# Investigating Laser Beam Welding as an In-Space Joining Technique via Thermal Vacuum and Microgravity & Vacuum Experiments

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**[1]NASA/MSFC; NASA/JSC[2]; NASA/LaRC[3]**

Presented to WAMS26 on 2026-06-09

# A team effort!

Interns from collaborating universities

Rich network of academic, government, and industrial partners

Multiple NASA Field Centers

In-flight photos credit: Tasha Dixon/Zero-G

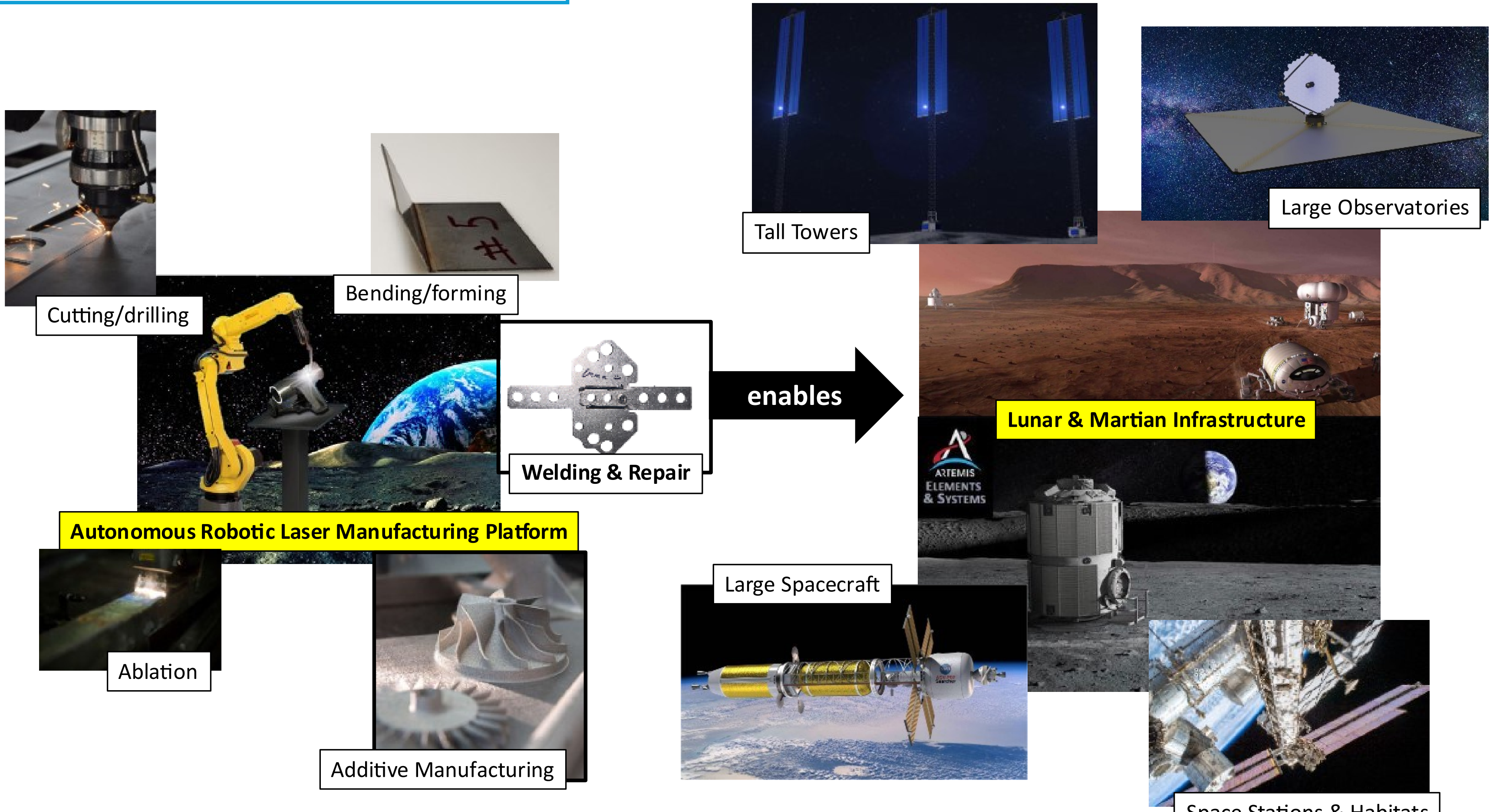
# History of in-space welding

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 |

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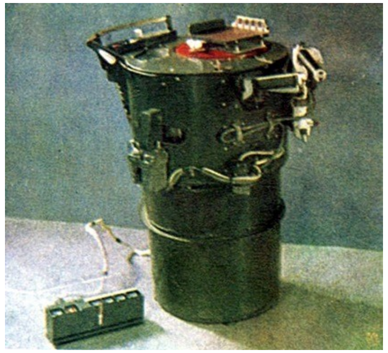
# Timeline of In-Space Welding and Joining

ISAM
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING



*Progress in Space Stagnated and Moved to Parabolic Flights*

Credit: Tasha Dixon/Zero-G

**FIRST SPACE WELD**
1969. "Vulkan" on Soyuz 6. 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. EBW (USSR)
**FIRST MANUAL OPEN SPACE WELD**

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

1993. Parabolic $CO_2$ LBW (CAN)

1999. ISWE on Shuttle (USA/UKR/RUS) **CANCELLED**
Components went to Mir as FLAGMAN

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

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

Parabolic (USSR). 1965-

Parabolic EBW for Skylab (USA). 1972

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

Parabolic EBW (UKR/RUS). 1993
Parabolic EBW (USA/UKR/RUS). 1994

Drop Tower GTAW 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.
EBW = Electron beam welding,
LBW = Laser beam welding,
UHT = Universal Hand Tool,
ISWE = In-Space Welding Exp.;
not all experiments included

2018. New Ukrainian EBW tool 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

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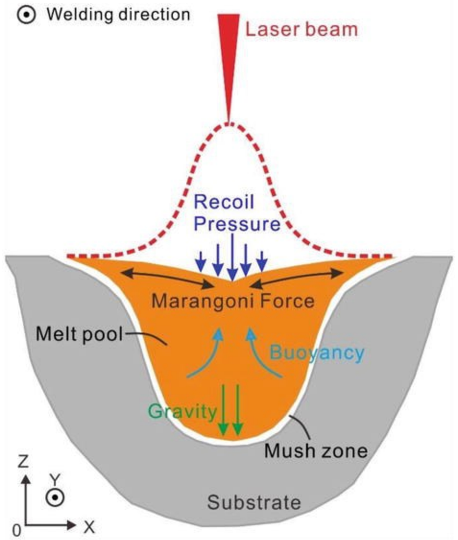
# In-space effects that influence welding

| 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

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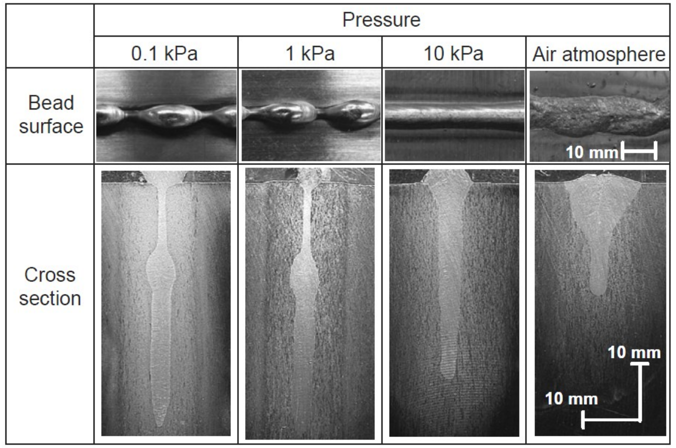
Reduced gravity is unique among the above effects in that it cannot be reproduced for prolonged periods on earth.

**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.

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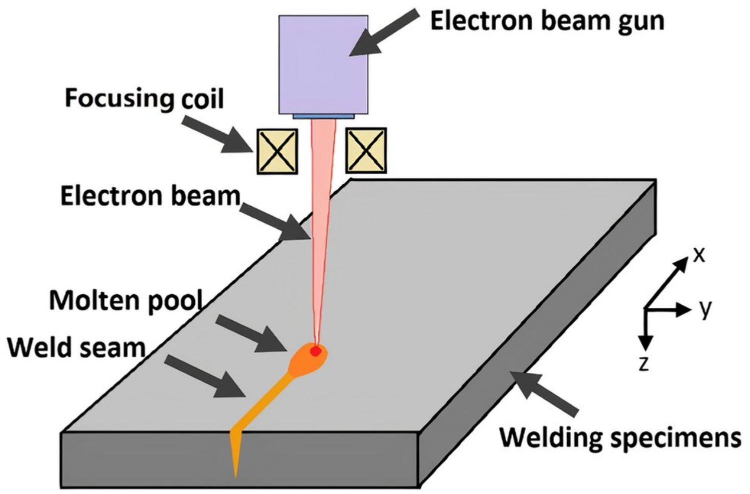
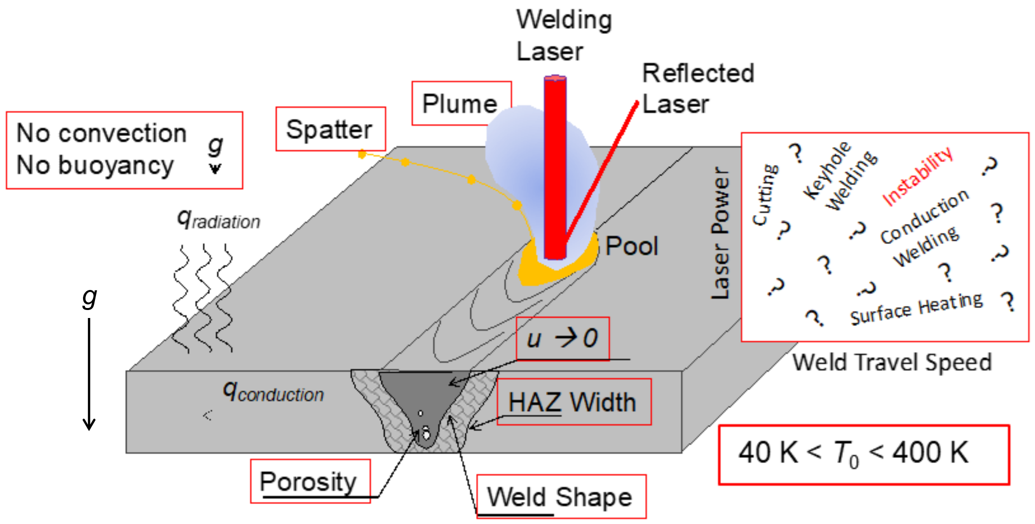
# Why laser beams in space?




Licensed under CC BY 4.0 from Yin et al., 2023, doi: 10.1007/s00170-022-10682-6.



