Establishing an In-Space Joining Ecosystem at NASA Marshall via Laser Beam Welding

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NASA Marshall Space Flight Center

Presented on 2025-01-08 at AIAA SciTech in Orlando, FL

In-space welding enables space infrastructure

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

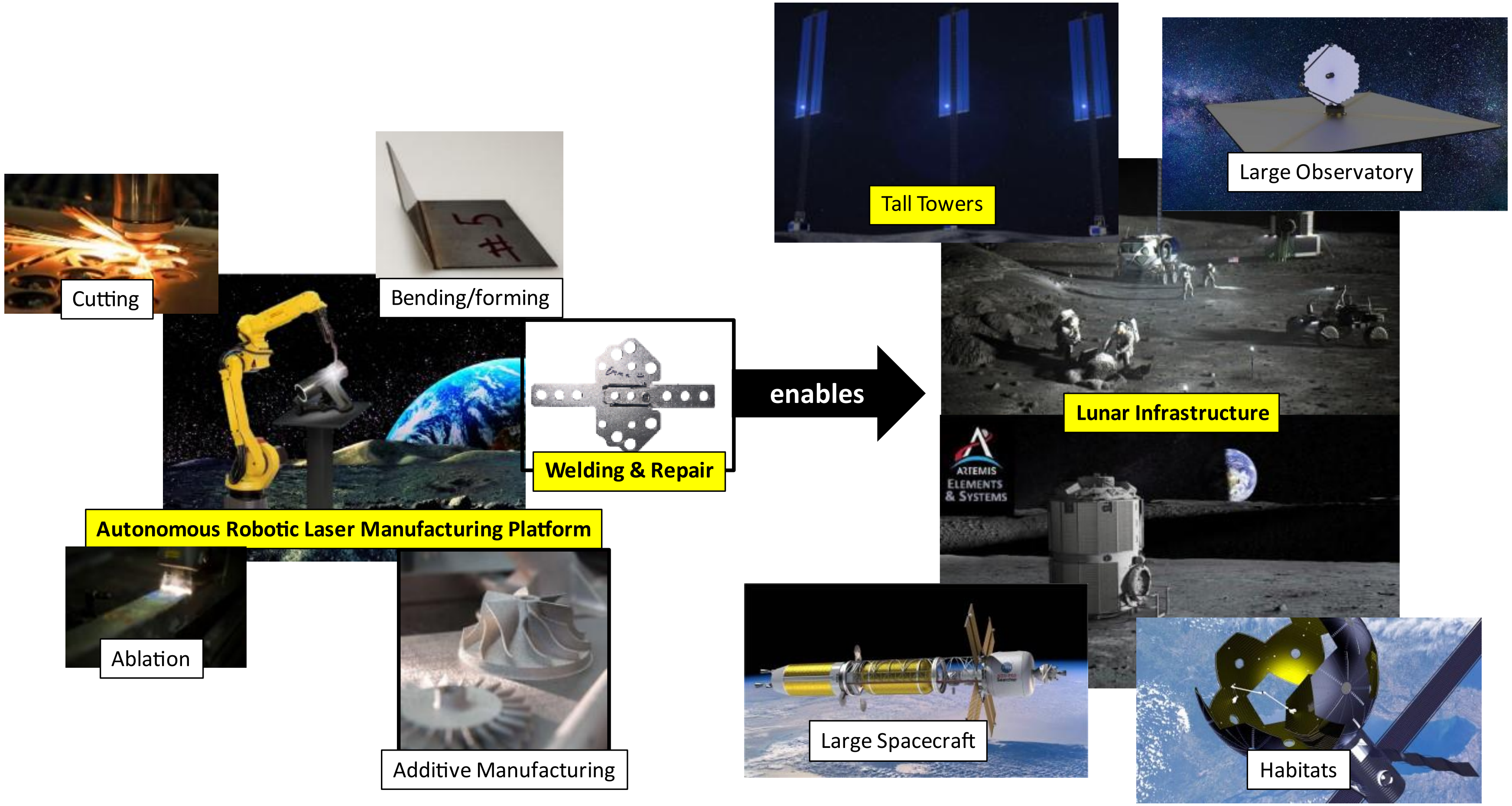
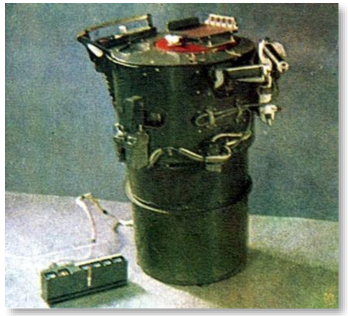


