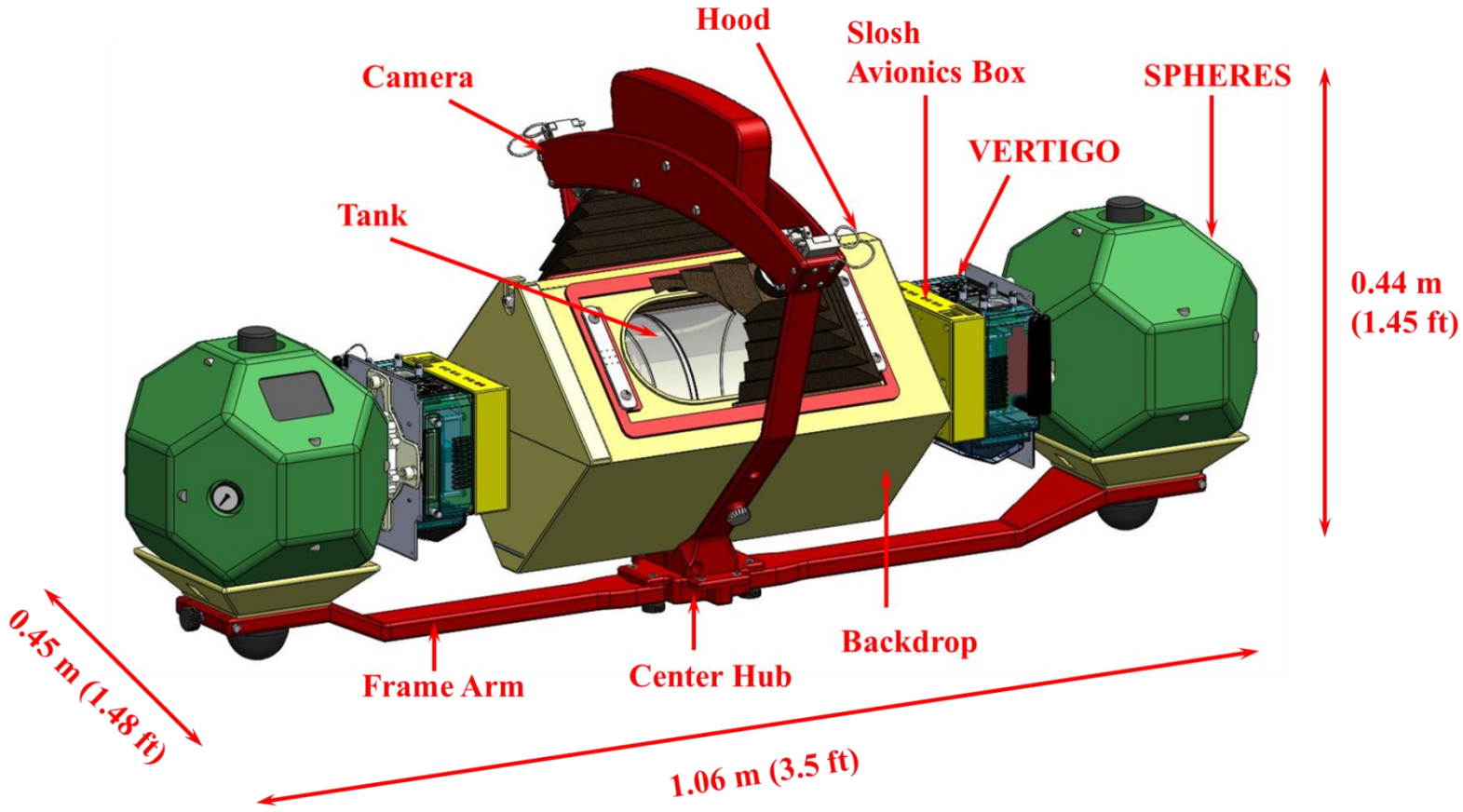
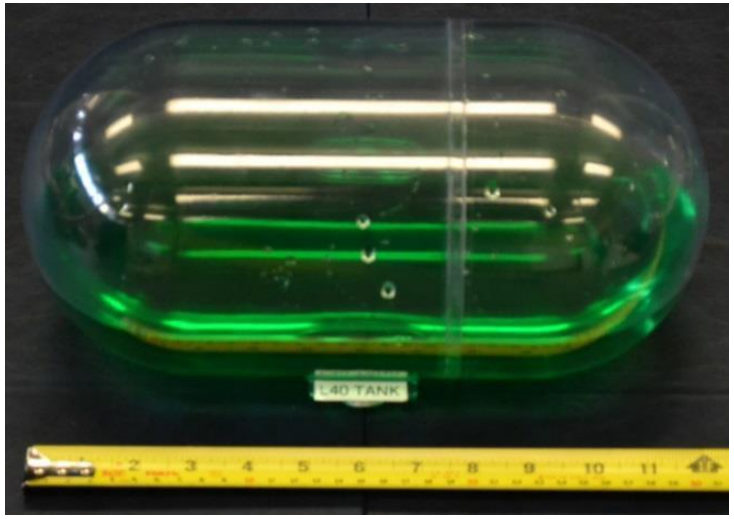
SLOSH EXPERIMENT OVERVIEW

