Acquisition of Long-Duration, Low-Gravity Slosh Data Utilizing Existing ISS Equipment (SPHERES) for Calibration of CFD Models of Coupled Fluid-Vehicle Behavior

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Extended Abstract

Accurate prediction of coupled fluid slosh and launch vehicle or spacecraft dynamics (e.g., nutation/precessional movement about various axes, attitude changes, ect.) requires Computational Fluid Dynamics (CFD) models calibrated with low-gravity, long duration slosh data. Recently completed investigations of reduced gravity slosh behavior have demonstrated the limitations of utilizing parabolic flights on specialized aircraft with respect to the specific objectives of the experiments. Although valuable data was collected, the benefits of longer duration low-gravity environments were clearly established. The proposed research provides the first data set from long duration tests in zero gravity that can be directly used to benchmark CFD models, including the interaction between the sloshing fluid and the tank/vehicle dynamics.

To explore the coupling of liquid slosh with the motion of an unconstrained tank in microgravity, NASA's Kennedy Space Center, Launch Services Program has teamed up with the Florida Institute of Technology (FIT), Massachusetts Institute of Technology (MIT) and the Office of the Chief Technologist (OCT) to perform a series of slosh dynamics experiments on the International Space Station using the SPHERES platform. The Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) testbed provides a unique, free-floating instrumented platform on ISS that can be utilized in a manner that would solve many of the limitations of the current knowledge related to propellant slosh dynamics on launch vehicle and spacecraft fuel tanks. The six degree of freedom (6-DOF) motion of the SPHERES free-flyer is controlled by an array of cold-flow CO2 thrusters, supplied from a built-in liquid CO2 tank. These SPHERES can independently navigate and re-orient themselves within the ISS. The intent of this project is to design an externally mounted tank to be driven inside the ISS by a set of two SPHERES devices (Figure 1). The tank geometry simulates a launch vehicle upper stage propellant tank and the maneuvers replicate those of real vehicles. The design includes inertial sensors, data acquisition, image capture and data storage interfaces to the SPHERES VERTIGO computer system on board the flight article assembly. The design also includes mechanical and electronic interfaces to the existing SPHERES hardware, which include self-contained packages that can operate in conjunction with the existing SPHERES electronics.

The SPHERES-Slosh investigation is computer controlled and requires only minimal interaction with the ISS crew. Once the package is on station, an ISS crewmember takes the hardware out of the storage container and assembles a few pieces to complete the system. Once this operation is complete, the SPHERES units (already on station) are attached on both ends of the assembly. The SPHERES are integrated using a clamp system that rigidly attaches the CO2 tank to the testbed frame. Finally, the cameras and IMUs are connected to the VERTIGO computer system to form the completed system.

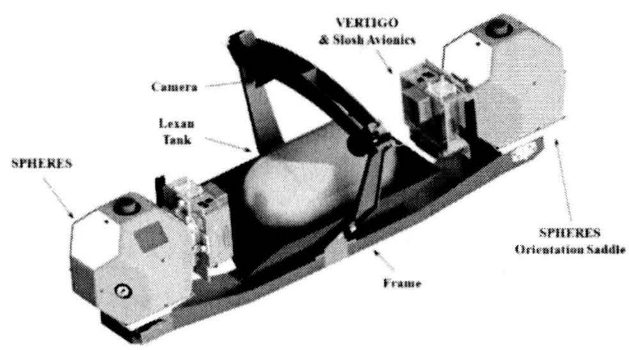

Figure 1
SPHERES Slosh Experiment

Once the unit is fully assembled, it is ready for research operations to begin. This simply involves an ISS crewmember powering on all units. This includes both SPHERES units and the SPHERES Laptop computer. Once all units are up and running, the entire assembly is placed in the center of the ISS module and allowed to free float. The ISS crewmember runs the software on the SPHERES Laptop which commands the SPHERES to perform a pre-specified set of maneuvers. After the test run is complete (5 minutes approx.), the unit is reoriented to the center of the module and a new test begins. Provided our allotted mission time allows, these tests continuously run until the on-board memory is full, or the CO2 propellant aboard the SPHERES runs out. At this point, the crewmember attaches the hard drives to the SPHERES Laptop computer and downloads all of the test data for transmission back to earth.

The principal goal of this inverstigation is to acquire long duration slosh data consisting of both video and position data. Since liquid propellants normally constitute a large percentage of the vehicle's mass, it is important to predict the effects they will have on the vehicles trajectory. In other words, a vehicle with liquid propellants will move differently from the same vehicle using solid propellants. This is caused by the forces imparted to the vehicle as the liquid moves around inside the tanks. This investigation will use video cameras to photograph the liquid inside a clear tank. At the same time, Inertial Measurement Units (IMU) will measure the position of the system as a function of time. This will generate enough data to quantitatively determine the differences between a tank with liquid and one without. The data will also be used to benchmark CFD models currently in use.

Undergraduate and graduate (MS and PhD level) students from the Florida Institute of Technology (Florida Tech) and the Massachusetts Institute of Technology (MIT) are actively involved in the liquid slosh dynamics research project onboard ISS. At Florida Tech 5 undergraduate students, 3 graduate students and 2 faculty members are involved. At MIT several undergraduate students, 1 graduate student, 1 research scientist and 1 professor are involved in the project. In addition to college-level student participation, several outreach activities specifically geared toward elementary and high school students are being prepared in conjunction with this effort. The SPHERES slosh dynamics project serves as a lesson module and provides examples for existing STEM (Science, Technology, Engineering and Mathematics) programs already in place at local elementary and high schools in Brevard County, Florida. Besides producing a rich set of CFD calibration data, this experiment will engage and inspire elementary and high school students to explore careers in science and engineering.

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This Package was prepared for the 1st Annual International Space Station (ISS) Research and Development Conference and may only be used in that context

Agenda

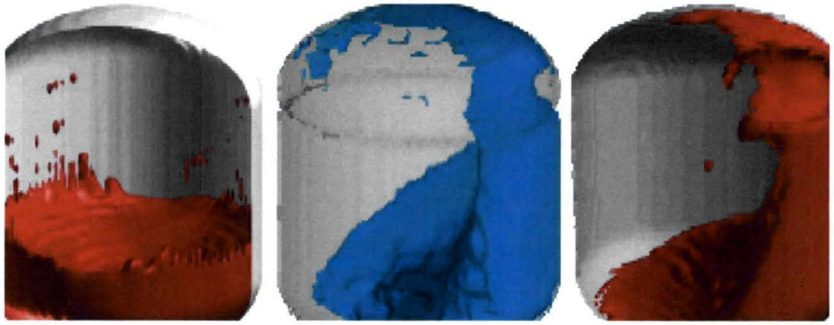
- Background, Motivation and Objectives
- Slosh Team
- Experiment
  - Structure
  - Data Acquisition
  - Launch Configuration
- Operations
- Conclusions

Background and Motivation: Slosh Dynamics Research

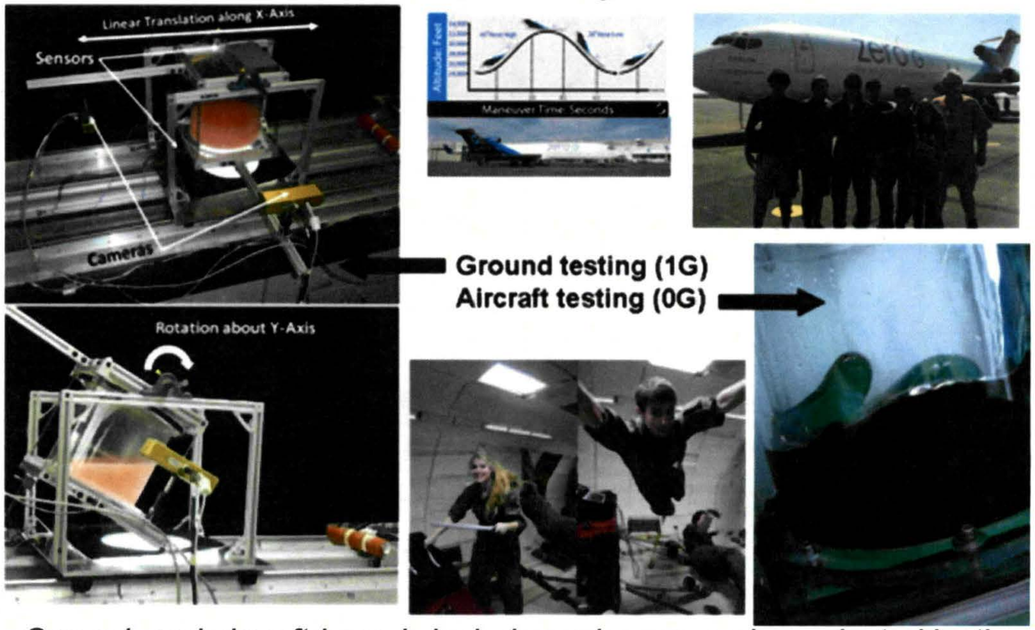
- NASA must ensure maximum safety and performance of rocket launch vehicles
  - Liquid slosh behavior still modeled with high level of uncertainty and models not validated with zero gravity experimental data
  - ***Example: $Billion+ Delta IV launch postponed because of slosh CFD uncertainty***

