Maturation of In-space Welding in Reduced Gravity and Reduced Pressure Environments Through Progression to Suborbital Flight Experiments

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NASA Marshall Space Flight Center

Presented on 2024-10-17 at AWS Professional Program in Orlando, FL

In-space welding enables space infrastructure

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

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

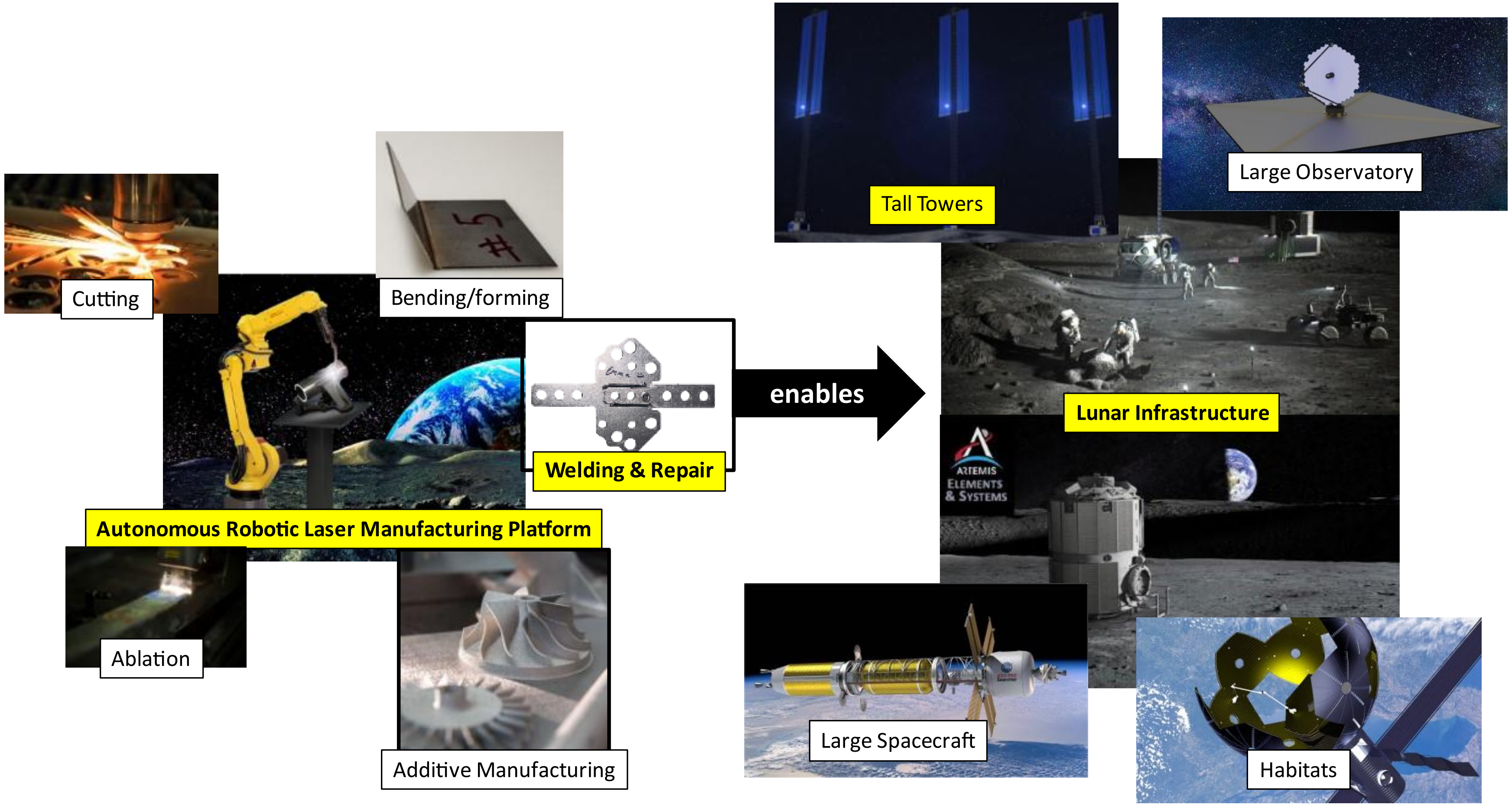
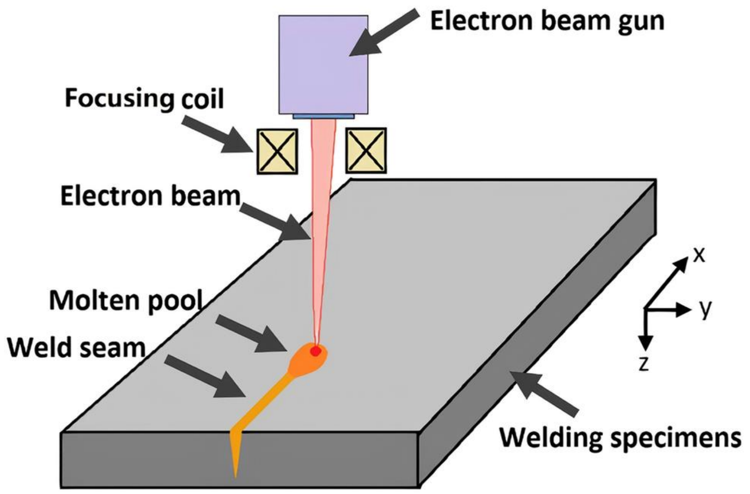
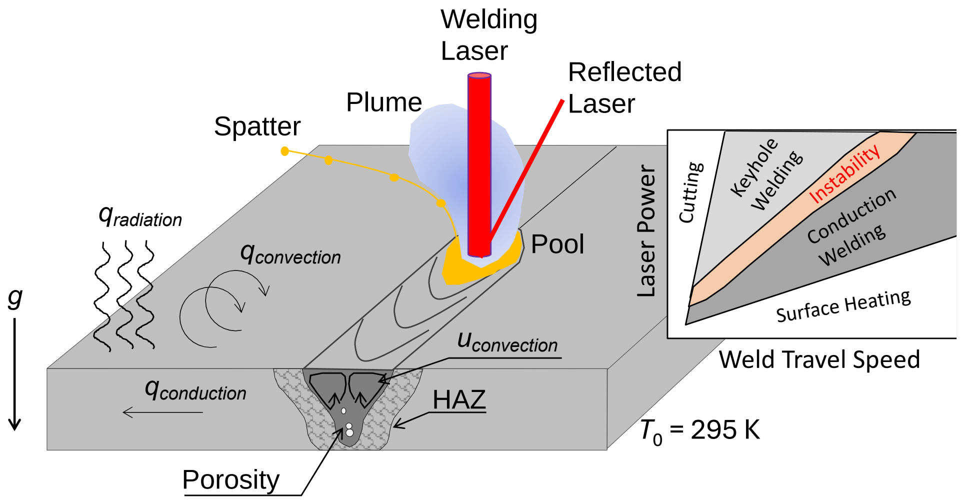


Image credit: ThinkOrbital, www.mechanicalcaveman.com

Why laser beam welding in space?





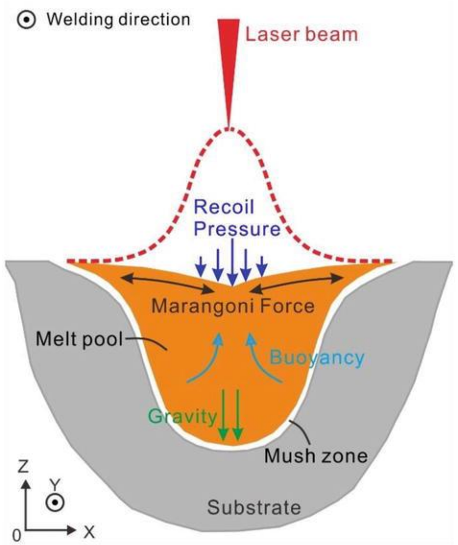
High-energy Beam Process → ↓ Criteria	Electron	Laser	Status
IVA flexibility (*e.g.* in habitat) & EVA flexibility (*e.g.* in vacuum, Lunar surface, on Mars)	●	○	Capability available after planned development
Workpiece variety (*e.g.* geometry, material)	◒	○	
Suitable for operation on end effector of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

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

In-space effects that influence welding

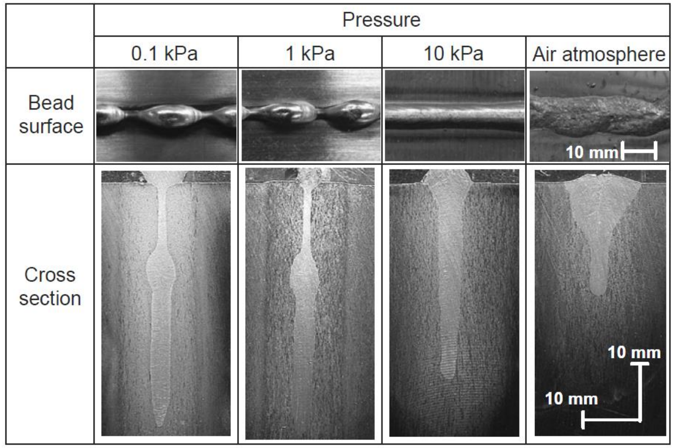
Variable	Case 1: In Space	Case 2: Chamber Inside Habitat	Case 3: Inside Habitat	Case 4: Lunar Surface	Case 5: Martian Surface	Baseline: Earth	Capabilities Needed at Present
Gravity	μ*g*	μ*g*	μ*g*	0.17 *g*	0.38 *g*	1 *g*	μ*g* to 0.38 *g*
Atmosphere	Vacuum (10^{-19} Pa)	Vacuum (10^{-4} Pa)	>21% O_2, <101 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 – 396 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.



