Experiments and Simulations of Liquid Mass Gauging and Slosh Dynamics in Microgravity

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Experiments and Simulations of Liquid Mass Gauging and Slosh Dynamics in Microgravity

by

Jedediah Morse Storey

A dissertation submitted to the College of Engineering and Science of the Florida Institute of Technology in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Aerospace Engineering

Melbourne, Florida December, 2023
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Abstract

Title: Experiments and Simulations of Liquid Mass Gauging and Slosh Dynamics in Microgravity

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Advancements in liquid propellant management science and technologies are key to increasing safety, decreasing cost, and increasing payload mass of space missions. Propellant usually comprises a large portion of the total mass of launch vehicles and spacecraft, so liquid propellant sensing, as well as predicting and controlling the motion of it, are important. Electrical Capacitance Tomography (ECT) is an emerging sensing technology that is capable of measuring the distribution of liquid anywhere inside of a tank, potentially making it useful for measuring slosh and gauging mass. An ECT-instrumented tank was successfully tested in microgravity for the first time. Basics of ECT measurement theory, details of the experiment setup, data processing, ground test results, and the flight test results are discussed. The results suggest ECT will be useful as a propellant mass gauging technology in both accelerated and microgravity environments. The accuracy of the ECT-measured 3D liquid distributions is also assessed. Computational fluid dynamics (CFD) programs are critical to predicting slosh dynamics, but CFD programs require extensive experimental validation before the results can be trusted. Microgravity slosh test data is lacking, and most of what is available is inadequate for CFD
validation. The SPHERES-Slosh Experiment (SSE) was created and successfully utilized to acquire long-duration, low-gravity liquid slosh data while operating on the International Space Station (ISS). The SSE test sessions yielded a dataset of correlated inertial measurement unit data and images that can be used by design engineers and space mission planners to benchmark CFD models. The combination of long-duration, low-gravity, measured motion, and known initial conditions aspects of the SSE dataset had not been achieved in any prior slosh experiments, making it unique and valuable. Mechanical, electrical, and software design, fabrication, qualification testing, ground testing, and ISS operations of the SSE, along with CFD validation using the test data, are presented. The duration of good agreement between test and CFD was case-dependent. Improving the trajectories calculated from the measured motion data is necessary before long-duration validation of low-gravity slosh CFD can be claimed.
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<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>APL</td>
<td>Applied Physics Laboratory</td>
</tr>
<tr>
<td>ARC</td>
<td>Ames Research Center</td>
</tr>
<tr>
<td>Bo</td>
<td>Bond number</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CI</td>
<td>Confidence Interval</td>
</tr>
<tr>
<td>CM</td>
<td>Center of Mass</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control (machining)</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DCSS</td>
<td>Delta Cryogenic Second Stage</td>
</tr>
<tr>
<td>DoF</td>
<td>Degree(s) of Freedom</td>
</tr>
<tr>
<td>ECT</td>
<td>Electrical Capacitance Tomography</td>
</tr>
<tr>
<td>EMI</td>
<td>ElectroMagnetic Interference</td>
</tr>
<tr>
<td>FDM</td>
<td>Fused Deposition Modeling</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FIR</td>
<td>Finite Impulse Response</td>
</tr>
<tr>
<td>FOP</td>
<td>Flight Opportunities Program</td>
</tr>
<tr>
<td>Fr</td>
<td>Froude number</td>
</tr>
<tr>
<td>FVM</td>
<td>Finite Volume Method</td>
</tr>
<tr>
<td>GSE</td>
<td>Ground Support Equipment</td>
</tr>
<tr>
<td>GSP</td>
<td>Guest Scientist Program</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>H</td>
<td>Horizontal orientation</td>
</tr>
<tr>
<td>ICDF</td>
<td>Inverse Cumulative Distribution Function</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transform</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>KSC</td>
<td>Kennedy Space Center</td>
</tr>
<tr>
<td>LBP</td>
<td>Linear Back Projection</td>
</tr>
<tr>
<td>LH₂</td>
<td>Liquid Hydrogen</td>
</tr>
<tr>
<td>LN₂</td>
<td>Liquid Nitrogen</td>
</tr>
<tr>
<td>LO₂</td>
<td>Liquid Oxygen</td>
</tr>
<tr>
<td>LSP</td>
<td>Launch Services Program</td>
</tr>
<tr>
<td>LW</td>
<td>Landweber</td>
</tr>
<tr>
<td>MA</td>
<td>Moving Average</td>
</tr>
<tr>
<td>MAPTIS</td>
<td>Materials and Processes Technical Information System</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>MPG</td>
<td>Modal Propellant Gauging</td>
</tr>
<tr>
<td>MSFC</td>
<td>Marshall Space Flight Center</td>
</tr>
</tbody>
</table>
NBP - Normal Boiling Point
NVF - Notional Volume Fraction
OS - Operating System
PCB - Printed Circuit Board
PI - Principal Investigator
PMD - Propellant Management Device
PTC - Passive Thermal Control
Re - Reynolds number
RF - Radio Frequency
RFI - Radio Frequency Interference
RFMG - Radio Frequency Mass Gauging
SLA - Stereolithography
SNR - Signal to Noise Ratio
SPHERES - Synchronized Position Hold Engage Reorient Experimental Satellites
SSD - Solid State Drive
SSE - SPHERES-Slosh Experiment
STP - Standard Temperature and Pressure
UI - Uncertainty Interval
We - Weber number
VERTIGO - Visual Estimation for Relative Tracking and Inspection of Generic Objects
V - Vertical orientation (Voltage symbol in equations)
VF - Volume Fraction
VoF - Volume of Fluid (CFD method)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>(a)</td>
<td>acceleration ([\text{m/s}^2])</td>
</tr>
<tr>
<td>(A)</td>
<td>area ([\text{m}^2])</td>
</tr>
<tr>
<td>(C)</td>
<td>capacitance ([\text{F}])</td>
</tr>
<tr>
<td>(C^*)</td>
<td>normalized capacitance, nondimensional</td>
</tr>
<tr>
<td>(D)</td>
<td>tank diameter ([\text{m}])</td>
</tr>
<tr>
<td>(e)</td>
<td>error</td>
</tr>
<tr>
<td>(F)</td>
<td>force ([\text{N}])</td>
</tr>
<tr>
<td>(g)</td>
<td>unit grams, not to be confused with (G)</td>
</tr>
<tr>
<td>(G)</td>
<td>Earth gravity, acceleration ([9.81 \text{ m/s}^2])</td>
</tr>
<tr>
<td>(h)</td>
<td>fill height ([\text{m}])</td>
</tr>
<tr>
<td>(L)</td>
<td>characteristic length ([\text{m}])</td>
</tr>
<tr>
<td>(m)</td>
<td>mass ([\text{kg}])</td>
</tr>
<tr>
<td>(Q)</td>
<td>charge ([\text{C}])</td>
</tr>
<tr>
<td>(R)</td>
<td>tank radius ([\text{m}])</td>
</tr>
<tr>
<td>(S)</td>
<td>sensitivity matrix ([\text{F/F/m}])</td>
</tr>
<tr>
<td>(t)</td>
<td>time ([\text{s}])</td>
</tr>
<tr>
<td>(U)</td>
<td>velocity ([\text{m/s}])</td>
</tr>
<tr>
<td>(v)</td>
<td>volume ([\text{m}^3])</td>
</tr>
<tr>
<td>(V)</td>
<td>voltage ([\text{V}])</td>
</tr>
<tr>
<td>(z)</td>
<td>slosh wave amplitude ([\text{m}])</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>angular acceleration ([\text{rad/s}^2])</td>
</tr>
<tr>
<td>(\beta)</td>
<td>iteration step size</td>
</tr>
<tr>
<td>(\delta)</td>
<td>momentum diffusion length ([\text{m}])</td>
</tr>
<tr>
<td>(\epsilon)</td>
<td>permittivity distribution ([\text{F/m}])</td>
</tr>
<tr>
<td>(\epsilon^*)</td>
<td>normalized permittivity distribution, nondimensional</td>
</tr>
<tr>
<td>(\epsilon_0)</td>
<td>vacuum permittivity ([\text{F/m}])</td>
</tr>
<tr>
<td>(\epsilon_R)</td>
<td>relative permittivity, (= \epsilon / \epsilon_0)</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>frequency parameter, nondimensional</td>
</tr>
<tr>
<td>(\mu)</td>
<td>dynamic viscosity ([\text{Ns/m}^2])</td>
</tr>
<tr>
<td>(\nu)</td>
<td>kinematic viscosity ([\text{m}^2/\text{s}])</td>
</tr>
<tr>
<td>(\rho)</td>
<td>density ([\text{kg/m}^3])</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>surface tension ([\text{N/m}])</td>
</tr>
<tr>
<td>(\phi)</td>
<td>electric field potential ([\text{V}])</td>
</tr>
<tr>
<td>(\tau)</td>
<td>torque ([\text{Nm}])</td>
</tr>
<tr>
<td>(\omega)</td>
<td>rotation rate ([\text{rad/s}])</td>
</tr>
<tr>
<td>(\Omega_n)</td>
<td>(n^{th}) mode slosh frequency ([\text{rad/s}])</td>
</tr>
</tbody>
</table>
Acknowledgement

Within the Kennedy Space Center (KSC) Launch Services Program (LSP), I am very grateful to Brandon Marsell for his support, which was instrumental to me completing this degree. I would also like to thank Dr. Paul Schallhorn, Jacob Roth, Michael Elmore, Scott Clark, the Fluids Group, the Studies Board, upper management, and Flight Analysis IT for their support. Within KSC, I would like to thank the UB directorate, in particular Dr. Robert Youngquist, Dr. Mark Nurge, Dr. Chris Biagi, and Austin Atkins for their invaluable guidance and support of anything related to ECT, and the SI directorate, in particular Flight Operations, and Safety and Mission Assurance. I would like to thank the NASA Flight Opportunities Program (FOP), in particular Earl Adams and Alexander Van Dijk, and Zero-G corporation for their guidance and support flying me and the ECT experiment. Funding for the ECT experiment was provided by the LSP Studies Board and the FOP.

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Last, yet foremost, thank you to my research advisor and mentor, Dr. Daniel Kirk, with whom I’ve had the pleasure of working for many years.
Chapter 1
Introduction

1.1 Background

In the 1950’s, NASA began studying the management of fluid in vessels due to the relevance to rocket and spacecraft propellant tanks. Two related subfields of fluid management in propellant tanks are the sensing, e.g. gauging, of liquid propellants and the fluid dynamics of the motion, i.e. slosh, of propellants. At the time, scientists and engineers did not have access to modern computers capable of solving optimization equations for multidimensional inverse problems, e.g. tomographic reconstruction, which limited the classes of technologies available for propellant sensing. The computers of that time were also incapable of solving the discretized Navier-Stokes equations, so scientists and engineers were limited to analytical solutions, mechanical analogies, experiments, and resulting correlations to model propellant slosh [1]. By 1970, computational integral methods for the solution of analytical slosh potential flow equations had been developed [2] [3], but progress in the field of computational slosh stalled. With the rise of modern computers in the 1980’s and 1990’s, numerically solving the discretized Navier-Stokes equations became feasible [4], and computational fluid dynamics (CFD) was born. The development of multiphase methods for CFD [5] enabled the simulation of fluid slosh dynamics. Concurrently, the increase in computational power allowed for the use of optimization methods for solving multidimensional inverse problems [6], which gave rise to the various forms of tomographic imaging that are now commonplace.
1.2 Motivation

Because liquid propellant usually makes up a large portion of the total mass of launch vehicles and spacecraft, advancements in liquid propellant management science and technologies are key to increasing safety, decreasing cost, and increasing payload mass of space missions. Recent large investments in the space industry, including the development of numerous new launch vehicles, design of in-space propellant depots, the return astronauts to the Moon, and the advent of private space stations, have spurred research in this field [7].

The fluid dynamics of liquid propellants in an accelerated environment, such as on a planetary body or while a space vehicle is thrusting, are different than in a low acceleration environment, i.e. low-gravity (low-G) or microgravity [8]. The science of liquid propellant management in accelerated environments is more mature than for low-G environments partially because of the relative ease of performing ground testing [9].

The ability to accurately sense liquid propellant in rocket and spacecraft tanks is important for space mission planning, design, and operations [9]. Improving the accuracy of propellant tracking and mass gauging over all phases of flight, including those generating unsettled configurations, will increase mission assurance and performance by lowering required propellant mass dispersions, margins, and residuals. For example, the primary criteria for second stage deorbit burns is remaining propellant and its associated uncertainty; reducing the uncertainty of the propellant measurement reduces the remaining propellant required for a burn, thus potentially easing orbital debris concerns. Settling
burns are another example; these maneuvers are performed to settle the propellant at one end of the tank, but in doing so, expend propellant. Reducing the uncertainty of propellant mass gauging when the propellant is unsettled may reduce the need for settling burns during long coasts, thus saving propellant. Electrical Capacitance Tomography (ECT) is an emerging sensing technology that is capable of measuring the distribution of liquid anywhere inside of a tank [6], potentially making it useful for gauging propellant mass and measuring slosh in microgravity (see Chapter 3).

In space, the influence of sloshing liquid propellants may hamper maneuvers, such as spacecraft docking, pointing of observational satellites, passive thermal control (PTC) maneuvers, or stability of in-space propellant depots. Slosh can increase boil-off of cryogenic propellant via droplets evaporating from contact with warm tank surfaces, increasing the pressure inside the tank and the chances of tank venting [1] [10]. Slosh during propellant transfer can affect the thermal state of the propellant and ullage, which may cause performance issues during tanking and de-tanking operations.

As an example of the potential impact of slosh on rocket performance, a prelaunch review of the CFD propellant-slosh predictions within the second stage of a Delta IV launch vehicle led to a launch stand-down until the issue could be resolved. A worst-case scenario predicted that the LH₂ would not remain constrained in the aft end of the tank and could be ingested into the tank vent relief system, resulting in a thrust imbalance and loss of vehicle control. The analysis team concluded that it was imperative to “determine proper methodology for future Delta IV second-stage propellant-slosh analysis” [11]. In another example, the NEAR satellite went into safe mode because of an unexpected reaction after
an orbital maneuver that was likely attributable to propellant slosh, which caused a one-year delay of the project [12]. Another example of a dramatic propellant-slosh problem occurred at the end of a yaw maneuver during the Apollo 11 first moon-landing mission, and additional thruster activity was needed for course corrections before the lunar lander finally landed at a different spot than originally planned [13].

Mechanical analogies of slosh are linear mechanical system of oscillating point masses and rigid bodies, e.g. pendula or spring-masses, that are used to model the fluid dynamics of slosh [1]. These mechanical slosh analogies are used in launch vehicle and spacecraft control systems to predict the fluid force and torque response from vehicle motion. CFD is vital for simulating and predicting slosh dynamics in microgravity because the assumptions (which CFD is not subject to) underpinning the analytical methods and mechanical analogies often used to model slosh in accelerated environments [14] begin to breakdown in low-gravity [8]. Surface tension terms are available for mechanical analogy equations of slosh in low-gravity [14], but the type of slosh that can be modeled with these equations is limited to low-amplitude (linear) surface oscillations on a known liquid configuration. Slosh with enough inertia in low-gravity will become unsettled (examples of this are shown in Chapter 5), thus violating the linear system and known, stable liquid configuration assumptions.

CFD has been used extensively to simulate and predict propellant slosh, despite not being properly validated for microgravity environments, and several rocket and spacecraft mishaps, a few of which were described earlier, have caused the validity of CFD-predicted slosh results to be questioned. Although CFD simulations can be used to predict the
dynamics of slosh, the uncertainty from discretization and the physics models coupled with
the chaotic nature of slosh necessitates extensive validation of these simulations with data
from tests in a physically relevant environment. For slosh simulations, CFD validation
consists of comparing test and simulation liquid distributions, forces, and/or moments.
Ground slosh data exists in the scientific literature and industry for a multitude of tank
shapes and fluids, and CFD programs have been validated using this data [15]. However,
microgravity slosh test data is lacking, and, as discussed in Section 2.2, most of what is
available is inadequate for CFD validation. Collecting microgravity slosh data and using it
to validate CFD is necessary.

1.3 Contributions and Objectives

Planned contributions include advancing ECT for tank microgravity liquid mass gauging
by testing a prototype in low-gravity for the first time, demonstrating an ECT system
accurate enough to be a useful microgravity liquid mass gauge, performing the first 3D
tomographic reconstruction of sloshing liquid from low-gravity ECT test data, determining
methodology for processing the ISS SPHERES-Slosh Experiment (SSE) data for CFD
validation, and increasing the confidence in, and accuracy of, low-gravity slosh CFD
simulations by validation with long-duration, low-gravity slosh data.

The research objectives are:

1. Demonstrate accurate low-gravity liquid mass gauging in a tank instrumented with
an ECT system on a parabolic aircraft flight.
2. Calculate 3D liquid distributions from the parabolic flight experiment ECT data and assess their quality with regard to usefulness for CFD validation.

3. Using the SSE, collect high-resolution video of long-duration, low-gravity, coupled-motion slosh with synchronized motion data and well-defined initial conditions.

4. Assess the quality of the SSE dataset with regard to its usefulness for CFD validation.

5. Attempt validation of low-G slosh CFD simulations using SSE data.

1.4 Approach

ECT is an imaging technology that is capable of reconstructing the 3D material, e.g. liquid propellant, density distribution inside of a tank in real time, regardless of where the material is located in the tank. If the objective is liquid mass gauging, the density distribution can be volumetrically integrated to obtain mass. Prior to the research described herein, ECT had not yet been tested in microgravity. An ECT-instrumented tank was successfully tested on the ground and on a parabolic flight aircraft. High-G and low-G liquid mass gauging accuracy is assessed. The accuracy of the ECT-measured 3D liquid distributions is also assessed.

The ISS SPHERES-Slosh Experiment Program studied the behavior of liquid motion within a tank under microgravity conditions. The SSE Program was a collaboration between teams at Kennedy Space Center (KSC), Florida Institute of Technology (FloridaTech), and Massachusetts Institute of Technology (MIT). The SSE successfully
collected an extensive library of high-resolution video of long-duration, low-G slosh with motion data and well-defined initial conditions. The combination of the aspects of the SSE dataset (long-duration, low-G, measured motion, well-defined initial conditions) had not been achieved in any prior slosh experiments, making it unique and valuable.

1.5 Thesis Overview

The thesis is structured as follows: Chapter 2 summarizes past literature used during this research, Chapter 3 details the ECT parabolic flight experiment and its results. Chapter 4 describes the design and development of the ISS SSE, which is necessary in order to understand the discussion in Chapter 5 about the operation and results of the SSE. Chapter 5 also presents CFD validation cases using the SSE dataset. Finally, Chapter 6 includes conclusions and future work.

Despite the ECT project occurring later chronologically, the SSE program is presented after the ECT project in this thesis because the CFD validation presented used the SSE dataset.
Chapter 2
Literature Review

2.1 Liquid Propellant Sensing

Currently operational liquid propellant tracking and mass gauging technologies have major drawbacks for space applications. Differential pressure transducers and point probes require the propellant to be settled, which requires settling burns, and offer only single-point location indication. Concentric cylinder capacitive liquid level gauges also require the propellant to be settled because capillary action in microgravity causes internal wicking and inaccurate liquid level measurements [16]. Integrating propellant consumption rates over time allows for the estimation of remaining propellant mass, but it suffers from error accumulation and results in large error when the remaining propellant is low [16]. Modal Propellant Gauging (MPG) works by using piezoelectric actuators to ping the tank wall and measuring the resulting vibration. MPG has a claimed resolution of 3-4% at fill fractions between 10 and 50% in low gravity, but the propellant must be in contact with the tank walls and settled in a calibrated configuration for MPG to be accurate [17]. MPG cannot measure the location of unsettled propellant in a tank. Radio Frequency Mass Gauging (RFMG) uses antennae inside of the tank to generate and measure radio frequency (RF) electromagnetic waves. RFMG can work with unsettled propellant and has a reported uncertainty of ±1% full scale in 1 G and ±6% full scale in low-G [18]. RFMG accuracy is dependent on how close the simulated fluid configurations are to the actual configuration, meaning it is dependent on the size of the database of pre-computed high-fidelity RF
simulations. The best fit simulated fluid configuration gives the propellant mass and location.

Historically, ECT has been used in various industries, such as the petrochemical industry, to measure two-phase flow in pipes [19]. NASA ran a feasibility study and partially developed a whole-tank capacitive gauging system for the Apollo program in the 1960’s [20], but computers powerful enough to do tomographic reconstruction did not exist at the time. In 2007, Ref. [21] demonstrated an ECT system with a new image reconstruction algorithm for 3D high contrast dielectric distributions. NASA did some preliminary research into ECT in 2013 [22], but the work was not completed, and no publications on the results of that work exist. Ref. [23] used an ECT-instrumented cylindrical tank with kerosene to demonstrate measuring liquid mass to within 1% of full tank mass, reconstructing the liquid distribution for imaging, and tracking of liquid center of mass (CM), which enabled estimation of slosh forces. Depending on the details of the ECT system and process, multi-kHz sample rates are achievable, allowing for real-time gauging measurements. Ref. [24] discusses fabrication of flexible electrodes for ECT and presents test data from subscale propellant tanks instrumented with these electrodes. Ref. [25] slosh-tested an ECT-instrumented carbon fiber tank with silicone oil and an engineered fluid. Some slosh tests induced wave breaking, and some tests were run with a bubbler (to modify density). The liquid fill level measurements for these tests were repeatable to within 0.1% of full tank volume, and accurate to within 1-2%, though the authors stated they believed most of that error to be systematic and correctable, and thus claimed 0.1% accuracy. Images of the 2D liquid distribution during sloshing were computed from the
ECT data and compared to video frames, showing good qualitative agreement. ECT systems have also been tested with cryogens. Ref. [25] mentions testing an ECT system with LN$_2$, though no details are provided. Ref. [26] shows successful test results from an ECT system in an LH$_2$ Dewar. The ECT system was used to measure LH$_2$ relative permittivity, and its fill level resolution was within 0.5 mm, though details of the electrode fabrication method were not published. A research group at KSC [27] has successfully tested ECT systems in LN$_2$ tanks, and the electrodes have survived many thermal cycles, though the details of this research have not been published yet. Prior to the experiment discussed in Chapter 3, no successful low-gravity tests of ECT had been conducted.

2.2 Slosh

The NASA SP-106 document [1] compiles and summarizes all of the major analytical and experimental slosh work through 1965. An update was released by F. Dodge, one of the major authors of SP-106, in 2000 that contains some more recent information, including a section on low-G slosh [14]. Ibrahim’s 2005 Liquid Sloshing Dynamics textbook [8] covers essentially everything in [1] and [14], plus more.

Little microgravity slosh data exists, primarily due to the costs associated with obtaining such data. Although testing in a drop tower is inexpensive relative to other microgravity laboratories, and microgravity slosh experiments have been conducted using them [28], the short duration (2-5 s) of these tests makes their use in CFD validation limited. Some longer duration microgravity slosh testing has been conducted using sounding rockets [29] [30], parabolic flight aircraft [31], orbital launch vehicles [10] [32], and spacecraft [33] [34].
The examples referenced here are not an exhaustive list, but all of these experiments either involve imprecise low-gravity environments, as is the case for sounding rockets and parabolic flight aircraft, or a lack of high-quality motion data, initial conditions, and/or imagery (from modern sensors), e.g. the 1960’s and 1970’s tests. If “long-duration” is defined as on the order of the duration of spacecraft maneuvers (scaled if the experiment tank is subscale), then only experiments performed in space can provide the long-duration, low-G slosh data that is necessary for CFD validation.

Prior conference presentations, Refs. [35 - 39], covered different portions of the SSE program, and Ref. [40] details the majority of the design process, but no comprehensive papers have been published to date. This thesis is the first comprehensive publication of the SSE program.
Chapter 3
Propellant Sensing with Electrical Capacitance Tomography

ECT is a sensing technology that works by measuring the capacitance between many pairs of electrodes mounted to the wall of a vessel. If the walls of the vessel are electrically conductive, these electrodes must be mounted to the inner surface of the wall. The electrodes should cover most of the wall surface area for the ECT system to be accurate throughout the volume of the vessel. Since capacitance is related to permittivity, which in turn is approximately related to the gas and liquid densities via the Claussius-Mossotti relation [41], it is possible, via tomographic techniques, to reconstruct the 3D density distribution of the material contained in the vessel, regardless of where the material is located in the vessel. Volumetric integration of the density distribution yields the mass of the material in the vessel. Figure 1 is a basic diagram of an ECT system.

Figure 1: Example ECT System
ECT technology needed to be demonstrated in microgravity to verify that it can work accurately for space-like fluid configurations. Although the definition of accuracy and accuracy targets vary in the literature, the liquid mass gauging accuracy goal for this study is defined to be lower than 1% total ECT system liquid mass error. I was the principal investigator (PI) for a NASA study that successfully tested an ECT-instrumented tank on a parabolic flight aircraft in May 2022. The basics of ECT measurement theory, practical considerations for implementing an ECT system for a real tank, details of the experiment setup, electrostatic simulations, data processing, uncertainty analysis, ground test results, and results from the microgravity parabolic flights will be presented. Herein, “ECT system” refers to all hardware and software, including ECT reconstruction algorithms, required to obtain a 3D liquid distribution and liquid mass measurement.

3.1 ECT Theory

ECT systems rapidly measure capacitance between all pairs of electrodes. These capacitances are used in one of many different methods for solving the “inverse problem” to obtain a permittivity distribution in the domain (tank). The distribution is often presented as an image, so this process is often referred to as “reconstruction” [6]. In this work, “reconstruction” refers to the permittivity (fluid) distribution calculated by an ECT algorithm. The “forward problem” uses a known permittivity distribution to solve the electrostatic partial differential equations for the capacitances, typically obtained via simulation (see Section 3.6).
If electrode $k$ is raised to a voltage $V_k$ with respect to electrode $j$, and all other electrodes are at the same voltage as electrode $j$, then the capacitance of the $j,k$ electrode pair, $C_{j,k}$, is calculated as the integral over the surface of electrode $j$ of the permittivity distribution ($\epsilon$) times the gradient of the electric potential ($\phi_k$):

$$C_{j,k} = \frac{Q_j}{V_k} = -\frac{1}{V_k} \iint_{A_j} \epsilon \nabla \phi_k \, dA$$  

(1)

If $n$ is the number of electrodes, there will be $N = \frac{n(n-1)}{2}$ unique $j,k$ electrode pairs. Note in Eq. 1 that the capacitance is proportional to the permittivity on the surface of the electrode, and the potential function depends on permittivity. Discretizing and linearizing yields:

$$\Delta C = S \cdot \Delta \epsilon$$  

(2)

The sensitivity matrix, $S$, maps changes in permittivity to changes in capacitance.

Typically, the capacitances and permittivity distribution are normalized to be between 0 and 1. Normalized capacitance is calculated as:

$$C^* = \frac{C_{j,k} - C_e}{C_f - C_e}$$  

(3)

where $C_e$ and $C_f$ are measured capacitances of the $j,k$ electrode pair when the tank is empty and full of liquid, respectively. If $S$ now maps between normalized capacitance and normalized permittivity, then the forward problem becomes:

$$C^* = S \cdot \epsilon^*$$  

(4)
$C^*$ is a $N \times 1$ vector, and if $\epsilon^*$ is a $M \times 1$ vector, then $S$ is a $N \times M$ matrix. $M$ is the number of mesh “cells”, or “voxels”, in the electrostatic simulation, so $M \gg N$. Most ECT methods calculate $S$ using empty tank simulations and assume $S$ is constant, i.e. not affected by permittivity distribution. Although this assumption is physically inaccurate and results in error, it facilitates a solution with low computational cost that does not require a priori knowledge of the permittivity distribution [42]. Each element of $S$ is calculated as follows:

$$S_{l,i} = \frac{\varepsilon_0 v_i \nabla \phi_j \cdot \nabla \phi_k}{V_j V_k}, \quad i = 1 \ldots N, \quad l = 1 \ldots M, \quad (5)$$

where $v_i$ is the volume of the $i$th cell. If Eq. 4 is the forward problem, then it follows that the inverse problem is:

$$\epsilon^* = S^{-1} \cdot C^* \quad (6)$$

Unfortunately, the inverse problem is under-determined and ill-posed [6], meaning $S^{-1}$ does not exist. There are many methods for solving ill-posed problems like the ECT inverse problem, and Ref. [6] presents six of the simplest ones, of which Linear Back Projection (LBP) is used to produce the results shown in Section 3.8. LBP assumes that the inverse of the sensitivity matrix is its transpose, $S^{-1} = S^T$:

$$\epsilon^* = S^T \cdot C^* \quad (7)$$

$S^T$ can be thought of as a linear mapping from the capacitance vector space to the permittivity vector space. Despite this assumption not having a strict mathematical basis, LBP can provide useful results, and LBP is fast enough to be run in real-time. However, LBP permittivity distributions tend to be smeared and cannot capture sharp phase
interfaces without thresholding. For the case of two immiscible phases, such as a tank partially filled with an incompressible liquid, the normalized permittivities can be assumed to be volume fractions in each cell (or voxel), which are integrated to obtain a total liquid volume. The total liquid volume is then multiplied by a single liquid density to get liquid mass. In addition to volume and mass, center of mass can be calculated from reconstruction results.