- Need universal experimental data set to benchmark CFD models
  - Ground-based testing at 1G completed
  - Micro-gravity testing using aircraft completed

- **Need for dedicated, long duration slosh data set for model validation**

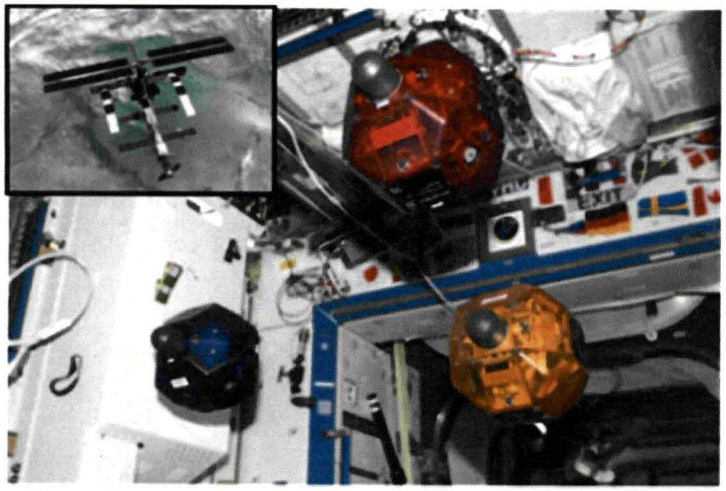


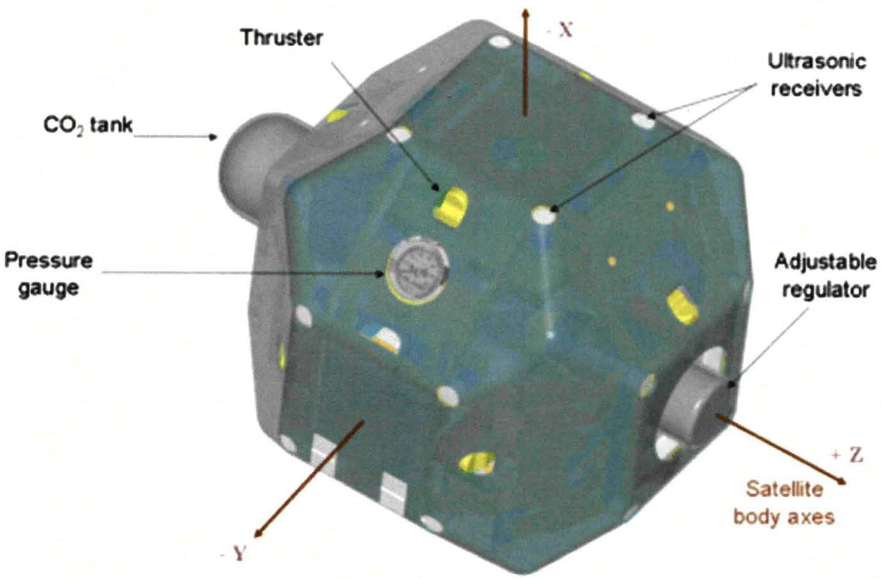
"The Boeing Delta IV Launch Vehicle – Pulse-Settling Approach for Second-Stage Hydrogen Propellant Management", Acta Astronautica Volume 61, June-August 2007



Ground- and aircraft-based slosh dynamics research conducted by the Florida Institute of Technology under NASA grants

Background and Motivation: SPHERES





- Current experimental methods to obtain CFD benchmarking data are insufficient due to:
  - short-duration (drop tower tests and parabolic "zero-g" flights)
  - low-fidelity and non-low gravity conditions (ground test beds)
- Need minutes of slosh data
- Partner with MIT to develop SPHERES-based liquid slosh experiment
- 6-DOF motion of SPHERE satellite controlled by a series of cold-flow CO_2 thrusters supplied by a liquid CO_2 tank
- Predictions provided by 6-DOF Multi-physics solver will be verified by experiments performed using SPHERE satellite

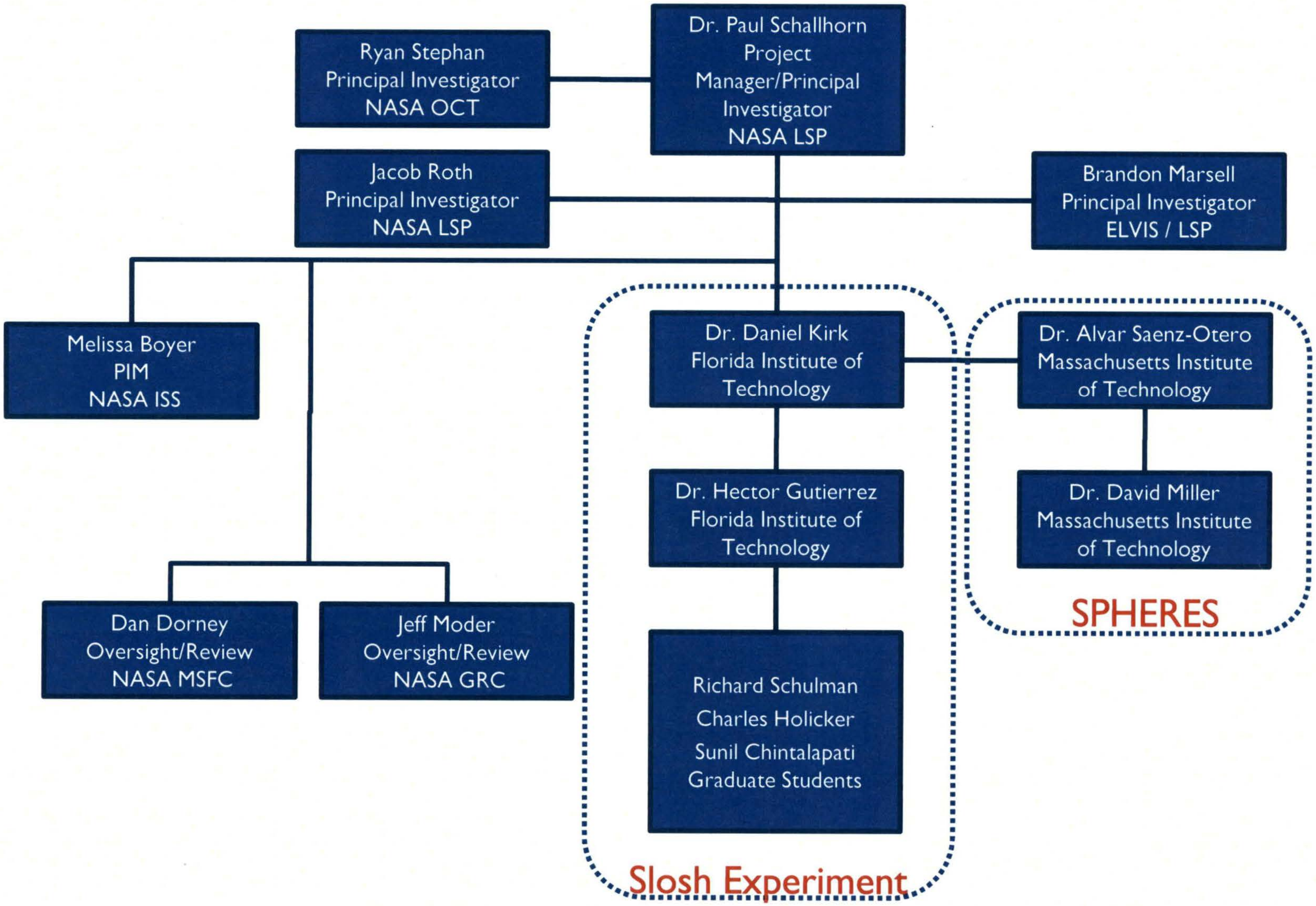
Overall Goal, Objectives and Readiness

- **Overall Goal:** Acquire long-duration, low-gravity slosh data for calibration of detailed Computational Fluid Dynamics (CFD) models of coupled fluid-vehicle behavior

