Laser Beam Welding in Thermal Vacuum and in Microgravity to Mature In-Space Welding

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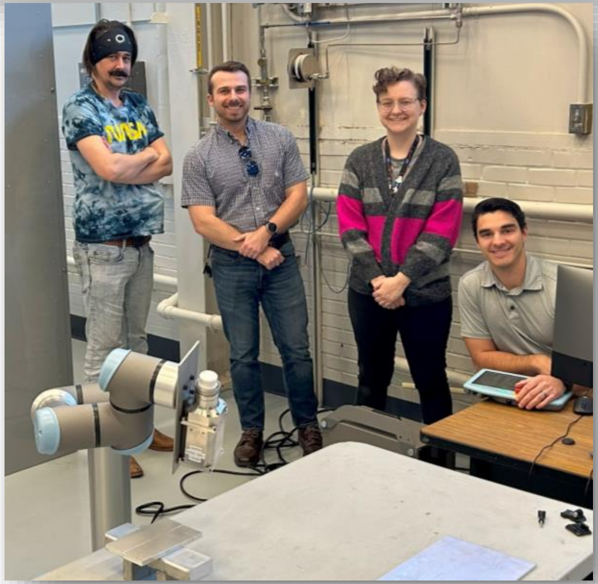
[1]NASA/MSFC; [2]NASA/LaRC; [3]NASA/JSC; [4]ESSCA/Amentum; [5]NASA OSTEM Internship

A team effort!

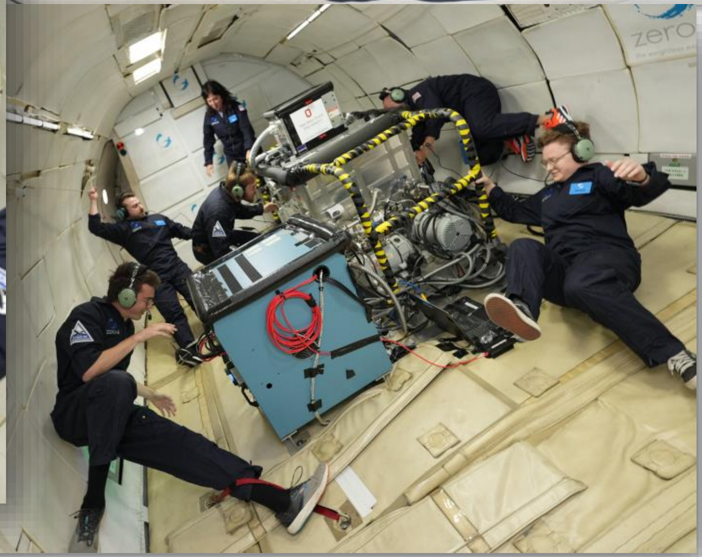
ISAM
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

Interns from collaborating universities



Multiple NASA Field Centers

Rich network of academic, government, and industrial partners



Introduction to in-space laser manufacturing

Laser beam welding, laser forming, and allied processes

In-space laser manufacturing enables space infrastructure

Initial work on in-space welding (ISW) as a heritage process

Method → ↓ Criteria	**Fasteners/ rivets**	**In–Space Welding (ISW)**
Joint strength & rigidity	◒	○
Joint hermeticity	●	○
Joint mass	●	○
Joint design & manufacturing simplicity	◒	○
Joint reliability	◒	○
Repair versatility	●	○
Associated cost & upmass	◒	○
● - Poor	◒ - Satisfactory	○ - Good

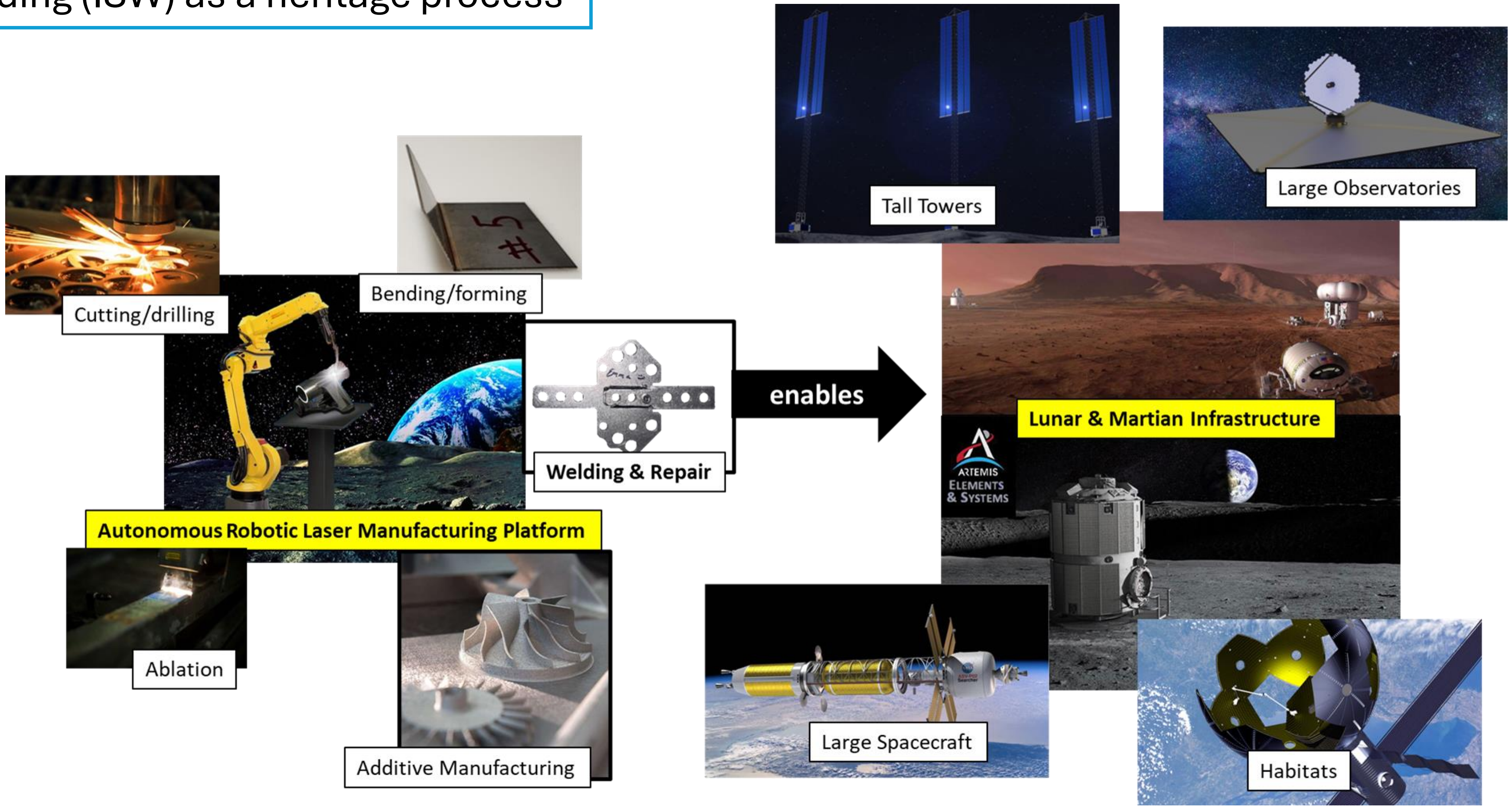
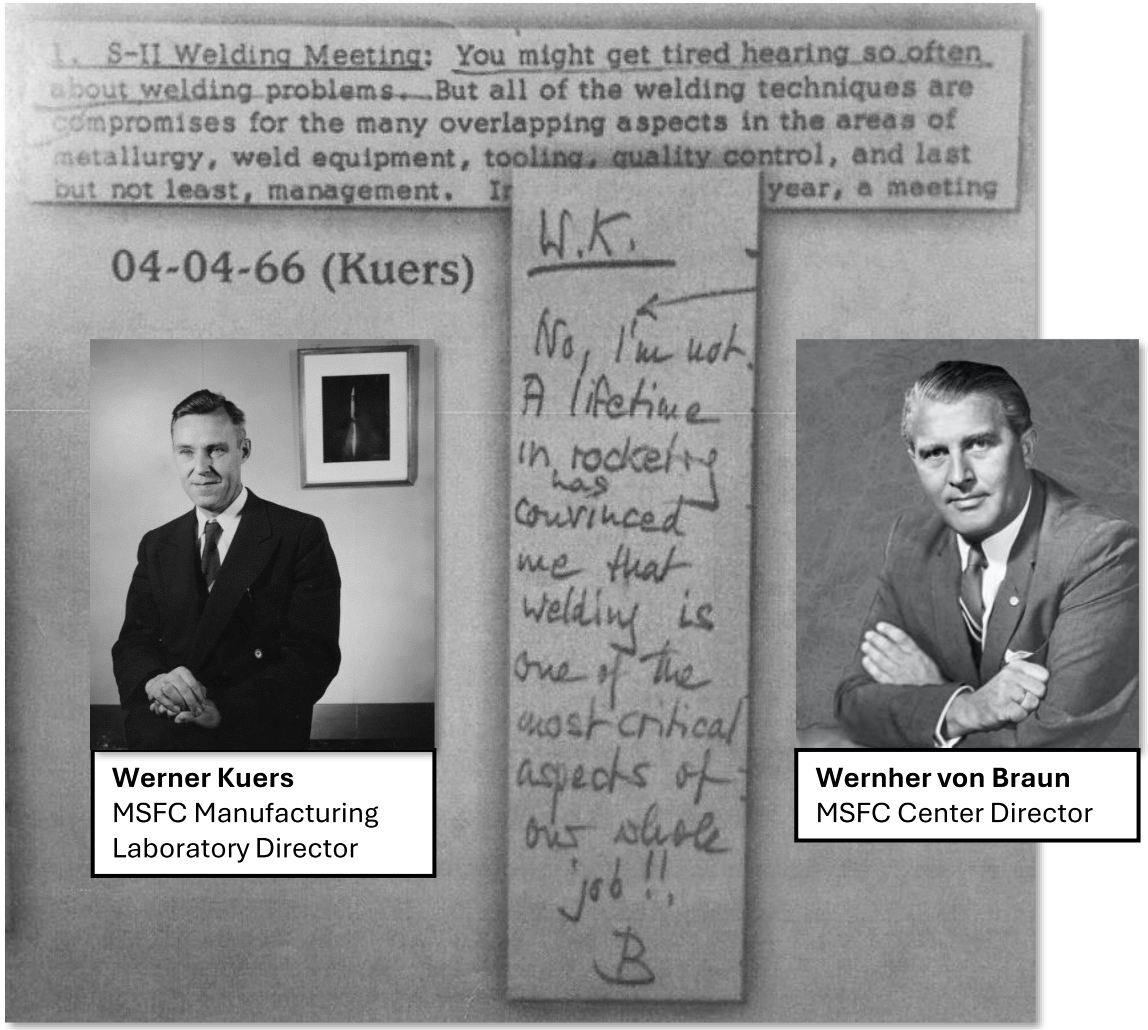


Image credit: ThinkOrbital, www.mechanicalcaveman.com

Welding enables space exploration



1966 correspondence between Wernher von Braun and Werner Kuers

"The complexity of welding is readily apparent when one considers that fusion welding involves temperature gradients of thousands of degrees, over distances of less than a centimeter, occurring on a time scale of seconds, involving multiple phases of solids, liquids, gases, and plasma."

Thomas Eagar, MIT, 1990

Quoted in North, Ed., *Advanced joining technologies: proceedings of the International Institute of Welding Congress on Joining Research*, 1990.

Adapted from: Sowards, *American Welding Society Professional Program*, 2023.

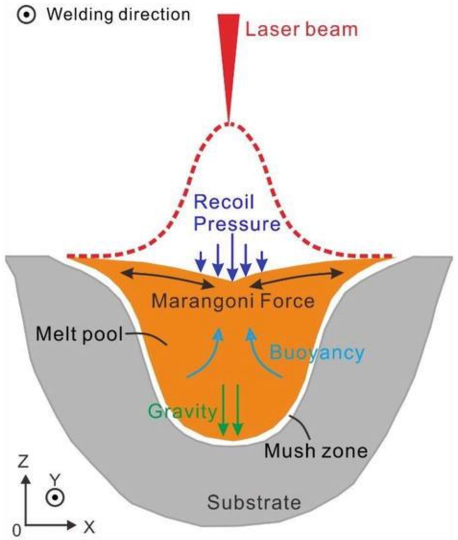
In-space effects that influence welding

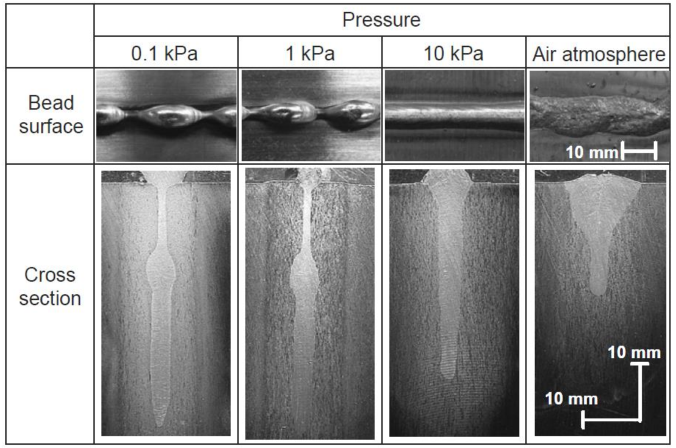
Variable	Case 1: In Space	Case 2: Chamber Inside Space Habitat	Case 3: Inside Space Habitat	Case 4: Lunar Surface	Case 5: Martian Surface	Baseline: Earth	Capabilities Needed at Present
Gravity	μg	μg	μg	0.17 *g*	0.38 *g*	1 *g*	μg to 0.38 *g*
Atmosphere	Vacuum (10^{-19} Pa)	Vacuum (10^{-4} Pa)	>21% O_2, <101 kPa	Vacuum (10^{-9} Pa) or habitat	$95CO_2$-$2.6N_2$-1.9Ar-$0.2O_2$-0.06CO (0.6 kPa) or habitat	$78N_2$-$21O_2$-0.9Ar-0.1other, 101 kPa	HV (10^{-1} Pa) UHV (10^{-5} Pa) XUHV (10^{-9} Pa)
Temperature	Extremely low ISS Exterior: 120 K – 395 K	~ 293 K	~ 293 K	40 K – 400 K	133 K – 300 K	~ 293 K	40 K – 400 K
Space Suit	Yes	No	No	Yes	Yes	No	

Table adapted and expanded from original source: Masubuchi, 1990, doi: 10.2207/qjjws1943.59.421

Reduced gravity is unique among the above effects in that it cannot be reproduced for prolonged periods on earth.