1

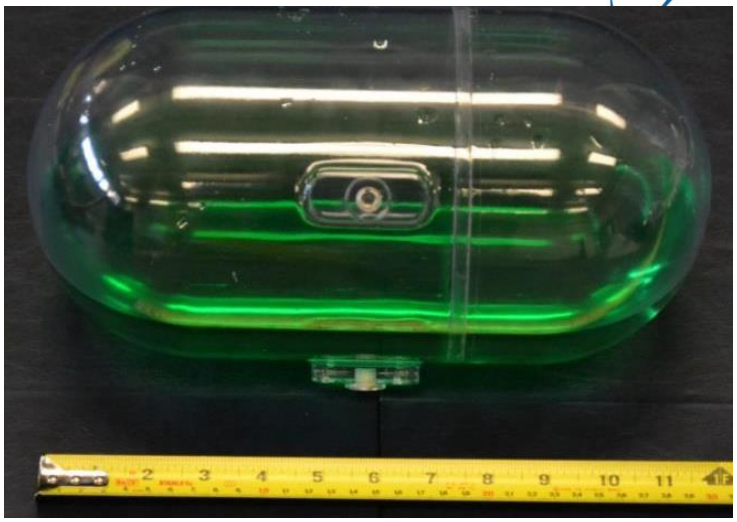
Overview


Hood
Slosh
Avionics Box
Camera
SPHERES
VERTIGO
Tank
0.44 m
(1.45 ft)
0.45 m (1.48 ft)
Backdrop
Frame Arm
Center Hub
1.06 m (3.5 ft)

