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- Today's session will be recorded
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  - Use the chat throughout the session to ask questions

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- Designed to distill and share the most important lessons learned to:
  - Increase the impact of suborbital flight tests
  - Transfer best practices
  - Optimize the experience of current and prospective program participants
- Part of a broad effort to capture, organize, and communicate lessons learned by suborbital researchers
- An opportunity to hear from subject matter experts on best practices for preparing for suborbital flight tests

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- Webinars are held 1st Wednesday of each month at 10 a.m. PT
- Topics will be announced in the Flight Opportunities newsletter and website
- Session recordings will be posted on the Flight Opportunities website
- Let us know session topics you would like to see covered

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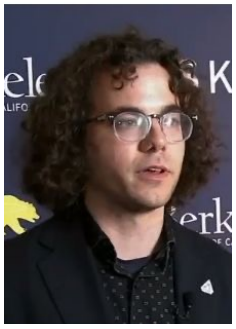
Today's Speakers

Hayden Taylor, Ph.D.
Associate Professor
Mechanical Engineering
University of California, Berkeley



Taylor Waddell
Pathways Engineer
NASA's Kennedy Space Center
Ph.D. student
University of California, Berkeley

Kathleen Karika
Director for Research Operations
Virgin Galactic

5

5

6

Volumetric Additive Manufacturing for In-Space Manufacturing

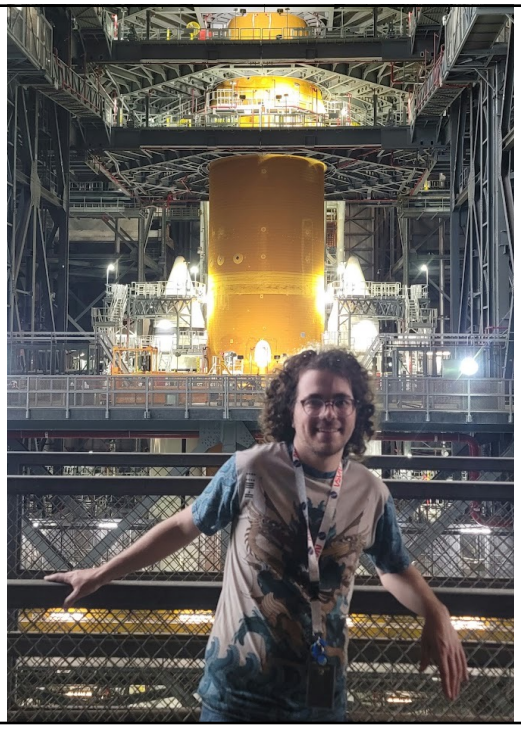
Presented by Taylor Waddell
Prof. Hayden Taylor's Group
Department of Mechanical Engineering
University of California Berkeley

Email: Twaddell@berkeley.edu

7

Taylor Waddell

- 4th Year PhD Student at UC-Berkeley in Mechanical Engineering.
- Undergraduate degrees in Mechanical Engineering & Computer Science from UW-Madison.



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1

Hayden Taylor

- Associate Professor in Mechanical Engineering and Vice Chair of Instruction UC-Berkeley.
- Specializing in manufacturing.
- B.A. & M.Eng in Electrical and Electronic Engineering Cambridge.
- Ph.D. Electrical Engineering and Computer Science MIT.

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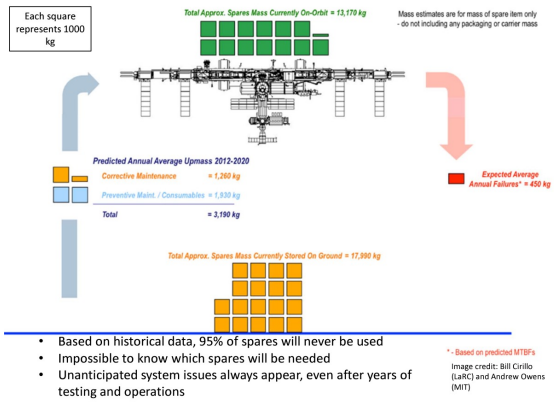
The Purpose of In-Space Manufacturing.



- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

Image credit: Bill Cirillo (LaRC) and Andrew Owens (MIT)

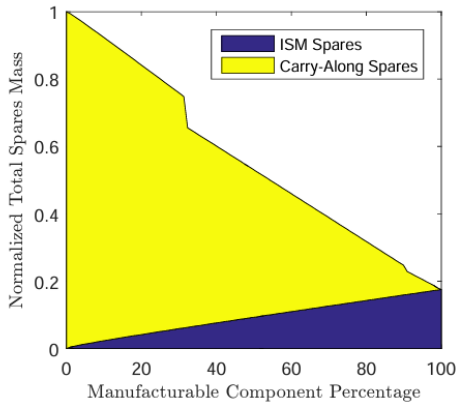


Image Credit: Matthew Moraguez (MIT)

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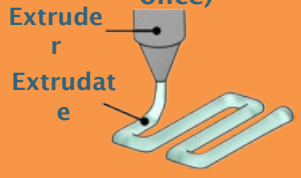
Increasing the dimensionality of printing.

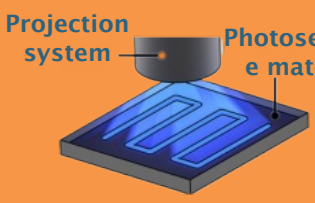
0D/1D (Point-at-once)



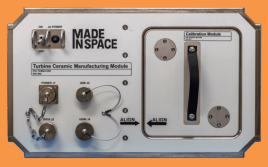
BioFabrication Facility

Additive Manufacturing Facility

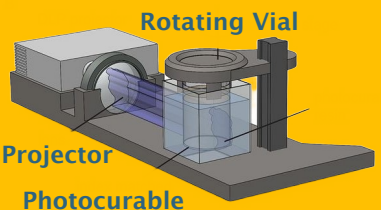
2D (Layer-at-once)



Ceramics Manufacturing Module



3D (CAL!)



Redwire Space. [Online]. Available: https://redwirespace.com/about/.
J. S. Miller and J. A. Burdick, "Editorial: Special issue on 3D printing of Biomaterials," *ACS Biomaterials Science & Engineering*, vol. 2, no. 10, pp. 1658–1661, 2016.
B. E. Kelly, I. Bhattacharya, H. Heidari, M. Shusteff, C. M. Spadaccini, and H. K. Taylor, "Volumetric additive manufacturing via tomographic reconstruction," *Science*, vol. 363, no. 6431, pp. 1075–1079, 2019.

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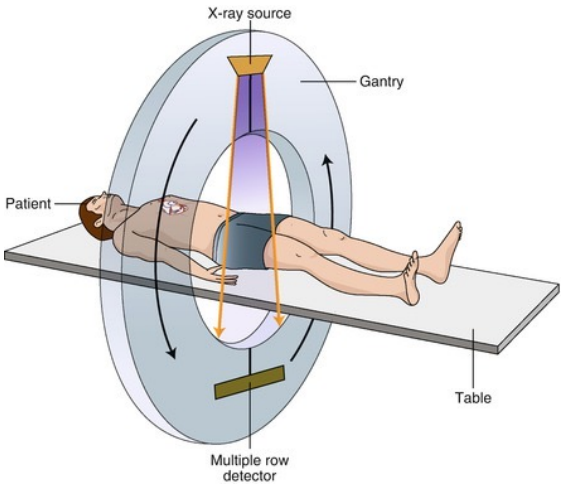
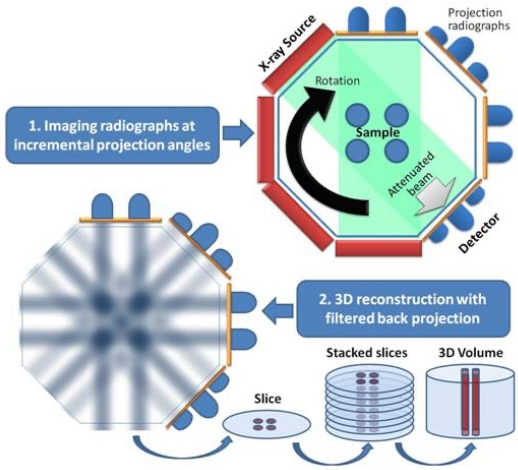
Theory behind Computed Axial Lithography.