Current Work: Integrate existing capabilities across academia, government, and industry to investigate space environmental effects on welding processes to inform computational models, and to create public-private partnerships to develop and implement space welding technologies.

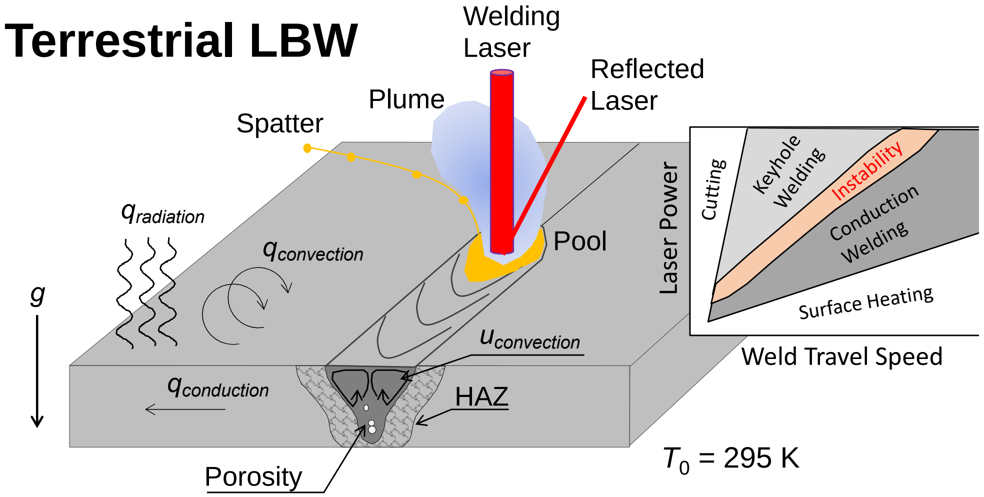




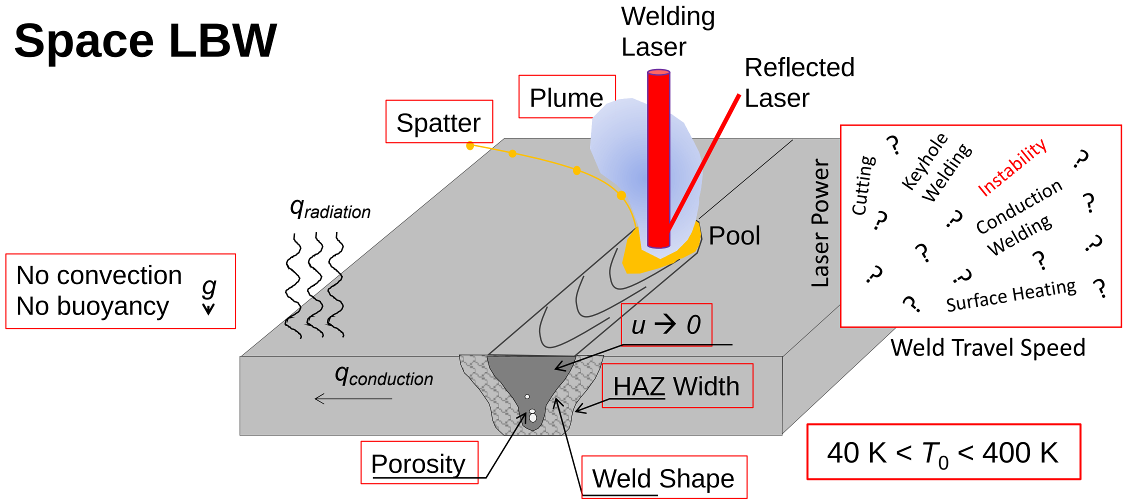
Key effects to consider for in-space LBW

Red boxes indicate instrumentation and modeling opportunities.

Terrestrial LBW



Space LBW



Issue #1 Weld heat transport has profound effect on size of a weld and its metallurgical transformations and hence weld properties:

Temperature gradient and cooling rate are proportional to thermal conductivity and T_0^2

Issue #2 Reduced gravity reduces buoyancy-induced convection:

Development of weld pool shape and porosity evolution are altered, and chemical effects become dominant, e.g., surface-active elements influence weld penetration due to thermocapillary flow. (minute alloy chemistry changes are important)

Issue #3 Reduced pressure/vacuum in space:

Heat transport is dominated by radiation and conduction rather than by convection. Weld shape and width, and weld strength will be influenced by change in weld cooling.

Reduced pressure influences laser beam keyhole stability, evaporation of volatile species, safety issues, etc.

From: Sowards, *American Welding Society Professional Program*, 2023.

Timeline of In-Space Welding and Joining

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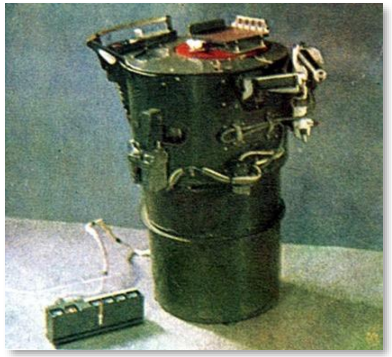


Progress in Space Stagnated and Moved to Parabolic Flights

1960s | 1970s | 1980s | 1990s | 2000s | 2010s | *2020s*

FIRST SPACE WELD
1969. Soyuz-6. Vulkan EBW, PAW, GMAW (USSR)

FIRST AMERICAN SPACE WELD
1973. Skylab. EBW, braze experiments (USA)

1979. Salyut-6. Isparitel braze coating (USSR)

1983. Salyut-7. Isparitel M, deposition (USSR)
1984. Salyut-7. UHT (USSR)
FIRST MANUAL OPEN SPACE WELD

1988. Mir, Yantar
EB melt/weld (USSR)

1993. Parabolic
CO_2 LBW (CAN)

1999. ISWE components went to MIR
(USA/UKR/RUS) **CANCELLED**

2021. SUBSA-BRAINS braze metal.
2023-. Lockheed NASA Public-private JOINS.
2024. EBW in space by ThinkOrbital
2024-2025. Parabolic fiber LBW Flight.
Ohio State and NASA

Parabolic Vulkan
experiment (USSR). 1965

Parabolic for Skylab (USA). 1972

Parabolic Nd:YAG LBW (USA). 1988/89

Parabolic UHT Experiment 1993
Parabolic ISWE Experiment 1994

Drop Tower GTA Weld Experiment (JP). 1998

Parabolic GHTA Weld Experiment (JP). 2001

It has been over 50 years since NASA has performed a weld in space.

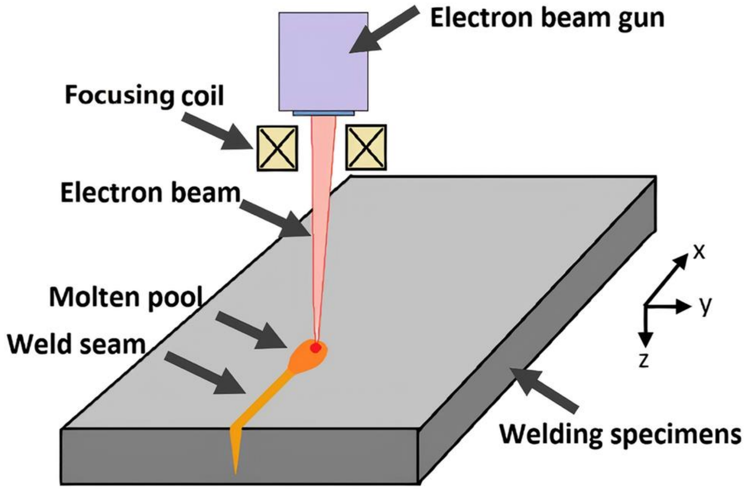
n.b.
Electron beam welding = EBW,
Laser beam welding = LBW

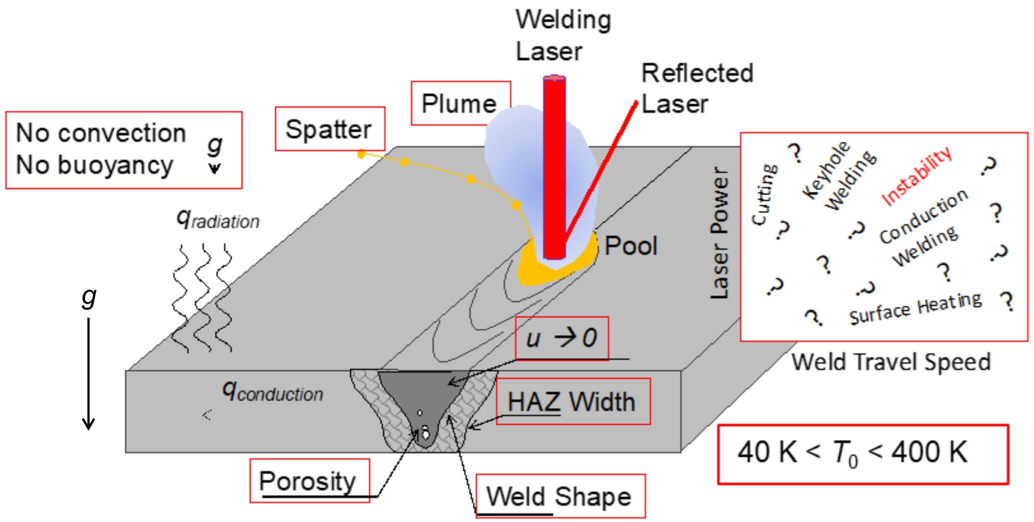
2018. New Ukrainian EBW Gun Patented

2024-2026. NASA Early Career Initiative:
LBW within TVAC
2025-. NASA Early Stage Innovations grant
(computational models of Lunar welding)
2025-. DISCMAN LBW parameter
development on ISS. NASA

NASA

Why laser beams in space?





High-energy Beam Process → **↓ Criteria**	**Electron**	**Laser**	**Status**
IVA flexibility (e.g. in habitat) & EVA flexibility (e.g. in vacuum, Lunar surface, on Mars)	●	○	Capability available after planned development
Workpiece variety (*e.g.* geometry, material)	◒	○	
Suitable for operation on end effector of robotic arm (*e.g.* EMI, mass, power delivery, heat rejection)	●	○	
Compatible with inspection tools & able to repair welds	◒	○	
Capable of bending/forming structures	●	○	
Power requirements & energy efficiency	○	◒	Commercial lasers
Suitable for additive manufacturing	○	○	Future work in space
Perform subtractive manufacturing – cutting, drilling, etc.	◒	○	
● - Poor ◒ - Satisfactory ○ - Good			

List inspired in part from: Tamir et al., *Thirtieth Space Congress*, 1993.