Tanks



20% fill

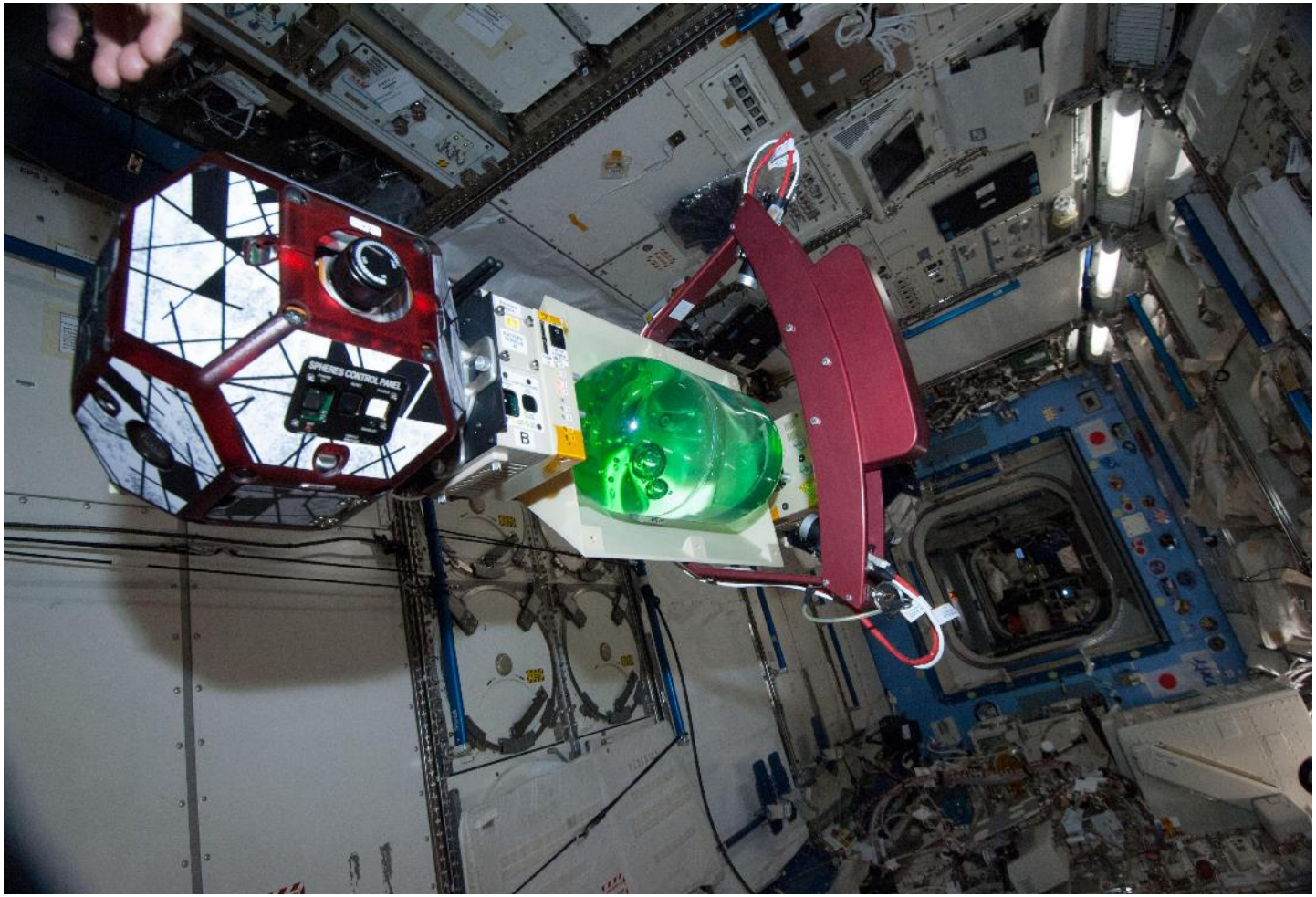


40% fill

- 3D printed
- Filled with water + green food coloring for contrast
- Sealed

3

On Station

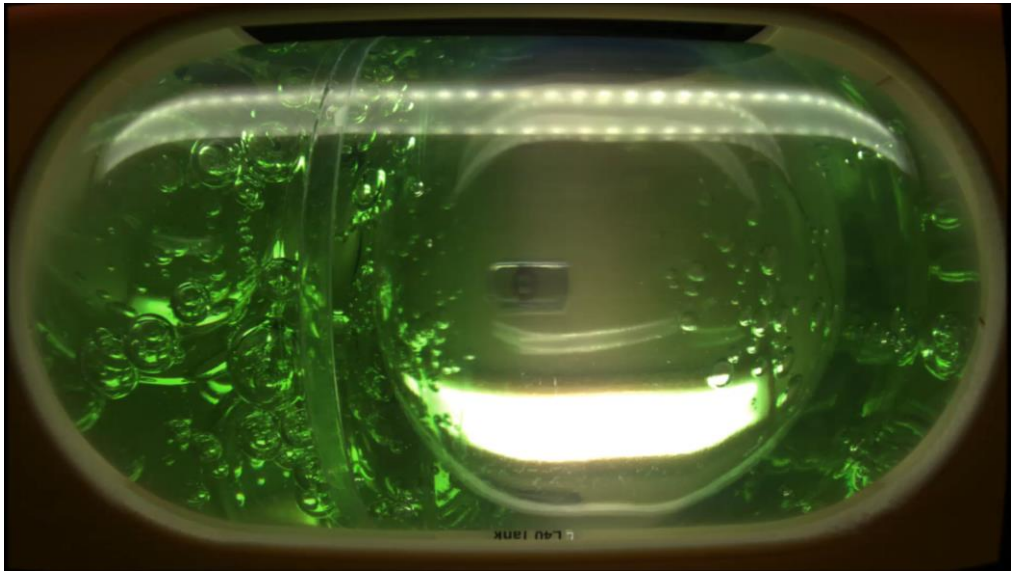


Sessions

- **All sessions completed**
  - **Checkout session completed 1/22/2014**
  - **Science 1 completed 02/28/2014**
  - **Science 2 completed 06/18/2014**
  - **Science 3 completed 09/09/2014**
  - **Science 4 completed 07/17/2015**
  - **Science 5 completed 08/07/2015**
  - **Science 6 completed 09/10/2015**
  - **Science 7 completed 11/12/2015**
  - **Science 8 completed 10/07/2016**

Session Overview

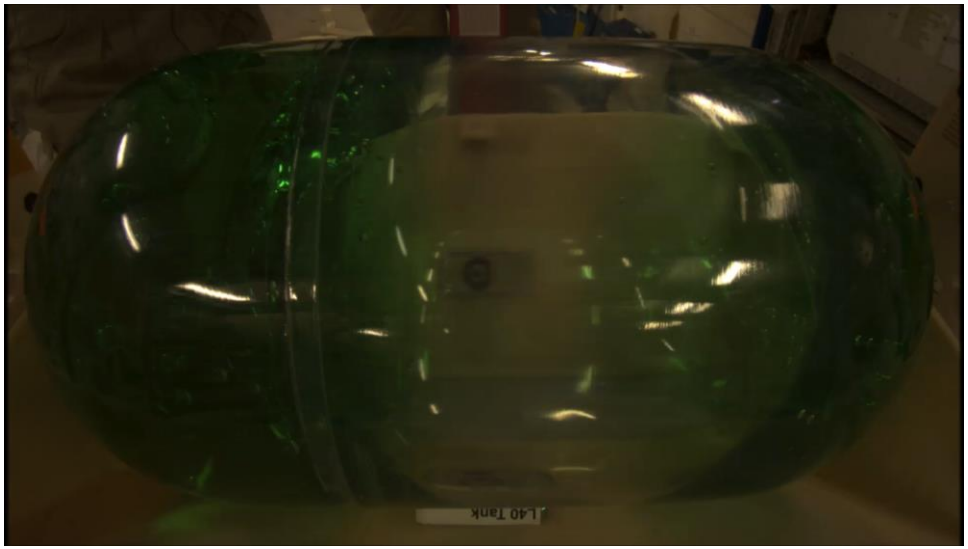
- **Checkout Session**
  - **40% tank**
  - **12 runs completed**
  - **All runs were spheres powered**
  - **Successfully checked out all hardware and data collection methods**
  - **Verified inertia and thruster performance**
  - **Noticed large bubbles trapped in the liquid caused bad initial condition**



Checkout_session.mp4

Session Overview

- **Science #1**
  - **40% tank**
  - **11 runs completed**
  - **A few runs were "hood off" to allow crew members to monitor fluid as they optimized an initialization technique**
  - **Most runs were spheres powered (low fluid motion)**