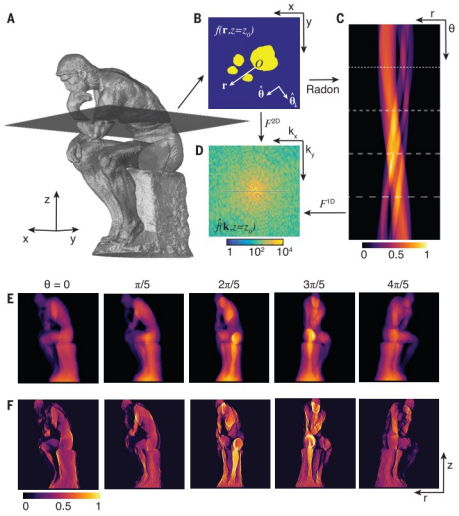


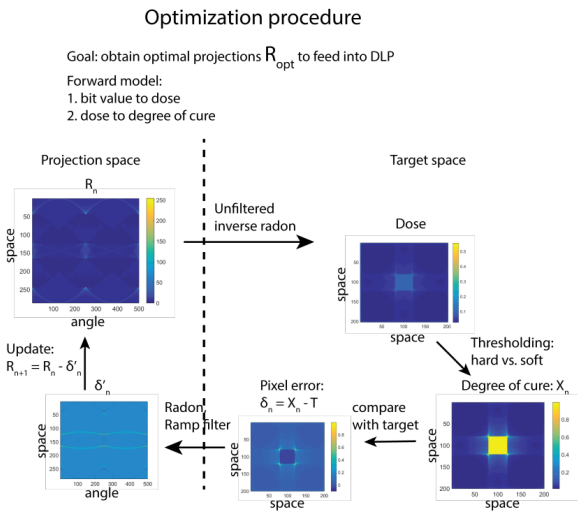
Computed Tomography

C. M. University, "X-ray computed tomography - X-ray computed tomography facility - carnegie Mellon University," X-ray computed tomography - X-ray Computed Tomography Facility - Carnegie Mellon University, https://www.cmu.edu/me/xctf/xrayct/index.html.
U. Themes, "Basic principles in Computed Tomography (CT)," Thoracic Key, https://thoracickey.com/basic-principles-in-computed-tomography-ct/.

12

Computational Workflow of Creating Projections.





Projection creation for Thinker mesh.

B. E. Kelly, I. Bhattacharya, H. Heidari, M. Shusteff, C. M. Spadaccini, and H. K. Taylor, "Volumetric additive manufacturing via tomographic reconstruction," *Science*, vol. 363, no. 6431, pp. 1075–1079, 2019.

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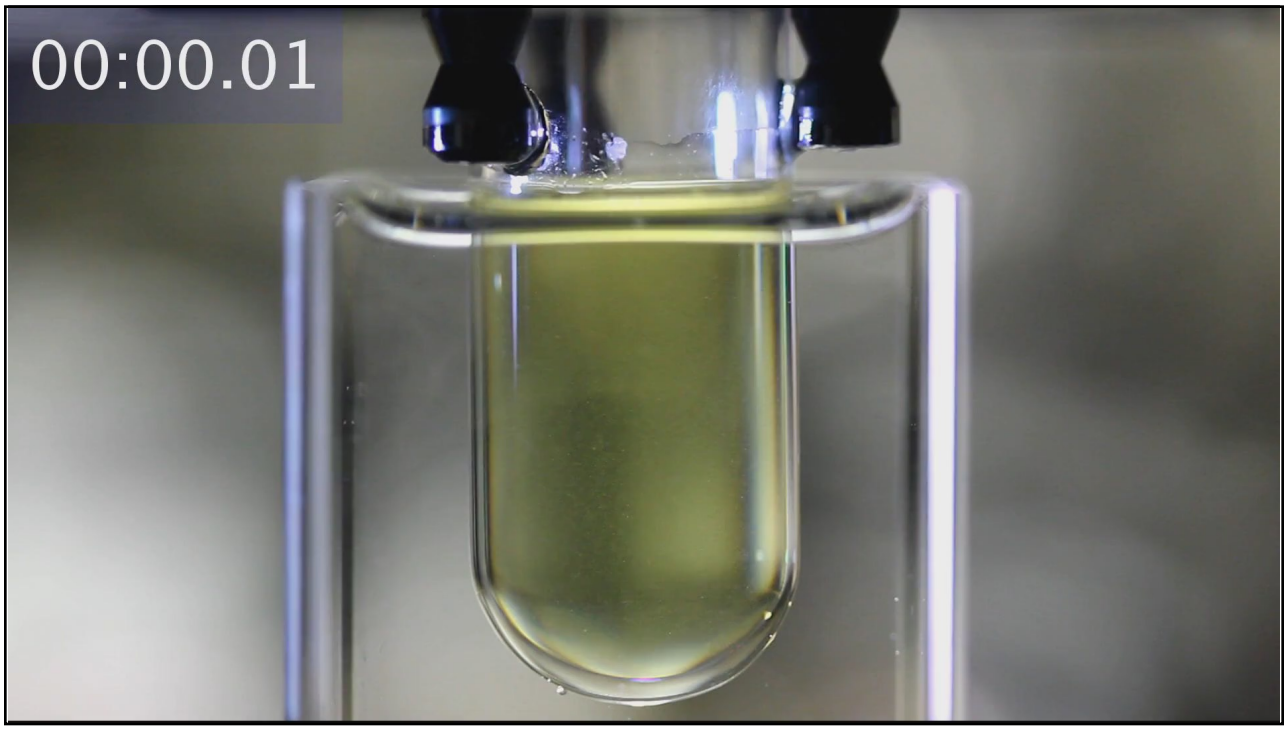

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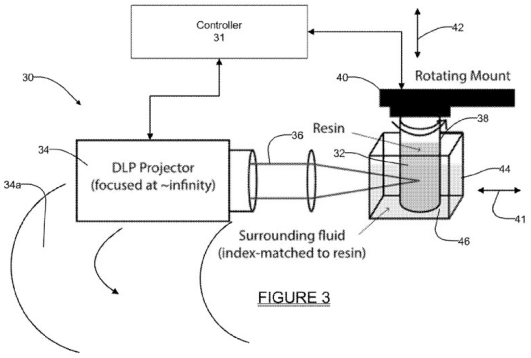
CAL is both Simple and Fast.

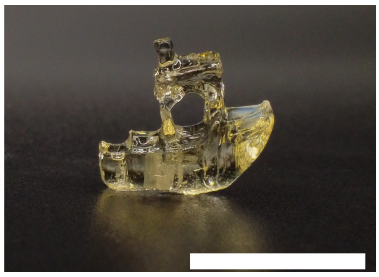


WO 2018/208378
4/5
PCT/US2018/032475

CAL Patent US11370173B2

Speed

- **FFF: 3 Minutes (Cura)**
- **SLA: 32 Minutes (Preform)**
- **CAL: 20 Seconds**

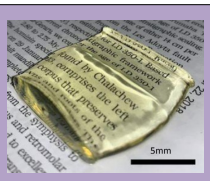


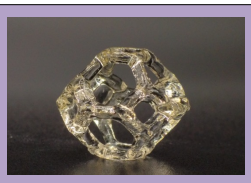
Scale bar 12.7mm

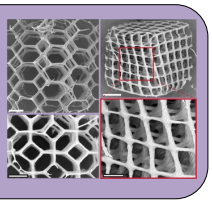
15

CAL is a highly desirable process for ISM.