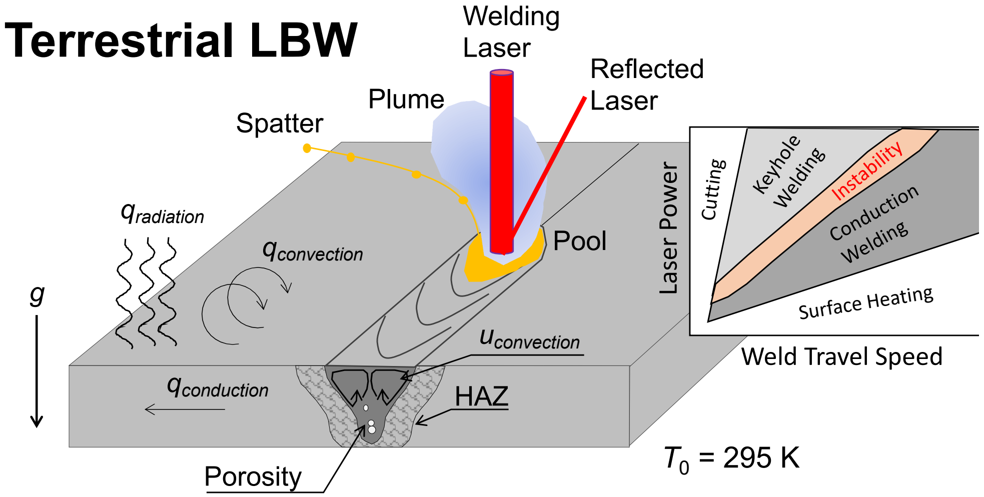

| High-energy Beam Process → ↓ Criteria | Electron | Laser | Status |
|---|---|---|---|
| IVA flexibility (e.g. in habitat) & EVA flexibility (e.g. in vacuum, Lunar surface, on Mars) | ● | ○ | Capability available after planned development |
| Workpiece variety (*e.g.* geometry, material) | ◒ | ○ | |
| 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.

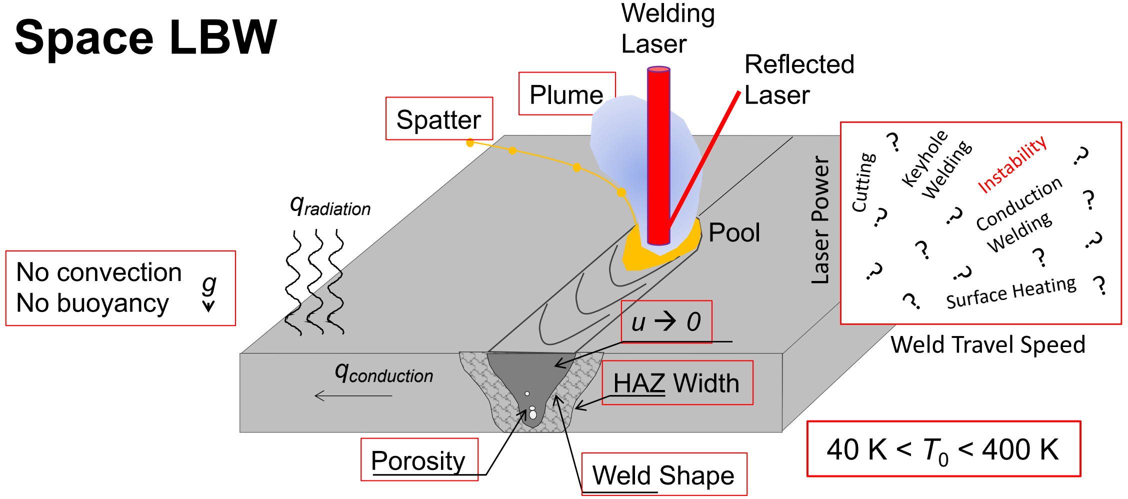
# Key effects to consider for in-space LBW

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.

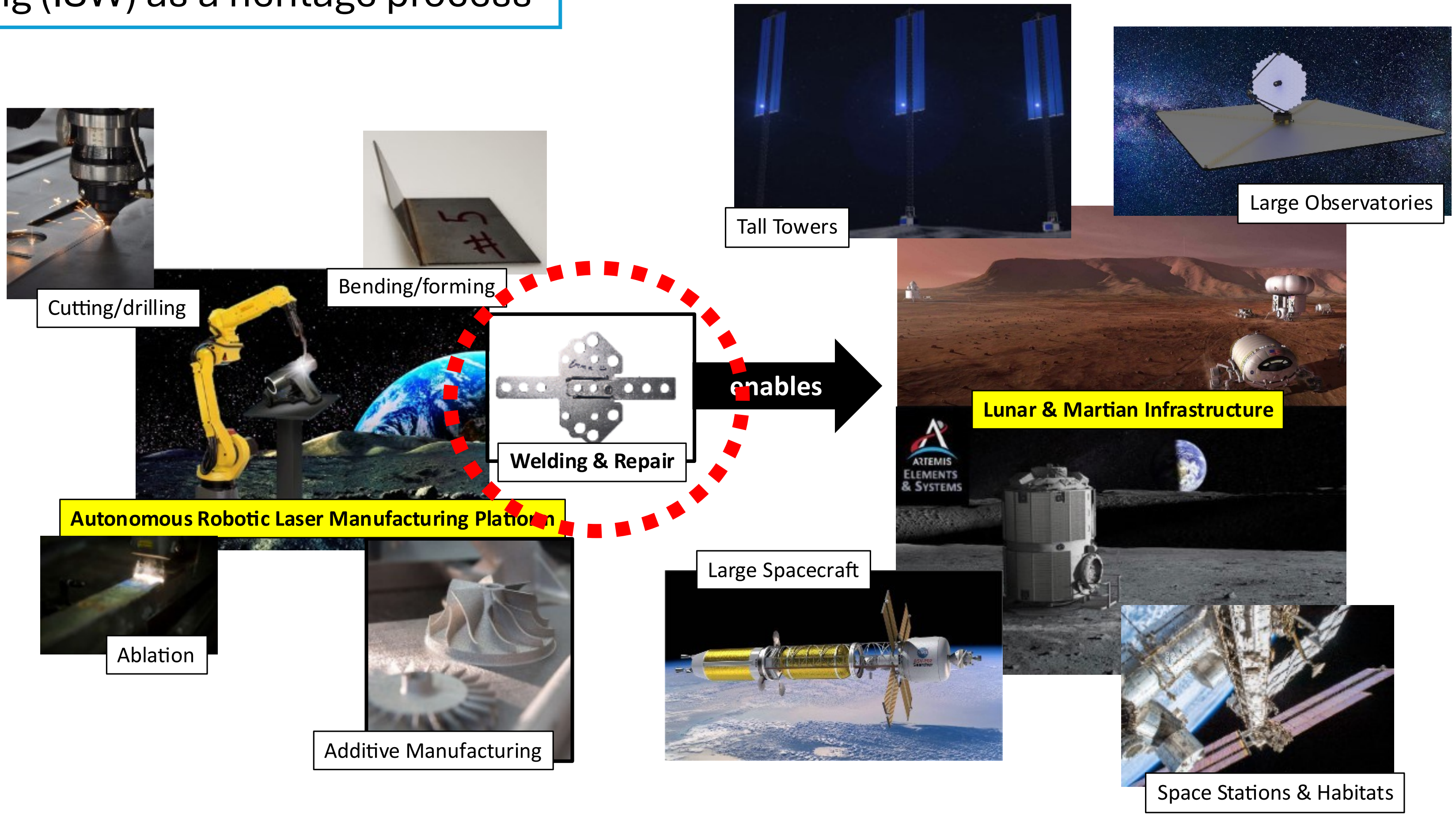
From: Sowards, *American Welding Society Professional Program*, 2023.

# Some current efforts at NASA

Thermal vacuum and combined vacuum & microgravity experiments to provide validation data for computational modeling

# In-space laser manufacturing enables space infrastructure

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

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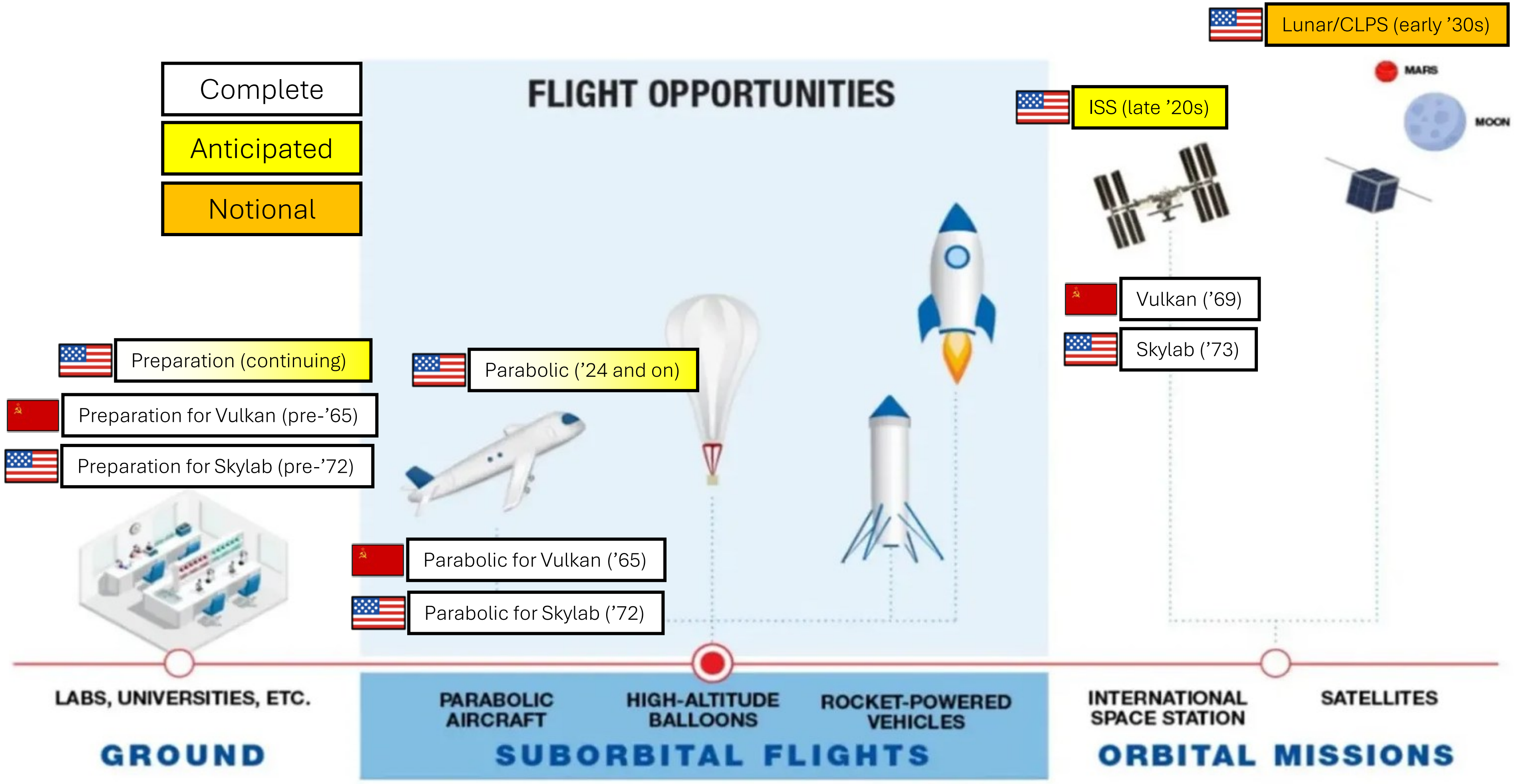
# Progression of flight experiments