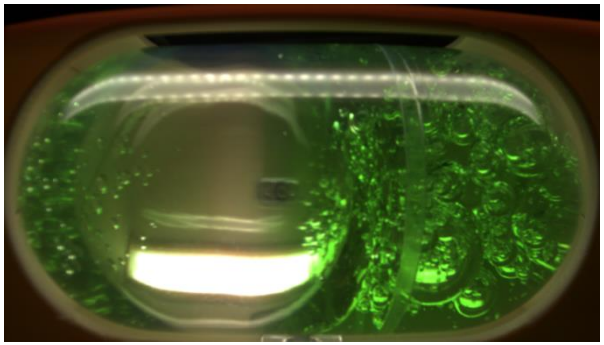
science 1 hood off.mp4

Initial Condition Video

evolution of settling.mp4

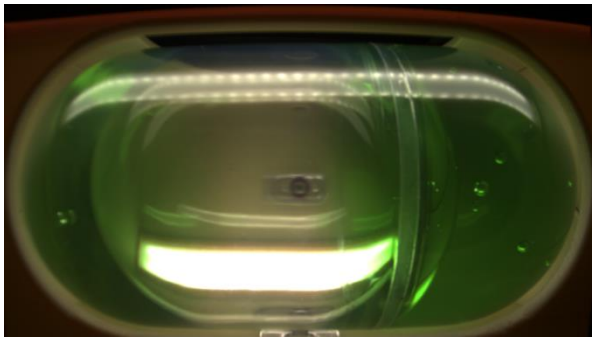
Initial Condition

Checkout



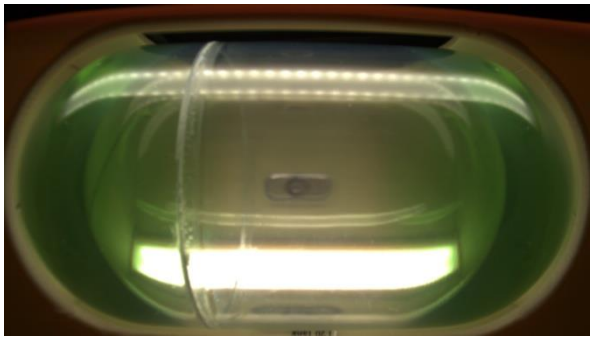
Bad initial condition

Science #1



Good initial condition 40%

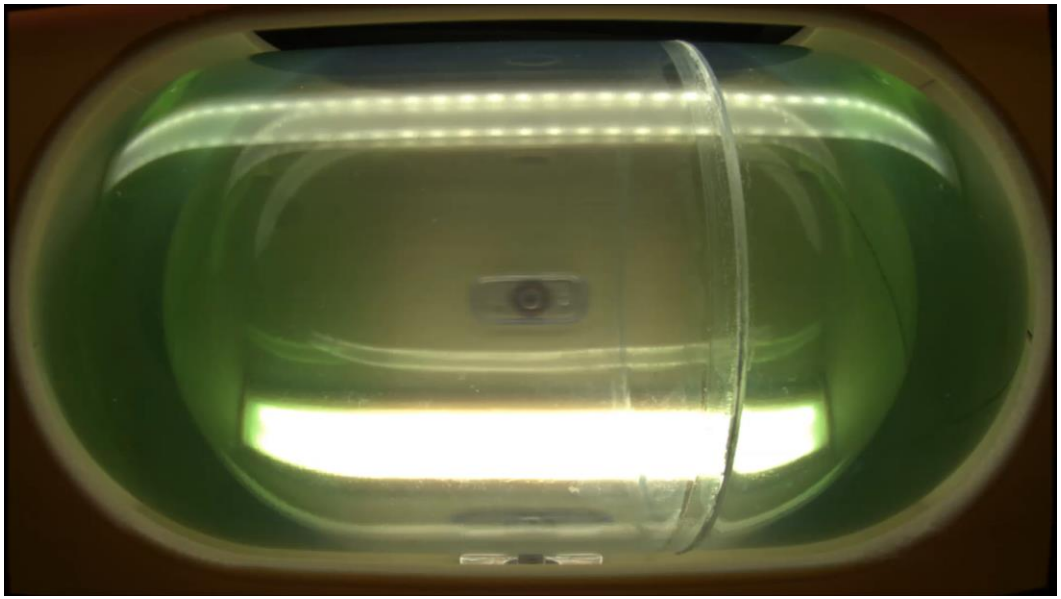
Science #2



Good initial condition 20%

Session Overview

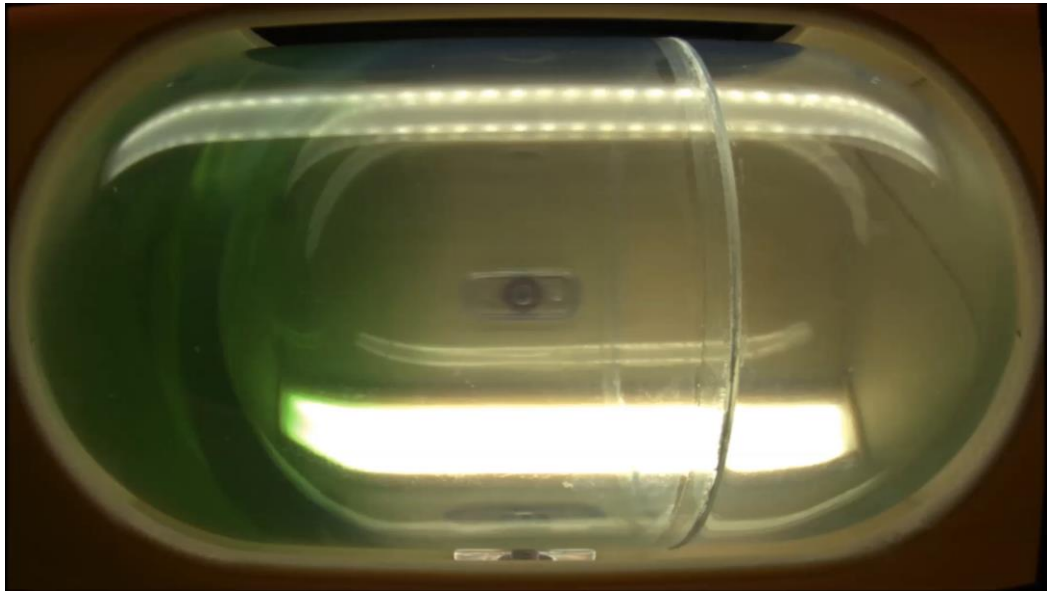
- **Science #2**
  - **20% tank**
  - **17 runs completed**
  - **All runs include initial settling maneuver**
  - **Several crew-induced motions included**
  - **Much more interesting fluid motion (first breaking wave captured)**