- **Project Objectives**
  - Utilize existing SPHERES satellites to propel transparent fluid-filled tank
  - Acquire system and liquid position data for known applied forces using IMU and imaging systems
  - Benchmark CFD model predictions

- **Value to Agency**
  - Liquid fueled rocket engines are here to stay
    - Throttleable
    - Efficient
    - High thrust
  - Predicting spacecraft and launch vehicle slosh dynamics is critical for mission success
    - Longer missions
    - More challenging maneuvers
    - Safety concerns
  - Better models = more reliable, safer systems
  - Current CFD models lack **long-duration** benchmarking data and hence are limited in their predictive abilities
  - Access to such data would greatly improve CFD fluid slosh model predictions, benefiting spacecraft and launch vehicle design and ops

Slosh Team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Principal Investigator
NASA OCT
Jacob Roth
Principal Investigator
NASA LSP
Brandon Marsell
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Massachusetts Institute of Technology
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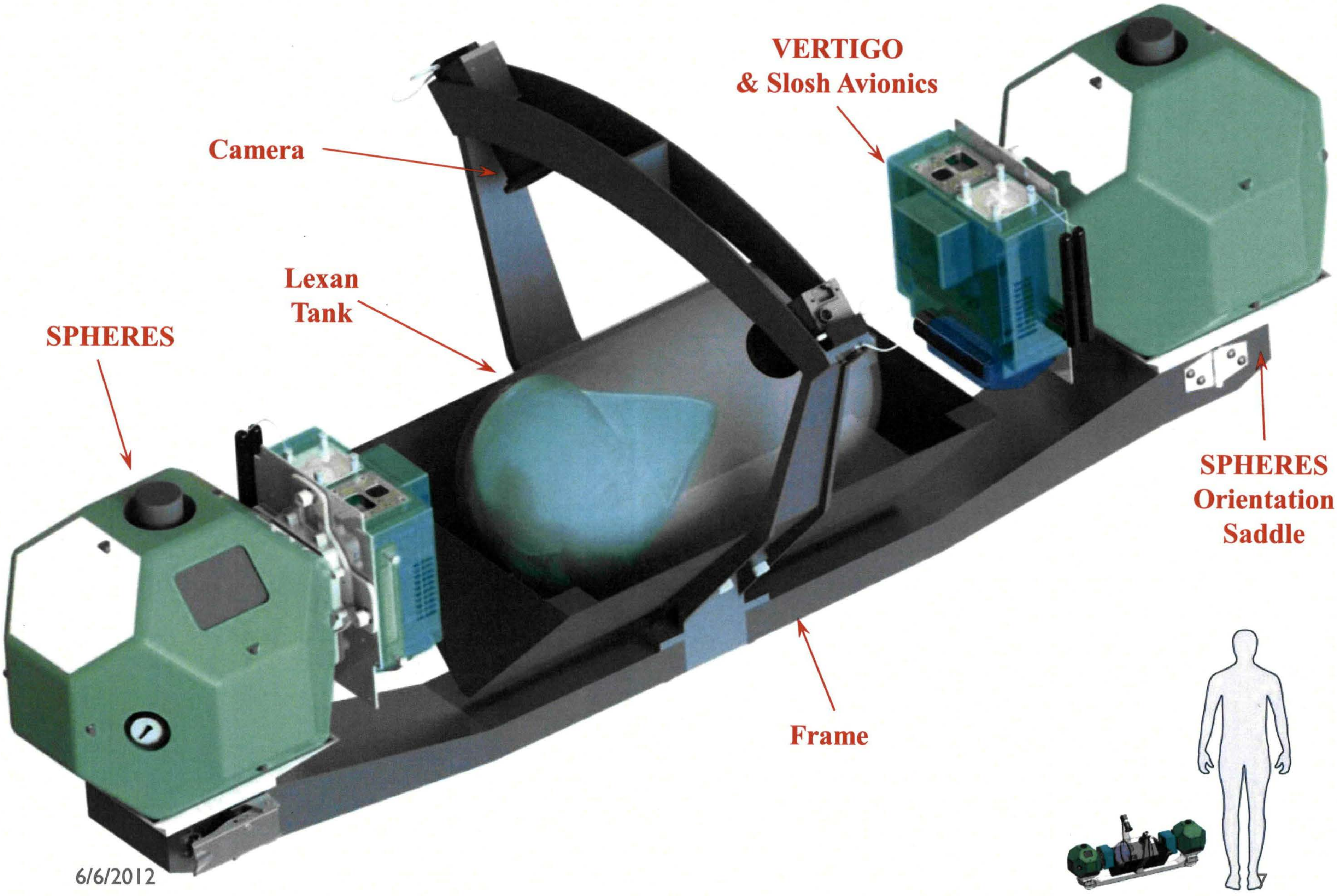
Massachusetts Institute of Technology
SPHERES