In-space laser manufacturing enables space infrastructure

Initial work on in-space welding (ISW) as a heritage process

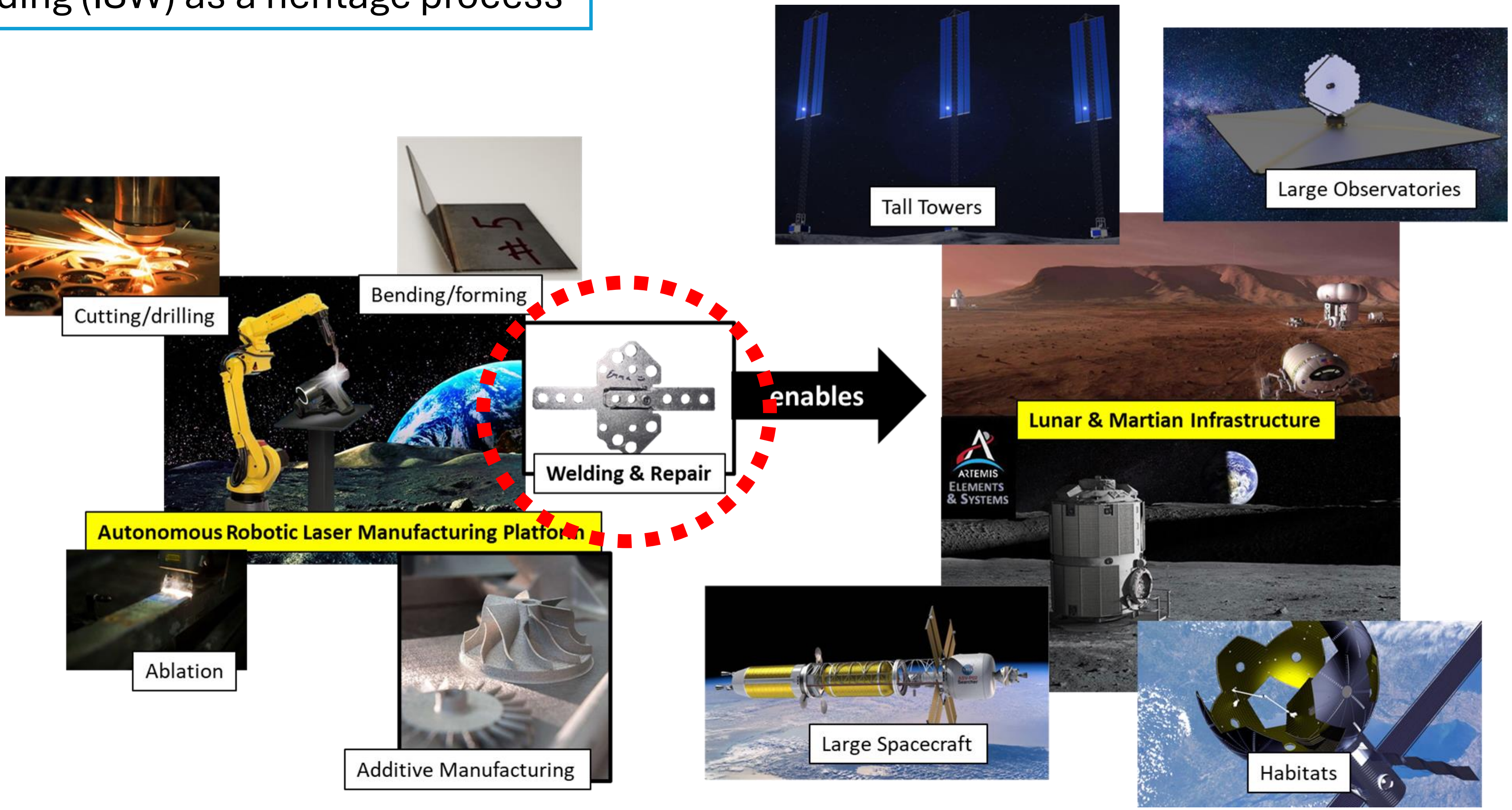
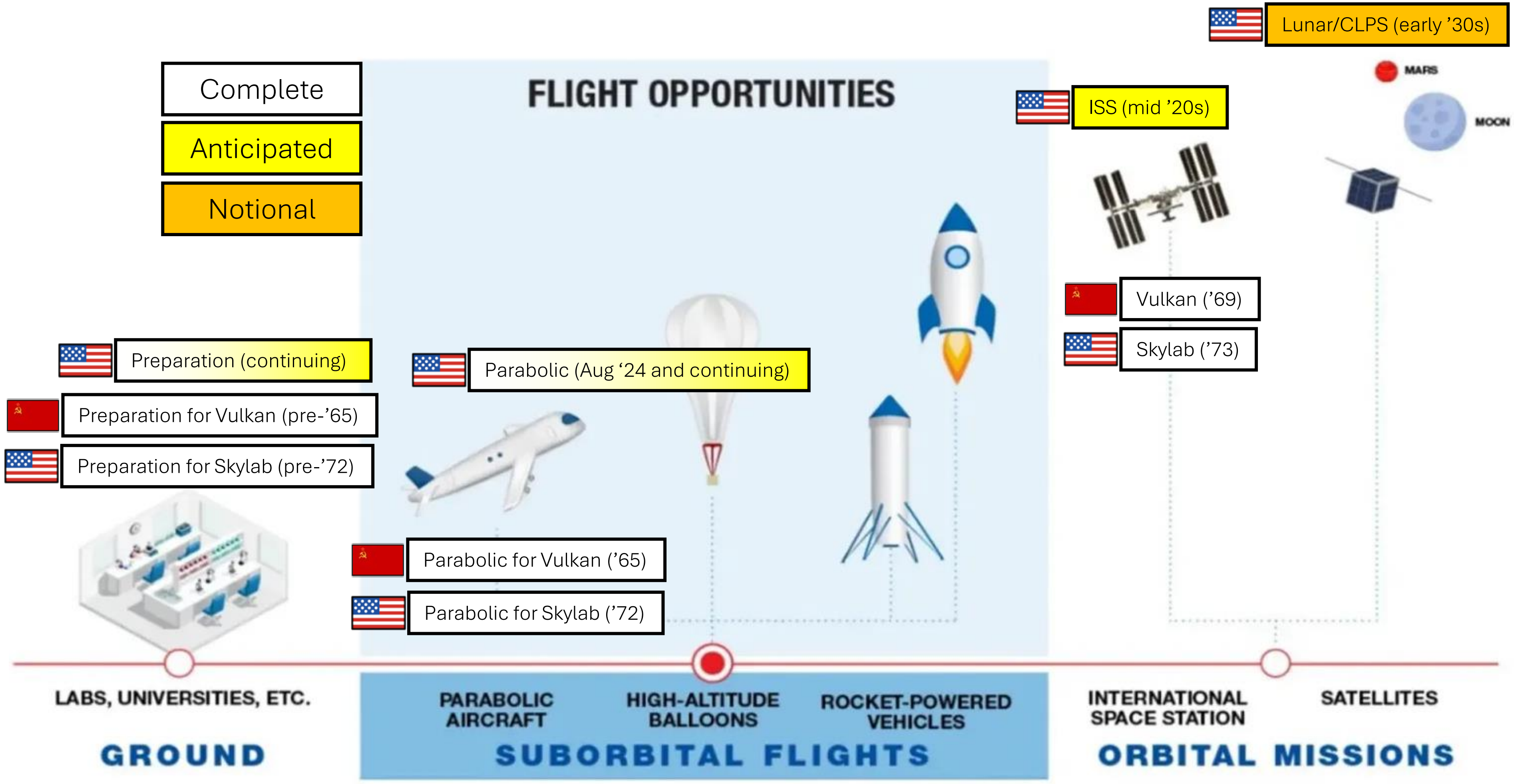
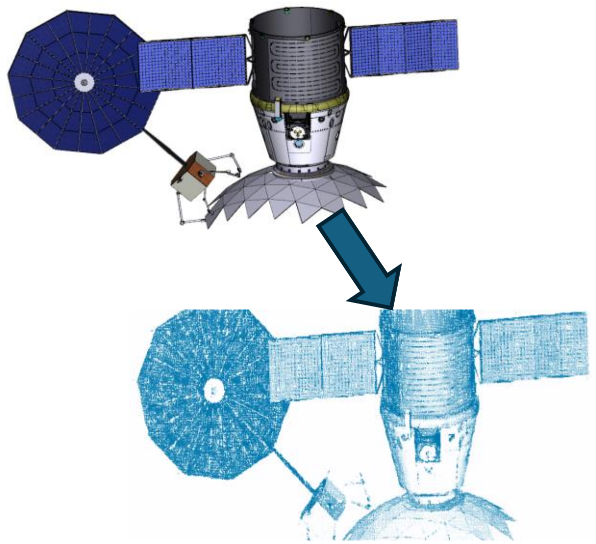


Image credit: ThinkOrbital, www.mechanicalcaveman.com

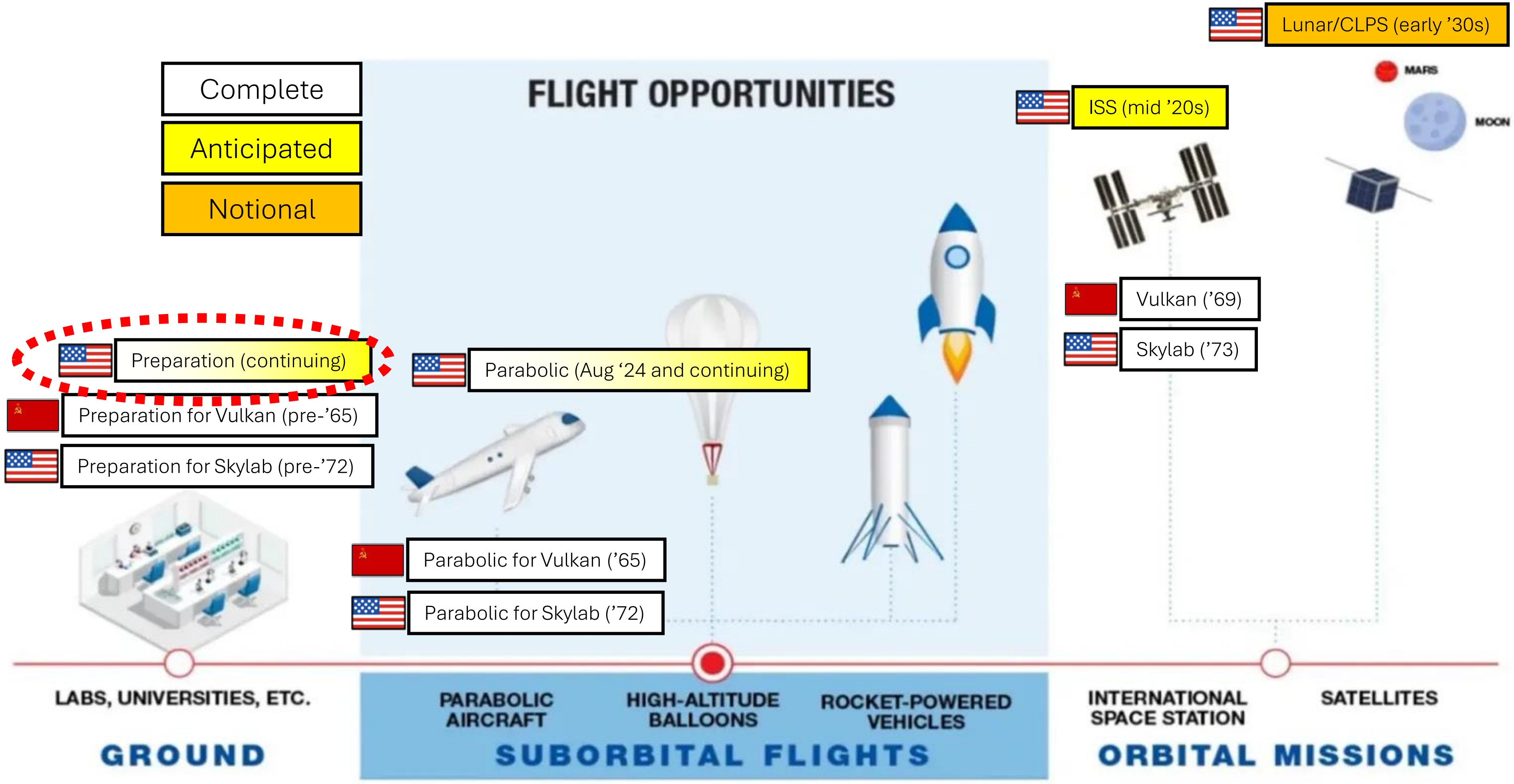
Progression of flight experiments



Concurrent development of Digital Twin using collected data



Progression of flight experiments



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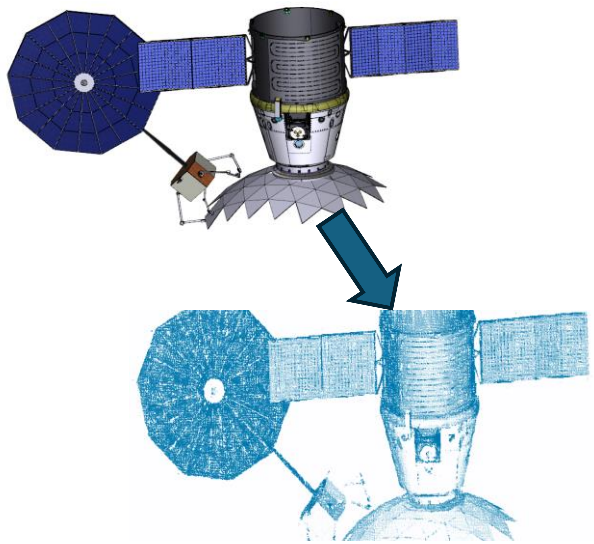
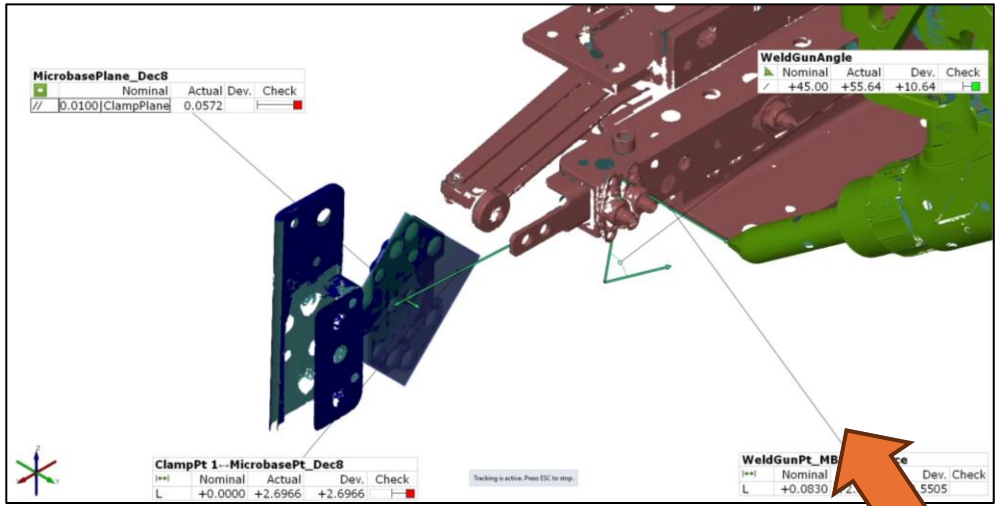