Linearization (Eq. 2), the linear assumption between fill level and capacitance inherent in the capacitance normalization (Eq. 3), assuming $S$ is constant and not dependent on permittivity distribution (Eq. 5), and the linear mapping of LBP (Eq. 7), all introduce errors that manifest as nonlinearities in the gauging results. Section 3.7.2 discusses partial corrections, but these nonlinearities are not always correctable.

Landweber (LW) is a variation of the steepest gradient descent method that attempts to minimize the capacitance residuals via iteration. A variation of this method, “projected Landweber”, constrains the normalized permittivity solution to be between 0 and 1 by making all values greater than 1 be 1 and all values less than 0 be 0. Eq. 8 is the projected LW iterative algorithm.

$$
\epsilon^*_k + 1 = P[\epsilon^*_k - \beta S^T(S \epsilon^*_k - C^*)],
$$

$$
P[f(x)] = \begin{cases} 
0 & \text{if } f(x) < 0 \\
\text{f(x)} & \text{if } 0 \leq f(x) \leq 1 \\
1 & \text{if } f(x) > 1
\end{cases} \quad (8)
$$

where $\beta$ is a positive scalar that sets the $k$th step size. The derivation of Eq. 8 is available in Ref. [6]. The initial condition for $\epsilon^*$, the number of iterations, and $\beta$ must be decided, and
they influence how fast LW converges and the final result. LW reconstructions tend to have a sharper interface between fluid phases than LBP. Similar to LBP, LW is simple enough to be run in real-time, though it is slower than LBP, and speed is heavily dependent on the number of mesh cells, or voxels, in the discretized finite element method (FEM) or finite volume method (FVM) solution. Due to the large amount of data collected in this study, LW was computationally impractical to run for all time steps, so it was only run on select time steps. Results from reconstruction with LW are presented in Section 3.9.

One method for obtaining a liquid volume fraction (VF) is averaging the absolute value of the normalized capacitances [43], called the “mean C method” in this work. Despite it not being a tomography technique, the mean C method is simpler and faster than LBP. The mean value, which ideally ranges from 0 to 1, is multiplied by the tank volume to get liquid volume, and then by liquid density to obtain measured mass. In reality, the measurements have nonlinearities, and the normalized capacitances can be outside of the range from 0 to 1.

3.2 Practical Considerations

3.2.1 Propellant Compatibility

As mentioned in Chapter 2, ECT systems have been tested with cryogens. A simulant liquid with a low permittivity, near that of cryogens (see Section 3.3.2), was chosen for this study. Since low permittivity liquids are non-conductive and the electrodes are discharged in the ECT electronics, the power dissipation inside the propellant tank is miniscule, on the order of picowatts/liter [27]. The use of liquids with high permittivities, i.e. partially
conductive liquids like water or some storable propellants, in ECT systems poses a few challenges [21]. To prevent significant current flow through the conductive liquid in the tank, the electrodes must be electrically isolated from the liquid (and the tank wall) by a low permittivity material. The use of a high permittivity liquid increases electric field nonuniformity and worsens the empty tank assumption for sensitivity matrix calculation. Ref. [42] presents a more physically accurate sensitivity matrix to address this, but since that matrix relies on knowledge of the permittivity distribution, solving the inverse problem becomes coupled and computationally intensive. Displacement Current Phase Tomography is a method related to ECT that uses alternating current (AC) excitation and is more accurate for high permittivity liquids [44].

3.2.2 Mass and Tank Size

Discussion of the mass of a potential flight-like ECT system is warranted since this experiment was small scale. Certain components of the ECT system, e.g. the electronics package, would essentially have the same mass regardless of rocket or spacecraft size. Because the electrodes need to cover most of the wall, electrode mass, as well as any tank or propellant electrical insulating material (should it be needed), would scale with the wall surface area. Because the system only measures capacitances, the electrodes conduct negligible current, suggesting the electrodes could have a thickness on the order of microns. Potential fabrication methods include electroplating or a vapor deposition process. Thin electrodes mitigate thermal stress cracking/debonding concerns associated with coefficient of thermal expansion (CTE) mismatch between the electrodes, insulation
material, and tank wall. Electrode wiring mass scales linearly with number of electrodes and tank radius.

Consider a hypothetical 16-electrode ECT system applied to a 3 m diameter spherical tank. Electronics (with enclosure) mass might be 3 kg. 10µm thick pure aluminum electrodes, a 0.2 mm thick layer of polyimide insulation, and associated wiring would yield a total system mass of about 14 kg. A 3 mm thick wall aluminum-lithium alloy spherical tank would be approximately 230 kg (without any additional structure), making this ECT system about 6% of the tank dry mass. Compared to a tank with propellant, the ECT system represents 0.1% of the tank mass including a 90% fill of LO₂, or 1.2% mass for the same fill level of LH₂. Ignoring other potential benefits, the mass of an ECT system could be substantially lower than the resulting reduction in propellant margin mass. A localized ECT system, perhaps installed only near a sump or vent, could save further mass by forgoing measurement of the entire tank.

Volumetric resolution worsens as radius is increases. Interestingly, the signal-to-noise ratio (SNR) improves as radius increases since electrode area scales with the square of radius, while the distance between opposing electrodes scales with the radius. The SNR improvement can be traded for volumetric resolution by increasing the number of electrodes. The limiting noise source is typically in the ECT electronics, which limits minimum electrode size, ultimately limiting the maximum number of electrodes and volumetric resolution.
3.2.3 Internal Tank Features

Many tanks, including the test tank in this study, have internal features. If the features are non-conductive, they will likely not significantly affect the ECT system’s accuracy [25]. If the features are conducting to the rest of the tank, they can reduce the accuracy of the ECT system in their vicinity because they will shield parts of the tank and propellant. In addition, conductive surfaces will “intercept” electric field lines, reducing the field strength in regions that are not shielded. Larger conducting features, e.g. a metallic propellant management device (PMD) or baffle, will probably shield more fluid. However, if the conductive features are used as electrodes or have electrodes applied to them, the additional electrodes might increase the accuracy of the ECT system by increasing volumetric resolution.

3.3 Experiment Design

3.3.1 Requirements

As previously stated, the objectives of the study were: 1. demonstration of accurate low-G liquid mass gauging in a tank instrumented with an ECT system on a parabolic aircraft flight, and, 2. assess the usefulness of the ECT-measured liquid distributions for validation of low-G slosh CFD simulations. High-level requirements were derived from these objectives. Example high-level requirements included:
• The experiment apparatus shall have an ECT-instrumented tank with all hardware and software necessary for measuring and recording data that can be used to calculate 3D liquid distributions and liquid mass.

• Post-processing scripts shall be written that read the ECT test data, implement ECT methods, and calculate mass gauging uncertainty.

• To monitor functionality, the apparatus shall have hardware that displays the ECT data in real-time.

• The fill level in the tank must be adjustable, so the tank shall have hardware that allows for filling and draining of the test liquid.

• To simplify logistics and ground operations, the apparatus shall be small enough to be manipulated and carried by hand.

• The apparatus shall conform to all requirements imposed by the parabolic flight provider.

NASA FOP and the parabolic flight provider imposed many experiment requirements, including, but not limited to, structural, electrical, pressure vessel, and hazards analysis [45] [46]. These, along with the high-level requirements, drove the experiment design and concept of operations.

3.3.2 Fluid Selection

Testing the ECT system with a cryogen would have been ideal considering liquid propellants are often cryogens. Although cryogens can be flown on research parabolic flights, cost constraints precluded their use in this experiment. Thus, selecting a simulant
liquid with relative permittivity as close to cryogenic propellants ($\varepsilon_R \approx 1.2 - 1.6$) as possible was important. All non-toxic and non-flammable 3M™ Novec™ and FC engineered fluids, as well as mineral oil and distilled water, were surveyed to compile a list of candidate simulants. Water was included despite having a high relative permittivity because it is widely used as a simulant.

Fluid dynamic similarity between the spherical subscale test tank (0.175 m diameter) with the simulant fluid candidates and a “real” tank (3 m diameter) with cryogenic propellants was important for obtaining realistic unsettled fluid configurations during the flights. A scaling study was conducted to examine the Reynolds ($Re$), Weber ($We$), and Bond ($Bo$) of the test and real tanks. These nondimensional numbers provide insight into the fluid dynamic “regime”, i.e. whether inertia, body acceleration, viscous, or surface tension forces dominate the fluid dynamics. The goal of this analysis was to select a simulant to use in the test tank that achieves the best fluid dynamic similarity to real propellants in the real tank. Eqs. 9-12 define the Reynolds, Weber, Bond, and Froude ($Fr$) nondimensional numbers, respectively.

\[
Re = \frac{\text{inertia}}{\text{viscous}} = \frac{\rho UL}{\mu} \quad (9)
\]

\[
We = \frac{\text{inertia}}{\text{surface tension}} = \frac{\rho UL^2}{\sigma} \quad (10)
\]

\[
Bo = \frac{\text{body acceleration}}{\text{surface tension}} = \frac{\rho aL^2}{\sigma} \quad (11)
\]

\[
Fr = \frac{\text{inertia}}{\text{body acceleration}} = \sqrt{\frac{We}{Bo}} = \frac{U}{\sqrt{aL}} \quad (12)
\]
\[ \frac{\rho}{\mu} \frac{U}{L} = \frac{\sigma}{a} \]

, where \( \rho \) is density, \( \mu \) is dynamic viscosity, \( U \) is characteristic velocity, \( L \) is characteristic length, \( \sigma \) is surface tension, and \( a \) is body acceleration, e.g. gravity. The maximum slosh wave velocity at the fluid surface is used as the characteristic velocity, and tank diameter is used as the characteristic length. If these nondimensional numbers are similar between the subscale test and real tanks, then the scale test data will be similar to what would be obtained by testing the real tank. Figure 2 depicts three different fluid dynamic regimes based on \( We \) and \( Bo \). The diagonal line is \( Fr=1 \). For both \( We \ll 1 \) and \( Bo \ll 1 \), the liquid in the tank is dominated by surface tension, or “capillary”, forces. Inertia forces dominate for \( We \gg 1 \), and body forces dominate for \( Bo \gg 1 \). Past experience with tank slosh testing suggests \( Bo \gtrsim 100 \) is necessary to avoid the majority of surface tension effects.

Accordingly, for this work, the definition of “low-G” (low-gravity) is \( Bo \lesssim 100 \), and the definition of “microgravity” is \( Bo < 1 \). The parabolic flight experiment in this study will experience both high and low acceleration environments, so it will cover most of Figure 2.
Although seemingly straightforward, scaling analysis is complicated by the fact that these nondimensional numbers are unsteady due to the dynamic nature of slosh, and it is usually impossible to match every nondimensional number of interest. Several assumptions are made to perform scaling analysis for this study: the tanks are spherical with no internal features, filled to 50% volume fraction, planar slosh wave amplitude is \(1/10\)th of the tank diameter, the cryogens in the real tank are at their normal boiling points (NBPs), and the simulant liquids are at standard temperature and pressure (STP).
The first asymmetric slosh mode frequency of a spherical tank does not have a simple analytical solution. Ref. [47] tabulates the slosh frequency parameter for various wave numbers and modes versus fill level. For 50% fill fraction and first mode:

$$\lambda = \frac{\omega^2 R}{a} = 1.56, \text{ for } \frac{h}{2R} = 0.5,$$

where $\lambda$ is the nondimensional frequency parameter, $R$ is tank radius, and $\omega$ is frequency in rad/s, and $h$ is fill height. Eq. 13 assumes no surface tension forces, the inclusion of which makes Eq. 13 dependent on contact angle. Fig. 4.20 of Ref. [14] plots the first and second asymmetric slosh modes’ frequency parameter in a spherical tank assuming a 0 deg contact angle (perfectly wetting). For cryogens, 0 deg contact angle is a generally a good assumption, but it is a poor assumption for water. That plot was tabularized (taking into account radius versus diameter), the above $\lambda = 1.56$ asymptote from Eq. 13 added in, and Figure 3 was created.
The frequency parameter asymptotes to 1.56 at high Bond number ($\lambda \approx 1.56, Bo \gtrsim 100$), as expected. Frequency can be used to estimate the maximum slosh wave velocity at the fluid surface.

$$U = U_{\text{max}} = \Omega_1 z,$$

where $z$ is the wave amplitude (assumed to be 1/10*D).

The nondimensional numbers were calculated over a scale test acceleration range of 0.0001-20 m/s$^2$. 20 m/s$^2$ is chosen as the high end of the acceleration range because that is approximately the maximum acceleration achieved during pull-out of the parabolas. The acceleration experienced by some launch vehicle upper stages during attitude control maneuvers is on the order of 0.0001 m/s$^2$, so this is used as a lower limit for the real tank.
Figure 4 plots $We$ versus $Bo$ for the scale tank with a few select simulants over accelerations $0.0001$-$20\ m/s^2$ and the real tank with the three cryogens over accelerations $0.0001$-$1\ m/s^2$. Only the endpoints of the curves are marked: ‘o’ for simulants and ‘+’ for cryogens.

![Figure 4: We vs. Bo](image)

All of the simulants achieve $Bo < 1$ at the low end of the acceleration range, so surface tension effects should be observable during the low-G portions of the parabolas. For high $Bo$, $Fr \approx 0.177$, but $Fr$ drops at low $Bo$ due to surface tension modifying the first mode frequency. Different values of $Fr$ will result from different choices of wave amplitude. Water has the lowest $Bo$ and $We$ of the simulants considered, resulting in the least overlap with the cryogens. That, in addition to its relative permittivity being the highest of the
simulants, makes water a poor choice for this study. 3M FC-72 [48] achieves the highest $Bo$ and $We$ of the simulants, resulting in the most overlap with the cryogens. A way to interpret these results is the scale test tank with FC-72 on the parabolic flight will be fluid dynamically similar to the real tank with cryogens in an acceleration environment of near 0 m/s$^2$ to about 0.15 m/s$^2$.

Reynolds number is an indicator of laminar versus turbulent boundary layers during sloshing, which affects viscous wall damping and dissipation in tanks. Ideally, $Re$ of the subscale tank should be as close to that of the real tank, but that is rarely possible due to the relatively low viscosity of cryogens. For this analysis, $Re$ in the real tank is 70-180 times larger than in the test tank with FC-72, so viscous damping is not expected to be similar. This is considered acceptable for this study because slosh damping similarity and characterization is not an objective. That said, FC-72 is better than many of the other simulants surveyed in this respect. For example, mineral oil $Re$ is about 300 times lower than FC-72 $Re$.

FC-72 was determined to have the best fluid dynamic similarity, as well as the lowest relative permittivity, of the candidate fluids, so it was selected as the test fluid. During the flights, $Bo$ ranged from near 0 to approximately 100,000 and $We$ from near 0 to approximately 3,000. Dielectric spectroscopy performed at the Applied Physics Laboratory (APL) at KSC confirmed FC-72’s relative permittivity to be within the measurement uncertainty of the datasheet value of 1.7 and showed it had a low dependence on temperature.
FC-72 has a high vapor pressure, so ground handling equipment was designed to prevent as much evaporation as possible within cost constraints. The temperature-dependent liquid properties required accurate tank temperature measurement with time, which the experimental apparatus achieves. The gas volume in the tank consisted of a mixture of FC-72 vapor and air and was assumed to be an ideal gas for state calculations. Modeling the ullage gas as an ideal gas was acceptable due to the relatively small effect of phase change in the sealed tank, so the uncertainty introduced by this assumption was negligible.

3.3.3 Apparatus Design and Details

ECT hardware was not developed as part of this study due to cost and time constraints. Instead, a “plug-and-play” experiment apparatus was rented for the duration of the study. The apparatus is shown in Figure 5. The aluminum base plate and frame, ruggedized laptop for displaying the ECT system’s graphical user interface (GUI), Inertial Measurement Unit (IMU, left of laptop), and secondary containment box (top center) are visible. Data was stored on an external USB solid state drive (SSD). The test tank, ECT electronics, and fill/drain hardware were contained inside the sealed secondary containment box bolted to the base plate behind the laptop. NASA provided the power distribution, IMU, external SSD, and ground support equipment (GSE) hardware; all other hardware came with the rented apparatus. This apparatus met or exceeded all design requirements.

---

1 Company not disclosed as stipulated in the rental contract
The 6-axis Analog Devices 16460 [49] IMU, connected to a RaspberryPi 4B, was used for recording motion during testing. This was placed in a case fastened to the apparatus’ base plate. Custom software handled IMU data collection and storage, and it was time-synchronized with the ECT laptop clock. IMU +Y was aligned with the long side of the apparatus base plate, IMU +X pointed out away from the tank, and IMU +Z was normal to the apparatus base plate pointing “up”. The tank +X axis was aligned with the IMU +Y.
axis, and the tank was rotated -115° about its +X axis resulting in the tank +Y and +Z axes having components in the IMU -Z direction. Figure 5 shows these coordinate systems. The “horizontal” orientation is shown in Figure 5, where “up” is perpendicular to the baseplate in IMU +Z. Relative to the horizontal orientation, the “vertical” orientation is rotated 90 deg about the IMU +X axis such that the laptop end is pointing up. Ground tests were performed in both orientations. Rotation rates were small for the ground tests, so there was no need for kinematic transformations of the measured accelerations to account for the difference between the IMU and tank origins. Flight tests were only performed in the horizontal orientation, with the +Y IMU axis pointing in the aircraft forward direction. The experiment was considered a rigid body and the aircraft motion was large relative the test apparatus, so there was no need for kinematic transformations from the IMU origin to the tank origin.

The test tank was made of aluminum and approximately spherical with an internal diameter of 0.175 m. It is “approximately” spherical due to the presence of internal features, such as electrodes. The tank had eight spherical-octant-shaped, approximately 1 mm thick, electrodes adhered to the inside wall of the tank. Each hemisphere of the tank had four electrodes covering most of the inside wall surface. The electrodes were insulated from the tank wall and fluid by a solid polymer-composite insulator with a relative permittivity of about 3.5. The gaps between the four electrodes in each half of the tank were 6 ± 1 mm, and the gap between electrodes across the tank split plane was 15 ± 1 mm. The gap uncertainties come from electrode installation placement error and, while their uncertainty was estimated, the actual locations of the electrodes could not be measured due to the
rental contract prohibiting the tank from being opened. There was additional geometry inside the tank that was confirmed to exist but not disclosed due to intellectual property concerns and therefore not accounted for in this study. Simulation validation (Section 3.6) suggests the current physical model of the tank is adequate despite the unaccounted-for geometry. The gaps between the electrodes were filled with a solid polymer with a relative permittivity of about 3.5 to prevent liquid from flowing between the electrodes. The gap filler was slightly recessed into the gaps, and none is present within 1.5 mm of the tank split plane or around the fill/drain valve ports. The split plane contained eight aluminum tabs that projected radially 7 mm into the tank; these were extraneous features leftover from a previous iteration of the tank. The tank remained sealed during testing and was equipped with low-volume fill/drain valves to minimize liquid transfer error. This test tank was a prototype; Section 3.10 discusses some of its mechanical flaws, error sources, and corresponding suggested mechanical improvements. Simplified internal tank geometry, assuming zero electrode placement error, was created in computer aided design (CAD) software for usage in simulation and internal volume estimation. Figure 6 shows this model’s fluid occupied volume. The octant indentations represent the electrodes, and the embossed strips are the gaps between the electrodes. The tank X-axis is normal to the split plane, which cuts through the center of the widest gap.
A Maxim DS18B20 digital temperature sensor was fastened to the outside wall of the tank. The internal fluid temperature was assumed to be the tank wall temperature since the tank was operated in temperature-controlled environments (a laboratory or aircraft), sealed in a secondary containment box, and had a large thermal mass and thermal conductivity. Temperatures varied from approximately 23-29 °C over all collected data.

The ECT electronics consisted of a power supply, on-board processor, and capacitance measurement circuitry, with ethernet connectivity for sending data to the laptop. The ECT
electronics were mounted to an aluminum plate adjacent to the test tank inside the secondary containment box.

A camera was not part of the experiment and would have only been marginally useful since the tank was opaque, which would have restricted the view to a small (currently nonexistent) port. A fisheye lens would have been required to observe most of the inside of the tank from the port. From past experience using fisheye lenses in slosh tanks [15], correcting the image warping from a fisheye lens is difficult. Furthermore, the simulant liquid was transparent with no tint, which would have made visual determination of liquid location difficult and subsequent comparisons to ECT reconstruction results poor.

The following data were collected for every ground and flight test: raw capacitances between all electrode pairs (100Hz), tank wall and ECT electronics temperatures (100Hz), 3-axis accelerations and 3-axis rotation rates from the IMU (variable data rate, ≈400Hz), and the actual (scale-measured) mass of liquid in the tank.

3.4 Ground Testing

Tests were performed on the ground prior to the flight campaign to practice/refine test procedures and to generate data for mass gauging calculations. Capacitances were measured with the tank empty and full and used to normalize measured capacitances (Eq. 3). Temperatures varied from approximately 23-29 °C over all collected data. The various temperatures during the empty and full tests allowed for derivation of temperature corrections of capacitance. Capacitance measurements were taken at 10 fill levels between
0 and 100%, in the horizontal and vertical orientations, in order to derive settled corrections for those orientations (see Section 3.7.2).

Impulse free-decay slosh testing was performed on the ground. The apparatus, with the IMU on board, was placed on a rolling cart. The cart was manually pushed along one axis, quickly stopped, and the slosh was allowed to decay. Actuation was repeated once in the horizontal and vertical orientations, for each of 10 fill levels, or notional volume fractions (NVF). “Notional” indicates these target volume fractions were not precisely hit during filling. The actual liquid mass, and therefore actual volume fraction, in the tank for each test is known accurately due to filled liquid mass being measured with a precision scale.

### 3.5 Parabolic Flight Testing

The experiment flew on four parabolic flights over three days. Fill level was varied between flights: 5%, 20%, 50%, and 80% NVFs were tested, in that order. The actual volume fractions were within 2% of the NVFs. Each flight typically consisted of 30 parabolas: two Martian gravity, three Lunar gravity, and 25 low-G parabolas. Parabolas are flown five in a row, with the aircraft doubling back on its flight path between each row. With four flights, this totals 100 low-G parabolas over the experiment campaign.

Generally, there were a few minutes of 1 G flight between the parabola sets, and about 50 s of hyper-G (≈1.8 G) and 18 s at < 1 G for each parabola. Data was recorded from before takeoff until parking at the hangar after landing. The low-G portions of the parabolas were somewhat unsteady, oscillating around 0 G, which is why they are referred to as “low-G” in this thesis. Hyper-G and level flight were steadier. Every parabola was unique, and
different pilots resulted in slightly different motion characteristics. The unsteadiness of the low-G portions was actually a benefit for this experiment because it drove significant, somewhat random, liquid motion and resulting distributions inside the tank, allowing for the characterization of the low-G mass gauging error for this particular ECT system. The Bond number range of the low-G portions is similar to that of some space vehicle reaction/attitude control maneuvers, and the high-G portions are analogous to propulsive burns, albeit without the corresponding propellant tank draining.

3.6 Electrostatic Simulation

Electrostatic simulations of the empty tank were necessary for deriving the sensitivity matrix (see Section 3.1), which was necessary for ECT reconstruction. These simulations only had to be done once. Commercial software with an electrostatic solver, STAR-CCM+ [50], was used for all simulations. A mesh independence study was conducted to find an adequate mesh resolution. Since the test tank had three-plane symmetry, this symmetry was enforced on the mesh, i.e. the mesh of each of the eight spherical octants associated with each of the eight electrodes was identical, which facilitated consistent numerical error. The polyhedral mesh had approximately 800,000 cells in the fluid region and 4,900,000 cells in the solid polymer dielectric region. Figure 7 shows two cross-sections of the final mesh.
A nominal empty or full simulation used the following boundary conditions: the electric potential of the tank wall and seven electrodes were held at 0 V and the eighth electrode was held at a non-zero potential. The simulated electric field was imported into MATLAB [51] and transformed to yield the electric field from the perspective of the other seven electrodes being individually raised to a potential. A similar transformation process was used for the simulated electrode pair capacitances, yielding an 8x8 capacitance matrix. The capacitance matrix is symmetric, and the diagonal of the matrix are self-capacitances, which are not used in the present solution. This left 28 unique capacitances. Total simulation time was less than one minute. Figure 8 shows contour plots of electric potential and electric field magnitude on a cross-section through the charged electrode. The high electric field in the gaps between the charged and adjacent electrodes is clear in Figure 8b.
Additional electrostatic simulations were performed to generate “simulated data” for testing ECT algorithms. This followed a similar process to the empty tank simulations, except a specific permittivity (test liquid) distribution was applied to the tank volume. Since this distribution was not always symmetric, a simulation with each electrode individually raised to a potential had to be run. The normalized simulated capacitances were used to develop and test the ECT algorithms because, unlike the test data, the true (simulation input) liquid distribution was known, which allowed for error calculation, and the simulated data did not contain electrical noise.

Simulated and test capacitances were compared for the empty and full cases in order to validate the electrostatic simulation. Additionally, reconstruction comparisons were made between simulated data and test data for settled (known liquid distribution) cases. The normalized simulated and test capacitances were similar enough to result in qualitatively similar reconstructed 3D distributions when processed with the same ECT reconstruction.
algorithm. The validated simulation methodology implies that any remaining error in ECT (test) mass gauging and reconstruction, after accounting for known uncertainties, comes from the ECT algorithm, tank design/fabrication flaws, and other ECT system error sources.

