# PRELIMINARY RESULTS FROM PROPELLANT MASS GAUGING IN MICROGRAVITY WITH ELECTRICAL CAPACITANCE TOMOGRAPHY

TFAWS

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Jed Storey, NASA LSP Fluids Analyst, PI
Brandon Marsell, NASA LSP Environments and Launch Approval Branch Chief
Mike Elmore, a.i. Solutions Fluids Analyst
Scott Clark, a.i. Solutions Project Manager

# The Propellant Mass Gauging Problem

- Propellant mass gauging technologies that are designed to work in an accelerated environment, where the propellant remains settled at one end of the propellant tank, do not work well in a microgravity environment because the propellant is not necessarily settled.
  - Example current technologies: differential pressure transducers, liquid level probes, Pressure-Volume-Temperature (PVT), Spectral Mass Gauging (SMG), Modal Propellant Gauging (MPG), Radio Frequency Mass Gauging (RFMG)
- Most propellant tank mass gauging systems currently in-use have at least one major drawback. Examples:
  - Require propellant to be settled in aft end of tank and/or quiescent
  - Propellant must be in contact with walls
  - Require 100's of pre-computed simulations that are compared to measurements to find a best fit propellant distribution
  - Require the propellant to be constant density
  - Require mechanical actuators
  - Most have low (>3%) mass gauging accuracy
- Need a technology that addresses these issues

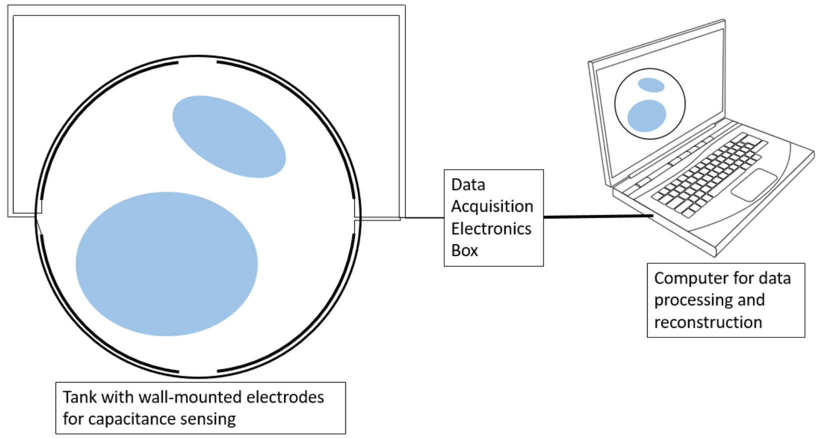
# Impacts of Mass Gauging Improvements



- Applicable to all launch vehicle and spacecraft providers, as well as their customers
- Improvements to accuracy and precision:
  - More accurate propellant utilization tracking
  - Lower propellant mass dispersions
  - Lower required residuals/margins for filling-topping as well as final residuals
  - Improvements to final residuals and mass dispersions mean more informed decisions on whether or not to perform a deorbit burn = potential to reduce orbital debris
- Enable mass gauging during all phases of flight:
  - During launch vehicle ascent, using a mass gauging technology that is immune to slosh would be able to track propellant utilization more accurately.
  - In space, the propellant would not need to be settled before obtaining mass measurements, which improves efficiency, reduces propellant consumption, and allows for tracking cryogenic boil off
- Impacts: improved mass gauging accuracy, lower risk, slight performance improvement, reduced orbital debris

# Electrical Capacitance Tomography

- The Technology
  - ECT works by measuring the capacitance between multiple pairs of thin, conducting plates.
  - Since capacitance is related to permittivity, which in turn is related to density, it is possible, via tomography math, to measure the distribution of liquid inside of a tank using ECT.
  - If the measurements are fast enough, this can be done in real time.
  - Finally, integration of the density distribution yields the mass inside the tank.




Example ECT System

- ECT is not new. Originally developed for the oil and gas industry to measure multi-phase mass flow rate in pipes.
- ECT has recently been applied to tanks to measure liquid volume and mass.

# Electrical Capacitance Tomography

- July 2020: ECT demonstrated better accuracy (<0.1% volume error[1]) over all fill levels than all current mass gauging technologies
  - Source: Behruzi, 2020
- Has been tested in plastic, composite, and metal tanks
- Will theoretically work during all phases of flight, from launch through microgravity, including during slosh (tested), boiling (bubbler tested), free-floating liquid, variable density liquid
- Has the ability to track propellant distribution inside a tank in real-time in 3D, which could help prevent vapor-pull through and liquid venting, and potentially allow for future advancements such as active slosh control.
- Had not been tested in microgravity until now

# Experiment Purpose and Objective



- Primary Objective: Demonstration of accurate liquid mass gauging in a subscale propellant tank using an ECT system during a zero-g parabolic aircraft flight.
- Secondary Objective: obtain the 3D liquid distribution vs. time and use this in a CFD validation study
- Expected TRL after flights: 6
  - TRL 6: "System/subsystem model or prototype demonstration in a relevant environment"
- Tertiary goal: encourage US-based funding for ECT development work

- Funded by an LSP Study in 2021
- NASA Flight Opportunities Program funded the flights on Zero-G's "G-force 1" aircraft
  - Flew in May 2022
- Technology *Demonstrator*: LSP did not design nor develop the ECT hardware. LSP rented it from a company that already had a plug 'n play setup.