Science 2.mp4

Session Overview

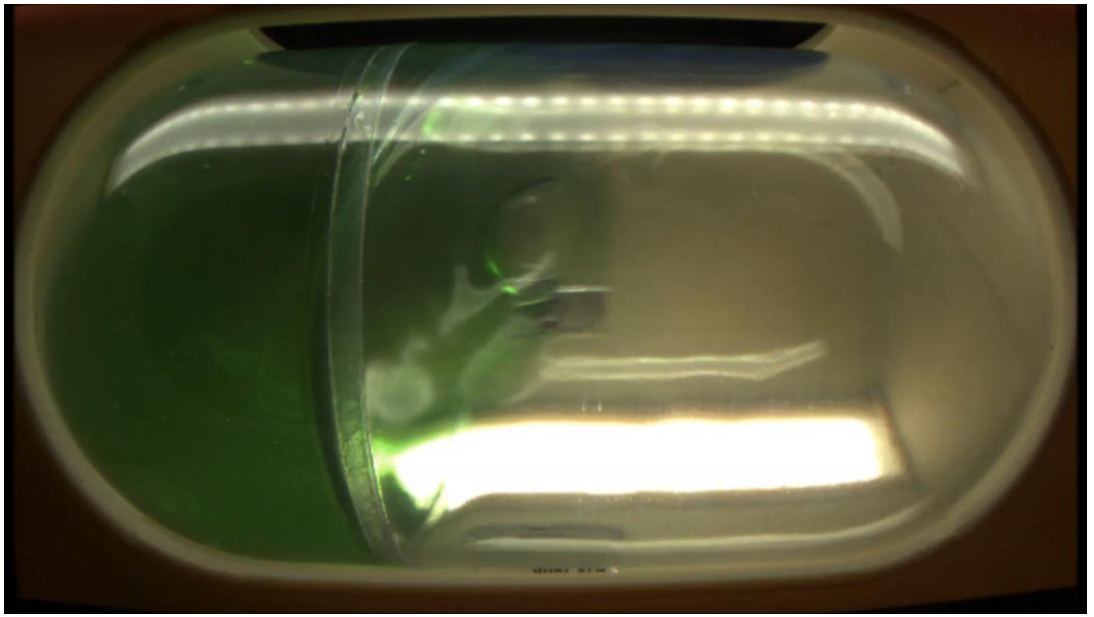
- **Science # 3**
  - **20% tank**
  - **16 runs completed**
  - **Varying initial conditions**
  - **All crew induced motions**
  - **Several breaking waves captured (long lasting fluid globs captured)**



Science 3.mp4

Session Overview

- **Science # 4**
  - **40% tank**
  - **15 runs completed**
  - **Varying initial conditions**
  - **All crew induced motions**
  - **Repeated Science 3 maneuvers with 40% tank**



Science 4.mp4

Session Overview

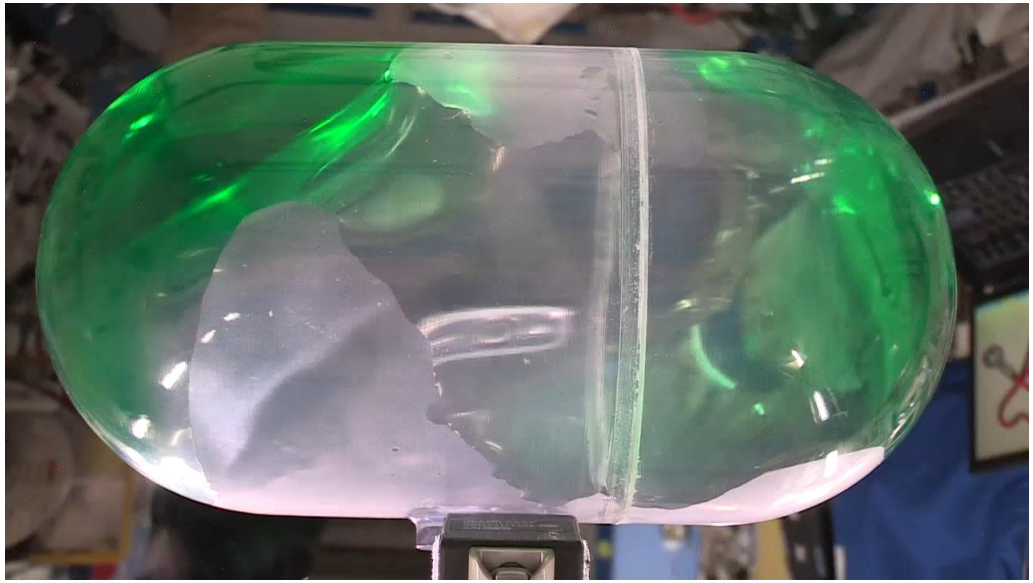
- **Science # 5**
  - **40% tank**
  - **4 runs completed**
  - **Varying initial conditions**
  - **All crew induced motions**
  - **Tried to look at shift from surface tension dominated motion to inertial dominated**
  - **Completed many “bare tank” runs with a DIY headcam**

Session Overview

- **Science # 6**
  - **40% tank**
  - **~12 runs completed**
  - **Varying initial conditions**
  - **All crew induced motions**
  - **Tried to look at shift from surface tension dominated motion to inertial dominated**
  - **Not able to download data (ran out of HD space)**