3.7 Data Processing

3.7.1 Measurement Data Processing

ECT system measured capacitances, tank temperature, IMU, and scale measurements were read into MATLAB for post-processing. The raw capacitance data were filtered with a high-order, 10 Hz-cutoff, low-pass filter to reduce electrical noise. 10 Hz is more than twice the highest third-mode slosh frequency of the tank, meaning that liquid motion signal content was retained. Capacitances of like-pairs of electrodes were averaged, then normalized, leaving 28 unique capacitances vs. time. Temperature and IMU data were also low-pass filtered. Initial fluid state in the tank for each test was determined by the temperature and liquid mass immediately after a filling procedure was completed. The initial fluid state and the transient temperature were used to account for evaporation and condensation; the time-varying, temperature-corrected, actual liquid mass and volume were calculated and stored. Liquid mass losses during filling were considered. Empty and full tank capacitances measured over time and in multiple tests were used to derive the linear dependence of capacitance on temperature. Notably, temperature corrections were relatively small, 0-0.6 %/°C.
Table 1 is a matrix of time-averaged measurements of the empty tank capacitances. Each row index and each column index represent an electrode number (see Eq. 1), so each element is the capacitance for that electrode pair. The diagonal elements are self-capacitances, which are not useful, so they are shown as zero. This tank geometry (nominally) has five unique electrode pair configurations, listed in order of increasing capacitance magnitude: 1. Opposing (across tank), 2. Diagonal across the split plane between tank hemispheres, 3. Diagonal within a hemisphere, 4. Adjacent across the split plane between tank hemispheres, and 5. Adjacent within a hemisphere. With an ideal geometry and no noise, like the simulations, all of the capacitances of a given electrode configuration will be identical, and the empty (and full) tank capacitance matrix is symmetric. An asymmetric capacitance matrix can be caused by noise, tank geometry asymmetries, and fluid distribution asymmetries. Low-pass filtering for electrical noise and time-averaging made the random noise negligible for the capacitances presented in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>5.71E-13</th>
<th>7.36E-14</th>
<th>5.24E-13</th>
<th>2.01E-13</th>
<th>5.20E-14</th>
<th>2.37E-14</th>
<th>5.97E-14</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.72E-13</td>
<td>0</td>
<td>5.27E-13</td>
<td>7.37E-14</td>
<td>5.97E-14</td>
<td>1.94E-13</td>
<td>5.74E-14</td>
<td>2.33E-14</td>
<td></td>
</tr>
<tr>
<td>7.40E-14</td>
<td>5.33E-13</td>
<td>0</td>
<td>5.49E-13</td>
<td>2.28E-14</td>
<td>5.60E-14</td>
<td>1.91E-13</td>
<td>5.23E-14</td>
<td></td>
</tr>
<tr>
<td>5.25E-13</td>
<td>7.55E-14</td>
<td>5.51E-13</td>
<td>0</td>
<td>5.24E-14</td>
<td>2.14E-14</td>
<td>5.55E-14</td>
<td>1.72E-13</td>
<td></td>
</tr>
<tr>
<td>2.01E-13</td>
<td>6.13E-14</td>
<td>2.3E-14</td>
<td>5.18E-14</td>
<td>0</td>
<td>5.36E-13</td>
<td>7.23E-14</td>
<td>5.46E-13</td>
<td></td>
</tr>
<tr>
<td>5.16E-14</td>
<td>1.95E-13</td>
<td>5.69E-14</td>
<td>2.25E-14</td>
<td>5.40E-13</td>
<td>0</td>
<td>5.64E-13</td>
<td>7.42E-14</td>
<td></td>
</tr>
<tr>
<td>2.33E-14</td>
<td>5.77E-14</td>
<td>1.90E-13</td>
<td>5.70E-14</td>
<td>7.31E-14</td>
<td>5.67E-13</td>
<td>0</td>
<td>5.29E-13</td>
<td></td>
</tr>
<tr>
<td>5.97E-14</td>
<td>2.4E-14</td>
<td>5.28E-14</td>
<td>1.74E-13</td>
<td>5.53E-13</td>
<td>7.68E-14</td>
<td>5.38E-13</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
The matrix of test measured empty tank capacitances in Table 1 is not symmetric, which supports the assertion that tank geometry asymmetries exist. The mean of the all elements of the same electrode configuration approximates the nominal, zero-error, capacitance for that electrode configuration. Each element of the matrix in Table 2 is the percent difference between the corresponding element of the matrix in Table 1 and the mean of the all elements of with its electrode configuration.

**Table 2: Empty Tank Capacitance Matrix Electrode Configuration Variation, %**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>4.7</th>
<th>-0.8</th>
<th>-3.8</th>
<th>6</th>
<th>-6.9</th>
<th>3</th>
<th>6.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8</td>
<td>0</td>
<td>-3.3</td>
<td>-0.6</td>
<td>6.9</td>
<td>2.2</td>
<td>2.8</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>-0.2</td>
<td>-2.2</td>
<td>0</td>
<td>0.7</td>
<td>-0.7</td>
<td>0.2</td>
<td>0.5</td>
<td>-6.4</td>
<td></td>
</tr>
<tr>
<td>-3.7</td>
<td>1.8</td>
<td>1.1</td>
<td>0</td>
<td>-6.1</td>
<td>-6.8</td>
<td>-0.7</td>
<td>-9.4</td>
<td></td>
</tr>
<tr>
<td>5.8</td>
<td>9.7</td>
<td>-0.1</td>
<td>-7.2</td>
<td>0</td>
<td>-1.8</td>
<td>-2.5</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>-7.6</td>
<td>2.9</td>
<td>1.8</td>
<td>-2.2</td>
<td>-1</td>
<td>0</td>
<td>3.4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>3.3</td>
<td>0.3</td>
<td>2</td>
<td>-1.4</td>
<td>3.9</td>
<td>0</td>
<td>-3</td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>4.3</td>
<td>-5.5</td>
<td>-8.3</td>
<td>1.4</td>
<td>3.5</td>
<td>-1.4</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

There is significant variation in capacitance for a given electrode configuration, up to 9.7% for configuration 2, and 9.4% for configuration 4. This is likely a consequence of the electrode placement error mentioned in Section 3.3.3.

### 3.7.2 Settled Corrections

When the liquid was settled, the relationship between actual and measured mass (or volume) was not linear due to various ECT system errors. During ground testing (Section
3.4), capacitance measurements were taken at 10 fill levels between 0 and 100%, in the horizontal and vertical orientations in order to derive settled corrections for volume gauging in those orientations. These corrections allow for the removal of some of the nonlinearity in the gauging measurements. A settled correction was applied when the IMU acceleration vector and CM angles (with respect to the orientation’s “up” axis) were within specific, small angle limits, i.e. when the liquid was mostly settled in the orientation for which the correction was derived. For the parabolic flights, this resulted in the settled corrections being tapered in or out during the transitions between low-G and high-G.

Most real launch vehicles and spacecraft have only one primary acceleration axis, so a fill and drain test need only be performed with the tank in that orientation to obtain data for deriving settled corrections. They are referred to as “corrections” in this study because they were applied after the data was collected. However, in a real application, they would be derived beforehand and programmed into the real-time processor of the ECT system, making them more of a settled “calibration” than a correction.

All fully settled portions of ground and flight-day (but not in-flight) data were identified. The 28 capacitances were time-averaged for each portion. The normalized capacitances were averaged in the mean C method (see Section 3.1) to calculate a volume fraction, which was multiplied by tank volume to obtain a measured liquid volume point. This was done for every portion, yielding multiple measured volume points. This was repeated with LBP. Two types of settled corrections were derived.
The first type, called “capacitance corrections”, fit 28 splines to the 28 measured capacitances across measured fill levels. An additional 28 splines were fit for the same capacitances across actual fill levels. Subtracting these yields 28 splines that provide the normalized capacitance errors given the measured volume (one for each electrode pair). These were computed for each orientation and each method (mean C and LBP). The capacitance error splines are evaluated at a measured volume, and the resulting capacitance errors are subtracted from the measured capacitances to correct them. The measured volume is then recomputed using the corrected capacitances.

The second type of correction, called a “volume correction”, was derived by fitting a spline to the actual vs. measured volume points, and the fit was evaluated at measured volumes to obtain corrected measured volumes. This correction does not affect (or correct) any capacitance measurements. The volume correction process is the same for both the mean C and LBP methods, but their spline fits are different.

Table 3 lists the minimum and maximum errors of all of the settled measured volume points (see above) for the mean C method and LBP for both horizontal (H) and vertical (V) orientations. Liquid volume error is defined as $e = \frac{v_m - v_a}{v_a}$, where $v_m$ is the ECT measured liquid volume and $v_a$ is the actual liquid volume in the tank at that fill level. “Capacitance” indicates capacitance corrections and “Volume” indicates volume corrections.
Table 3: Settled Correction Methods Error Comparison

<table>
<thead>
<tr>
<th>Correction Method</th>
<th>H Min Error, %</th>
<th>H Max Error, %</th>
<th>V Min Error, %</th>
<th>V Max Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean C, Uncorrected</td>
<td>-7.8</td>
<td>6.9</td>
<td>-13</td>
<td>68</td>
</tr>
<tr>
<td>mean C, Capacitance</td>
<td>-12</td>
<td>1.2</td>
<td>-11</td>
<td>7.0</td>
</tr>
<tr>
<td>mean C, Volume</td>
<td>-1.8</td>
<td>2.2</td>
<td>-2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>LBP, Uncorrected</td>
<td>-6.6</td>
<td>32</td>
<td>-17</td>
<td>134</td>
</tr>
<tr>
<td>LBP, Capacitance</td>
<td>-7.1</td>
<td>2.5</td>
<td>-13</td>
<td>12</td>
</tr>
<tr>
<td>LBP, Volume</td>
<td>-2.1</td>
<td>2.0</td>
<td>-2.5</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Overall, the volume corrections resulted in less error and improved gauging linearity more than the capacitance corrections. All results presented in Section 3.8 used the volume correction type. The corrected volume data was used in the calculation of the other parameters, e.g. mass.

Theoretically, it would be possible to perform settled tests or simulations in many orientations and fill levels, which would allow settled corrections to be derived for any fill level and orientation. These could then be applied whenever the liquid surface is close to planar, using acceleration and/or CM data to determine orientation. Furthermore, these would potentially allow for the correction of transient measurement variations due to approximately-planar sloshing. However, it was decided that this was not worth the effort because of filtering (Section 3.7.3) and the fact that this project is primarily concerned with low-G, for which corrections of this type are not possible because the liquid may be in a nonplanar/unsettled configuration.
3.7.3 Liquid Motion Filtering

This section describes filtering of the mass gauging measurement. Filtering of the capacitances to reduce electrical noise is covered in Section 3.7.1. As will be discussed in Sections 3.8.1 and 3.8.2, the liquid motion (slosh) caused variability in the gauging results, requiring the ECT-computed liquid mass (or volume) to be filtered in order to reduce measurement variability and improve the ECT system accuracy. For the rest of Chapter 3, “filter” will refer to filtering out the liquid motion effects in the ECT gauging results.

Only filters that could be implemented in real-time were considered. Linear phase finite impulse response (FIR) low-pass filters, including a backwards-looking moving average (MA) smoother, meet the real-time criterion but have phase delays. The phase delay is approximately the width of the window for a backwards-looking MA. Rate limiting filters are a type of filter that limits the rate of change of the input signal. For each new time point, the rate-of-change of the input signal, computed by finite difference, is compared to a rate limit. If the rate limit, which can be positive or negative, is violated, the output value at the new time point is calculated by the rate limit multiplied by the time step added to the previous data point. Higher rate limits result in less filtering because the output signal more closely tracks the input signal. A rate limiting filter is only active when a rate limit is violated, but rate limiting during prior time steps can cause a transient offset between the input and output signals, i.e. phase delay. The phase delay is worse for lower rate limits (higher filtering) because it takes more time steps for the output to track changes in input. The phase delay from a rate limiting filter can be lower than a backwards MA when both are designed for a similar magnitude of noise reduction. To further reduce phase delay, the
offset can be reset by setting the output signal equal to the input signal (offset=0) if specified (system dependent) criteria are met. Rate limits should be selected to bound the rates of the system. Having different positive and negative rate limits that do not correspond with the physics of the system can result in a low or high bias. For example, having a small positive rate limit and a large negative rate limit for filtering the results of a steady (but noisy) process will result in the output signal being biased low, while having equal magnitude positive and negative rate limits would not result in a bias. Rate limiting is not computationally intensive, and backward differences permit real-time usage. In filter testing, differences in output for finite difference accuracy orders over three were negligible, thus third order was selected. One disadvantage of rate limiting a signal is that the output signal is piecewise linear, not smooth. If a smooth output signal is required, either the rate limited output must be smoothed, or a different filter, e.g. moving average, must be used.

In a real flight tank the various fill and drain rates will be knowable to within some uncertainty, so rate limit tables can be pre-generated for a rate limiting filter implemented in the tank’s ECT system. A launch vehicle upper stage will be used as an example. For an on-orbit cryogenic tank when no propellant is being consumed, the negative rate limit could be set to the worst-case boil-off rate. Main engine burn results in the highest drain rate, and the drain rate, along with its uncertainty (for adding margin), will be known from engine modeling and testing. The ECT system would know when the engine is burning, look up the negative rate limit in a table, and set the negative rate limit to that for the duration of the burn. Because the ECT system will have a settled liquid (in primary thrust
axis) calibration (see Section 3.7.2), the accuracy during settling or a burn will be higher, which would allow for the use of the offset reset feature to reduce phase delay after a transition from low-G to high-G.

After comparing various filters, a rate limiting filter was selected for the ECT system in this study. No liquid was added to, or drained from, the tank during a test, meaning the rate limit could theoretically be zero, but this is equivalent to setting the output signal equal to the first time point of the input signal and is akin to a 0 Hz cutoff frequency in a classical low-pass filter, which is not useful. Similar to the launch vehicle upper stage example above, the rate limiting filter for this ECT system utilizes the offset reset feature at transitions from unsettled, low-G to settled, high-G. The “settled, high-G” state was determined by when the IMU acceleration vector and CM angles (with respect to the horizontal orientation’s “up” axis) were within specific, small angle limits, i.e. when the liquid was mostly settled in the horizontal orientation. The selection of rate limits is discussed in Section 3.8.2.

3.7.4 Uncertainty

Formal uncertainty calculations were performed on all data following the standard process described in Ref. [52]. All reported errors are for a 95% confidence level. The adjective “actual” will refer to scale-derived measurements and “ECT-measured” will refer to capacitance-derived measurements.

CAD of the tank was used to calculate total internal volume (2.792 L), which is estimated to have an uncertainty of ±1% and no random error. The digital tank temperature sensor
has a fixed bias error of 0.3 °C, and has internal filtering, so no random error was reported. The test liquid [48] datasheet provides equations for density and vapor pressure versus temperature without reported uncertainties, so their uncertainties are assumed to be negligible. Temperature uncertainty was propagated through these equations. The precision scale was calibrated and had a fixed bias error of ±0.01 g and a negligible random error. The fill operation evaporation loss was measured to be 4 ±2 g per operation during the flight campaign (±1 g per operation during the ground test campaign) and used to correct the scale-measured mass. Phase change in the tank was calculated. These uncertainties were fully propagated through calculations to provide the transient uncertainties for actual liquid mass, volume, and volume fraction.

The ECT system’s capacitance measurements had a fixed bias error of 2.5e-17 + 0.005C F, where C is the measurement value. The capacitance measurement random error was assumed to be normally distributed and calculated from the standard deviation of static measurements for each electrode pair, generally on the order of 1e-16 F. The capacitance measurement, temperature, and temperature correction linear fit uncertainties were propagated to the empty and full capacitance measurements and normalization, resulting in transient uncertainties for the normalized capacitances.

For the mean C method, the normalized capacitance uncertainty was propagated through the average to obtain the uncertainty on ECT-measured volume fraction, and ultimately volume uncertainty along with ECT-measured mass uncertainty. Normalized capacitance uncertainty was propagated through LBP reconstruction calculations using Monte Carlo, i.e. random sampling of the normal distribution of the normalized capacitance. A normal
distribution was fit to the resulting volumes, and the standard deviation of that fit was used to calculate random error for ECT-measured volume due to the normalized capacitance uncertainty. The volume uncertainty was propagated to volume fraction and mass uncertainties in a similar manner as the mean C method. Random uncertainty due to the settled corrections, which, in uncertainty terminology, are actually a form of fixed bias (offset) error correction, was determined to be negligible. This make sense because there is unique volume for every fill level in a given tank orientation. Of course, the orientation had uncertainty, but this was captured in the random uncertainty on the mean measurements instead of in the settled corrections.

Some effort was spent quantifying the error of the LBP process, i.e. errors associated with linear and approximate-inverse assumptions of the LBP reconstruction algorithm applied to an inherently nonlinear and ill-posed problem. A code based on an Inverse Fast Fourier Transform (IFFT) was written to rapidly generate millions of random unsettled-liquid-like distributions, simulate the capacitances using the sensitivity matrix, perform LBP, calculate volume error, and then calculate fixed bias and random error versus fill level. This extra uncertainty was included in transient results when the liquid was in an unsettled state, resulting in a wider LBP confidence interval (CI) during those times. The LBP process random error was also included in the uncertainty intervals for mean measurement results. The sensitivity matrix elements were assumed to have no uncertainty, and errors associated with tank geometry, which are known to exist but were never quantified (see Section 3.3.3), are still not accounted for. A similar method was used to estimate the errors.
associated with the mean C method process, but this was ultimately not used because it was determined to be unnecessary.

The uncertainty on the total tank volume was accounted for in the mean C method, but not LBP because LBP returns a volume directly. In order to account for tank volume uncertainty in the total uncertainty of the LBP results, an uncertainty would have to be calculated for the volume of each cell in the simulation mesh. The cell uncertainties would then have to be propagated through the sensitivity matrix calculation and the liquid volume calculation step after reconstruction. This was impractical and neglected.

In Section 3.8, total accounted-for uncertainty will be presented as a 95% confidence interval band around the transient gauging curves. Maximum liquid mass errors, defined relative to both actual liquid mass and full-tank liquid mass, from the transient results are also reported. Additionally, for every test, an uncertainty interval (UI) at a 95% confidence level about the mean of the test’s measurements is reported as a “time-averaged accuracy”. These results provide estimates of this ECT system’s gauging accuracy, the determination of which was a primary objective of this experiment.

3.8 Gauging Test Results and Discussion

3.8.1 Results Primer

In the interest of conciseness, results presented in this section represent a subset of the large amount of test data collected. The tests selected for presentation are representative; they are not necessarily the tests with the highest accuracy gauging. Unless otherwise
noted, liquid mass error is defined as $e = \frac{m_m - m_a}{m_a}$, where $m_m$ is the ECT measured liquid mass and $m_a$ is the actual liquid mass currently in the tank, which was derived from precision scale measurements. Note that this error is not relative to a full tank. The “Mean C” curve is the mean C method with the settled corrections. The “LBP” curve is LBP with the settled corrections. The “rate limited” curves have most of the liquid motion effects filtered out by a rate limiting filter (see Sections 3.7.3 and 3.8.2). The “actual” line is a scale-derived measurement. The 95% confidence interval for each parameter is plotted as a lighter-shade band (“95% CI” in the plot legends) around the parameter curve and represents the known transient uncertainty (see Section 3.7.4). For example, in the liquid mass plots, the CI represents the uncertainty of the transient mass measurements. The liquid mass error curves are an estimate of this ECT system’s transient accuracy, and the distance between the CI and 0 on these plots represents unaccounted-for system uncertainties.

The ECT sensitivity varied throughout the volume of the tank. Liquid near the edges of an electrode, where the electric field was highest, had a larger effect on capacitance of that electrode than liquid in the center of the tank, where the electric field was the lowest. The liquid moving between areas of high and low sensitivity caused variations in the capacitance measurements, thus causing oscillations in the mean C method results. The sensitivity matrix used in LBP, and many other ECT algorithms, accounts for some of the volumetric sensitivity. However, the ill-posed nature of the inverse problem (see Section 3.1), along with the capacitances variability and inaccuracies in modeled geometry, resulted in the variation in the LBP results. The uncertainty of the LBP process for random,
unsettled liquid configurations was characterized (see Section 3.7.4) and can be seen as a widening of the LBP CI during unsettled portions of the tests.

3.8.2 Liquid Motion Filtering: Selection

The liquid gauging results were filtered to reduce measurement variability and improve the ECT system accuracy. Data from one ground and one flight test are shown for comparing the effectiveness of different filters. Figure 9 is a plot of corrected liquid volume vs. time from the 50% NVF free-decay ground test with a zoomed inset plot of the last decay portion. Figure 10 is a plot of corrected liquid volume vs. time from one set of five parabolas from the 50% NVF flight. Figure 11 is zoomed in on the last low-G portion of Figure 10. The “ECT C Corrected” curve is the corrected mean C method, which is filtered with different techniques. The same filtering is applicable to corrected LBP results (or the results from any other ECT method). The “30s MA filter” applies a moving average with a backwards-looking 30 s window. A 30 s window was chosen based on approximate timescales for common upper stage maneuvers and slosh, and even though a larger window would smooth out the liquid motion variations more, it would cause worse phase delay. The “rate limit” curves utilize a rate limiting filter (described in Section 3.7.3) with different rate limits. The “high” rate limit was estimated from the liquid oxygen consumption rate in a 3 m diameter-class launch vehicle upper stage during main engine burn, scaled by the volume ratio of the test tank to the stage’s tank. The high rate limit is considered a realistic bound for a negative (drain) rate limit. The “medium” rate limit is $1/7$ the high rate. Although the high rate limit generally results in less filtering than the MA, the medium rate limit value was set to result in more. The “low” rate limit is $1/10$ the
medium rate. Both positive and negative rate limits have the same magnitude to prevent an output bias because the test tank was filled and drained at the same (zero) rate during tests. Although a rate limit of approximately zero is physically accurate for these tests, this results in all but the first data point being ignored, which is not useful. Liquid volume is used in Figures 9-11, but the same rate limits are applicable to liquid mass when multiplied by liquid density.

Figure 9: Filter Comparison (50% NVF, impulse free-decay test)
Figure 10: Filter Comparison (50% NVF flight, 5 parabolas)

Figure 11: Filter Comparison, Parabola 5
The effectiveness of the 30 s MA filter at suppressing the oscillations from slosh is between that of high and medium rate limits. In Figure 9, the MA line changes slope around 485 s because it is backwards looking, and the moving average contacts the rapid change in the “ECT C Corrected” curve around 455 s (485-30). Similar slope changes are visible in the MA line in Figure 10. The rate limited curves exhibit less phase delay than the MA filter. Phase delay is further reduced by the use of the rate limiting filter’s offset reset feature (see Section 3.7.3), the effect of which can be seen as a jump in the high and medium rate limit curves in Figure 11 near 365 s. The offset reset feature was not used in any of the rate limited ground test results because it did not seem to help, but it was used in the rate limited flight test results because it seemed to help more often than not. Not using the offset reset feature, e.g. where the high-G gauging uncertainty is high, still results in less phase delay than the MA filter. The high rate limit retained some of the signal oscillation, while the low rate limit effectively removed all oscillation. Although somewhat arbitrary, this range of rate limits was chosen to demonstrate their effects on filtering transient gauging data. The medium rate limit was selected to create the “rate limited” curves in Sections 3.8.3 and 3.8.4. Despite the low rate limit being the most physically relevant to this test tank and resulting in the lowest error, demonstrating the effects of a higher rate limit was useful, and the medium rate limit offered a good balance.

Although a rate limiting filter was chosen for this study using the above process, other filters could have been used instead to filter out the variations due to liquid motion. A comprehensive examination of optimal filters for various, specific applications is outside the scope of this thesis.
3.8.3 Ground Test Results

Transient plots of IMU data, liquid mass, and liquid mass error are presented from the 50\% NVF impulse free-decay test. Transient liquid mass and mass error plots from the 5\%, 30\%, and 70\% NVF impulse free-decay tests are also presented in this section, with additional plots in Appendix A. Figure 12 shows the 3-axis accelerations and 3-axis rotation rates measured by the IMU in the IMU axes for the 50\% NVF test in both horizontal and vertical orientations. This is presented first to quantitatively characterize the primarily single-axis motion of the impulse tests.

![Figure 12: IMU Data, 50\% NVF Ground Slosh Test](image)

Refer to Figure 5 for coordinate system and experiment orientation information. The experiment started in the horizontal orientation (\(a_Z\) reads 1 G), was manually given two impulses, rotated up to the vertical orientation (\(a_Y\) reads 1 G) around 280 s, then given two impulses. Each impulse was primarily in one axis, along Y in the horizontal orientation or
along Z in the vertical orientation. The time between impulses allowed for the slosh to decay. This was the standard process for all of the ground slosh tests. The inset plot in Figure 12 is zoomed in on the second impulse. The initial push, slow, reverse, and stop accelerations are all visible in $a_Y$. There were minor oscillations about all axes. This motion profile is representative of all of the horizontal orientation impulses in the ground testing. The vertical orientation impulses were similar, except with motion primarily in the Z direction instead of Y, and the minor oscillations were a little (1-3x) larger, but still relatively small. The reason the oscillations were larger was because the experiment was sitting on its end with the long side of the baseplate pointing up, which allowed the apparatus to rock more than in the horizontal orientation. Breaking waves were audible in the tank for many fill levels’ impulses, meaning the impulses were generally strong enough to exciting vigorous sloshing.

Figure 13: ECT Liquid Mass vs. Time, 50% NVF Ground Slosh Test
Figure 13 and Figure 14 are for the same test shown in Figure 12. The impulses caused a slosh wave inside the tank that decayed over time due to damping. The uncorrected results had different offsets for both orientations and both methods that the settled corrections corrected. When the liquid was mostly settled, the actual liquid mass was within the corrected mean C method’s and LBP’s CIs, indicating good accuracy. The only portion of this plot that did not have a settled correction applied was during the 90 deg rotation to the vertical orientation (near 270s) because the liquid was not settled and not in an orientation for which a correction had been derived. The fully settled liquid mass value for each orientation was nearly constant. The mean C method results have a wider CI than the LBP results because the uncertainty of the total tank volume is relatively high and was propagated to the total uncertainty calculation for the mean C method volume, while LBP returns a liquid volume directly, so tank volume uncertainty is not included in its total uncertainty. The only exception to this is when the liquid is unsettled during the rotation, where the aforementioned widening of the LBP CI is visible. The comments from this figure apply to the other ground test results and will not be repeated for sake of brevity.
Figure 14 is the percent error calculated from the transient data shown in Figure 13. As mentioned previously, liquid mass error is defined relative to the actual liquid mass currently in the tank, not to a full tank. The larger error in the vertical orientation than the horizontal orientation was likely due to the large electrode gap being more exposed to fluid in the vertical orientation (see Section 3.3.3). Comparing the mean C and LBP methods is easier in the zoomed inset plot. Some features are present in both curves, but they can also exhibit no correlation or anti-correlation. The slosh oscillations in both methods have similar magnitudes and decay at approximately the same rate. Tabulated maximum absolute value errors for all tested fill levels for the mean C method and LBP are presented in Table 4 and Table 5, respectively. In all of the tests, the corrected mean C method and LBP error curves were near 0% when the liquid was mostly settled, indicating good
accuracy. Filtering out the liquid motion effectively increased the mass gauging system accuracy.

Figures 15-20 are plots of liquid mass and mass error for the 5%, 30%, and 70% NVF tests. Plots of volume fraction and the transient results from other fill levels are included in Appendix A.

![Figure 15: ECT Liquid Mass vs. Time, 5% NVF Ground Slosh Test](image-url)
The lowest fill levels tended to have higher errors, particularly during the rotation. Shown in Figure 16, the liquid reorienting during the rotation in the 5% NVF test resulted in the highest error seen during ground testing. Once the liquid was mostly settled in the vertical orientation, the settled corrections were applied, resulting in low error.
Figure 17: ECT Liquid Mass vs. Time, 30% NVF Ground Slosh Test

Figure 18: ECT Liquid Mass Error vs. Time, 30% NVF Ground Slosh Test
Unlike for the 5% NVF test, the liquid reorienting during the rotation in the 30% NVF test (Figure 18) resulted in a similar error range to that of the impulse sloshing.

Figure 19: ECT Liquid Mass vs. Time, 70% NVF Ground Slosh Test
In Figure 20, the LBP curve has a larger oscillation magnitude and mostly covers the mean C data.

Tables 4 and 5 list the maximum absolute value measured liquid mass errors from all ground tests. As mentioned previously, liquid mass error is defined as $$e = \frac{m_m - m_a}{m_a}$$, where $$m_m$$ is the ECT measured liquid mass and $$m_a$$ is the actual liquid mass currently in the tank. The first column is the NVF test identifier. The “H” and “V” columns are for the horizontal and vertical orientations, respectively, excluding the rotation between orientations. The “all” columns used all of a fill level’s data, including the unsettled rotation, and include error in both percent and grams. The “RL” columns used the rate limited filtered data. The “Full” column used all of the fill level’s rate limited data, but
defined error relative to the 100% full tank liquid mass, 

\[ e_{\text{Full}} = \frac{m_m - m_a}{m_T} \]

where \( m_T \) is the full tank liquid mass.

### Table 4: Maximum Liquid Mass Errors, Ground Tests Mean C Method

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<th>NVF, %</th>
<th>H, %</th>
<th>RL H, %</th>
<th>V, %</th>
<th>RL V, %</th>
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<th>all, %</th>
<th>RL all, g</th>
<th>RL all, %</th>
<th>RL all, %Full</th>
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### Table 5: Maximum Liquid Mass Errors, Ground Tests LBP Method

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<tr>
<th>NVF, %</th>
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<th>RL H, %</th>
<th>V, %</th>
<th>RL V, %</th>
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The “all” errors were dominated by the rotation. There was not a clear trend for mass error in grams. The mass error in percent tended to increase as fill level decreased. This was due to rapidly decreasing actual liquid mass, which appears in the denominator of the percent error calculation. The unfiltered mean C method generally had lower maximum errors than unfiltered LBP. The highest filtered, oriented error was 2.7%, and this occurred during the 5% NVF test in the vertical orientation. The maximum error relative to full tank liquid mass was below 1% for all fill levels and tended to increase slightly as fill level increased due to $m_a$ approaching $m_T$. These maximum mass errors give a sense of the worst-case transient error for this ECT system during slosh testing in a 1 G environment.