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

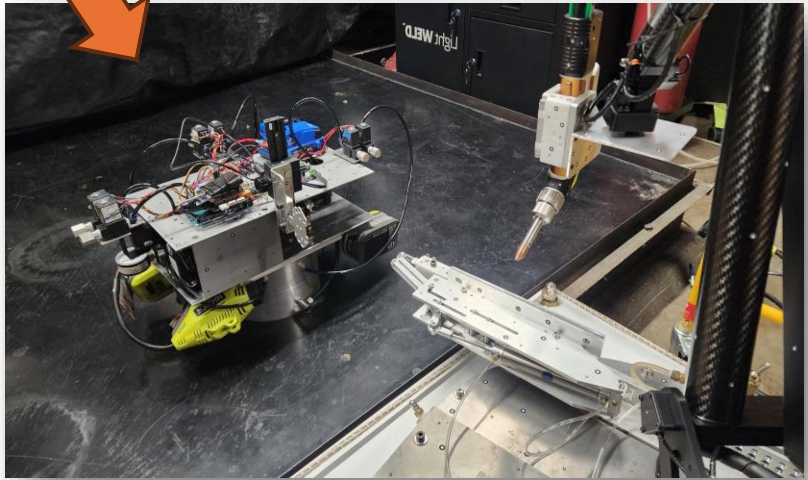
Ground testing LBW and allied processes

Laser enclosure readily reconfigurable for various setups, enabling rapid development



Structured light scan of joint fit-up on 3-degree-of-freedom (3DOF) Flat Floor

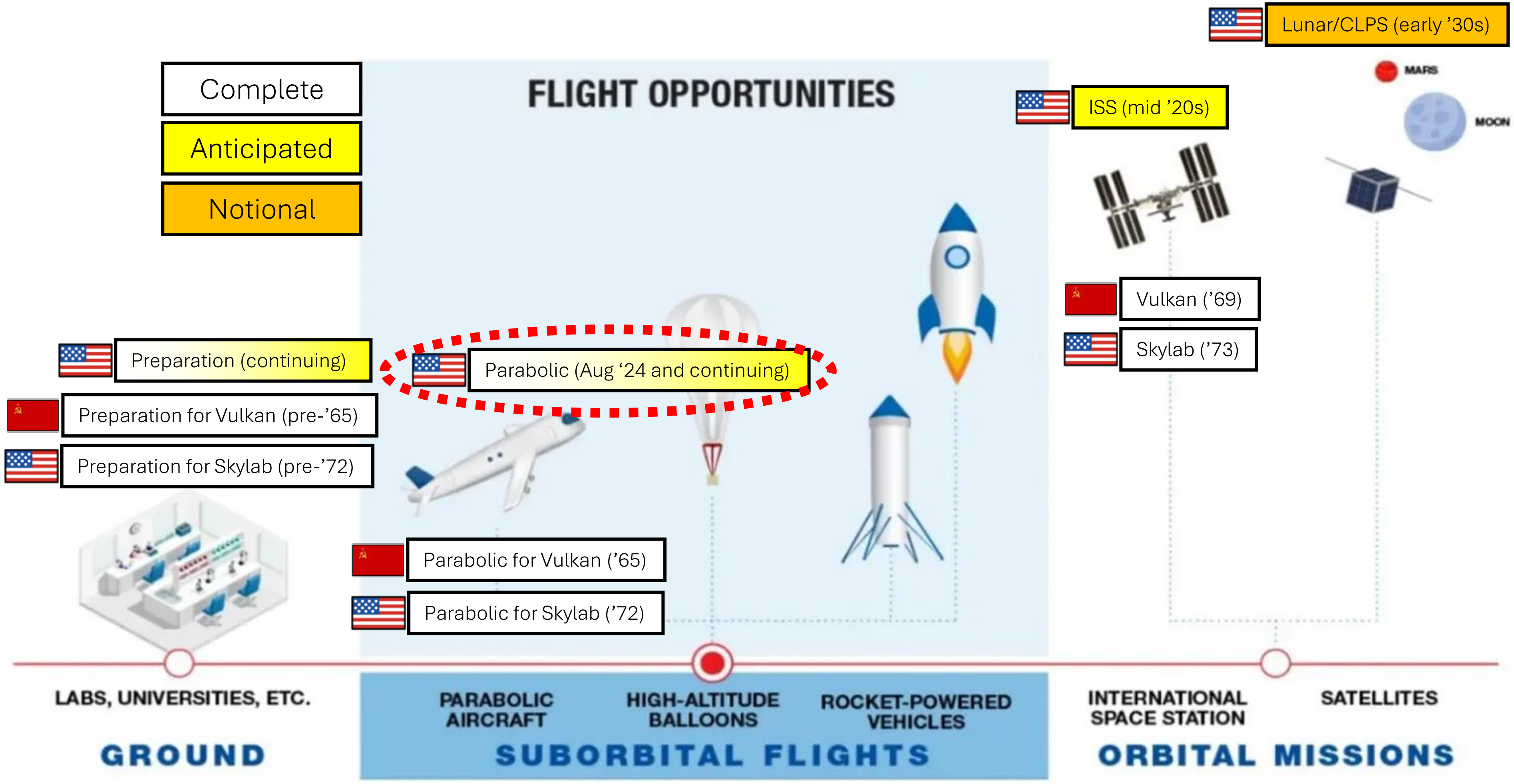
Simulating approach & capture and reactive forces during LBW using 3DOF



Planned:
Glovebox capable of variable composition atmosphere and with regolith simulant (Lunar, Martian, etc.) via handheld LBW

Ground testing gives confidence to proceed to flight.

Progression of flight experiments



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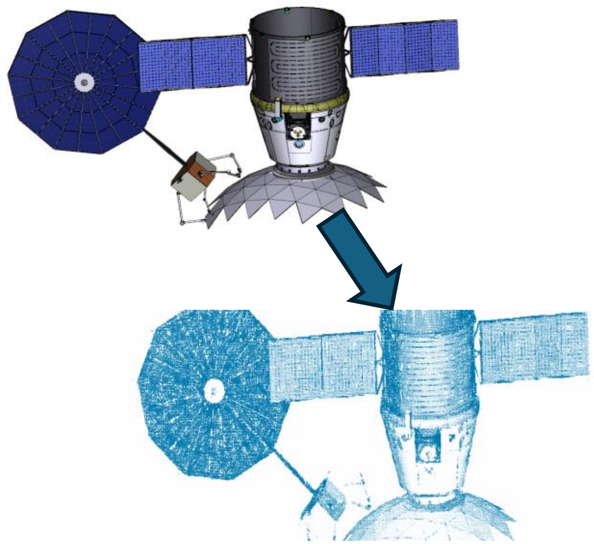


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Collaboration with the Ohio State University on parabolic flight

Integration and Ground Demonstration of Self-contained Laser Welding System for Parabolic Microgravity Experiments.

- OSU. Profs: Ramirez, Panton, Horack, Nassiri, Williams, Nate Ames, Bob Rhoads. Undergrad capstone team. Grad students: Eugene Choi, Aaron Brimmer, Will McAuley.
- NASA. Jeff Sowards, Karen Taminger (LaRC), Will Evans, Zach Courtright, Louise Littles, Andrew O'Connor, Emma Jaynes, Ben Rupp, Tom Bryan.

Modern fiber lasers enable high-power LBW

Courtesy: IPG Photonics

Retrofitted flight-proven vacuum chamber from NASA/LaRC for LBW

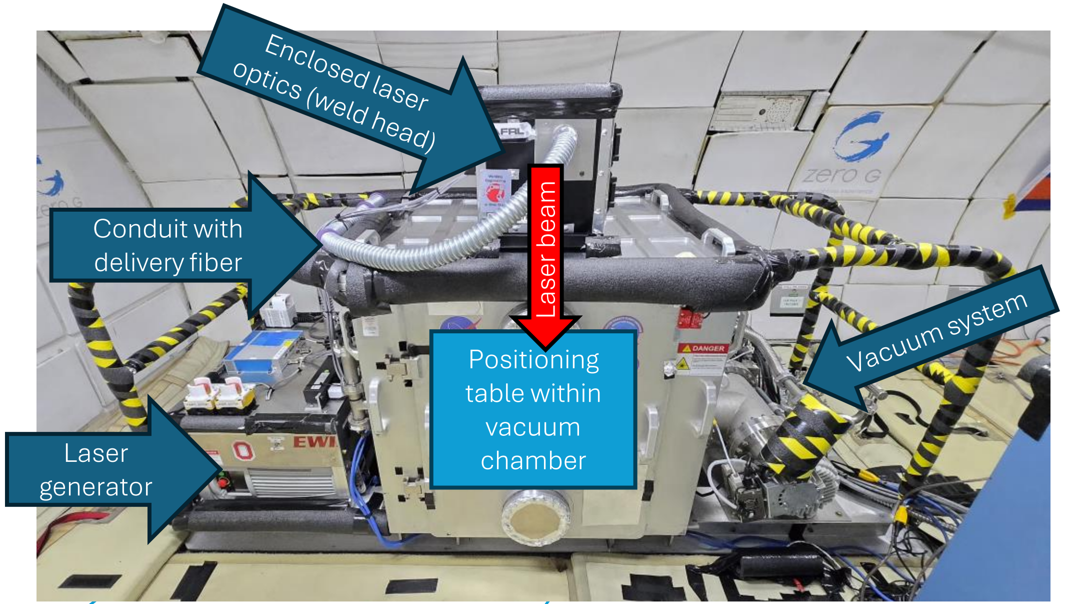
Leverage LBW expertise & workforce development at OSU

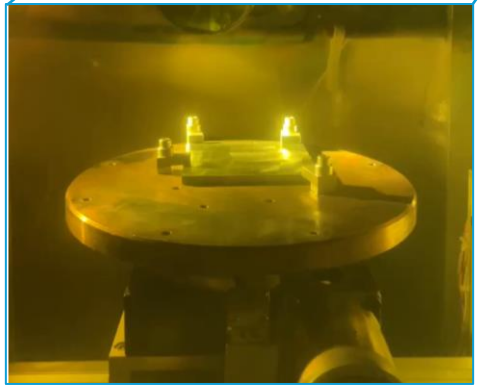
Vacuum LBW experiment during parabolic flight

Parabolic flight – spot welds and short line welds possible during parabola length (10-15 seconds of best available low gravity)

Adapted in part from: Choi, *Worldwide Advanced Manufacturing Symposium* (2024).