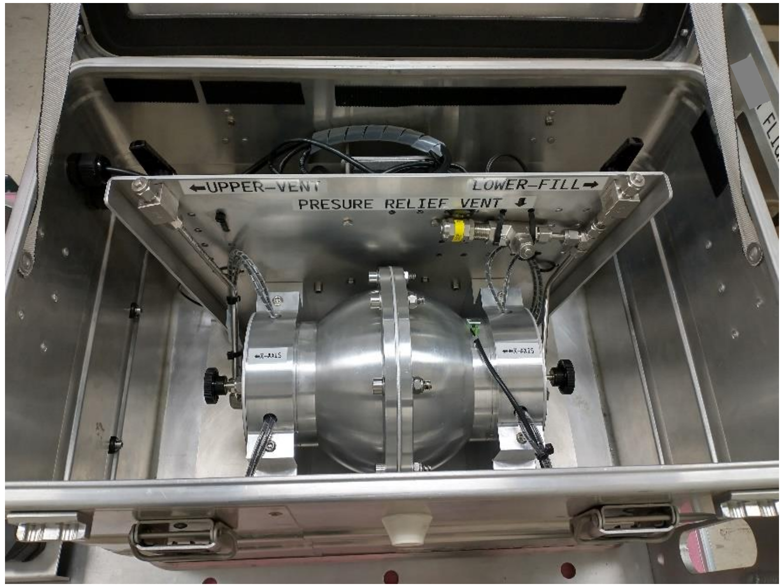
# Experiment Requirements



- ECT-instrumented test tank
- Software user interface showing current measured volume or mass
- Record raw capacitance data at a sample rate of at least 100Hz
- Test setup had to comply with the many requirements imposed by Zero-G
  - Zero-G Payload User’s Guide describes the requirements
  - Many of Zero-G’s requirements come from FAA regulations
  - All components of the experiment have to survive 9g’s in every direction in a “one-mounting-bolt-out” scenario: fore, aft, up, down, left, right. In lieu of testing, this requires extensive FEA to verify.
  - Mounting requirements
  - Liquid secondary containment
  - Electrical requirements
  - Hazards Analysis
  - The required Payload Integration Package that the team generated details compliance with all Zero-G requirements
- The Flight Opportunities Program and NASA HQ require all flight experiments to pass an Air Flight Worthiness Safety Review Board (AFSRB) prior to flying.

# Experiment Design Overview

- 2.8L aluminum, spherical test tank partially filled with a non-hazardous propellant simulant liquid
- Tank has 8 thin, internal electrodes, 4 in each half, which cover most of the inside surface of the tank.
- Tank remains sealed during flight and inside a secondary containment box.
- ECT system installed in test tank, with data acquisition box outside the test tank
- Laptop runs data acquisition software
- LSP addition to meet secondary objective: Small single board computer collects data from a 6-DoF IMU
- Everything mounted to a 10mm thick aluminum plate, which is bolted to the aircraft deck.
- Total volume: 1.2m x 0.6m x 0.5m
- Total mass: approximately 50kg
- Total power requirement: 110VAC, 170W (nominal).



# Propellant Simulant Selection



- All 3M FC and Novec engineered fluids were reviewed.
  - Nonhazardous, nontoxic, nonflammable, no transportation controls
- 3M FC-72 was selected because it has the lowest dielectric, near 1.7, which makes it closest to the cryogenic propellants' dielectrics (1.2-1.6)
- A nondimensional scaling analysis was performed to assess fluid dynamic similarity between the simulants in the 2.8L spherical test tank and cryogens ($LO_2$, $LH_2$, $LCH_4$) in a 3m diameter spherical full scale tank.
  - First mode slosh frequency (including low-g surface tension effects) was used to estimate a slosh velocity for calculating Weber number
- It turns out that 3M FC-72 also has the highest density/surface tension ratio, making it the most similar in terms of Weber and Bond numbers to cryogens in a full scale tank in low gravity.
- Reynolds number is not similar.
  - The extremely low viscosity of cryogens makes Re matching in subscale tanks difficult.
  - Fortunately, viscous slosh damping is not the focus of this study.
- Novec 649 was a close second to FC-72, both in terms of dielectric and nondimensional numbers.