The previous results looked at the data in a transient manner. Since the fill level did not change during a test, all of the data points could be considered measurements of a single, constant measurand, allowing for the calculation of measurement uncertainty. In a real tank application, this would be like averaging multiple liquid mass measurement samples, treating the variability due to liquid motion as random noise. The uncertainty interval around that mean measured mass is a measure of the ECT sensor system’s accuracy for that fill level. This is different than the uncertainty propagated and displayed on the previous transient plots as a confidence interval. The fixed bias portion of the transient uncertainty is included in the mean measurement’s UI, but the random uncertainty comes from the probability distribution of all of the measurements. The mass measurements are not normally distributed because the test process (periods of settled and sloshing) was not a Gaussian random process, and the resulting probability distribution was asymmetric about its mean. For each test, a nonparametric kernel distribution was fit to the probability
distribution of measurements, and the inverse cumulative density function (ICDF) of that fit returned the asymmetric UI for a 95% confidence level.

Table 6 lists the actual, scale-derived volume fractions and liquid masses in the tank for each test/NVF. The uncertainty on the actual volume fraction is dominated by the uncertainty on the total tank volume. The test times represent the amount of data used for the mean and UI calculation, which was all of the data for the ground tests.

Table 6: Actual Mass, Ground Tests

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<th>Actual VF, %</th>
<th>Actual Mass, g</th>
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<td>5.3 +/- 0.06</td>
<td>247 +/- 1</td>
<td>297</td>
</tr>
<tr>
<td>10</td>
<td>10 +/- 0.11</td>
<td>483 +/- 1</td>
<td>565</td>
</tr>
<tr>
<td>20</td>
<td>22 +/- 0.22</td>
<td>1039 +/- 1</td>
<td>748</td>
</tr>
<tr>
<td>30</td>
<td>30 +/- 0.31</td>
<td>1418 +/- 1</td>
<td>923</td>
</tr>
<tr>
<td>40</td>
<td>38 +/- 0.38</td>
<td>1758 +/- 1</td>
<td>846</td>
</tr>
<tr>
<td>50</td>
<td>51 +/- 0.51</td>
<td>2392 +/- 1</td>
<td>550</td>
</tr>
<tr>
<td>60</td>
<td>61 +/- 0.62</td>
<td>2863 +/- 1</td>
<td>947</td>
</tr>
<tr>
<td>70</td>
<td>70 +/- 0.70</td>
<td>3235 +/- 1</td>
<td>816</td>
</tr>
<tr>
<td>80</td>
<td>79 +/- 0.79</td>
<td>3681 +/- 1</td>
<td>662</td>
</tr>
<tr>
<td>90</td>
<td>89 +/- 0.90</td>
<td>4164 +/- 1</td>
<td>653</td>
</tr>
</tbody>
</table>

Table 7 shows the mean measured masses and the UIs about the mean measured masses in different formats for each test using the mean C method results. “RL” used the rate-limited filtered results. The UI is given in grams, % of measurement, and % full scale (full tank).

Table 8 is the same as Table 7 but for the LBP method. The term “time-averaged accuracy” or “uncertainty of the mean mass measurement” is used to distinguish these from the “maximum transient mass errors”.
Table 7: Time-Averaged Liquid Mass Gauging Accuracy, Ground Tests, Mean C Method

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>Mean Mass, g</th>
<th>Mean Mass UI</th>
<th>RL Mean Mass, g</th>
<th>RL Mean Mass UI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>%</td>
<td>%Full</td>
<td>g</td>
</tr>
<tr>
<td>5</td>
<td>253</td>
<td>+132 , -14</td>
<td>+52 , -5.6</td>
<td>249</td>
</tr>
<tr>
<td>10</td>
<td>485</td>
<td>+12 , -12</td>
<td>+2.4 , -2.5</td>
<td>484</td>
</tr>
<tr>
<td>20</td>
<td>1045</td>
<td>+29 , -26</td>
<td>+2.8 , -2.5</td>
<td>1045</td>
</tr>
<tr>
<td>30</td>
<td>1418</td>
<td>+39 , -31</td>
<td>+2.8 , -2.2</td>
<td>1417</td>
</tr>
<tr>
<td>40</td>
<td>1757</td>
<td>+30 , -41</td>
<td>+1.7 , -2.3</td>
<td>1758</td>
</tr>
<tr>
<td>50</td>
<td>2401</td>
<td>+62 , -47</td>
<td>+2.6 , -2</td>
<td>2402</td>
</tr>
<tr>
<td>60</td>
<td>2853</td>
<td>+41 , -41</td>
<td>+1.4 , -1.4</td>
<td>2854</td>
</tr>
<tr>
<td>70</td>
<td>3219</td>
<td>+40 , -56</td>
<td>+1.2 , -1.7</td>
<td>3221</td>
</tr>
<tr>
<td>80</td>
<td>3681</td>
<td>+42 , -48</td>
<td>+1.1 , -1.3</td>
<td>3683</td>
</tr>
<tr>
<td>90</td>
<td>4146</td>
<td>+44 , -44</td>
<td>+1.1 , -1.1</td>
<td>4148</td>
</tr>
</tbody>
</table>
**Table 8: Time-Averaged Liquid Mass Gauging Accuracy, Ground Tests, LBP Method**

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>Mean Mass, g</th>
<th>Mean Mass UI</th>
<th>RL Mean Mass, g</th>
<th>RL Mean Mass UI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>%</td>
<td>% Full</td>
<td>g</td>
</tr>
<tr>
<td>5</td>
<td>254</td>
<td>+249 , -26</td>
<td>+98 , -10</td>
<td>+5.3 , -0.56</td>
</tr>
<tr>
<td>10</td>
<td>486</td>
<td>+15 , -18</td>
<td>+3.1 , -3.6</td>
<td>+0.32 , -0.38</td>
</tr>
<tr>
<td>20</td>
<td>1044</td>
<td>+20 , -15</td>
<td>+1.9 , -1.5</td>
<td>+0.42 , -0.33</td>
</tr>
<tr>
<td>30</td>
<td>1417</td>
<td>+38 , -25</td>
<td>+2.7 , -1.7</td>
<td>+0.81 , -0.53</td>
</tr>
<tr>
<td>40</td>
<td>1761</td>
<td>+29 , -35</td>
<td>+1.7 , -2.0</td>
<td>+0.63 , -0.76</td>
</tr>
<tr>
<td>50</td>
<td>2399</td>
<td>+58 , -30</td>
<td>+2.4 , -1.2</td>
<td>+1.2 , -0.64</td>
</tr>
<tr>
<td>60</td>
<td>2852</td>
<td>+44 , -42</td>
<td>+1.5 , -1.5</td>
<td>+0.94 , -0.90</td>
</tr>
<tr>
<td>70</td>
<td>3217</td>
<td>+36 , -51</td>
<td>+1.1 , -1.6</td>
<td>+0.77 , -1.1</td>
</tr>
<tr>
<td>80</td>
<td>3669</td>
<td>+31 , -38</td>
<td>+0.83 , -1.0</td>
<td>+0.66 , -0.81</td>
</tr>
<tr>
<td>90</td>
<td>4141</td>
<td>+23 , -20</td>
<td>+0.56 , -0.5</td>
<td>+0.50 , -0.44</td>
</tr>
</tbody>
</table>
All actual masses fall within the UIs in Tables 7 and 8, meaning the various sources of uncertainty are captured adequately. The extreme positive UI limit for the 5% NVF case is due to the jump in the measurement during the rotation between orientations being significantly larger than for the other fill levels. The rate limiting filter reduces the random uncertainty component of the total uncertainty by reducing the magnitude of the slosh-induced oscillations. If the random uncertainty is already low, as it is for many fill levels over 5% VF, then using the rate limited data does little to improve accuracy. These UIs provide a sense of the time-averaged accuracy of this ECT system during slosh testing in a 1 G environment.

3.8.4 Flight Test Results

Transient plots of IMU data, liquid mass, and liquid mass error are presented for one set of five low-G parabolas from the 50% NVF flight. Transient liquid mass and mass error plots are also presented for one set of five low-G parabolas from the other three flights. Figure 21 shows the 3-axis accelerations and 3-axis rotation rates measured by the IMU in the IMU axes for five parabolas during the 50% NVF flight. This is presented first to quantitatively characterize the parabolic flight motion.
Refer to Figure 5 for coordinate system and experiment orientation information. The variation in $a_Z$ from 1 G to about 1.8 G (hyper-G) to near 0 G is clearly visible. There is a small $a_Y$ component, about 1 m/s$^2$ during hyper-G, associated with the aircraft pitching. This resulted in “down” not being precisely perpendicular to the aircraft deck. Lateral acceleration, $a_X$, is negligible. Pitch rate, $\omega_X$, is the largest amplitude rotation rate and follows $a_Z$ because the parabola maneuver consisted of the plane pitching up to climb (hyper-G) then pitching down to simulate free fall. Yaw rate, $\omega_Z$, is negligible. Roll rate, $\omega_Y$, can be significant during hyper-G and was mainly in response to atmospheric turbulence, but since the experiment was mounted near the center of the cabin, which should have been near the aircraft’s roll axis, the roll rate does not show up much in the accelerations. The high (negative) roll rate at the end of this set of parabolas was the aircraft banking to line up its flight path for the next set of parabolas. As this figure shows, each parabola was unique in both timing and magnitude.
Figures 22-24 are for the same parabolas shown in Figure 21.

**Figure 22**: ECT Liquid Mass vs. Time, 50% NVF Flight Test

**Figure 23**: ECT Liquid Mass vs. Time, 50% NVF Flight Test, Zoomed in Y
During settled, high-G flight, the actual liquid mass was within the corrected mean C method’s and LBP’s CIs, indicating good accuracy. The CI on actual mass is too small to be visible in these plots, and the CIs are not shown on the rate limited curves for plot coherence. The decay waveform after a low-G portion at the beginning of a hyper-G portion was due to the free-decay of slosh, and the primary frequency of these portions was near the theoretical first asymmetric slosh mode frequency. The remaining high frequency content during steady level flight (before 50 s in this plot) or hyper-G post-slosh-decay was due to small aircraft motions and atmospheric turbulence causing small amplitude random (not clearly first mode) slosh. The settled liquid mass measurements appear repeatable, but low-G measurements are much more varied due to sensitivity variation (see Section 3.8.1). Both mean C method and LBP have up and down spikes during low-G. The rate limited curves have the higher frequency liquid motion effects, such as slosh and spikes, filtered out. The abrupt changes in the rate limited curves at the transitions from low-G to high-G are caused by the offset reset feature of the rate limiting filter (see Section 3.7.3). Except during low-G, where the widening of the LBP CI is visible, the mean C method results have a wider CI than the LBP results because the uncertainty of the total tank volume is relatively high and was propagated through the total uncertainty calculation for the mean C method volume, while LBP returns a liquid volume directly (see Section 3.7.4).
Figure 24: ECT Liquid Mass Error vs. Time, 50% NVF Flight Test

Figure 24 is the percent error calculated from the data shown in Figure 22. As mentioned previously, liquid mass error is defined relative to the actual liquid mass currently in the tank, not to a full tank. During settled, high-G flight, the corrected mean C method and LBP curves were near 0%, indicating good accuracy. The error percent during low-G varies. Filtering out the variations from liquid motion resulted in less error during low-G, effectively increasing the mass gauging system accuracy. All of the above comments on results presented in Figures 22-24 apply to the other flights’ (NVFs) results.

In Figure 23, the offset reset feature helps reduce phase delay in the rate limited mean C curve, but it does not help the rate limited LBP curve in this case. Whether or not the offset reset feature helped was case and method dependent, but it was used for all rate limited flight data curves for consistency. For the set of parabolas shown in Figure 24, the mean C
method error in low-G ranges from about -14% to 4%, and the LBP method ranges from about -12% to 10%. The mean C method filtered curve ranges from about -1.0% to 0.4%, and the LBP filtered curve ranges from about -0.3% to 0.4% error during low-G and up to 1% at the transition from low-G to high-G.

Figure 25 and Figure 26 are Figure 21 and Figure 24, respectively, zoomed in on the first parabola in order to show the low-G portion in more detail.

Every parabola was unique, but the general characteristics were similar and all included high-G, transition to low-G, small oscillations near 0 G, transition to high-G, and high-G portions. The Figure 25 acceleration y-axis is zoomed in on the low end to show the unsteadiness in $a_Z$ during the low-G portion of the parabola. $a_Z$ oscillates below 1 m/s$^2$ and hits 0 briefly. The low-G $a_Z$ oscillations are due to the pitch rate, $\omega_X$, oscillations as evidenced by similar relative magnitude peaks with the pitch rate leading 90 deg out of
phase. The slight correlation between roll rate, $\omega_Y$, and yaw rate, $\omega_Z$, could be evidence of roll-yaw coupling, however, the magnitude of the yaw rate is quite low. The coupling between roll rate and lateral acceleration, $a_X$, is clear, and shows that the IMU origin was not on the aircraft roll axis.

The oscillations during low-G generally correspond in time with the motion oscillations, but the peak magnitudes do not correspond, i.e. a large motion peak does not imply a large amplitude response in the ECT system, due to the chaotic nature of slosh and the previously discussed sensitivity variations. Comparing the mean C and LBP methods is easier in this plot. Some features are present in both curves, but they can also exhibit no correlation or anti-correlation. The limited rates of the filtered curves are visible during the

![Figure 26: ECT Liquid Mass Error vs. Time, 50% NVF, 1 parabola](image)

The oscillations during low-G generally correspond in time with the motion oscillations, but the peak magnitudes do not correspond, i.e. a large motion peak does not imply a large amplitude response in the ECT system, due to the chaotic nature of slosh and the previously discussed sensitivity variations. Comparing the mean C and LBP methods is easier in this plot. Some features are present in both curves, but they can also exhibit no correlation or anti-correlation. The limited rates of the filtered curves are visible during the
large up and down spikes. The aforementioned wider LBP CI during low-G is more obvious in this plot.

Figures 27-32 are the liquid mass and mass error plots for a set of five parabolas from the 5%, 20%, and 80% NVF flights. Plots of volume fraction are included in Appendix B.

Figure 27: ECT Liquid Mass vs. Time, 5% NVF Flight Test
For the set of parabolas in Figure 28, the mean C method error during low-G ranges from about -40% to 53% and the LBP method ranges from about -50% to 102%. For reference, -40% error at this fill level is about 80 g, or 47 mL, about 1.7% of the total tank volume. The mean C method filtered curve ranges from about -6% to 0.4%, and the LBP filtered curve ranges from about -7% to 6% during low-G.
Figure 29: ECT Liquid Mass vs. Time, 20% NVF Flight Test

Figure 30: ECT Liquid Mass Error vs. Time, 20% NVF Flight Test
The 20% NVF fill level had the largest ECT measurement oscillations from slosh between low-G periods. Unlike the other fill levels, the mean C method calculates significantly larger slosh oscillations during hyper-G than LBP. Furthermore, if the absolute value in the mean C method is removed, the hyper-G slosh oscillation magnitudes look similar to those calculated by LBP. The large slosh wave motion for this fill level resulted in some of the primarily negative normalized capacitances’ oscillations being out-of-phase with some of the other capacitances. Negative normalized capacitance occurs when a measured capacitance is less than the corresponding empty tank capacitance, which can happen when the presence of test liquid in certain regions of the tank warps the electric field in such a way as to reduce the capacitance below that of the empty tank value. The absolute value flips the negative valleys, making them positive peaks and partially in-phase, resulting in larger amplitude oscillations when all of the capacitances are averaged together compared to averaging the non-absolute-valued capacitances. The larger amplitude slosh delayed the activation of settled corrections for a few seconds into the hyper-G environment, as much as 6 s for the fourth parabola in Figure 30. For this set of parabolas, the mean C method error ranges from about -22% to 15% and the LBP method ranges from about -9% to 35%. Filtering out variation due to liquid motion results in less error during high-G and low-G sloshing, effectively increasing the mass gauging system accuracy. The mean C method filtered curve ranges from about -0.2% to 2.5%, and the LBP filtered curve ranges from about 0.5% to 3.7%. As in the 50% NVF plot (Figure 24), the mean C method low-G measurements tended to be lower than the LBP low-G measurements.
Figure 31: ECT Liquid Mass vs. Time, 80% NVF Flight Test

Figure 32: ECT Liquid Mass vs. Time, 80% NVF Flight Test
For the set of parabolas in Figure 32, the mean C method error during low-G ranges from about -8.5% to 1.7%, and the LBP method ranges from about -8.3% to 1.4%. The mean C method filtered curve ranges from -1.3% to -0.4%, and the LBP filtered curve ranges from about -1.3% to -0.1%. Unlike the 20% and 50% fill levels, the mean C method low-G measurements tended to be lower than the LBP low-G measurements.

The mean C method and LBP mass error CIs encompassed the 0% error line for all fill levels during the settled, hyper-G portions of the parabolas, indicating accurate settled liquid mass gauging. The variations during low-G would occasionally cause mass error to be within the measurement uncertainty of, or cross, 0% error. However, the variations swept a wide range of mass errors, so the precision of the ECT system without filtering was worse during low-G. The LBP method’s low-G variations tended to span a wider range of errors than the mean C method, indicating the LBP mass measurements were less precise. Using a rate limiting filter to filter out liquid motion effects significantly reduced the variation from the steady settled value, improving the precision and accuracy of the ECT system.

Table 9 and Table 10 are the flight data equivalents of Table 4 and Table 5, respectively. The values in the first two data columns of each table are the magnitude of the largest low-G spike during that flight in grams and percent. Note that these spikes may or may not be in the presented transient plots because only five of the 25 low-G parabolas from each flight were plotted.
Table 9: Maximum Liquid Mass Errors, Flight Mean C Method

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>g</th>
<th>%</th>
<th>RL, g</th>
<th>RL, %</th>
<th>RL, %Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>140</td>
<td>70.2</td>
<td>25</td>
<td>12.3</td>
<td>0.5</td>
</tr>
<tr>
<td>20</td>
<td>239</td>
<td>23.2</td>
<td>54</td>
<td>5.3</td>
<td>1.2</td>
</tr>
<tr>
<td>50</td>
<td>364</td>
<td>14.8</td>
<td>76</td>
<td>3.1</td>
<td>1.6</td>
</tr>
<tr>
<td>80</td>
<td>327</td>
<td>8.6</td>
<td>49</td>
<td>1.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 10: Maximum Liquid Mass Errors, Flight LBP Method

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>g</th>
<th>%</th>
<th>RL, g</th>
<th>RL, %</th>
<th>RL, %Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>262</td>
<td>131.3</td>
<td>58</td>
<td>29.1</td>
<td>1.2</td>
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<td>20</td>
<td>362</td>
<td>35.2</td>
<td>75</td>
<td>7.3</td>
<td>1.6</td>
</tr>
<tr>
<td>50</td>
<td>294</td>
<td>11.9</td>
<td>118</td>
<td>4.8</td>
<td>2.5</td>
</tr>
<tr>
<td>80</td>
<td>346</td>
<td>9.1</td>
<td>220</td>
<td>5.8</td>
<td>4.7</td>
</tr>
</tbody>
</table>

The mass error in percent tended to increase as fill level decreased. This was due to rapidly decreasing actual liquid mass, which appears in the denominator of the percent error calculation. The filtered data maximum errors generally did not correspond in time with the maximum errors of the unfiltered data. Similar to the ground tests, the mean C method generally had lower maximum errors than LBP. These maximum mass errors give a sense of the worst-case transient error for this ECT system during low-G flight testing.

The previous results looked at the data in a transient manner. As was described and done for Tables 7 and 8, all of the data points from a test could be considered measurements of a single, constant measurand, allowing for the calculation of a measurement mean and UI, which is the ECT sensor system’s accuracy for that fill level.
Table 11 shows the actual, scale-derived volume fractions and liquid masses in the tank for each test (NVF). The uncertainty on the actual volume fraction is dominated by the uncertainty on the total tank volume. The test times represent the amount of data used for the mean and UI calculation: one set considers all data from the flights, while the other uses only the low-G portions of the flights. The 80% NVF flight had a different pilot that flew parabolas that were more unsteady, and the flight was shorter, so the total low-G time was significantly lower than the other flights.

Table 11: Actual Mass, Flight Tests

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>Actual VF, %</th>
<th>Actual Mass, g</th>
<th>Total Test Time, s</th>
<th>Low-G Test Time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.2 +/- 0.06</td>
<td>200 +/- 2</td>
<td>10080</td>
<td>408</td>
</tr>
<tr>
<td>20</td>
<td>22 +/- 0.2</td>
<td>1030 +/- 2</td>
<td>10535</td>
<td>346</td>
</tr>
<tr>
<td>50</td>
<td>53 +/- 0.5</td>
<td>2467 +/- 2</td>
<td>9890</td>
<td>317</td>
</tr>
<tr>
<td>80</td>
<td>81 +/- 0.8</td>
<td>3795 +/- 2</td>
<td>8247</td>
<td>254</td>
</tr>
</tbody>
</table>

Table 12 shows the mean measured masses and the UIs about the mean measured masses in different formats for all data from each flight test using the mean C method results. “RL” used the rate-limited filtered results. The UI is given in grams, % of measurement, and % full scale (full tank). Table 13 is the same as Table 12 but for the LBP method. Table 14 and Table 15 are the same as Table 12 and Table 13, respectively, but only use the low-G portions of the flights.
### Table 12: Time-Averaged Liquid Mass Gauging Accuracy, Flight Tests Mean C Method

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>Mean Mass, g</th>
<th>Mean Mass UI</th>
<th>RL Mean Mass, g</th>
<th>RL Mean Mass UI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g</td>
<td>%</td>
<td>%Full</td>
</tr>
<tr>
<td>5</td>
<td>199</td>
<td>+19, -14</td>
<td>+9.7, -7.1</td>
<td>+0.41, -0.3</td>
</tr>
<tr>
<td>20</td>
<td>1037</td>
<td>+53, -75</td>
<td>+5.1, -7.2</td>
<td>+1.1, -1.6</td>
</tr>
<tr>
<td>50</td>
<td>2455</td>
<td>+33, -97</td>
<td>+1.3, -3.9</td>
<td>+0.7, -2.1</td>
</tr>
<tr>
<td>80</td>
<td>3775</td>
<td>+51, -85</td>
<td>+1.3, -2.3</td>
<td>+1.1, -1.8</td>
</tr>
</tbody>
</table>

### Table 13: Time-Averaged Liquid Mass Gauging Accuracy, Flight Tests LBP Method

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>Mean Mass, g</th>
<th>Mean Mass UI</th>
<th>RL Mean Mass, g</th>
<th>RL Mean Mass UI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g</td>
<td>%</td>
<td>%Full</td>
</tr>
<tr>
<td>5</td>
<td>199</td>
<td>+59, -26</td>
<td>+30, -13</td>
<td>+1.3, -0.55</td>
</tr>
<tr>
<td>20</td>
<td>1043</td>
<td>+96, -16</td>
<td>+9.2, -1.5</td>
<td>+2.0, -0.34</td>
</tr>
<tr>
<td>50</td>
<td>2461</td>
<td>+37, -111</td>
<td>+1.5, -4.5</td>
<td>+0.8, -2.4</td>
</tr>
<tr>
<td>80</td>
<td>3767</td>
<td>+69, -199</td>
<td>+1.8, -5.3</td>
<td>+1.5, -4.3</td>
</tr>
</tbody>
</table>
Table 14: Time-Averaged Liquid Mass Gauging Accuracy, Low-G Mean C Method

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>Mean Mass, g</th>
<th>Mean Mass UI</th>
<th>RL Mean Mass, g</th>
<th>RL Mean Mass UI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g</td>
<td>%</td>
<td>%Full</td>
</tr>
<tr>
<td>5</td>
<td>202</td>
<td>+87, -58</td>
<td>+43, -29</td>
<td>+1.9, -1.2</td>
</tr>
<tr>
<td>20</td>
<td>997</td>
<td>+129, -146</td>
<td>+13, -15</td>
<td>+2.8, -3.1</td>
</tr>
<tr>
<td>50</td>
<td>2327</td>
<td>+142, -149</td>
<td>+6.1, -6.4</td>
<td>+3.0, -3.2</td>
</tr>
<tr>
<td>80</td>
<td>3720</td>
<td>+124, -169</td>
<td>+3.3, -4.5</td>
<td>+2.7, -3.6</td>
</tr>
</tbody>
</table>

Table 15: Time-Averaged Liquid Mass Gauging Accuracy, Low-G LBP Method

<table>
<thead>
<tr>
<th>NVF, %</th>
<th>Mean Mass, g</th>
<th>Mean Mass UI</th>
<th>RL Mean Mass, g</th>
<th>RL Mean Mass UI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g</td>
<td>%</td>
<td>%Full</td>
</tr>
<tr>
<td>5</td>
<td>230</td>
<td>+118, -84</td>
<td>+51, -36</td>
<td>+2.5, -1.8</td>
</tr>
<tr>
<td>20</td>
<td>1143</td>
<td>+161, -137</td>
<td>+14, -12</td>
<td>+3.4, -2.9</td>
</tr>
<tr>
<td>50</td>
<td>2440</td>
<td>+192, -149</td>
<td>+7.9, -6.1</td>
<td>+4.1, -3.2</td>
</tr>
<tr>
<td>80</td>
<td>3639</td>
<td>+157, -127</td>
<td>+4.3, -3.5</td>
<td>+3.4, -2.7</td>
</tr>
</tbody>
</table>
All actual masses fall within the UIs in Tables 12-15, meaning the various sources of uncertainty are captured adequately. One interesting result is that the UIs in the low-G-only results are more symmetric than for those computed using all of the flight data. This is because the liquid motion in the tank, and resulting ECT system measurements, during low-G was nearly a normal random process, resulting in nearly symmetric probability distributions. One of the goals of this project was to excite random liquid motion in the tank in low-G in order to characterize the ECT system’s low-G performance, and the fact that these measurement probability distributions were nearly normal shows that this was achieved. The accuracy of the ECT system without the rate limiting filter was better for the full flights than the low-G portions due to the settled corrections being applied during high-G portions, which were the majority of the flight time. However, the accuracy of the ECT system with the rate limited data was similar for the full flights and low-G portions, and the LBP results were actually slightly better in the low-G case. The effect of the rate limiting filter is a reduction in random uncertainty component of the total uncertainty by reducing the magnitude of the slosh-induced variations; if the random uncertainty is already low, as it was for the 50% and 80% NVF cases using all of the flight data, then using the rate limited data does little to improve accuracy. These UIs provide a sense of the time-averaged accuracy of this ECT system in a flight-like environment.

3.9 Reconstruction Results

This section presents examples of ECT reconstruction of the liquid volume in the tank using LBP and LW. Reconstruction visualizations were created by exporting the reconstructed 3D permittivity distribution from specific timesteps from MATLAB and
loading them into STAR-CCM+, which was used to generate 3D graphics. Percent liquid mass error in this section is defined relative to the actual mass in the tank, not a full-tank, similar to the “%” column of Table 10, but for specific time points instead of the maximum transient error. The mass errors are included so gauging accuracy comparisons can be made between LBP and LW.

A camera would not have been useful in this experiment for the reasons mentioned in Section 3.3.3 and was not included. Thus, reconstruction validation was done by comparing known, settled liquid configurations with their ECT reconstructions. As discussed in Section 3.6, this was taken a step further by simulating the actual liquid configuration to generate simulated capacitance data, then comparing the test data reconstruction to a reconstruction of the simulated data, which were qualitatively similar to within the simulation mesh resolution. These comparisons accomplished two things. First, they helped validate the electrostatic simulations. Second, they showed that the reconstruction errors that will be discussed shortly are not error in test data collection, but error from the tank geometry/design and the ECT reconstruction method.

The coordinate system in the lower left corner of the graphics below is in tank body frame. Refer to Figure 5 for more information about the experiment coordinate systems. There are two types of graphics: contour plots of permittivity on the tank YZ (X=0) cross-section, and 3D renderings of the liquid surface/volume. There are two primary viewpoints: View 1 has tank -X coming out of the page and IMU -Z is image “down”, View 2 is at an angle with tank -X-Y+Z coming out of the page. The contour plots and about half of the volume
renderings use View 1. The other volume renderings use View 2. Red represents gas for
the contour plots, and blue represents the liquid in all figures.