Extended flight campaign using proven hardware





in situ thermal data and videography

First flown in August 2024:

Successfully welded during 69 out of 70 total parabolas – including both Lunar (0.17 g) and low gravity (0.01 g) profiles

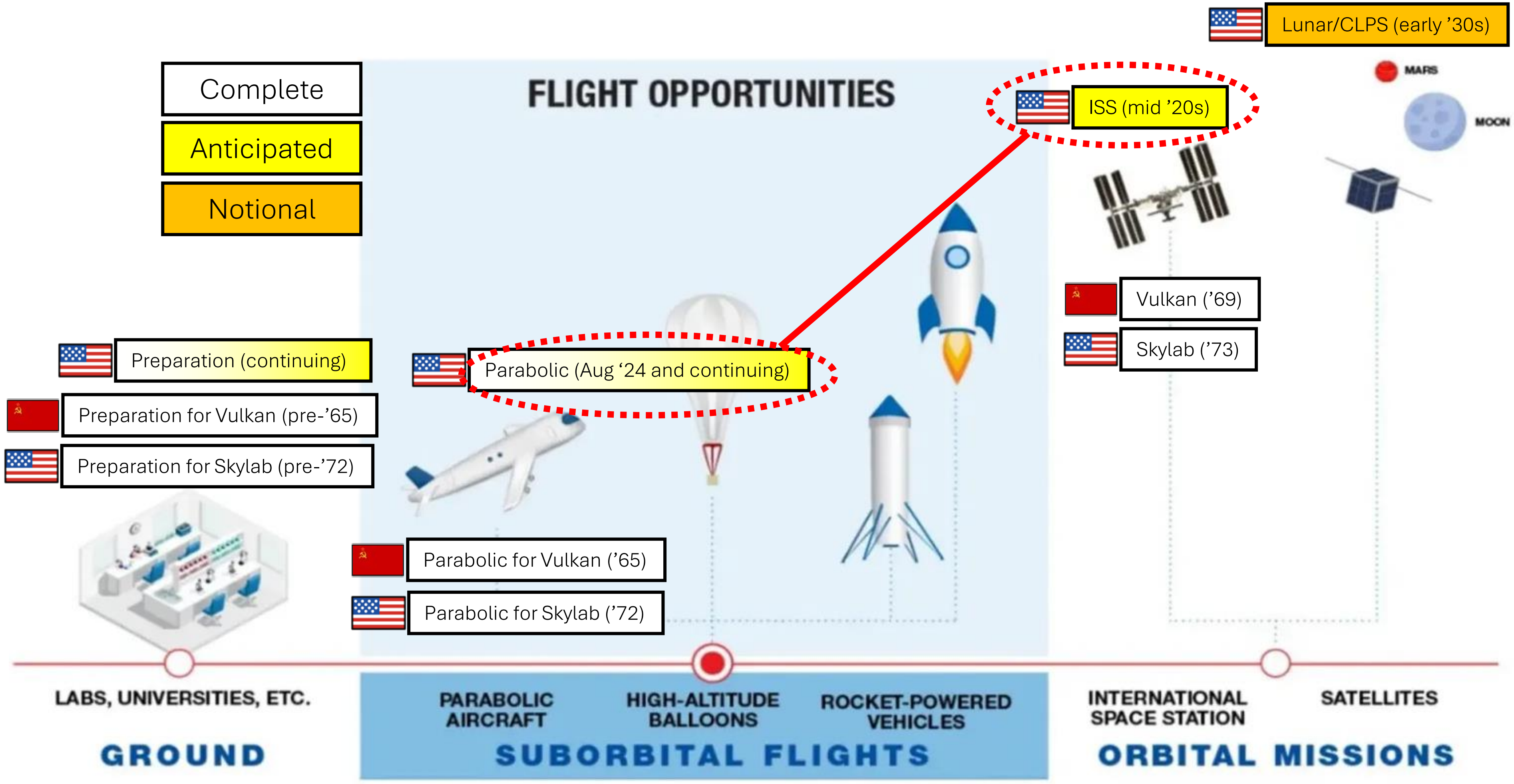
Flight in May 2025:

- **Hermetic welds** (pressure vessels, etc.) and **realistic joints** (lap, butt-lap, etc.)

Upcoming flights:

- Continuous melt pools established and maintained through **gravity transitions**
- **Reduced order alloys** (*e.g.* Al-Cu for AA2219) to ease computational modeling

Progression of flight experiments



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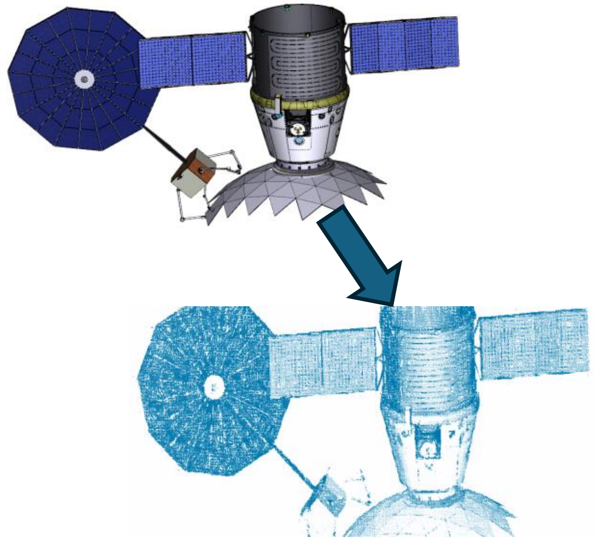

Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Simulating space conditions for welding

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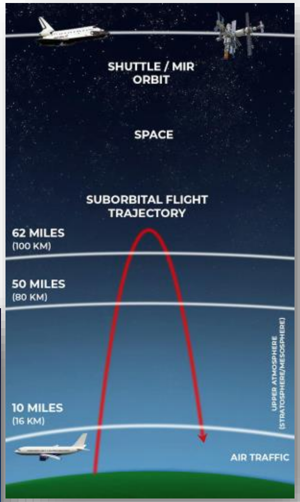
Experimental platform → ↓ Criteria	Drop tower	Parabolic flight	Suborbital flight
Length of microgravity [s]	<5	20-25	>180
Gravity (quality) [g]	10^{-5}	10^{-3}-10^{-2} (up to 2.0)	10^{-4}
Mass allowed [kg]	10^2	10^2	10^1
Cost [$]	$	$$	$$$

Microgravity / Reduced Gravity

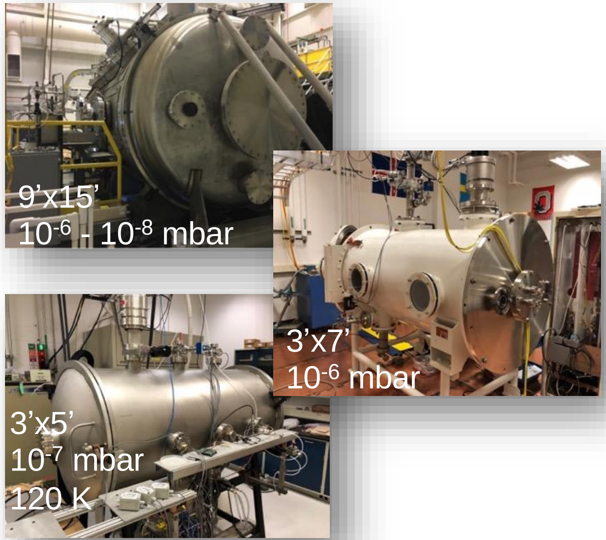
Drop tower

Parabolic flight

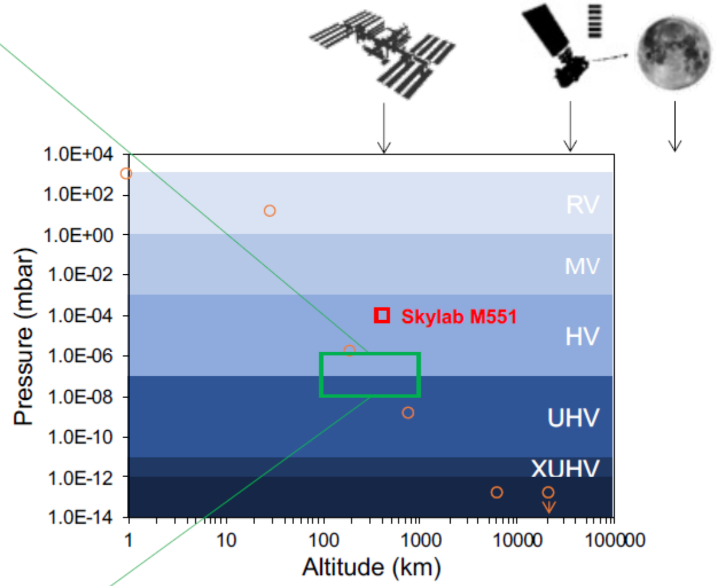


Suborbital flight

Vacuum and Reduced Temperature



MSFC has multiple facilities to simulate vacuum and reduced pressure, including variable atmospheric composition



Numerous experiments with welding systems in vacuum chambers on parabolic flights

Mladenov, Koleva, and Trushnikov, *E+E*, 2019.

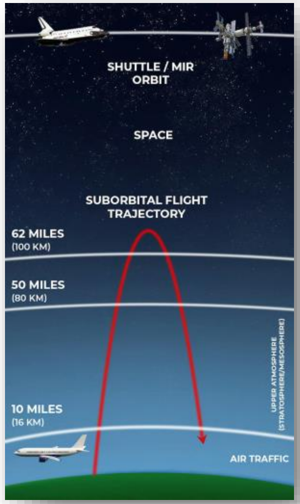
Low Earth Orbit (LEO)
μg

Lunar surface
0.17 *g*

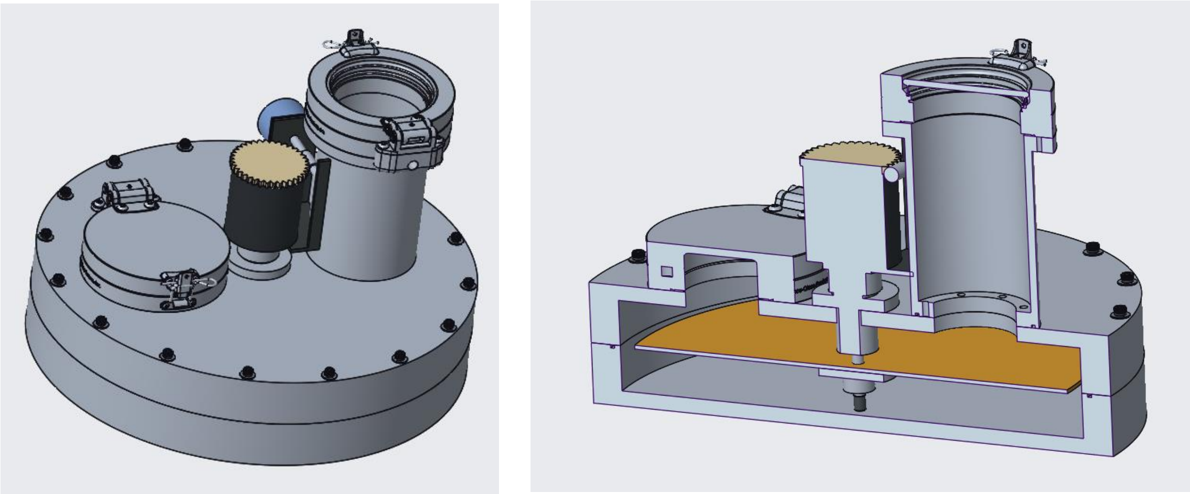
Martian surface
0.38 *g*

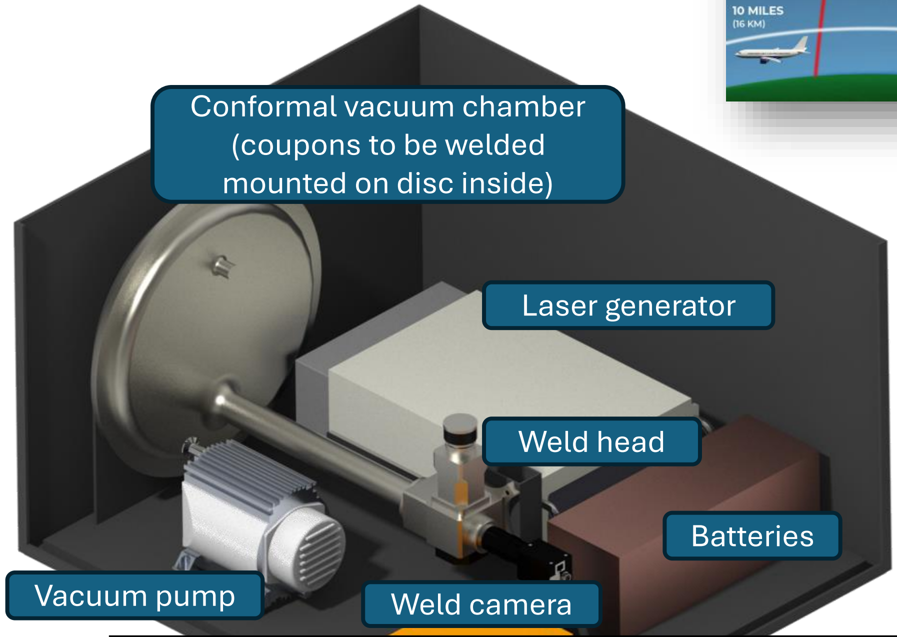
Evolve from parabolic to suborbital flight experiments

Parabolic	Suborbital
Tens of seconds in reduced or μg	Minutes in reduced or μg
Two-*g* during pull out (weld solidified?)	Hi-*g* only before welding (launch)
g-jitter complicates effect of gravity	Reduced *g*-jitter



