ECHO

Electrical Capacitance to High-resolution Observation (ECHO)

Embry-Riddle Aeronautical University

<u>Students</u>

Bruce Noble | Grant Bowers | Aidan Kihm | Sanaya Nichani
Jakobe Denby | David Clay | Ian Naegeli | Cooper Nelson
Christopher Leclair | Max Klein | Owen Smith | Connor Shackelford

<u>Advisors</u>

Dr. Siwei Fan | Dr. Ron Madler

2025 Human Lander Challenge Forum, Huntsville, AL

Acknowledgements

- Embry-Riddle Undergraduate Research Institute (URI)
    - Embry-Riddle Innovation Fund
    - Embry-Riddle E-Prize
- Embry-Riddle Environmental Health and Safety (EHS)

Dr. Siwei Fan
Dept. Aerospace Eng.

Dr. Ron Madler
Dept. Aerospace Eng.

Bruce Noble
Project Manager

Grant Bowers
Deputy Project Manager

Aidan Kihm
Finance Officer

Sanaya Nichani
Testing Officer

Jakobe Denby
Safety Officer

David Clay
Media Officer

Ian Naegeli
Research, Simulations

Cooper Nelson
Research, Testing

Christopher LeClair
Research, Testing

Max Klein
Research, Testing, Safety

Owen Smith
Research, Safety

Connor Shackelford
Research, Machine Learning

Agenda

Introduction

- Background
- Motivation

Solution

- ECT Overview
- ECHO System
- Simulation
- Machine Learning

Verification & Validation

- Verification
- Validation
- Experiment
- Risk Analysis

Planning

- Budget
- Timeline

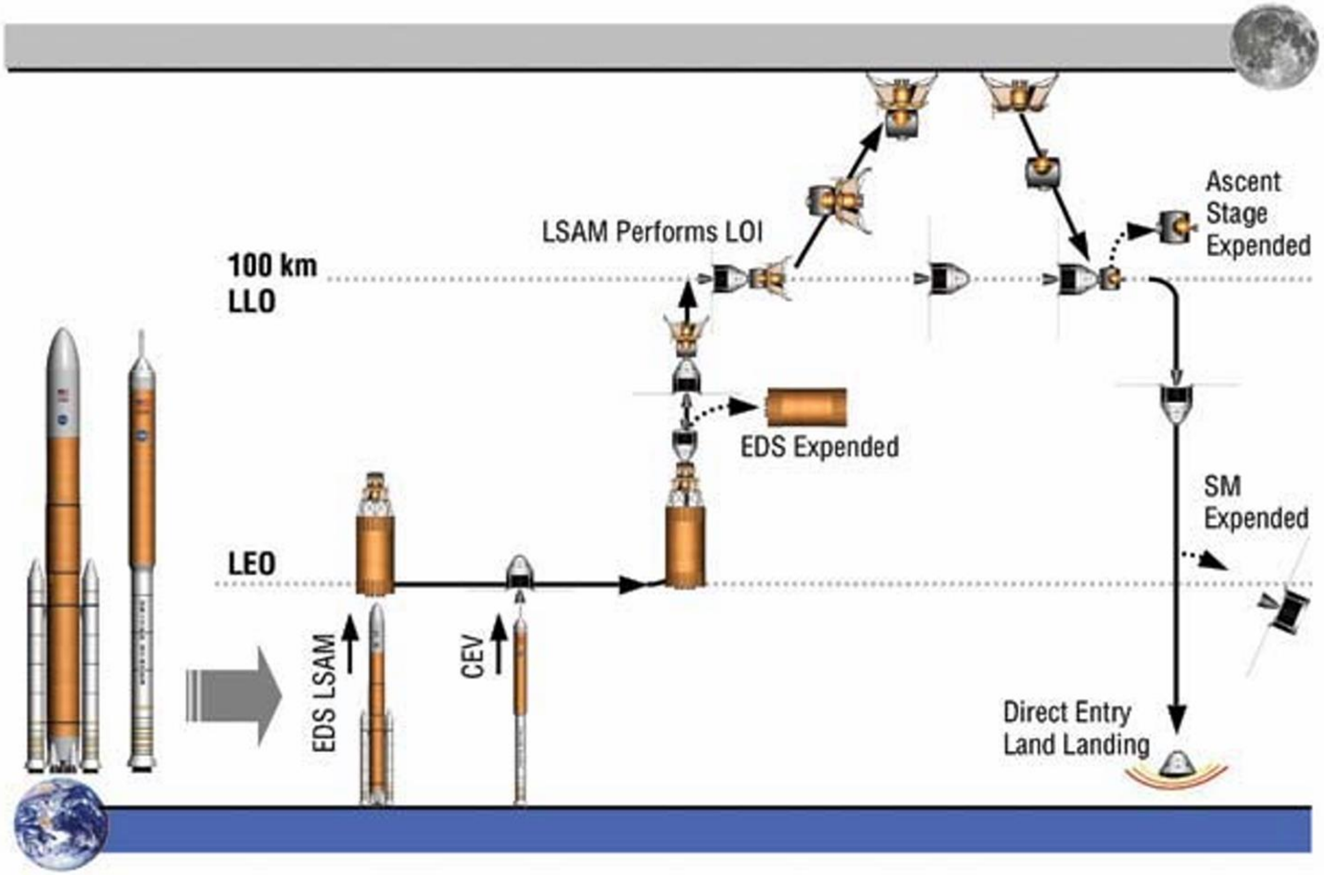
Summary

- Conclusion
- Future Work

Introduction – Background

- Mission planning and success
  - Maneuvers
  - Mission span
  - Propellant for future missions
- Missions of all types
  - Satellites in Earth orbit
  - Moon and Mars
  - Deep space

(Zimmerli, 2007)



The ESAS Lunar Sortie Mission Architecture Concept (Zimmerli, 2007)

Introduction – Motivation

Boiloff

- ➢Heat exchange evaporates propellant
- ➢Propellant is vented to prevent overpressurization

Propellant due to Sloshing

- ➢Imparts internal moments
- ➢Difficult to measure
    - Continuously moving
    - Does not contact a single location

(Lee et al., 2018)

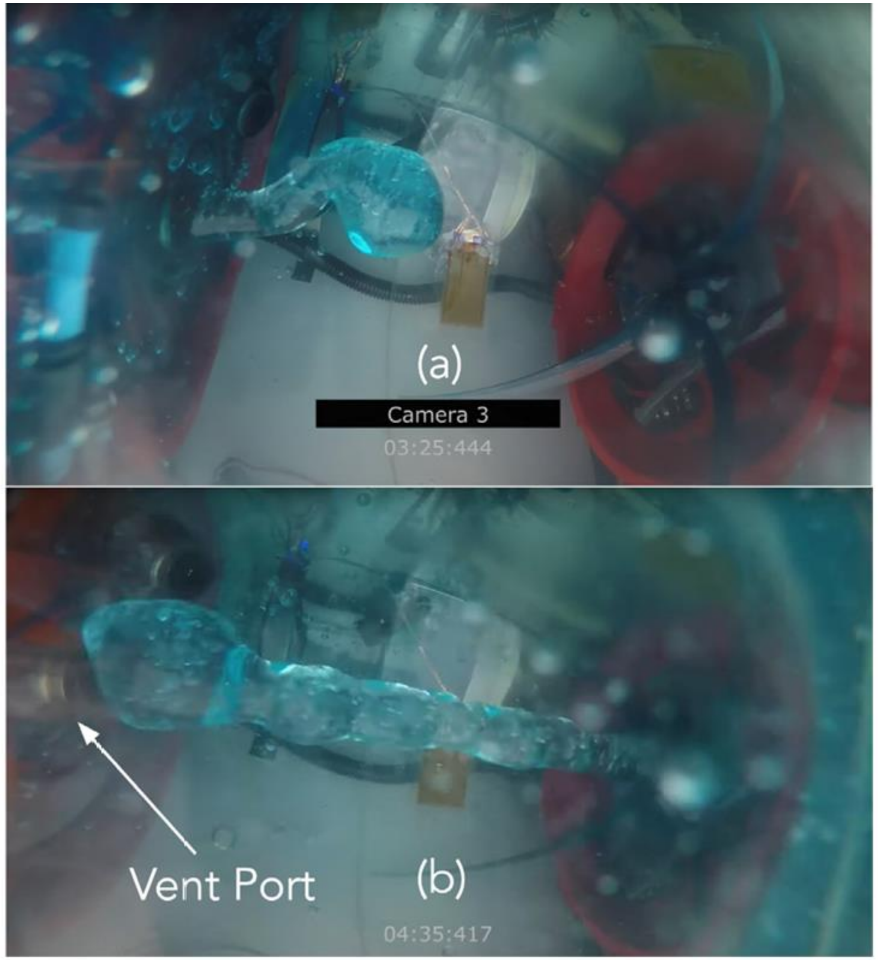


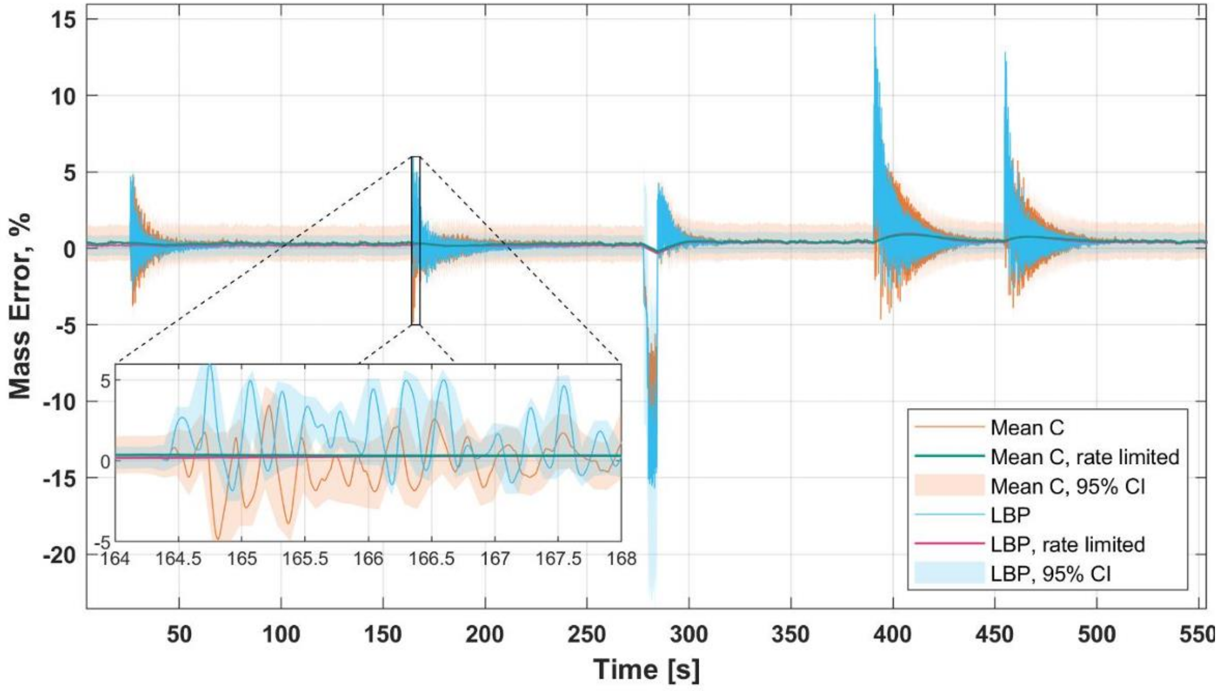
Fig. 15. (a) Recirculation of water from the vent port during the P11 microgravity drain. (b) Recirculation of water from the drain port during microgravity fill.