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

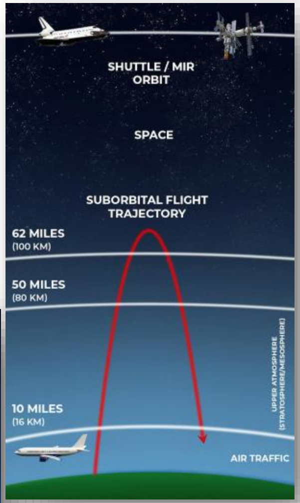
Simulating space conditions for welding

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

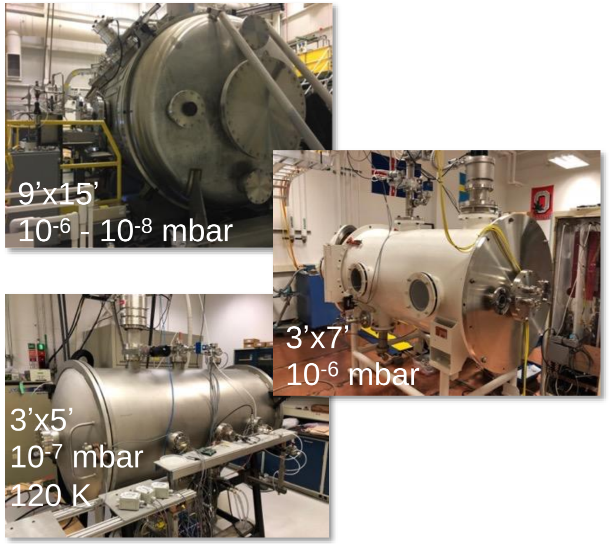
Drop tower

Parabolic flight

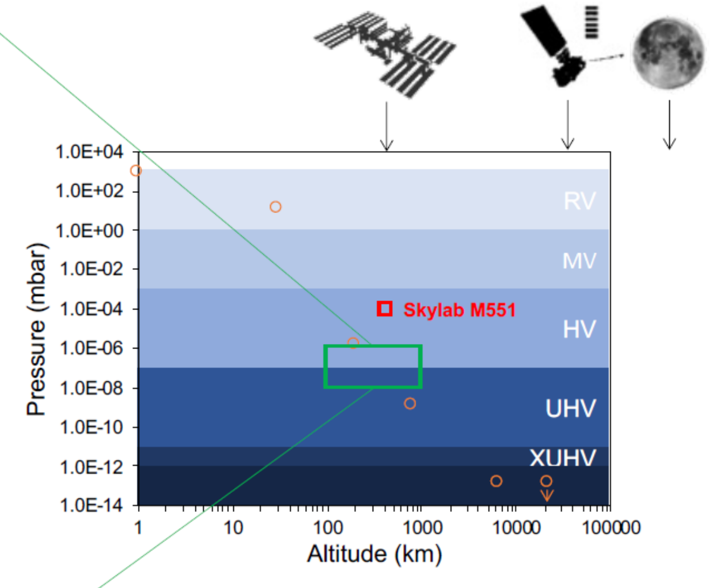


Suborbital flight

Vacuum and Reduced Temperature



Example of MSFC capabilities to simulate reduced pressure / vacuum at 100 to 1000 km altitude.



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

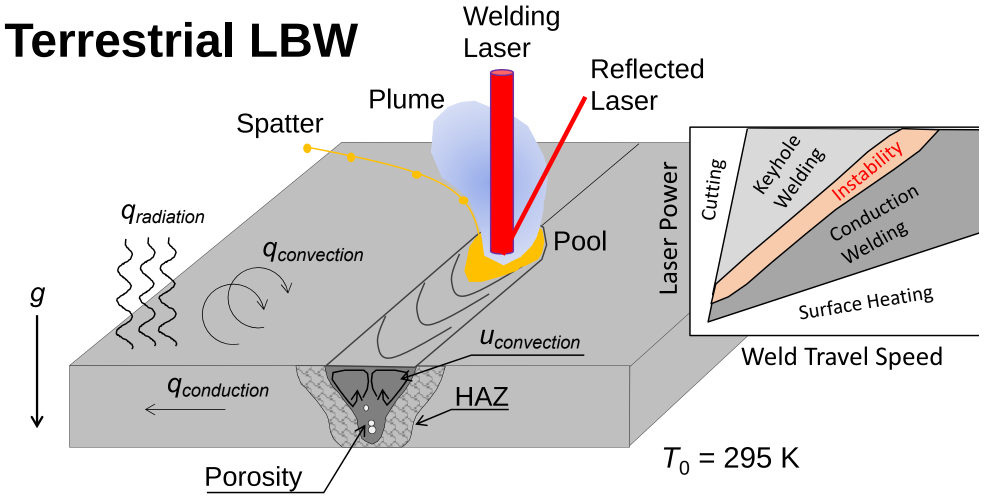
0.38 *g*

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

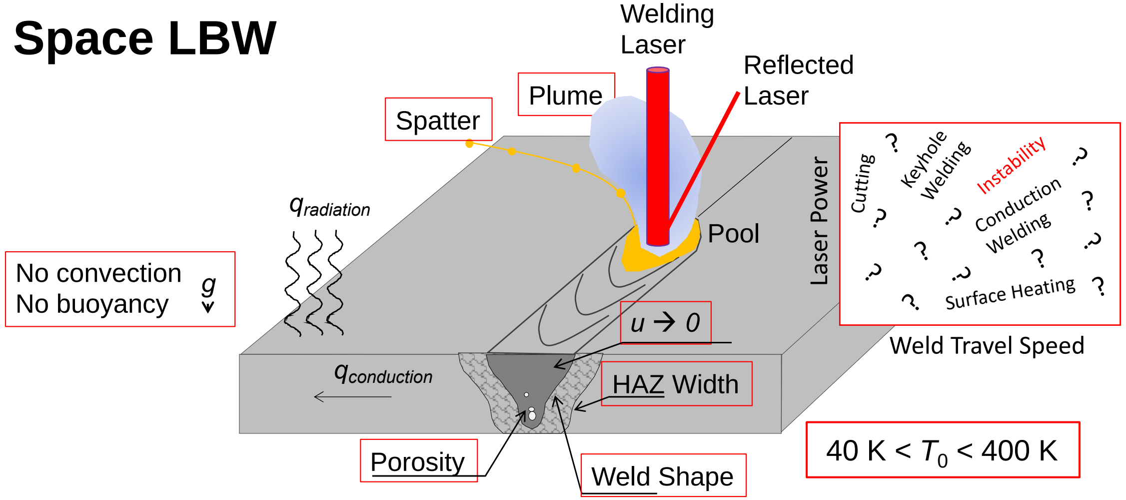
Key effects to consider for in-space LBW

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)