Figures 33 and 34 are from the 50% NVF ground test in the horizontal orientation at a time
point when the liquid surface was quiescent. Figure 33 shows the reconstructed liquid
volume via LBP (translucent) and surface (opaque) in blue. The green surface is the best
estimate of the actual liquid surface, which was set by varying simulation fill height until
liquid volume matched the actual (scale-derived) liquid volume in the tank. The green
surface is an “estimate” because there is some minor uncertainty on orientation and from
the mesh resolution. To be clear, the green surface was not simulated, nor is it a
reconstruction. The surfaces are isosurfaces computed with an iso-value halfway between
the gas and test liquid permittivities. The small-scale roughness is due to the simulation
polyhedral mesh being used for rendering; interpolating to a finer mesh for these figures
would have made them look smoother, but they would not have been more accurate.
The majority of the reconstructed liquid surface is flat, though tilted slightly about X, and is warped near electrode gaps. The warping is due to many of the modeling errors discussed previously: assuming a linear solution to a nonlinear ill-posed problem, high electric field gradients near the electrode gaps, using a sensitivity matrix derived from an empty tank, the conducting tabs, unmodeled geometry, among others. The warping-near-electrode-gaps effect is present in all of the reconstructions. The warping is asymmetric because, in the horizontal orientation, the tank electrodes were not in a symmetric configuration relative to the gravity vector, i.e. it was rotated about X (see Figure 5).

Compared to Figure 6, the electrode gaps are difficult to see because the tank wall had to be made more translucent in order to clearly see the liquid volume, but their locations can be inferred by examining the locations of the visible tabs in Figure 33. Warping in the vertical orientation was confirmed to be symmetric, though vertical orientation
reconstructions are not presented here since they are not relevant to the flight tests. The warping results in imperfect reconstruction, which results in mass error. However, the CM and general liquid location are close to correct.

Figure 33 used LBP with a threshold halfway between the gas and liquid permittivity to make the gas-liquid interface sharp. Figure 34 shows contour plots that compare LBP and LW with and without a threshold. Figure 34b is a cross-section of Figure 33 with the same view as Figure 33a.
In general, LBP results in permittivity smear across most of the domain, and this characteristic is clear in Figure 34a. LW tends to sharpen the gas-liquid interface, with more iterations generally resulting in a sharper interface; some permittivity smear is still present in Figure 34c, primarily in the liquid region. LBP is used to initialize LW, which is partially why the gas-liquid interface in Figure 34b is similar to the ones in Figure 34c and d. The LW with threshold surface is slightly flatter than the LBP with threshold surface.

Using a threshold can result in more or less mass error, depending on the case. Adjusting the threshold value can result in low, or even 0, mass error, but doing that arbitrarily is not recommended, and if a priori information of the “true” mass exists to guide setting the threshold value, then the need to do ECT mass gauging at all is questionable.
Figures 35-37 are from the 20% NVF ground test in the horizontal orientation at a time point when the liquid surface was quiescent.

Figure 35: Contour Plots of 20% NVF Ground Test Reconstruction. Gas is red, liquid is blue. Liquid mass errors: a) -7.7%, b) -8.9%, c) -18.7%, d) -24%
Figure 35a is LBP, and b-c show progressive sharpening of the gas-liquid interface with LW. Figure 35d uses a threshold halfway between the gas and liquid permittivity. The liquid mass errors are greater than those from the 50% NVF examples. Lower fill levels generally had higher % mass errors, see Table 5. Figure 36 is similar to Figure 33, but for the 20% NVF test and uses LW with threshold. The reconstructed liquid volume and surface are in blue, and the green surface represents the actual liquid surface.

Figure 36: LW Liquid Volume Reconstruction from 20% NVF Ground Test: a) View 1, b) View 2. LBP reconstruction in blue, actual surface in green.

The warping is more extreme than what was seen in the 50% NVF reconstruction, and the negative mass error is apparent. The surface appears to be pulled up towards the gaps around the tank port holes and pulled down elsewhere. The CM and general liquid location (on bottom of tank) are close to correct despite of the warping. Unlike LBP, LW has parameters that adjust how it optimizes, e.g. number and step size of iterations, and these affect the resulting reconstruction. Furthermore, since LW is a type of steepest gradient
descent, the initial condition influences which local minimum LW finds and converges towards. Figure 37 is the same case reconstructed with different LW settings.

Figure 37: 20% NVF Ground Test Reconstruction: a) Contour Plot, b) Volume/surface View 1, c) Volume/surface View 2
The warping is still present in Figure 37, but it is slightly flatter in the middle of the tank and has +5.8% liquid mass error instead of -24%. Adjusting LW settings involves trial and error and should be similar between cases being compared. All of the following flight test reconstruction figures used the same LW settings, similar to those used to make Figure 34d, for consistency.

Figures 39-41 are from the 50% NVF flight test at various time points before, during, and after a low-G parabola, the same low-G parabola that was plotted in Figure 25 (IMU) and Figure 26 (liquid mass error). Figure 38 is a plot of net acceleration vs. time for this parabola, with the reconstructed time points marked and labeled with their subplot letters.

![Figure 38: Acceleration at Reconstructed Time Points, 50% NVF Flight](image)

Contour plots of permittivity are not included since the settled time points’ contour plots look almost identical to Figure 34d, and 2D contour plots are not useful for 3D volume.
visualization for the unsettled time points. For completeness, the 50% NVF flight settled time point LBP (no threshold) reconstruction liquid mass error was -4.6%, and the LW (no threshold) one was -7.7%. Mass errors for all of the flight test time points reconstructed with LW (with threshold) are in Table 16.

<table>
<thead>
<tr>
<th>Point</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>-5.1</td>
</tr>
<tr>
<td>b</td>
<td>-4.9</td>
</tr>
<tr>
<td>c</td>
<td>-4.3</td>
</tr>
<tr>
<td>d</td>
<td>+7.5</td>
</tr>
<tr>
<td>e</td>
<td>-6.5</td>
</tr>
<tr>
<td>f</td>
<td>+0.8</td>
</tr>
<tr>
<td>g</td>
<td>-6.1</td>
</tr>
<tr>
<td>h</td>
<td>-5.6</td>
</tr>
</tbody>
</table>
Figure 39: Reconstructed Time Points from 50% NVF Flight, View 1
Figure 40: Reconstructed Time Points from 50% NVF Flight, View 2
Time point “a” is in hyper-G and the liquid is settled. The reconstructed volume renderings look similar to those from the 50% NVF ground test. The green surface is perpendicular to the IMU Z axis with fill level set to match the actual liquid volume in the tank. Unlike the ground test figures, this green surface is not the best estimate of the real surface because the aircraft flew at a few degrees positive angle of attack, which was visible in the IMU data as the acceleration vector having a slight IMU -Y (tank -X, aircraft aft) component. The effect of this can be seen in Figure 40a as liquid slightly above the green surface in (tank) -X and slightly below in +X, i.e. the CM also has a slight (tank) -X component. This is encouraging because it means that, even though the base solution is warped, small relative differences can be measured and supports the theory that the CM is close to correct. The net acceleration dropped to 1 m/s² at time point “b”. The liquid surface is tilted slightly more than at point “a”, indicating the liquid has just started to rise up the wall on
the left in Figure 39b. The acceleration dropped to 0.5 m/s² at time point “c”. The green surface was removed since the liquid is no longer settled. The liquid is primarily on the -X+Z side of the tank, which is somewhat difficult to visualize from Views 1 and 2, which is why Figure 41c is included. There is some surface warping towards the electrode gaps around both tank ports. Based on the settled results, the real surface is likely less warped than that, though some liquid collection near the ports is expected at low Bond number.

Points “d”, “e”, and “f” are near 0 g, and unsteadiness in the aircraft acceleration results in somewhat random liquid motion. The ullage bubble shifts to the opposite side of the tank between points “d” and “e”. Point “e” shows some liquid blobs remaining on the side of the tank the liquid was formerly on, and two of these blobs are detached from the bulk liquid. Figure 41e is an alternative view. Due to the slight recess of the polymer filler in the electrode gaps, and the lack of polymer in the tank split plane and around the tank ports (see Figure 6), liquid collecting in these regions at low Bond number is expected. However, the reconstructed shapes of those blobs may not be accurate due to their low volume. Point “g” is at the beginning of pull out, and “h” is approximately halfway through the transition from low-G to hyper-G. The liquid begins planar and/or rotary sloshing around point “h”, and this damps out during the time in hyper-G between this and the next parabola.

Reconstructions of other times, tests, and fill levels are not presented here for sake of brevity. Reconstructions (and mass gauging accuracy) of the 5% NVF tests are the least accurate. The 5% NVF settled reconstructions are usually blobs in an electrode gap on the bottom (direction of gravity) of the tank with no surface features indicative of the true (flat)
gas-liquid interface. Thus, the volume of liquid in the 5% NVF cases is likely near or below the volumetric/spatial resolution of this ECT system. However, that is not to say this ECT system cannot measure volumes of liquid that small; it clearly can, as was shown in Section 3.8. In other words, this ECT system cannot accurately reconstruct a 3D spatial liquid distribution, i.e. shape, of a volume near or smaller than its volumetric resolution, and this negatively affects its mass gauging accuracy.

LBP is the simplest ECT method, and LW is arguably the simplest iterative ECT method. LW provided sharper gas-fluid interfaces than LBP at the expense of computational effort, and both can have thresholds applied to create binary, gas-liquid, distributions. Despite their simplicity, and the many hardware issues discussed in Section 3.10, these methods were able to locate liquid in the correct octant/region of the tank, get the CM close to correct, and, at least for fill levels higher than approximately 20%, reconstruct the shape of the liquid volume, albeit with significant warping in the vicinity of electrode gaps.

If the computed 3D liquid distributions were more accurate, they could be directly compared to 3D liquid distributions predicted by slosh simulations to quantitatively validate CFD, but their accuracy is currently inadequate due to the warping and other issues discussed above. Implementation of more advanced reconstruction methods from the literature, as well as the development of new ones, to improve the accuracy of the computed 3D liquid distributions is ongoing research. An additional challenge with CFD validation using fluid volumes is that pre-calculating and storing the millions of test time point 3D reconstructions is infeasible due to the storage space that would require. Instead, the ECT algorithms need to be integrated with the CFD software to co-solve the slosh
simulation and tomographic reconstruction, which, in addition to reducing storage space requirements, would make quantitative comparison of the 3D fluid volumes easier since importing large amounts of data (the ECT reconstructions) would not be necessary. Unfortunately, no such software exists, but a concept has been developed for a custom ECT module in OpenFOAM [53]. OpenFOAM is an open-source CFD software, and validation of it with low-G slosh data will be presented in Chapter 5.

Incidentally, OpenFOAM already contains an electrostatic solver, which could be validated in a similar manner to STAR-CCM+’s (see Section 3.6). Prior to attempting CFD validation with the ECT test data, the accuracy of different ECT algorithms with unsettled fluid configurations could be assessed using the following process. While a slosh simulation is run, the electrostatic solver calculates simulated capacitance data for each time step’s CFD-predicted fluid distribution. The capacitance data is fed into the ECT module, which reconstructs the fluid distribution using the different ECT algorithms. Error between the input and out fluid distributions can be computed to assess the accuracy of the ECT algorithms. Of course, the CFD may not have been validated yet (see Chapter 5), but high accuracy fluid simulation is unnecessary for comparing the accuracy of the ECT algorithms. After the best ECT algorithm is selected (and its uncertainty quantified), then the ECT+CFD co-solver could be used to reconstruct the test data, run slosh CFD using the IMU data, and compare the two 3D distributions for each time step to quantitatively validate the CFD.
3.10 Recommendations for ECT Hardware Improvements

The prototype nature of this ECT system must be stressed: design and fabrication were inexact, and only the simplest ECT methods were implemented. The gaps between the four electrodes in each half of the tank were $6 \pm 1 \text{ mm} \ (\pm 17\%)$, and the gaps between electrodes across the tank split plane were $15 \pm 1 \text{ mm} \ (\pm 7\%)$. From investigating capacitance measurement imbalances (see Section 3.7.1), it is clear that the electrode installation placement error contributed significantly to the overall system error. The gap uncertainties were estimated, but the actual locations of the electrodes could not be measured due to the rental contract prohibiting the tank from being opened. Some internal tank features were not disclosed by the company that built the apparatus, so these were not included in the simulation model. The accuracy of the modeled tank geometry affects the accuracy of the sensitivity matrix, so these errors in model geometry could account for the generally higher error of the LBP results compared to the mean C method results. The split plane gap contained eight aluminum tabs that projected $7 \text{ mm}$ radially into the tank; these were extraneous features leftover from a previous iteration of the tank. Electrically conductive and grounded internal features, like these tabs, reduce the ECT system’s accuracy in the vicinity of the features [25].

The gaps between the electrodes in this tank were filled with a low dielectric solid material, which prevents the liquid from interacting with some of the strong electric field that develops between electrode edge surfaces. Doing this is particularly important if the electrodes have sharp edges/corners, like the ones in this tank. Sharp electrode edges cause increased charge concentration and electric field strengthening in the tank volume near the
edges, which results in larger electric field gradients and higher non-uniformity in the tank electric field, so they should be avoided in future ECT systems for this application.

Spacing electrodes further from the wall helps reduce edge-to-grounded-wall interaction at the expense of higher system mass. Accurate placement of the electrodes in the tank and the simulation model are helpful in reducing uncertainty and error. Although gaps between electrodes are necessary and larger gaps result in lower electric field gradients in the tank, this tank had an unnecessarily large gap around the split plane that resulted in a deadband in the settled gauging results. A trade study for size and shape of the electrodes and gaps should be done via simulation in the design phase. Though not possible with this test tank, extraneous conductive features inside the tank should be avoided if they are not treated as separate electrodes. If internal features are unavoidable, which is often the case in real tanks, they should be included in the simulation model. All of these mechanical improvements would reduce the mass gauging variability observed during sloshing and low-G by reducing the variation in sensitivity throughout the tank volume.

A previous ground based ECT slosh experiment achieved higher gauging accuracy than this experiment for settled liquid and vigorous sloshing in 1 G [25]. That experiment had more, better fabricated, and more accurately placed electrodes, likely contributing to the higher accuracy. The tank geometry was a cylindrical section (quasi-2D) and without conducting internal features. Although the specifics of the ECT methodology are not included in Ref. [25], the same company mentions using LBP in Ref. [23].

Increasing the number of electrodes would increase volumetric resolution and gauging accuracy. However, there is a limit because increasing the number of electrodes means
decreasing electrode area. Every ECT system’s electronics will have some noise, which limits the smallest measurable capacitance. The electrodes cannot be made so small that their capacitance is lower than the smallest measurable capacitance, i.e. below the signal to noise ratio (SNR). That said, the capacitances measured in this tank were significantly higher than the system’s noise threshold, so there could (should) have been more electrodes. The ECT electronics package was also a prototype. Electronics improvements may be able to reduce noise and increase capacitance measurement accuracy.

3.11 ECT Study Conclusions and Future Work

Basics of ECT theory, details of the experiment setup, data processing, and test results were presented. A formal uncertainty analysis was completed, and the various forms of error, uncertainty, and accuracy have been defined and quantified in this project. With a target accuracy of 1% of measurement, the results indicate that this ECT sensor is not a useful gauge without additional signal processing after ECT calculations, i.e. filtering out the effects of slosh. Many types of sensors are not useful without filtering, so the inclusion of a digital filter in the ECT system is reasonable. If the rate limiting filter developed for this ECT system is included, then the maximum transient error (relative to actual liquid mass, not to a full tank) results indicate that this ECT system is a useful gauge for fill levels greater than 30% (greater than 10% in the horizontal orientation) in an accelerated environment (Bond number >> 100). The uncertainty of the mean mass measurement in an accelerated environment varied with fill level, from a maximum of about 8% (relative to actual liquid mass, not to a full-tank) at the lowest fill level to a minimum of about 0.5% at the highest fill level. In a low-G environment, this ECT system was able to achieve
maximum transient errors between about 12% for the lowest fill level (5% NVF) and 1.3% for the highest fill level (80% NVF), and uncertainty of the mean mass measurements ranging from about 8.5% to 1.1%. Thus, this ECT system did not achieve the 1% target if percent was defined relative to the actual (scale-measured) liquid mass.

If the 1% target is instead full-scale, i.e. defined relative to a full tank, as is commonly done for mass gauging technologies, this ECT system in an accelerated environment was able to achieve maximum transient errors ≤ 0.8% and uncertainty of the mean mass measurements <1% for all fill levels. In a low-G environment, maximum transient errors ranged between about 0.5% and 1.6%, and uncertainty of the mean mass measurements ranged from about 0.3% to 0.9%. Thus, whether or not this ECT system achieved the 1% accuracy target is dependent on the definition of accuracy. Regardless of definition, the low-G accuracy was generally worse than that seen during the ground slosh testing, which highlights the importance of low-G, flight-like environment testing. I hypothesize that a significant improvement in accuracy would be achievable with the hardware improvements mentioned in Section 3.10.

Liquid motion in the tank caused oscillations in the gauging results. Filtering out liquid motion effects significantly reduced the variations, improving the precision and accuracy of the ECT system. Although the rate limiting filter is an improvement over a moving average, filtering could still be improved. In particular, the rate limits for rate limiting filters need careful adjustment to match the current physical operation, e.g. draining.
Only impulse free-decay tests were performed on the ground. Sustained excitation of planar slosh is unlikely to impact accuracy due to the success of filtering out the effects of the consistent oscillations from slosh in the pre-filtered measurements. Sustained, random, multi-axes excitation ground tests were not run and could impact accelerated environment accuracy. That said, unsteadiness during the non-parabolic (high-G) portions of the flights produced multi-axis random excitation, and the ground test results’ error bounded the error during those portions of the flights. The quoted accuracy numbers are for a tank with a constant fill level. Filling and draining could negatively affect accuracy and should be tested both on the ground and in low-G. Each low-G portion of a parabola only lasted for approximately 18 s. If an ECT system is used in a tank experiencing longer periods of microgravity, filtering (with any type of filter) out the liquid motion effects on the ECT gauging results might be less successful, resulting in more gauging error. On the other hand, heavier filtering, such as lower rate limits in a rate limiting filter, could be used because the propellant drain rate would be zero or near zero for cryogens (boil-off). This would be like using a rate limit lower than the “medium” rate limit used for this study’s ECT system. Additionally, extended periods of microgravity will be steadier than the low-G environment of the parabolic flights, resulting in less liquid motion. Since the liquid motion in the tank drives the gauging variations, which drive the gauging error, the long-term accuracy depends heavily on where and how much the bulk liquid moves. Some practical implementation details, mechanical design suggestions, and examples were discussed, but an in-depth analysis of specific applications of ECT systems to flight tanks is beyond the scope of this work.
The settled calibration/corrections were only useful when the liquid was settled near the orientation for which they were derived. The lack of unsettled, microgravity corrections is a major challenge for ECT mass gauging. Testing at a finer fill level resolution could improve the settled corrections, but more accurate settled corrections will not significantly reduce uncertainty. Three of the largest system uncertainties were the total tank volume uncertainty driven by uncertainty of the as-built geometry, LBP process random uncertainty (LBP only), and the normalized capacitance uncertainty, which was composed of many propagated uncertainties. Preemptively addressing uncertainty in future ECT test programs would be worthwhile to ensure success.

Although it is not clear from these results which method, mean C or LBP, is better for mass gauging, it is clear that more accurate reconstruction methods could improve the ECT system accuracy. To be useful in an ECT measurement subsystem of a flight controller, the ECT algorithm must have a low enough computational cost to be implemented in real-time. The real-time requirement could be relaxed if low-rate gauging measurements are acceptable. More accurate reconstruction methods are also needed because the current accuracy of the computed 3D liquid distributions is inadequate for slosh CFD validation. Since mechanical improvements are straightforward to implement, and previous works demonstrated functionality with cryogens, my current research focuses on implementing more advanced ECT methods from the literature and new algorithm development. The development of an open-source ECT+CFD co-solver to facilitate CFD validation is planned future work.
4.1 Introduction

The ISS SPHERES-Slosh Experiment (SSE) Program collected, cumulatively, hours of high-resolution video of low-G slosh data. Chapters 1 and 2 cover background, motivation, and literature review. This chapter presents the mechanical, electrical, and software design, fabrication, qualification testing, and ground testing of the SSE. The content of this chapter focuses on information useful to understanding the CFD validation results presented in Chapter 5. Refs. [38] and [40] contain more details of the design.

4.1.1 Objectives

The primary objective of the SSE program was to collect high-resolution imagery of long-duration, low-gravity, coupled-motion slosh with synchronized motion data and well-defined initial conditions. Another objective was to use this dataset to validate microgravity slosh CFD simulations. High-level design requirements were derived from these objectives.

4.1.2 Technical Approach

After the need for this dataset was identified, and the experiment objectives defined, the next step was establishing the approach and high-level design requirements. Utilizing the ISS Laboratory was significantly less expensive than a bespoke satellite, and utilizing
existing hardware already on the ISS, the Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) robots, reduced costs and enabled rapid development. The SPHERES were miniature satellites designed by the Massachusetts Institute of Technology (MIT) Space System Laboratory (SSL) to operate inside of the ISS. ISS payload requirements documents and regulations drove many of the design decisions. Interchangeable optically clear tanks partially filled with liquid were the primary component of the experiment. Two SPHERES were required to be able to apply symmetric thrust to the tank, and the tank was sized based on the capabilities of the SPHERES thrusters. The SPHERES thrust, as well as ISS crewmember-applied motion, resulted in accelerations and rotation rates, which were measured with inertial measurement units (IMUs), and the resulting slosh was coupled with the motion of the whole apparatus. Various maneuvers simulating the motion of real spacecraft were performed. Finally, attached cameras recorded video of the liquid in the tank in the tank reference frame.

4.1.3 Phases

The SSE program had multiple phases. Since the SPHERES were propelled with CO₂ cold-gas thrusters, Phase 1 attempted to induce and measure the slosh of CO₂ in a SPHERES propellant tank. This was done first since it required no additional hardware. This phase was ultimately unsuccessful, and it indicated that a larger, externally mounted tank was required. Phase II concluded in 2013 and was the design, fabrication, and ground testing of the SSE. Following phases included launch (Cygnus Orb-1) and the science sessions, during which the low-G slosh data was collected. Official test sessions concluded in 2016.
4.2 Maneuvers and Scaling

This section presents a discussion and analysis of the dynamics of the maneuvers that the experiment will perform while operating on the ISS. The experimental maneuvers are specifically selected to mimic a range of typical maneuvers associated with upper stage launch vehicle operation. A scaling analysis based on similitude of relevant non-dimensional parameters is developed and is then used to demonstrate the ability of the experiment to replicate full-scale upper stage operations. Opportunities and constraints from this analysis are used to inform the design of the experiment.

4.2.1 Maneuvers

For this program, “long” duration slosh is defined as similar duration to on-orbit spacecraft maneuvers, which typically last between several seconds to several minutes. On-orbit maneuvers of launch vehicle upper stages were used to inform the selection of maneuvers the SSE would perform and to determine relevant accelerations for input to a nondimensional scaling analysis.

To prevent vapor pull-through and gas ingestion into the rocket engine, propellant settling maneuvers typically use reaction or attitude control thrusters to apply a small acceleration to settle the liquid propellant at the sump of the tank. Passive thermal control (PTC) maneuvers are rotations about a stage’s primary acceleration axis (roll) during long coasts that distribute solar heating around the stage’s tanks, preventing hot spots. An attitude change maneuver reorients the stage to point in a specific direction and sometimes involves both a translation and a rotation. Attitude change maneuvers are performed for various
reasons, such as orienting a stage for a main engine burn or spacecraft separation event.

Tank dimensions, thrusts, time durations, accelerations, rotation rates, and angular accelerations for these maneuvers were selected from publicly available data for a variety of launch vehicles [54 - 65].

### 4.2.2 Nondimensional Scaling Analysis Overview

To ensure fluid dynamic similarity between actual spacecraft and the SSE, relevant nondimensional scaling parameters were matched (where possible) between the full-scale upper stages and the SSE’s tanks and maneuvers. The analysis in this section is similar to the scaling analysis performed for the ECT parabolic flight project (see Section 3.3.2), but focused on maneuvers instead of fluid selection. Ideally, this analysis would also inform the selection of the test fluid, however due to ISS regulations, permissible test fluids were limited and distilled water was selected. Other microgravity laboratories, such as drop towers and parabolic flight aircraft, allow a wide range of test fluids, including cryogens and engineered fluids.

The parameters relevant to the experiment are acceleration, $a$, characteristic length of the tank, $L$ (chosen to be the tank diameter, $D$), liquid velocity, $U$, dynamic viscosity, $\mu$, density, $\rho$, and surface tension, $\sigma$. Acceleration and velocity are dependent on the maneuver. These parameters can be arranged into several nondimensional numbers that provide insight into the fluid dynamic “regime”, i.e. whether inertia, body acceleration, viscous, or surface tension forces dominate the fluid dynamics. Eqs. 9-12 in Section 3.3.2 defined the Reynolds number ($Re$), Weber number ($We$), Bond number ($Bo$), and Froude
number \((Fr)\), respectively. As mentioned previously, \(Re\) similarity is only necessary for accurate measurements of viscous damping in slosh testing, and \(Re\) for subscale slosh testing of full-scale cryogenic tanks is rarely matched in practice. Since accurate measurement of viscous damping was not a primary objective of the SSE, \(Re\) similarity was not necessary.

Relevant scale velocity and acceleration needed to be derived for each maneuver type to examine \(Bo\) and \(We\). Because of the dependence on tank size, this analysis was iterated in tandem with the preliminary experiment design.

4.2.3 Settling Maneuver Scaling

To perform the scaling analysis, it is assumed that the initial velocity of the liquid relative to a stationary pill-shaped tank is zero, and the initial collated liquid location is at one end of the tank. For the actual SSE experiments, it is recognized that these initial conditions are difficult to attain. Further, it is known that even small variations in initial conditions can lead to different fluid dynamic behaviors for the same motion. For the purposes of the scaling analysis, the tank is accelerated at an acceleration, \(a\), towards end of the tank that initially held the liquid. In the reference frame of the tank, this results in the liquid traversing the major axis of the tank for an assumed distance of \(2R\), and impacting the tank wall with a final velocity, \(U\). Eq. 15 is used to compute final velocity.

\[
U^2 - 0 = 2a2R \rightarrow U = \sqrt{4aR}
\]  

Eq. 15

\(We\) and \(Bo\) were calculated for all tanks for various \(a\), the results of which are plotted in Figure 42. The “water” points are from the SSE.
The dashed line represents $Fr=1$. All calculated points have $Fr=4$ due to $a$, $U$, and $L$ being related by Eq. 15, which means the rocket upper stage and SSE tanks are slightly in the inertia-dominated regime for this maneuver. Neither $Bo$ nor $We$ could be matched with water as the SSE test fluid. Matching $We$ and/or $Bo$ would require a larger tank and a simulant liquid with a larger $\rho/\sigma$ ratio. Larger $a$, resulting in larger $U$, can partially compensate, however, acceleration is ultimately limited by the thrust performance of the SPHERES, or ISS crewmembers if maneuvered manually.

An alternate relationship between acceleration and velocity can be derived from planar slosh with an assumed (scaled) wave amplitude (Section 3.3.2, Eqs. 13 and 14), which may be used if the liquid is already located at the end of the tank opposite the direction of acceleration, i.e. the tank sump. This method’s results are similar to those shown in Figure 42: a nearly-constant $Fr$ in either the inertia or body acceleration regime, depending on
assumed wave amplitude, and the SSE tank resulting in lower \( We \) and \( Bo \) than the full-scale tanks.

### 4.2.4 Passive Thermal Control Maneuver Scaling

PTC maneuver scaling was accomplished by adjusting the rotation rate of the SSE tank about its major axis to obtain similar \( We \) and \( Bo \) as full-size upper stage vehicles. The smaller radius of the SSE tank meant that the rotation rate of the SSE had to be higher to produce the required centripetal acceleration and velocity at the tank wall consistent with full-scale vehicles. The rotating tank wall accelerates adjacent liquid due to viscous drag, and centripetal acceleration causes the liquid to collect on the tank wall. Eventually, the liquid achieves a steady state condition similar to solid body rotation. The amount of time it takes for this condition to develop is related to the momentum diffusion length scale. The solution to the Navier-Stokes equation for impulsively started flat plate at constant speed, which can be used as an analog to the case of a rotating tank if curvature effects are ignored, results in \( \delta \propto \sqrt{\nu t} \), where \( \nu \) is kinematic viscosity, and \( t \) is time. This can be used to estimate the required SSE (r)evolution time as follows:

\[
\frac{\delta_{fs}}{R_{fs}} \left( \frac{1}{\delta_{SSE}} \right) \left( \frac{R_{SSE}}{R_{fs}} \right) = 1 = \frac{\sqrt{v_{fs}t_{fs}}}{\sqrt{v_{SSE}t_{SSE}}} \rightarrow t_{SSE} = \frac{v_{fs}}{v_{water}} \frac{t_{fs}}{t_{water}}
\]

where the subscript \( fs \) denotes one of the full-scale tanks. For example, the ratio \( \frac{v_{fs}}{v_{water}} \) for \( LH_2 \) is approximately 0.21, meaning the SSE tank takes about 1/5 as long as a \( LH_2 \) tank to reach a similar rotating fluid state. This assumes no radial baffles, stringers, isogrid, or
other internal tank structure that could enhance the liquid’s rotation, are in the tank, which is the case for the SSE tank (smooth walls), but is not the case many examples of actual upper stage tanks, which means Eq. 16 $t_{SSE}$ is an overestimate. The fact that $t_{SSE} < t_{fs}$ is convenient because it means the simulated PTC maneuver performed with the SSE can be shorter than with a full-scale tank.