Introduction – Current Developments

Current Propellant Tracking

- ➢Book Keeping
- ➢Pressure Volume Temperature
- ➢Modal Mass Gauging
- ➢Radio Frequency Mass Gauging
- ➢Electrical Capacitance Tomography

(Doherty et al., 2010; Storey et al., 2023)



ECT Liquid Mass Error vs. Time, 50% NVF Ground Slosh Test (Storey et al., 2023)

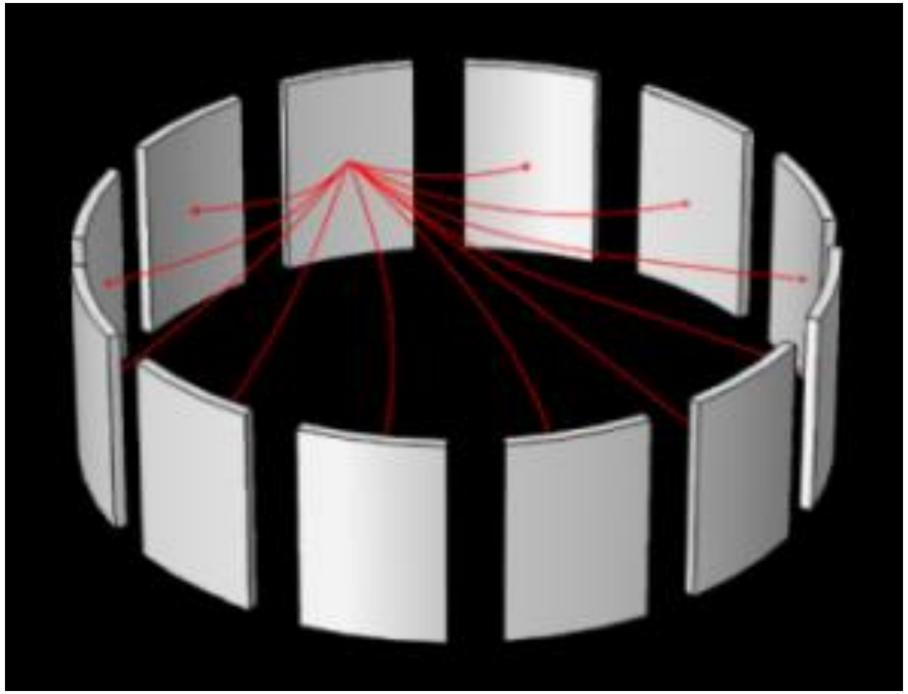
Solution - Trade Study

Criteria	Weight	Scale	Radio waves	Modal Gauging	ECT, ECVT
Testability	15%	3-0	2	3	2.5
Difficulty	10%	3-0	2.5	3	2
Interest	10%	3-0	2	2	2.5
Innovation	40%	3-0	1	2	3
Past Knowledge	5%	3-0	1.5	1	1
Available Information	15%	3-0	2.5	2.5	3
Effectiveness	5%	3-0	2	2.5	3
Weighted Total %	100%	3-0	57%	77%	89%

Electrical Capacitance Tomography (ECT) was selected

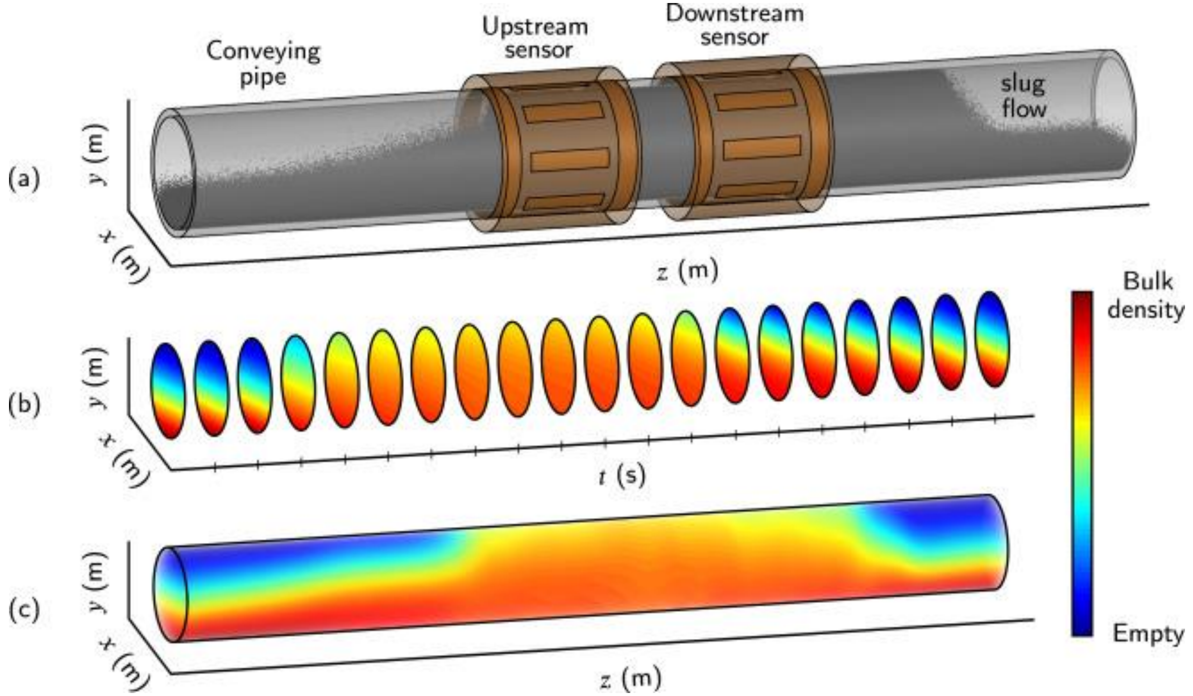
Solution – ECT Overview

ECT Visualization



(Tech4Imaging)

Dual Plane ECT System and Reconstruction

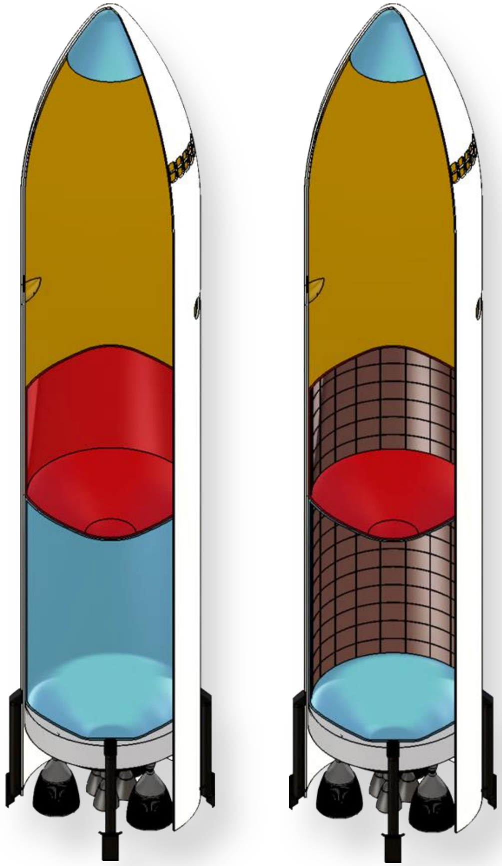


(Suppan et al., 2023)

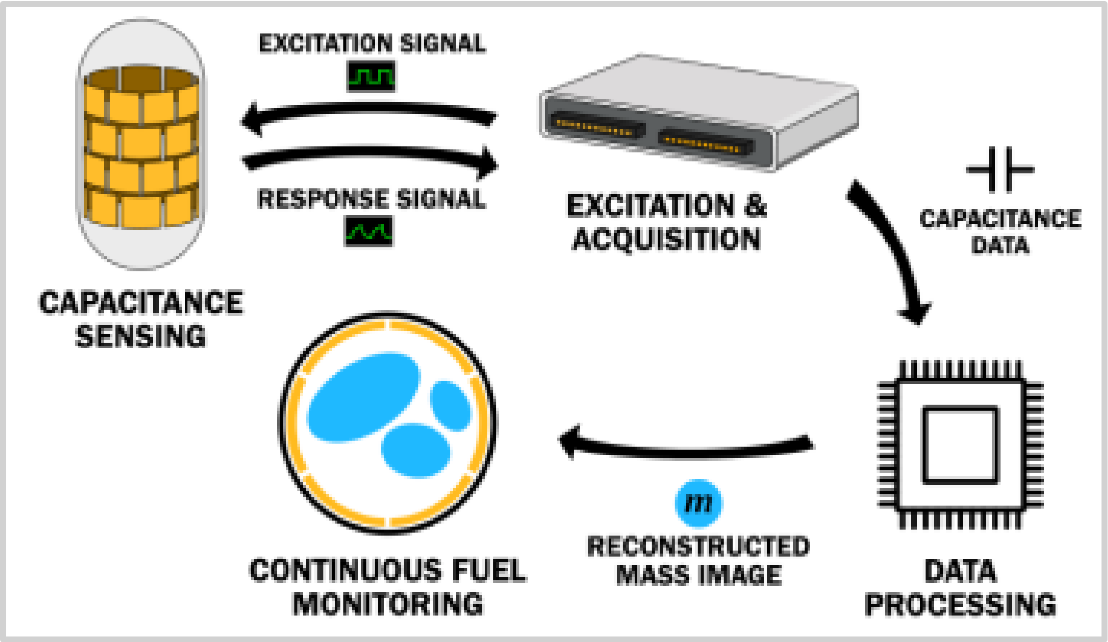
ECT faces two challenges: accuracy and speed

