enterprise seek to undertake in the coming years

- Lunar and Martian missions
- In-space propellant transfer
- Nuclear propulsion
- Space habitats

- Reduced propellant margin / increased payload mass
  - Current missions typically include a non-trivial ‘extra’ propellant to account for gauging uncertainties and for settling burns
- Improved accuracy of propellant and vehicle mass without settling burns
  - Reduced risk
  - Improved accuracy of flight mechanics and trajectory design
- Improved CG determination
  - ensures thrust vector coincides with CG,
  - improves stability, minimizes propellant usage

STMD EARLY CAREER INITIATIVE (ECI)

- Two-year, technology-development project led by an early career civil servant
  - Exploring, developing, testing techniques for ‘whole-tank’ capacitive mass gauges
- Half of team must be early career
- Must have a project mentor - a senior civil servant
- Must partner with an external entity

KSC

Dr. Chris Biagi	Applied Physics	Early Career
Nick Spangler	Applied Physics	Early Career
Luke Bird	Electrical/Avionics Eng.	Early Career
Austin Atkins	Physics/Mechanic	Early Career
Adam Swanger	Cryogenic Research Eng.	Early Career
Marco Nacif	Mechanical Eng.	Early Career
Jed Storey	Fluids/Thermal Eng.	Early Career
Dr. Mark Nurge	Applied Physics	Mentor
Dr. Bob Youngquist	Applied Physics	Mentor
Jenna Fothergill	UB	Project Manager
Eric Smith	SE&I	Systems Engineer

GRC

Mariano Mercado	Aerospace Engineer	Early Career
Jesse Defiebre	Fluids Engineer	Early Career
Dr. Jason Hartwig	Research Aerospace Eng.	Mentor

TECH4IMAGING



Dr. Qussai Marashdeh (T4I) - CEO
Ben Straiton (T4I) - Product Manager
Matt Charleston - Product Development Engineer

BENEFIT OF ECI - DEVELOP CAPABILITY AND TECHNOLOGY

- It's an excellent opportunity to
  - Develop NASA's early career workforce with accelerated experience
  - Develop transformative concepts into useable technology that will enable future space missions
- Helps establishes relationships and partnerships
  - The team is highly diverse and works closely together
  - Often need to seek additional resources within NASA
  - GRC and KSC work together in the development, along with the external partner
- Team members can (mostly) focus on what they enjoy
  - Gaining new skills in analysis, hands-on experimentation, programming, physics and engineering
- For me personally
  - The satisfaction of delving into a fascinating application of physics
  - Working with and learning from so many different people
  - Improving my capability to get things done with a diverse team using interpersonal, leadership, and project management skills



Skills + Knowledge + Experience = Capability

Thanks!

SENSOR DESCRIPTION

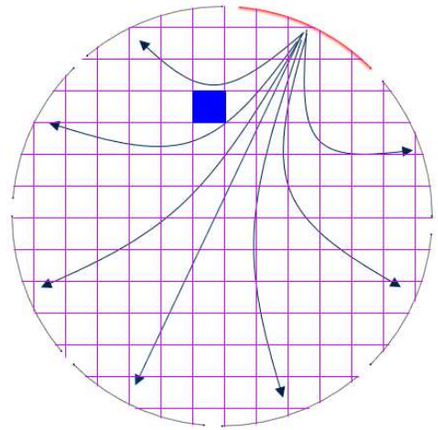
Processing Algorithms - ECT and ECVT

$$C = f(\varepsilon) \longrightarrow \Delta C = \frac{df}{d\varepsilon}\Delta\varepsilon \longrightarrow \mathbf{C} = \mathbf{S}\ \boldsymbol{\varepsilon}$$

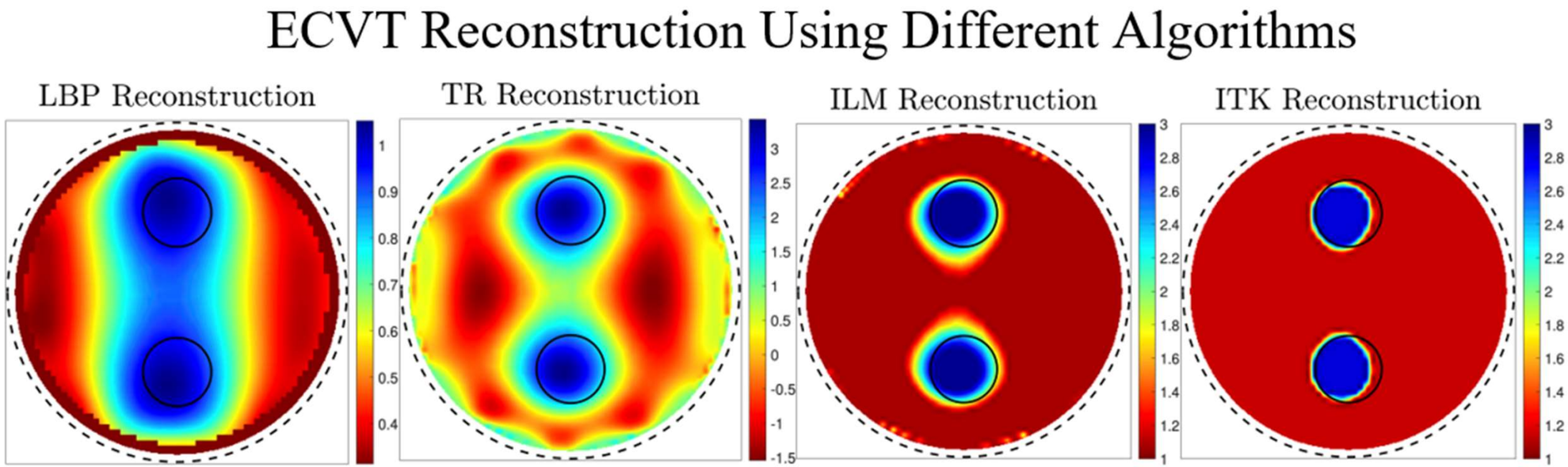
M x 1 = (M x N) (N x 1)