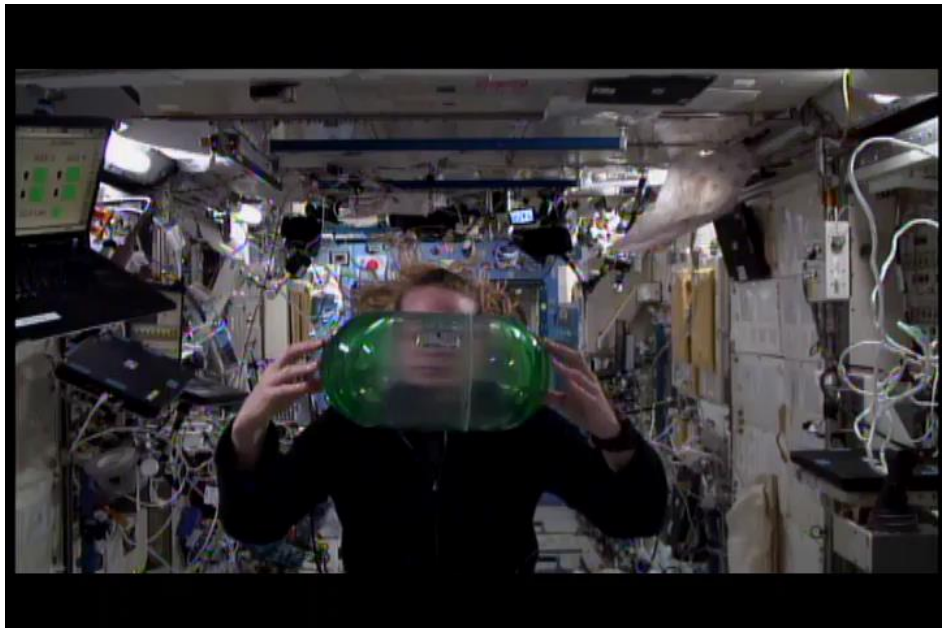
Session Overview

- **Science # 7**
  - **20% tank**
  - **Nothing worked**
    - » **Bad batteries**
    - » **Ran out of HD space again**
    - » **SPHERES lost connectivity**
    - » **Bad backup HD**
  - **Crew member rigged up a DIY slosh experiment**
  - **Collected some very high quality, highly dynamic slosh video**
  - **This video has proven to be extremely useful**



Session Overview

- **Science # 8**
  - **20% tank**
  - **Session carried out by crew member Kate Rubins**
  - **Continued to have problems with the experiment**
    - » **Both SPHERES and Slosh hardware showing its age**
    - » **Problems with communication, power-up, battery life, and hard drives**
  - **Session ended with a series of tank only maneuvers**
    - » **Produced very high quality videos**
    - » **Videos helped determine the line between body force driven flow and surface tension driven flow**



Other videos

CFD

Initial CFD

- **Reconstruction and CFD completed for a couple runs**
  - **Star-CCM+**
  - **Simplified trajectory reconstruction using 1 acceleration axis**
  - **Excellent qualitative match**

The SPHERES-Slosh Data Pipeline

- **Responsible for reading, correcting, filtering, transforming data**
- **Writes a trajectory file in format usable by the CFD software**
- **6DoF: 3-axis translation, 3-axis X-Y-Z body-frame rotations**
  - **All IMUs in a different coordinate system: need to transform data to "CFD body frame"**
  - **Accelerations required 3D rigid body kinematic transformations**
- **Written in MATLAB, > 1500 lines**

The SPHERES-Slosh Data Pipeline Challenges

- Many challenges
- IMUs had low, variable data rates (20-30 Hz) and cameras had low, variable frame rates (0.5-2 fps)
  - Data hard to read in, lots of noise, difficult to filter, SPHEREs accelerometers clip at high accelerations, etc.
  - Hard to resolve sloshing events with low camera frame rate
- No clocks were synchronized
  - A-side SPHERE and B-side SPHERE were on different clocks, but so were the A-side SPHERE and A-side Slosh avionics box, as well as the A-side camera
  - Difficult to match up A/B side data folders
  - Difficult to time-align the data and images
    - » Custom time-alignment algorithms
    - » Custom real-time video writer based on repeating images
- No absolute position reference (SPHEREs metrology system not used): dead-reckoning/inertial-only reconstruction scheme. The IMUs' noise results in reconstructions getting worse over time.