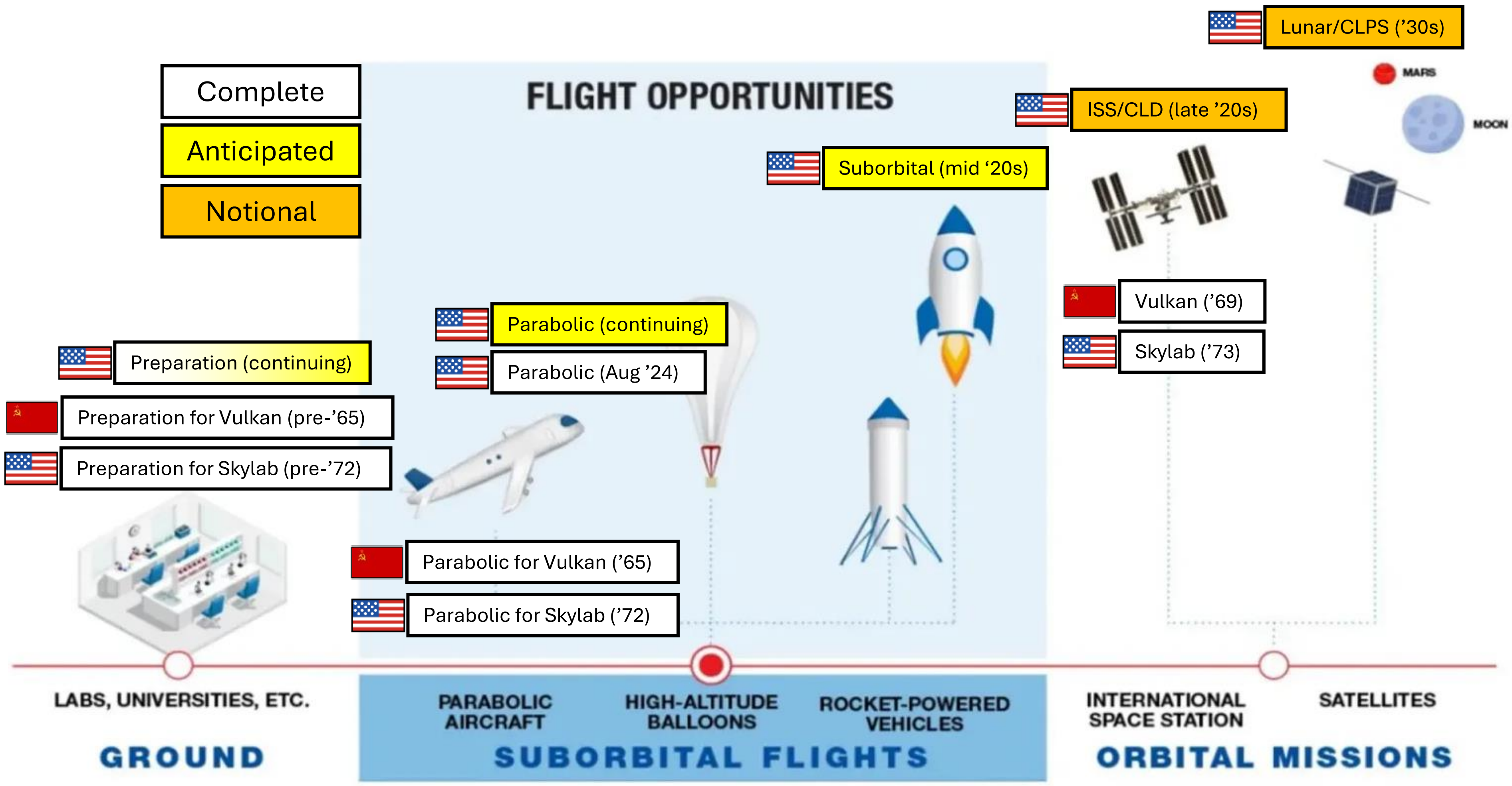
Issue #3 Reduced pressure/vacuum in space:

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.

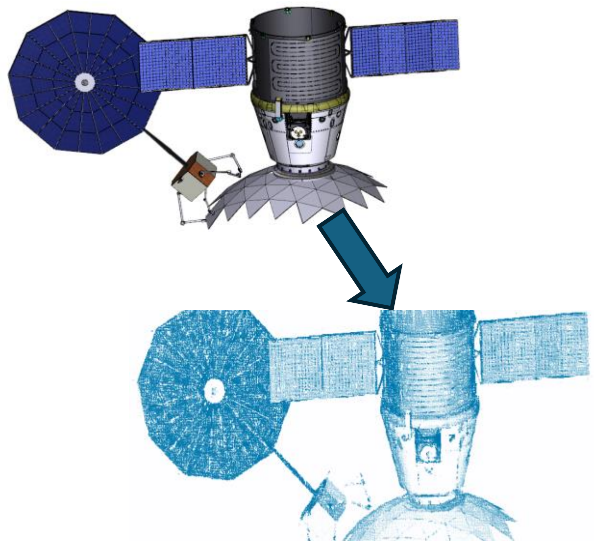
Reduced pressure influences laser beam keyhole stability, evaporation of volatile species, safety issues, etc.