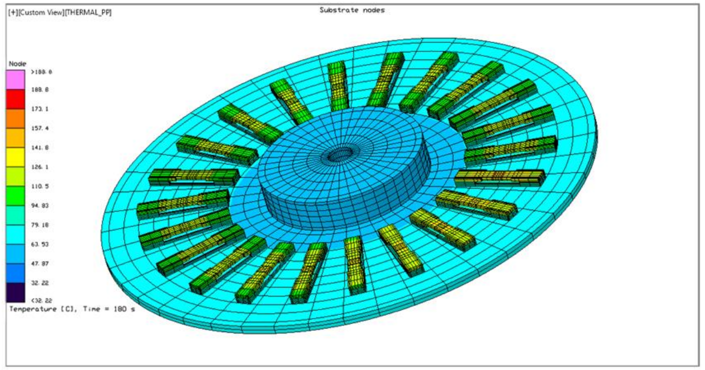
Initial protoflight hardware design





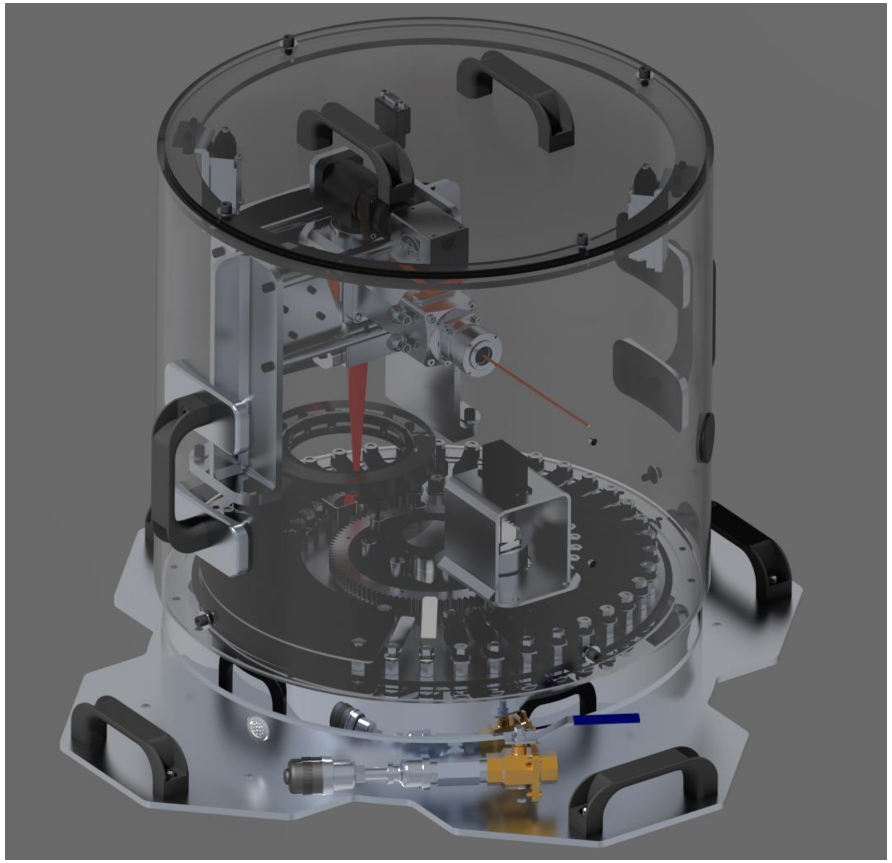
Conceptual design developed with MSFC Advanced Concepts Office

Thermal and structural modeling

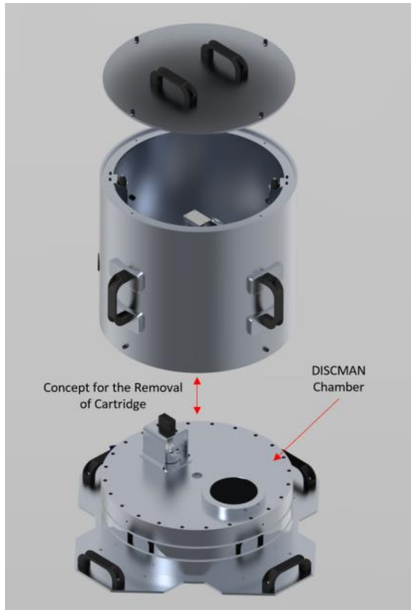


Serendipitous opportunity to re-target for Bishop Airlock on ISS: <u>long microgravity duration</u> with ability to pause, reflect, and <u>change welding parameters & schedule mid-flight</u>!

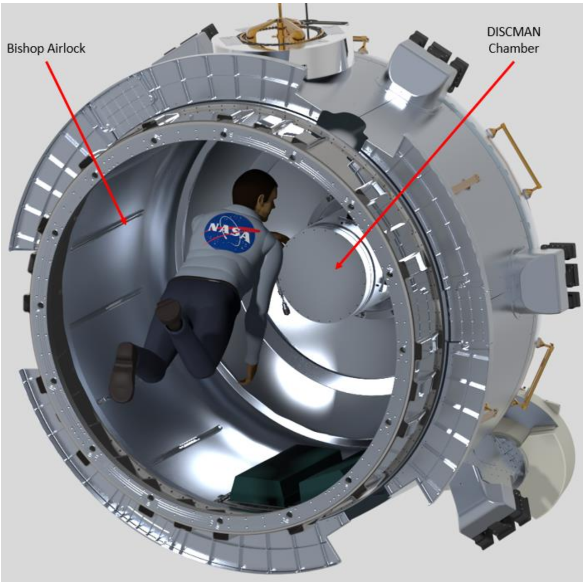
DISCMAN – LBW parameter development on ISS



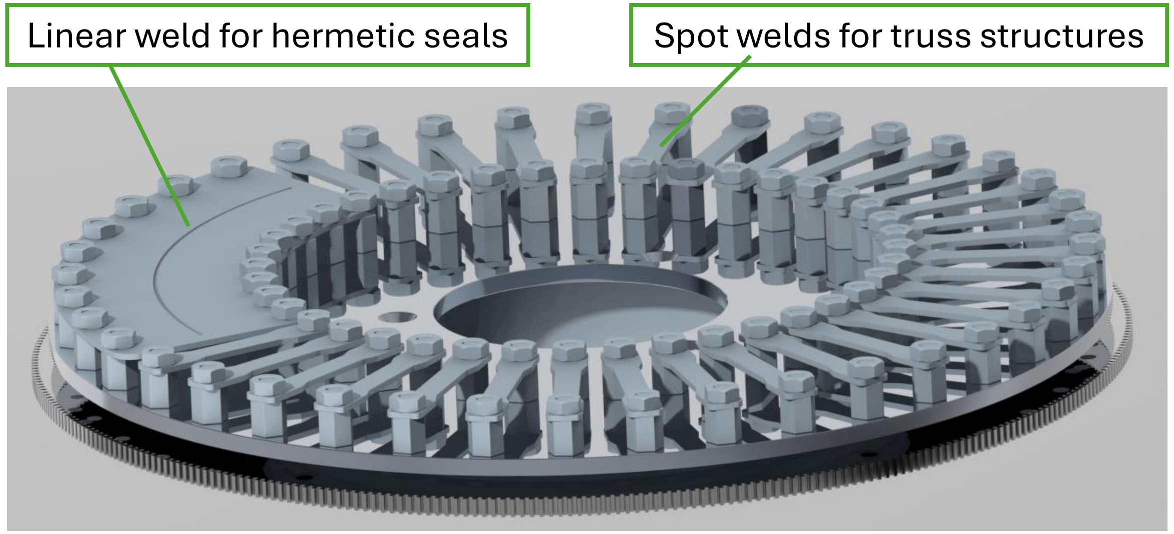
Translucent render of chamber and enclosure



Vacuum chamber as swappable cartridge with pre-mounted workpieces that can be exchanged on orbit by crew



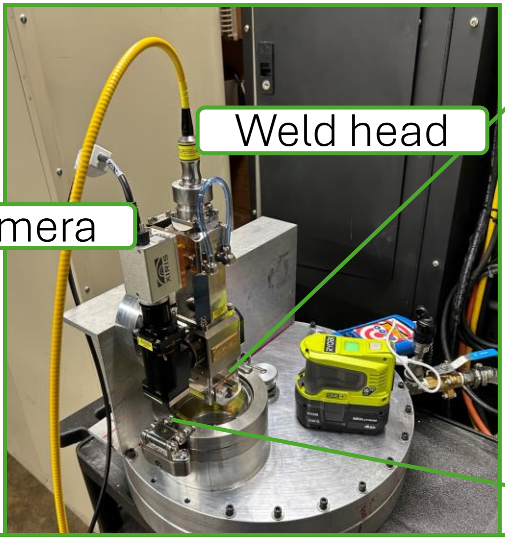
Notional depiction of DISCMAN on ISS



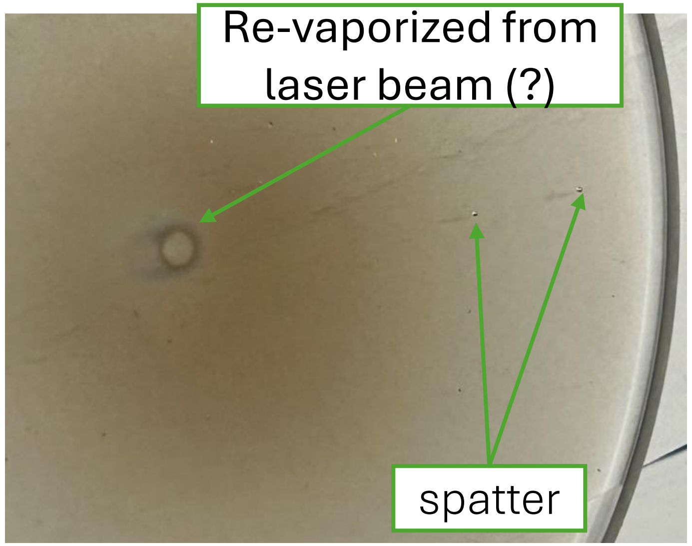
Notional DISCMAN workpiece geometries:

- Spot/short lines similar to butt-lap
- Long, linear welds similar to tubes
- Other innovative workpieces (cutting, forming)

Latest prototype status – initial operating capability



First pre-programmed spot & line welds of DISCMAN under vacuum



Concern: metal vapor coating lens, also spatter

Current mitigation: sacrificial cover glass over each specimen

Protoflight unit in fabrication with instrumentation

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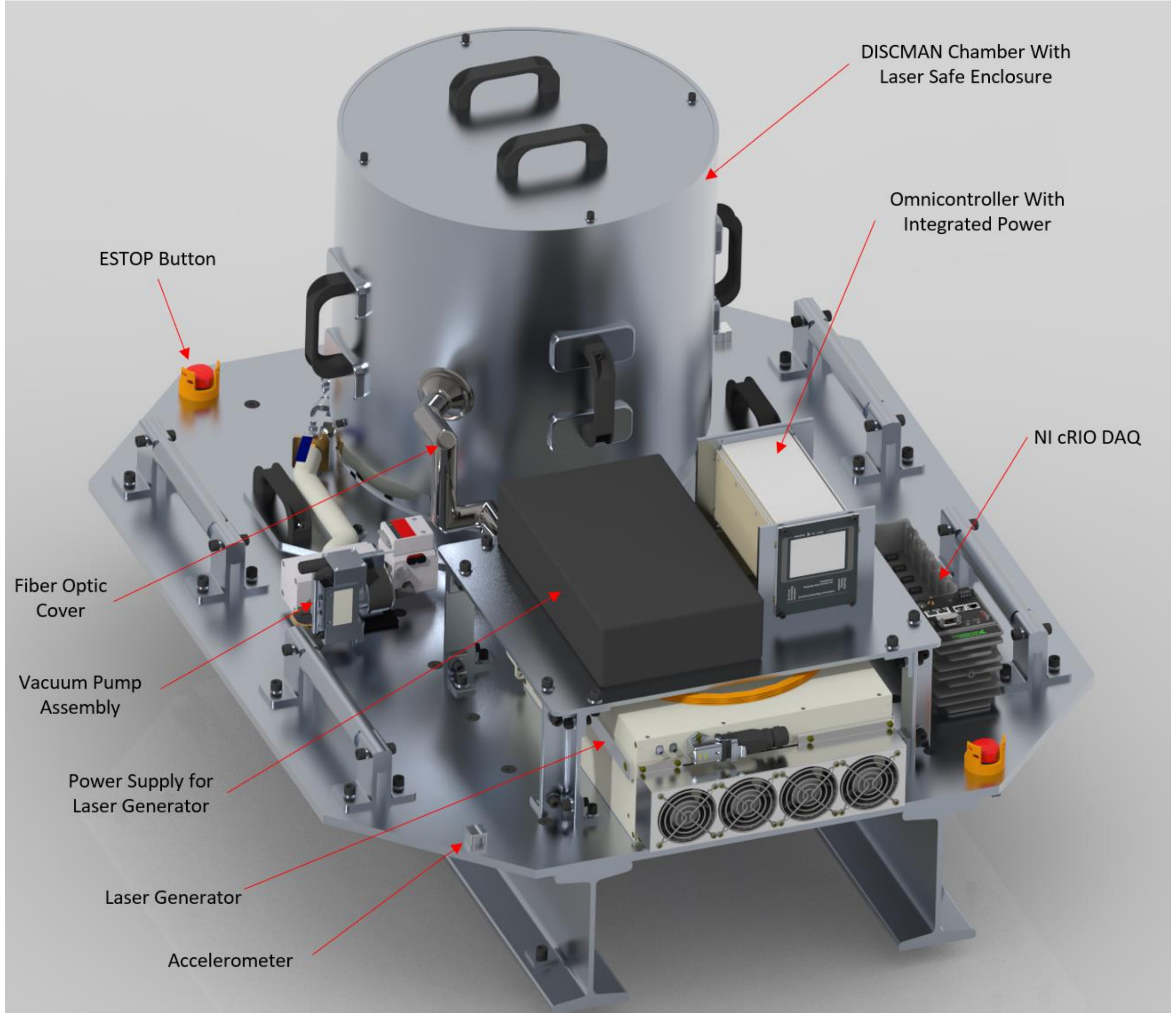