An ISS safety requirement limited the rotation rate (axial roll) of the SSE to 60 deg/s. Despite this limitation, $We$ and $Bo$ similarity were achievable for this maneuver.

4.2.5 Attitude Change Maneuver Scaling

The attitude change maneuver consists of both a translation and rotation, and the rotation is about an axis other than the tank-axial/roll axis. Tank dimensions, maneuver time, and degrees rotated set the angular and linear accelerations and velocities, which are used to calculate $We$ and $Bo$. Similar to the PTC maneuver, the rotation rate can be adjusted to achieve $We$ and $Bo$ similarity between the SSE and full-scale tanks. However, the rotation rate was limited to 10 deg/s due to an ISS safety requirement, which is lower than the axial roll rate limit because the SSE sweeps a larger area when rotated about a non-roll axis.

4.2.6 Manoeuvres and Scaling Analysis Results Summary

Water was selected as the test fluid for the SSE due to ISS operational and safety requirements. In summary, the scaled maneuvers resulted in the SSE operating in either inertia or acceleration dominated regimes. $Re$ similarity was not achieved for the proposed ISS experiments. Exact $Bo$ and $We$ similarity was not achievable for the scaled settling
maneuvers, but similitude was achievable for the PTC and attitude change maneuvers. Additionally, the capillary dominated regime \((Bo < 1, We < 1)\) was achievable by keeping the acceleration, and resulting fluid velocity, low, i.e. by performing low acceleration, slow maneuvers that generally resulted in surface waves with no bulk fluid motion.

4.3 Design and Fabrication

This section presents the design requirements, mechanical design, and fabrication of the SSE.

4.3.1 Design Requirements

Section 4.1.2 provided an overview of the SSE design requirements and constraints. Leveraging assets that were already available on the ISS, specifically two SPHERES with Visual Estimation for Relative Tracking and Inspection of Generic Objects (VERTIGO) flight computers, was helpful to reduce cost and complexity of the SSE design, although in some cases was accompanied by inherent performance limitations associated with SPHERES and VERTIGO. Additional SSE hardware included a tank, mechanical connections between the tank and SPHERES, cameras, and associated electronics and hardware to support data acquisition and integration of the experiment.

The tank needed to be clear, partially filled with water, and permanently sealed for crewmember safety. Ideally multiple fill levels, meaning multiple interchangeable tanks, would be tested to expand the scope of the data set for validation. The tank shape needed to be generic, yet representative of actual upper stage propellant tanks. A cylindrical section
with hemisphere ends (pill) shape was selected to provide an aspect ratio of 2:1, meaning that the length of the tank was twice the diameter.

Due to the fundamentally 3D nature of possible liquid distributions in microgravity within a tank, it was decided that multiple camera angles would be beneficial. Two cameras with orthogonal views of the tank were specified.

By comparing the limits of the SPHERES accelerometers, ±25.6 mG, and gyroscopes, ±83 deg/s, with results of the maneuver scaling analysis, it was also determined that an additional, higher-range IMU was required (see Section 4.4.4).

System mass needed to be minimized to maximize achievable acceleration, however this requirement was constrained by ISS experiment structural safety factors. ISS requirements also constrained material selection. The detailed design choices that flowed from these requirements will be discussed in this section.

4.3.2 Layout

In order to minimize undesired resultant off-axis motion, the tank centroid and center of mass of the whole apparatus was placed symmetrically on the axial thrust axis of the two SPHERES, as shown in Figure 43. This placement guarantees that any paired thruster firings on the two SPHERES will not induce rotation on the rigid (liquid-less) system. This layout offers a few camera locations that satisfy the orthogonal view requirement.
4.3.3 Connecting Structure

Various concepts and design trades were made after the basic layout was set. The primary structure would be aluminum because it was an allowed material, stiffer than plastic, and less dense than steel. The SPHERES CO\textsubscript{2} cylinders would be used for holding the SPHERES, but an alignment feature in the SPHERES mount would be necessary because the CO\textsubscript{2} cylinders were round. The SPHERES holders would be connected by arms to a central hub that had provisions to hold the tank. The hub would have four arm connection points, allowing for different tank orientations or future expansion. A structure around the tank would be needed to hold a counterweight opposite the arms to offset the mass of the SPHERES holders and arms. The cameras could be used as some of the counterweight, so they were also mounted to this structure.
4.3.4 Material Limitations and Selection

Since this experiment would be aboard the ISS, it was subject to the many requirements and regulations of manned space flight. For materials, the three primary concerns are flammability, off-gassing, and material degradation. Materials and Processes Technical Information System (MAPTIS) and MSFC-STD-3029 [66] are the two governing material databases.

Aluminum alloy was chosen for the primary structure for the reasons discussed previously. Aluminum can exhibit stress cracking, but NASA and ISS granted a waiver for the use of AL2024-T351 as long as it was anodized. 316 stainless steel was used in the camera system components because it is corrosion resistant and has a high surface hardness, and its high density (along with the camera locations) helped reduce the mass of the counterweight.

The remaining major components were 3D printed from plastic using Fused Deposition Modeling (FDM) and Stereolithography (SLA) technologies. The SSE was the first experiment onboard ISS to use multiple 3D-printed parts for its structural components. A polyetherimide plastic, Ultem, is a suitable MAPTIS approved non-flammable thermoplastic that can be used in FDM 3D printers. Although expensive, Ultem is high-strength and low-density, and it was used to fabricate many of the components of the SSE. The transparency requirement for the tank proved challenging. In order to minimize seams and make fabrication simpler, the tanks were SLA 3D printed out of Lexan, specifically Somos WaterClear Ultra 10122. However, samples of the tank material failed flammability
testing. NASA granted a waiver for this material under the condition of it being encased in Ultem or other flame-retardant/nonflammable materials. Encasing the tank proved necessary anyways in order to provide a clean backdrop and minimize reflections for the cameras. A component of this was an accordion style bellow that extended from the Ultem case (“hood”) around the tank to each of the cameras. The bellow was made from NABELLE 20 and 60, making it nearly 100% opaque, as well as non-flammable. The remaining components, such as fastening hardware and electronics, were made from preapproved materials.

Due to the use of 3D printed structural components being new with this experiment, there were some lessons-learned.

- Screw holes, inserts, or imbedded hardware should not be placed near edges or corners such that they compromise the wall thickness of a part. Use counterbores in lieu of countersinks to alleviate radial stresses.

- A structural finite element analysis (FEA) should be performed on all 3D printed components. Local stress concentrations should be identified and mitigated in the design. 3D printing creates a nonhomogeneous, anisotropic product, and this should be taken into account in the structural analysis and margin on factor of safety.

- A skilled machine operator is required to adjust the printer settings to ensure the best product possible.
- A record of the printer logs should be delivered to the experiment PI for traceability and future replication.

- Installation torque for fasteners in 3D printed parts should be calculated.

- A powerful backlight should be used to inspect the part for any cracks.

- Batch production coupons should be printed and logged.

- Based on the structural analysis, identify the portion of the component receiving the highest stress, replicate that portion as a coupon of that same batch, and destructively test the coupon. The resultant force for deflection and yield of the product should be matched against simulation and failure must occur within the established factor of safety.

The only 3D printed component failure was a corner of one of the Ultem avionics boxes, which had cracked off between packing before launch and unpacking on the ISS after launch, though when this occurred is unclear. Fortunately, this flaw was not a functional impediment.

4.3.5 Final Design

The final design is presented before further discussing its components and subassemblies to make visualization for the reader easier. The design evolved to what is shown in Figures 44 and 45 through many iterations and design reviews.
Figure 44: SSE Full Assembly

Figure 45: Component View of SSE
4.3.6 Major Assembly Components and Interfaces

The SSE was a multi-part assembly and would have to be disassembled for stowage for launch and on the ISS, so tool-less assembly was desired to make assembly/disassembly simple for the crewmembers. Thumbscrews, pins, and alignment features were utilized for their ease of use and manufacture, and all fasteners had to be captive as per regulations.

The two frame arms attached to the center hub via thumbscrews. A SPHERES robot was installed on the end of each frame arm. As shown in Figure 46, it rested in a saddle for alignment and had a thumbscrew-driven clamp that gripped the CO$_2$ tank to fix it in place.

![Figure 46: SPHERES Mount](image)

The tank had features for threaded fastener inserts, which interfaced with the center hub structure around the tank via thumbscrews. The tank attachment points also held the Ultem backdrop. The cameras needed to be precisely and repeatably positioned and oriented. They were held in a stainless steel dovetail mount by a pin, and the mount was permanently attached to the central structure. The avionics boxes plugged into the VERTIGO flight computers and did not require additional mounting hardware. An ISS
regulation required all edges of parts to be rounded. For all edges of thickness 6.4 mm or
greater, a minimum of 3.0 mm radius was required. This applied to the majority of the
external edges, both metallic and plastic, of the SSE. Some of the edges fell under the 3.0-
6.4 mm category, and these had a minimum radius of 1.5 mm.

4.3.7 Center of Mass Analysis

In 6 degree-of-freedom (DoF) rigid body motion, net moments must be zero to produce a
pure translational movement. The easiest method to achieve this is to place the CM of the
experiment on the thrust plane of SPHERES. Because the layout of the experiment (Figure
43) resulted in symmetry in two planes, the CM offset from the origin (tank centroid) was
zero in two axes. A counterweight was required to bring the CM offset to zero in the other
axis. In an effort to minimize the mass of this counterweight, it was added as far away from
the centroid as possible. The counterweight is the aluminum block at the top of the center
structure in Figure 44. The counterweight turned out to be a convenient handle for the
crewmembers.

Of course, not all of the components of this experiment were rigid bodies. The SSE had
three tanks partially filled with fluid: the SSE test tank and the CO₂ tank in each
SPHERES. The CO₂ tanks’ long dimension was along the counterweighted axis, so the
mass of the counterweight was set assuming the CO₂ tanks were half full. The CO₂ tanks
started full, and drained as the thrusters were used. The two SPHERES did not necessarily
have symmetric firing patterns, meaning the CO₂ tanks did not necessarily drain at the
same rate. CM shifts due to the water in the SSE tank and CO₂ relocating were calculated
in order to create a CM envelope. Worst case CM movement along the long axis of the SSE tank was approximately ±7 mm, and approximately ±2 mm in the other axes. The CO$_2$ was only about 1% of the mass of the SPHERES, but the large moment arm to the CO$_2$ tanks magnified its effects. Although the majority of the CM envelope was due to the water, the slosh effects of the CO$_2$ in the collected data may not be negligible.

4.3.8 Tank Design

Several design iterations resulted in the internal tank dimensions shown in Figure 47.

![SSE Tank Internal Dimensions, mm](image)

**Figure 47: SSE Tank Internal Dimensions, mm**

Because the tank had to be sealed to prevent leaks, it was classified as a pressure vessel and subject to proof testing with a 1.5 atm pressure differential (Section 4.7.4). Finite Element Analysis (FEA) was performed to determine an adequate wall thickness for the tank, which would be 3D printed out of Lexan. Acceleration effects were considered in addition to the differential pressure requirement. The FEA determined that a wall thickness of 3.175 mm would provide a minimum factor of safety of 13 on stress, well above the requirement [67].
The tank was designed to be printed in two parts, filled with water, and then permanently joined with an adhesive. Two tank volume fractions would be tested: 20% and 40%. A solid mass simulator was also 3D printed. The tank mounting features, consisting of two bosses with threaded inserts on the 3D printed tank and thumb screws, are visible in Figure 45 and Figure 51a.

4.3.9 Fabrication

After the final detailed design passed review, the components were fabricated. All metal parts were CNC machined and had quality assurance inspections to confirm tolerances were met. The aluminum parts were sandblasted and anodized according to MIL-A-8625. A custom printed circuit board (PCB) was created for the Slosh Avionics. The Ultem parts were 3D printed, as was the tank.

The tank surface had a rough finish, so it was polished to make it optically clear before filling. Green dye (food coloring) was added to the distilled water via syringe, and a dispensing bottle was used to fill the tank. A precision scale was used during filling to ensure the target fill level in the tank was achieved. The two halves of the tank were then bonded together. This was repeated for the other tanks.

Two complete SSE units were fabricated, a flight unit and spare/ground unit.
4.4 Electrical Components and Design

The description of SSE electrical components and design in this section is abridged for conciseness and because this hardware has been deorbited. For more details, including electrical schematics, see Refs. [38] and [40].

4.4.1 Communication and Power

Figure 48 is a simplified schematic of the SSE’s power and communication.

![Communication and Power Schematic](image)

**Figure 48: Communication and Power Schematic**

A crewmember would command the start of the experiment using the provided controls on the Graphical User Interface (GUI) on an ISS laptop. SPHERES 1 would indicate to SPHERES 2 the start of the experiment through a synchronized wireless signal. This signal
triggered both VERTIGO units using a UART serial port connection between each of their PICO ITX P830 computers and connected SPHERES. The goal was to trigger both sides with a maximum delay of 1 ms in order to ensure synchronization between the two VERTIGO units, but this was not achieved (see Section 5.2). Each Slosh Avionics box was designed to be compliant with the VERTIGO interface requirements and connected to VERTIGO via its ERF8 header, which held all extensible payload connections. The PICO ITX P830 computers handled command to, and data collection from, the cameras via ethernet and the Slosh Avionics IMUs via USB, using an FTDI as an intermediary. The FTDI also provided the additional benefit of regulating power for the IMU. 12 V power for the cameras and lighting came from the VERTIGO battery through an internal regulator and then a PXD30W DC regulator in the Slosh Avionics box. The Slosh Avionics boxes had external LEDs for indication of operating mode and functionality. Total Slosh Avionics power consumption was around 25 W each.

4.4.2 Electrical Design Requirements

The VERTIGO and Slosh Avionics contained certified circuit protection elements, including over/under/reverse-voltage, electromagnetic interference (EMI) attenuation, radio frequency interference (RFI) attenuation, and current limiting. Best practices were followed for PCB design, wire sizing, and cable fabrication. All connectors on the Slosh Avionics box were female, which prevented any accidental pin contact or shorting by a crewmember. All electronics passed quality inspection and were tested for EMI and RFI (Section 4.7.2).
4.4.3 Data Storage

The SSE used three 32 GB USB drives that were approved and compatible with the ISS laptops, and four internal SSDs for data storage. The VERTIGO operating system (OS) was installed on the SSDs, which were essentially identical to the original SSDs in the VERTIGO units except for SSE-specific drivers, e.g. camera drivers, and software, which meant they did not require qualification testing. The use of components that were already flight qualified benefited the project budget and schedule. Two of the SSDs served as backups. Backups and redundancy in failure-prone electrical hardware improved the likelihood of successful experiment execution.

4.4.4 Inertial Measurement Units and Reference Frames

The Slosh Avionics boxes had redundant CH Robotics UM6 IMUs. These 6-axis IMUs were selected to extend the measurable range of accelerations and rotation rates to ±2 G and ±2000 deg/s, respectively. Only one IMU in each box was used at a time. Table 17 and Figure 49 provide the positions of the Slosh IMUs’ origins in the local (attached) SPHERES’ body frame, the origin of which is at the geometric center of a SPHERES.

<table>
<thead>
<tr>
<th>IMU</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.184</td>
<td>0.049</td>
<td>-0.025</td>
</tr>
<tr>
<td>2</td>
<td>0.184</td>
<td>-0.049</td>
<td>-0.025</td>
</tr>
</tbody>
</table>

Table 17: Slosh IMU Positions in Local SPHERES' Body Frame, meters
The SPHERES accelerometers and gyroscopes had ranges of ±25.6 mG and ±83 deg/s, respectively. Table 18 provides the positions of the individual SPHERES accelerometers in the SPHERES’ body frame.

**Table 18: SPHERES Accelerometer Positions in the SPHERES’ Body Frame, meters**

<table>
<thead>
<tr>
<th>Accelerometer</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-axis</td>
<td>0.0519</td>
<td>0.0217</td>
<td>0.0327</td>
</tr>
<tr>
<td>Y-axis</td>
<td>-0.0266</td>
<td>0.0335</td>
<td>0.0330</td>
</tr>
<tr>
<td>Z-axis</td>
<td>0.0328</td>
<td>-0.0437</td>
<td>0.0335</td>
</tr>
</tbody>
</table>

Figure 50 shows the SPHERES and SSE reference frames and their origins.
The SSE body frame is parallel to SPHERES 1’s (“primary” SPHERES) body frame, translated to the geometric center of the SSE tank. The SPHERES 1 and 2 body frame origins are located at $X = -0.42$ m and $X = +0.42$ m, respectively. Relative to SPHERES 1, SPHERES 2 (“secondary” SPHERES) is rotated 180 deg about its local Z axis.

Knowledge of these reference frames and positions is necessary for applying rigid body kinematic transformations to the individual accelerometers’ data in order to transform the inertial data into the SSE body frame. The four sets of accelerations and rotation rates can then be fused and integrated to obtain position and orientation versus time, i.e. trajectories (see Section 5.2.1).

4.4.5 Cameras and Lighting

Two 5MP IDS UI-5580CP ethernet cameras, with wide-angle, low-distortion lenses, mounted to the center hub structure provided imagery of the tank from two, orthogonal
perspectives in the SSE reference frame. Figure 51 shows the cameras and SSE lighting assembly.

![Figure 51: SSE Lighting. a) Cross Section, b) Lighting Assembly with both lights on](image_url)

The goal was to evenly illuminate the tank while having as few reflection artifacts as possible. The tank was encased by the backdrop, hood, and bellows. The tank being encased with matte materials helped to minimize reflection artifacts in the images. There were two LED light strips with diffusers, called “light panels”, one mounted in the hood and one in the backdrop.

The cameras were tested for alignment and picture quality using a color-board. The cameras’ settings, such as exposure, contrast, and brightness were varied to maximize image quality, and these settings were programmed into the SSE software.
The locations of the center of the sensors in the cameras are in Table 19. Knowledge of the camera locations is important for accurately reproducing their views during post-processing of CFD simulations. The cameras are aimed at the geometric center of the tank.

<table>
<thead>
<tr>
<th>Camera Side</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (primary)</td>
<td>0</td>
<td>-0.174</td>
<td>0.174</td>
</tr>
<tr>
<td>2 (secondary)</td>
<td>0</td>
<td>0.174</td>
<td>0.174</td>
</tr>
</tbody>
</table>

### 4.5 Software and Data

The SSE software built upon the existing SPHERES and VERTIGO platforms developed by MIT. The SPHERES and VERTIGO software had an application interface (API) for researchers using them as part of the Guest Scientist Program (GSP) [68]. The API consisted of simplified code capable of controlling the rest of the software and hardware. Custom SPHERES and VERTIGO software files based on the GSP were written for the SSE to interface with the Slosh Avionics, control the SPHERES, and handle communication between all components.

A parameter file controlled the Slosh Avionics functionality, such as camera settings and which IMU would be used. The slosh IMUs operated in asynchronous serial communication, and the data was collected at a variable rate of approximately 20-30 Hz. Image acquisition was not synchronized between the primary and secondary avionics and had a variable rate of 1-2 fps. Each image frame was triggered after the previous frame had
been transferred from the camera to the avionics. Saving of the previous frame occurred while the next frame was being exposed and transferred. This was done to optimize CPU time, which was necessary because the VERTIGO CPUs were a performance bottleneck.

The SPHERES metrology system was not used for this experiment due to a hardware issue and because the experiment often traveled outside of the volume defined by the beacons. Thus, no absolute position or orientation data was recorded.

The collected data directory structure is as follows. Each test session is numbered and has an “_A” (primary) and “_B” (secondary) side folder. Inside of those folders are “TP_1201_Slosh” folders, and inside those are individual test folders labeled “run_<timestamp>”. Inside each run folder are a “GSdata” folder, for data, and an “images” folder. The IMU data from the SPHERES is saved to an “imu_data.txt” file, while the IMU data from the Slosh Avionics box is saved to a “slosh_imu.txt” file. The first line of the slosh_imu.txt file has either “ttyusb0” or “ttyusb1”, which correspond to the active IMU, IMU 1 or IMU 2 (see Figure 49), respectively. Slosh Avionics IMU accelerations are in units of G’s and rotation rates are in deg/s. SPHERES accelerations are in m/s² and rotation rates are in rad/s. Data was saved in the IMU’s coordinate system, so it must be rotated and transformed in post-processing. The images folder contains a file called “imageTimetags.csv”, which has a timestamp corresponding to the beginning of data collection and times of each image in milliseconds relative to the starting timestamp. The 5 MP images were cropped to the area of interest (approximately 2.4 MP) before being saved as uncompressed .bmp files. Various other files, such as test logs and script logs, are also in the test data directory structure.
Although the original intention was to have all data and image collection synchronized, this was not achieved. The two Slosh Avionics boxes and two SPHERES all ran on different clocks and had different reference times. The lack of time synchronization, along with some other data issues, made post-processing difficult. Data processing challenges will be discussed in Section 5.2.

### 4.6 Trajectory Planning

Substantial effort went into creating SPHERES thruster maps, planning maneuver profiles, and optimizing thruster firing sequences to execute the maneuvers. Trajectory sensitivity to shifts in CM due to liquid motion was also calculated for each maneuver. Unfortunately, the thrusters had degraded over the life of the SPHERES, and their thrust was insufficient to execute the desired maneuvers. The majority of the test sessions used manual motion generation, where the crewmember would apply forces and torques to the SSE by hand. Manual motion allowed for a wider range of accelerations and rotation rates than what would have been achievable with ideal SPHERES thrusters, and coupled slosh-motion occurred if the crewmember released the SSE after force application.

The CAD-computed moments of inertia of the SSE with the 40% fill fraction mass simulator tank are shown in Table 20. An attempt was made to verify these inertias during the first ISS test session by using the measured angular accelerations and expected thrust from the SPHERES thrusters, but this was unsuccessful due to degraded thruster performance. Linear accelerations and known SSE mass were used to attempt to characterize the thrust performance of groups of thrusters, but the uncertainty on the
calculated thrust resulted in large uncertainty on the moments of inertia, with the CAD values falling within that range.

Table 20: SSE Moments of Inertia, kg-m²

<table>
<thead>
<tr>
<th>Moment of Inertia</th>
<th>CAD Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{XX}</td>
<td>0.3151</td>
</tr>
<tr>
<td>I_{YY}</td>
<td>2.5471</td>
</tr>
<tr>
<td>I_{ZZ}</td>
<td>2.4326</td>
</tr>
</tbody>
</table>

4.7 Verifications and Qualification Testing

The SSE had to pass many verifications and qualification tests required by NASA to be flight rated. NASA standards, e.g. [69] [70], describe the required verifications and tests, as well as details of how they must be performed. A flight safety data package, which identified the SSE’s hazards, was also required, and the identified hazards required mitigations and verifications. All of these requirements were considered during the design process, so all final, post-assembly verifications passed. A summary of the verifications and qualification testing performed is presented in this section. The SSE failed some qualification tests, which either resulted in waivers or rework, and these will be discussed in more detail. Since the SPHERES and VERTIGO boxes were already qualified and on the ISS, no verifications or testing of their components were necessary, though SPHERES and VERTIGO ground units were used in some of the tests since they were integral parts of the SSE.
4.7.1 Verifications

All components and materials used in the SSE had to be assessed for flammability and off-gassing. Materials needed to be on the MAPTIS list of approved materials, to pass flammability and off-gassing testing, or accepted based on similarity or analysis. For example, the AL 2024 used in the SSE frame is on the MAPTIS list, the 3D printed Ultem passed flammability and off-gassing testing, and the cameras were accepted by analysis.

In addition to flammability and off-gassing, all materials were assessed for compatibility and toxicity. No material compatibility issues were discovered. The distilled water in the tank was dyed with trace amounts of green food coloring, and it was assigned a toxicity hazard level rating of 0.

The Slosh Avionics boxes, cameras, hood, and backdrop were identified as susceptible to temperature changes, making them potential touch temperature hazards. All surfaces that crewmembers can touch must remain in the temperature range of 4-45 ºC. The complete, assembled, flight article underwent touch temperature testing at Marshall Space Flight Center (MSFC). The SSE was powered on, and temperature readings of the identified components were taken every five minutes for a total duration of 60 minutes. All components remained within the required temperature range.

Because the SSE had electrical components, its potential to cause electrical power injuries had to be assessed. This verification included a design review of the schematics, review of possible failure modes, and inspections of the Slosh Avionics boxes and wiring harnesses. The power source for the SSE was VERTIGO’s battery, and VERTIGO had been
previously qualified for flight. Various design choices (Section 4.4.2) were made with electrical and crew safety in mind, which resulted in the SSE passing the electrical verifications.

There is a human spaceflight requirement that all vented containers must have a total ventable volume to vent area ratio of less than 2000 in. The Slosh Avionics box had a ventable volume to vent area ratio of 296 in, which met the requirement. The test tanks were not subject to this requirement because they were not vented. Figure 52 is a picture of the Slosh Avionics box with the vent highlighted.

![Slosh Avionics Box](image)

**Figure 52: Slosh Avionics Box Vent**

The SSE was designed to be a free-floating experiment inside of the ISS. An assessment of force, acceleration, and kinetic energy during planned maneuvering was performed to verify that they were low enough for a crewmember to safely grab the SSE frame during a test. It was determined that the SSE would not impede other crew activities nor impede
egress to adjacent modules. The SSE required a crewmember to initiate maneuvers, and an operation control required a crewmember tend it at all times when not stowed.

4.7.2 EMI Qualification Testing

The complete SSE underwent radiated emissions testing for electromagnetic interference (EMI) at the MSFC EMI test facility. NASA SSP-30237 [71] prescribes test and emissions limits requirements. Previous EMI testing of SPHERES and VERTIGO showed the inability of VERTIGO electrical hardware to pass the radiated emissions test. The same exceedance was noted in SSE testing, with some additional signal emission strength in the 200 MHz – 1 GHz band from the Slosh hardware, and a waiver similar to VERTIGO’s was granted.

EMI susceptibility testing involved bombarding the SSE with electromagnetic radiation. The SSE was functional tested at each increment in the radiation spectrum. The SPHERES’ wireless link operated at 868.5 MHz, so loss of communication during interference testing at this frequency was expected. This testing took two days, and no off-nominal SSE performance was noted. Figure 53 is a picture from the EMI susceptibility testing.
4.7.3 Vibration Qualification Testing

Components that contained potentially shatterable materials were identified and appropriate mitigations were implemented. For example, the camera lens glass was susceptible to shattering during launch, so it was triple bagged, with the innermost bag being clear so that a crewmember could visually inspect the lens prior to opening the bag.

Vibration qualification testing of the SSE in its flight bag stowed configuration was performed. The SSE was manifested to fly on an Orbital Sciences (now Northrop Grumman) Antares. The Antares random vibration environment had been characterized on previous flights (Figure 54), and the random vibration testing envelope was set to meet or exceed the flight envelope.
Vibration qualification testing was performed using a single axis horizontal vibration table and a single axis vertical vibration table. All three axes of the stowed SSE were vibrated for 180 s, as per NASA qualification standard, across the full vibration envelope. All SSE hardware was inspected after testing, and no damage was found.

4.7.4 Tank Leakage Verification and Pressure Vessel Qualification Testing

The SSE test tanks posed a leakage hazard. Previously discussed materials selection and compatibility, quality inspections, and reviewed fill procedures served as mitigations for this hazard. NASA qualification standards for unpressurized, sealed containers required survivability with no leaking or rupture at a differential pressure of 1.5 atm. Four types of pressurization tests were performed.