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

Progression of flight experiments

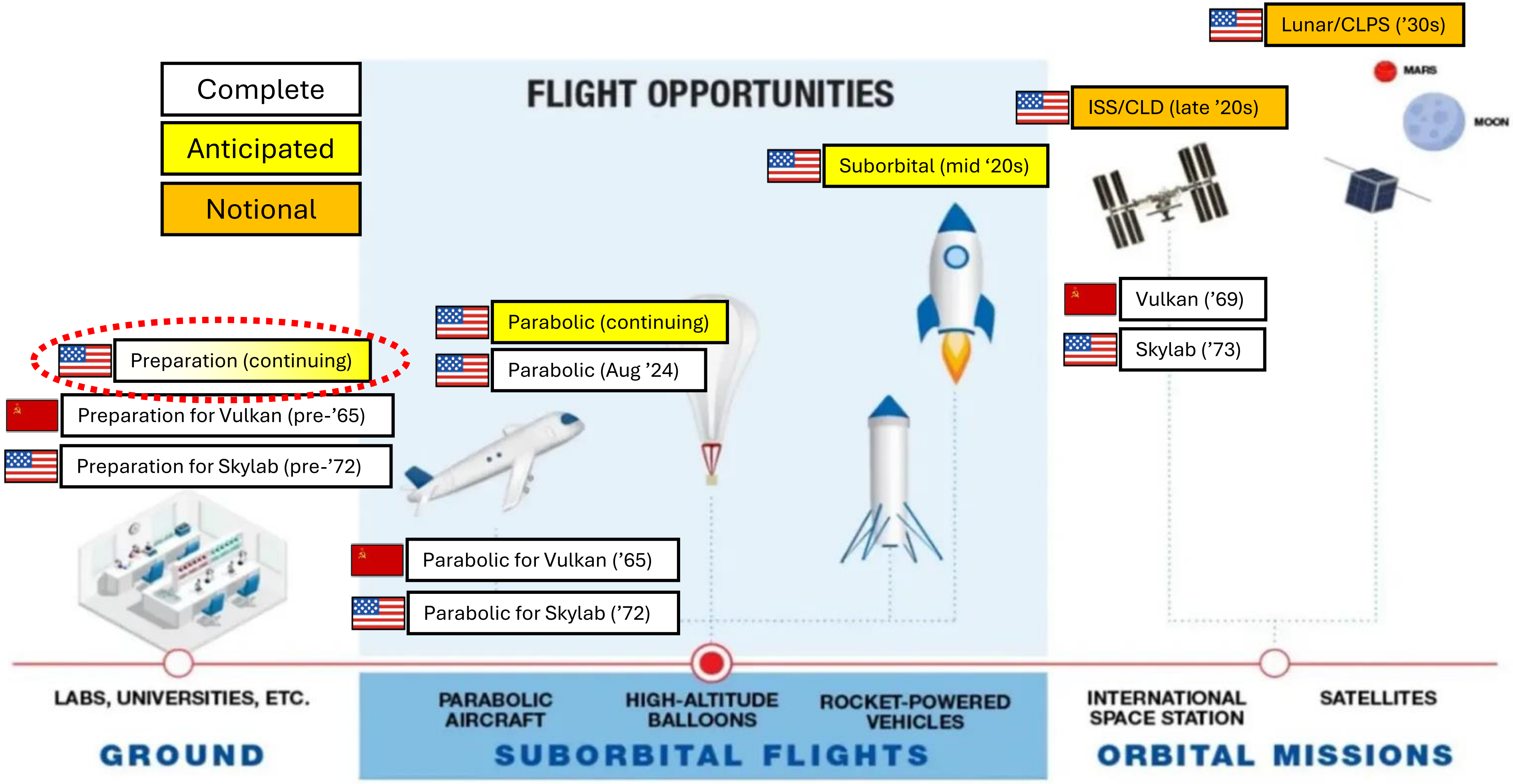


Concurrent development of Digital Twin using collected data



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

Progression of flight experiments



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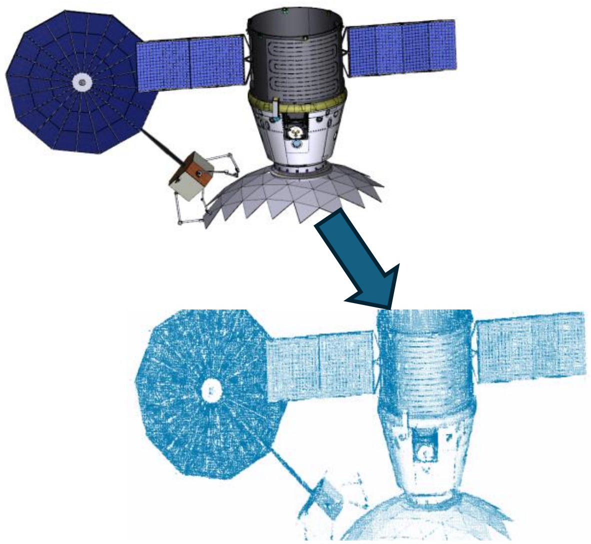
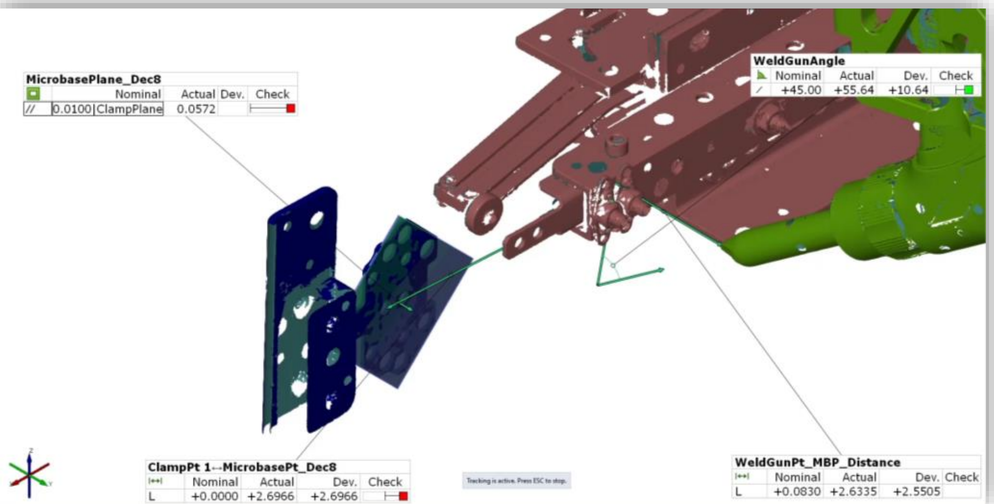


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Ground testing LBW on 3-DOF "Flat Floor"

ISAM
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

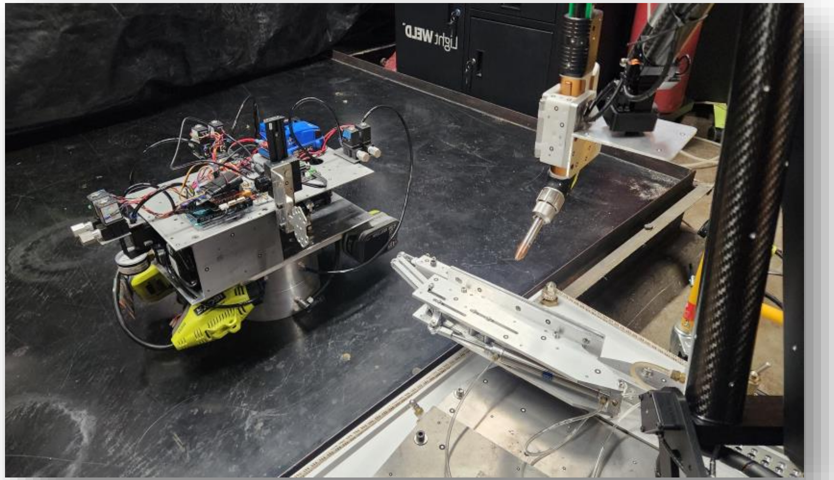
Enclosed LBW station for rapid parameter development



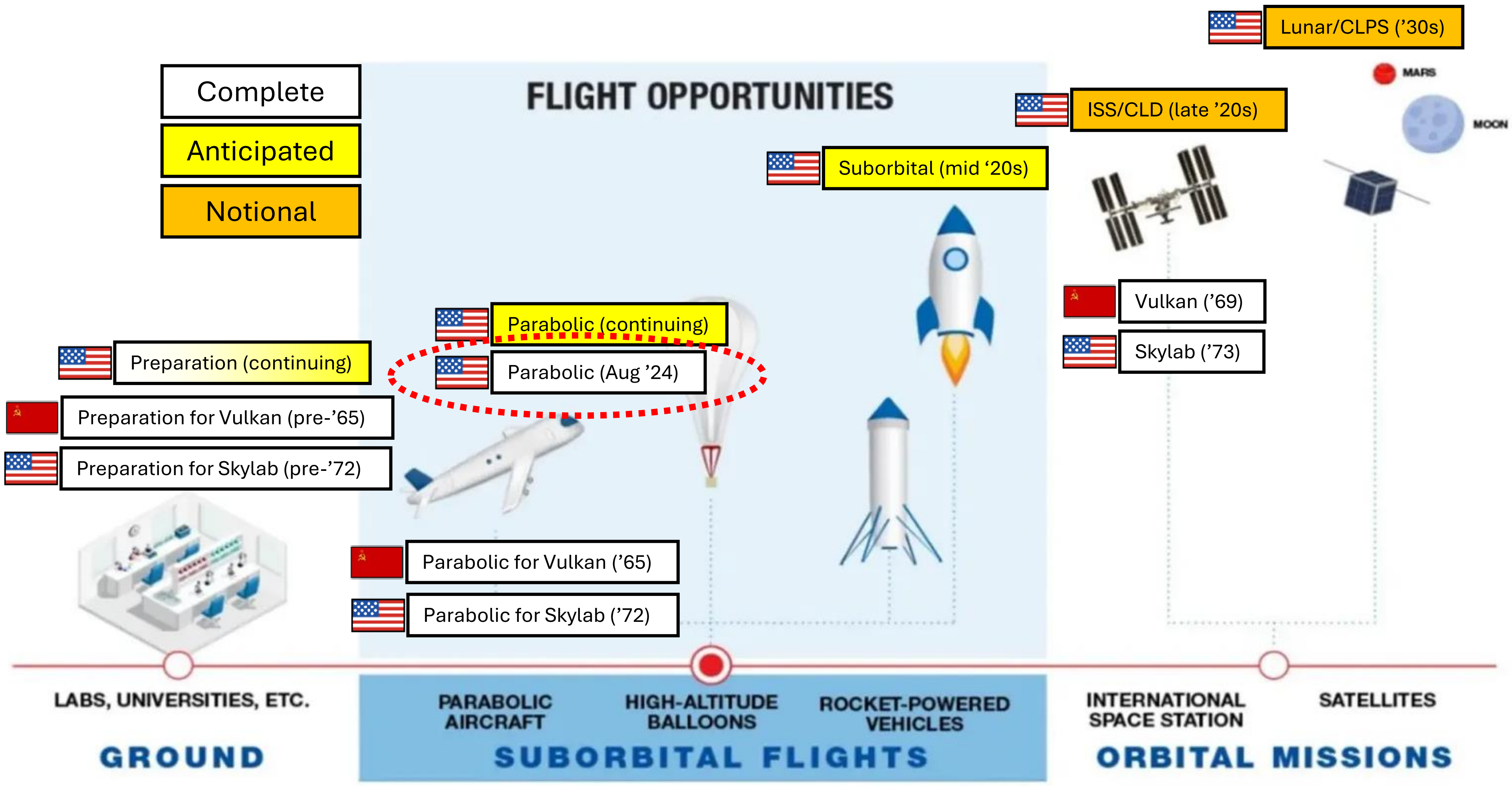
Structured light scan of joint fit-up on Flat Floor

Half of joint on mobile base, other half on floating robotic arm; LBW from side; *in situ* videography and thermography

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



Progression of flight experiments



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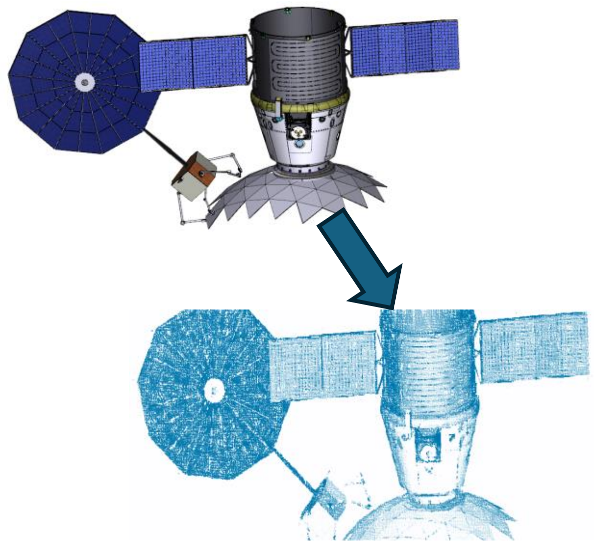


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Collaboration with Ohio State University on parabolic LBW

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.