Slosh Experiment



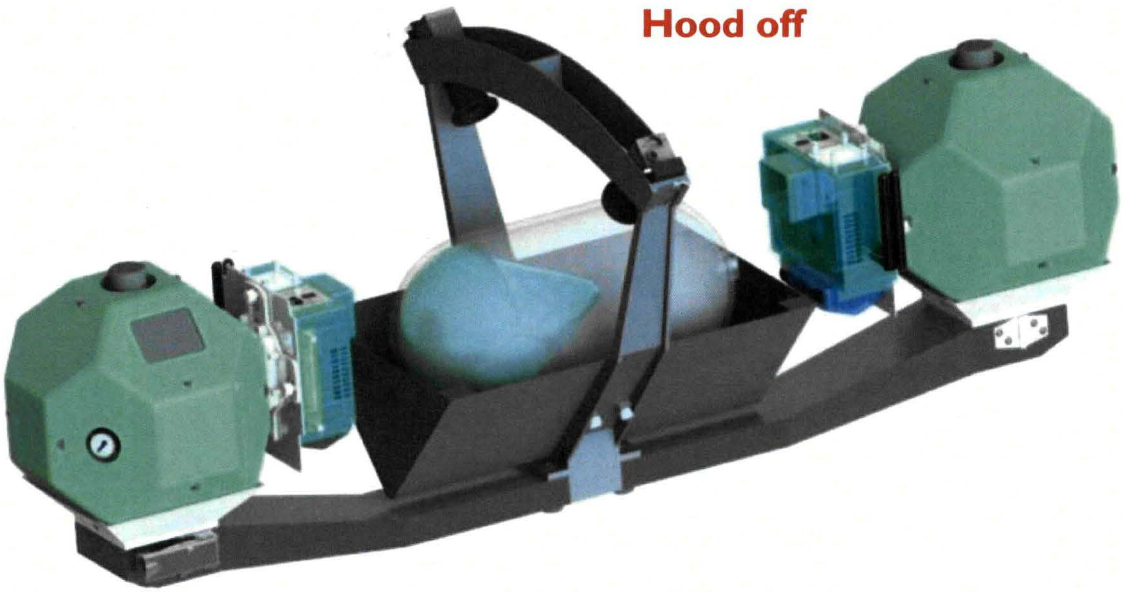
6/6/2012

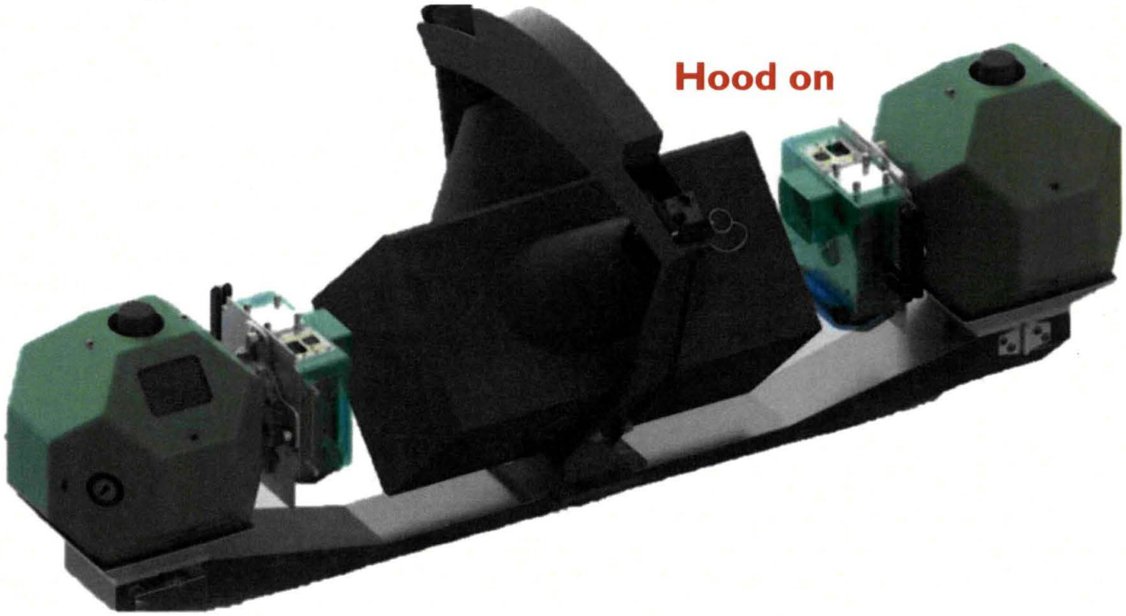
Key Systems

- **Tank**
  - Sizing study: Bond number analysis results
  - Cylindrical Lexan tank with spherical end-caps

- **DAQ System**
  - Slosh Avionics
  - Camera, lens and hood enclosure
  - IMU's on SPHERES and Slosh tank
  - VERTIGO Computer

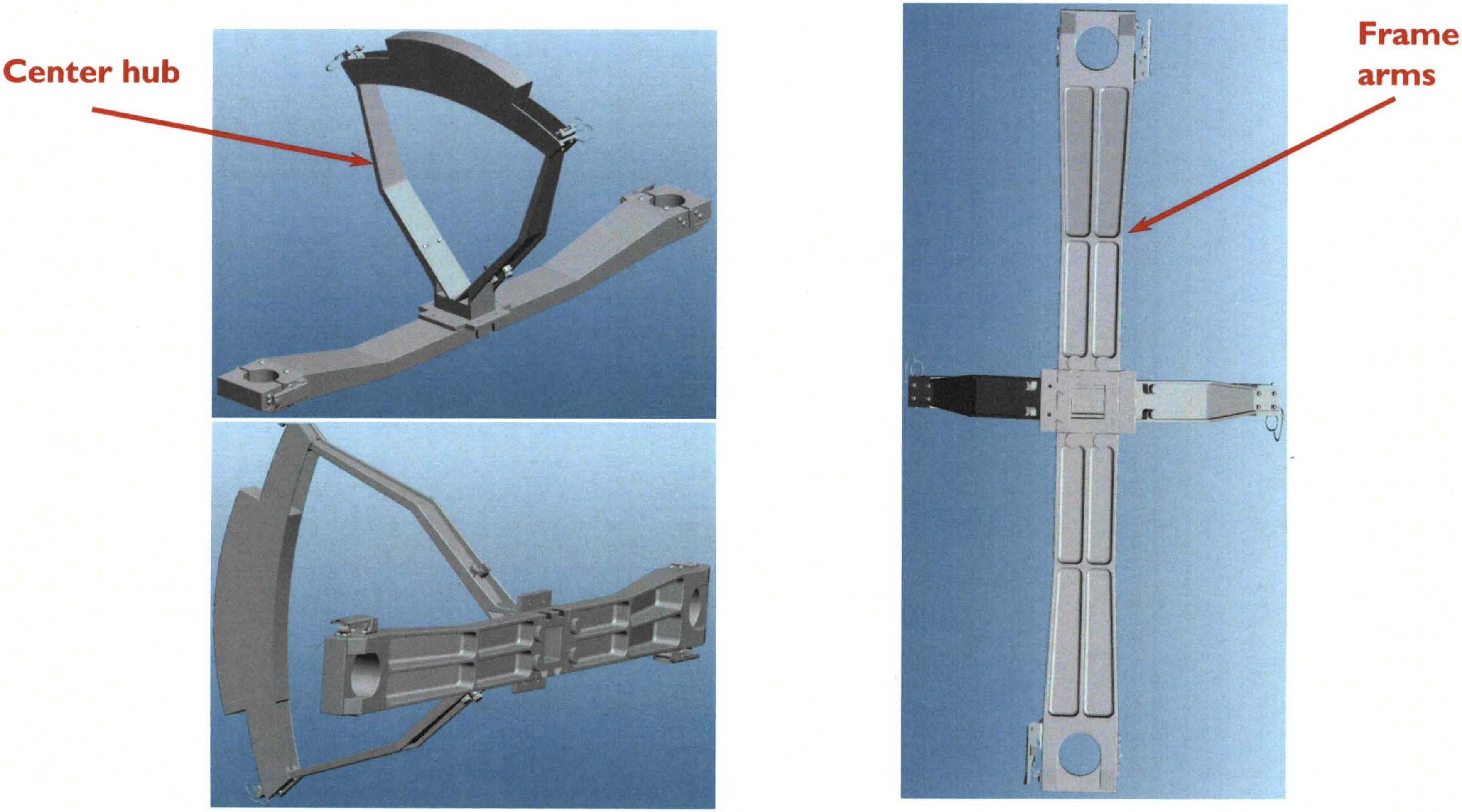
- **Mounting Hardware**
  - Aluminum frame
  - Cup/Clamp design