Solution – ECHO System

Blue Moon with ECHO



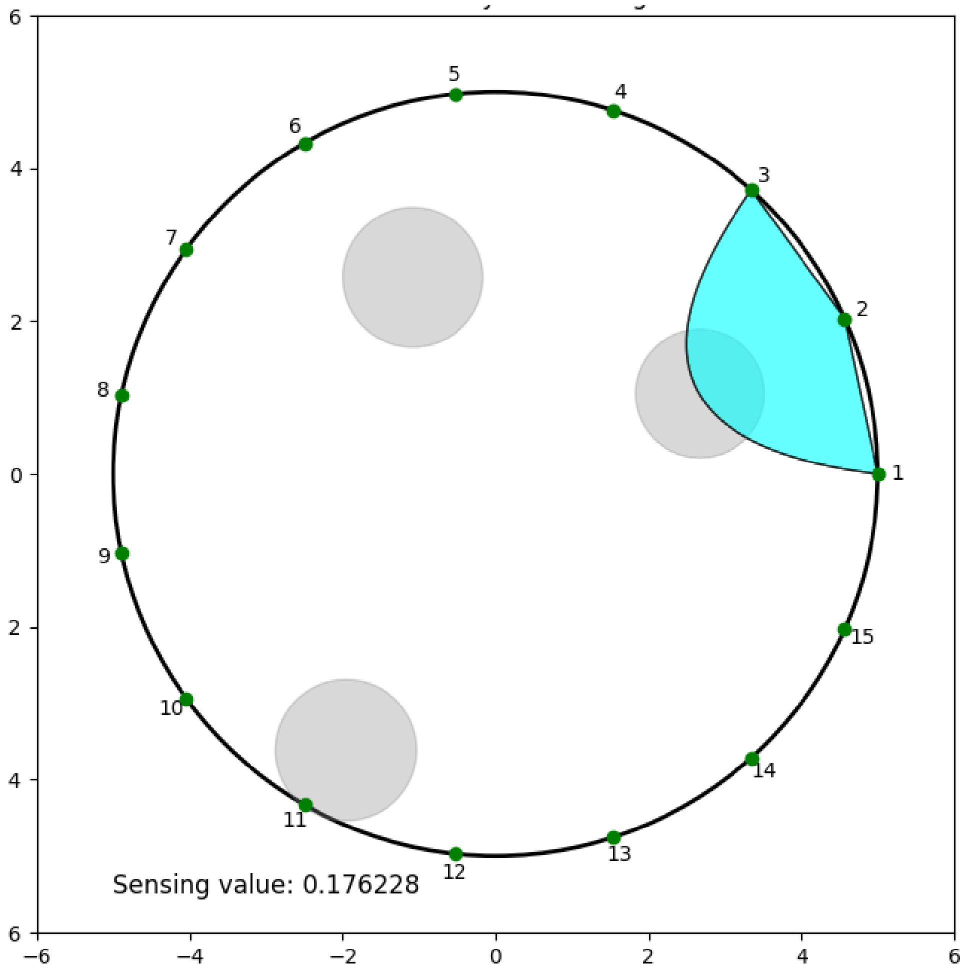
Starship with ECHO



ECHO Operational Cycle

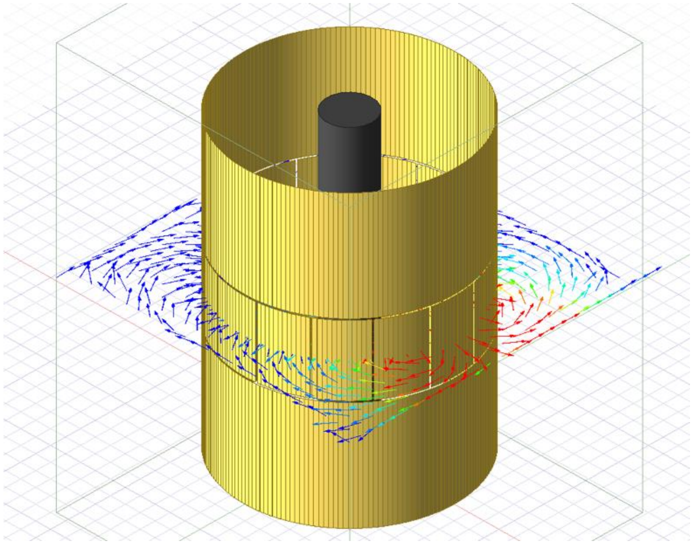
Solution – Capacitance Measurement

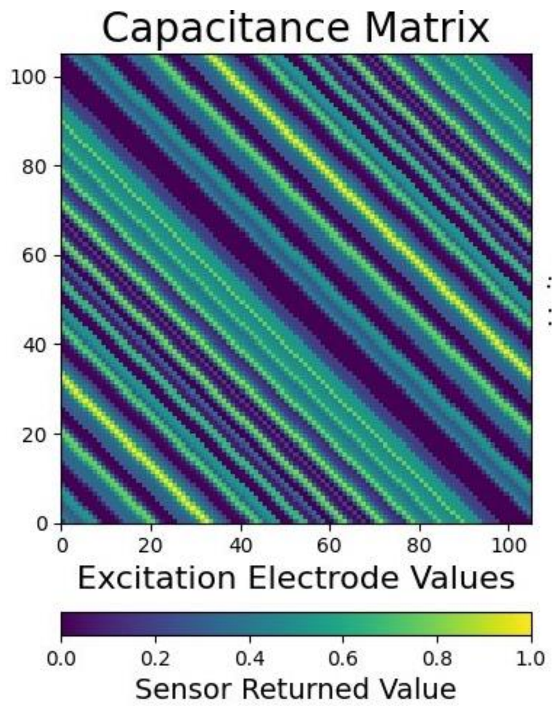
- ➢ Electrodes excited sequentially
- ➢ Remaining electrodes take measurement
  - 14 simultaneous measurements
  - 15 set measurements per cycle
- ➢ Voltage changes according to permittivity



Solution – ECHO Simulation

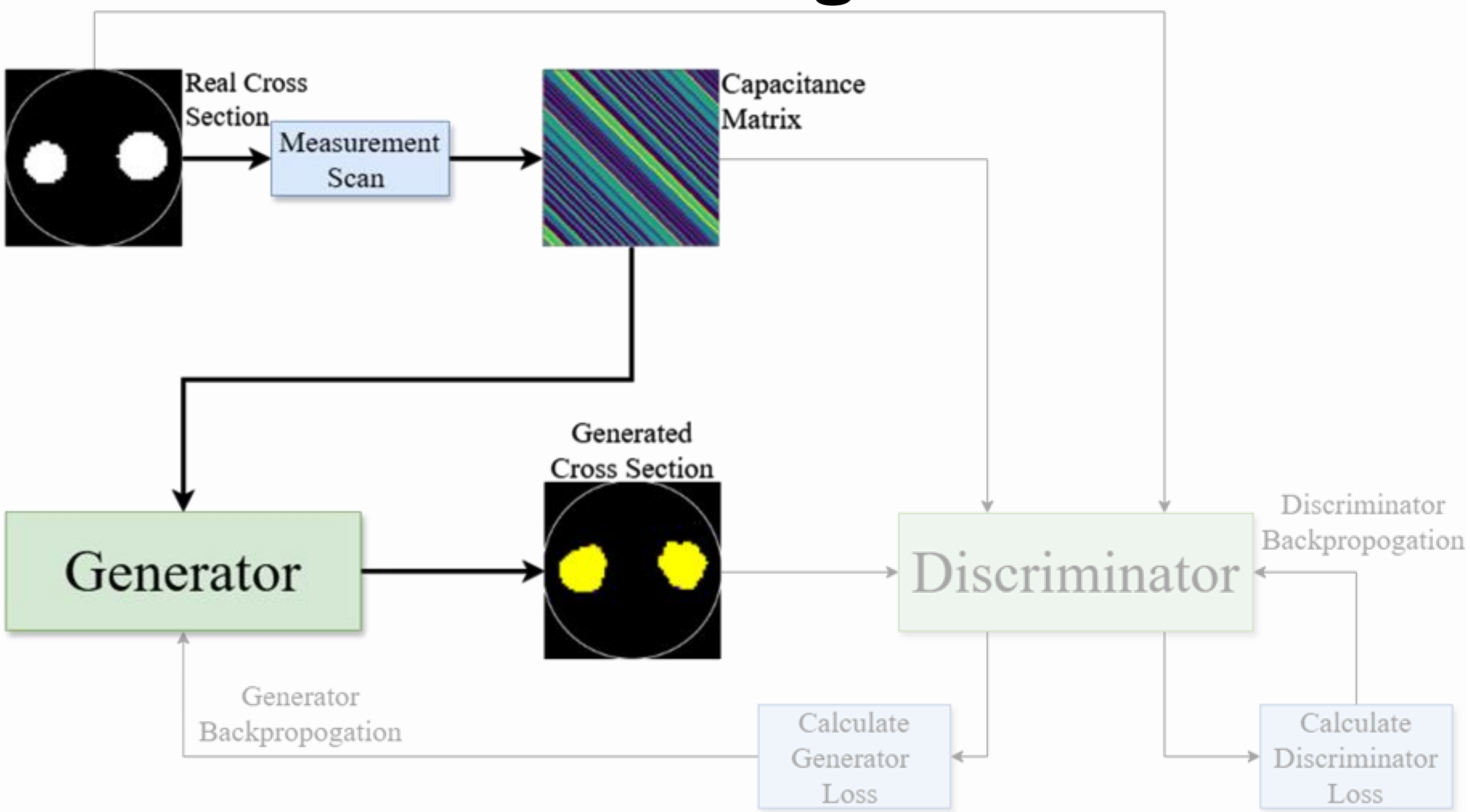
- Inter-electrode Capacitance simulated in ANSYS Maxwell
- Processed to obtain simulation data (voltage arrays)
- Simulation data used for training