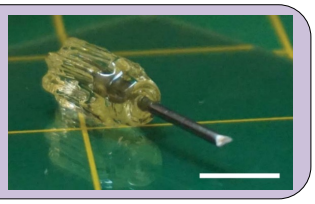
No Support Structures & No Layering
- Allow for fine details
- Reduces needed material
- Smoother surfaces







Overprinting
- Form over new objects
- Repair broken parts
- Join geometry together



Mechanically simple
- Easy to maintain and repair.
- Low energy consumption.
- Low total volume.

Chemically simple
- Low or non-toxic materials.
- Little waste.
- Large range of materials.

B. E. Kelly, I. Bhattacharya, H. Heidari, M. Shusteff, C. M. Spadaccini, and H. K. Taylor, "Volumetric additive manufacturing via tomographic reconstruction," *Science*, vol. 363, no. 6431, pp. 1075–1079, 2019.
J. T. Toombs, M. Luitz, C. C. Cook, S. Jenne, C. C. Li, B. E. Rapp, F. Kotz-Helmer, and H. K. Taylor, "Volumetric additive manufacturing of silica glass with microscale computed axial lithography," *Science*, vol. 376, no. 6590, pp. 308–312, 2022.

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SpaceCAL Can be Critical for Space Exploration.

Property of CAL.	Benefit for Space Exploration.
- Enclosed/Does not need flat gas interface.	- Poses low risk to the crew.
- Fast.	- Works well in an emergency.
- Wide range of materials.	- Can repair and maintain many subsystems.
- Low SWaP Values compared to current printers.	- Can work well with strict requirements.

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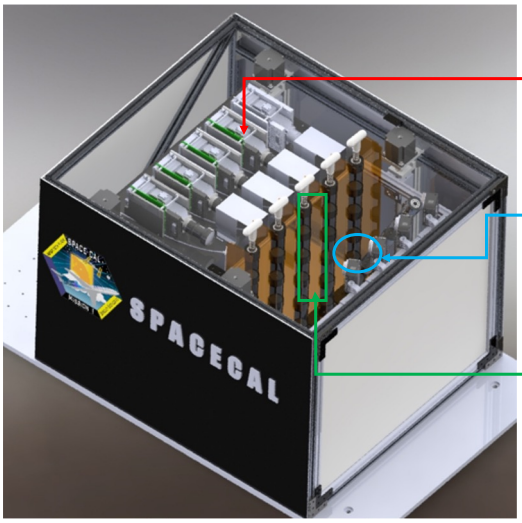
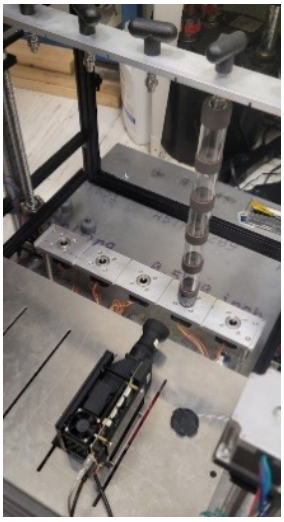
SpaceCAL Mission 1 in Simple Terms.





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CAL Successfully Demonstrates Operation in Microgravity.

1 projector failed.
Errors in mixing happened.
1 vial stack got stuck.

5 different materials demonstrated.

96 vials of 120 succeeded.
154 parts were fabricated.

1 projector failed.
Errors in mixing happened.
Errors in calibration.

7 different materials successfully demonstrated.

256 vials of 390 succeeded.
314 parts were fabricated.

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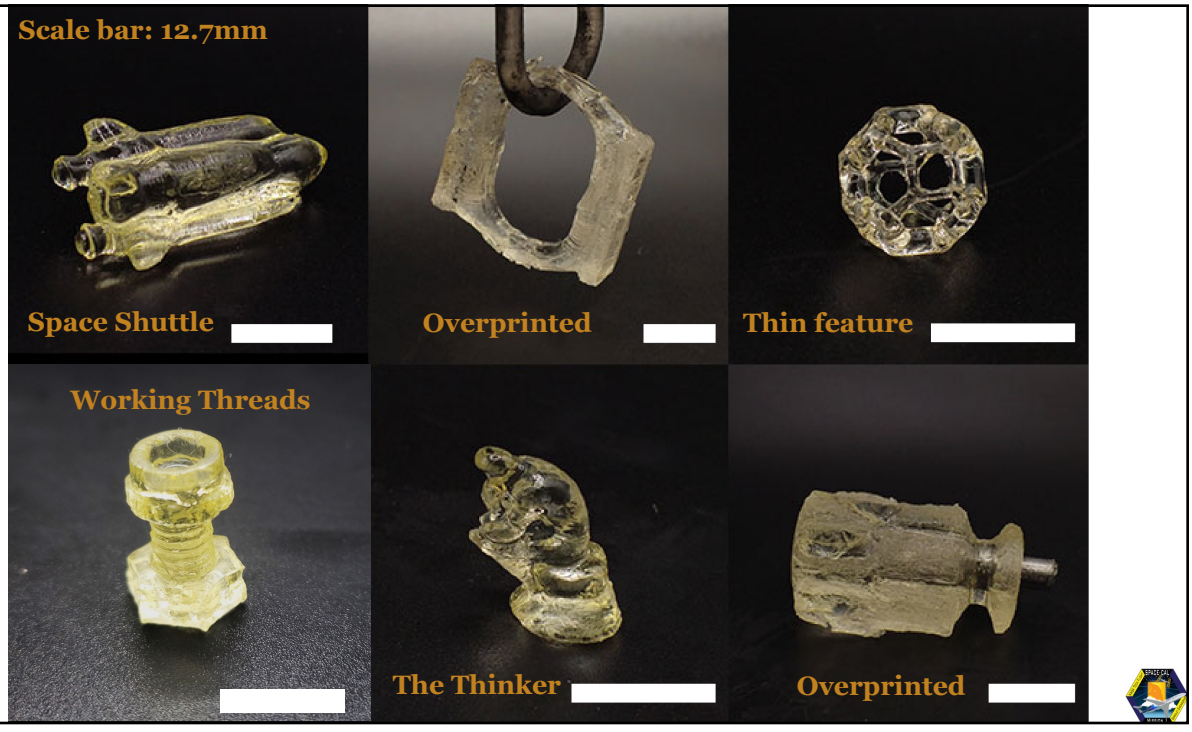

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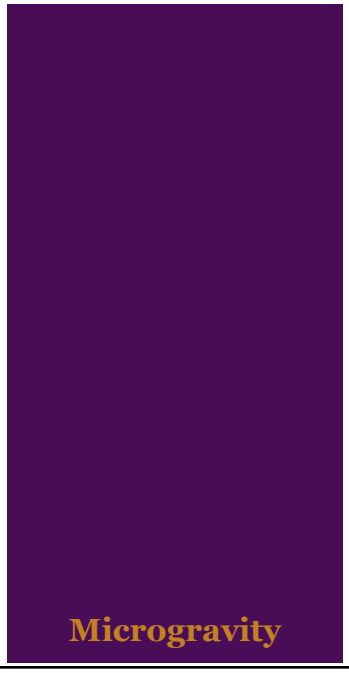
Microgravity parts remain still while earth-based parts float.

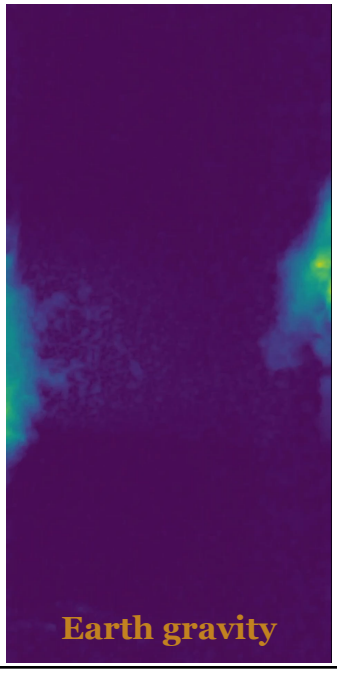


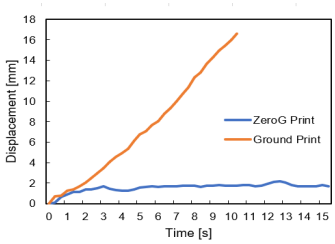
Realtime.