Heritage parabolic vacuum chamber from NASA/LaRC

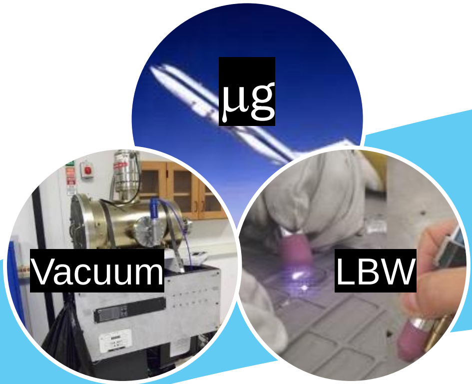
Laser Beam Welding

Courtesy: IPG Photonics

Modern high-power fiber lasers enable LBW for space; Welding times within microgravity parabola length (15-20 seconds)

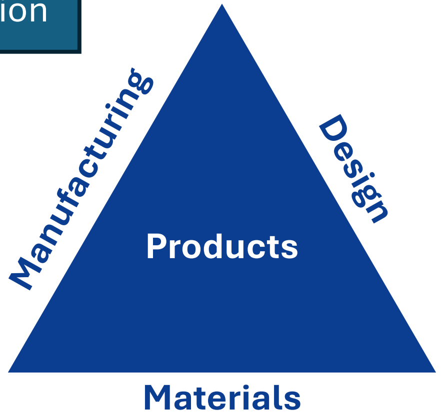
OSU has following talk with in-depth technical discussion

Generate Model Calibration Data



OSU-NASA CAN

Leverage LBW expertise and workforce development at OSU

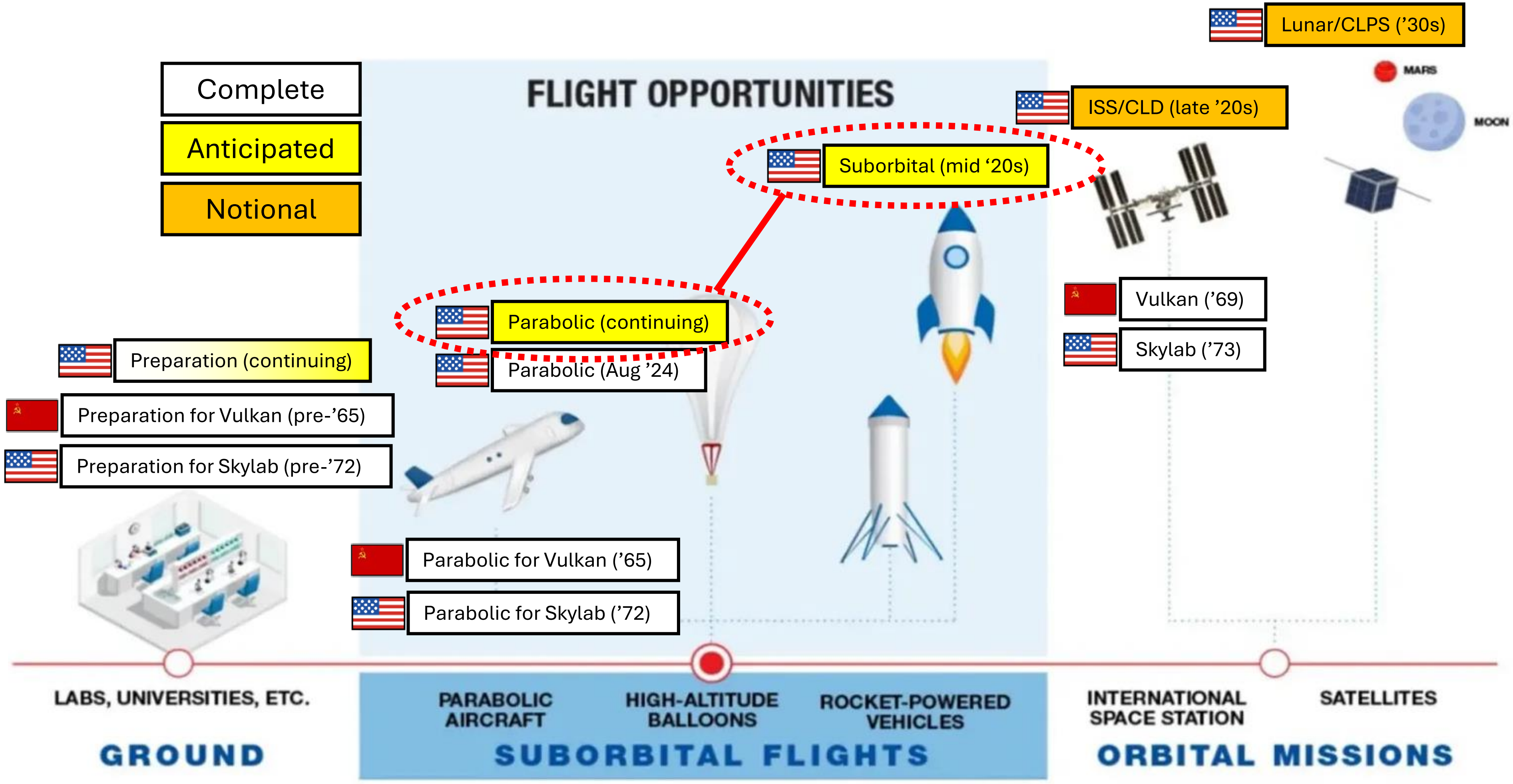


Integrated Computational Materials Engineering (ICME)

Retrofitted vacuum chamber in flight on Zero-G 727 aircraft

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

Progression of flight experiments



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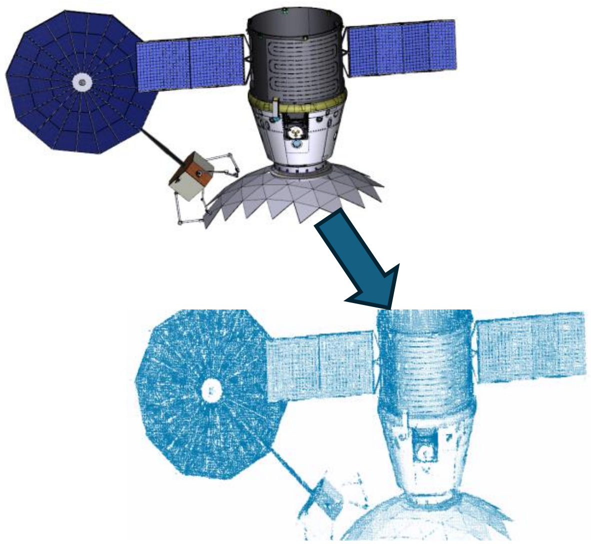
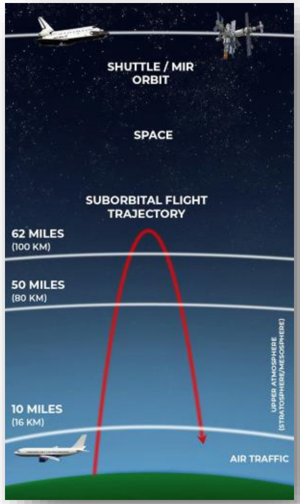


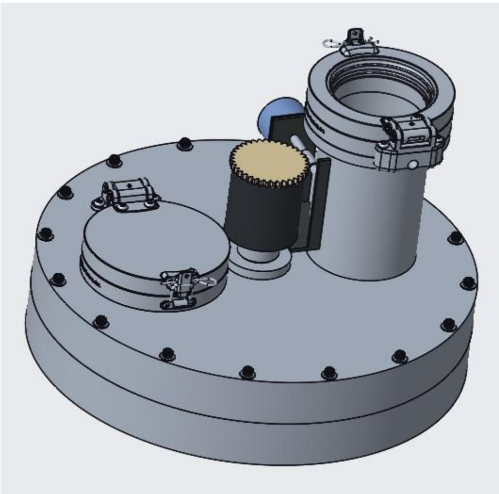
Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

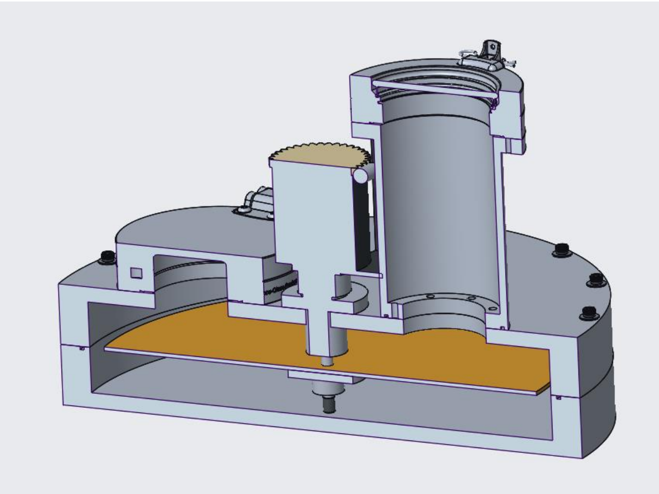
Evolve from parabolic to suborbital flight experiments