# Pre-Flight

- Before March:
  - Zero-G Payload Integration Package documentation, FEA simulations, hazards analysis, etc.
- March-April:
  - Generated test procedures and practiced them.
- Experiment delivered to Ft. Lauderdale FBO without any damage. Ran check out tests when the team arrived.
- The team passed the Zero-G TRR with 2 things to correct.
  - Even though the frame didn't have any sharp corners and was deburred, Zero-G recommended foam padding for hard edges. The team had to zip-tie/tape foam noodles/pipe insulation around all of the frame bars. This ended up being a good thing to do, added to lessons learned.
  - Also had to label the kill switch location.
- Picture: Experiment installed in aircraft after adding the foam.

# Zero-G Flights

- Flew 4 flights
  - 4 fill levels: 5%, 20%, 50%, 80%
    - “Notional” volume fractions
    - Measured actual loaded liquid masses with a precision scale
  - Original first flight was bumped to 5/11 due to aircraft mechanical problems on 5/9.
  - Second flight was also on 5/11.
  - Third flight was on 5/12
  - Fourth flight was on 5/13
  - Approximately 100 0g parabolas total, plus some Lunar and Martian

# Flight Lessons Applied and Learned



- Lessons Applied:
  - Applied some lessons from previous experience and teams that have flown before.
  - Bring and fly backups, never know who will get sick.
    - Nominally scheduled 3 flyers per day
    - One of the flyers got motion sickness on the first flight, but got lucky and the other flyers didn't get sick.
  - Have thorough, practiced, well-organized procedures for everything.
  - Practice procedures thoroughly on the ground prior to flight.
  - Build in schedule margin.
  - Ship the experiment early. It's far better for it to arrive early than late.
  - If have laptop or computer that is part of the experiment, set it to never sleep, even if lid is closed.
  - Make sure *everything* is secured or it will float away.
  - Backup all data.
- Lessons Learned:
  - Tape/zip-tie foam around all exposed frame members, even if no sharp corners. Hard surfaces on the outer edges of the experiment's envelope should have padding.
  - Tape, file, or hot glue over cut zip tie ends. Cut zip tie ends are sharp enough to scratch skin.
  - Design multiple flight day experiments to not need to be unbolted/removed from the plane.
  - 0g parabolas are not steady nor consistent. This was actually good for our experiment, but might not be for others.
  - Put a GPS tracker in your shipping crate

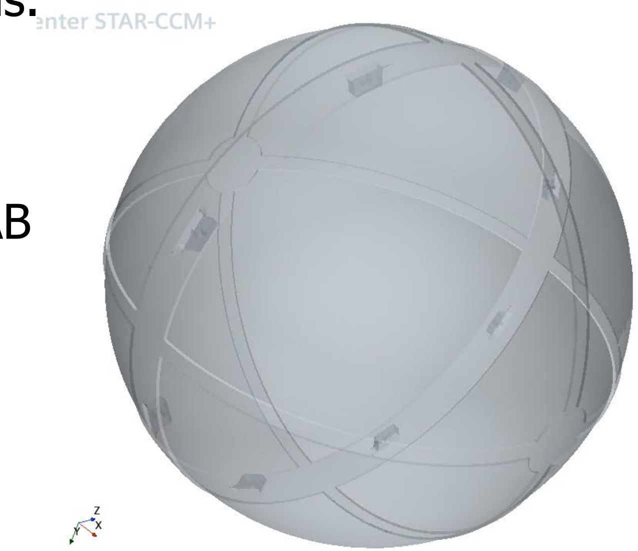
# Experiment Performance

- No incidents.
  - Some motion sickness, small scratches, bumps.
  - No liquid spills.
  - No realized hazards.
- Experiment performed nominally.
  - No major errors encountered.
  - Collected ~25GB of ECT and IMU data.
- Preliminary data checks looked promising.
- The experiment software reconstructs liquid location and calculates fill% in tank in real time.
  - The transitions to 0g caused significant liquid motion, which is good.
  - Observed swings of +/- 1-4% fill during 0g. The center of that swing wasn't necessarily the known fill%. Swing amount depended on fill level, and each parabola was different.


Jed monitoring data while floating upside down

# Analysis

- Did not want to rely on the mass gauging calculations from the closed-source software that came with the experiment.
- One of the requirements was recording of raw capacitance data to allow our own reconstruction and mass gauging algorithms to be implemented.
  - Implemented Linear Back Projection (LBP) and Landweber (LW)
- Realistic inside-tank geometry created in CAD
- Electrostatic simulations performed in STAR-CCM+ for generating the sensitivity matrix
  - Also used to create “simulated data” for testing the processing algorithms.
- Simulation outputs and test data imported into MATLAB
- Reconstruction done in MATLAB
  - Also calculate volume, mass, and center of mass (CM) location in MATLAB
  - 3D permittivity distribution is exported
- Imported the reconstruction into STAR-CCM+ for visualization