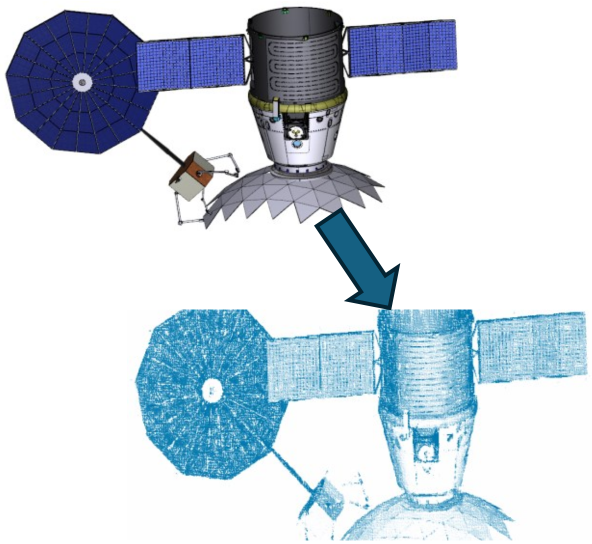
Complete

Anticipated

Notional

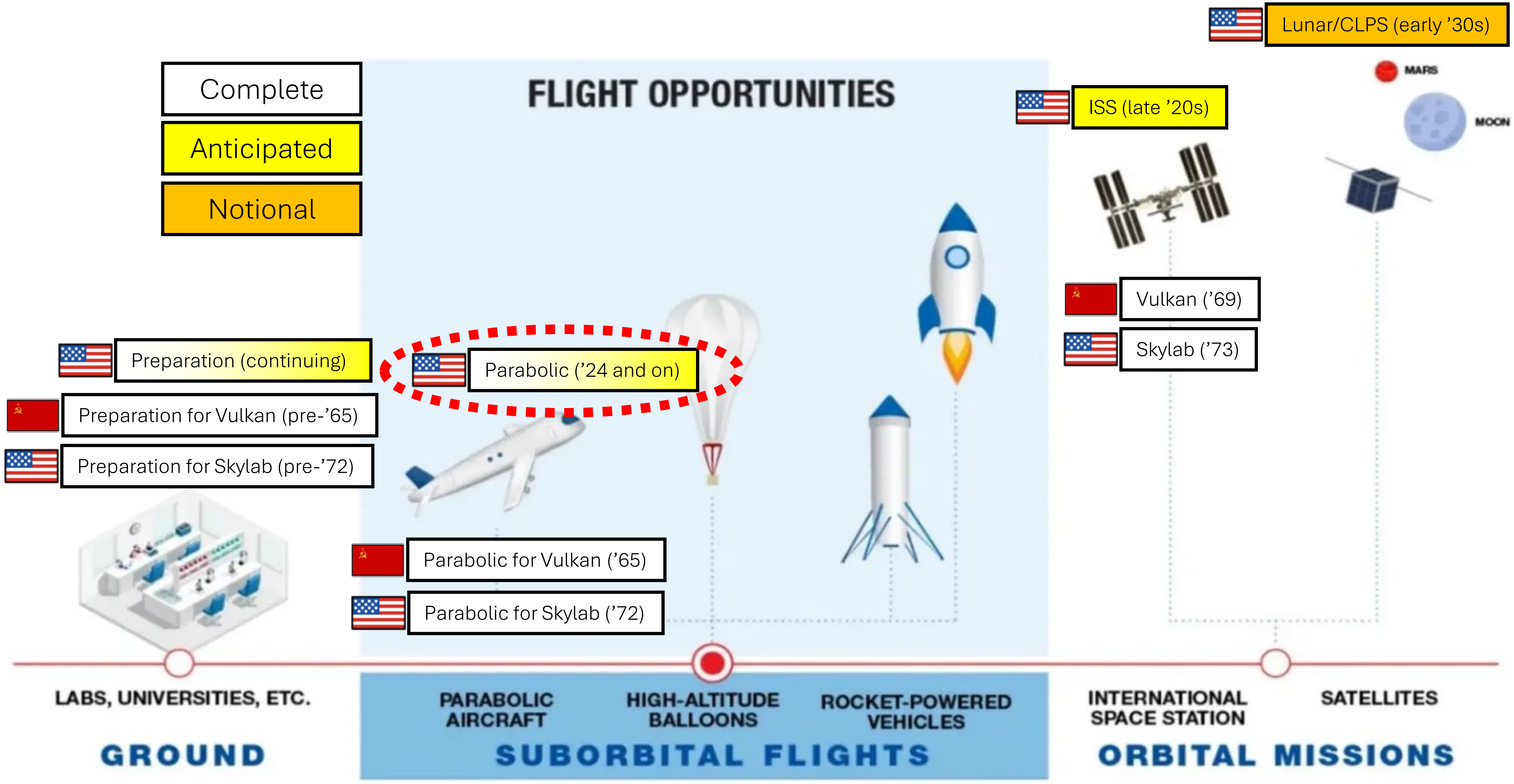



Concurrent development of Digital Twin using collected data



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

# Progression of flight experiments

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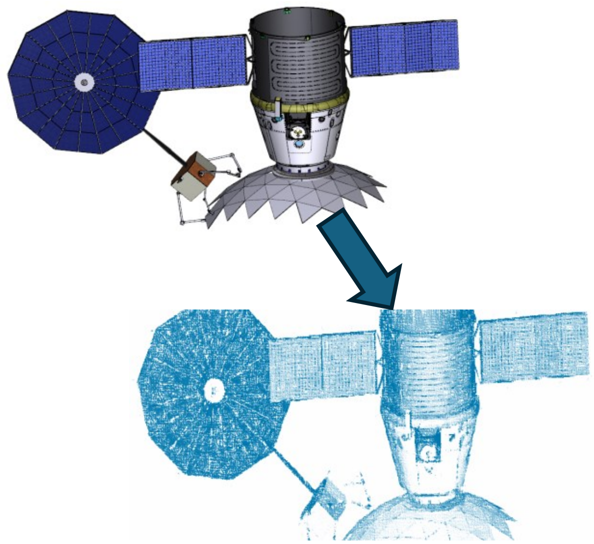


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

# 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.

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

Leverage LBW expertise & workforce development at OSU

Vacuum LBW experiment during parabolic flight

Credit: Tasha Dixon/Zero-G

Modern fiber lasers enable high-power LBW

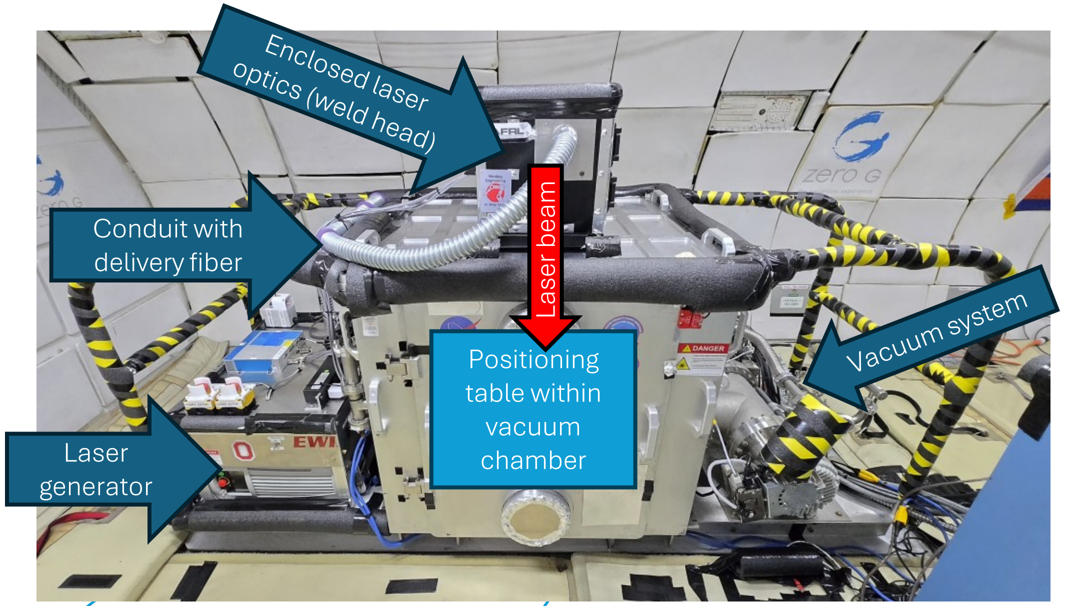
Courtesy: IPG Photonics

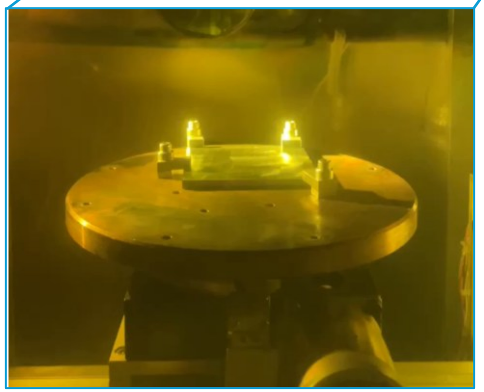
<u>Would you like to learn more?</u>
Thursday June 11th at 12:25 in Newton 2 –
"In-Space Manufacturing Using Laser Beam Welding"

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

# Extended flight campaign using proven hardware





*in situ* thermal data and videography

<u>First flown in August 2024:</u>
**Successfully welded during 69 out of 70 total parabolas** – including both Lunar (0.17 g) and low gravity (~0.01 g) profiles

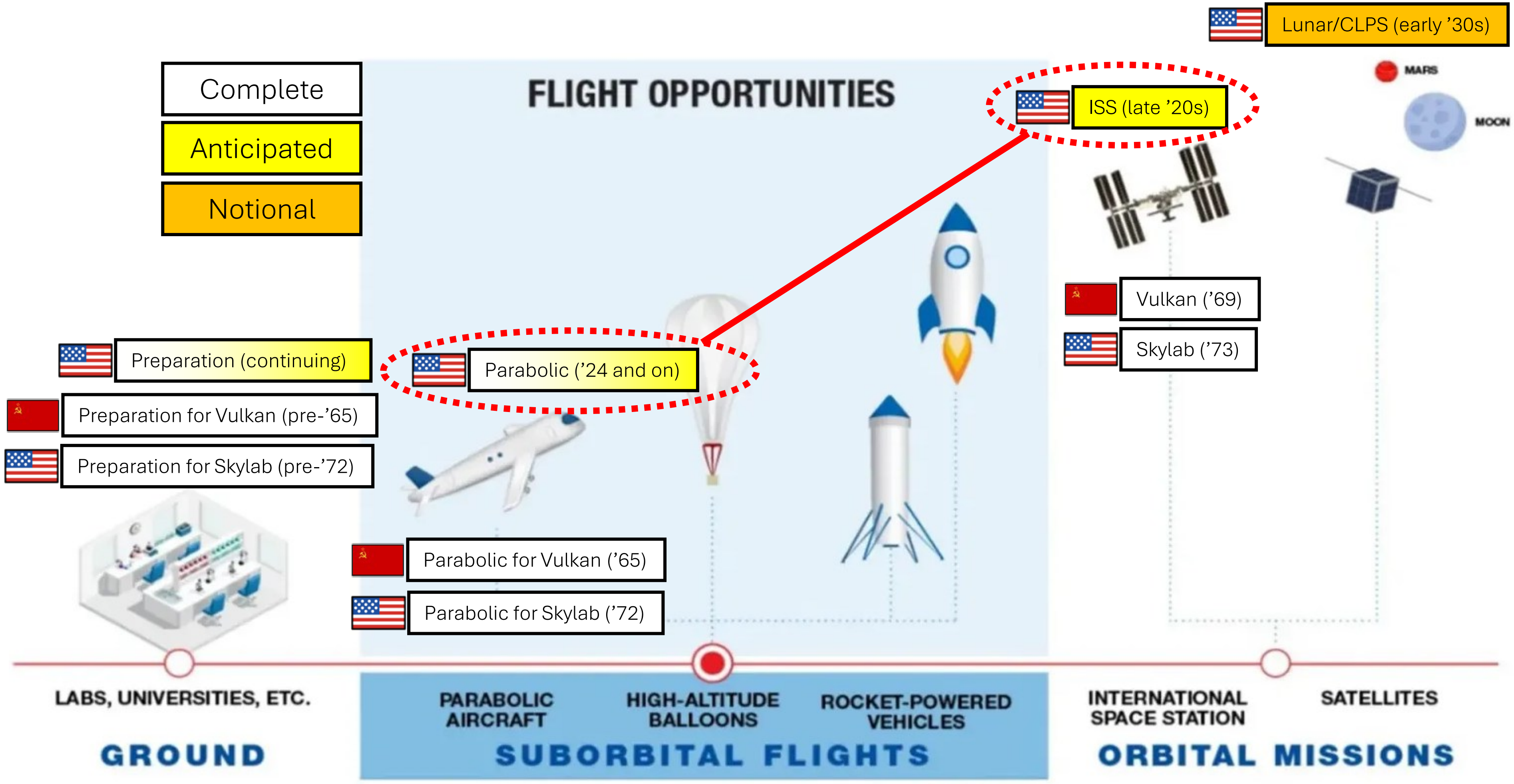
<u>Flight in May 2025:</u>
**Hermetic welds** (pressure vessels, etc.) and **realistic joints** (lap, butt-lap, etc.)