- A SSE tank filled full of water was gradually pressurized from ambient pressure to a pressure differential of 1.5 atm (22.0 ± 1.0 psig) over 80 seconds.
Pressure was held constant for 60 s, then the tank was depressurized and inspected.

- A SSE tank filled full of water was rapidly pressurized to a pressure differential of 1.5 atm in 0.5 s. Pressure was held constant for 60 s, then the tank was depressurized and inspected.

- An empty SSE tank was gradually pressurized from ambient pressure to a pressure differential of 1.5 atm over 80 seconds. Pressure was held constant for 60 s, then the tank was depressurized and inspected.

- An empty SSE tank was rapidly pressurized to a pressure differential of 1.5 atm in 0.5 s. Pressure was held constant for 60 s, then the tank was depressurized and inspected.

The first tank iterations failed pressure testing. Two failure modes existed, both related to the bond between the tank halves. The first was a failure of the adhesive, resulting in the two halves of a tank separating with no material fracture. The second, and most common, failure mode was fracturing of the tank material along the bond seam. Figure 55 is a picture of the second failure mode.
Changing the adhesive resulted in the flight tanks passing pressurization testing. It was hypothesized that the original adhesive diffused into the 3D printed Lexan, weakening it at its minimum thickness (the lap joint), resulting in failure. A lesson learned from this is to perform adhesive-material compatibility testing prior to adhesive application on potential flight articles.

4.8 Functional Checkouts and Ground Testing

All verifications, functionality checks, integration tests, and ground tests had detailed procedures and were designed to meet NASA guidelines and regulations.

4.8.1 Mechanical Fit Check

A VERTIGO unit, courtesy of the MIT Space Systems Laboratory (SSL), and each of the four Slosh Avionics boxes were mated to check mechanical fit. Specifically, the electrical
header and four thumbscrew connections between VERTIGO and the Slosh Avionics box were inspected and passed for all four boxes.

4.8.2 Electrical Functionality and Integration Tests

Functionality of each Slosh Avionics box was tested while it was mated to the VERTIGO unit. All LED indicators were checked in all operational modes and verified to be functional. A camera was connected to the Slosh Avionics box, and test images were saved to the VERTIGO SSD. The test images were retrieved from VERTIGO and analyzed to ensure the camera settings and time stamps were correct. Frame rate was calculated to be between 1-2 fps, with an average of 1.45 fps, which was slower than desired due to hardware and software limitations of VERTIGO. The Slosh Avionics IMU data was recorded to the VERTIGO drive and verified to have correct time stamps. This was repeated for both IMUs in each box. The LED light panels’ luminance was measured with a luminance meter to verify that they were bright enough.

Synchronization between the primary and secondary VERTIGO units was not achieved, which resulted in the cameras and IMUs not being synchronized. This was accepted with the rational that the camera frames and IMU data could be manually time-aligned in post-processing.

4.8.3 Flat Floor Tests

The purpose of flat floor testing was to verify functionality of the integrated SSE, including the impact of depleting the SPHERES CO₂ propellant and the water tank fill level on intended motion profiles. Several difficulties were encountered during testing. The total
mass of the flat floor test setup was 30% higher than the SSE due to the air bearing hardware, and this resulted in lower accelerations. Interference between the SPHERES thrusters and the SPHERES metrology system prevented them from operating simultaneously, which either meant the metrology system had to be disabled or the maximum thruster duty cycle was limited to 40%. At 100% duty cycle, the maximum acceleration achievable in the flat floor setup was about 1/1000 G, which was on the order of the friction from flat floor imperfections. The translation and rotation maneuvers were completed, but the results were poor or inconclusive. The problems with low acceleration and flat floor friction would likely not apply when the SSE was in the ISS, so the tests’ success criteria were redefined to completing the maneuvers without striking the edge of the flat floor table, with no accuracy criteria. The motions were too low for the Slosh IMUs to read, but the SPHERES IMUs successfully measured acceleration and rotation rate.

4.9 Summary

SSE scaling and maneuver analyses, mechanical design, electrical design, software, fabrication, verifications, qualification testing, lessons learned, and ground testing were presented in this chapter. The SSE was stowed aboard Cygnus Orb-1, which launched on January 9, 2014. The launch was a success and the SSE safely arrived on the ISS.
Chapter 5
The ISS SPHERES-Slosh Experiment:
Slosh Data Acquisition and CFD Validation

This chapter will examine ISS operations, assess the quality of the SSE dataset, and present CFD validation using the test data.

5.1 ISS Operations

One checkout and eight Science sessions on the ISS were completed. Extensive procedures and test plans were developed for each session. Table 21 lists the tested tank, primary mode of motion application, and date of each session.

<table>
<thead>
<tr>
<th>Session</th>
<th>Tank</th>
<th>Motion Application</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Checkout</td>
<td>40%</td>
<td>SPHERES</td>
<td>Jan 22, 2014</td>
</tr>
<tr>
<td>Science 1</td>
<td>40%</td>
<td>SPHERES</td>
<td>Feb 28, 2014</td>
</tr>
<tr>
<td>Science 2</td>
<td>20%</td>
<td>Crewmember</td>
<td>Jun 18, 2014</td>
</tr>
<tr>
<td>Science 3</td>
<td>20%</td>
<td>Crewmember</td>
<td>Sep 9, 2014</td>
</tr>
<tr>
<td>Science 4</td>
<td>40%</td>
<td>Crewmember</td>
<td>Jul 17, 2015</td>
</tr>
<tr>
<td>Science 5</td>
<td>40%</td>
<td>Crewmember</td>
<td>Aug 7, 2015</td>
</tr>
<tr>
<td>Science 6</td>
<td>40%</td>
<td>Crewmember</td>
<td>Sep 10, 2015</td>
</tr>
<tr>
<td>Science 7</td>
<td>20%</td>
<td>Crewmember</td>
<td>Nov 9, 2015</td>
</tr>
<tr>
<td>Science 8</td>
<td>20%</td>
<td>Crewmember</td>
<td>Oct 7, 2016</td>
</tr>
</tbody>
</table>

The checkout session consisted of unpacking the SSE, inspecting for damage during transportation to the ISS, first assembly, and testing data collection. Figure 56 shows the partially assembled SSE in the ISS.
For the data to be useful for CFD validation, the fluid initial condition must be known and easily reproducible in the simulation. The checkout session revealed that a large number of bubbles were dispersed throughout the water in the tank, which was not conducive to reproduction in CFD as an initial condition. Science 1 tested three maneuvers performed by a crewmember that were designed to remove bubbles and produce a better initial condition. The first maneuver involved accelerating the system along the SSE’s X-axis (see Figure 50 for the SSE coordinate system) and quickly bringing it to a stop. The second method involved spinning the experiment about one of the SPHERES. Both of these methods were effective at collecting all of the water on one side of the tank, but required a large amount of space to execute. The third method became the preferred method because
it took less space and proved to be most effective at removing bubbles. This method involved gripping the counterweight and spinning the SSE about its Z-axis, which resulted in the water splitting in half and collecting in the two domes. Figure 57 illustrates the difference between a bad initial condition, as seen during the checkout session, and a good, or “well-defined”, split initial condition after implementing the initialization maneuver.

a) Checkout

b) Science 1
Eleven SPHERES-actuated test maneuvers were completed during the Science 1 session. This session revealed that the thrust from the SPHERES was inadequate to achieve significant fluid motion. The crewmembers were able to push the SSE in order to simulate the maneuvers and produce accelerations high enough to cause significant fluid motion.

Science 2 was the first session to use the 20% fill tank. Several translation, rotation, and pitching tests were performed. Science 2 included a few SPHERES-actuated test maneuvers, but all maneuvers in later sessions were performed manually by the attending crewmember. Science 3 included some maneuvers relevant to spacecraft deployment, as well as high-definition video of manual tank manipulation without the rest of the SSE.

Science 4 replicated the maneuvers performed in Science 3 with the 40% tank. Science 5 had fewer maneuver tests, but it included high-definition video of manual tank manipulation to induce slosh and examine the transition between surface tension-dominated and acceleration-dominated regimes. Some of the manual tank manipulation
video is from a headcam the crewmember was wearing. Science 6 focused on maneuver tests not performed during Science 5 and benefited from upgraded external video cameras in the ISS module. The SPHERES and/or VERTIGO units malfunctioned for Science 7 and no data was recorded. A high-definition video camera was attached to the tank by a makeshift selfie-stick to record video of the tank. The camera-and-tank apparatus was manipulated to induce slosh, and it was also allowed to drift freely for some tests. Science 8, which occurred 11 months later, was an attempted redo of Science 7, but similar malfunctions prevented data collection, so the tank was manually manipulated by the attending crewmember. A few short, unofficial sessions of manual manipulation of both tanks were completed in early 2017, providing some additional high-definition video.

5.2 Experiment Data and Processing

This section presents the methodology used for processing the SSE data, including a discussion of data quality issues and remedies, how 6 DoF trajectories were calculated from the IMU data, and the creation of videos from SSE camera images. Descriptions of microgravity fluid phenomena observed in SSE and external camera videos are also included.

5.2.1 Trajectory Calculation

The CFD simulations require a trajectory profile for moving the tank. The trajectory of the SSE within the ISS, i.e. its position and orientation, is reconstructed from data from the two sets of discrete SPHERES 3-axis accelerometers and gyroscopes and the two Slosh
Avionics 6-axis IMUs. There were a total of 12 gyroscopes and 12 accelerometers, four in each axis.

A data pipeline was created in MATLAB that reads, interpolates, filters, and corrects the IMU data. A simplified diagram of this code is shown in Figure 58. “Adaptive” in this context refers to the particular function’s ability to automatically handle multiple off-nominal cases, e.g. missing data.
Since the IMUs were not located at the center of the tank, the accelerations have to be transformed to the tank geometric center (the SSE body axes origin) using 3D rigid-body kinematics [72]. Most inertial navigation systems have an external absolute position/orientation correction, e.g. GPS, to prevent the accumulation of integration error. Since no absolute reference was available for corrections, computing the position and orientation of the tank in time is purely inertial/dead reckoning. The ISS module had low-definition cameras inside, and these “external” (to the SSE) videos were used to sanity check the predicted trajectories. Despite all attempts to reduce it, the cumulative error from dead reckoning often results in noticeably incorrect position and/or orientation by approximately 30 s, depending on the amount of motion (particularly rotation) in the test. The inertial reference frame was set to the SSE body frame at the start of a test.

Table 22 summarizes the challenges faced while writing the data pipeline, their consequences, and how they were addressed.

### Table 22: Data Processing Challenges

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Consequences</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Some tests missing SPHERES IMU data and images for one or both sides; sometimes data folders were blank or not written</td>
<td>Difficult to find which side 1 test folders correspond to side 2 test folders; cannot use some tests</td>
<td>Manually find which tests have data problems and exclude them.</td>
</tr>
<tr>
<td>No clocks synchronized (sides 1/2 SPHERES, Slosh Avionics, cameras all on different clocks)</td>
<td>Difficult to find which side 1 test folders correspond to side 2 test folders; time alignment difficult</td>
<td>Manual folder correspondence; data time alignment algorithms; video time alignment done manually by eye</td>
</tr>
<tr>
<td>Issue</td>
<td>Impact</td>
<td>Solution</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Sides 1/2 gyro/accel X/Y/Z (all 24 channels) were not necessarily aligned in time</strong></td>
<td>High computation error; nonsense trajectory</td>
<td>Data time alignment algorithms</td>
</tr>
<tr>
<td><strong>Variable time steps for IMU data</strong></td>
<td>Automated file reading difficult; computations difficult</td>
<td>Flexible reading scripts; resample and interpolate data</td>
</tr>
<tr>
<td><strong>Low (20-30Hz) IMU data sample rates</strong></td>
<td>Aliased signals; noise; high integration error</td>
<td>No resolution, but resampling, interpolating, and filtering helped.</td>
</tr>
<tr>
<td><strong>Slosh IMU files have both raw and scaled, gyroscope and accelerometer data in randomly changing order</strong></td>
<td>Automated file reading difficult; many text reads necessary; all require separate time vectors</td>
<td>Flexible reading script; parallel text reading loops; time alignment algorithms and interpolation</td>
</tr>
<tr>
<td><strong>Missing data points, negative time steps</strong></td>
<td>Automated file reading difficult</td>
<td>Flexible reading scripts; resample and interpolate</td>
</tr>
<tr>
<td><strong>Slosh IMU signal dropouts from asynchronous data writing and CPU overload</strong></td>
<td>Occasional large (up to 2s) apparent time step. Data during that pause is written in a burst of short (&lt;1 ms) time step data after pause. Causes unrealistic results after interpolation.</td>
<td>Signal dropout detection algorithm and warnings; time-compressed data redistribution correction algorithm</td>
</tr>
<tr>
<td><strong>SPHERES gyroscopes and accelerometers</strong></td>
<td>Occasional large (up to 3s) apparent time step. Data lost. Causes unrealistic results after interpolation.</td>
<td>Signal dropout detection algorithm and warnings; reject SPHERES data in signal dropout regions.</td>
</tr>
<tr>
<td><strong>SPHERES accelerometers have lower acceleration limit than Slosh accelerometers</strong></td>
<td>SPHERES accelerometers saturate during high acceleration maneuvers</td>
<td>Detect signal saturation and warn user. Reject SPHERES accelerometer data in saturated regions.</td>
</tr>
<tr>
<td><strong>SPHERES gyroscopes have lower rotation rate limit than Slosh gyroscopes</strong></td>
<td>SPHERES gyroscopes saturate during high rotation maneuvers</td>
<td>Detect signal saturation and warn user. Reject SPHERES gyroscope data in saturated regions.</td>
</tr>
<tr>
<td>Slosh accelerometers and gyroscopes have poor signal-to-noise ratio near low end of measurement range.</td>
<td>High integration error from noise leads to nonsense trajectory (experiment ending up in space)</td>
<td>Filtering; defaulting to SPHERES acceleration and rotation rate data when below limits.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>All signal channels have different zero-motion offsets; gyroscopes self-calibrate when powered on, resulting in biases if SSE is rotating.</td>
<td>Require perfectly stationary initial condition for test, which was nearly impossible in microgravity, to correct all signal offsets. Compounding integration error leading to nonsense trajectory.</td>
<td>Crewmember attempts to achieve stationary initial condition for power-up and test; exclude tests with significant initial motion; offsetting and amplitude alignment algorithms.</td>
</tr>
<tr>
<td>Slosh IMUs not at center of tank</td>
<td>Cannot simply average the accelerometer data</td>
<td>3D kinematic transformation of accelerations to tank center before fusing</td>
</tr>
<tr>
<td>SPHERES IMUs are made of distributed single axis sensors not at center of tank</td>
<td>Cannot simply average the accelerometer data</td>
<td>3D kinematic transformations of individual accelerations to center of SPHERES, then all to center of tank before fusing</td>
</tr>
<tr>
<td>IMUs in body axes</td>
<td>Must be transformed to inertial frame for trajectory calculations</td>
<td>Direction Cosine Matrix (DCM) – based integration algorithm</td>
</tr>
<tr>
<td>Camera frame rates are low (typically &lt;2 fps) from CPU overload</td>
<td>Cannot see flow feature development for some slosh events. Time alignment difficult.</td>
<td>None.</td>
</tr>
<tr>
<td>Camera frame rates are variable from asynchronous image data writing</td>
<td>Cannot simply write all images to a movie at a constant frame rate</td>
<td>Automated video writing script that repeats images to achieve a real time video.</td>
</tr>
<tr>
<td>Experiment leaves box defined by sonic beacons; beacons did not function. No absolute position information.</td>
<td>Cannot use sensor fusion/correction algorithms. Resulting position and orientation after some time (about 30 s) unreliable.</td>
<td>Dead reckoning/inertial navigation algorithm for position and orientation. Must use SPHERES sensors where possible and filters to minimize accumulating error, which is ultimately unavoidable.</td>
</tr>
</tbody>
</table>
CO₂ tank fill levels, 20% vs 40% test tank, water shifting experiment center of mass, error in inertia calculations during experiment design | Center of tank was not necessarily the center of rotation. Example: slight +Z (SSE body frame) component during X-rotations (roll) results in geometric center of tank tracing a circle. | None. Calculations must be accurate enough to resolve the rotation of tank center.

The maneuver for Science 2 test 11 involved the crewmember pushing and pulling the experiment along the SSE X-axis. Figure 59 is the 6 DoF trajectory in the inertial frame for the first 35 s of this test calculated by the data pipeline. As mentioned above, the pipeline uses dead-reckoning, DCM-based integration [73] to obtain the position and orientation of the SSE from the IMU data. The inertial reference frame was set to the SSE body frame at 0 s. The plotted orientations are about the axes indicated in the legend.

![Figure 59: Calculated Trajectory of Science 2 Test 11](image)

The external video of this test indicates that the roughly linear trends in the X and Z orientations are not physical. The trajectory error is from multiple sources mentioned in
Table 22, but the linear nature of the orientation drift suggests some bias remained after averaging the various processed rotation rate signals. The effects of these errors on simulation accuracy are discussed in Section 5.4.2.

5.2.2 Experiment Videos

Multiple cameras were used during the SSE test campaign.

The SSE had two, orthogonal high-definition cameras that took images of the water in the test tank. Because the image framerate was low and variable (0.5-2 fps), and images were time stamped, a custom video creation script was written in MATLAB that repeated a frame an appropriate number of times before inserting the next frame to obtain a constant frame rate. The time uncertainty between the unsynchronized primary and secondary sides’ images was estimated to be half the cameras’ frame time, ±0.25-1 s.

The ISS module had multiple low-definition cameras that continuously recorded, though the videos from these were not always available, and they sometimes had gaps due to loss-of-signal periods. These are referred to as “external” cameras. The low resolution made identifying SSE features and some motions difficult. They had broken auto-focuses, which resulted in the video being out of focus or caused the focus to continuously vary across its full range. They often suffered from underexposure, making the videos too dark to make out details. Figure 60 is an example, unedited frame from one of these cameras at the beginning of Science 2 test 11.
The external video files were provided as continuous recordings and had to be manually cut for each test. Despite the problems with the external videos, they are useful for sanity checking the calculated trajectories. The module cameras were upgraded before Science 6, which was the last session to successfully collect data.

Various high-definition cameras already on the ISS were used to record videos of the tank, while it was not installed in the SSE, being manipulated by the attending crewmember. Data storage and transmission limitations prevented these from being used for all tests.

5.2.3 Observations

Fluid behavior observations were noted in many of the sessions. As shown in Figure 57 and mentioned earlier, a fluid film coats the tank walls and no meniscus is visible. The film retracted, resulting in a dry wall, when the acceleration experienced by the tank was above
some threshold. Air bubbles trapped in the water were often observed and necessitated the initial conditioning methods discussed in Section 5.1. Water droplets were observed to bounce off each other and the bulk fluid surface (example: Figure 76), sometimes coalescing. Spinning and stopping the tank resulted in slosh waves propagating around the tank.

The attending crewmember was asked to manipulate the tank while it was not installed in the SSE during some of the Science sessions. During Science 5, they were asked to provide visual feedback on the film retraction, which corresponds to the transition between the surface tension-dominated and acceleration-dominated regimes. Science 3 included a rotation test that also exhibited this transition. The tank was initially given rotation about its major axis and released. The major axis had the minimum moment of inertia, making the rotation unstable. The rotation axis began changing as energy was dissipated by viscous drag, until stable rotation about a tank minor axis was achieved. The new axis of rotation was the axis of maximal moment of inertia. The larger radius of the new rotation resulted in higher centripetal acceleration experienced by the water, which caused retraction of the fluid film. Figure 61 is a sequence of images from a HD video camera from this test.
The tank-only tests were useful for observing fluid behavior, but they did not have IMU data. Although the rotation rates could be estimated from a video, the estimated motion
would not be known accurately enough to reproduce the case in CFD. Comparing a tank-only test and corresponding CFD case might show similar fluid phenomena, but this would be the only verification possible from such a comparison. Strict CFD validation requires measured motion simulation input and comparing the resulting simulation and test videos.

5.3 CFD Approach

CFD simulations were performed using STAR-CCM+ and OpenFOAM. This section will describe some of the initial validation and error work, the final mesh and simulation settings, and video creation.

5.3.1 Contact Angle

Before any simulations with motion were attempted, a SE-FIT [74] surface solution was compared to OpenFOAM and STAR-CCM+ to verify their surface tension and static contact angle implementations in zero gravity. SE-FIT is a minimum surface energy calculator, which calculates the theoretical steady-state liquid-gas interface shape in a tank for a given acceleration, surface tension, and contact angle. Contact angle is the angle of the liquid at a solid-liquid-vapor interface and is independent of acceleration environment [28]. Starting with all of the water on one side of the tank and an initially flat fluid interface in OpenFOAM and STAR-CCM+, transient simulations were run until surface oscillations were within one cell height. Static fluid surfaces from all three programs were extracted for multiple contact angles and compared in MATLAB. The three surfaces were all within one CFD mesh cell width for each contact angle checked.
The “real” contact angle of the water in the test tank was difficult to obtain. Contact angle experiments were performed at FloridaTech using a sample of the tank’s 3D printed material and deionized water droplets. Figure 62 is a picture of the contact angle experiment setup.

A 5 MP machine vision camera with a zoom-macro lens was mounted on a vertical stage, which aligned the camera with the top of the sample. The sample was attached to a rotary stage driven by a stepper motor. A precision syringe was used to dispense a single drop on the sample. The image acquisition and rotary stage were controlled by LabVIEW [75]. A MATLAB program was written to measure the contact angle from the high-resolution images and average repeated cases. The results were a static contact angle of 62.4 deg, advancing contact angle of 66.8 deg, and receding contact angle of 33.7 deg. Uncertainty on all contact angle measurements was approximately ± 10 deg.
The SSE images revealed a thin film of water coating the inside wall of the tank when the acceleration experienced by the tank was below an unknown threshold. As can be seen in Figure 57c, this fluid film around the middle of the tank decreased the apparent contact angle significantly below 62 deg. The same MATLAB program was used to estimate the modified contact angle from multiple stationary SSE images, and the result was a contact angle of approximately 28 deg, close to (within experiment uncertainty of) the receding contact angle measured in sample testing.

5.3.2 CFD Initial Conditions

Two methods for obtaining an initial condition for the simulation fluid surface were tried. Method 1 involved initializing the water to be roughly in the correct location, running a transient, no-motion simulation until the fluid surface stabilized, then saving the final solution. The final solution could then be used as the initial solution for all cases with that initial water distribution, e.g. evenly split or all on one side. Method 2 used SE-FIT to generate the initial condition. This was faster and gave a more axisymmetric surface. However, SE-FIT can be difficult to use and sometimes has convergence issues. This method required extracting the final SE-FIT fluid surface in Paraview [76] and then importing it into the CFD simulation as an initial condition. In OpenFOAM, this was done using a topoSetDict in setFields. After experimenting with both options extensively, method 1 was preferred.
5.3.3 OpenFOAM Troubleshooting

Nonphysical high frequency fluid surface and force oscillations were observed in some of the early CFD simulations. These oscillations were traced to three sources: 1. parasitic currents due to the surface tracking scheme, 2. numerical instabilities, and 3. low precision tabulated motion data. The parasitic currents were only present with no motion and less diffusive, i.e. 2nd order, numerical schemes. When motion was added, and the fluid dynamics become inertia-dominated, these currents became negligible. Numerical instabilities were removed with careful selection of schemes and settings. The tabulated trajectories for the initial test cases were generated with OpenFOAM’s 6DoF generator, which writes values with six-digit precision (default C++ stream operator precision). Due to the incompressibility assumption and the slight inaccuracies introduced by using only six-digit precision for position input, the calculated forces were noisy. When the motion table was generated with double precision, all noise in the force waveforms was eliminated.

5.3.4 Motion

There were two options for motion input for the CFD. The first option considered the CAD-calculated inertias (Table 20) and the SPHERES’ thruster firings as force inputs, and the resulting coupled slosh-motion 6 DoF accelerations and rotation rates (or trajectory) could be compared to the measured IMU data. However, the SPHERES-actuated cases did not excite significant fluid motion, so all cases considered for CFD validation were crewmember-actuated, and since the forces and moments applied by the crewmember are
unknown, the first option was not used. Instead, the calculated trajectory of the test was used as the motion input for the meshed tank in the CFD.

5.3.5 Settings and Post-Processing

The OpenFOAM mesh was created using snappyHexMesh, OpenFOAM’s built-in mesher. The mesh was hexahedral dominant with prism layer cells along the wall and had a smooth transition from the wall layer cells to the core mesh. A mesh independence study was attempted using a 1 DoF sinusoidal motion test case and meshes of 800,000, 2.4M, and 6M cells. Force in the axial direction and images of the fluid surface were used to compare the cases. The smallest mesh case was expected to begin to differ from the medium and large mesh cases first, and then the medium case would begin to differ from the large mesh case a few seconds later. However, all cases began showing differences starting around the time of the first fluid impact due to direction reversal, which means the mesh study was inconclusive. The smallest mesh was selected to reduce simulation times.

The following settings were used for all OpenFOAM simulations: second order accurate time and space formulations, PIMPLE solution scheme, multiphase Volume-of-Fluid (VoF), laminar, constant density fluids (air and water), static contact angle of 28 deg (see Section 5.3.1). Using the apparent contact angle instead of the measured static contact angle of 62.4 deg resulted in a qualitatively better initial fluid distribution, despite the absence of the fluid film on the wall around the middle of the tank. All residuals were driven to 1E-4 or lower for every time step. The position and orientation were commanded, and isosurfaces at a volume fraction of 0.5 were recorded every 0.02 s. Time step was
automatically adjusted based on CFL number, which was set at 1.5 because any higher resulted in instabilities.

Paraview was used to process the isosurfaces and create videos. Simple opacity, diffuse shading, and specular shading were used, and only the clear tank walls and isosurface at a volume fraction of 0.5 were rendered. The bulk fluid is not shown or colored, so volumes that appear not to have any green fluid, but are bound by the wall and an isosurface, should in fact be green. This can be accomplished in Paraview using the Threshold filter, but it requires OpenFOAM to write a full output (as opposed to only an isosurface) at every time step, and the final folder size for each test would have required a prohibitive amount of storage space. Python batch scripts were written to recreate the SSE camera perspectives using the 6 DoF motion and automate the rendering process.

STAR-CCM+ settings were similar to OpenFOAM settings, except the mesh had 3.5M cells, temporal discretization was first order, time step was fixed at 1 ms, and the contact angle was set to either 0 or 30 deg. Any contact angle less than 15 deg resulted in a fluid film coating the tank wall, but, despite higher mesh resolution near the tank wall, it was unrealistically thick, which made the initial fluid distribution less accurate than using a \( \approx 30 \) deg contact angle. Finer meshes were tried and generally resulted in thinner films, but a high enough resolution mesh for a (qualitatively) accurate film formation was not simulated due to computational constraints. Fluid film models that could interface with VoF were not available in OpenFOAM or STAR-CCM+ when these simulations were run. The 30 deg contact angle allowed for better initial fluid distribution at the expense of the fluid film coating the tank wall. Motion data was imported as linear velocity in one axis for
the STAR-CCM+ cases. Saved isosurfaces were rendered in a similar manner to the OpenFOAM isosurfaces.

5.4 CFD Validation

Test cases were selected for validation. Slosh simulations of the SSE tank moved with a trajectory from each test were run, and videos of the fluid surface from the perspective of the SSE cameras were rendered for comparison to the test videos.

5.4.1 Case Selection for CFD Validation

Some tests were missing some or all data and/or images; these were excluded. The motion in many tests was too low to induce significant sloshing. Some had non-steady initial conditions, and these had to be excluded because steady, known initial conditions are required for trajectory calculation. A variety of maneuvers was desired for CFD validation. The cases listed in Table 23 are the final selections.
<table>
<thead>
<tr>
<th>Science</th>
<th>Test</th>
<th>Primary Side Folder</th>
<th>Secondary Side Folder</th>
<th>Maneuver Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>11</td>
<td>run_2014_06_18_16_34_33</td>
<td>run_2014_06_18_16_28_08</td>
<td>X-axis periodic translation</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>run_2014_06_18_16_44_23</td>
<td>run_2014_06_18_16_37_58</td>
<td>Y-axis periodic translation</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>run_2014_09_09_11_37_51</td>
<td>run_2014_09_09_11_30_39</td>
<td>single push along +X axis</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>run_2014_09_09_12_16_54</td>
<td>run_2014_09_09_12_09_43</td>
<td>single push along +X axis</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>run_2014_09_09_12_29_35</td>
<td>run_2014_09_09_12_22_25</td>
<td>translate and spin about +X axis</td>
</tr>
</tbody>
</table>
5.4.2 Validation

Rendered videos of the CFD fluid surface are compared to videos created from the SSE camera images to qualitatively assess agreement. Due to the aforementioned lack of synchronization between sides, IMUs, and cameras, the test videos and CFD videos had to be time aligned manually. The test-CFD time alignment uncertainty was estimated to be ±0.5 s, similar to the time alignment uncertainty between the primary and secondary sides’ images (Section 5.2). The low, variable frame rate of the SSE cameras meant that some flow features were not well-resolved. That, coupled with the time alignment uncertainty, means that a test image and CFD image may not be at precisely the same real time in the following comparisons.