- 'Sensitivity Matrix', **S**
  - Discretize volume into voxels (3-D pixels)
  - Evaluate all capacitances with liquid in a single voxel (all others filled with gas)
  - Repeat for each voxel
  - Assemble an M x N matrix **S** for M capacitances and N pixels/voxels
- Algorithms using sensitivity matrix
  - Linear back projection $\boldsymbol{\varepsilon} = \mathbf{S}^{\mathrm{T}}\mathbf{C}$
  - Singular-Value Decomposition $\mathbf{S} = \mathbf{U}\boldsymbol{\Sigma}\boldsymbol{V}^{\boldsymbol{T}} \longrightarrow \boldsymbol{\varepsilon} = \mathbf{V}\boldsymbol{\Sigma}^{-1}\boldsymbol{U}^{\mathrm{T}}\mathbf{C}$
  - Tikhonov Regularization $\boldsymbol{\varepsilon} = \left(\mathbf{S}^{\mathrm{T}}\mathbf{S} + \mu\mathbf{I}\right)^{-1}\mathbf{S}^{\mathrm{T}}\mathbf{C}$
  - Iterative Tikhonov $\boldsymbol{\varepsilon}_{\mathbf{k+1}} = \boldsymbol{\varepsilon}_{\mathbf{k}} - \left(\mathbf{S}^{\mathbf{T}}\mathbf{S} - \gamma\mathbf{I}\right)^{-1}\mathbf{S}^{\mathrm{T}}(\mathbf{S}\boldsymbol{\varepsilon}_{\mathbf{k}} - \mathbf{C})$
  - Landweber Iteration $\boldsymbol{\varepsilon}_{\mathbf{k+1}} = \mathrm{P}[f(x)] = \mathrm{P}[\boldsymbol{\varepsilon}_{\mathbf{k}} - \alpha\mathbf{S}^{\mathrm{T}}(\mathbf{S}\boldsymbol{\varepsilon}_{\mathbf{k}} - \mathbf{C})]$

$$P = \begin{cases} 0 & \mathrm{f(x)} < 0 \\ f(x) & 0 \le \mathrm{f(x)} \le \varepsilon_r \\ \varepsilon_r & \mathrm{f(x)} > 1 \end{cases}$$

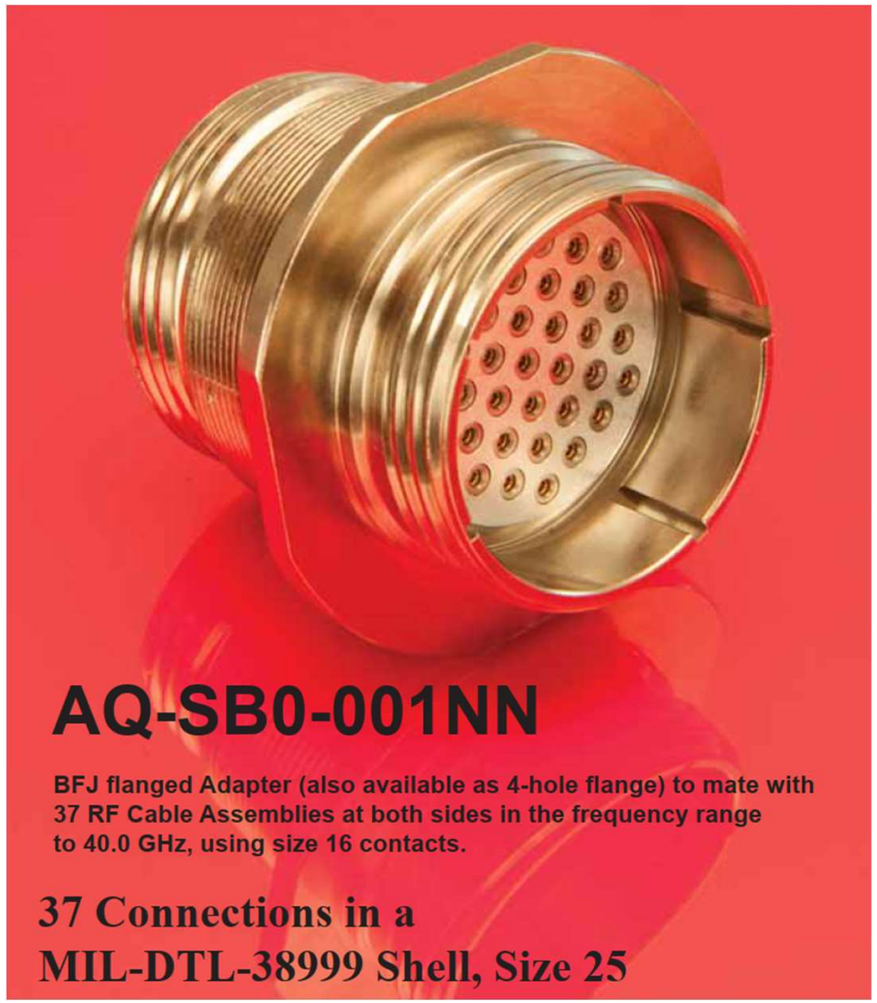


SENSOR DESCRIPTION



www.tech4Imaging.com

ELECTRODE CONNECTIONS



1.625”

Spectrum Elektrotechnik GmbH Germany
https://www.spectrum-et.com