Published AISI316L stainless steel results – major difference is porosity: <u>10.1016/j.matdes.2026.116100</u>

Methods paper: <u>10.1016/j.actaastro.2026.05.036</u>

Credit: Tasha Dixon/Zero-G

# Progression of flight experiments

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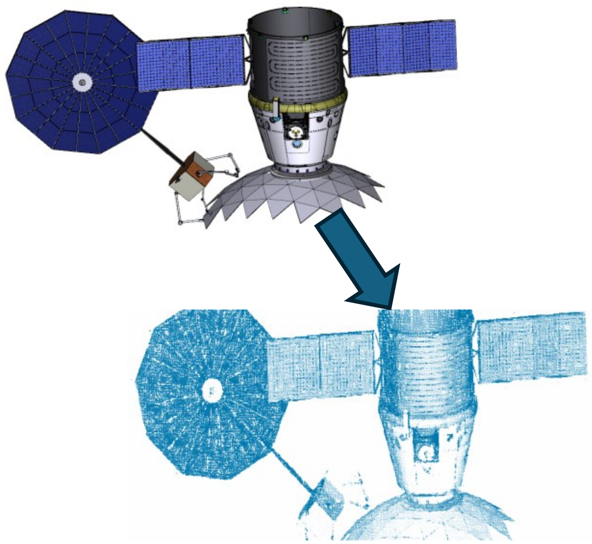
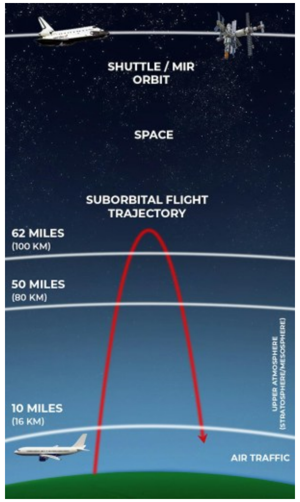


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

# 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 |

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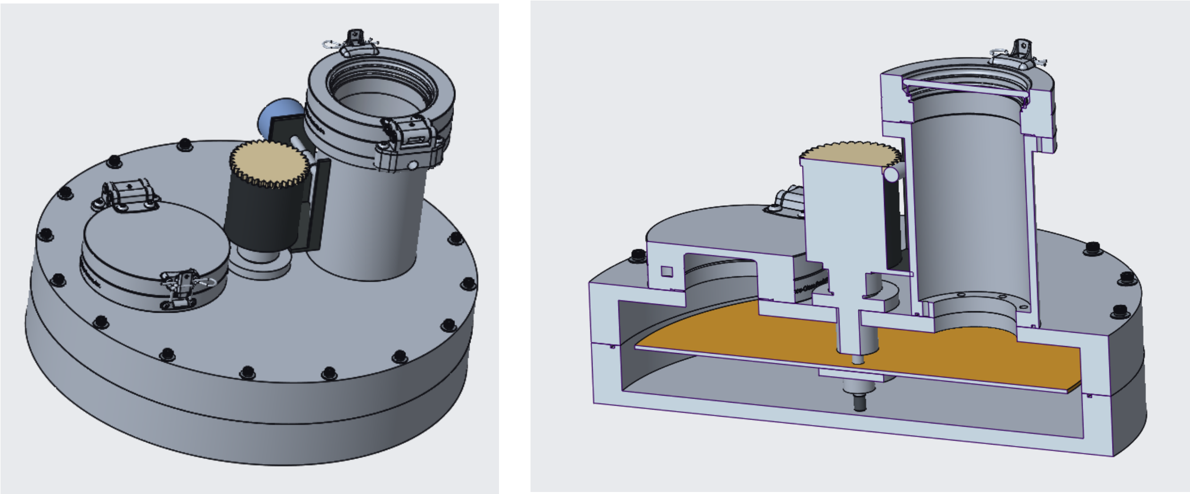
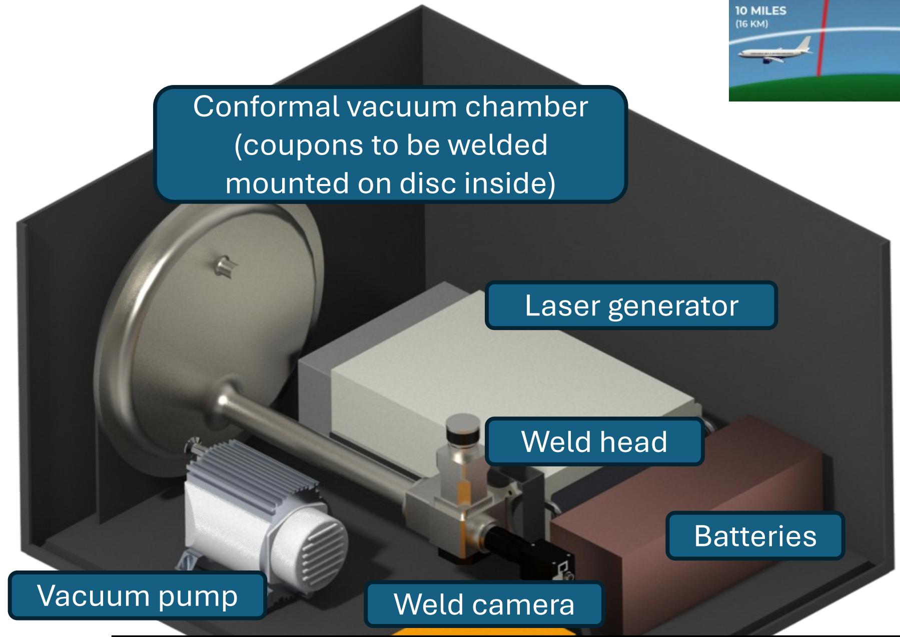
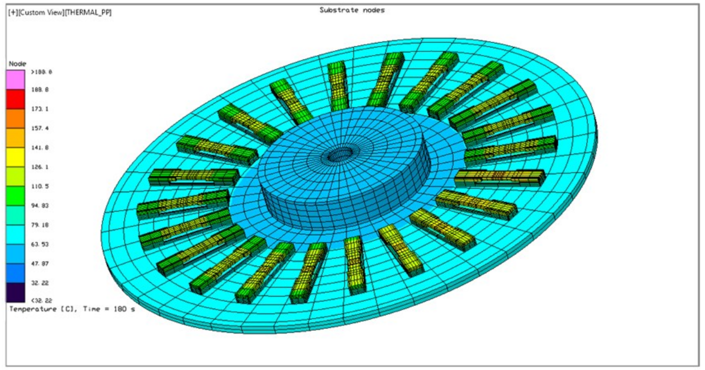
Initial protoflight hardware design






Conceptual design developed with MSFC Advanced Concepts Office

Thermal and structural modeling

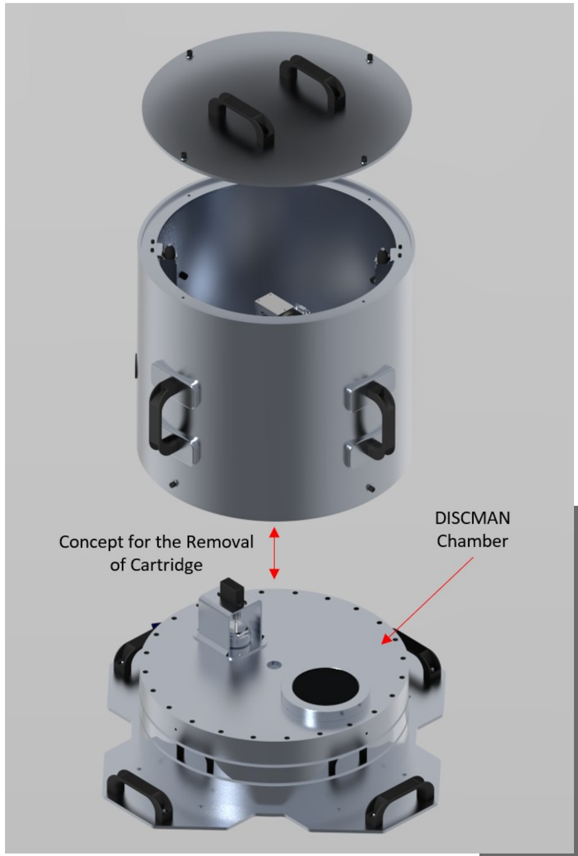


Serendipitous opportunity to re-target for Bishop Airlock on ISS: long microgravity duration with ability to pause, reflect, and change welding parameters & schedule mid-flight!