Printed in PEGDA700.

Viscosity of fluid is ~0.1Pa-s

Video width is 23.5mm.





Gravity vector

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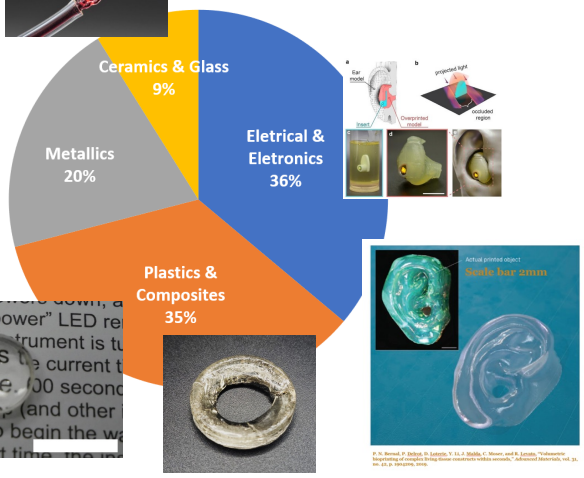
Expanding CAL to Fabricate Flight Hardware.

Percentage of replaceable parts on the ISS by material type.



ISM Process	Specific Energy (MJ/kg)	Max Process Rate (kg/hr)	Auxiliary Power (W)
FFF	220	0.022	75
Bound Metal AM	150	0.096	75
CNC	14.7	10	300
Milling			
Wire-arc AM	13.2	0.5	750
Ultrasonic AM	12.2	0.68	500
SpaceCAL	6.793e-4	43.2	1036
CAL4	6.793e-4	55.7	96

M. M. Johnston, M. J. Werkheiser, K. G. Cooper, M. P. Snyder, and J. E. Edmunson, "3D Printing in Zero-G ISS Technology Demonstration," presented at the AIAA Space 2014, San Diego, CA, Aug. 2014. Accessed: Nov. 25, 2023. [Online]. Available: https://ntrs.nasa.gov/citations/20140012888
"Volumetric additive manufacturing of silica glass with microscale computed axial lithography | Science." Accessed: Aug. 26, 2022. [Online]. Available: https://www.science.org/doi/10.1126/science.abm6459
Toombs, Joseph T., et al. "Ethyl cellulose-based thermoreversible organogel photoresist for sedimentation-free volumetric additive manufacturing." Macromolecular Rapid Communications, vol. 44, no. 7, 2023, https://doi.org/10.1002/marc.202200872.

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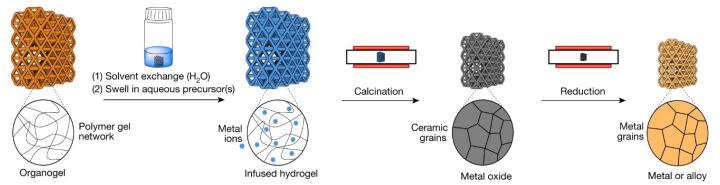
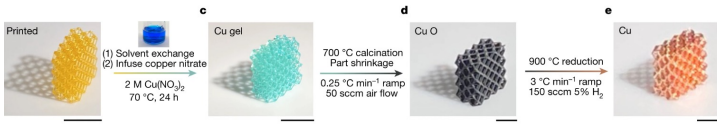
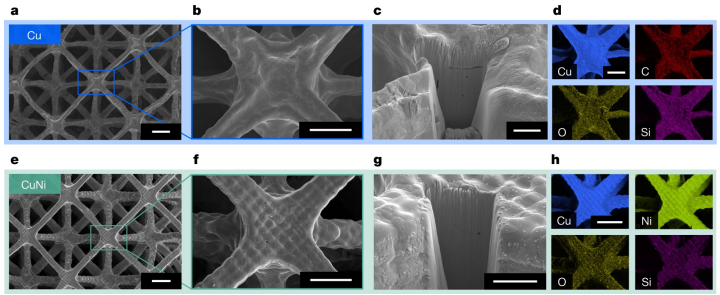
Basic Principle of Hydrogel Infusion Additive Manufacturing.

Scale bars:
b,c-5mm.
d,e-1mm.





Scale bars:
a,e-100µm.
b,d,f,g-50µm.
c,g-20µm.



Saccone, Max A., et al. "Additive Manufacturing of Micro-Architected Metals via Hydrogel Infusion." Nature, vol. 612, no. 7941, 2022, pp. 685–690, https://doi.org/10.1038/s41586-022-05433-2.

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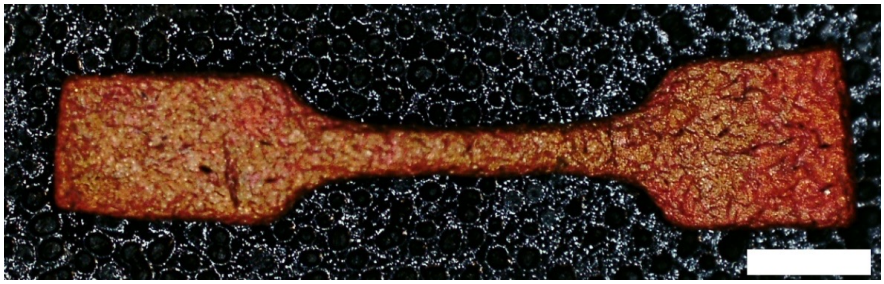
Success in creating fully copper parts.



Copper dogbone CAL-HIAM part. Scale bar: 1 mm (Left). Initial batch of dogbones fully processed (Right).

Berkeley
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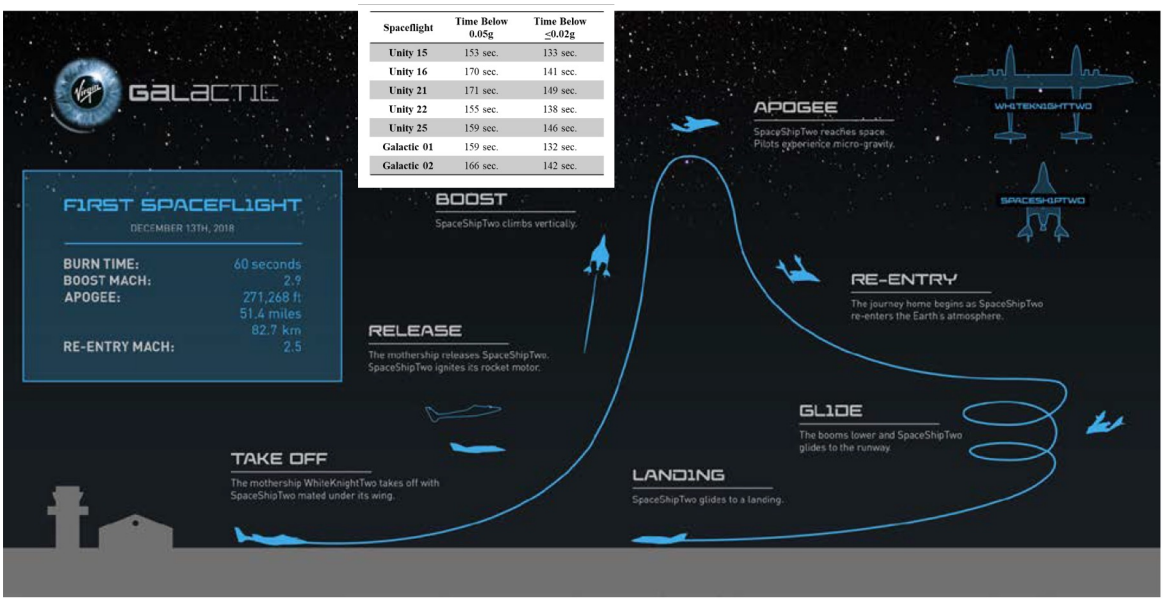
SpaceCAL Mission 3, a Sub-Orbital Space Test.