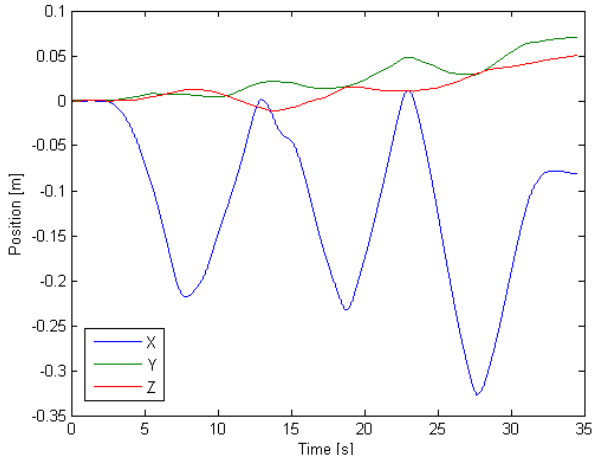
Initial Validation Case Selection

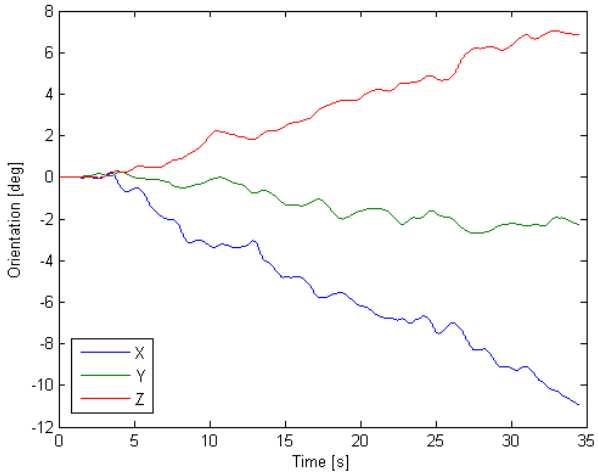
Science Mission	Test Number	A-side Folder	B-side Folder	Maneuver Description
2	11	run_2014_06_18_16_34_33	run_2014_06_18_16_28_08	x-axis periodic translation
2	13	run_2014_06_18_16_44_23	run_2014_06_18_16_37_58	y-axis periodic translation
3	4	run_2014_09_09_11_37_51	run_2014_09_09_11_30_39	single push along +x axis
3	16	run_2014_09_09_12_29_35	run_2014_09_09_12_22_25	spin about +x axis

- **Case selection challenges:**
  - **Some tests missing some or all data and/or images**
  - **Motion in many cases too low to induce significant sloshing**
  - **Non-steady initial conditions: these had to be excluded because the trajectory computation algorithm and CFD require steady initial conditions**
- **Variety of maneuvers desired**
- **All astronaut-actuated**
- **Processed with data-pipeline**
- **Science 2, test 11 is the one used in the initial CFD validation shown earlier**

6 DoF Trajectory Checks

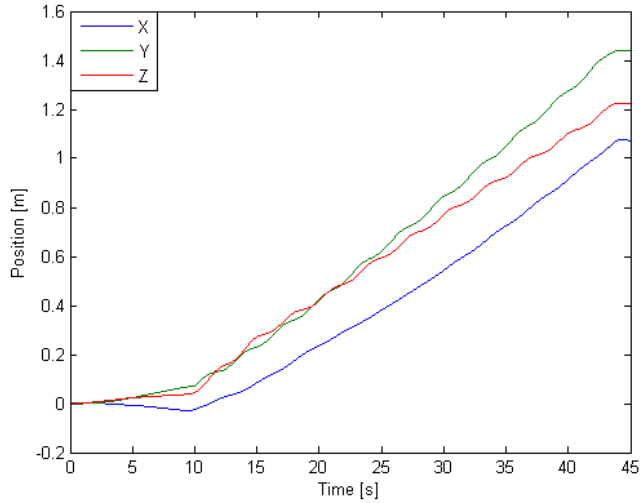
- **Trajectories were sanity checked using external video feeds of the experiments. Example of Science 2 Test 11:**