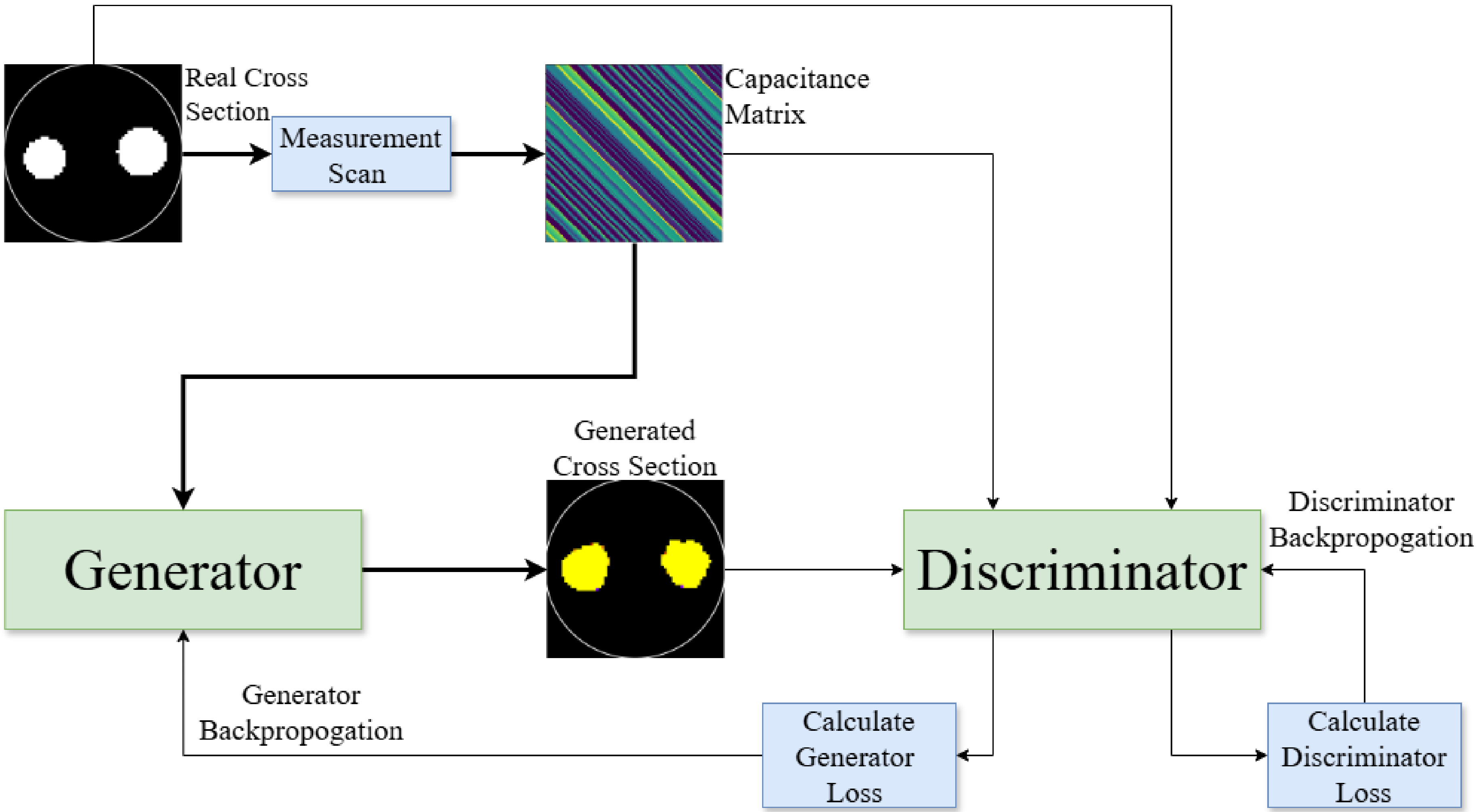


The reconstruction problem is ill-posed, using machine learning to infer area given measurement