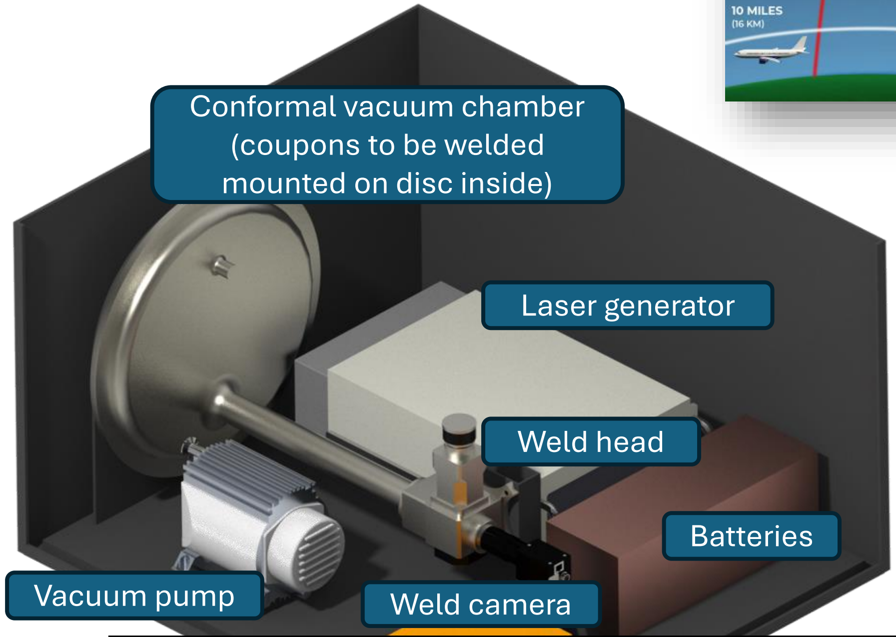
Parabolic	Suborbital
Tens of seconds in reduced or μg	Minutes in reduced or μg
Two-*g* during pull out (weld solidified?)	Hi-*g* only before welding (launch)
g-jitter complicates effect of gravity	Reduced *g*-jitter



Initial protoflight hardware design

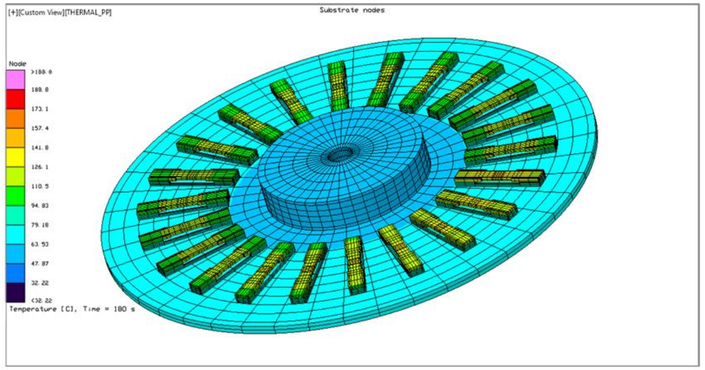


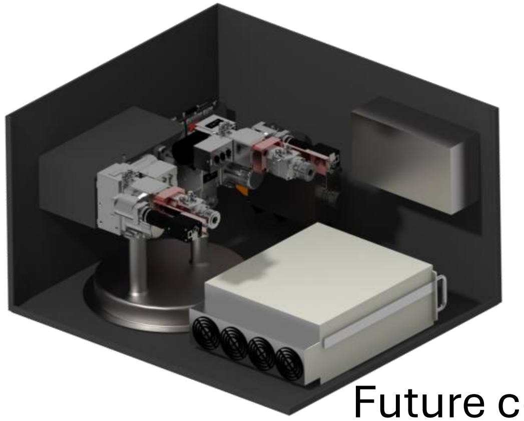




Conceptual design developed with MSFC Advanced Concepts Office

Thermal and structural modeling





Future concept: multiple weld heads

Practicalities of suborbital LBW

Laser module selected: 1500 W peak pulsed power, 1070 nm, Yb fiber

Requires batteries (excessive power draw from flight platform)

Fully automated control

Investigating (via ground testing) concerns re:

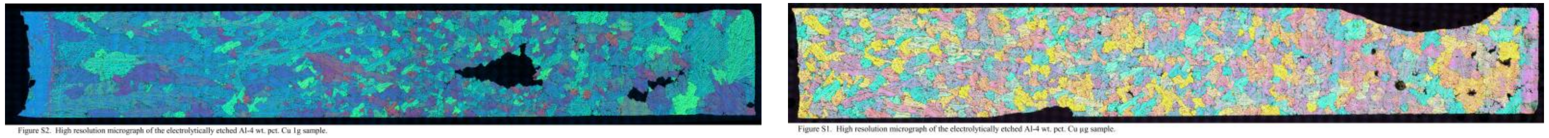
- Vapor deposition and spatter on vacuum window
- Loss of vacuum due to offgassing

Courtesy: IPG Photonics

Materials selected: stainless steel 316L, aluminum 2219-T87, Ti64

Also considering Al-Cu binaries:

- More tractable for computational models
- Previous flight experiments investigated solidification (Al-4wt%Cu in 1*g* and *ug* shown below)

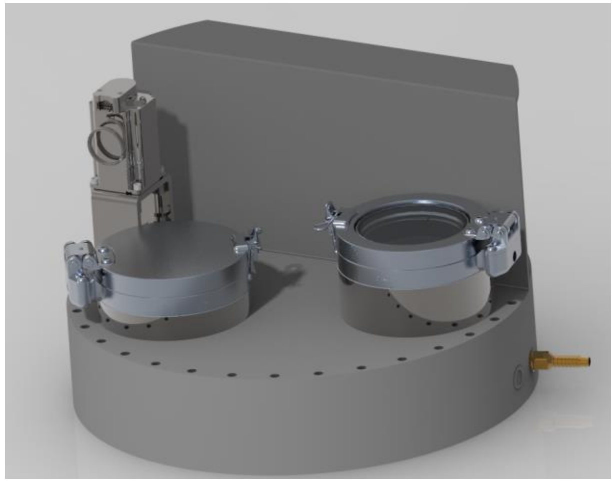


Beckermann, C, "Solidification Using a Baffle in Sealed Ampoules Effect of Convection on the Columnar-to-Equiaxed Transition in Alloy Solidification" NASA Physical Sciences Informatics (PSI). https://psi.ndc.nasa.gov/app/record/204999

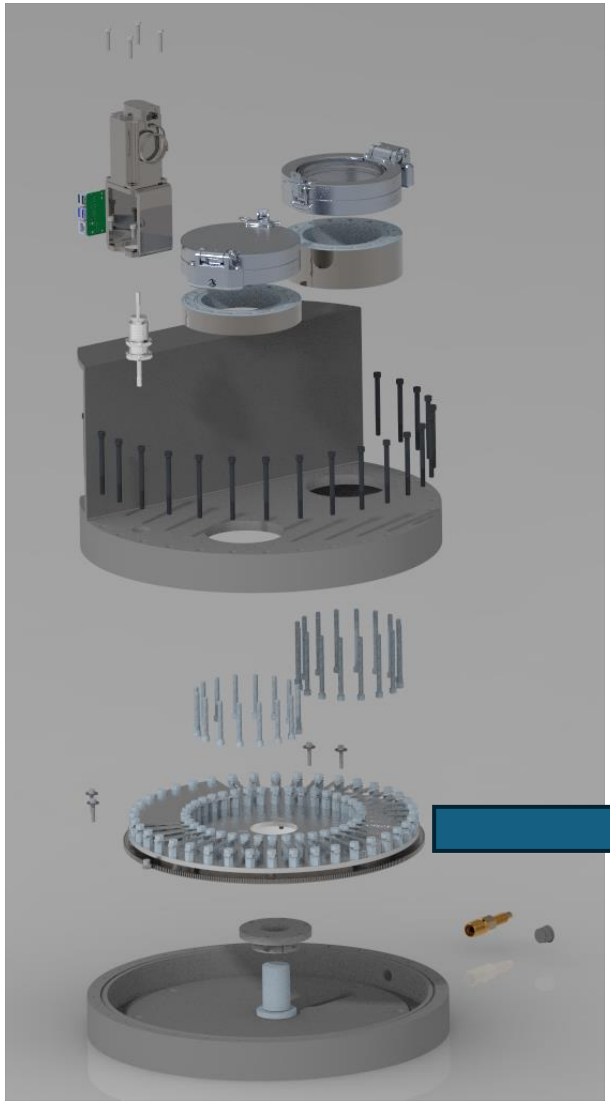
Data collection to anchor computational models

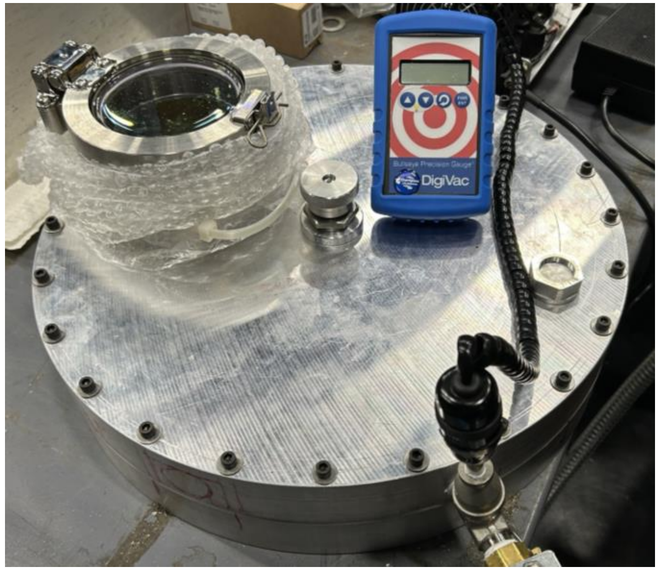
- Weld camera: 140+ dB HDR imaging for weld bead size & morphology
  - Coxial mount onto weld head for on-line alignment with specimens
- Thermal/weld camera: SWIR (InGaAs) thermography of weld
  - Reduced effect of emissivity shifts on thermal data
  - Enhanced view through weld fumes
- Thermocouples: provide calibration for thermography
  - Establish workpiece starting temperature (collateral heating)
  - Require slip ring (or similar) and pass-through into vacuum
- Plume characterization (ground only)
  - Spectrometer for chemistry, MWIR or Schlieren for morphology
- What else?