# ECT Math



- An electrode is "active" (raised to some voltage) and the rest are grounded, "sensing".
- Capacitance is calculated as the integral over the sensing electrode surfaces of the permittivity distribution times the gradient of the potential distribution divided by the potential difference between the electrode pairs.
- This is repeated for every, M=n*(n-1)/2, pair.
- Capacitance is thus a function of permittivity. Linearizing yields a simple sensitivity matrix formulation, S: MxN, where N is the number of cells in the mesh of your FV or FEM simulation used to generate S.
- Unfortunately, $S^{-1}$ does not exist because the problem is ill-posed and ill-conditioned (N>>M). It's also not linear, despite the assumption that it is.
- Linear back-projection (LBP) assumes that $S^{-1} = S^T$, i.e. S is a linear mapping from permittivity vector space to capacitance vector space.
- Despite the non-physicality of these assumptions, LBP works surprising well, though the liquid reconstruction is smeared over a wide range of permittivity.

$$C = \frac{Q}{V} = -\frac{1}{V}\iint_{\Gamma} \varepsilon(x, y)\nabla\phi(x, y)\,\mathrm{d}\Gamma$$

$$C = \xi(\varepsilon) \longrightarrow \Delta C = \frac{\mathrm{d}\xi}{\mathrm{d}\varepsilon}(\Delta\varepsilon) + \mathrm{O}((\Delta\varepsilon)^2)$$

$$\Delta C = s\,\Delta\varepsilon$$

$$\boldsymbol{\lambda} = \boldsymbol{S}\boldsymbol{g}$$ (normalized)

$$\boldsymbol{g} = \boldsymbol{S}^{-1}\boldsymbol{\lambda} \longrightarrow \hat{\boldsymbol{g}} = \boldsymbol{S}^T\boldsymbol{\lambda}.$$ (LBP)

# ECT Math

- There are many other methods, some more (and some less) accurate.
- Iterative methods allow the capacitance error to be driven lower than a single step method can.
- Landweber: Goal is to minimize capacitance residual with steepest gradient descent.
- $\alpha$ is a relaxation factor, usually chosen empirically.
- The "P"rojected form enforces the normalized permittivity to be between 0 and 1 every iteration, which helps prevent divergence.
- Landweber is generally the best simple iterative algorithm.
  - There are more advanced iterative methods, such as level set methods, but they are significantly more difficult to implement.
  - Neural networks have also been used
- All of this so far has been about solving the "inverse problem": finding g given λ. Solving the "forward problem" without FEM is difficult, but there are methods to do so.
  - Future work
- Primary math source: Yang, 2003

$$\frac{1}{2}\|S \cdot g - \lambda\|^2$$

$$f(g) = \frac{1}{2}(Sg - \lambda)^T (Sg - \lambda)$$

$$= \frac{1}{2}(g^T S^T Sg - 2g^T S^T \lambda + \lambda^T \lambda).$$

$$\nabla f(g) = S^T Sg - S^T \lambda = S^T (Sg - \lambda)$$

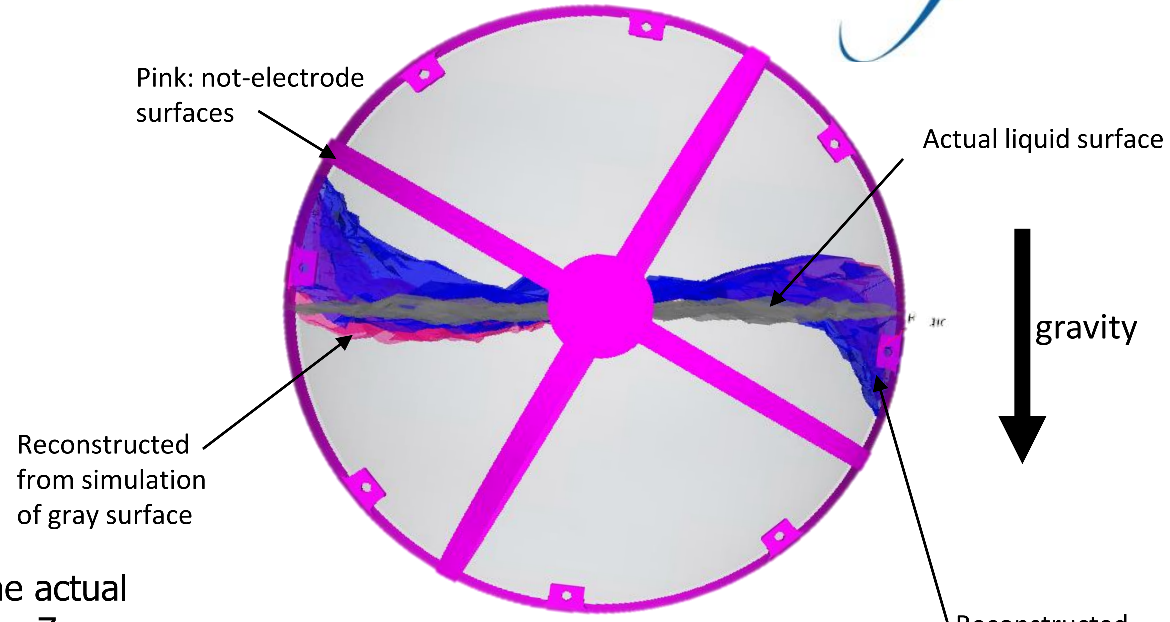
$$\hat{g}_{k+1} = \hat{g}_k - \alpha_k \nabla f(\hat{g}_k) = \hat{g}_k - \alpha_k S^T (S\hat{g}_k - \lambda)$$