The inertial reference frame was initialized to the SSE body frame (see Figure 50) at 0 s. In this section, “X”, “Y”, and “Z” axis labels refer to the inertial frame axes unless directly proceeded by “SSE”, e.g. “SSE X-axis”, in which case they are axes in the body frame.

Science 2 test 11 began with a split initial condition. The crewmember pushed and pulled the SSE primarily along the SSE X-axis in order to imitate satellite deployment from a spring-loaded-type separation system. Since the SSE was being moved by hand, there were minor rotations and off-axis translations present. The push-and-pull cycle was repeated multiple times, and the three cycles that were simulated can be seen in the trajectory in Figure 59. Science 2 test 11 was first simulated in STAR-CCM+, but only the X-axis translation was retained, making it a 1 DoF case. A 0 deg contact angle was used (Section 5.3.5). The full, approximately 35 s long, simulation and test videos were compared and show good qualitative agreement. Figure 63 shows six frame comparisons at different
times, with the SSE secondary side camera’s images on left and the corresponding CFD images on right. Time and acceleration direction are indicated in subplot captions.

Figure 63: Science 2 Test 11, 1 DoF STAR-CCM+
Figure 63a shows the steady split initial condition. The tank accelerates to image-left causing the fluid on the left to flow axially around the tank wall to the right, then flowing radially inwards in the right dome, forming the prominence shown Figure 63b. The acceleration reverses to slow the motion to the left, forming a larger prominence/geyser on the left side of the tank (Figure 63c). Figure 63d is near the maximum right acceleration point, and a centered blob breaks off the prominence in the experiment in Figure 63e, though not in the CFD until slightly later. The tank accelerates to the left in Figure 63f, resulting in the blob impacting the right dome, with waves propagating axially along the tank wall to the left.

Science 3 test 12 was also simulated in STAR-CCM+. Science 3 test 12 was a shorter test that consisted of an impulse push in X and free motion for a few seconds before it was stopped. In the simulation, motion was restricted to translation along the X-axis. The impulse caused a geyser that traversed the tank centerline and impacted near the center of the opposing dome. The CFD captured the geyser. Comparing the test and CFD videos showed a level of agreement similar to the comparisons shown in Figure 63, which, along with its brevity, is why images of this test are not presented.

Science 2 test 11 was simulated in OpenFOAM with the 1 DoF trajectory. This resulted in good agreement with the experiment and 1 DoF STAR-CCM+ results. Science 2 test 11 was then simulated in OpenFOAM with the full 6 DoF trajectory. The X-axis acceleration from the 1 DoF case was confirmed to be essentially identical to that used for the 6 DoF case, and nothing else in the case was modified. Figures 64-67 compare test and (6 DoF) CFD images from Science 2 test 11 at four time points during the maneuver. Both primary
and secondary side camera views are shown. The camera views are orthogonal, but the secondary camera was mounted rotated 180 deg about its pointing vector. Either side’s images could have been rotated to compensate, but this was not done because this was how the raw images were recorded. The coordinate system in the lower left corner of all following CFD images is aligned with the inertial frame, which was initialized to the SSE body frame at 0 s. An attempt was made to better capture the background color and lighting conditions in the rendering of the CFD images for the following cases, with limited success.

![Figure 64: Science 2 Test 11 at ≈8.4 s. Top: primary side. Bottom: secondary side](image)

In Figure 64, the bump in the center of the dome (left in primary side image, right in secondary side image) is much less pronounced in the CFD, possibly indicating too much filtering on X-axis acceleration. The bulk fluid distribution agreement is good. For example, the concentration of water on middle-right-back of primary side images, which
corresponds to bottom left in secondary side images, is in both the test and CFD images.

While regions of thick water on the wall are captured in the CFD, the thin fluid film coating the rest of the inside wall is not, as expected for the reasons described in Section 5.3. Small drops along the wall in the CFD (example: Figure 64 secondary side) appear and disappear at random in the videos. These are a rendering artifact from cells with low water volume fraction that occasionally breach the 0.5 iso-value threshold.

Figure 65: Science 2 Test 11 at ≈14.2 s. Top: primary side. Bottom: secondary side

In Figure 65, the bulk fluid distribution seems to agree well, and the prominence feature is present in all images.
In Figure 66, the prominence feature is present in all images, though it is not as centered in the dome in the CFD as it is in the test. The bulk fluid distribution agreement is not quite as good as it was in Figure 65, but concentrations under the prominence, in bottom-right and back of the primary side images, and in top of secondary side images, agree well.
In the secondary side test image of Figure 67, a large blob has broken off of a prominence. The lack of synchronization between the two sides’ cameras is obvious in Figure 67. The next primary side test frame shows the detached blob, but the frame in Figure 67, which is the closest in time to 27 s, shows it attached. In the experiment videos, this blob proceeds to traverse the tank centerline to the other side of the tank. The prominence forms off-center in the CFD with the attachment point on the wall’s cylindrical section, and this can be seen in the primary side CFD image in Figure 67. However, instead of a blob breaking off, the prominence collapses into the water along the side of the tank as if the tank wall rotated into it. The difference between this 6 DoF case and the 1 DoF case must be due to trajectory error, and due to the 1 DoF case agreeing better with the experiment, the majority of the 6 DoF trajectory error must be in the other five degrees of freedom.
Similar to Science 2 test 11, Science 2 test 13 began with a split initial condition. The motion was periodic translation primarily in Y. Figure 68 is the 6 DoF trajectory in the inertial frame for this test calculated by the data pipeline. The inertial reference frame was set to the SSE body frame at 0 s. The plotted orientations are about the axes indicated in the legend.

![Figure 68: Calculated Trajectory of Science 2 Test 13](image)

The periodic Y translation is clear in the external video and is approximately correct in magnitude in the position plot of Figure 68. The final Y position in the external video was below the initial Y position, but not -0.5 m lower as shown in the trajectory. The small periodic X translation is hard to confirm in the external video due to the camera angle. The trajectory’s approximately ±5 deg periodic rotations about Y and Z appear reasonable, but the rotation about -X is exaggerated. The external video showed about -10-15 deg final X orientation. Figures 69-72 compare test and CFD images from Science 2 test 13 at four time points during the maneuver.
The inertial +Y-axis is approximately up-down with a page-in component in the primary side images and up-down with a page-out component in the secondary side images. The axis orientation is approximate because of the rotations shown in the Figure 68 orientation plot. The water distribution in the CFD images in Figure 69 is approximately correct. In fact, the water distribution was approximately correct throughout the simulation video of Science 2 test 13, making it the best test-CFD comparison case. The pillar flow feature, which forms from water flowing inward along the wall from the domes, is about the same shape and in nearly the same location in the test and CFD images. The acceleration was high enough to cause the fluid film to retract from the dome ends, which can be seen in the test images.
The majority of the water is on the bottom of the primary side test and CFD images in Figure 70. The primary side CFD image seems to show a water location bias towards the left that is not present in the test image, but examination of the secondary side test image shows a bias of the water location towards back-right, which corresponds to bottom-left of the primary side images. The water is primarily on the back in both the test and CFD secondary side images. The CFD images show many filaments and small drops of water on the tank walls, which are from it attempting to resolve the fluid film and its retraction despite not having a high enough mesh resolution. There is a circumferential ring of water in the cylindrical section right-of-center in the primary side test image (left-of-center in secondary side test image). The circumferential rings form when acceleration (in SSE Y- or Z-axis) changes direction, causing circumferential flow around the wall that is contracted by surface tension into a ring. The surface tension contraction pulls water in axially along the tank wall until the wall-bound water thins to a film. The ring drains the water it collects.
to the side of the tank in the acceleration direction until no water remains on the wall, which is when the ring breaks. Because the CFD does not have high enough mesh resolution to fully resolve the fluid film, the location and evolution of these circumferential rings do not always match up with the test. For example, there are three circumferential rings in the CFD images in Figure 70 instead of one. That said, the fact that the CFD is predicting their existence is promising and shows that some of their physics is being modeled correctly.

![Image of water in tank](image)

**Figure 71: Science 2 Test 13 at ≈16.1 s. Top: primary side. Bottom: secondary side**

Figure 71 is approximately one translation cycle after Figure 70, so the majority of the water is back on the bottom of the primary side images and on the back of secondary side images (SSE -Y side of tank). The water location bias to left in the primary side images, corresponding to the right in the secondary side images, is present again. However, this time point is before all of the water has moved to SSE -Y side of the tank, so a relatively
thick fluid layer/film remains on the rest of the walls of the tank. This is seen in the CFD images as an unbroken isosurface surrounding the central air volume in the tank.

![Figure 72: Science 2 Test 13 at ≈28 s. Top: primary side. Bottom: secondary side](image)

Figure 72 is at the end of the test after motion is stopped. The majority of the water is in top-left and left dome of the primary side test image (front-right of secondary side test image). The CFD also has a concentration of water in those locations, but it predicts more water in the right dome in the primary side image than what is seen in the test. Two bubbles that formed from fluid surface agitation during the second translation cycle are visible in the secondary side test image. One of them is visible in the secondary side test image of Figure 71. The test video shows the bubbles moving around the tank with the bulk fluid motion. In fact, many images from tests with fluid surface agitation contain bubbles, which was why initial conditioning was necessary (see Figure 57). However, the corresponding CFD images do not show bubbles. Bubbles require a mesh much finer than
what was simulated because the thickness of the liquid film that forms the boundary of (at least part of) the bubble must be resolved.

Science 3 test 4 began with almost all of the water on one side of the tank and a fluid film covering the rest of the tank wall. The crewmember gave the SSE a single push (without holding onto it) in +X, which was initially approximately aligned with the long direction of the ISS module. The SSE traversed the length of the module, and then the crewmember stopped it about 10 s later. This maneuver could represent a spacecraft separation or docking event. Figure 73 is the 6 DoF trajectory in the inertial frame for this test calculated by the data pipeline. The inertial reference frame was set to the SSE body frame at 0 s. The plotted orientations are about the axes indicated in the legend.

The trajectory position plot shows the X-axis translation. The external video and knowledge of approximate dimensions of some features inside the module suggest that a 4 m translation is approximately correct. The small +Y translation is visible in the external video. The SSE had a slight multi-axis rotation at 0 s that the data pipeline assumed was...
gyro bias and zeroed out. To correct for this rotation, the crewmember performs a small reorientation between 1-3 s. The push occurs at approximately 4 s. The Z orientation change in the trajectory is exaggerated, about double what is seen in the external video, possibly due to the initial rotation present at 0 s. The SSE is grabbed by the crewmember around 14 s, and the rotation directions in the trajectory from 14-15 s appear to correspond to the way the crewmember moved the SSE after grabbing it. Figures 74-77 compare test and CFD images from Science 3 test 4 at four time points during the maneuver.

![Figure 74: Science 3 Test 4 at ≈4.1 s. Top: primary side. Bottom: secondary side](image)

In Figure 74, the fluid film is not present in the CFD, but it is in the test, though it has retracted from part of the primary side right (secondary left) dome. The prominence is not as large in the CFD, which could indicate over-filtering the push’s acceleration. In the test, the prominence turns into a geyser, which breaks up into two blobs of water.
The geyser breaking up is visible in the test images in Figure 75, and the first water blob has separated in the secondary side test image. This blob impacts the primary side right (secondary side left) dome and merges with the fluid film. The second blob is formed from the geyser “finger”. The second blob impacts the fluid surface formed from the water in the first blob, but it bounces off instead of merging and rolls around the tank while the SSE translates. Apart from the geyser, the CFD has approximately the correct water distribution in the primary side left (secondary right) dome, including the slant visible in the primary side images.
The second blob is still present at the time of Figure 76 and is adjacent to the fluid film on the cylindrical tank wall. The current theory for why droplets/blobs like these, which are present in many other test videos, do not merge with the bulk liquid is a thin layer of air trapped between the blob and the adjacent water prevents contact. Enough inertia or time experiencing body acceleration, with more acceleration requiring less time, is required to disperse the air layer and cause coalescence. The majority of the water is still in the primary side left dome in both test and CFD, though the test shows some water (from the first blob) in the primary side right dome. The small droplets on the wall in the CFD are from low water volume fraction cells, which was explained for Figure 64.
The crewmember stops the SSE around 14.9s. The water inertia causes it to move down the tank walls, into the dome on the right in primary side images, and form a small prominence and splash. The stop is rapid, causing the fluid motion to be fast, and the test image frame rate is too low to adequately capture it. The CFD fluid distribution is approximately correct, showing the majority of the water on the bottom-left in the secondary side image and top-right in the primary side image. The fluid surface is more disturbed in the test images, which could indicate over-filtering the stop’s acceleration. This simulation was stopped at about 15 s because the geyser was not resolved.

Science 3 test 16 began with a split initial condition. The crewmember imparted an approximately 19 rpm spin about the SSE X-axis and released it to imitate a passive thermal control roll. The SSE spun for around 30 s while translating approximately 2 m. Figure 78 is the 6 DoF trajectory in the inertial frame for this test calculated by the data.
pipeline. The inertial reference frame was set to the SSE body frame at 0 s. The plotted orientations are about the axes indicated in the legend.

Figure 78: Calculated Trajectory of Science 3 Test 16

Comparing this trajectory to the external video of this test, the translation magnitudes and total number of rotations are approximately correct. The wobbles in the Y and Z positions were because the center of mass and rotation of the experiment was slightly in the SSE +Z direction from the tank geometric center. Science 3 test 16 was simulated in OpenFOAM with this 6 DoF trajectory. Figures 79-82 compare test and CFD images from Science 3 test 16 at four time points during the maneuver.
As the tank spins, the water that started in the domes moves towards the cylindrical section due to centripetal acceleration, but because the spin axis is not aligned with the geometric center of the tank, this water motion is not symmetric. For the primary side images in Figure 79, the majority of the water is still in the domes, but some has migrated towards the cylinder, particularly in the top of the image where an axial-moving wave can be seen. That wave is visible on the back side in the secondary CFD image, but the secondary side test images are at about 1 fps during this time and miss it. The secondary side CFD image predicts little water in the bottom left, but there is water there in the test image, implying a possible discrepancy in rotation axis.
Figure 80: Science 3 Test 16 at ≈14.6 s. Top: primary side. Bottom: secondary side

For the primary side of Figure 80, the bulk of the water is near the bottom of the test and CFD images, which corresponds to near the center of the images for the secondary side. The test images show some water still in the tank domes, but the right dome of the primary side CFD image, which corresponds to the left dome in the secondary side, is mostly devoid of water. Surface waves in the cylindrical section are present in all images.
The liquid distribution is beginning to settle on the SSE -Z side of the tank in the test images of Figure 81, but there is too much water in the left dome in the primary side (and right dome in the secondary side) CFD image. The concentration of water on the bottom-right of the primary side is present in both test and CFD images.
By the time of Figure 82, the water has settled on the SSE -Z side of the tank. The centripetal acceleration is high enough that no fluid film is present on the tank dome walls. The CFD is rotating about a slightly different axis than the experiment, though the bulk of the water is still on the correct side of the tank.

5.4.3 SSE CFD Validation Conclusions and Future Work

Aside from the test-CFD time point alignment issues, most differences between the tests and CFD can be explained by the issues discussed in Section 5.2, particularly those that affect trajectory calculation, such as IMU noise, gyroscope bias, and integration error. Mesh resolution and aforementioned contact angle issues may be significant CFD error sources, but are likely smaller than the trajectory error sources given the good agreement between test and the 1 DoF cases.
Improving the 6 DoF trajectories may not be possible because every relevant data processing technique known me has been investigated. Tuning the filters more, possibly using adaptive filtering to avoid smearing impulse-like accelerations, and manual gyro bias modification might help, but the trajectories’ errors will still compound in time. A computer vision technique called “3D pose estimation”, which estimates the 3D position and orientation of an object from 2D images, was considered. The goal was to use trajectory information from the external videos of the tests to correct the trajectory computed from inertial data in a sensor fusion algorithm to produce a more accurate trajectory. However, the poor quality of the external videos (see Section 5.2.2), coupled with significant background noise in the form of a multitude of 3D objects attached to the internal walls of the ISS, would have required significant advances in this subfield of computer vision and was deemed to be outside scope. A simpler approach could be to restrict some of the degrees of freedom to within limits manually determined from the external videos, instead of the outright removal of degrees of freedom that was done for the 1 DoF cases. However, manually determining limits from all of the tests would be tedious and possibly infeasible. The simpler method could be tested on a few cases as a proof of concept; if it helps, then investment in the 3D pose estimation capability might be warranted.

The CFD validation is qualitative in nature because it involves the visual comparison of CFD videos to test videos. A MATLAB image processing script could be written to provide a quantitative assessment of image agreement by calculating the location of water in the test and CFD images. However, test images that have the fluid film or water covering the entire wall would prevent this binary water-no water method from working as
intended because the entire image would be seen as water. Although that might result in 0 error if the tank wall in the CFD is also coated in water, it cannot provide any comparison of internal water features. An extension of the binary water-no water assessment would involve examining the light intensity, or “green-ness”, to estimate a depth map of liquid in the test images, which could then be compared to the CFD 3D liquid volume projected on the 2D image plane. Both of these methods would suffer from error from reflections of the lights on the fluid surface and tank that cover 10-20% of the area of the test images (example: Figure 82), meaning this method would start with approximately 20% uncertainty, which is why it has not been attempted yet.

5.5 SSE Program Conclusions

Accurate prediction of coupled liquid propellant slosh and launch vehicle or spacecraft dynamics requires CFD models validated with long-duration, low-gravity slosh data. The primary objectives of the SPHERES-Slosh program were to collect high-resolution video of long-duration, low-gravity, coupled-motion slosh with synchronized motion data and well-defined initial conditions, and then use that dataset to validate slosh CFD simulations. IMU data and test imagery collection were successful. Having two, orthogonal camera views of the tank helped to visualize the 3D distribution of water and shape of flow features. Additionally, video was recorded of the tank outside of the SSE being manually manipulated by crewmembers, which resulted in several microgravity fluid behavior observations. Since no test data nor images were synchronized, the “synchronized” part of the objective was not successful, but this was partially remedied with algorithmic and/or manual time alignment. Coupled slosh-motion data is available in tests where the
crewmember released the SSE after imparting motion to it. If “long-duration” is defined as the approximate duration of the maneuvers performed, then it is clear that the 6 DoF trajectories need to be improved before claiming long-duration microgravity slosh CFD validation. That said, CFD validation was successful for shorter (case-dependent) durations and when some degrees of freedom of the trajectories were removed.

5.6 SSE Future Work

Another attempt will be made to leverage the external videos to obtain trajectory correction information. The method of restricting motion in some of the degrees of freedom to within limits manually determined from the external videos will be attempted first. If this method helps, then an automated 3D pose estimation computer vision capability might be developed.

Various avenues for improving the CFD exist. The use of an O-grid-type mesh and automatic mesh refinement of the fluid surface would improve solution accuracy. The latest OpenFOAM and STAR-CCM+ versions include fluid film models that work with VoF. A prohibitively large mesh would be required to resolve the fluid film, but modeling the film might now be possible without further mesh refinement. Another simulation improvement would be the use of a dynamic contact angle model instead of a static contact angle.

The CFD results presented in this paper only had the fluid surface rendered. Visualization could be improved by saving the liquid volume or bounding surfaces, instead of an isosurface of the fluid surface, although at the expense of increased data storage. Using
Blender instead of Paraview for CFD rendering would result in more realistic videos because controlling lighting, shadows, reflections, and refractions are all possible within Blender.

The CFD validation was qualitative in nature because it involved the visual comparison of CFD videos to test videos. 2D image processing techniques could possibly be used to compare and calculate error between the test and CFD images if the problem of light reflections can be resolved.

Re-running the 6 DoF trajectory CFD cases after making the above improvements is future work. More tests with complete data and well-defined initial conditions are available. Simulating more tests, with a wide variety of maneuvers, would enhance the CFD validation.

5.7 Future ISS Slosh Experiment Recommendations

In addition to the lessons learned discussed in Chapter 4, recommendations have been compiled for future experiments with similar objectives to the SSE. IMUs more accurate and less noisy than those in the SSE should be used. Error estimation calculations should be done as part of the IMU selection process. An absolute reference for correcting the inertial data, e.g. a functional metrology system or optical tracking, is essential for accurate trajectory calculation. Consistent IMU data rates $\gtrsim 100$ Hz and image acquisition rates $\gtrsim 20$ fps should be targeted in order to eliminate data collection errors, implement better filtering, and to resolve fast fluid flow features. If $\approx 20$ fps imagery is not achievable, sacrificing resolution for frame rate should be considered. The IMU data files should be in
a consistent format. All clocks need to be synchronized in future experiments to reduce errors introduced by time aligning in post-processing. Microprocessors with enough computational power to meet these requirements, plus significant margin, should be selected.

Since the 3D liquid distribution information is already available from the CFD, direct measurements of the 3D fluid volume in the test tank, such as those provided by ECT, would be ideal for quantitative CFD validation. Future ISS slosh experiments should consider installing an ECT system or other sensor capable of measuring where the liquid is in the test tank.

The SPHERES were retired in 2018 and deorbited, and the Slish apparatus was deorbited shortly thereafter. The SPHERES replacements, “Astrobee”, are currently on the ISS and operational. Astrobee provides researchers a new platform for performing a wide range of experiments and technology development. The Astrobee units use fans that can provide more thrust than the SPHERES CO$_2$ thrusters while eliminating the various issues associated with CO$_2$ tanks. They navigate based on a combination of inertial data and optical tracking that is more accurate than the SPHERES navigation system. The use of Astrobee in future low-gravity slosh experiments might address many of the issues encountered with the SSE.
Chapter 6
Conclusions

Two experiment programs, the Propellant Sensing with Electrical Capacitance Tomography study and the SPHERES-Slosh Experiment, were detailed in this thesis, and this chapter restates their conclusions, along with how all research objectives were met. Contributions and a synopsis of planned future work are also presented in this chapter.

Basics of ECT theory, comments on ECT system scaling, details of the parabolic flight experiment setup, data processing, test results, and ECT study conclusions were presented in Chapter 3. Liquid motion in the tank caused oscillations in the ECT gauging results. Filtering out liquid motion effects significantly reduced the variations, improving the gauging precision and accuracy. This ECT system did not achieve the 1% mass gauging accuracy target if percent was defined relative to the actual (scale-measured) liquid mass. If the 1% target is instead full-scale, i.e. defined relative to a full tank, as is commonly done for mass gauging technologies, this ECT system was able to achieve uncertainty of the mean mass measurements <1% for all fill levels on the ground and in low-gravity. The low-gravity accuracy was generally worse than that seen during the ground slosh testing, which highlighted the importance of low-gravity, flight-like environment testing. 3D liquid distributions were reconstructed from the ECT data, but, due to reconstruction artifacts, their accuracy was inadequate for validating CFD slosh simulations. Various hardware recommendations that could significantly improve ECT accuracy and suggestions for future ECT experiments were discussed. Current research focuses on implementing and
developing more advanced tomographic reconstruction methods to improve the ECT system’s reconstruction and mass gauging accuracy.

The SSE program succeeded in collecting high-resolution video of long-duration, low-gravity, coupled-motion slosh with motion data and well-defined initial conditions. Scaling analyses, mechanical design, electrical design, software, fabrication, qualification testing, ISS operations, and CFD validation cases were presented in Chapters 4 and 5. Manual manipulation of the tanks outside of the SSE resulted in several microgravity fluid behavior observations. Error in the 6 DoF trajectories computed from the IMU data were the largest source of simulation error, and the trajectories need to be improved before running more CFD cases and claiming long, maneuver, duration microgravity slosh CFD validation. That said, CFD validation was successful for shorter (case-dependent) durations and, in primarily single axis motion tests, when the trajectories were restricted to 1 DoF. Lessons learned and recommendations for future ISS slosh experiments were compiled. Current SSE-related research is focused on trajectory improvements, and, if successful, future work includes implementing CFD mesh and modeling improvements, as well as running more validation cases.

Several contributions to the field of microgravity fluid management science were achieved. A prototype ECT system installed in a tank was successfully tested in low-gravity for the first time, and given the microgravity performance, ECT as a tank liquid mass gauging technology has been advanced to a technology readiness level (TRL) of 6. The first 3D distributions of sloshing liquid in low-gravity were reconstructed from the test data using ECT methods. A methodology was developed for processing the SSE data to create
trajectories and test videos, which were used to validate low-gravity slosh CFD simulations.

My current and future research builds on the foundation laid by this work and is dedicated to fundamentally changing how low-gravity slosh is handled. Space vehicle control systems use mechanical analogies to model fluid slosh in accelerated environments, but these analogies are, with limited exceptions, inaccurate for modeling slosh in low-gravity (see Chapter 1). Although CFD may be used to predict slosh dynamics of specific maneuvers, possibly providing bounding fluid forces and torques resulting from the maneuvers for use in open-loop vehicle control, CFD is too computationally demanding to run in real-time inside of a control loop. Even if more advanced analogies of slosh are developed, or if advancements in flight computers and CFD allow for the real-time simulation of slosh, they are ultimately still simulacra.

I hypothesize that all slosh models used in space vehicle control systems can be replaced by a sensor that measures slosh. To accomplish this, the sensor must provide the fluid forces and torques. As demonstrated in the present work, ECT can transiently reconstruct the 3D distribution of fluid in a tank, though any technology capable of real-time 3D fluid distribution measurement could be viable in this application. If sequential 3D fluid volumes are differenced, then a 3D fluid velocity field can be calculated. The 3D fluid velocity field can be used to calculate the fluid forces and torques in a similar manner to incompressible CFD, though with significantly lower computational cost due to not having to solve the momentum equation for the velocity field. Thus, an ECT-instrumented tank, with the addition of these calculations, constitutes the hypothesized slosh sensor.
Control systems are simulated as part of their design process and often use mechanical analogies to model slosh. However, coupling the vehicle dynamics calculated by the controls analysis simulation with fluid dynamics predicted by CFD slosh simulations is more accurate, particularly for phases of flight when the mechanical analogies are invalid [77]. As mentioned previously, CFD is too computationally expensive to run in real-time, so the CFD will limit the execution speed of the controls-CFD co-simulation, but this is generally acceptable in simulations of control systems. Of course, the CFD methodology must be validated, perhaps by following a process similar to the one in Section 5.4, or using the conceptualized ECT-CFD co-solver that was discussed in Section 3.11, which could enable quantitative validation of CFD slosh simulations via comparison of simulated 3D volumes and 3D volumes reconstructed from test data using ECT methods. The ECT-CFD co-solver methodology could be utilized in the controls analysis-CFD co-simulation to provide pseudo ECT system measurements of the slosh simulated by the CFD. In other words, “actual” fluid forces and torques, calculated directly by the CFD, would be coupled with the vehicle dynamics calculated by the controls analysis tool, but the simulated control system would use the “measurement” of forces and torques from the simulated ECT-based slosh sensor “installed” in the CFD-simulated tank. The development of such analysis tools would enable the design of future control systems that utilize the hypothetical ECT-based slosh sensor to actively control slosh during all phases of flight. Realizing slosh measurement in the manner described could cause a paradigm shift in the management of low-gravity slosh and be a major advancement in space vehicle control.
References


[74] P. S. University, "SE-FIT V1.2 beta".


Appendix A

5% NVF (mass and mass error plots shown in body text)
10% NVF
20% NVF
20% NVF Horizontal Only (data during rotation from horizontal to vertical was lost)
20% NVF Vertical Only
30% NVF (mass and mass error plots shown in body text)
40% NVF

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[Graphs showing accelerations and rotation rates over time, with data for Liquid Mass as well.]
50% NVF (IMU, mass, and mass error plots are in body text)

60% NVF
70% NVF (mass and mass error plots shown in body text)
90% NVF
Appendix B

5% NVF

20% NVF
50% NVF

80% NVF