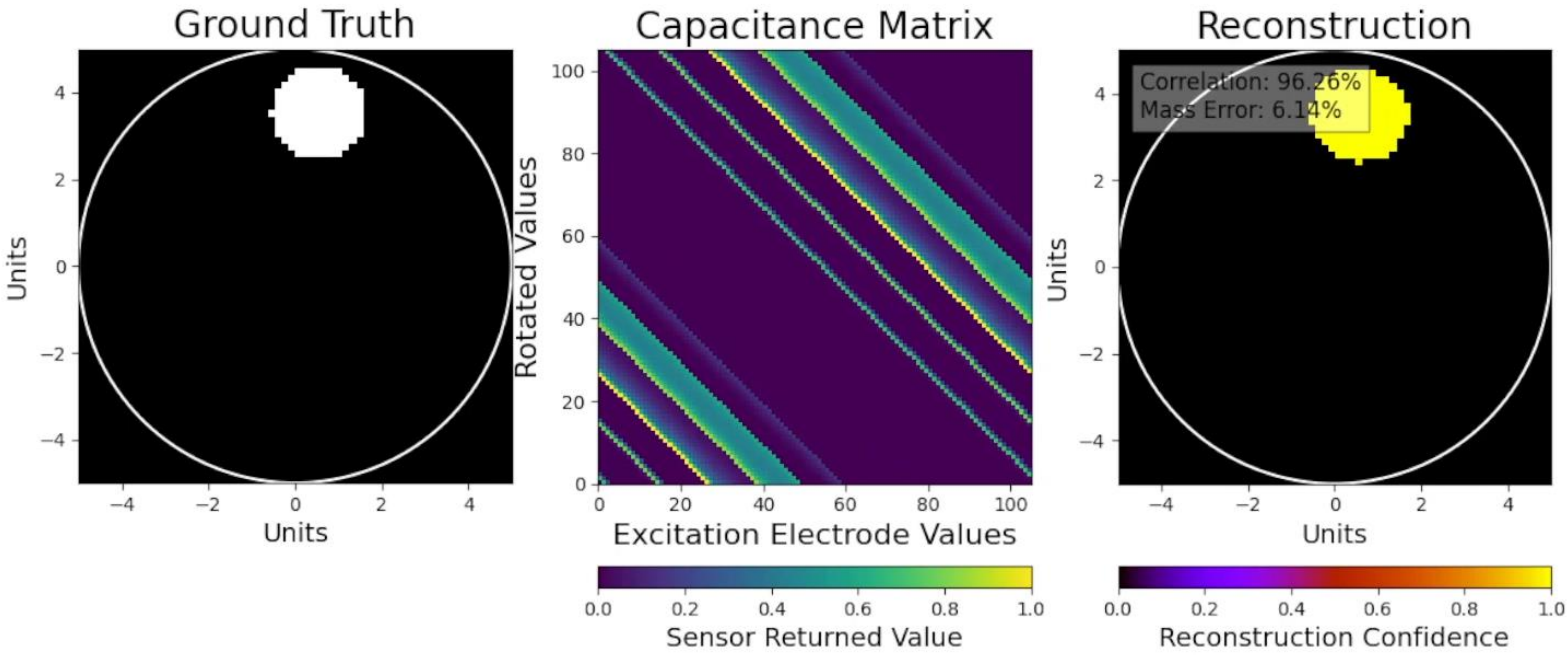
Solution – Machine Learning



Solution – Machine Learning



Solution – Reconstruction Results



Agenda

Introduction

- Background
- Motivation

Solution

- ECT Overview
- ECHO System
- Simulation
- Machine Learning

Verification & Validation

- Verification
- Validation
- Experiment
- Risk Analysis

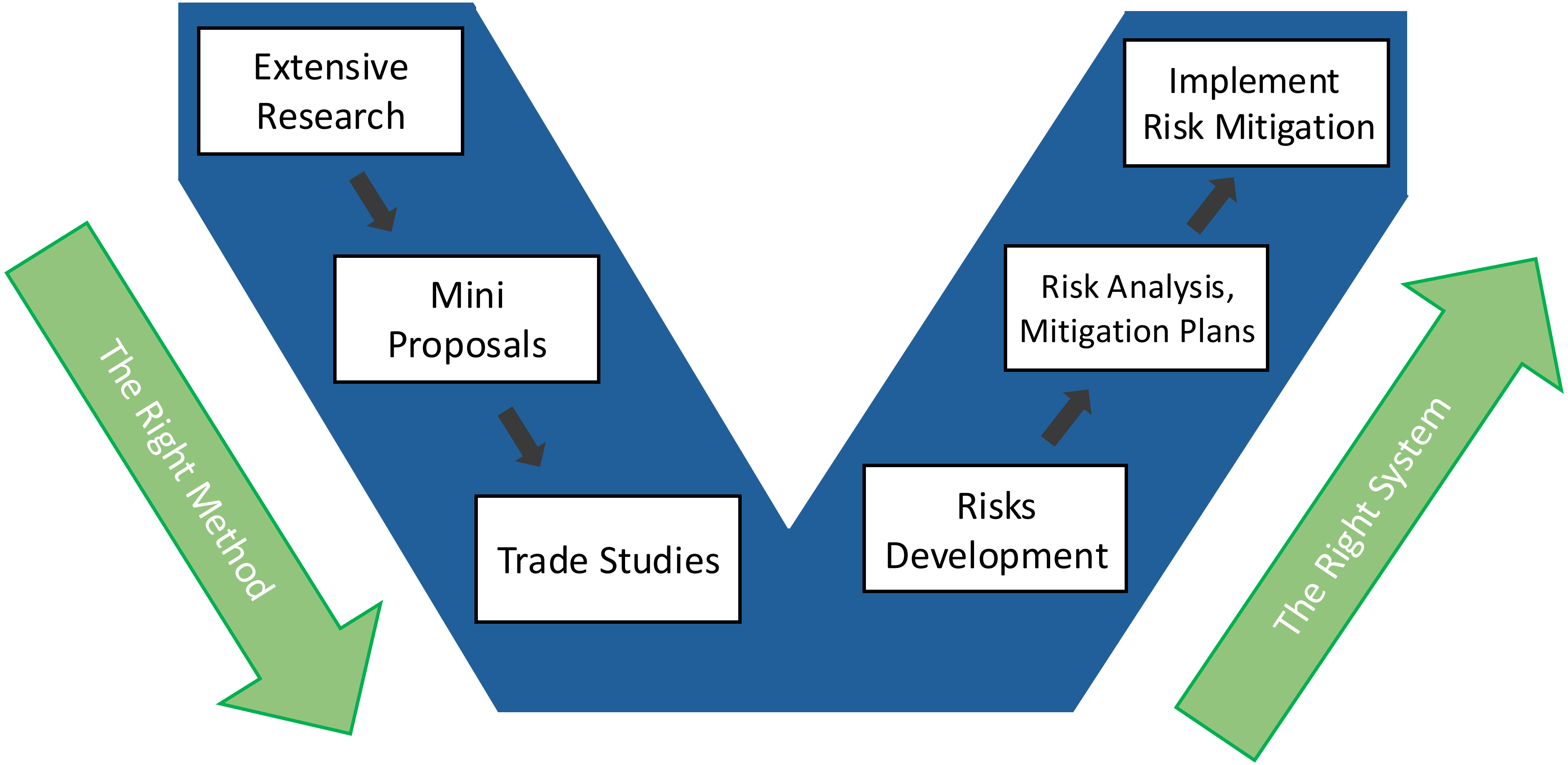
Planning

- Budget
- Timeline

Summary

- Conclusion
- Future Work

Verification



Req #	Requirement	Rationale	Verification method	Req met?
MTS-1.0	The MTS shall be able to derive mass via permittivity measurements.	HuLC Guidelines	Analysis	Met
MTS-1.1	Measurements taken by the system shall be within 5% error	To validate accuracy in a multitude of environments	Test	Not Met
MTS-2.0	The MTS should determine the location of the center of mass of the propellant.	HuLC Guidelines	Test	Not Met
MTS-3.0	The MTS shall perform 3D reconstruction and mass distribution of the interior of the tank	For visualization of the interior of a tank for additional information	Test	Not Met
MTS-4.0	The MTS should be able make measurements regardless of external influences (acceleration, jerk, microgravity)	There is a need for propellant mass gauging technology that can operate in microgravity and during sloshing conditions.	Test	Not Met
MTS-5.0	The MTS shall be testable and buildable	HuLC Guidelines. A prototype must be developed and tested within the academic year.	Analysis	Met
MTS-5.1	Test article shall be of reasonable mass and size for testing purposes at Embry-Riddle's campus	For ease of testing and moving	Test	Met
MTS-5.2	The MTS should be standardized to fit a variety of tanks with minimal tank intrusion.	Artemis tank designs very depending on the particular spacecraft and are subject to change.	Inspection	Not Met
MTS-6.0	The MTS should reliably function for a minimum of 12 months.	Some future Artemis and human lander missions will last several months.	Test	Not Met
MTS-8.0	The MTS shall inform of mass readings, post-calculation, to users in a friendly manner	Humans understand information better when it is presented in a concise and viable manner	Test	Not Met
MTS-9.0	Software shall capture, calculate and display mass data continuously	For efficient and timely reporting	Test	Not Met
MTS-10.0	The components of the MTS in contact with the tank wall shall be able to withstand cryogenic temperatures	It is assumed the system must be secured to the tank exterior to some extent.	Test	Not Met

Req #	Requirement	Rationale	Method	Req met?
MTS-1.0	The MTS shall be able to derive mass via permittivity measurements.	HuLC Guidelines	Analysis	Met
MTS-5.0	The MTS shall be testable and buildable	HuLC Guidelines. A prototype must be developed and tested within the academic year.	Analysis	Met
MTS-5.1	Test article shall be of reasonable mass and size for testing purposes at Embry-Riddle's campus	For ease of testing and moving	Test	Met

Validation

Goal: Mitigate problem of mass gauging propellant in microgravity

→

Trade Studies:
- System Design
- Testing Fluid
- ML Algorithm

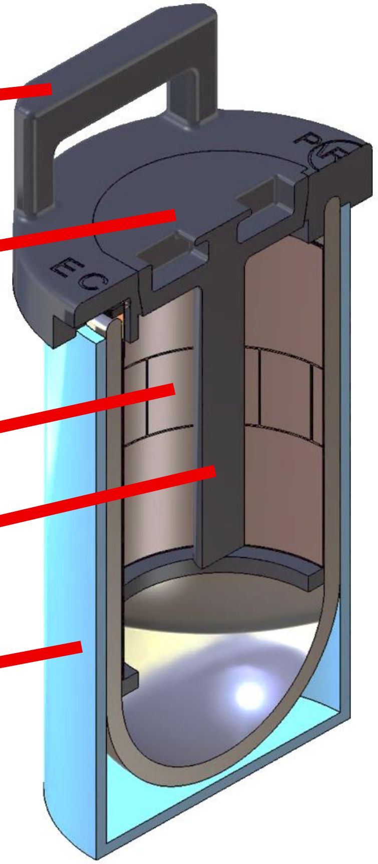
→

Develop prototype algorithm to determine ECHO's functionality within NASA specifications

Future of Verification and Validation

Cryogenic Testing TRL 5	Flight Testing TRL 6	Design and Fabrication	Environmental Testing TRL 7

Experiment – Testing Setup



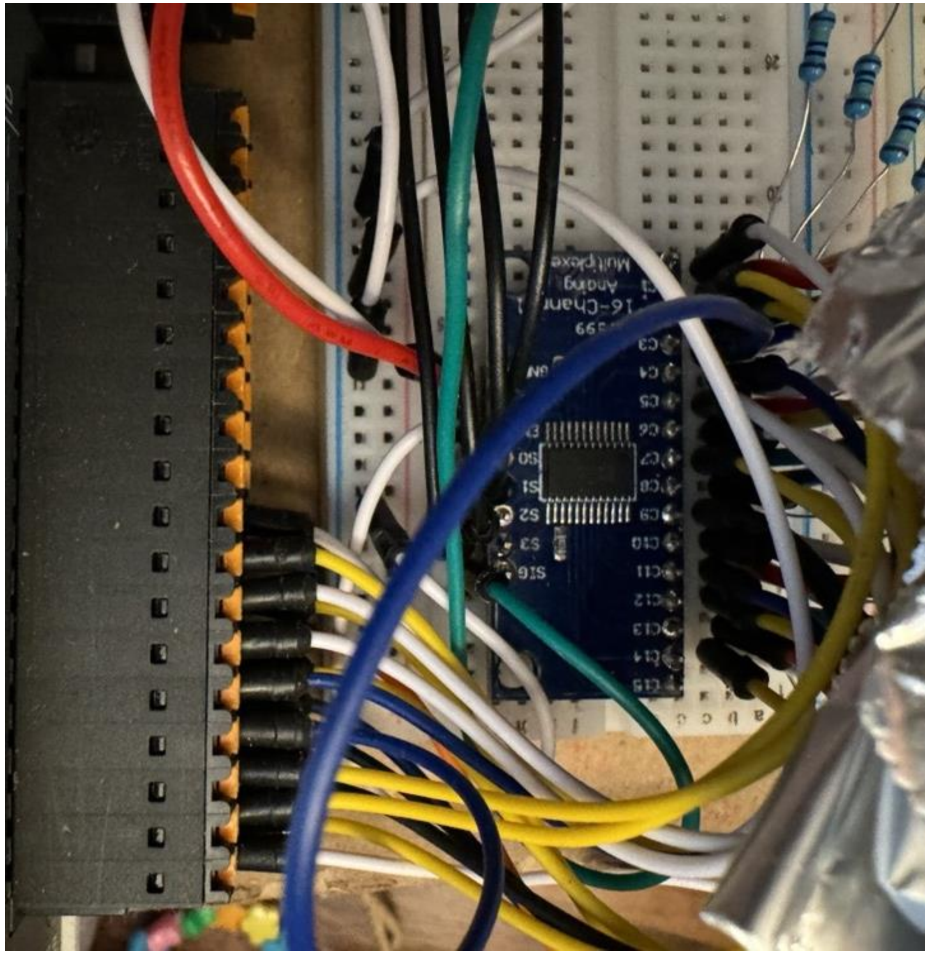
Experiment – Improvements

Circuit

- Demultiplexer
- 1 MΩ Pull-Down Resistors
- Faraday Cage

Filtering Methods

- Butterworth Bandpass Filter
  - Low/High-Frequency Clipping
- Gaussian Filter
  - Smooth and Clip Results