Render of DISCMAN protoflight unit for parabolic flight

Courtesy: IPG Photonics

Nominal 1500 W max. (pulsed), 250 W (continuous) fiber laser

High dynamic range (140+ dB) welding camera to monitor melt pool and spatter

Courtesy: Xiris Automation

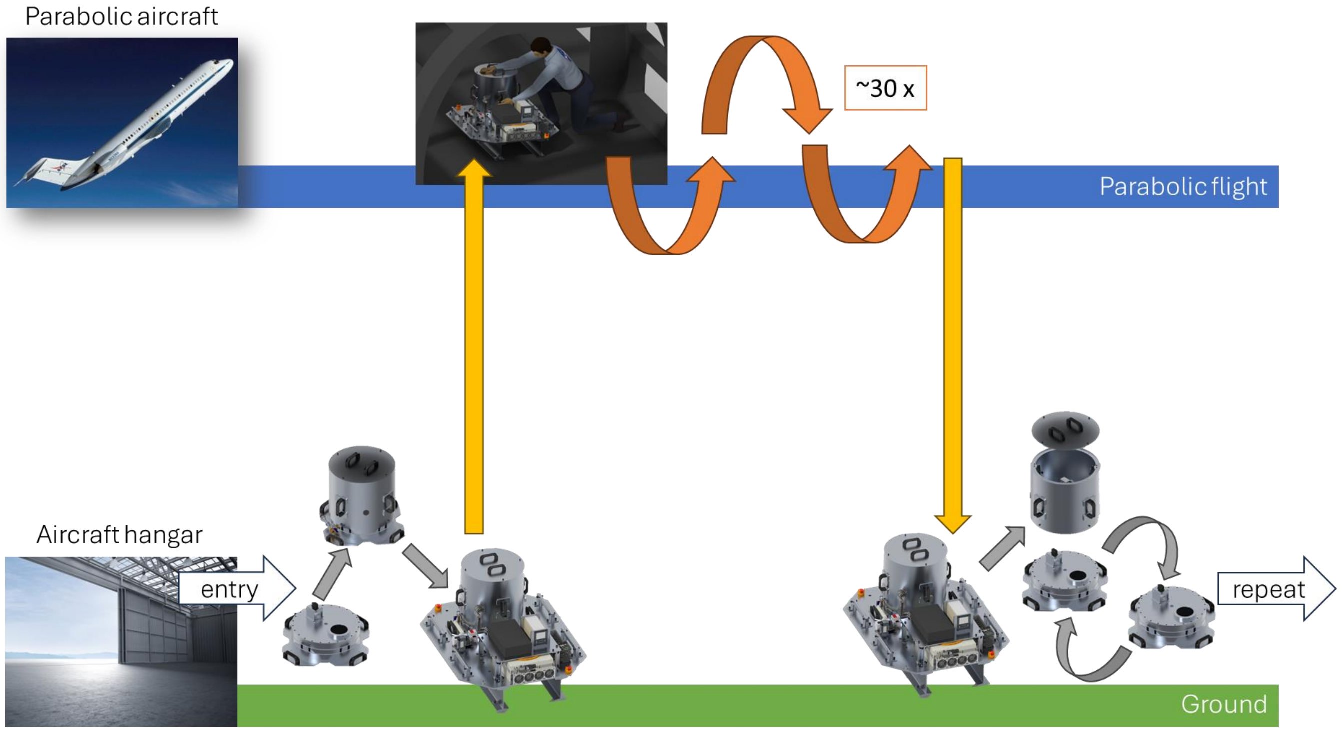
Short-wave infrared (SWIR) thermal camera to monitor thermal history, augmented by thermocouples on workpieces

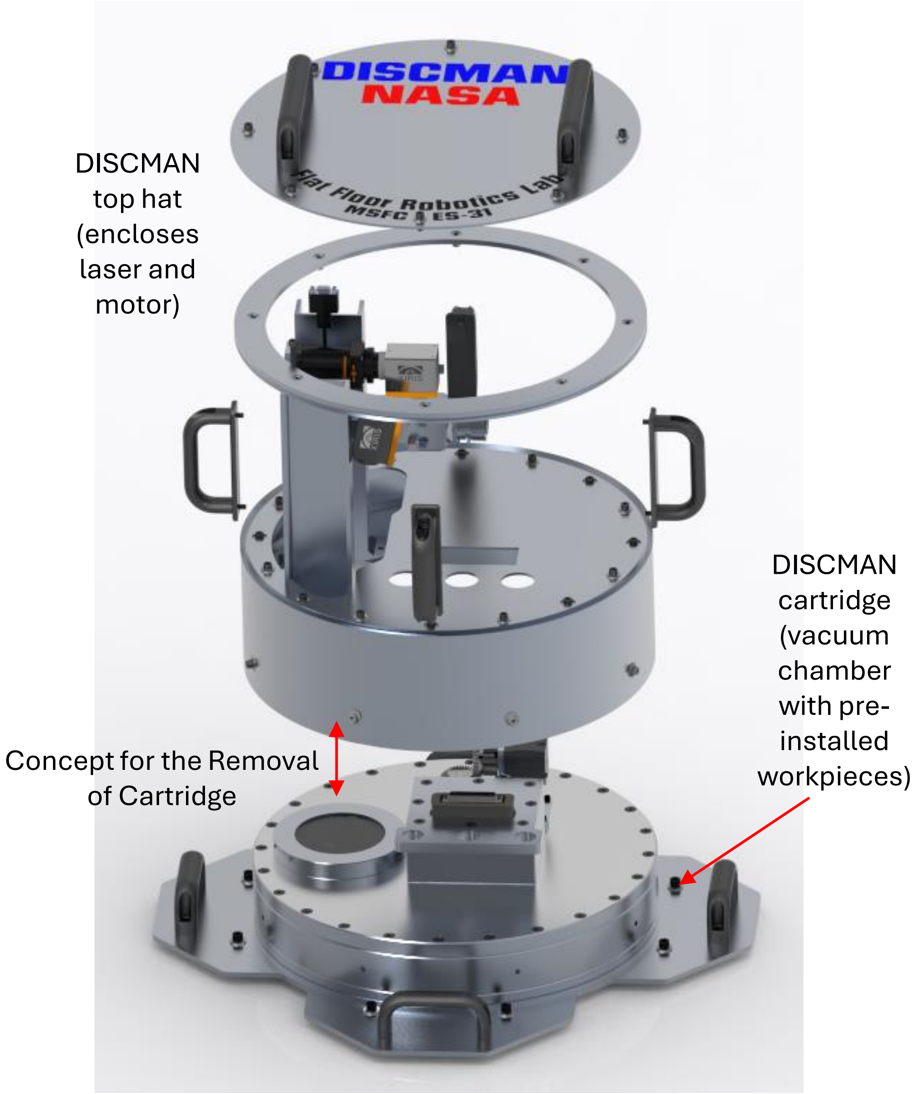
Licensed under CC BY-SA 3.0 from Liquidat

Compact turbomolecular pump to achieve high vacuum (<10^{-5} Torr, 10^{-3} Pa)

Highly instrumented to collect data to anchor computational models

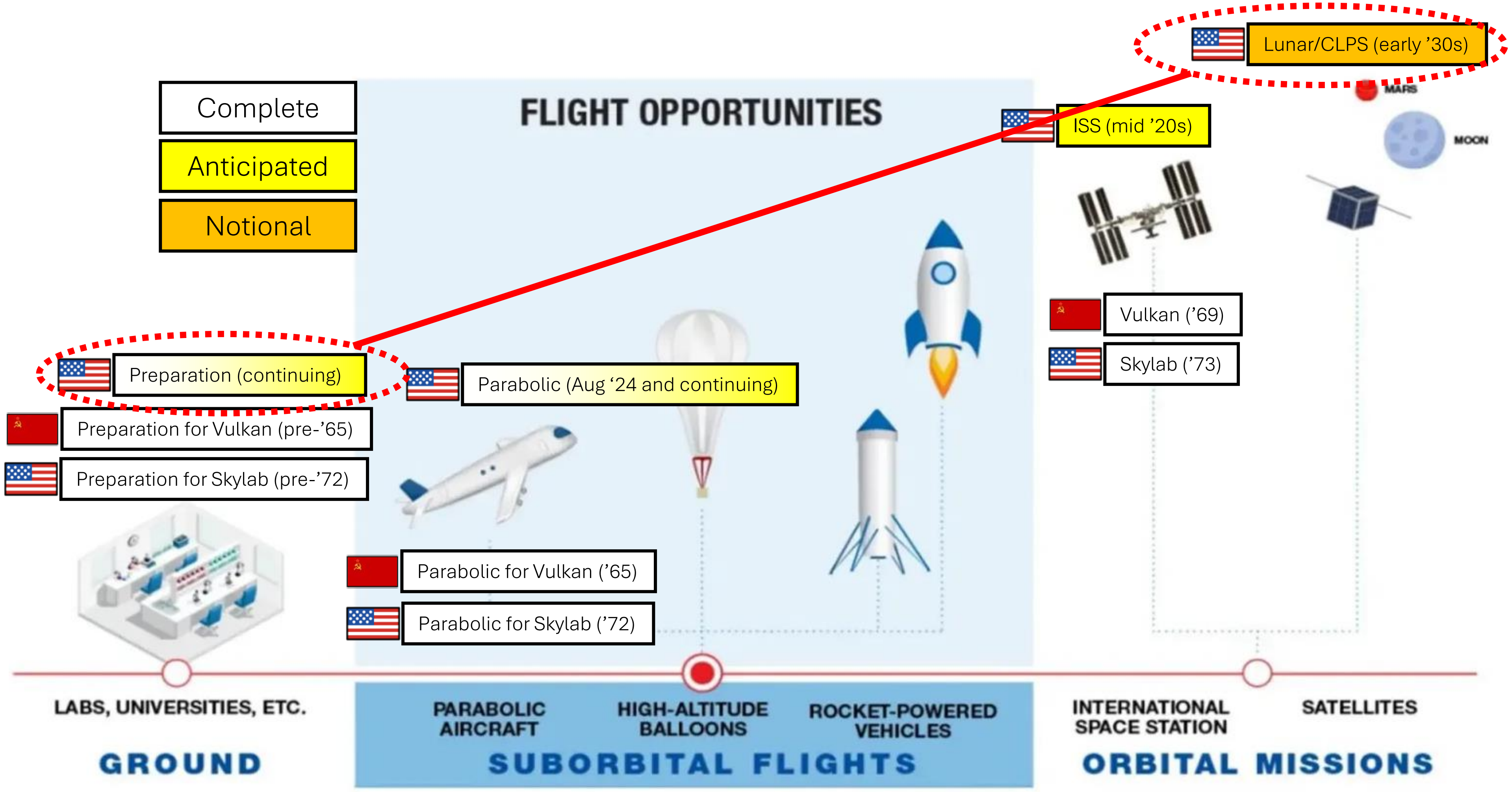
DISCMAN Phase I: de-risking parabolic flight, initial ISS design, and preliminary submission to ISS payload safety panel





- Parabolic flight de-risks gravity-sensitive equipment (*e.g.* rotating platen, vacuum pumps) and elucidates intriguing parameter spaces, perhaps crew operations
- Design evolving to meet more stringent safety and persistence requirement of ISS and Bishop Airlock

Progression of flight experiments



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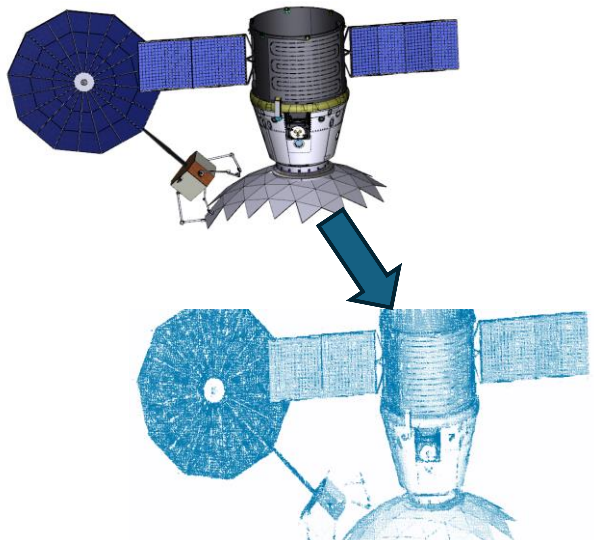
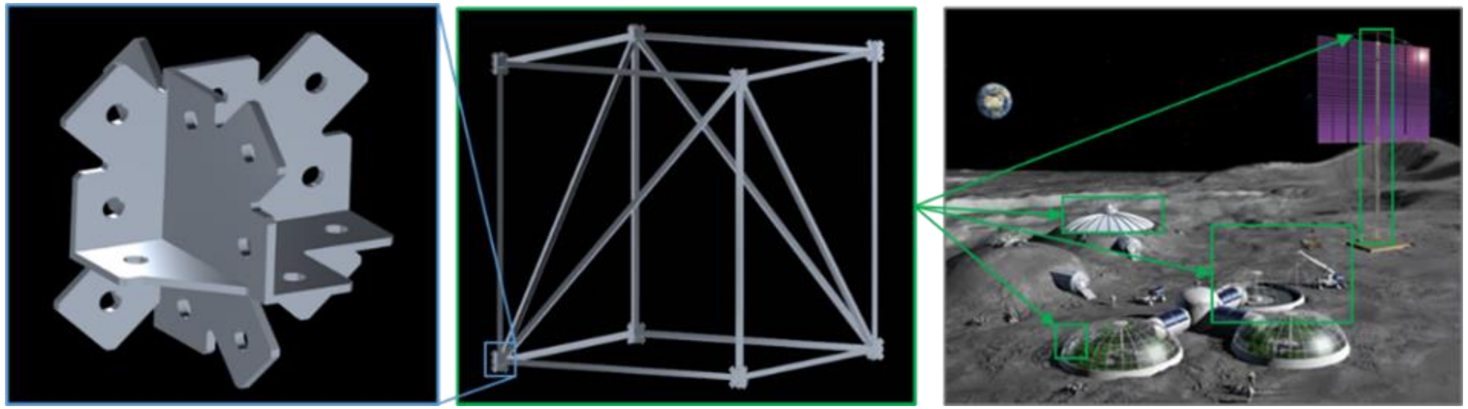