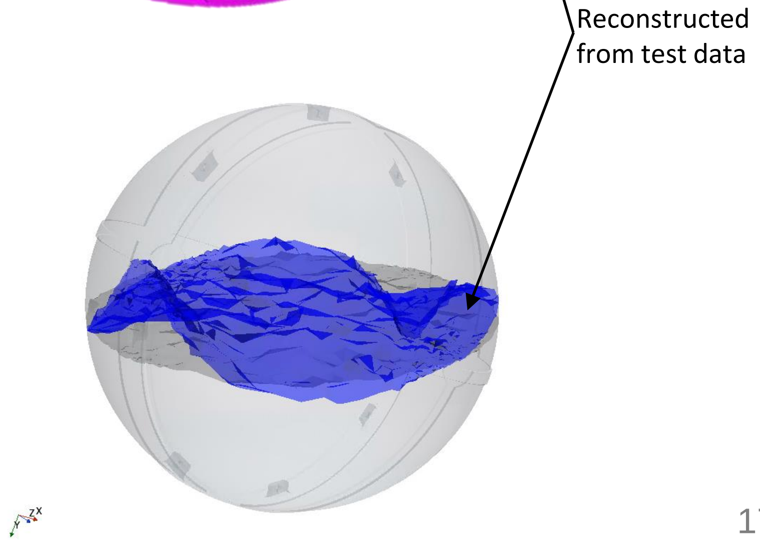
$$\hat{g}_k + 1 = P[\hat{g}_k - \alpha S^T (S\hat{g}_k - \lambda)]$$

$$P[f(x)] = \begin{cases} 0 & \text{if } f(x) < 0 \\ f(x) & \text{if } 0 \leqslant f(x) \leqslant 1 \\ 1 & \text{if } f(x) > 1. \end{cases}$$