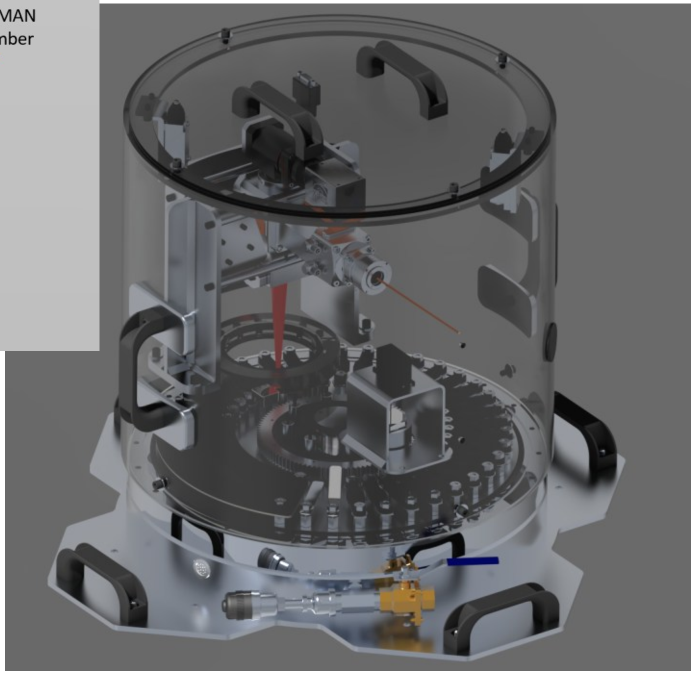
# DISCMAN – A persistent platform for LBW process development

**Key innovation:**
Vacuum chamber as swappable cartridge that can be exchanged on orbit by crew; cartridge contains disc with pre-mounted workpieces

DISCMAN can support any experiment requiring laser, vacuum, motion, microgravity (or just a subset)



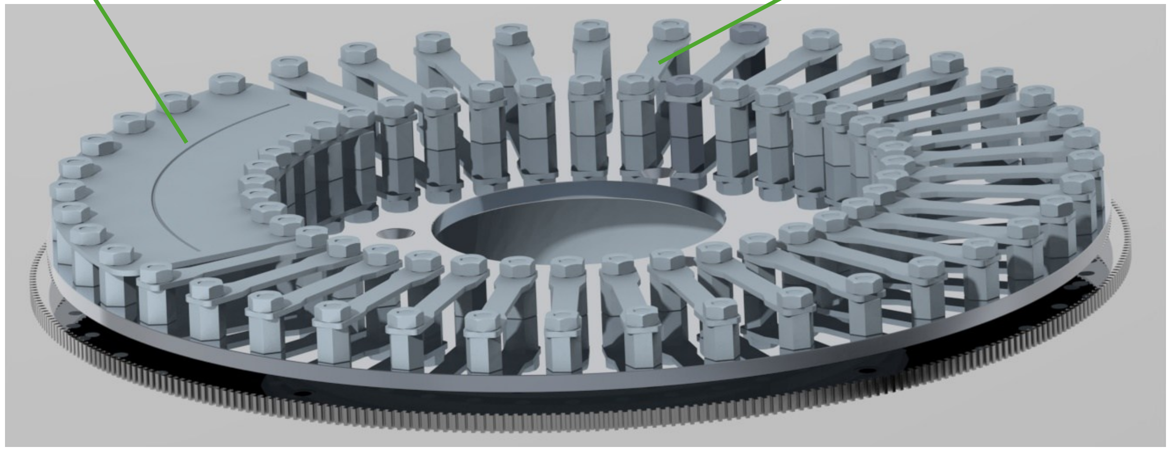

Simplified render of swappable cartridge and enclosure for laser



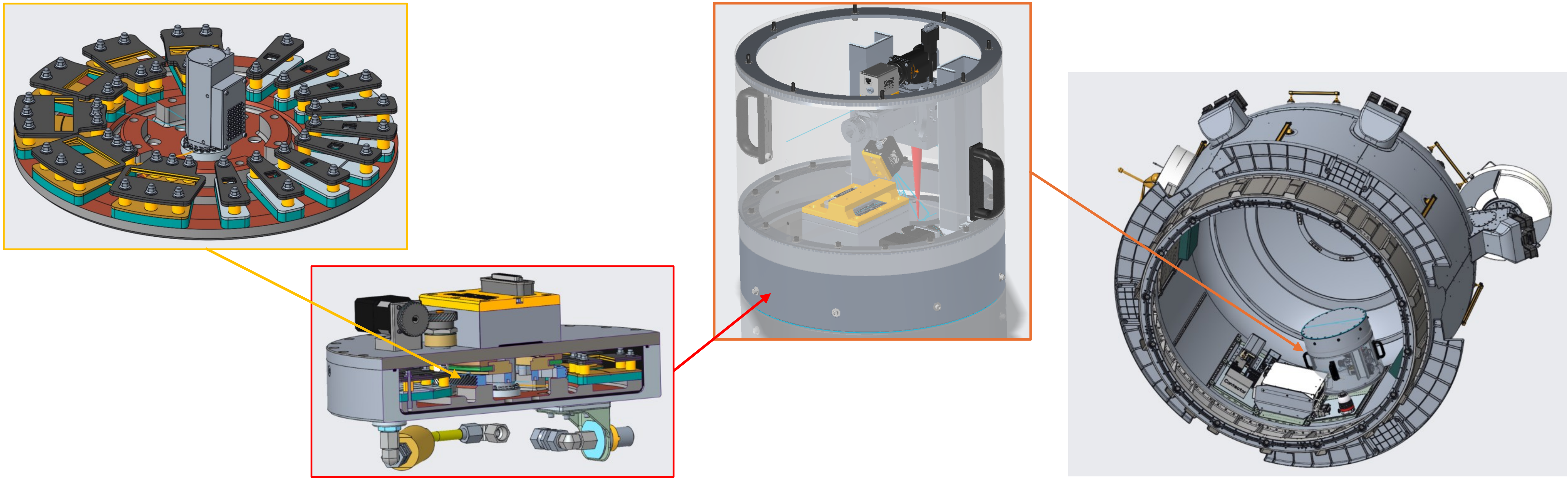
Translucent render of cartridge and enclosure

Notional DISCMAN workpieces and welds:

- Spots and short line welds for realistic joints
- Long, linear welds for steady state
- Future workpieces (cutting/drilling, forming)

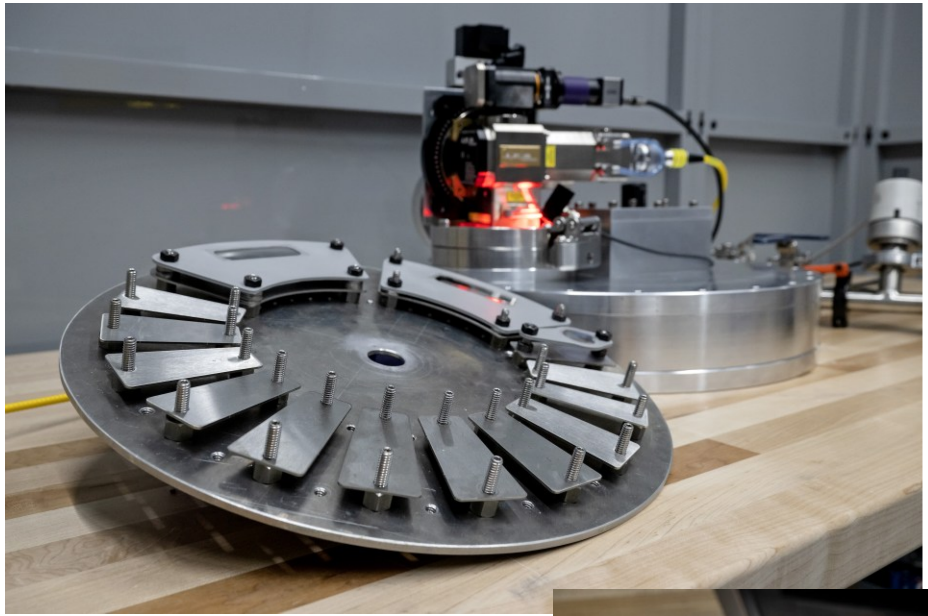


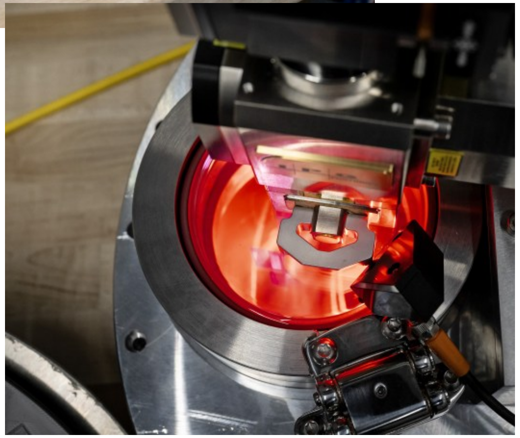
# Current DISCMAN effort: initial ISS design and preliminary payload safety



- Design evolving to meet more stringent safety and persistence requirements of ISS and Bishop Airlock
- Continuing to focus on LBW as first use case with ability to upmass additional, different cartridges later
- Recently added to Integrated Payload List and engaging with Voyager Technologies as integrator

# Ground testing unit (GTU) undergoing integration and testing





Depiction of GTU integrated for functional and operational testing; rapid reconfiguration ability enables responsive design and development

Courtesy: IPG Photonics

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

Licensed under CC BY-SA 3.0 from Liquidat

Compact turbomolecular pump to achieve **high vacuum** ($10^{-2}$ Pa)

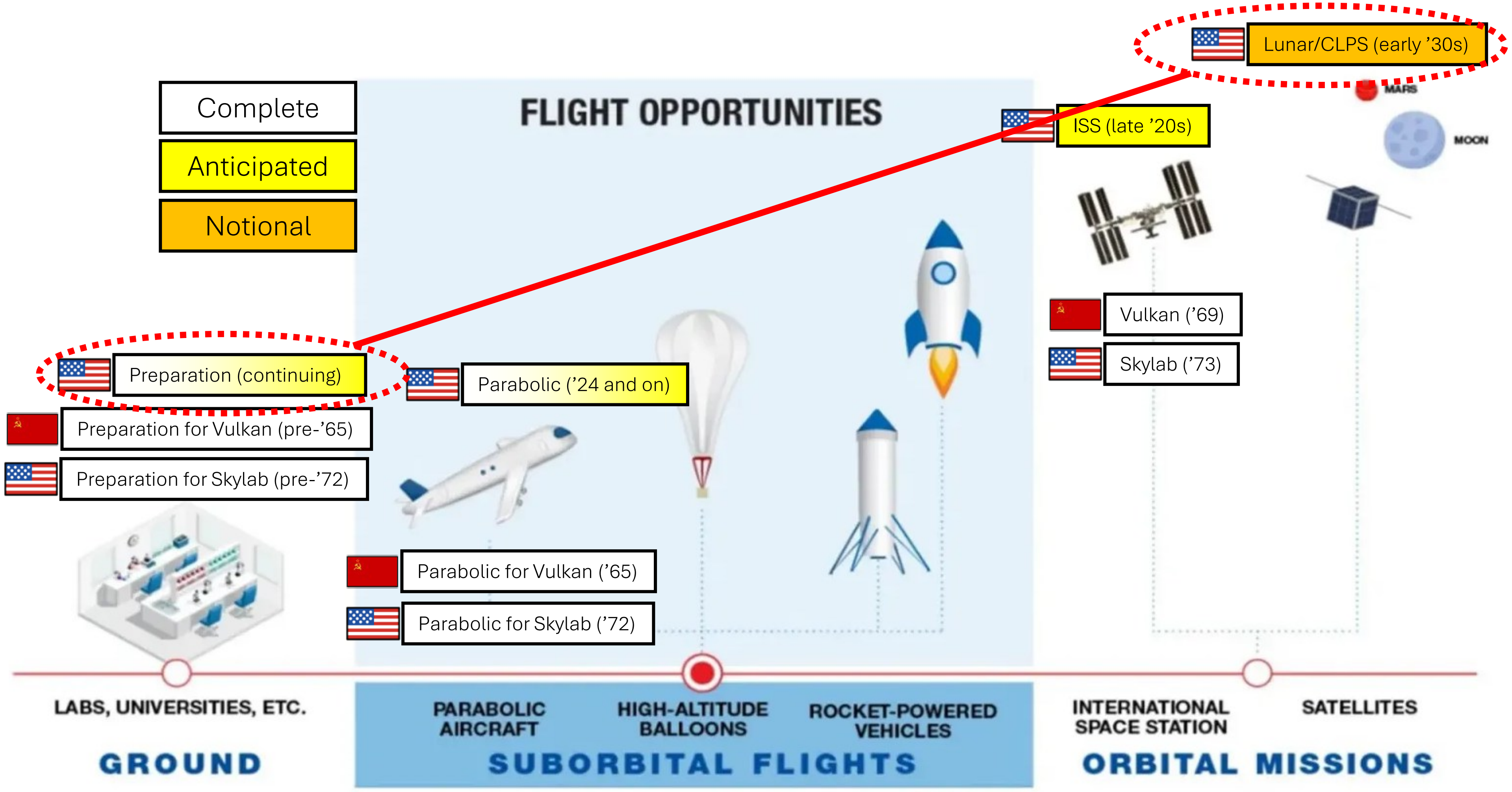
Highly instrumented to collect data to anchor computational models