Spaceflight	Time Below 0.05g	Time Below ≤0.02g
Unity 15	153 sec.	133 sec.
Unity 16	170 sec.	141 sec.
Unity 21	171 sec.	149 sec.
Unity 22	155 sec.	138 sec.
Unity 25	159 sec.	146 sec.
Galactic 01	159 sec.	132 sec.
Galactic 02	166 sec.	142 sec.

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SpaceCAL Mission 3, Overall Objective.

- Demonstrate and analyze the CAL printing process and post processing in a continuous microgravity environment. This will advance TRL to 7. The goal of this technology is for eventual On-Demand use in Space Exploration.
- Timeline start 09/2023. Launch 06/08/2024.

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SpaceCAL Mission 3, a Timeline of Experiment.

- Microgravity reached – Projector turns on, vials rotate, OST turns on, cameras turn on for recording.
- T+40 seconds – Projector turns off, fluid pumps turn on and flush with IPA, OST turns off, PIV lasers turn on.
- T+80 seconds – Solenoid valve switches to water, water displaces the IPA.
- T+120 Seconds – Projection Turns On, Pumps Turn Off
- T+140 Seconds – Everything Shuts down
- T+1 hour landing – Cartridges are removed.
- Within T+2 hours landing – Printed parts are removed.

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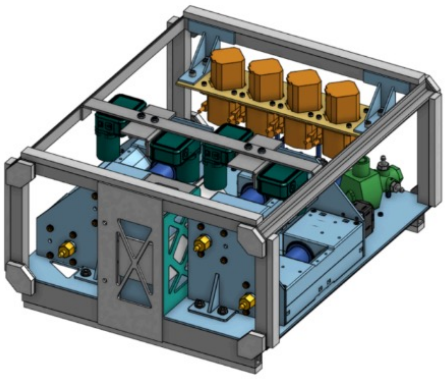
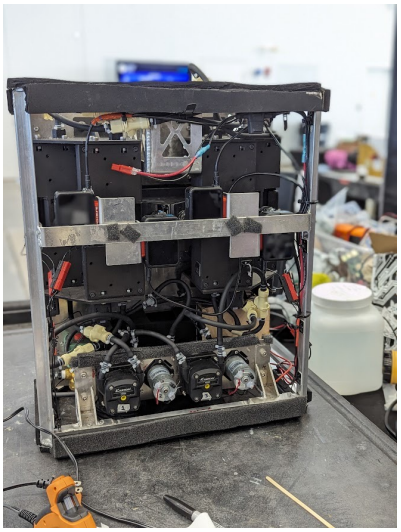
SpaceCAL Mission 3, General Layout of Experiment.





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SpaceCAL Mission 3, Optimizing Optical Output.

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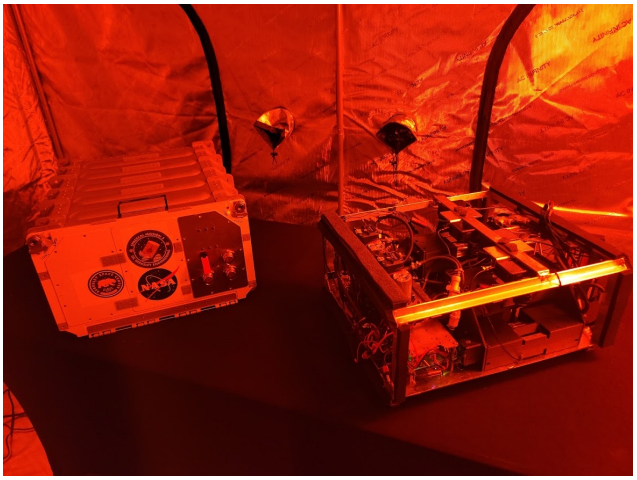
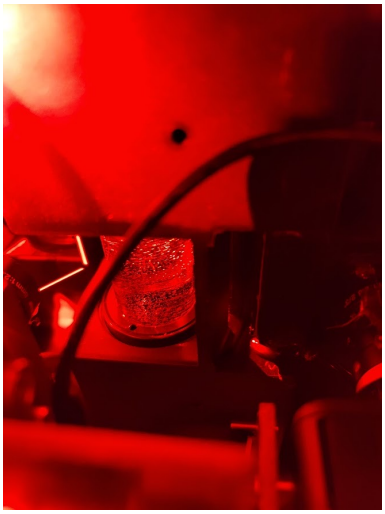
SpaceCAL Mission 3, Loading Into Unity.





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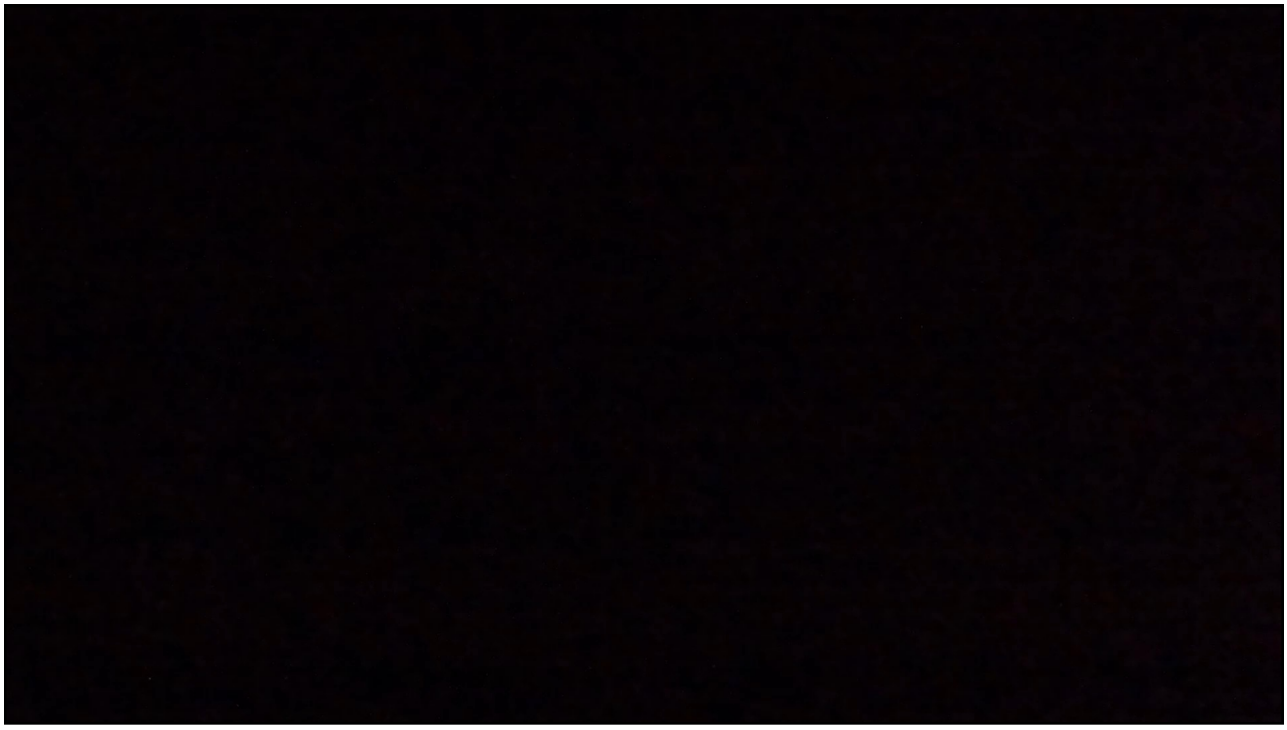