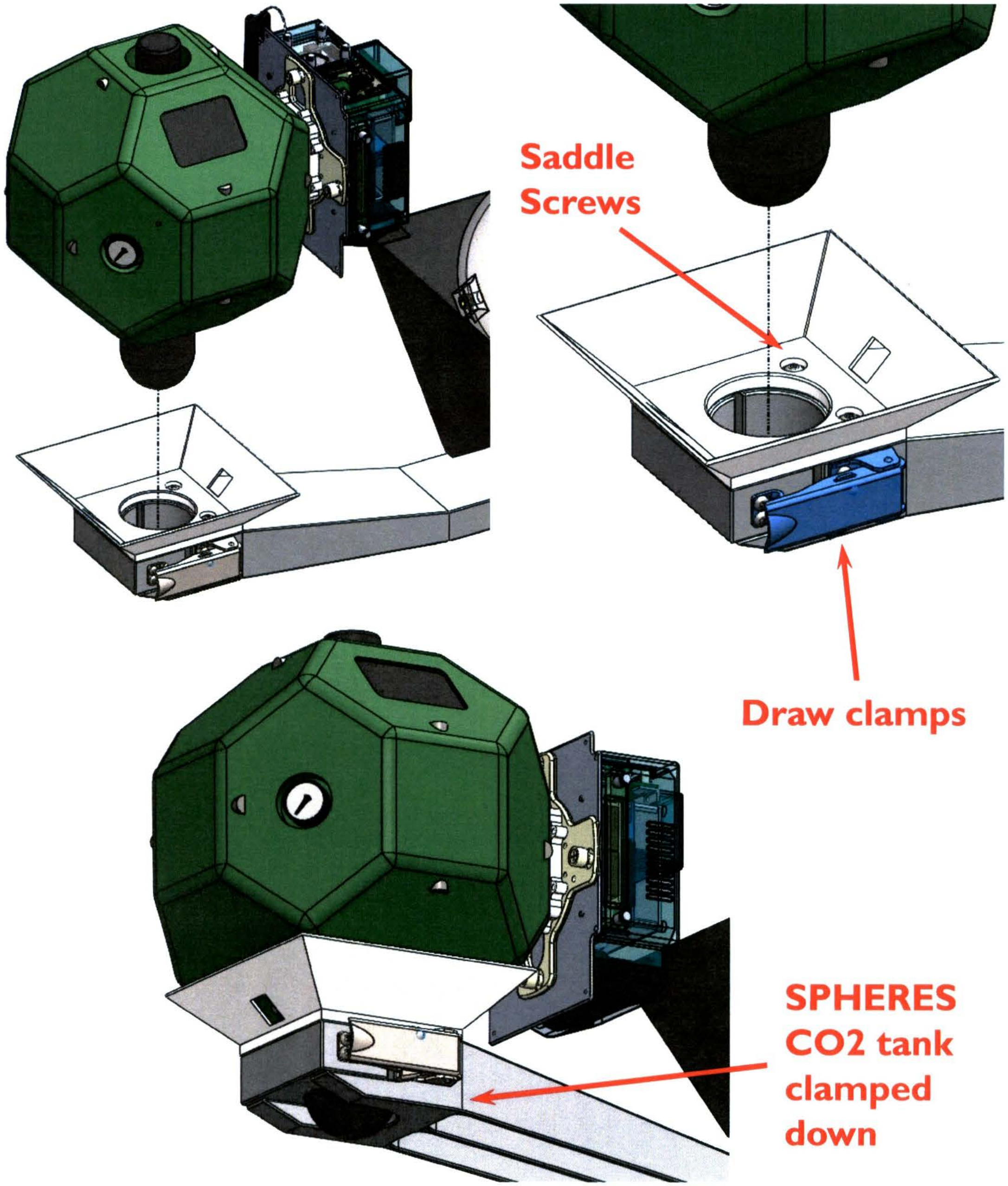


Main Frame

- 36.57" x 3.46" x 1.5" Aluminum 2024-T361 main frame (~1.54 kg)
- Raised ends for balancing and increased CO2 tank contact area
- Threaded holes for mounting SPHERES saddle and draw clamps

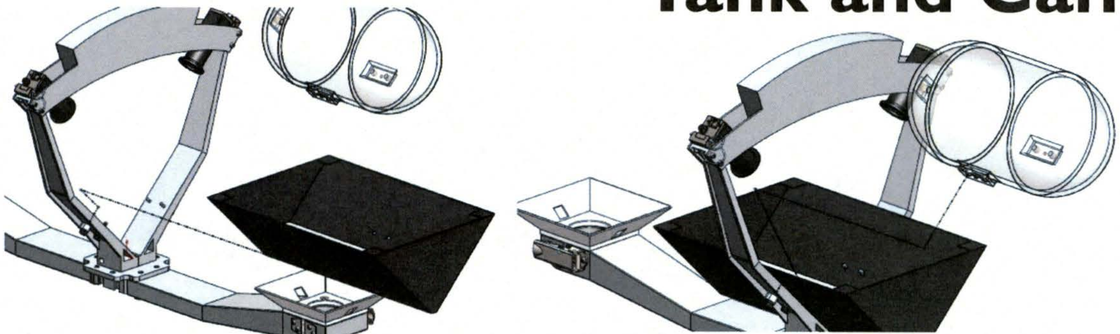


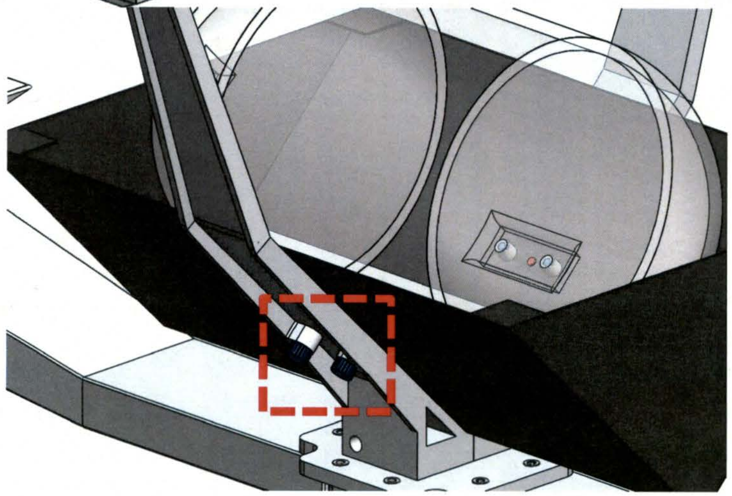
Connection Hardware



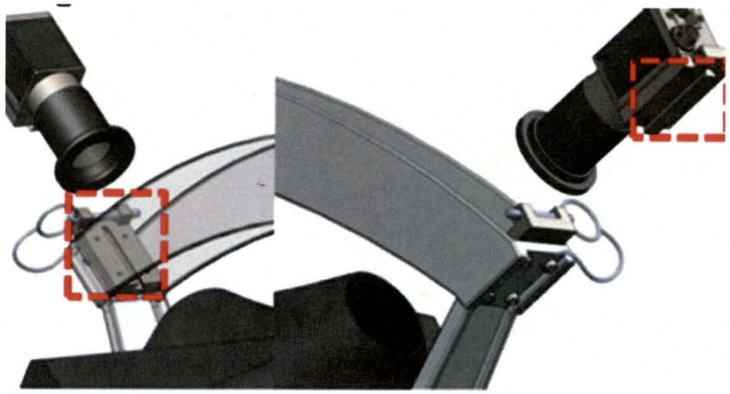
- Saddle screwed into main frame, ensures SPHERES are held in proper orientation with respect to the slosh tank
- CO_2 tank will be held in by two adjustable draw clamps
- Two tethers hold tank clamps to the main frame when unloaded

Tank and Cameras





Tank support



Camera dovetail alignment

- Tank held into support by 4 captive thumbscrews
  - Can be easily interchanged
- Cameras held at 150mm working distance from center of tank using dovetail design and locking pin
- Tank will be sealed and held at single fill level
- Shroud will keep Station lighting out of the tank section
- LED light panel and diffuser