Image credit: ThinkOrbital, www.mechanicalcaveman.com

Timeline of In-Space Welding and Joining



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 on orbit by ThinkOrbital
2024-2025. Parabolic fiber LBW Flight. Ohio State and NASA

Parabolic Vulkan experiment (USSR). 1965

Parabolic Skylab Materials (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

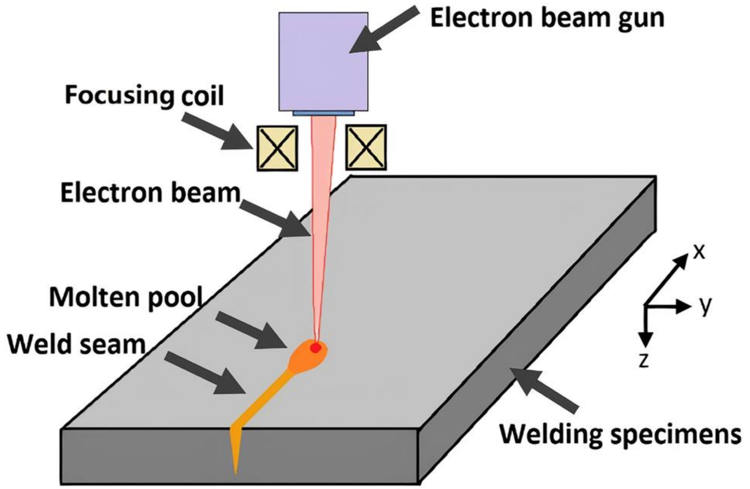
It has been over 50 years since NASA has performed a weld in space.

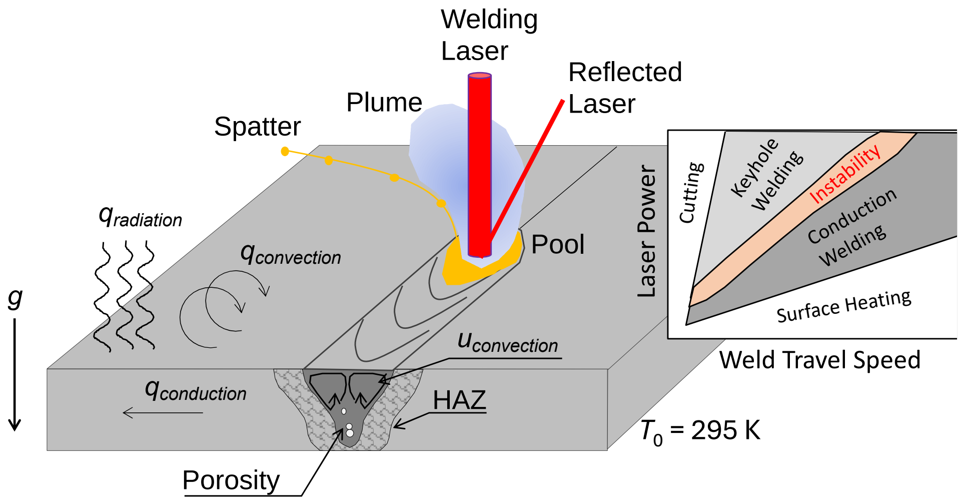
n.b.
Electron beam welding = EBW,
Laser beam welding = LBW

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)

Why laser beam welding in space?





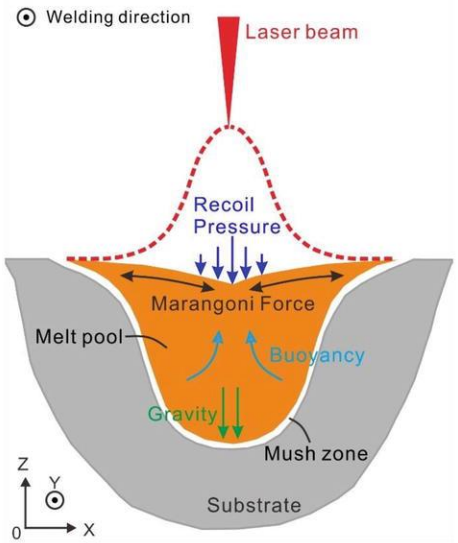
High-energy Beam Process → ↓ Criteria	Electron	Laser	Status
IVA flexibility (*e.g.* in habitat) & EVA flexibility (*e.g.* in vacuum, Lunar surface, on Mars)	●	○	Capability available after planned development
Workpiece variety (*e.g.* geometry, material)	◒	○	
Suitable for operation on end effector of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