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

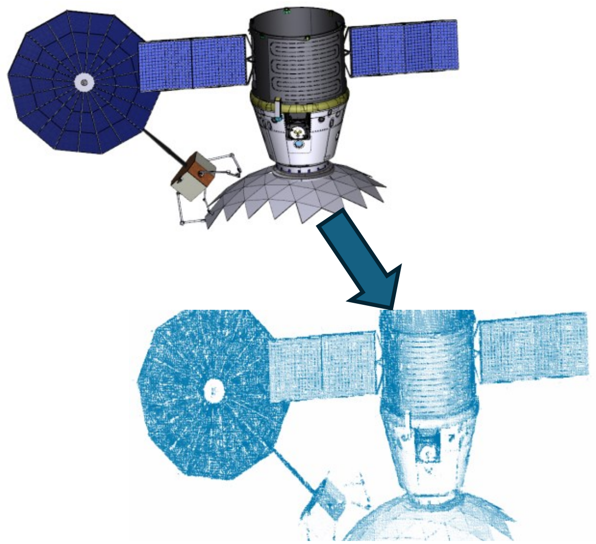

Courtesy: Xiris Automation

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

# Progression of flight experiments



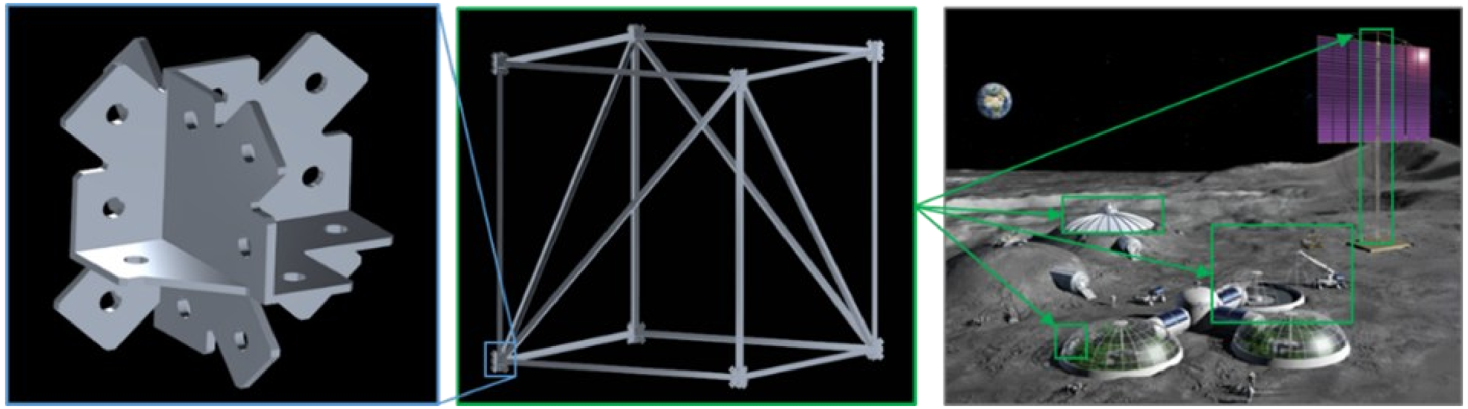

Concurrent development of Digital Twin using collected data



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

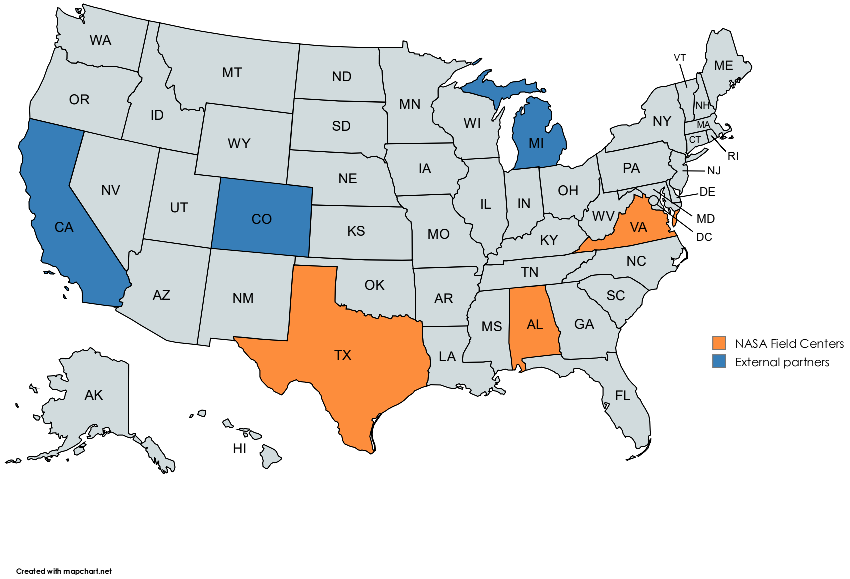
# Lunar Assembly and Servicing by Autonomous Robotics (LASAR)

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**

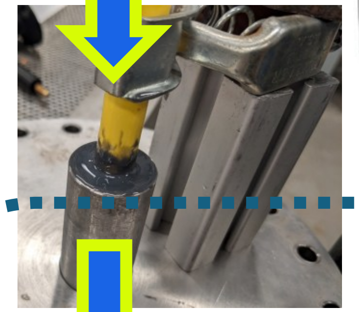
| Name | Role |
|---|---|
| Laserline | Laser Processing Partner |
| Motiv Space Systems | Robotics Hardware Partner |
| PickNik Robotics | Robotics Software & Autonomy Partner |

**Mentors**

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

# LASAR: TVAC demonstration upcoming

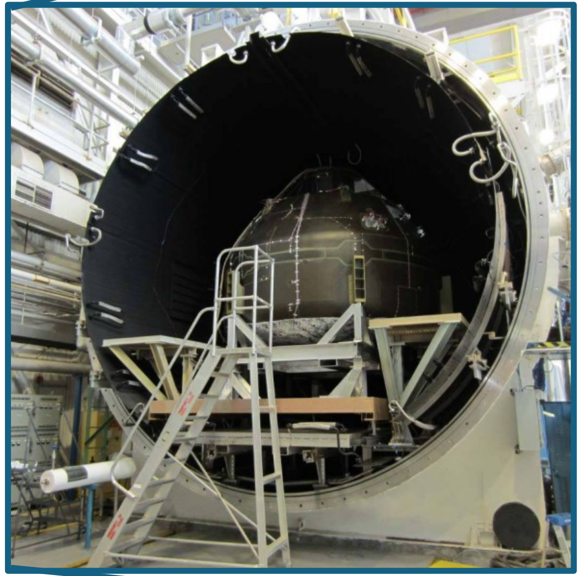
Pulling FY26 TVAC testing into FY25: minimum viable demonstration of high vacuum but ambient temperature LBW



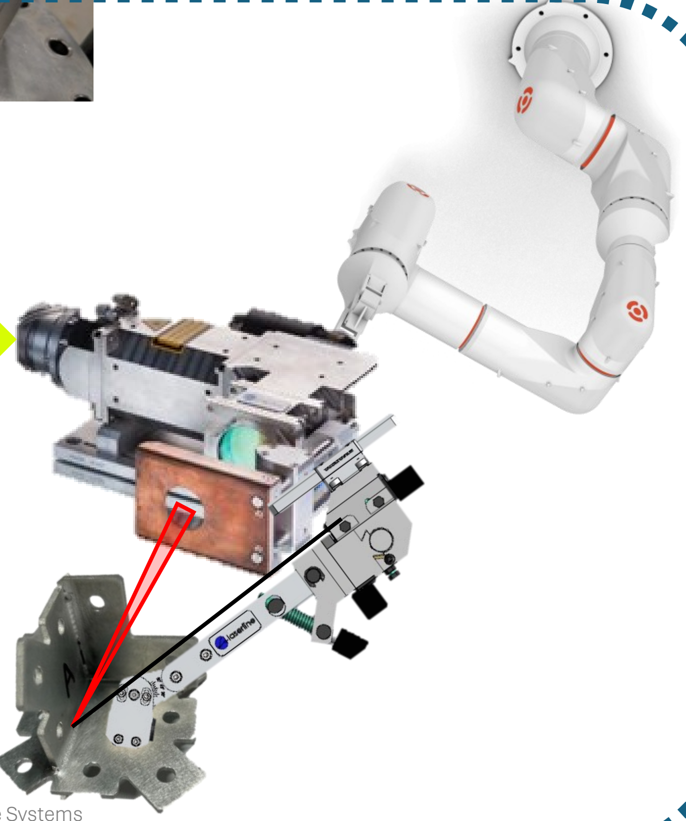
Laser generator, diode (outside TVAC)

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

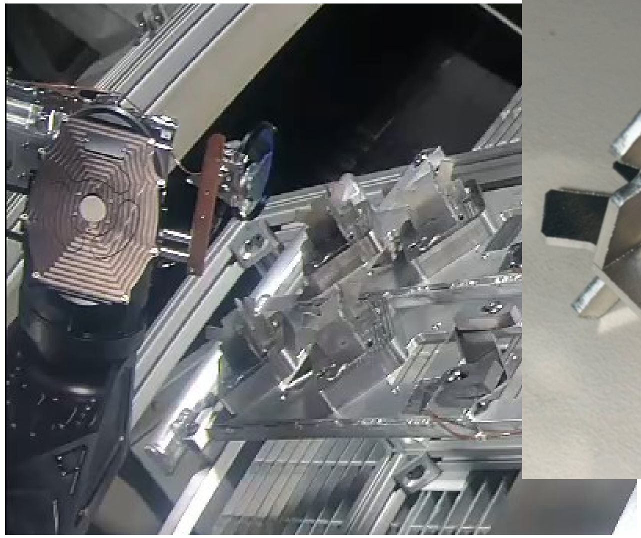


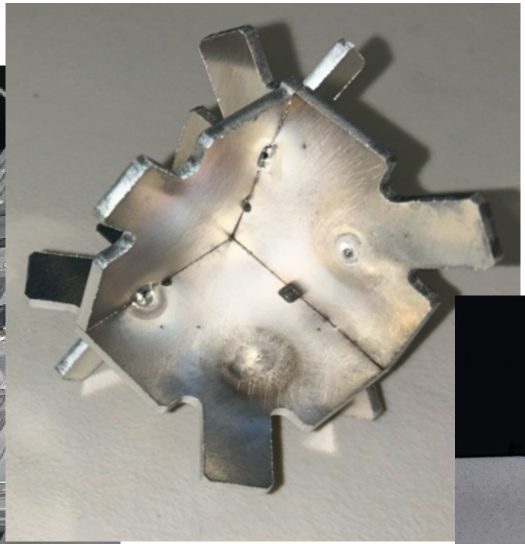
Credit: Laserline, Motiv Space Systems

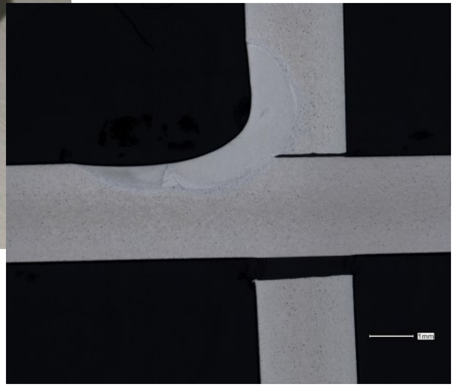
# First reported robotic LBW with (almost) all components under vacuum! First TVAC campaign of August 2025