Instrumentation and Image Acquisition

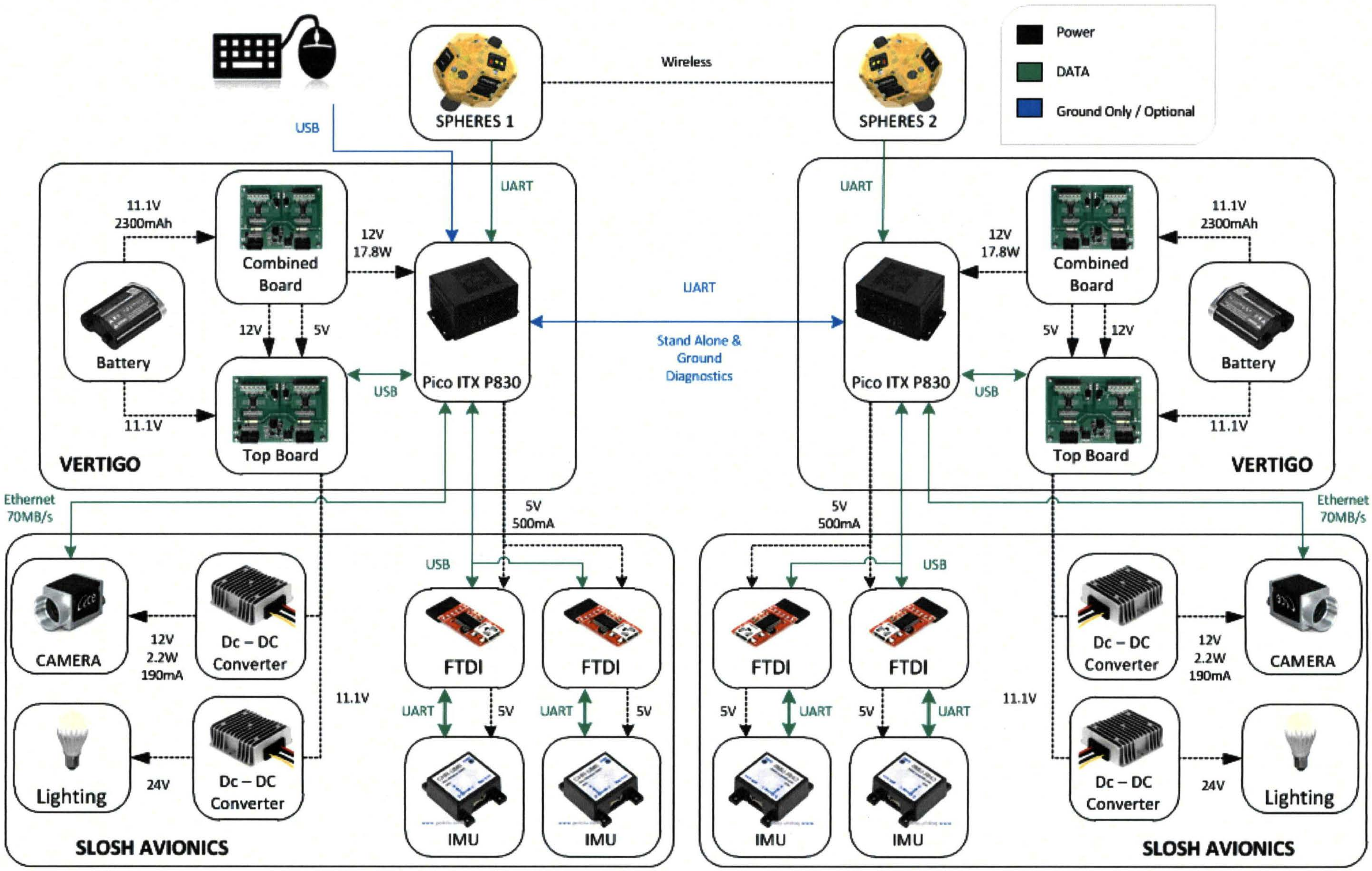
- Instrumentation and data acquisition system (Slosh Avionics) consists of:
  - four 6DOF inertial measurement sensors (3x accelerometer, 3X rotation rate sensors) for up to +/- 2g slosh maneuvers
  - Two high resolution monochrome gigabit-Ethernet cameras (5.1 MP, 14.6 frames/sec)
  - Image capture and data storage interfaces to two single-board computers synchronized by SPHERES

- Slosh Avionics operates in conjunction with the existing SPHERES and VERTIGO electronics

- Image acquisition:
  - High resolution images (5.1 MP/frame) for accurate image acquisition of slosh events
  - Max. Frame rate limits the timescale used to compare results to CFD
  - High aperture lens allows good imaging under limited lighting conditions

- Computer platform: single board Linux PC VIA-EPIA-P830 :
  - Video data transfer channel: Gigabit Ethernet (72MB/s average) uncompressed raw format
  - Linux UBUNTU operating system
  - Synchronization of two VIA-EPIA computers via SPHERES
  - Wired/Wireless interface available to download data to ISS computers
  - 64 GB of SDD to save experimental data and images
  - CPU tested working at 85% utilization while streaming data to SDD hard drive at max. frame rate (14/frames/sec at 5 MP/frame)

System Architecture



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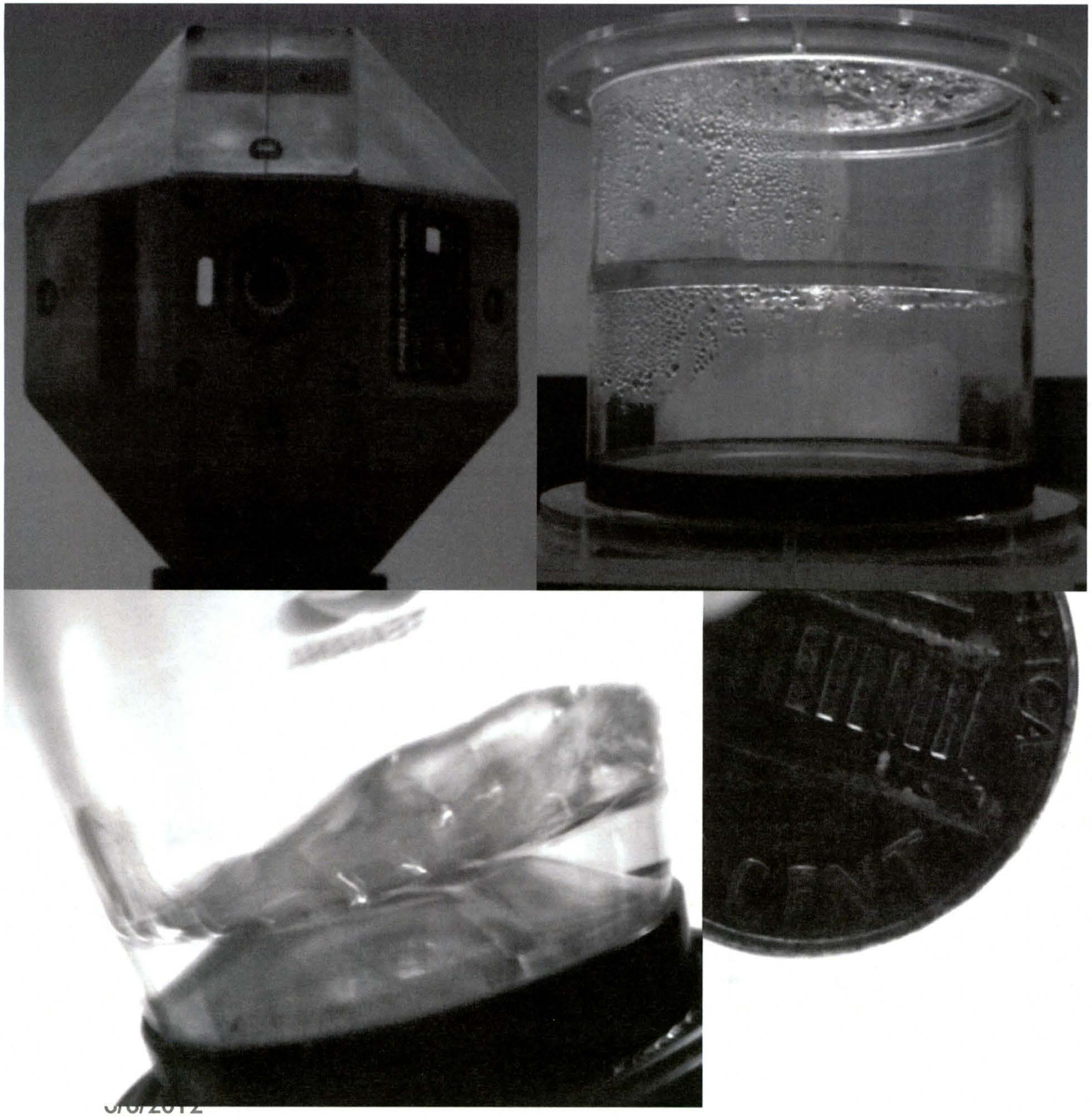
Basler Ace acA2500-14gm High Definition Industrial Camera