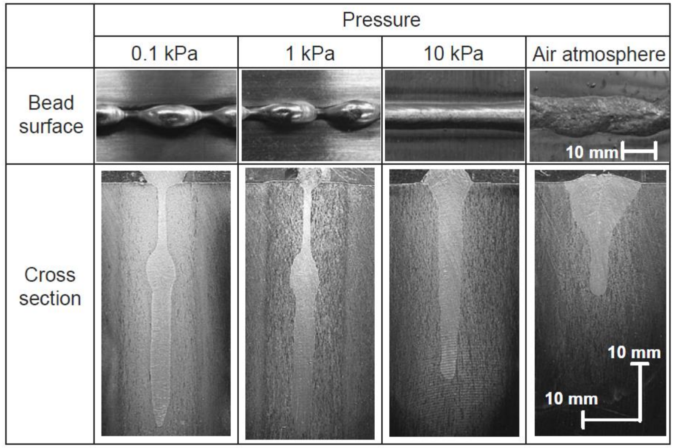
Variable	Case 1: In Space	Case 2: Chamber Inside Space Habitat	Case 3: Inside Space Habitat	Case 4: Lunar Surface	Case 5: Martian Surface	Baseline: Earth	Capabilities Needed at Present
Gravity	μg	μg	μg	0.17 *g*	0.38 *g*	1 *g*	μg to 0.38 *g*
Atmosphere	Vacuum (10^{-19} Pa)	Vacuum (10^{-4} Pa)	>21% O_2,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



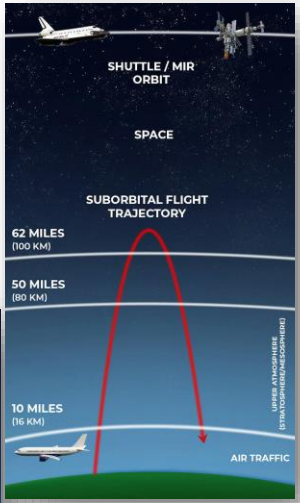
Simulating space conditions for welding

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

Low Earth Orbit (LEO)