Latest prototype status – design and fabrication

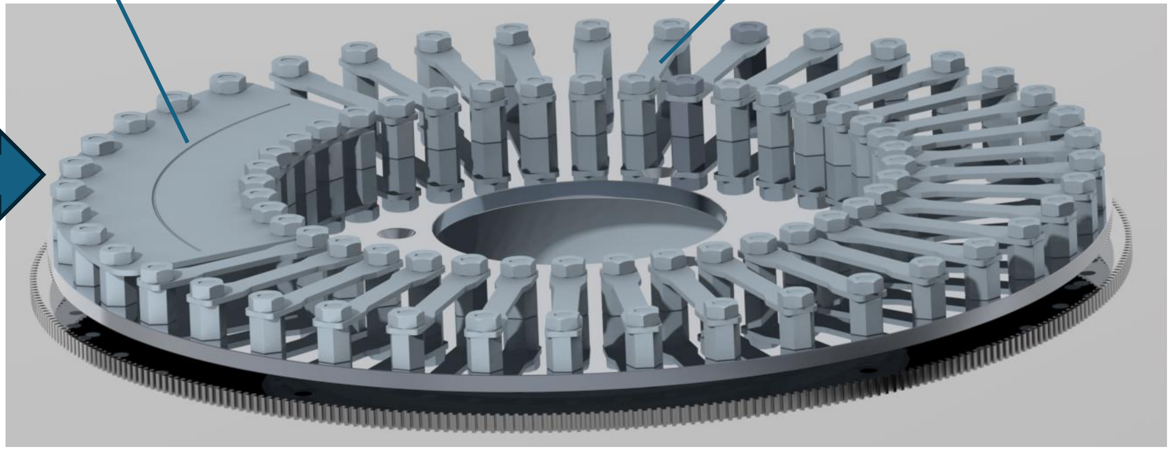


- Switched from central spindle to turntable driven by ring gear
- Added additional access door
- Reduced length of "stovepipe"
- Provided mounting plane for weld head, etc.

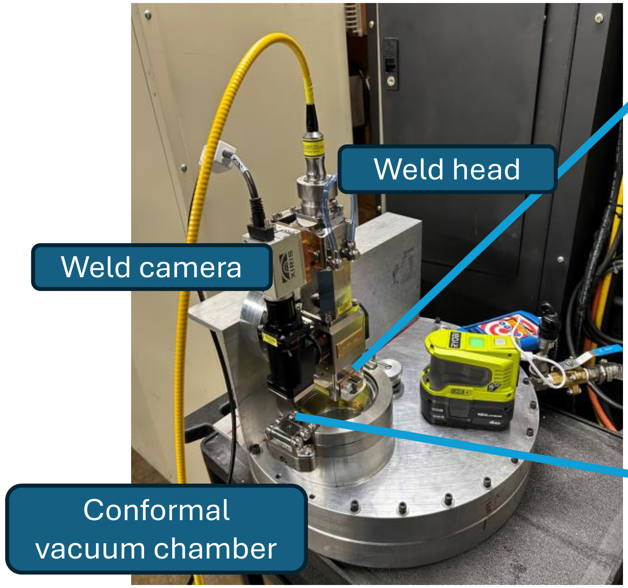


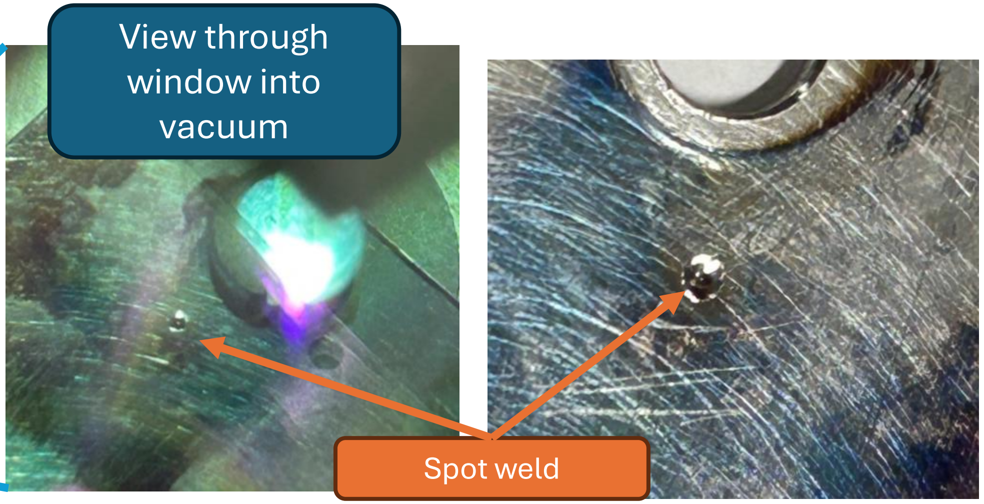


- Vacuum chamber robust and maintains <100 Pa
- Initial operating capability (spot welds without thermography) expected shortly



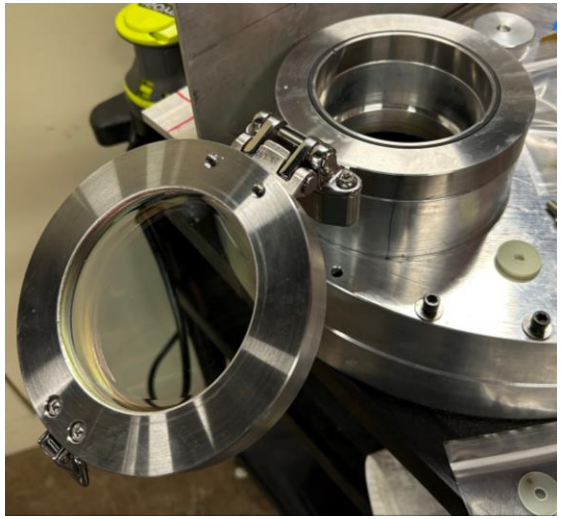
Latest prototype status – initial operating capability