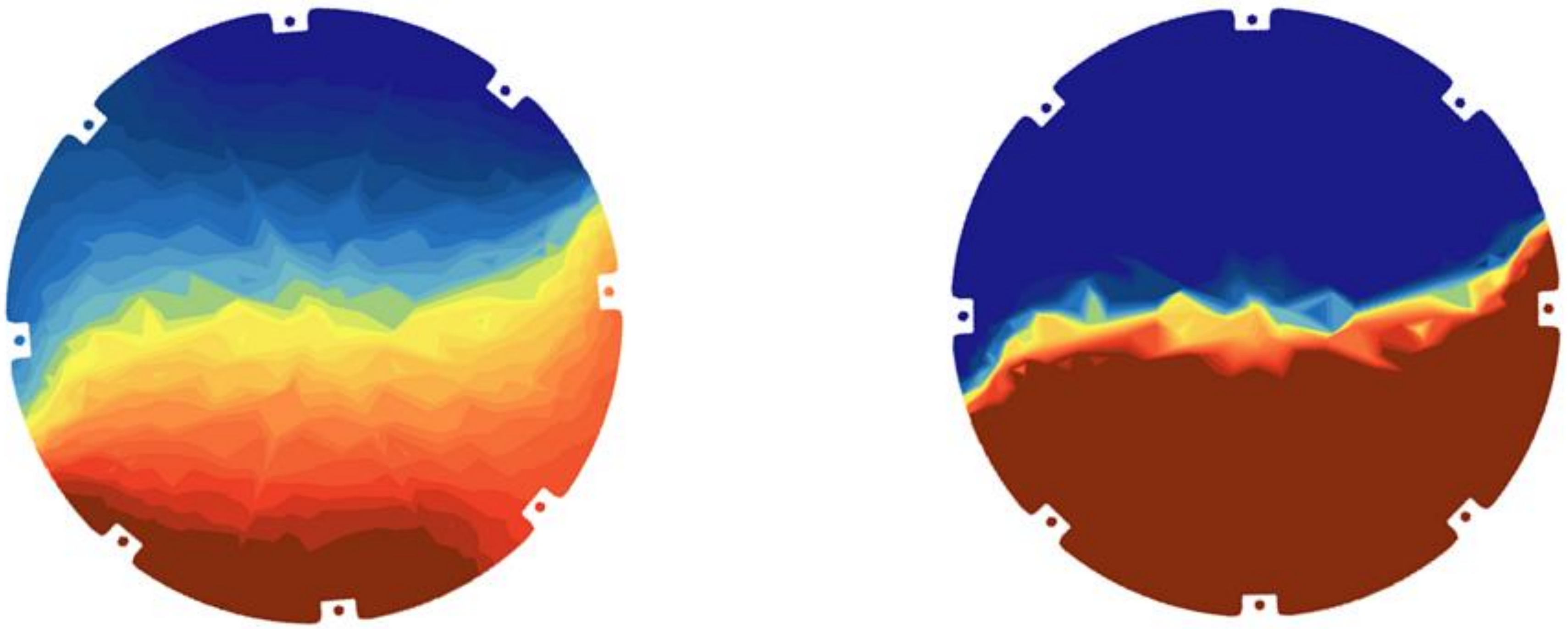
# Example Result

- Chose a data time step from a few seconds after starting data collection during our 3rd flight
  - Tank was in aircraft while aircraft was stationary on the ground
  - Actual fill level was approximately 52.6%
  - The experiment's software recorded 49.4% fill level at this time
  - Also simulated this case with a flat 50% fill level.
- Top picture
  - Gravity "down" is approximately image down.
  - Pink is everything that is not an electrode plate
  - Blue is the reconstructed isosurface from test data
  - Gray is a simulation input liquid isosurface, which was best guess for the actual liquid surface; the tank is rotated about its X axis such that neither Y nor Z are directly pointing down. That's how it was assembled.
  - Red (overlapping blue) is the reconstructed isosurface of the (gray input) simulation output.
  - The red (sim) and blue (test) reconstructed surfaces match well, and are mostly flat, except for regions on the left and right. In those regions, the reconstructed surface is "pulled" towards the high E-fields in the plate gaps, up on the left, and down on the right. This is not physical, and this doesn't happen when plates are symmetric relative to the liquid distribution.
- Bottom picture: Another view, with the simulated data reconstruction hidden