μg

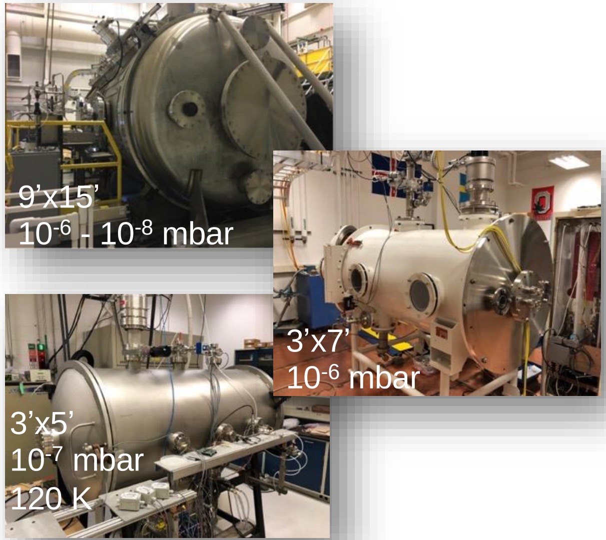
Lunar surface

0.17 *g*

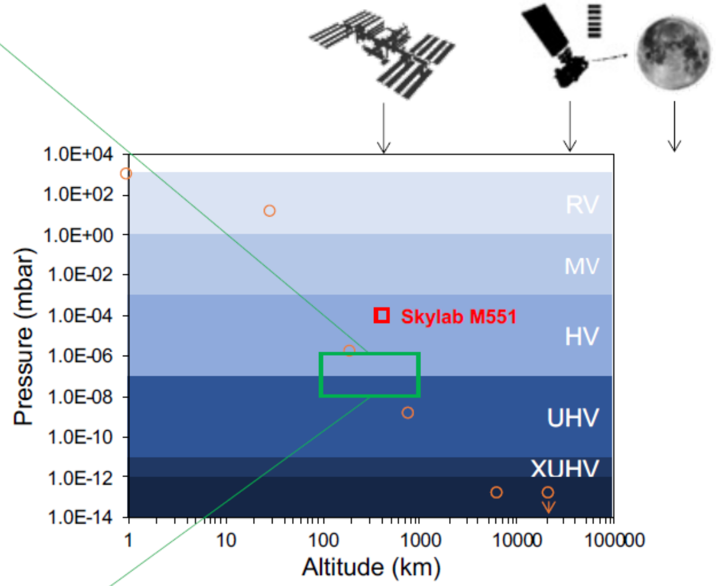
Martian surface

0.38 *g*

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

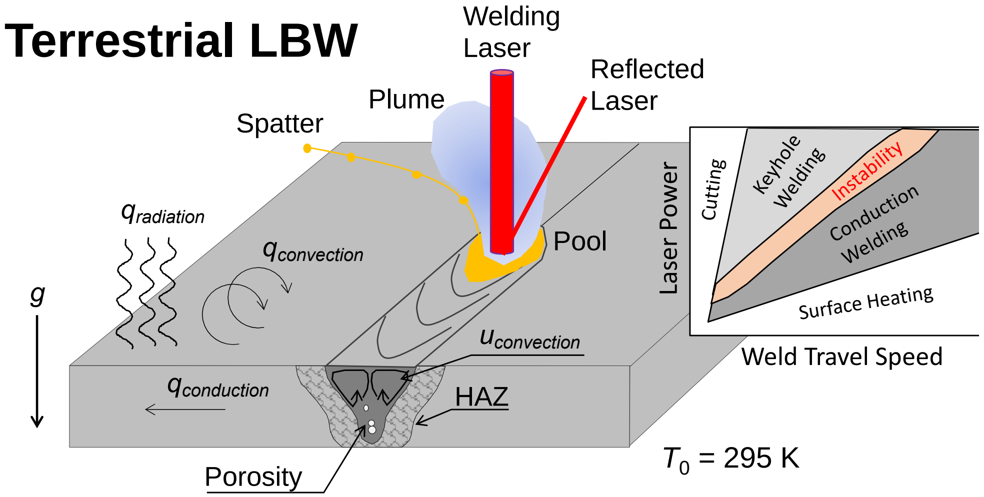
Mladenov, Koleva, and Trushnikov, *E+E*, 2019.

Key effects to consider for in-space LBW

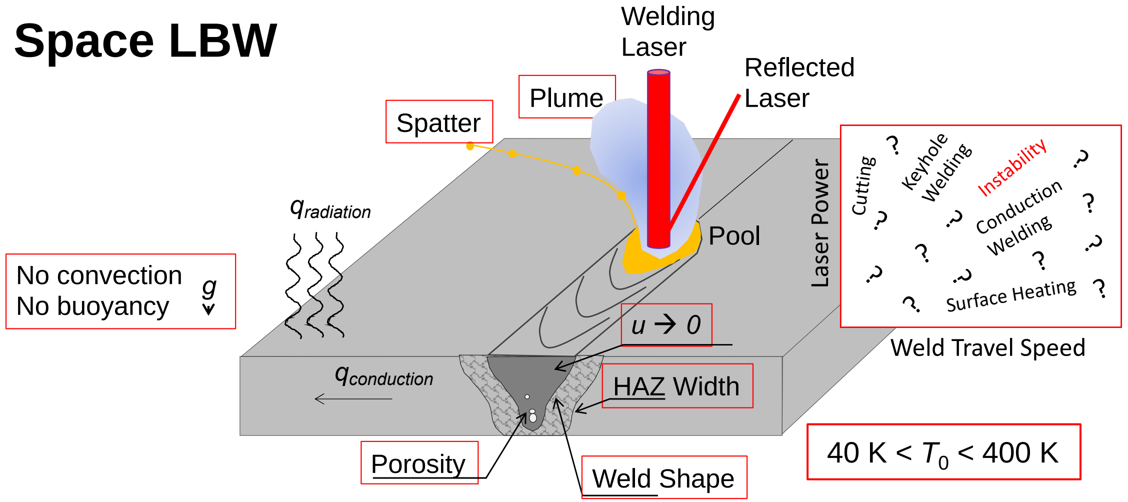
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

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)