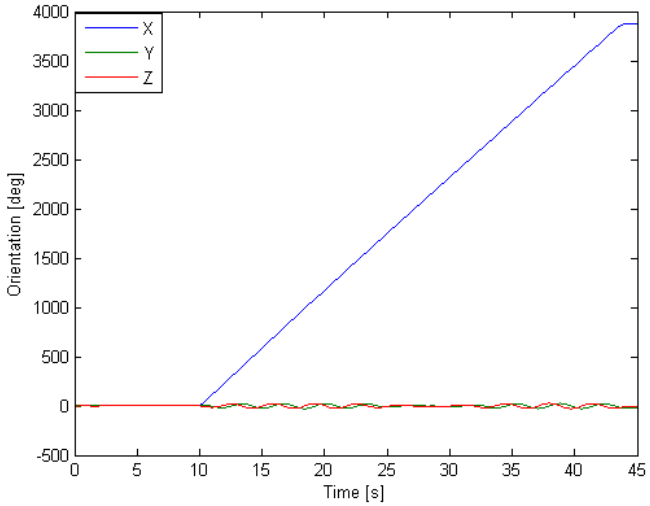




Trajectory Checks

- **Example of Science 3 Test 16:**





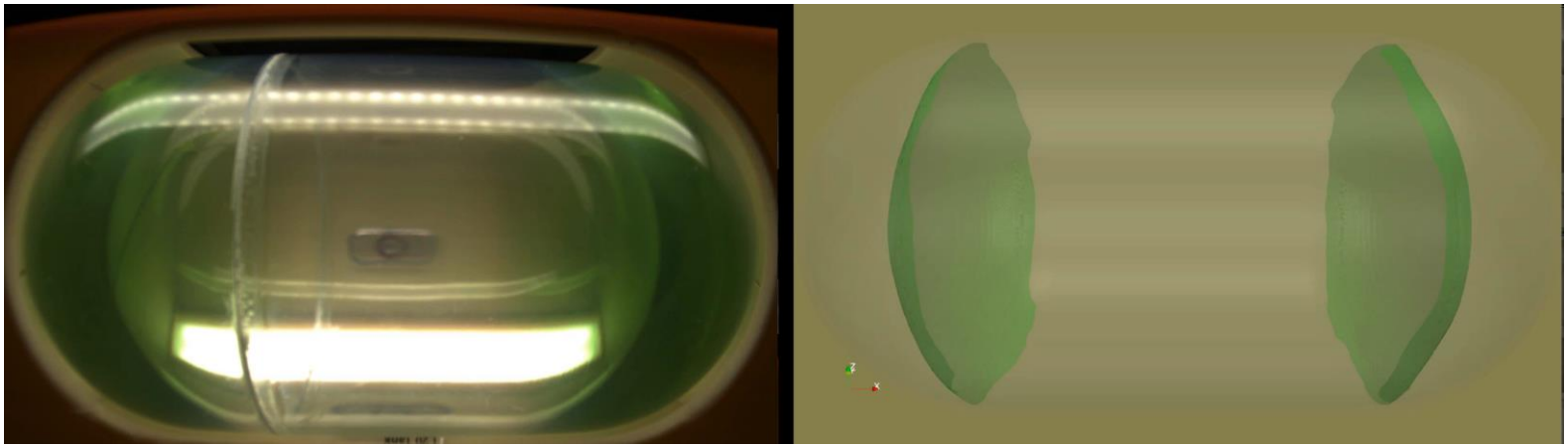
CFD Settings

- OpenFOAM
- ~800k cell, hexahedral dominant with prism layer cells along the wall and has a smooth transition from the wall layer cells to the core mesh
- 2nd order accurate time and space formulations, PIMPLE solution scheme, laminar
- Multiphase volume-of-fluid (VOF), constant density fluids (air and water)
- Surface tension, static contact angle
- Motion: position and orientation commanded (output from data pipeline)
- Automatic time stepping
- Isosurfaces at a volume fraction of 0.5 were recorded every 0.02 s

CFD Post-Processing

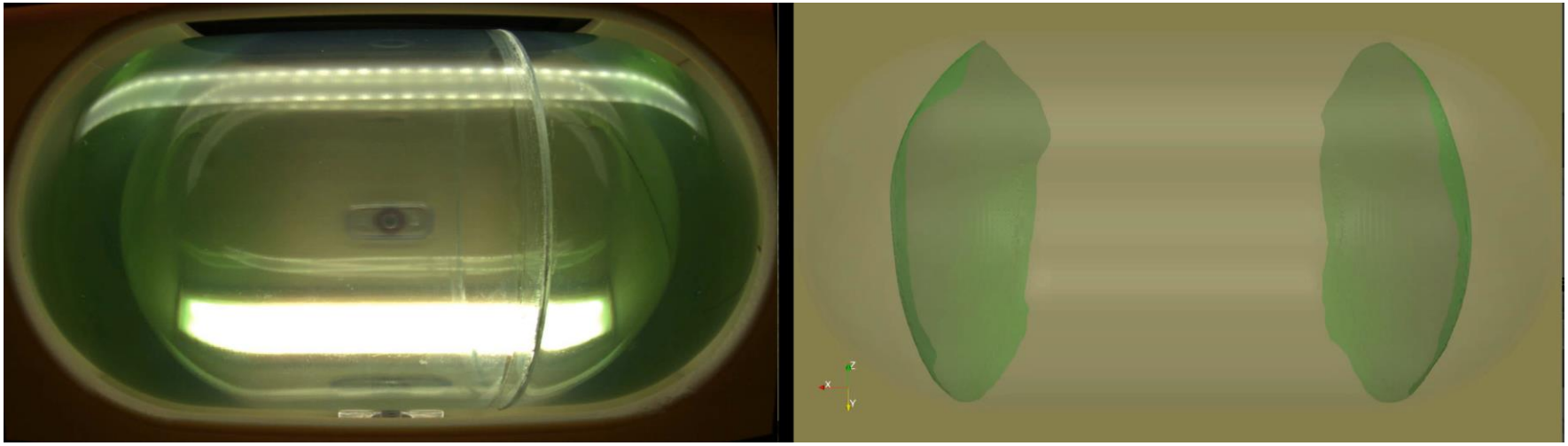
- **Paraview**
  - **Simple opacity, diffuse shading, and specular shading were used: fluid does not look particularly realistic**
  - **Note that the CFD images are just the clear tank walls and an isosurface at a volume fraction of 0.5. Bulk fluid is not colored.**
- **Python scripts written to automate post-processing and video creation**
- **A-side and B-side real time videos created**
  - **View point follows real experiment's A and B side cameras**
  - **Had to program 6DoF transformations**
- **Experiment and CFD videos had to be manually aligned in time due to lack of clock synchronization**

Science 2 Test 11 Results, A-side



- Low frame rate makes seeing slosh events difficult
- Bulk fluid distribution seems to agree fairly well, especially closer to beginning
- The cause for the drops along the wall in the CFD is unknown. They seem to appear and disappear at random
- Around 27s, a drop breaks off in the experiment. In the CFD, the prominence (that should have formed a drop) collides with the side of the tank, i.e. the tank wall rotates into the prominence

Science 3 Test 16 Results, B-side



- Low frame rate makes seeing slosh events difficult
- Bulk fluid distribution seems to agree fairly well
- The CFD appears to be rotating about a slightly different axis than the experiment
  - » Though the bulk of the fluid is still on the –z side of the tank, the CFD shows a skewed fluid distribution

Results/Discussion

- **Experiment data quality problems present challenges with working with this data set**
  - **Many lessons learned**
- **Trajectory reconstruction needs improvement**
  - **Restricted DoF (when possible) reconstructions are good**
- **Some qualitative CFD validation complete**
- **Went from idea, to hardware, testing, validation, and back to practical application**
  - **Jason-1 NASA mission**
  - **MMS NASA mission**

Thanks for coming!

- **Questions?**