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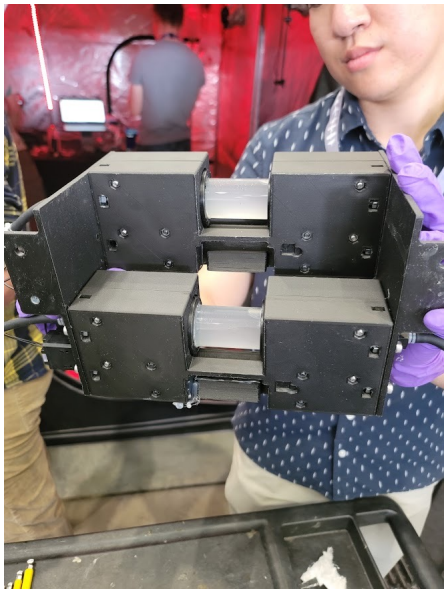
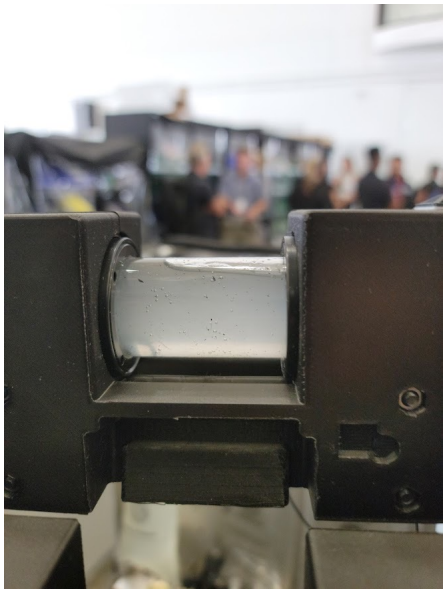
SpaceCAL Mission 3, Early Results.





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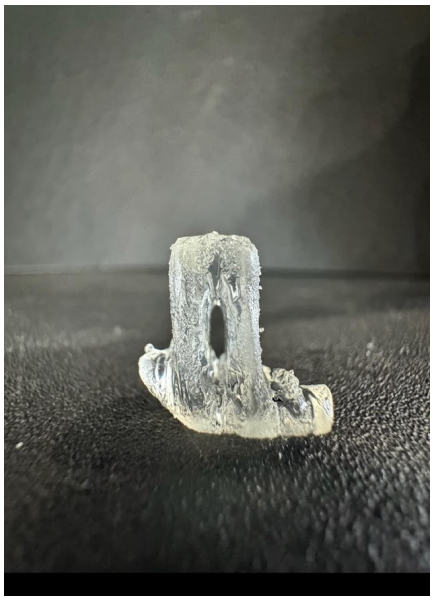
SpaceCAL Mission 3, Early Results.



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SpaceCAL Mission 3, Next Steps.

- Analyze microstructure of polymer parts, see if there are any gravitational differences.
- Analyze composition of end resulting fluid, see how much of the printing material remains in fluid.
- Analyze printing system SWaP capabilities.
- Understand where printing fidelity may have been lost.

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Partners.

NRC·CNRC

NASA TECHFLIGHTS

Lawrence Livermore National Laboratory

Virgin

IN SPACE MANUFACTURING
MAKE IT-DON'T TAKE IT

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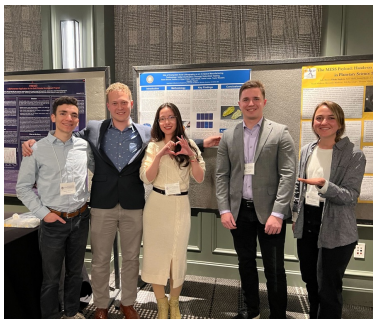
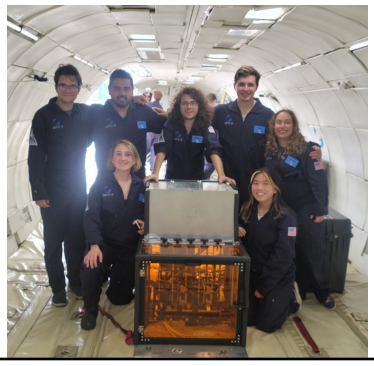
The people who make it happen.

- Tristan Schwab
- Christian Castaneda
- Tasha Lewis
- Dylan Potter
- Ingrid Shan
- Aemon Li
- Issam Bourai
- Jake Nickel
- Shiv Makim
- Garrett Miller
- Joseph Toombs
- Ashley Reilly
- Pranit Mohnot
- Anthony Moody
- Ameera Elgonemy
- Anusri Sreenath
- Audrey Young
- Dillon Balk
- Sean Chu
- Austin Portinause
- Brian Chung
- Skyler Chan





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Q/A
Email: Twaddell@berkeley.edu

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National Aeronautics and Space Administration
NASA
NASA Flight Opportunities
Community of Practice
October 2024 | Kathleen Karika
www.nasa.gov

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GALACTIC
Introduction and Overview
Kathleen Karika
Director, Research Operations
Kathleen.karika@virgingalactic.com

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VG by the Numbers
1st
Fully Crewed Commercial Spaceflight
2023
Start Commercial Operations
7
Research Missions Flown
GALACTIC
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Fully Reusable Suborbital System

Mothership:

- High-altitude, high-performance jet aircraft
- Capable of heavy-lift missions
- "Carrier craft" for Spaceship

Spaceship:

- Suborbital spaceplane
- Designed to safely and routinely transport people and payloads to suborbital space and back
- Carries a crew of two pilots, up to six astronauts, or equivalent research experiments

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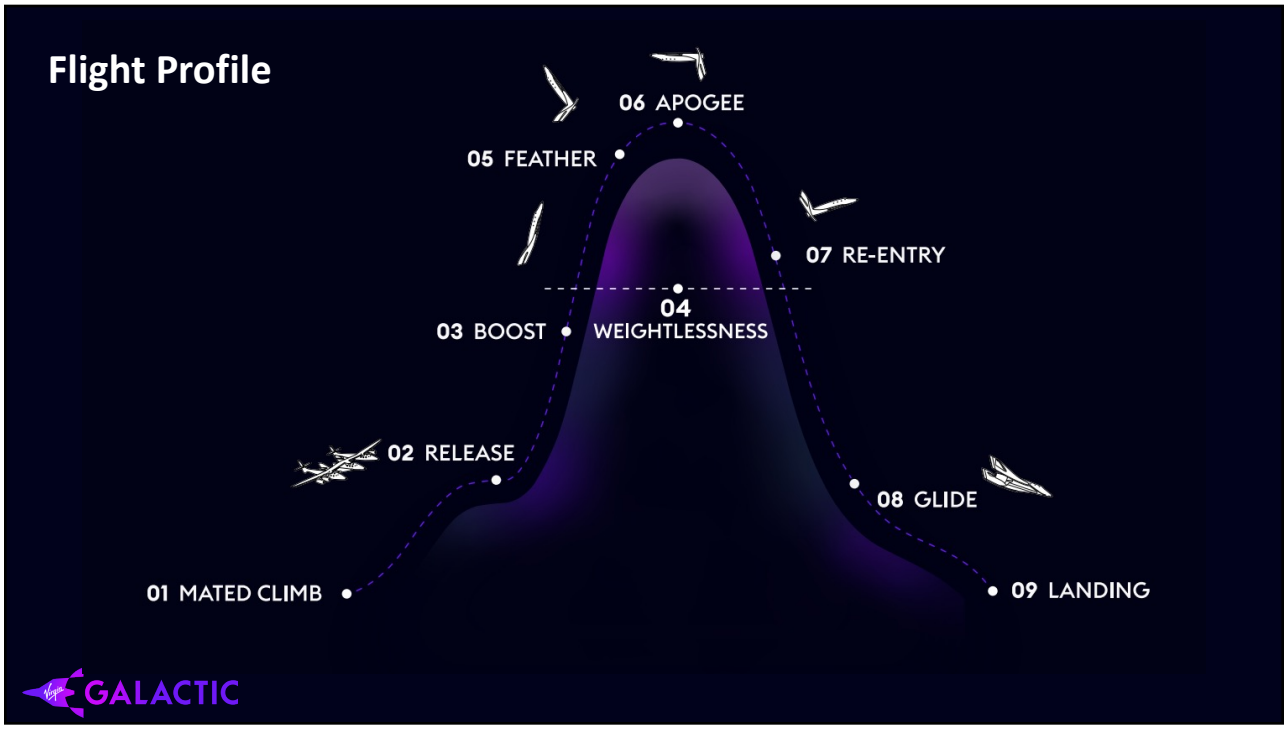