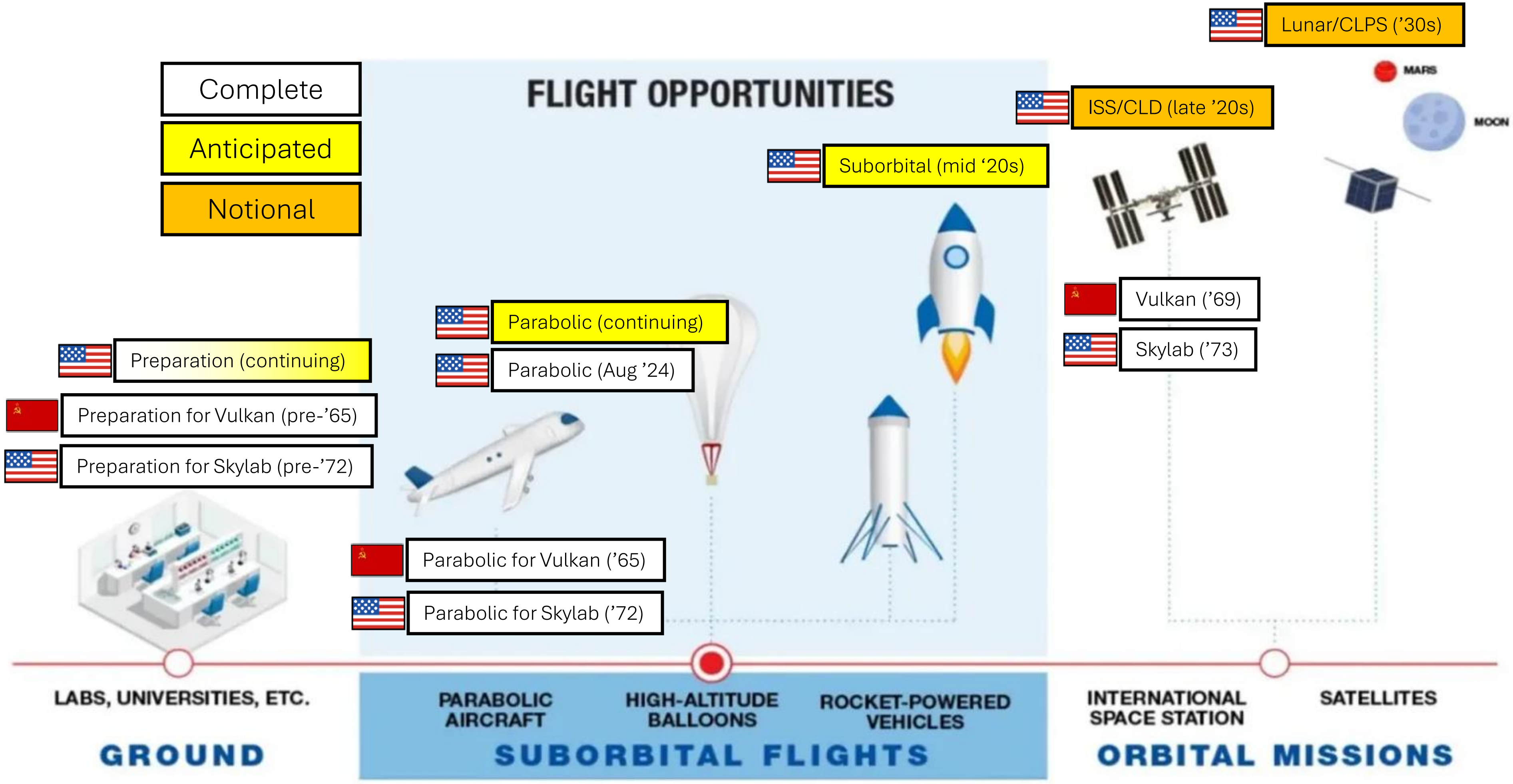
Issue #3 Reduced pressure/vacuum in space:

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.

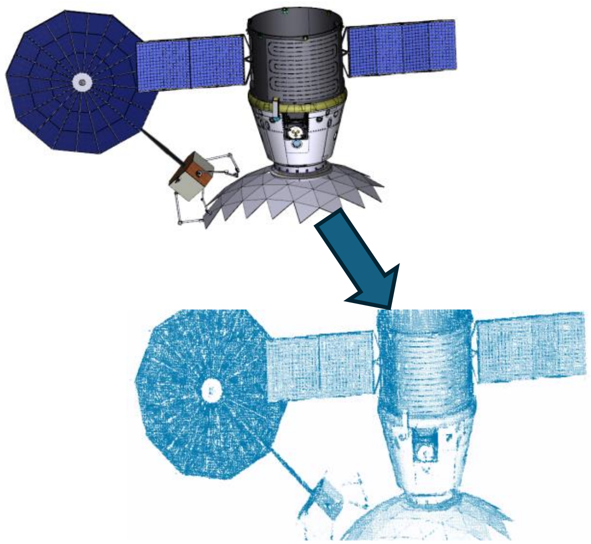
Reduced pressure influences laser beam keyhole stability, evaporation of volatile species, safety issues, etc.