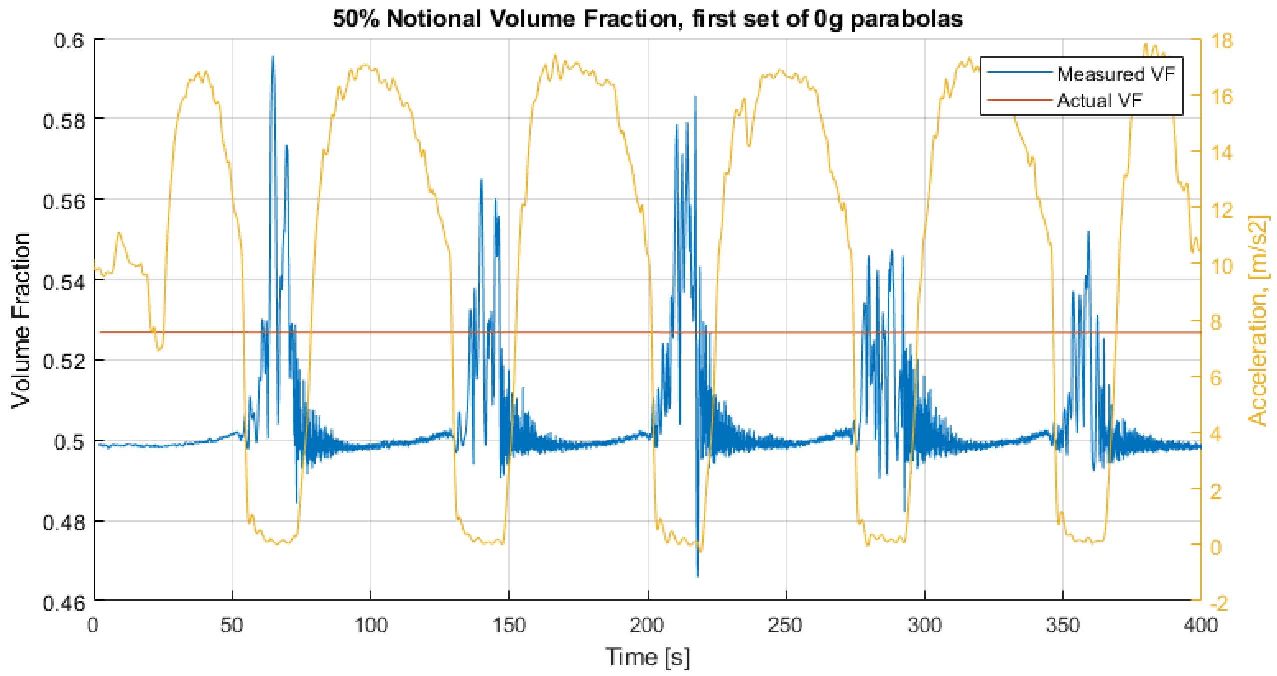



# Example Result

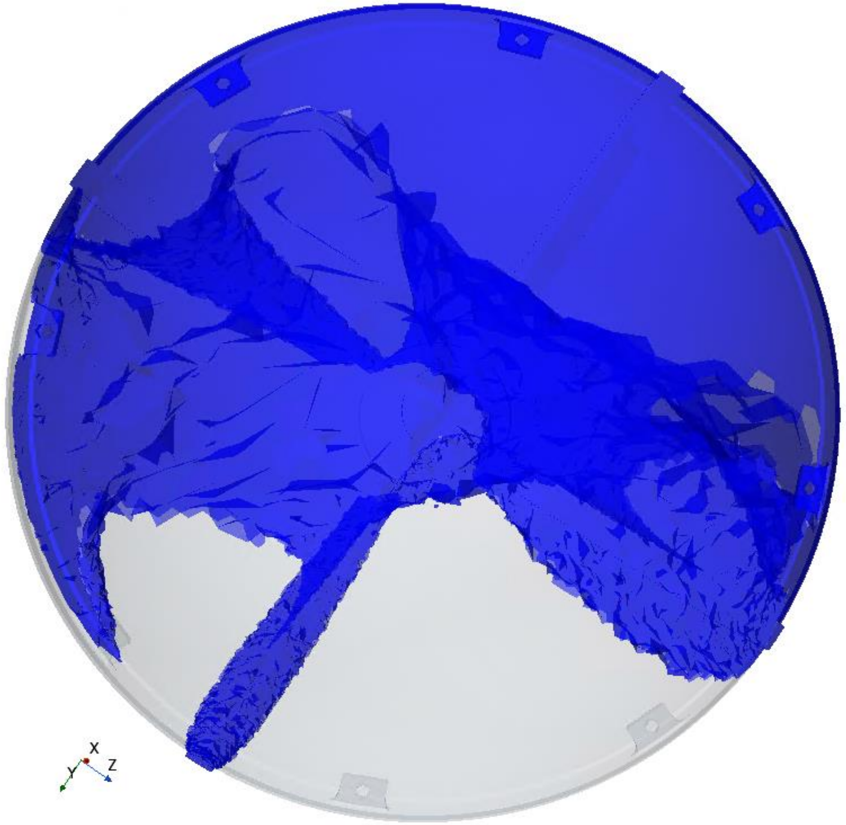


- Contour plots of test-data-reconstructed permittivity. Blue is no liquid, red is 100% liquid. Jagged-ness is from the finite-volume (FV) mesh.
- The permittivity smearing can be seen in the LBP result on the left.
- The interface is sharpened significantly thanks to LW on the right.
- Calculated volume fraction is 50.1-51.3%, depending on method. (~52.6% actual)