Bead-on-plate weld

Snowflake joint weld



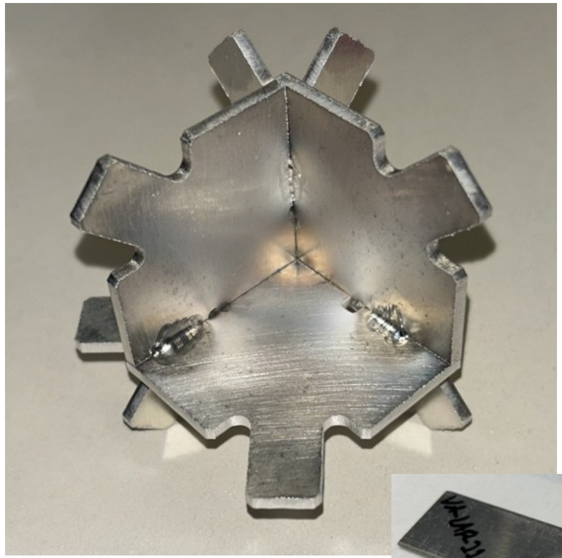




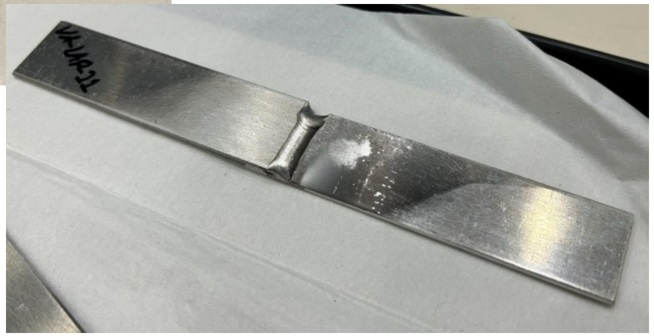
Successfully welded 2 of 3 seams of a snowflake joint under vacuum; mistargeted third seam (corrected for next campaign – now at cold/hot temperatures)

# Further progress during second TVAC campaign of Feb/Mar 2026

## More than a dozen snowflake joints welded under vacuum ambient (room temp.)

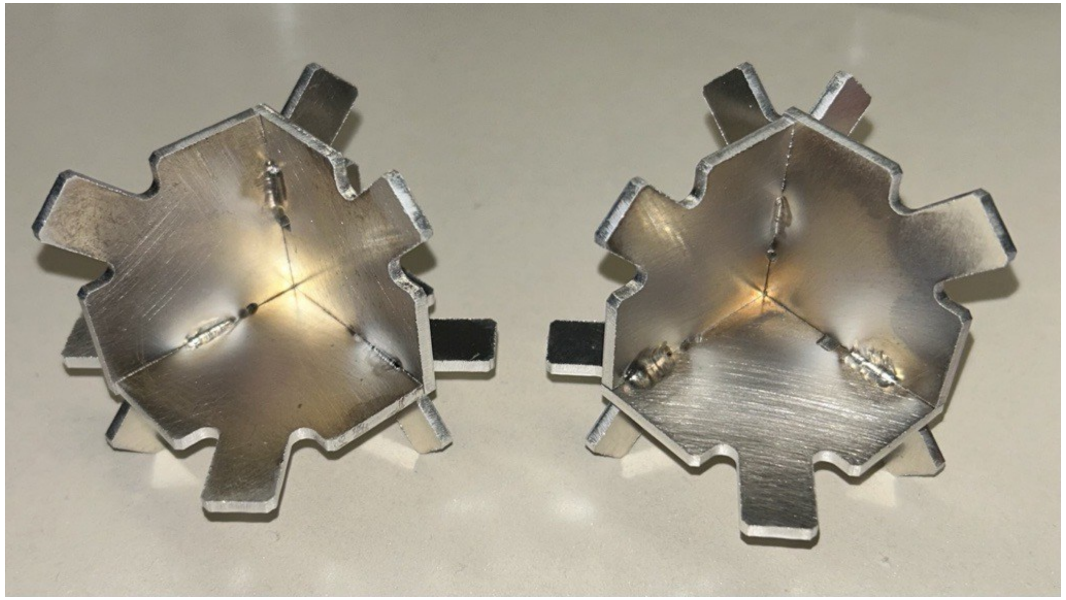


Undergoing distortion scans and mechanical testing



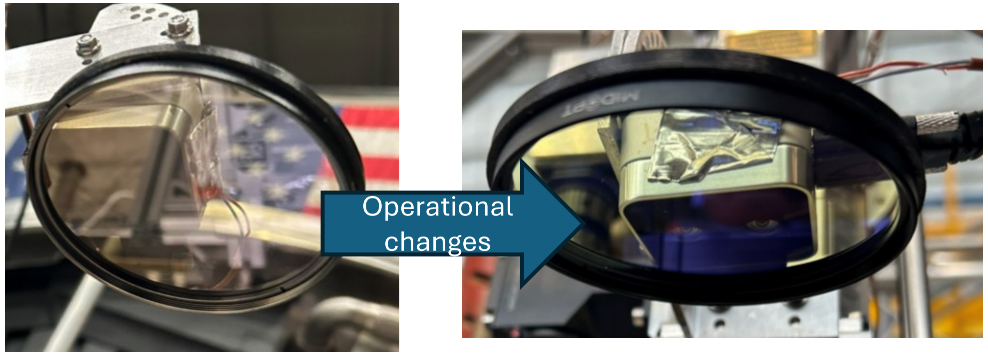
## First reported robotic LBW in TVAC!

- “cool” (left) – everything <0°C, except snowflake joint itself at -50°C
- “lukewarm” (right) – everything >30°C
- Time available in TVAC limited temperatures…not tech



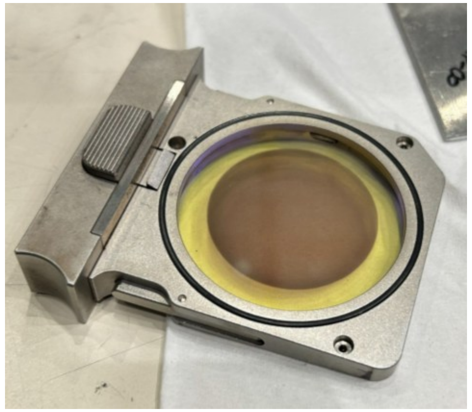
# Working through operational challenges in TVAC

## Metal vapor deposition still a concern; partially mitigated

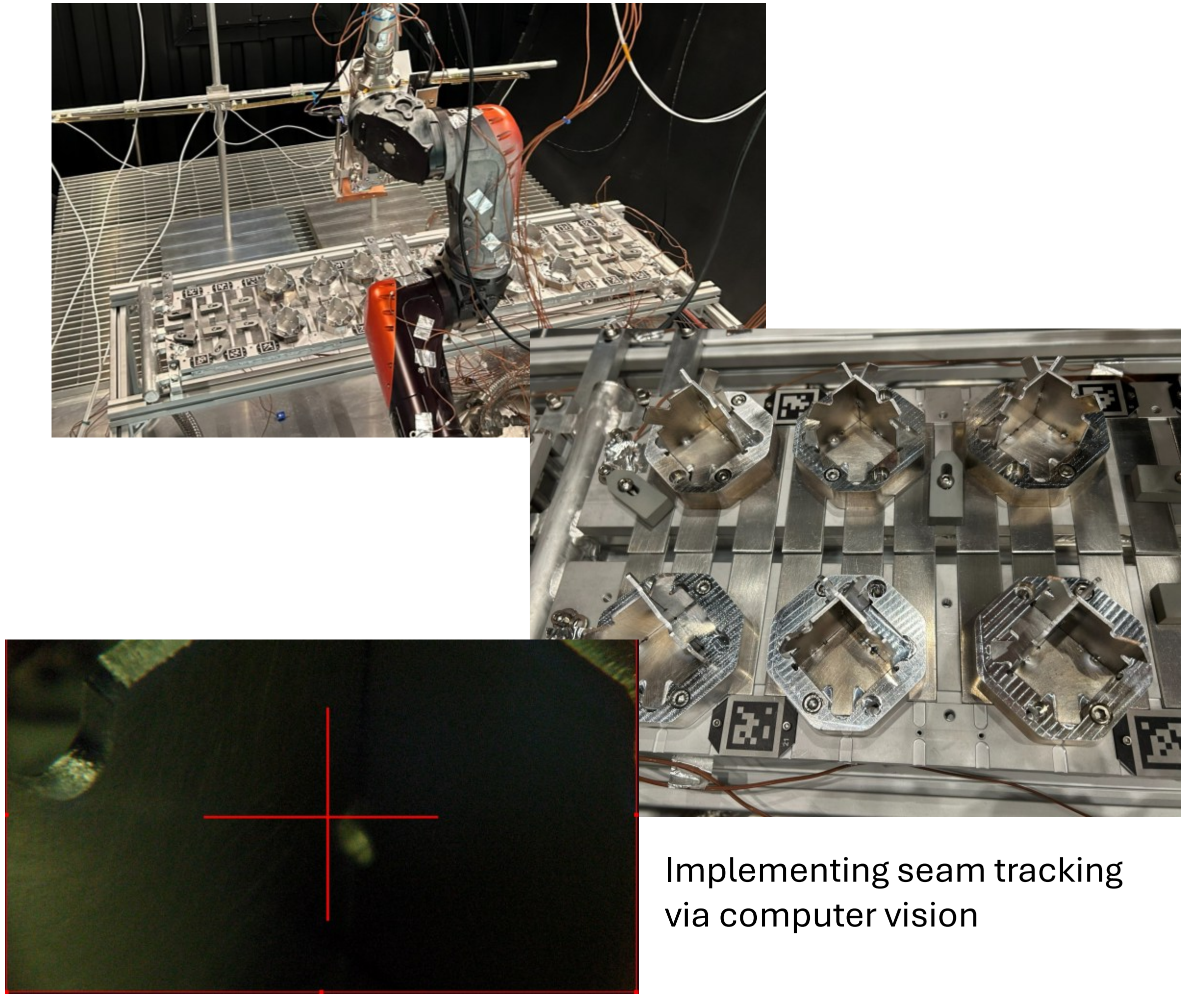



Implementing mechanical cover for stereo cameras

Remaining concern re occlusion of cover glass for laser optics itself



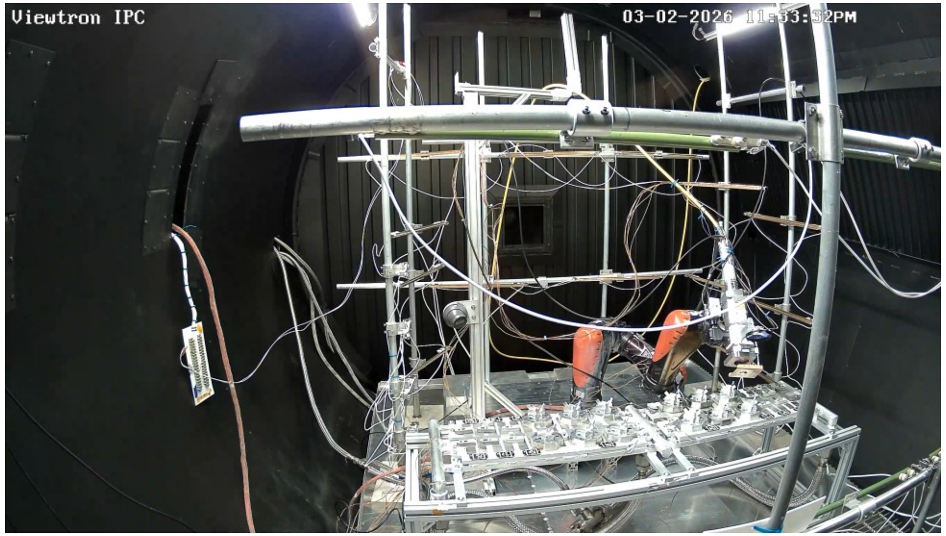
## Positioned end effector by stereo depth perception; reduced misalignment