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Operations

- Training, preparation, and payload integration at Spaceport America
- Timely payload access with late load and early unload options
- Full-size cabin mockup for testing and training

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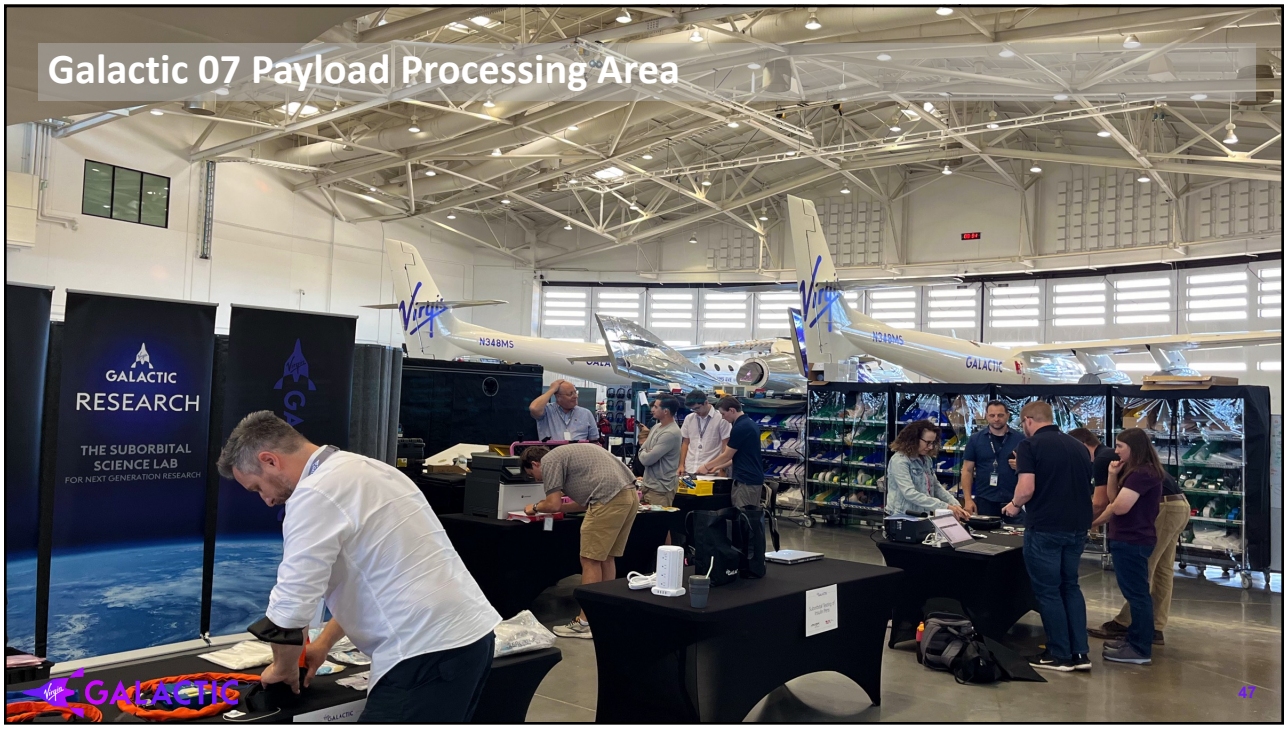

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Research Offerings

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Galactic 07 Cabin
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Research Process Summary
Pre-Contract
Post-Contract
Payload Information Form (PIF)
Contract
Payload Information Package (PIP)
Engineering Review
Management Review
On-Site Inspection
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NASA FLIGHT OPPORTUNITIES

National Aeronautics and Space Administration

Thank you!

Flight Opportunities website:
http://nasa.gov/flightopportunities

Contact us:
NASA-FlightOpportunities@mail.nasa.gov

FLIGHT OPPORTUNITIES PROGRAM
NASA AFRC ARC

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Backup

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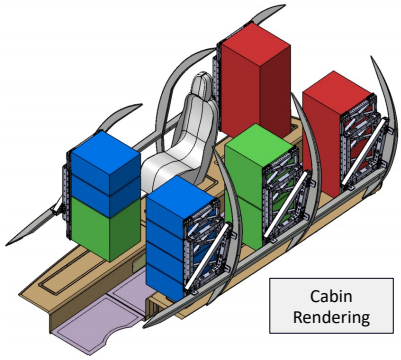
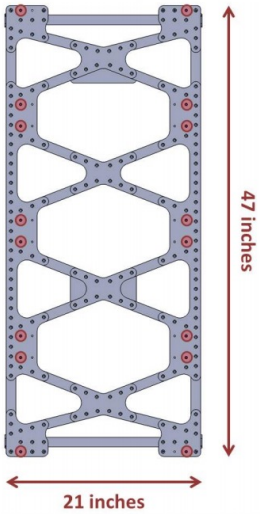
Rack-Mounted Payload Specifications



Cabin Rendering

Payload Rack Hardware



Locker Parameters

Type	Locker Dimensions	Volume (MLEs)	Maximum Weight	Maximum Power
Single	18.50" W x 11.25" H x 21.50" D (47.0cm W x 28.6cm H x 54.6cm D)	1	50 lbs. (23 kg)	50W
Double	18.50" W x 23.00" H x 21.50" D (47.0cm W x 58.4cm H x 54.6cm D)	2	100 lbs. (45 kg)	100W
Triple	18.50" W x 34.75" H x 21.50" D (47.0cm W x 88.3cm H x 54.6cm D)	3	150 lbs. (68 kg)	150W
Quad	18.50" W x 46.50" H x 21.50" D (47.0cm W x 118.1cm H x 54.6cm D)	4	200 lbs. (91 kg)	200W

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Previously Flown Research Payloads – NASA and U.S. Universities

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Galactic 01 – Italian Research Mission

- **What:** First Italian and first European suborbital human spaceflight mission
- **Who:** Italian Air Force (ItAF) and National Research Council of Italy (CNR)
- **Research:**
  - 3 Italian researchers
  - 12+ microgravity payloads from across Italy, including rack-mounted and wearable (details here)
- **Next Steps:** Mission Commander flew on Axiom's Ax-3 mission to the ISS

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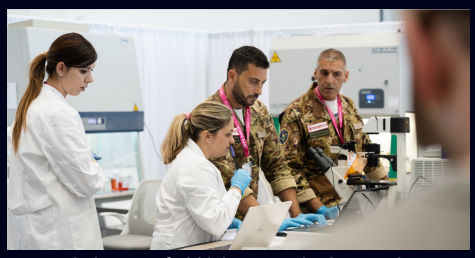
Galactic 01 – Italian Mission Research Mission



Neural plasticity field laboratory built in VG hangar

CNR crew member inspects payloads ahead of flight

ItAF Mission Commander activates payload during flight

Message to Italy during flight

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Galactic 05 – Privately Funded Research Mission

- **Who:**
  - **Southwest Research Institute (SwRI)**
  - **International Institute for Astronautical Sciences (IIAS)**
- **Research: 5 wearable experiments (details here)**
- **Next Steps: Repeat flights for "fly-fix-fly"**

SwRI: Shuttle-era Camera Mockup

IIAS: Astroskin Biosensor

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Galactic 07 – NASA and Turkiye-Funded Research Mission