Resolution horizontal/vertical	2592 pixels x 1944 pixels
Pixel Size horizontal/vertical	2.2 µm x 2.2 µm
Frame Rate	14 fps
Mono/Color	Mono
Interface	Gigabit Ethernet
Video Output Format	Mono 8, Mono 12, Mono 12 Packed, YUV 4:2:2 Packed, YUV 4:2:2 (YUYV) Packed
Pixel Bit Depth	12 bits
Synchronization	•external trigger •free-run •Ethernet connection
Exposure Control	•programmable via the camera API •external trigger signal
Housing Size (L x W x H) in mm	42 x 29 x 29
Housing Temperature	0 °C - 50 °C
Lens Mount	•C-mount •CS-mount
General Purpose I/O	2
Power Requirements	PoE or 12 VDC
Power Consumption (typical)	2.2 W
Power Consumption PoE	2.5 W
Weight (typical)	90 g
Sensor Type	Aptina
Sensor Name	MT9P031
Sensor Technology	Progressive Scan CMOS, rolling shutter
Sensor Size (optical)	1/2.5 inch
Sensor Type	CCD
Sensor Size (mm)	5.70 mm x 4.28 mm

Cameras



Frame Rate	14.7 fps
Resolution	2592 x 1944 pixels
Lens Aperture	1.4
Lens focal length	2/3" 8mm
CPU utilization at max. frame rate	87%
Data transfer rate (average)	70.2 MB/s
Measured camera temperature	38°C
Lighting conditions	Indoor with fluorescent lights

Inertial Measurement Module: CHR-UM6

Summary of Features

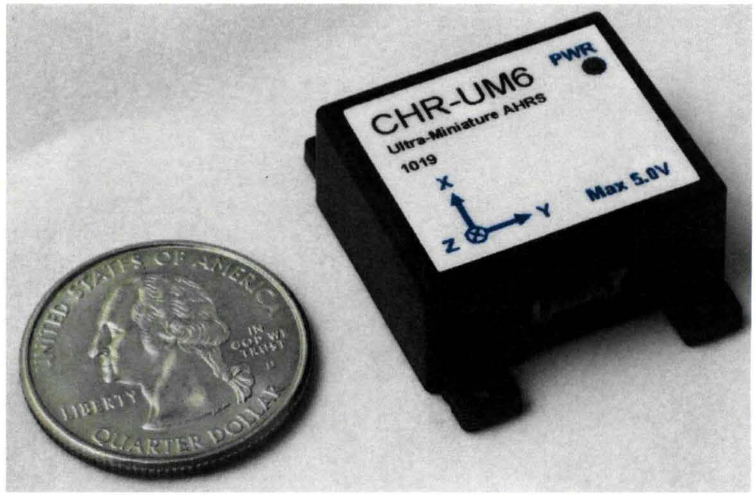
- Combines measurements from rate gyros, accelerometers, and magnetic sensors to measure orientation at 500 Hz.
- 9-DOF Raw measurements (3+3+3) or Euler Angle and Quaternion outputs
- Automatic gyro bias calibration and Cross-axis misalignment correction
- Rate gyro temperature compensation
- UART or SPI bus communication
- Onboard 3.3V regulator simplifies integration
- 32-bit ARM Cortex M3 CPU (72 MHz)- Open-source firmware with free development tools
- Adjustable serial output rates (20 Hz - 300 Hz) and baud rate (up to 115200 baud)

Gyro Characteristics:

- Measurement Range: +/- 2000 deg/sec
- Sensitivity: 14.38 LSB/(deg/sec)
- Linearity: +/- 0.2 % of full scale

Accelerometer Characteristics

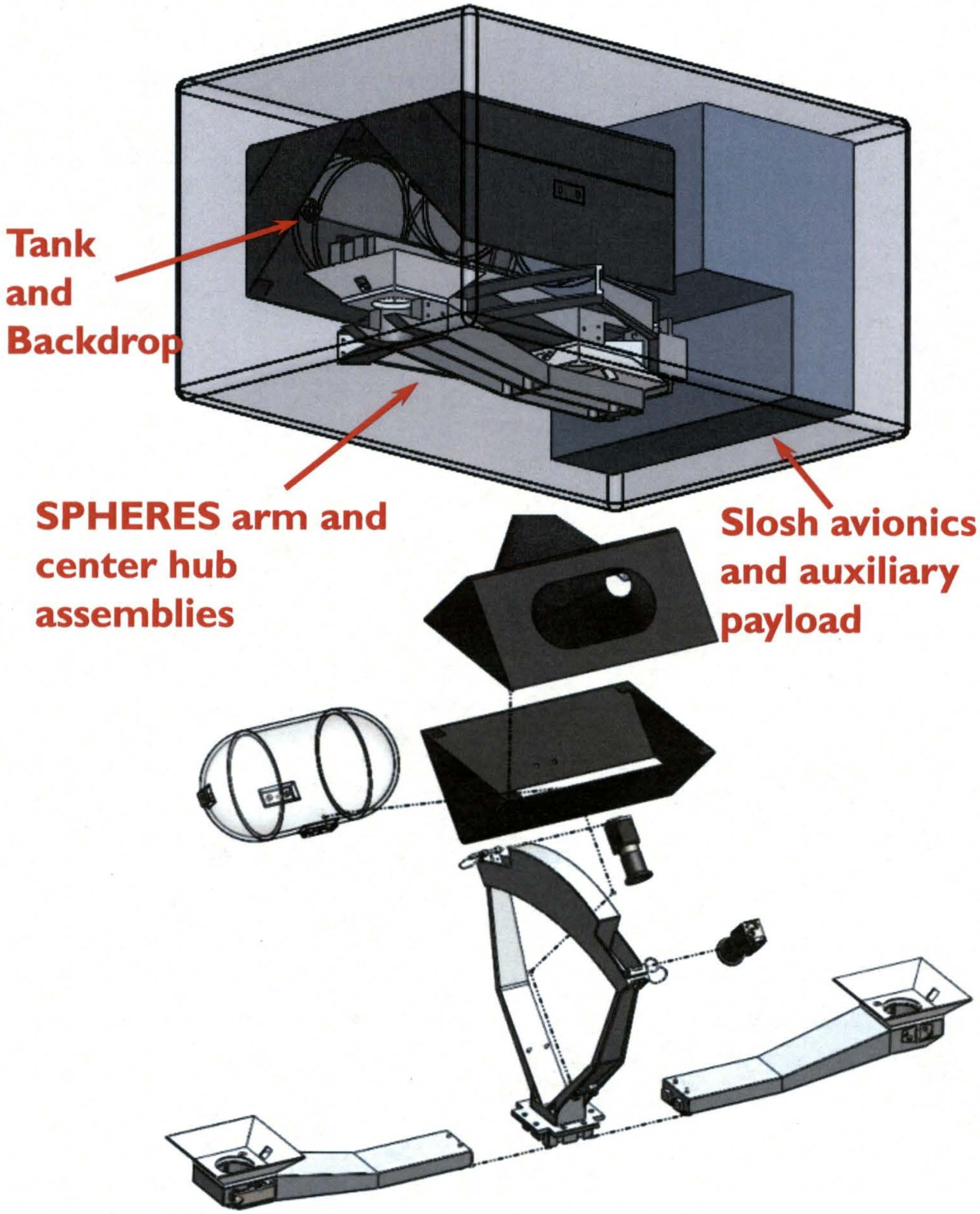
- Measurement Range: +/- 2 g
- Sensitivity (@Vdd = 3 V): 1 *mg/LSB*
- Sensitivity to temperature change: 0.01 %/°C



ISS Launch Configuration

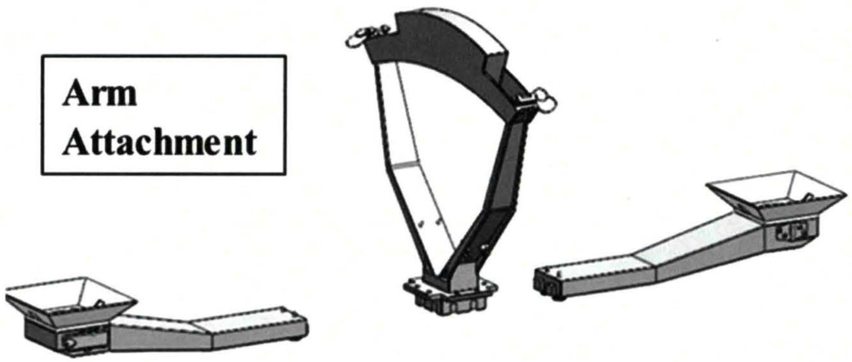
- A CAD model of stowage configuration is shown on right
- Array of stowage types for possible launch vehicles
- Tank Slosh Experiment modularized to fit two package sizes of stowage bags:

	Weight (kg)	L (cm)	W (cm)	H (cm)
SLOSH	21	74	49.5	36.3
M01	97.3	81.8	53.34	46
M03	82.4	74.9	50.2	48

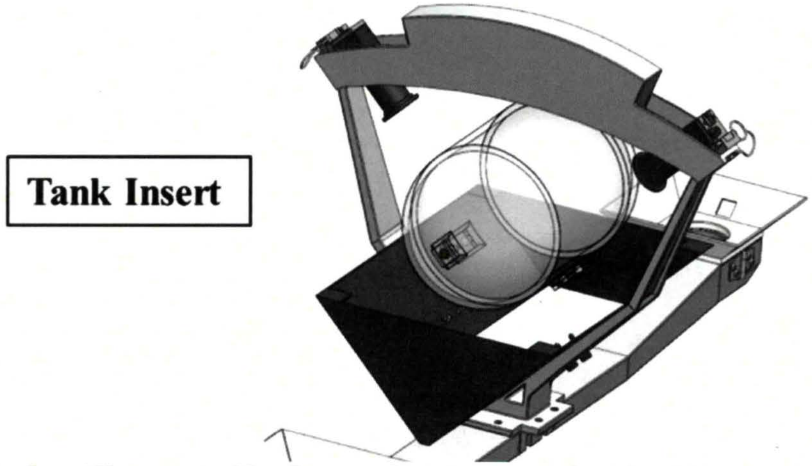


Crew Operations

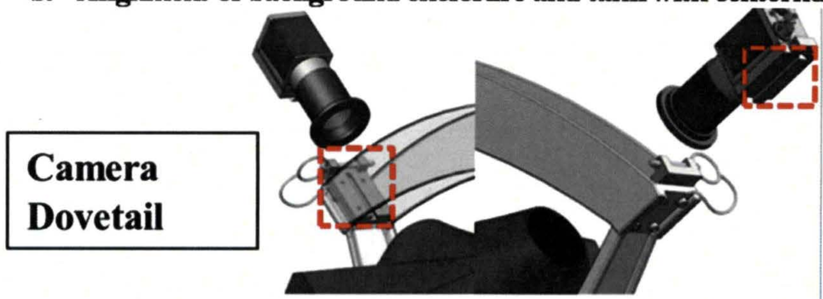
- TSE hardware in soft stowage bag will be transferred to the ISS and stowed until planned operations
- Crew operation are
  - Attach two frame arms with center hub (see Fig. a)
  - Mate dovetails and tightening thumbscrews finger to secure in place
  - Align backdrop to inner portion of center hub and mount tank inline with insert and holes (see Fig. b)
  - Tighten thumbscrews on camera arms finger to secure tank in place
  - Align hood over tank and clamp down to secure hood with backdrop
  - Align camera dovetails and slide camera in mounts and insert pin to secure camera in place (see Fig. c)
  - Wrap lens cloak around lens lip and tighten draw string
  - VERTIGO hardware will be attached to the SPHERES Expansion Port Mounting Adapter, via two of the four Expansion Port captive thumb screws.
  - Slosh Avionics connect to VERTIGO
  - SPHERES/VERTIGO/Slosh Avionics package is secured to the main frame via saddle which lock on to SPHERES CO2 tanks



a. Frame arm and center hub attachment



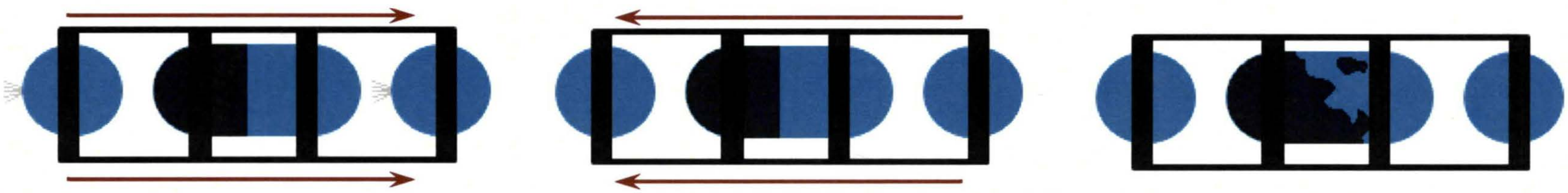
b. Alignment of background enclosure and tank with centerhub



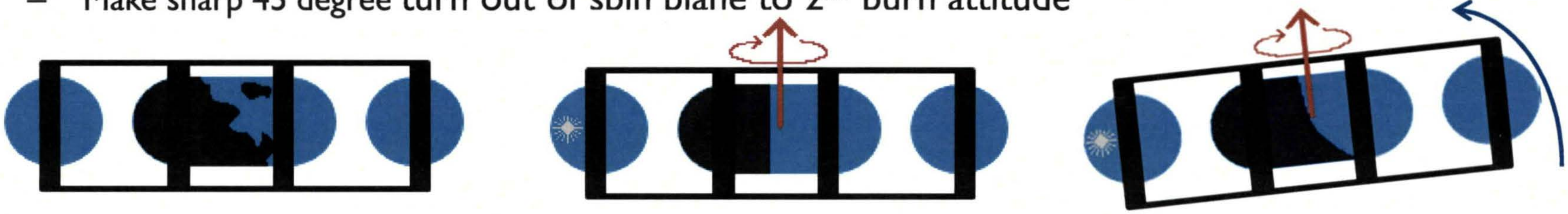
c. Camera alignment with dovetail method

Overview of Experiment Maneuvers

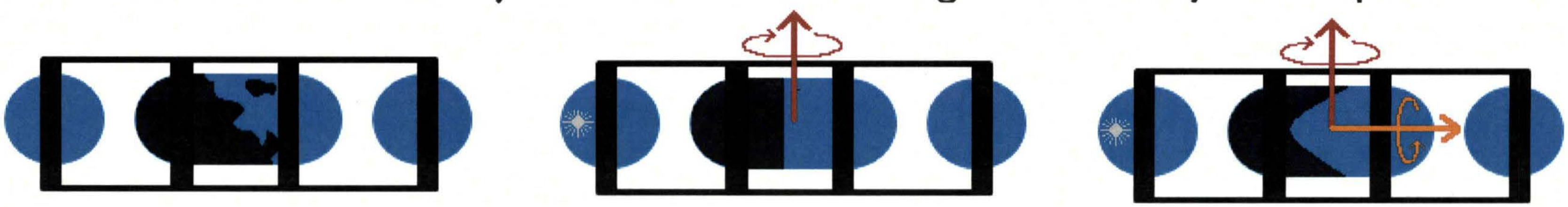
- **Maneuver 1: Simulate an engine shut down**
  - Accelerate system along major axis of tank for a fixed duration
  - Apply reverse thrust to accelerate system in opposite direction for a fixed duration



- **Maneuver 2: Simulate a turn to attitude**
  - Spin tank about a minor axis to settle all propellants
  - Make sharp 45 degree turn out of spin plane to 2nd burn attitude



- **Maneuver 3: Simulate a thermal roll**
  - Slowly spin tank about minor axis to attain constant spin rate and settle fluid
  - Thermal roll about major axis while maintaining constant major axis spin rate



Conclusions

- Slosh Experiment scheduled to launch in July 2013
- SpaceX-3
- Two Tanks
  - 20% fill level
  - 40% fill level
- Increment 35/36
  - 2 SPHERES test sessions
  - Checkout operations
  - Complete a set of three maneuvers
- Increment 37/38
  - 1 SPHERES test session
  - Final data collection
- Post increment 37/38 (~late 2013)
  - Slosh Experiment testbed will be handed over to SPHERES Program office at AMES
  - It will be available on board ISS for any future slosh users
    - Different tank geometries
    - Different fluids
    - Different maneuvers
    - Microgravity Fuel transfer testing