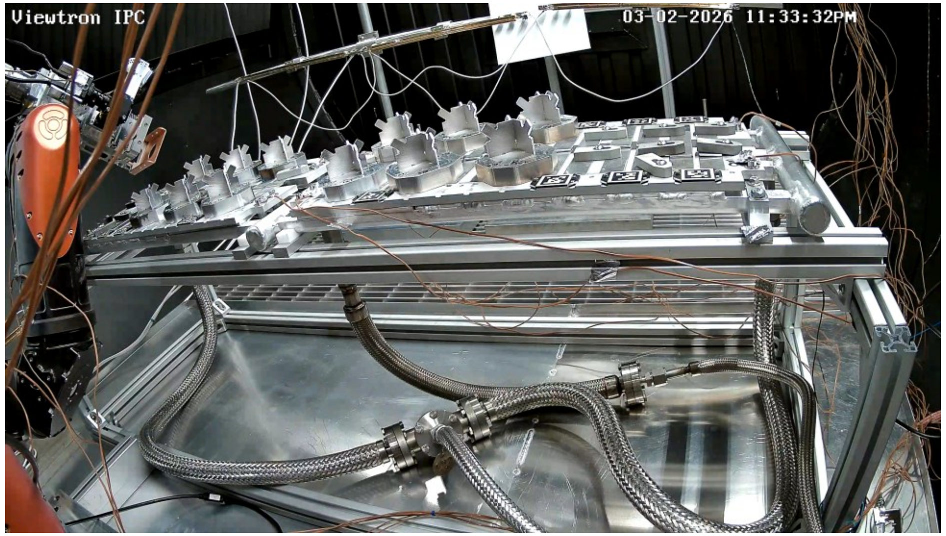


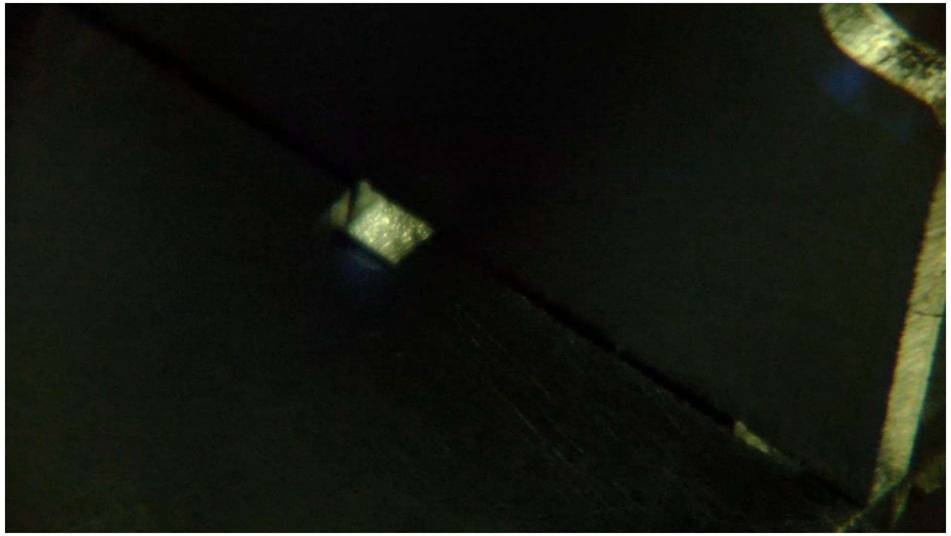
Implementing seam tracking via computer vision

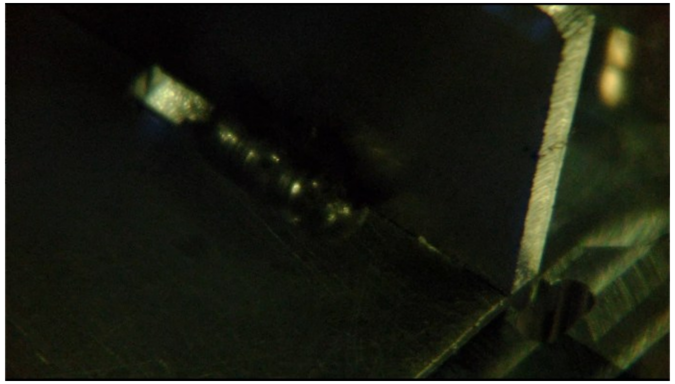
# “cool” snowflake – everything <0°C under vacuum

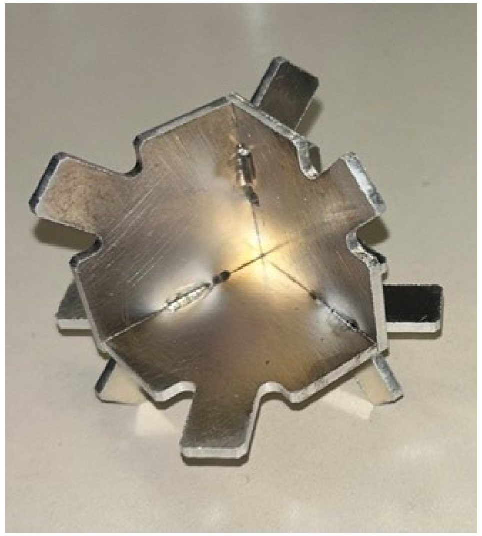








# Conclusion & Opportunities

Where do we go from here?

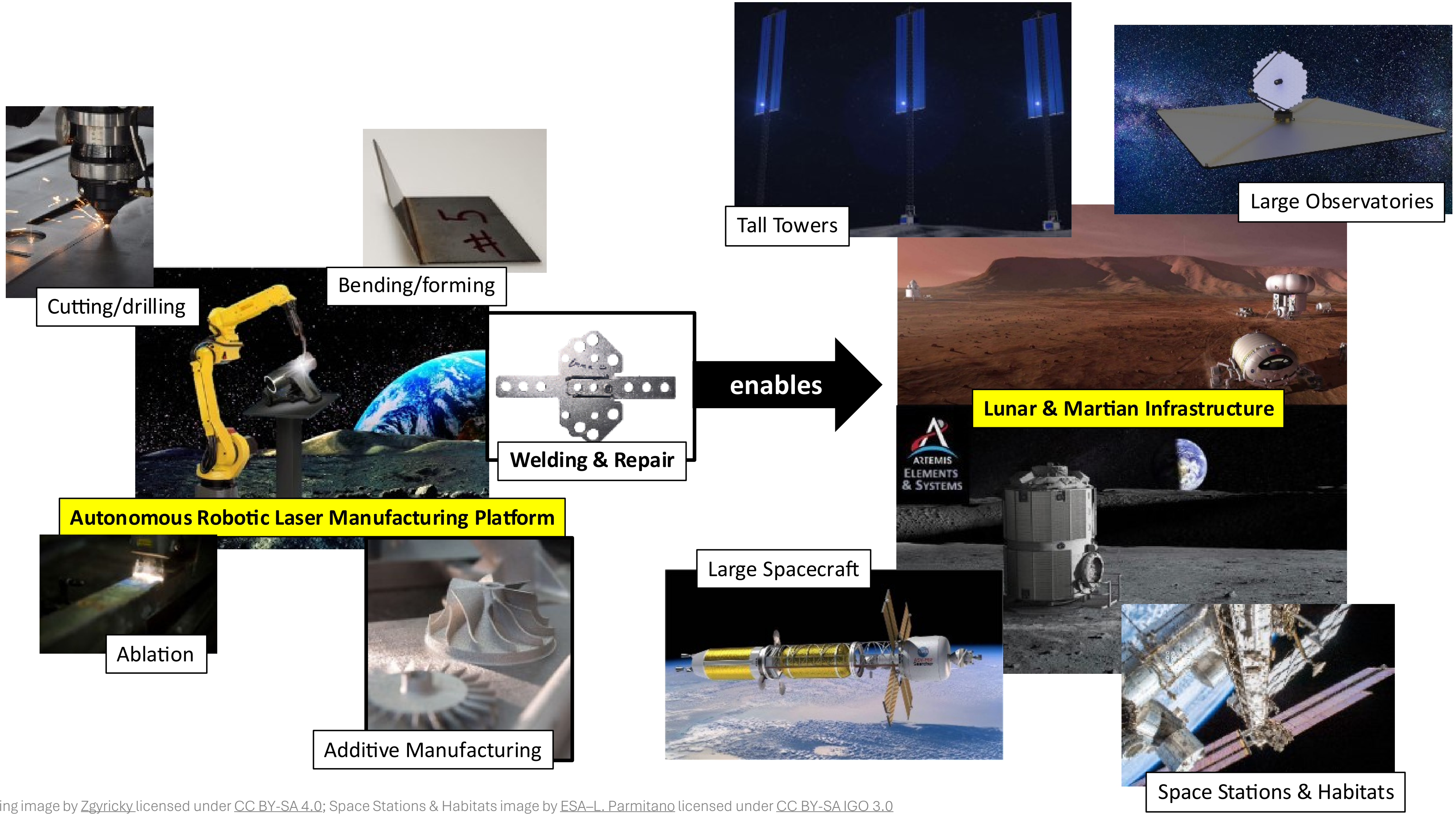
Engaging with NASA

# NASA leads the way to in-space welding

- 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 to:
  - 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 opportunities:
  - Modular flight unit hardware
  - Parabolic and orbital flight experiment know-how
  - Computational models anchored by collected data
  - Network of academic, government, and industrial collaborators

# We are just beginning to understand metallic manufacturing and joining in space...we must work together to enable these futures

ISAM IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

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# Opportunities for engagement

- Ask for our lessons learned on flight experiments (parabolic, ISS, etc.)
- Pursue a collaboration leveraging our data & expertise and your specialty
- Consider ways in which in-space welding could benefit your organization – what use cases can you think of that would be ripe for further discussion?
- Share your students! (not currently accepting applicants but stay tuned for future opportunities)
  - Space technology fellowship (NSTGRO): NSPIRES - NNH26ZTR001N-26NSTGRO_B6
  - Internships: Experimental support of in-space laser manufacturing

# 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, 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 future MSFC-OSU re-flight support from NASA Flight Opportunities


Any brand names or companies mentioned in this presentation do not constitute an endorsement by NASA.