Experiment – Initial Results

Measurement Matrix

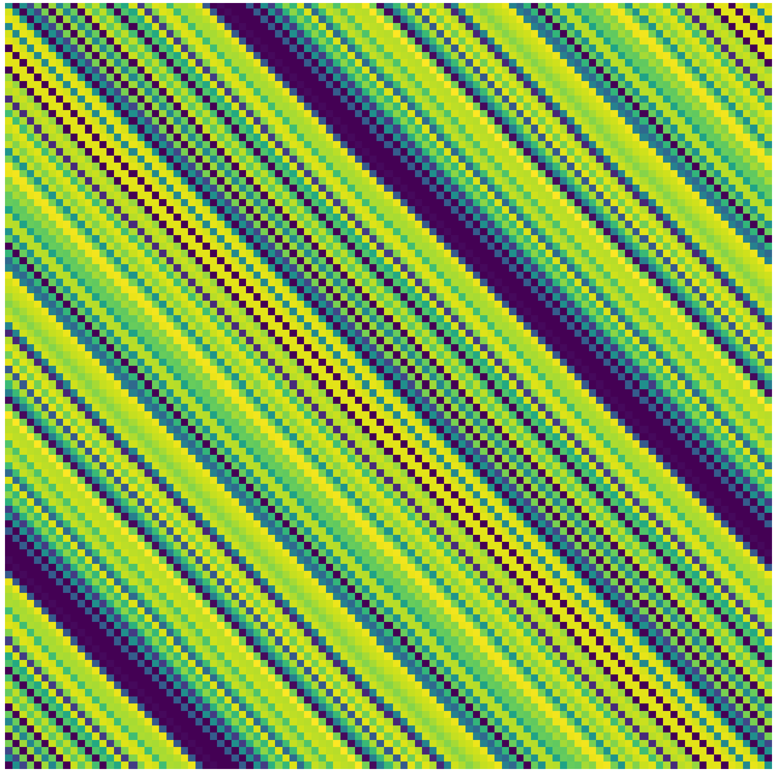


Image Reconstruction

Cross-Section

Experiment – Filtering Results

Measurement Matrix

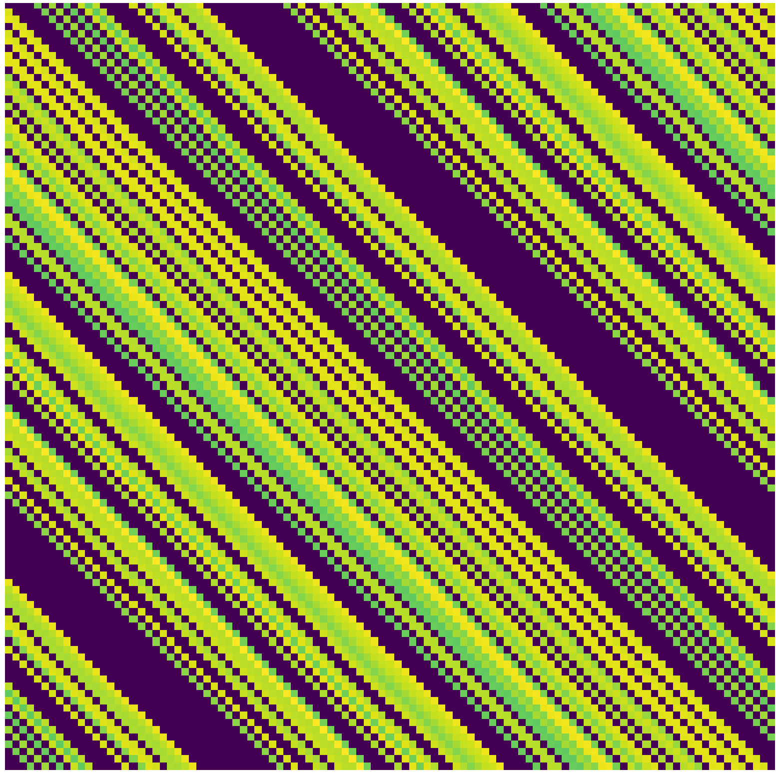
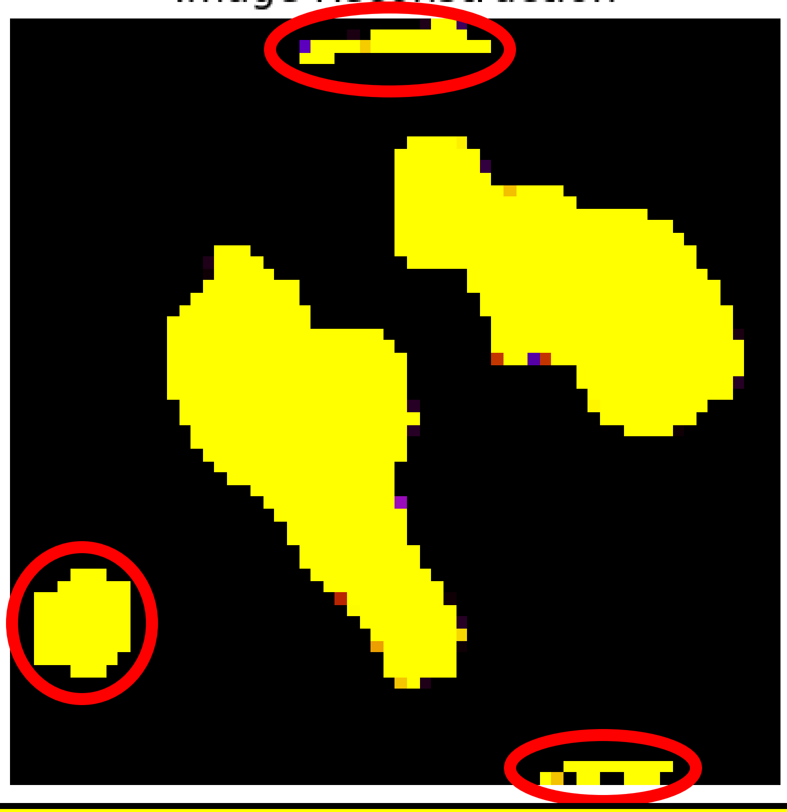


Image Reconstruction

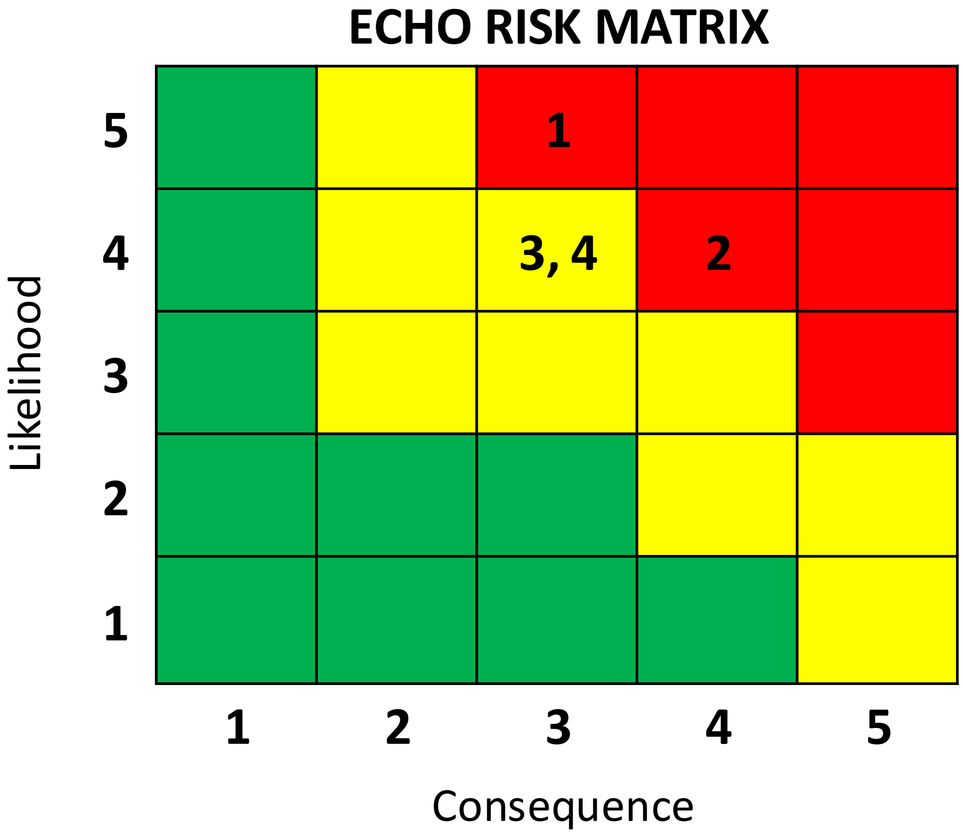


Cross-Section

Butterworth Bandpass and Gaussian filters greatly improve results

Risk Priority Matrix

1. Capacitor Sensor Error
2. Thermal Insulation Failure
3. Electrode Configuration
4. Communication Error



Risk Management

ID	Risk Name	Related Systems	Method	Plan
1	Capacitor Sensor Error	Electrodes	Watch	Accurate calibration, documentation
2	Thermal Insulation Failure	Tank Insulation	Research	Research different materials to use as insulation to prevent systems from touching the tank
3	Electrode Configuration	ECHO, Propulsion, Starship	Mitigate	Design new electrode arrays in irregular areas, like the ends of the tank
4	Communication Error	DAQ	Mitigate	Ensure connections are secured before and after test procedure

Testing with Liquid Nitrogen will mitigate multiple critical risks

Agenda

Introduction
- Background
- Motivation

Solution
- ECT Overview
- ECHO System
- Simulation
- Machine Learning

Verification & Validation
- Verification
- Validation
- Experiment
- Risk Analysis

Planning
- Budget
- Timeline

Summary
- Conclusion
- Future Work

Budget

- PCEC used to estimate System Cost
- CER formula based on instrumentation subsystems for historical launch vehicles
- Assumes total measurement system mass is 230 kg
- Total Non-Recurring: **$36.5M**; Recurring: **$5.5M**

Cost Phase	FY2015 $M	FY2026 $M
Non-Recurring	29.2	36.5
Design & Development	23.5	29.4
System Test Hardware	5.7	7.1
Flight Unit (Recurring)	4.4	5.5
TOTAL	**33.6**	**42.0**

Budget

- Total Project: **$91M**
- 10 employees
- 50% manufacturing margin
- 30% total cost margin

Mission Phase	Phase C	Phase C	Phase D	Phase D	
Year	FY 1 (2026)	FY2 (2027)	FY3 (2028)	FY4 (2029)	Total ($K)
PERSONNEL					
Science Personnel	80	82	84	86	332
Engineering Personnel	320	328	337	345	1,330
Technicians	60	62	63	65	249
Administration Personnel	120	123	126	129	499
Project Management	240	246	252	259	997
Total Salaries	820	841	863	884	**3,408**
Total ERE	229	235	241	247	**951**
TOTAL PERSONNEL	1,049	1,076	1,103	1,131	**4,359**
DIRECT COSTS					
System Cost (from CER)	10,500	10,773	11,046	11,319	43,638
Manufacturing Margin (50%)	5,250	5,387	5,523	5,660	21,819
Total Direct Costs	15,750	16,160	16,569	16,979	**65,457**
FINAL COST CALCULATIONS					
Total Projected Cost	16,799	17,236	17,672	18,109	**69,816**
Total Cost Margin (30%)	5,040	5,171	5,302	5,433	**20,945**
Total Project Cost	21,839	22,406	22,974	23,542	**90,761**

Timeline – 5 Year Plan

- 14 months for additional tests and preliminary design
- 18 months for detailed design and system integration
- 27 months for integrated and environmental testing
  - Conducted with the rest of the spacecraft