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

Progression of flight experiments

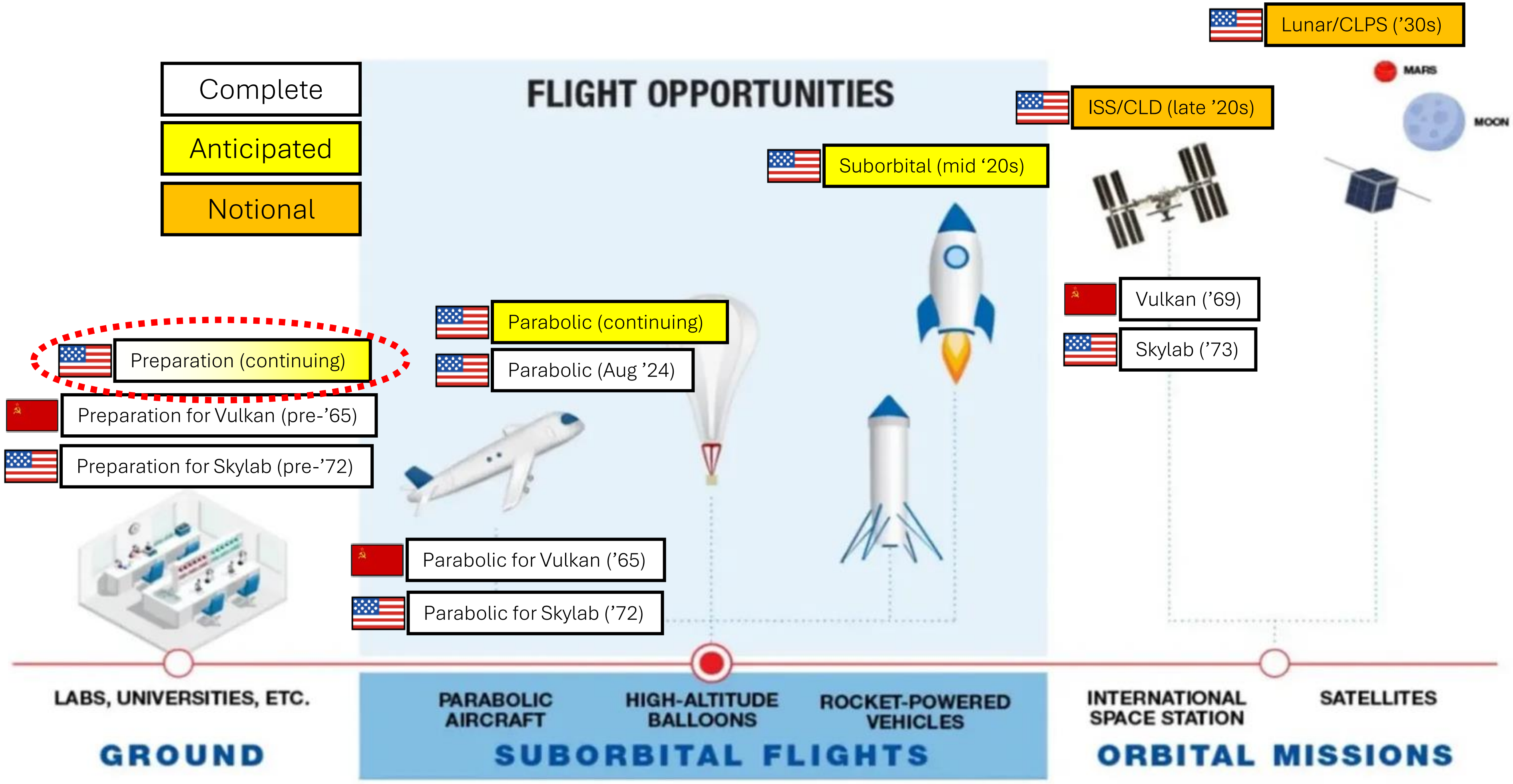


Concurrent development of Digital Twin using collected data



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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