- **Who:**
  - **Turkish Space Agency (TUA) in partnership with Axiom Space**
  - **Purdue University (NASA-funded)**
  - **UC Berkeley (NASA-funded)**
- **Research: 3 wearable experiments, 4 studies, 2 lockers (details here)**
- **Next Steps: NASA TechFlights 2024**

TUA: BEACON-R from Mass General

Purdue: Rotational Slosh with Undergrads

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Suborbital to Orbital – Astrosurgery

- **Principal Investigator:** Dr. George Pantalos, University of Louisville
- **Mission:** Refining mechanisms for rehydrating red blood cells in space environments
- **Application:** Transfusion therapy for astronauts on long-duration orbital and space exploration missions
- **Funding:** NASA Flight Opportunities awards
- **Research Type:** Autonomous and potential future human-tended

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Autonomous Research – Ignorosphere

- **Principal Investigator:** H. Todd Smith, Johns Hopkins University Applied Physics Lab (APL)
- **Mission:** Study the electric field in the lower ionosphere, which is informally called the "ignorosphere" because its altitude is too high for high-altitude balloons and aircraft and too low for orbiting spacecraft
- **Application:** Understand the Earth's complex electrical environment
- **Funding:** NASA Flight Opportunities award
- **Research Type:** Autonomous, rack-mounted payload locker

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Human-Tended Research – Plants in Space

- **Principal Investigator:** Rob Ferl and Anna-Lisa Paul, University of Florida
- **Mission:** Capture changes in gene expression during the transition to and from sustained microgravity
- **Application:** Plant growth in orbit and for human exploration missions
- **Funding:** NASA Flight Opportunities award
- **Research Type:** Human-tended experiment by Virgin Galactic astronaut

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National Astronaut – Turkiye

- **Principal Investigator:** Dr. Vladimir Ivkovic and Ms. JoAnna Pollonais, Massachusetts General Hospital and Harvard Medical School
- **Mission:** Use brain and physiological monitoring system to complete the first-ever continuous monitoring of blood and cerebrospinal fluid flow in all phases of spaceflight
- **Application:** Understand the mechanics behind spaceflight associated neuro-ocular syndrome (SANS) and study emotional and physiological responses associated with the Overview Effect
- **Funding:** Turkiye to Axiom Space
- **Research Type:** Human-tended experiment by Axiom Space/Turkish Space Agency (TUA) astronaut

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Suborbital to Orbital – Training

"This kind of training is an **entire mission compressed in a few minutes**, so you can experience all phases of the flight, from the takeoff to the boost, the coasting and then working in microgravity and re-entry…In a nutshell, it is a good environment to really **test all the things the astronauts are supposed to do once they get to the ISS**." – Col. Walter Villadei, ItAF

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Orbital to Suborbital – Combustion

- **Principal Investigators:** CNR's Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS)
- **Mission:** Combustion characteristics of renewable liquid biofuels and the behavior of complex fluids at high temperatures
- **Application:** Efficient technologies for eco-sustainable energy and propulsion systems
- **Flight History:** 2013 ISS Mission
- **Research Type:** Autonomous and human-tended

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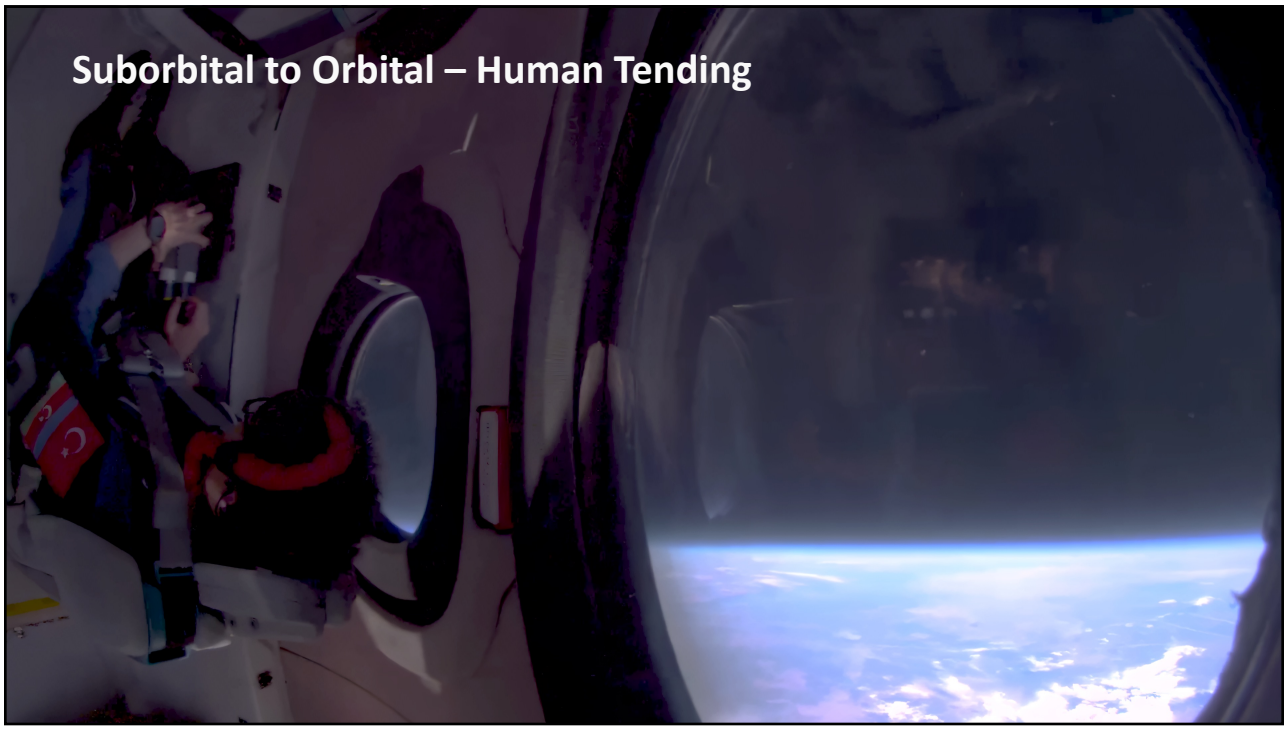
Suborbital to Orbital – Human Tending



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Suborbital and Orbital – Canada

- **Principal Investigators:** IIAS and Carré Technologies with support from CSA
- **Mission:** Collect wide-range of biometric data using the Astroskin device, a lightweight smart shirt
- **Application:** Continuous health monitoring using an integrated suite of biosensors
- **Flight History:** Parabolic, Suborbital, ISS
- **Research Type:** Human-tended

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Future Missions

NEWS • 06/20/24

VIRGIN GALACTIC ANNOUNCES NEW RESEARCH FLIGHT CONTRACT WITH REPEAT CUSTOMER

International Institute for Astronautical Sciences to Expand Research Conducted on Galactic 05 Flight

Second-Time Virgin Galactic Astronaut Kellie Gerardi to Lead IIAS Crew Aboard Next Generation Delta Spaceship

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Virgin Galactic Researchers

A summary of all research flown with Virgin Galactic can be found here: https://www.virgingalactic.com/research-overview

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Testimonials

"There are 194 nations on Earth and most of them **can't afford spaceflight until suborbital** came in – and now they all can."
– Alan Stern, SwRI
Galactic 05 Mission Specialist

"The **quality and repeatability of the microgravity environment** provided by Virgin Galactic's system is truly game-changing and the potential for a 'fly, fix, fly' approach opens the door to many exciting possibilities for IIAS to make discoveries that benefit future explorers."
– Kellie Gerardi, IIAS
Galactic 05 Mission Specialist

"This kind of training is an **entire mission compressed in a few minutes**, so you can experience all phases of the flight, from the takeoff to the boost, the coasting and then working in microgravity and re-entry…In a nutshell, it is a good environment to really **test all the things the astronauts are supposed to do once they get to the ISS**."
– Col. Walter Villadei, Italian Air Force
Galactic 01 Mission Commander, Ax-3 Astronaut

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