# Example Results – 0g

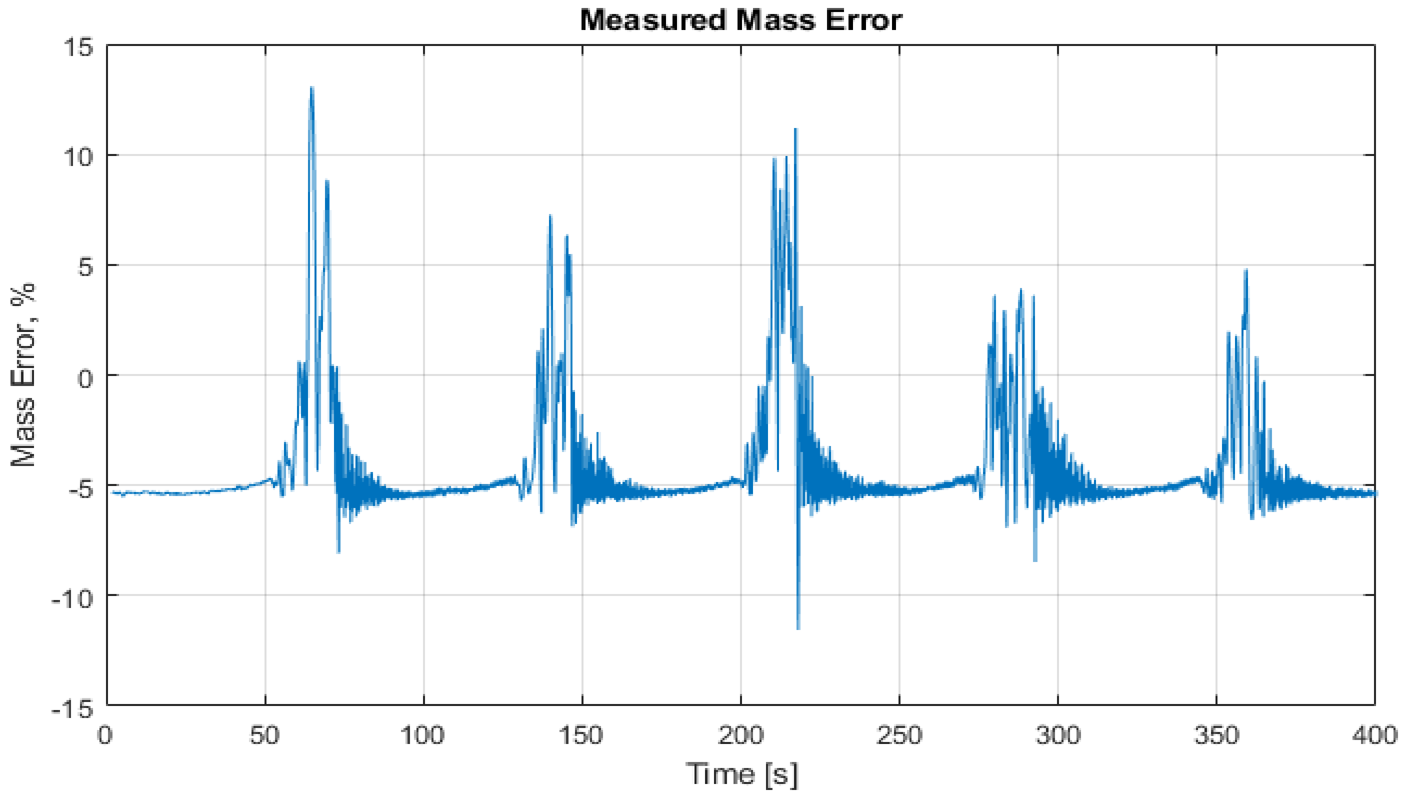



- Capacitance data was filtered with a 10Hz cut-off high order cheby2 low pass filter prior to reconstruction and volume calculation.
  - No additional filtering applied.
- Measured volume fraction swings from 47%-59%.
  - Slightly more than observed in-flight with the experiment's software
- Peaks occur during 0g, flat portions are during hyper-g (about 1.8g's).
- Slosh decay visible during initial portions of hyper-g.
- Settled capacitance corrections may be able to correct the offset present while under acceleration.




LW reconstruction of a time point during a 0g parabola from the 50% (notional) volume fraction flight. Aircraft deck is in direction of image down.

# Example Results – 0g




- Same fill and time range as plot on previous slide.
- Measured mass is calculated by multiplying measured volume by density, so mass error is dependent on measured volume error
- The -5% offset is due to the offset seen on the previous slide while under acceleration.
- Mass error in grams is lower for lower fill levels during 0g, but % error is higher.
- Significantly higher error during 0g than what was seen in ground-based laboratory tests[1]

# Error Sources and Improvements

- The electric field is not uniform, particularly near the electrode edges: high gradients.
- Linear assumption is poor in regions of non-uniform electric field.
  - Liquid moving between regions of high and low sensitivity causes the oscillations seen in the 0g portions of the plots.
- Electrodes have gaps between them
  - High, non-uniform E-fields in gaps
  - Gaps result in deadbands in settled liquid volume measurement
  - Electrode placement was not precise, resulting in variable gap sizes.
  - Some extraneous tank features in the split-plane gap
- Temperature
  - Permittivity and density are temperature dependent
  - Low vapor pressure liquid -> mass transfer from temperature changes
  - Sensor and electronics temperature dependence (small, on the order of 0.2% for the temperature range seen)
  - All of these temperature effects have been corrected.
- Mechanical improvements will likely reduce error. Examples:
  - More exact electrode placement
  - Smaller gaps between electrodes
  - Thinner electrode plates and/or preventing liquid from wicking/flowing between the electrodes.
  - More electrodes, though there is a limit because SNR decreases with decreasing electrode size.
- Some processing improvements could reduce error. Examples:
  - Moving average or other low-pass filtering techniques for volume and/or mass calculation will smooth spikes.
  - Nonlinear calibration or capacitance corrections based on ground tests at many fill levels. Useful for settled liquid only.

# Preliminary Experiment Results and Future Work

- **Primary objective achieved**: ECT sensor systems are useful as a propellant mass gauging technology in both an accelerated and microgravity environment
- Expect significantly better performance if previously mentioned improvements are implemented.
- Future work, all in progress:
  - Post-process all of the data
  - Uncertainty analysis and error correction
  - Implement more accurate reconstruction algorithms
  - Write journal papers
- Not currently planning another flight of this hardware.
  - Hoping to inspire other NASA researchers and industry to further develop and use this technology.

# Acknowledgements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LAUNCH SERVICES PROGRAM

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