Jan 2026
- Technology Completion

Jan 2027
- PDR
- Detailed Design

May 2027
- CDR
- Fabrication

Nov 2027
- SIR
- System Integration

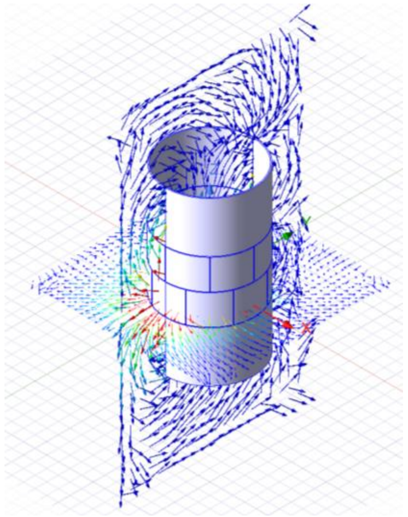
Jun 2028
- Develop System Confidence

Nov 2029
- ORR
- Prepare for Operations

Conclusion

- Developed a propellant gauging system using electrical capacitance tomography
- Conducted **simulations** and **experiments** of the ECHO system
    - Gathered simulation and experiment data
- Adopted and trained a Generative Adversarial Networks (GAN) for **cross-section reconstruction**
- ECHO shows strong potential for microgravity mass gauging

Render of Tank with Stacked Electrodes

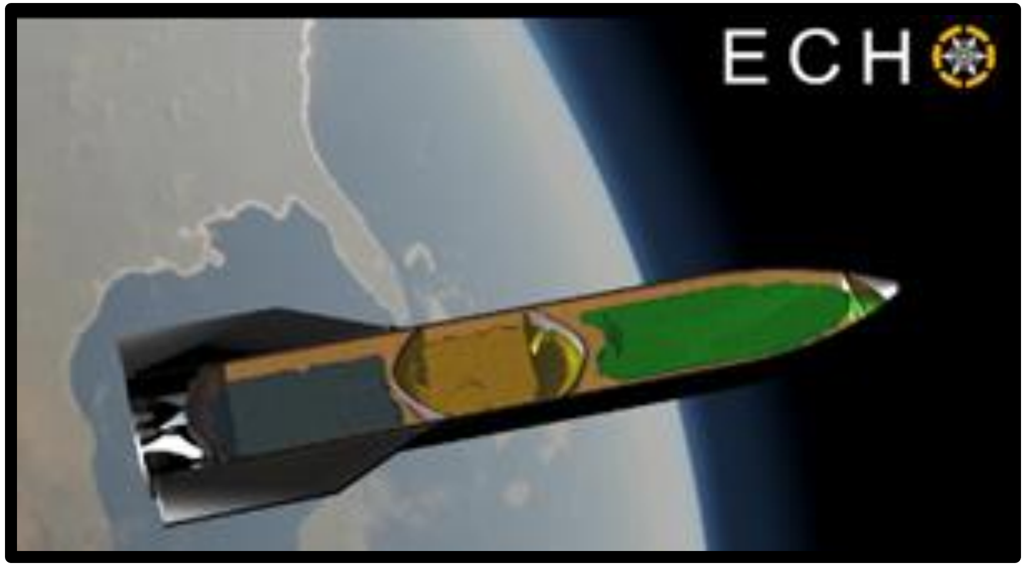


Simulation Image on ANSYS Maxwell

Future Work

- ➢ Cryogenic Testing
- ➢ Obtain more realistic and complex data
- ➢ Adopt other ML architectures
- ➢ Layered rows of electrodes for 3-D

Starship Implementation Concept Image



References

- Crosby, K. M., Werlink, R. J., & Hurlbert, E. A. (2024). *Liquid Propellant Mass Measurement in Microgravity*. Researchgate. https://www.researchgate.net/publication/349968986_Liquid_Propellant_Mass_Measurement_in_Microgravity
- Doherty, M. P., Gaby, J. D., Salerno, L. J., & Sutherlin, S. G. (2010). *Cryogenic Fluid Management Technology for Moon and Mars.* Missions. http://www.sti.nasa.gov
- Lee, D., Cho, M., Choi, H., & Tahk, M. (2018). *A study on the micro gravity sloshing modeling of propellant quantity variation.* Transportation Research Procedia, *29*, 213. https://doi.org/10.1016/j.trpro.2018.02.019
- Manning, Catherine G. (2023). *Technology Readiness Levels.* https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/
- Storey, J. M. (2023). *Propellant mass gauging in microgravity with electrical capacitance tomography.*
- Suppan, T., Neumayer, M., Bretterklieber, T., Puttinger, S., Feilmayr, C., Schuster, S., & Wegleiter, H. (2023). *Electrical capacitance tomography-based estimation of slug flow parameters in horizontally aligned pneumatic conveyors.* Powder Technology, 420. https://doi.org/10.1016/j.powtec.2023.118418
- Tech4Imaging. *Electrical Capacitance Volume Tomography.* www.tech4imaging.com. https://www.tech4imaging.com/electrical-capacitance-volume-tomography/
- Zimmerli, G. A. (2007). *Propellant gauging for exploration.*

ECHO

Electrical Capacitance to High-resolution Observation (ECHO)

Embry-Riddle Aeronautical University

Students

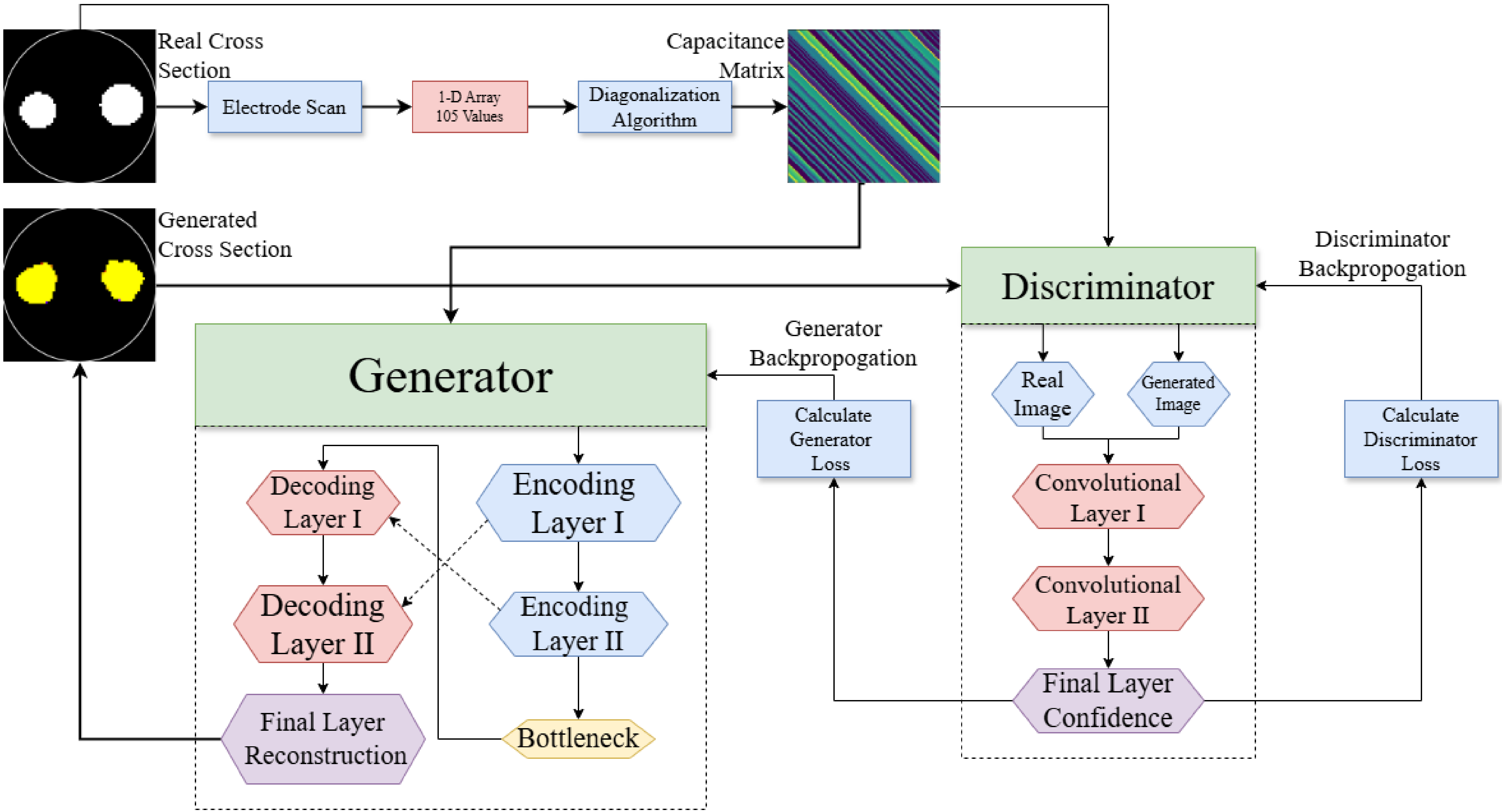
Bruce Noble, Grant Bowers, Aidan Kihm, Sanaya Nichani
Jakobe Denby, David Clay, Ian Naegeli, Cooper Nelson
Christopher Leclair, Max Klein, Owen Smith, Connor Shackelford