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

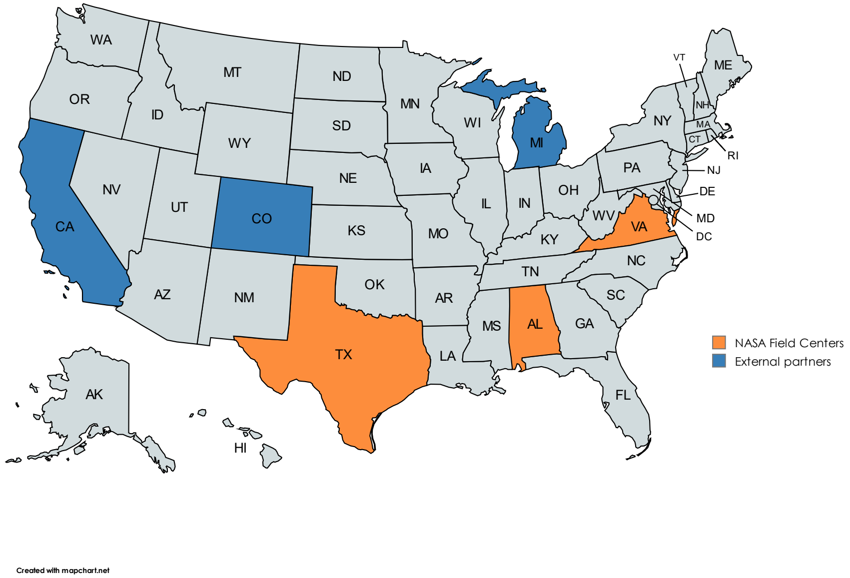
Lunar Assembly and Servicing by Autonomous Robotics (LASAR)

NASA-funded Early Career Initiative project:
Mature LBW and associated robotics & NDE (nondestructive evaluation) for Lunar infrastructure applications



Visualization of “snowflake” joint geometry used for Tall Lunar Tower

- Ruggedized laser optics and robotic arm suitable for thermal vacuum (TVAC)
- Supervised autonomous LBW of “snowflake” joint geometry
- Non-contact NDE of welds
- Repair of welds in TVAC



PI: Andrew O’Connor; PM: Jenny Jones (both NASA/MSFC)

NASA Core Team Members

Name	Center
Emma Jaynes	NASA/MSFC
Alex Sowell	NASA/JSC
Raju Subedi	NASA/MSFC
Brace White	NASA/LaRC
Supported by:	
Derrick Seubert	NASA/LaRC
Matthew Mahlin	NASA/LaRC
Parker Shake	NASA/MSFC

External Partners

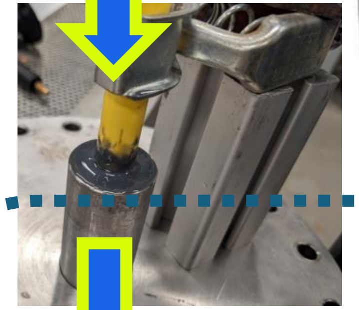
Name	Role
Laserline	Laser Processing Partner
Motiv Space Systems	Robotics Hardware Partner
PickNik Robotics	Robotics Software & Autonomy Partner

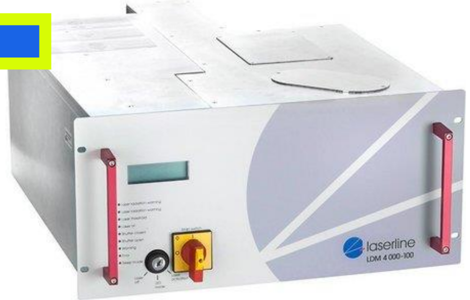
Mentors

Name	Role
Bill Doggett, PhD	LaRC In-Space Assembly SME
Jeffrey Sowards, PhD	MSFC Laser Welding SME

LASAR: TVAC demonstration upcoming

Pulling FY26 TVAC testing into FY25: minimum viable demonstration of high vacuum but ambient temperature LBW

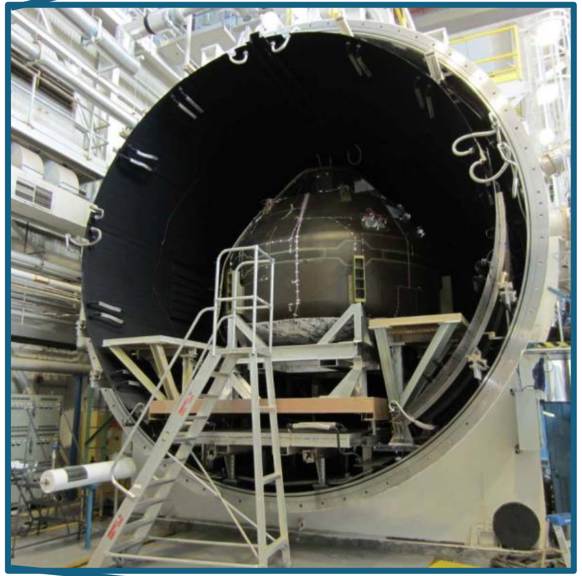




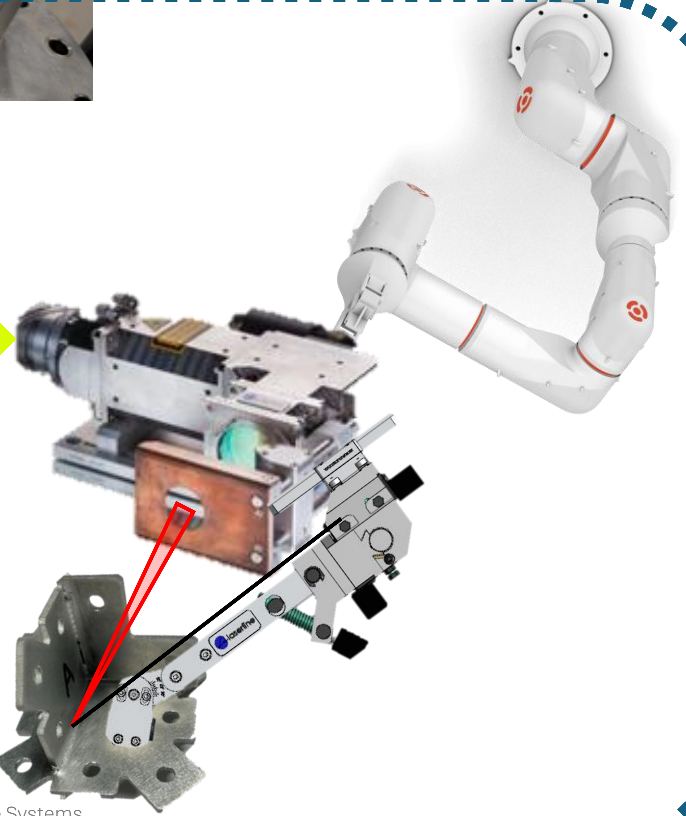
Laser generator, diode (outside TVAC)

Laser optics and delivery fiber to be placed within thermal vacuum representing Lunar surface

Components within dashed lines are within V-20 TVAC at MSFC(shown to right during unrelated test)



Laser focusing optics (weld head) & wire feeder mounted on robotic arm end effector

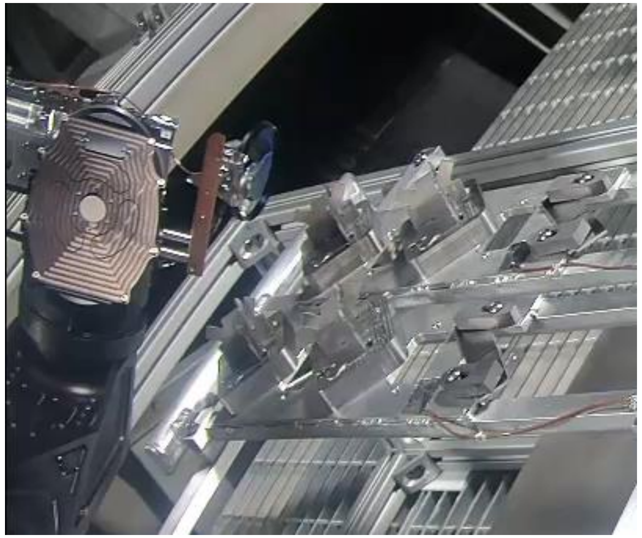


Credit: Laserline, Motiv Space Systems

Robotic LBW with (almost) all components under vacuum!

Bead-on-plate weld

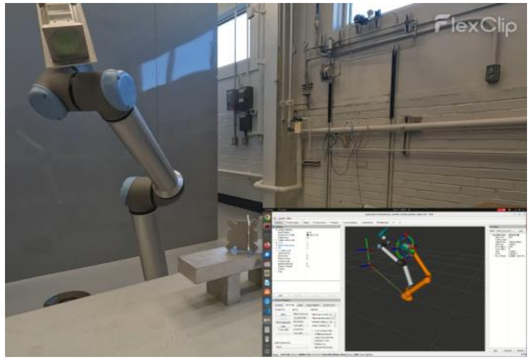
Snowflake joint weld



Successfully welded 2 of 3 seams of a snowflake joint under vacuum; mistargeted third seam (investigating)

LASAR: sub-team structure accelerates development

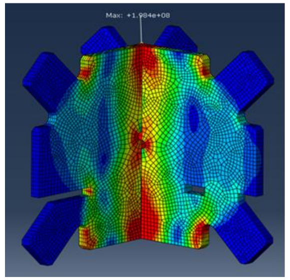
Robotics sub-team



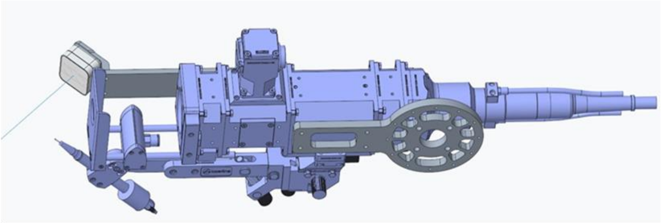
Mockup laser optics on robotic arm with concurrent Digital Twin

Flight-forward computer operating manipulator

Model of snowflake joint subjected to thermal fatigue



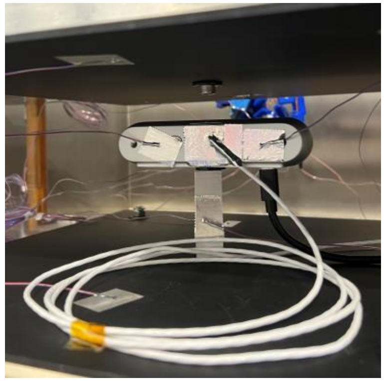
End effector with laser optics, video camera, and wire feeder



Structures sub-team

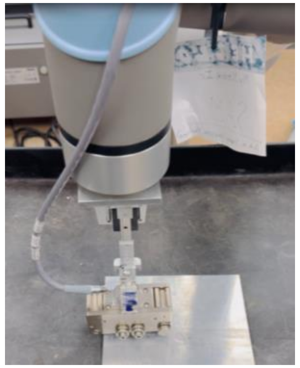
Adapted snowflake joint for LBW

Laser processing sub-team



Testing stereo video cameras in TVAC

Non-contact NDE robotic weld inspection



- Tasks on 2-week sprints tracked by Planner
- Integrating OneNote into workflow
- **Sub-teams** to align work with expertise at each NASA Field Center

NASA leads the way to in-space welding

ISAM
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

- NASA is rapidly advancing the state-of-the-art of in-space welding (ISW) through numerous efforts, of which this presentation focused on internal efforts in –
  - Laser beam welding (LBW): parabolic to orbital flight experiments
  - Robotic LBW: Thermal vacuum (TVAC) demonstrations
- Demonstration of ISW in space-like environments will enable:
  - Understand combined effects of reduced gravity, reduced pressure, varied temperatures
  - Provide validation datasets to anchor computational models
  - Mature ISW technology to enable joining structures in space
- Building ISW ecosystem of hardware, expertise, and partnering opps.
  - Modular flight unit hardware
  - Parabolic and orbital flight experiment know-how
  - Computational models anchored by collected data
  - Network of academic, government, and industrial collaborators

Acknowledgements

- NASA support from Marshall Space Flight Center Center-directed funds, Biological and Physical Sciences Division of NASA Science Mission Directorate, NASA Space Technology Mission Directorate, etc.
  - STMD: LASAR ECI, DISCMAN (GCD/Enable), ESI, etc.
- OSU support from Marshall Space Flight Center Center-directed funds via

  80NSSC22M0209 - Integration and Demonstration of Self-contained Laser Welding System for Microgravity Experiments –NASA CAN
- Second parabolic flight day Aug’ 24 and upcoming MSFC-OSU re-flight support from NASA Flight Opportunities