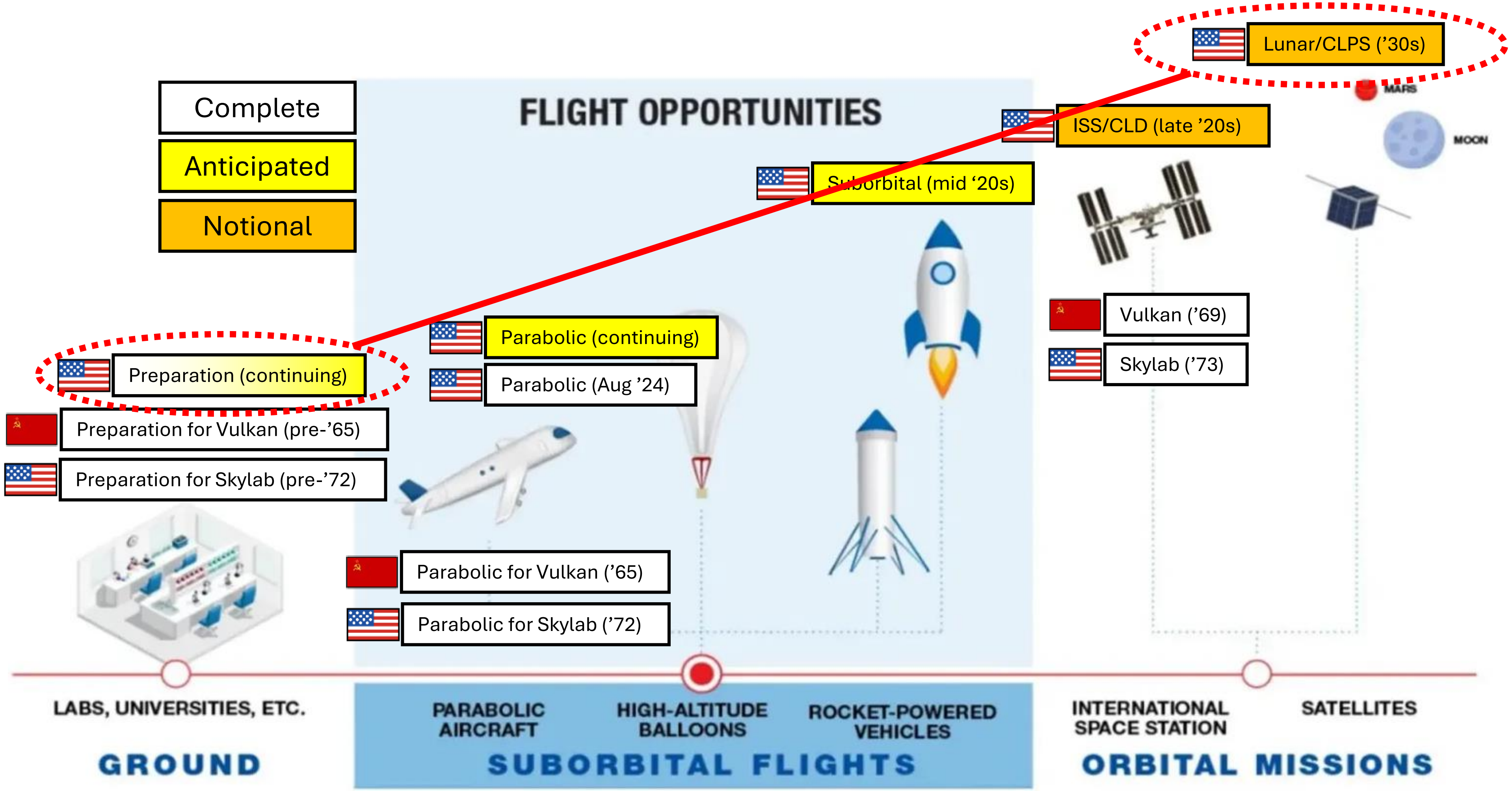
Coaxial weld camera in operation; thermal to follow

Rapid access to coupons

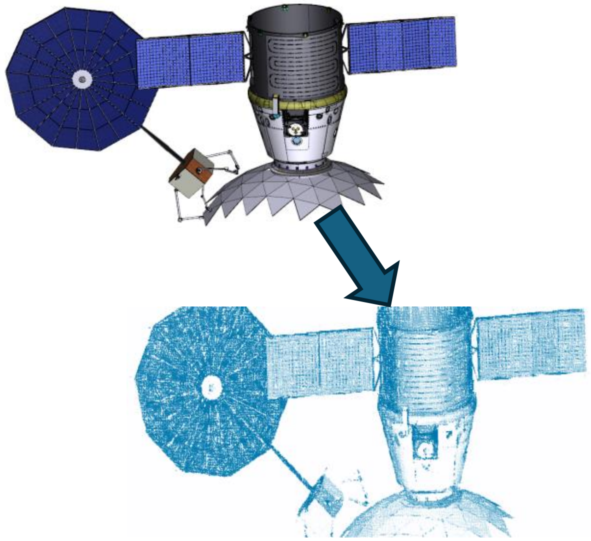


Concern: metal vapor coating, also spatter
Current mitigation: sacrificial glass
Investigating other mitigations

Progression of flight experiments



Concurrent development of Digital Twin using collected data

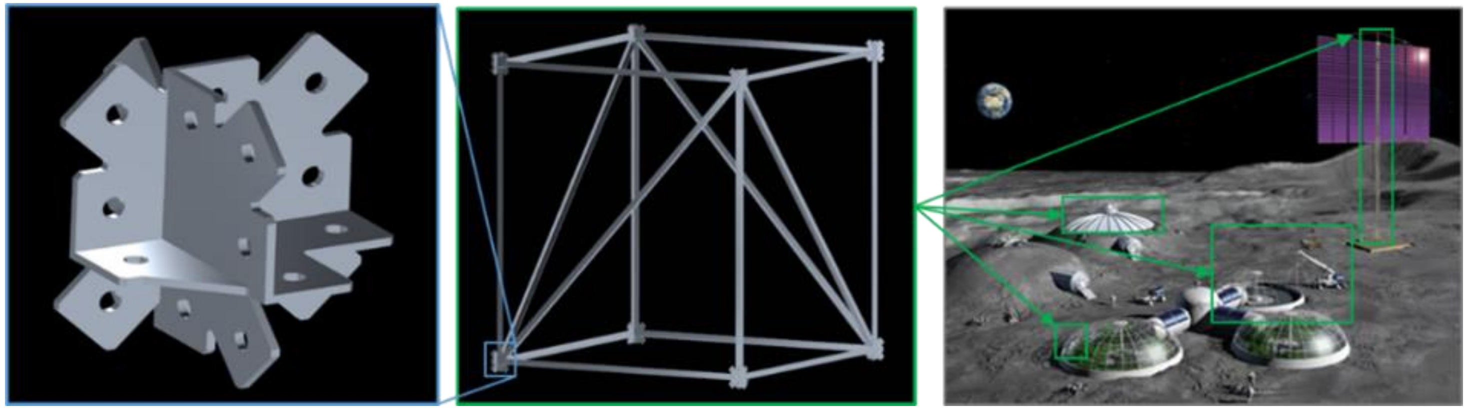


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

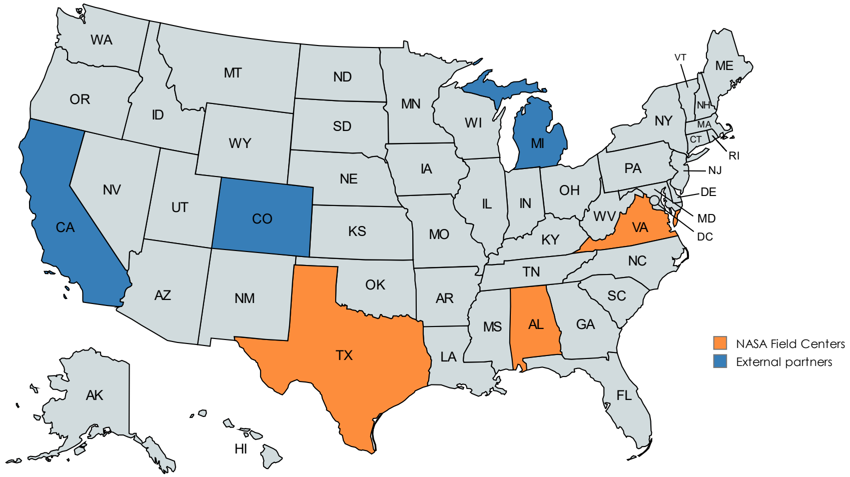
Lunar Assembly and Servicing by Autonomous Robotics (LASAR)

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

- Ruggedized laser optics and robotic arm suitable for thermal vacuum
- Supervised autonomous LBW
- Non-contact NDE of welds



PI: Andrew O'Connor; PM: Zach Courtright (both MSFC)



NASA Core Team Members

Name	Center
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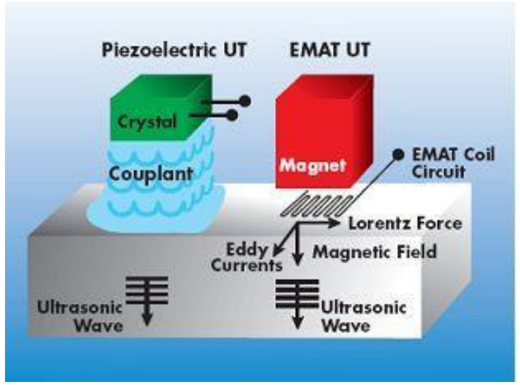
Alex Sowell	NASA/JSC
Raju Subedi	NASA/MSFC
Brace White	NASA/LaRC
Supported by:	
William Evans	NASA/MSFC
Matthew Mahlin	NASA/LaRC
Parker Shake	NASA/MSFC

External Partners

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

Mentors

Name	Role
Shaun Azimi	JSC Robotics SME
Bill Doggett, PhD	LaRC In-Space Assembly SME
John Fikes	MSFC Management SME
Jeffrey Sowards, PhD	MSFC Laser Welding SME



Electromagnetic acoustic transduction (EMAT) for NDE

Conclusions

- NASA and partners are progressing experiments from ground to flight
- Demonstration of LBW 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.
  - Suborbital flight unit hardware
  - Parabolic and suborbital 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 internal funds, Biological and Physical Sciences Division of NASA Science Mission Directorate, Space Nuclear Propulsion, NASA Space Technology Mission Directorate, etc.
- OSU support from Marshall Space Flight Center internal funds via
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- Second parabolic flight day support from NASA Flight Opportunities
- John Ivester (NASA/MSFC-EM42) for structured light scans of Flat Floor experiment