Advisors

Dr. Siwei Fan, Dr. Ron Madler

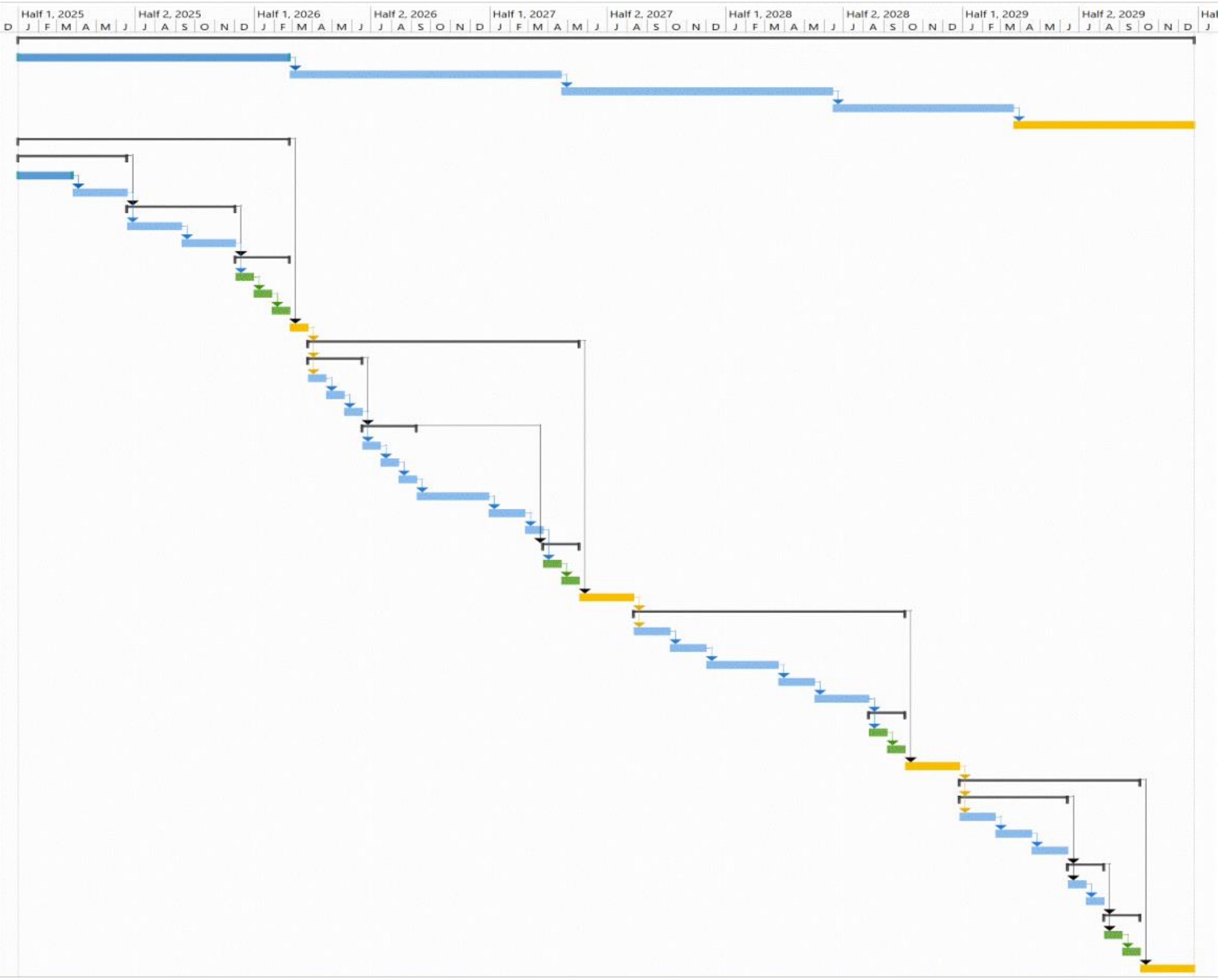
2025 Human Lander Challenge Forum, Huntsville, AL

Appendix


Real Cross Section
Electrode Scan
1-D Array 105 Values
Diagonalization Algorithm
Capacitance Matrix
Generated Cross Section
Discriminator
Discriminator Backpropogation
Generator
Generator Backpropogation
Calculate Generator Loss
Real Image
Generated Image
Calculate Discriminator Loss
Decoding Layer I
Encoding Layer I
Convolutional Layer I
Decoding Layer II
Encoding Layer II
Convolutional Layer II
Final Layer Confidence
Final Layer Reconstruction
Bottleneck

Project Timeline

Task Name	Duration	Start
PARSEC Overview	1300 days	1/1/25
Phase A	300 days	1/1/25
Phase B	300 days	2/25/26
Phase C	300 days	4/21/27
Phase D	200 days	6/14/28
Total Dedicated Margin	10 mons	3/21/29
Phase A	300 days	1/1/25
Test Candidate Additives	120 days	1/1/25
Particle Structure Test	3 mons	1/1/25
Particle Size Test	3 mons	3/26/25
Test Deployer Variations	120 days	6/18/25
Injection Angle Test	3 mons	6/18/25
Injection Velocity Test	3 mons	9/10/25
Reviews	60 days	12/3/25
SRR	1 mon	12/3/25
SDR	1 mon	12/31/25
PPP	1 mon	1/28/26
Phase A Margin	1 mon	2/25/26
Phase B	300 days	3/25/26
Determine Additive	60 days	3/25/26
Additive Chemical	1 mon	3/25/26
Additive Particle Size	1 mon	4/22/26
Additive Particle Shape	1 mon	5/20/26
Develop Deployer	60 days	6/17/26
Deployer Nozzle Size	1 mon	6/17/26
Deployer Flow Rate	1 mon	7/15/26
Deployer Angle	1 mon	8/12/26
System Tests	4 mons	9/9/26
Modifications	2 mons	12/30/26
Concept of Operations	1 mon	2/24/27
Reviews	40 days	3/24/27
BPP	1 mon	3/24/27
PDR	1 mon	4/21/27
Phase B Margin	3 mons	5/19/27
Phase C	300 days	8/11/27
Finalise Additive	2 mons	8/11/27
Finalize Deployer	2 mons	10/6/27
Integrated Test	4 mons	12/1/27
Finalize Con-Ops	2 mons	3/22/28
Manufacturing Process	3 mons	5/17/28
Reviews	40 days	8/9/28
CDR	1 mon	8/9/28
SIR	1 mon	9/6/28
Phase C Margin	3 mons	10/4/28
Phase D	200 days	12/27/28
Fully Integration Testing	120 days	12/27/28
Thermal Testing	2 mons	12/27/28
Vacuum Testing	2 mons	2/21/29
Vibrations Testing	2 mons	4/18/29
Prepare Launch Operations	40 days	6/13/29
Prepare Operations	1 mon	6/13/29
Prepare Ground Sopport	1 mon	7/11/29
Reviews	40 days	8/8/29
ORR	1 mon	8/8/29
FRR	1 mon	9/5/29
Phase D Margin	3 mons	10/3/29



Full Risk Matrix

ECHO RISK MATRIX

LIKELIHOOD	1	2	3	4	5
5			1		
4		6	3, 4	2	
3			5, 9		
2	13	11	7		
1			10	8, 12	
	CONSEQUENCES				

ID	Risk Name	Description	Related Systems	L	C	Method	Plan
1	Capacitor Sensor Error	Capacitors sensors transmit incorrect data leading to potentially inaccurate mass gauging data.	Electrodes	5	3	W	Accurate calibration, documentation
2	Thermal Insulation Failure	If the insulation for the electronics and structural components fail in cryogenic conditions, it may cause damage to the whole system.	Tank Insulation	4	4	R	Research different materials to use as insulation around tank to prevent systems from failing
3	Electrode Configuration	In periods of acceleration, the propellant may concentrate in a region without enough electrodes to gather data. This may cause errors in the reconstruction of data or even provide false readings.	ECHO, Propulsion, Starship	4	3	M	Design new electrode arrays in irregular areas, like the ends of the tank
4	Communication Interruption	During communication from the sensors, to the DAQ to the computer, any breakdown of communication could lead to no or incorrect data being transferred.	DAQ	4	3	M	Ensure connections are secured before and after test procedure

Full Risk Matrix

ECHO RISK MATRIX

LIKELIHOOD					
5			1		
4		6	3, 4	2	
3			5, 9		
2	13	11	7		
1			10	8, 12	
	1	2	3	4	5
	CONSEQUENCES				

ID	Risk Name	Description	Related Systems	L	C	Method	Plan
5	ECHO Mass	To accurately measure the mass of the full Starship propellant tanks, the mass of the ECHO system may exceed the critical point of mass where the inconvenience associated with mass exceed the convenience of having the measurement system.	ECHO, Propulsion, Starship	3	3	M	Reduce ECHO system mass and size without reducing the system's accuracy
6	ECHO Volume	The amount of volume the ECHO system takes up in the propellant tank will reduce the amount of propellant Starship could carry, reducing mission efficiency.	ECHO, Propulsion, GNC	4	2	A	The volume of the ECHO system could be reduced for efficiency, but few mitigation options are available
7	Power Consumption	The power it takes to run the ECHO system on the Starship scale exceeds the allotted power for the ECHO system by the Starship EPS	EPS, ECHO	2	3	W	ECHO would be designed with a set power budget; comparisons would be needed to determine if the electrical requirement would that given by Starship
8	Computer Memory/Processing Failure	Computer is unable to process information or handle new tasks until memory is freed. This would lead to incomplete data sets and incomplete mass gauging information.	ECHO, EPS	1	4	W	Ensure hard disks have enough space to record all data with extra space for redundancy

Full Risk Matrix

ECHO RISK MATRIX

LIKELIHOOD	1	2	3	4	5
5			1		
4		6	3, 4	2	
3			5, 9		
2	13	11	7		
1			10	8, 12	

CONSEQUENCES

ID	Risk Name	Description	Related Systems	L	C	Method	Plan
9	Radiation Environment Affecting Data	Computing and DAQ system are exposed to radiation environment leaving the potential for corruption of data by interacting with charges in memory systems.	ECHO, Starship	3	3	R	Research the average radiation environment in cislunar space and different shielding materials
10	Premature Test Failure	During testing, if ECHO's function ends prematurely, i.e. before the end of the test period, it would lead to incomplete data sets and thus potentially incomplete mass gauging information.	ECHO, Power	1	3	W	Recalibrate testing apparatus, ensure all components are functioning, and re-run the test
11	Immobilization By Orientation	In case of the issue of sensors slightly coming detached or even completely detached, it may impact the quality of measurements.	Electrodes	2	2	W	Observe during testing and adjust if issue becomes prevalent. If it does, adjust adhesives or placement to ensure sensors do not become dislodged
12	Computing System Protection Failure	If the ECHO system's DAQ or computer is not properly protected to potential violent forces, it could cause a failure of the system overall.	ECHO, DAQ	1	4	A	Ensure all parts are away from any hazards and maintain a careful posture when moving apparatus
13	Software Module Data Error	Error with data from different modules, whether that be an error passing, casting, or modifying data.	DAQ	2	1	M	Calibrate and test program before full testing to ensure little/no error