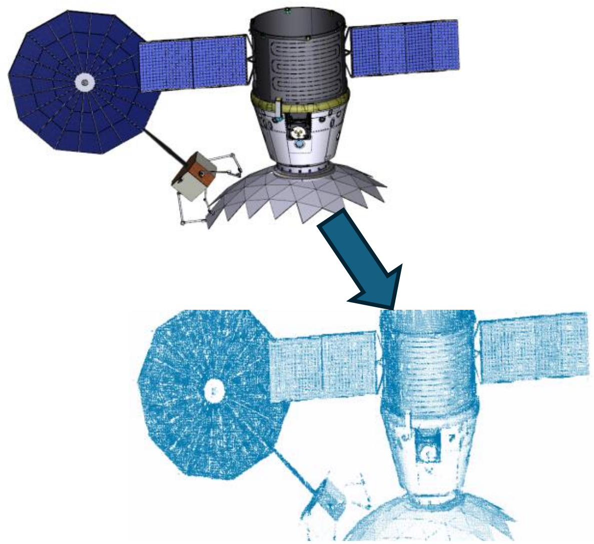
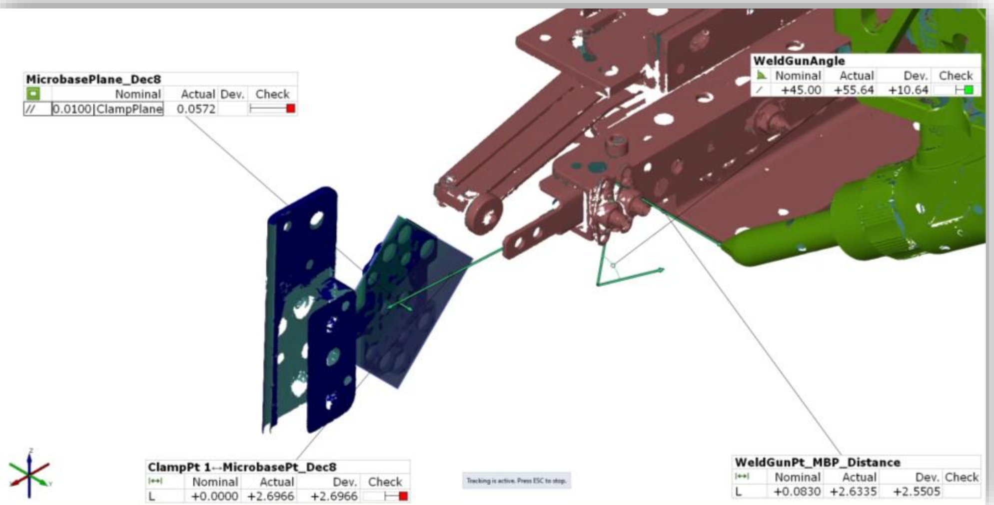


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

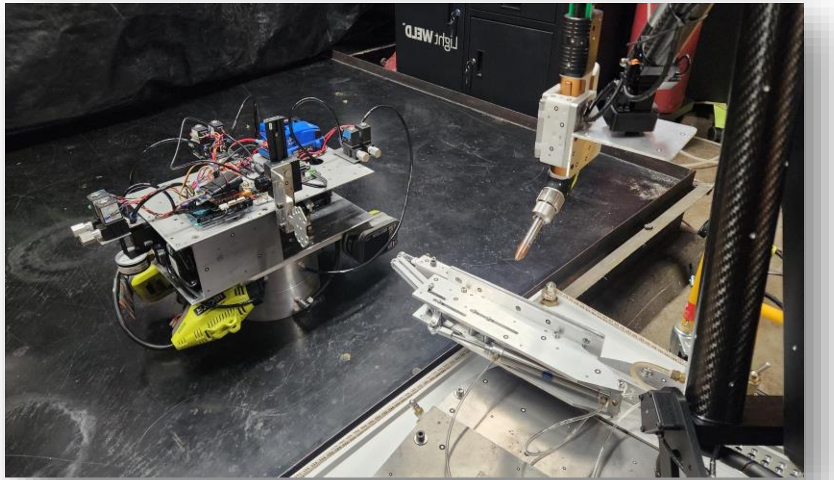
Ground testing LBW on 3-DOF "Flat Floor"

Enclosed LBW station for rapid parameter development



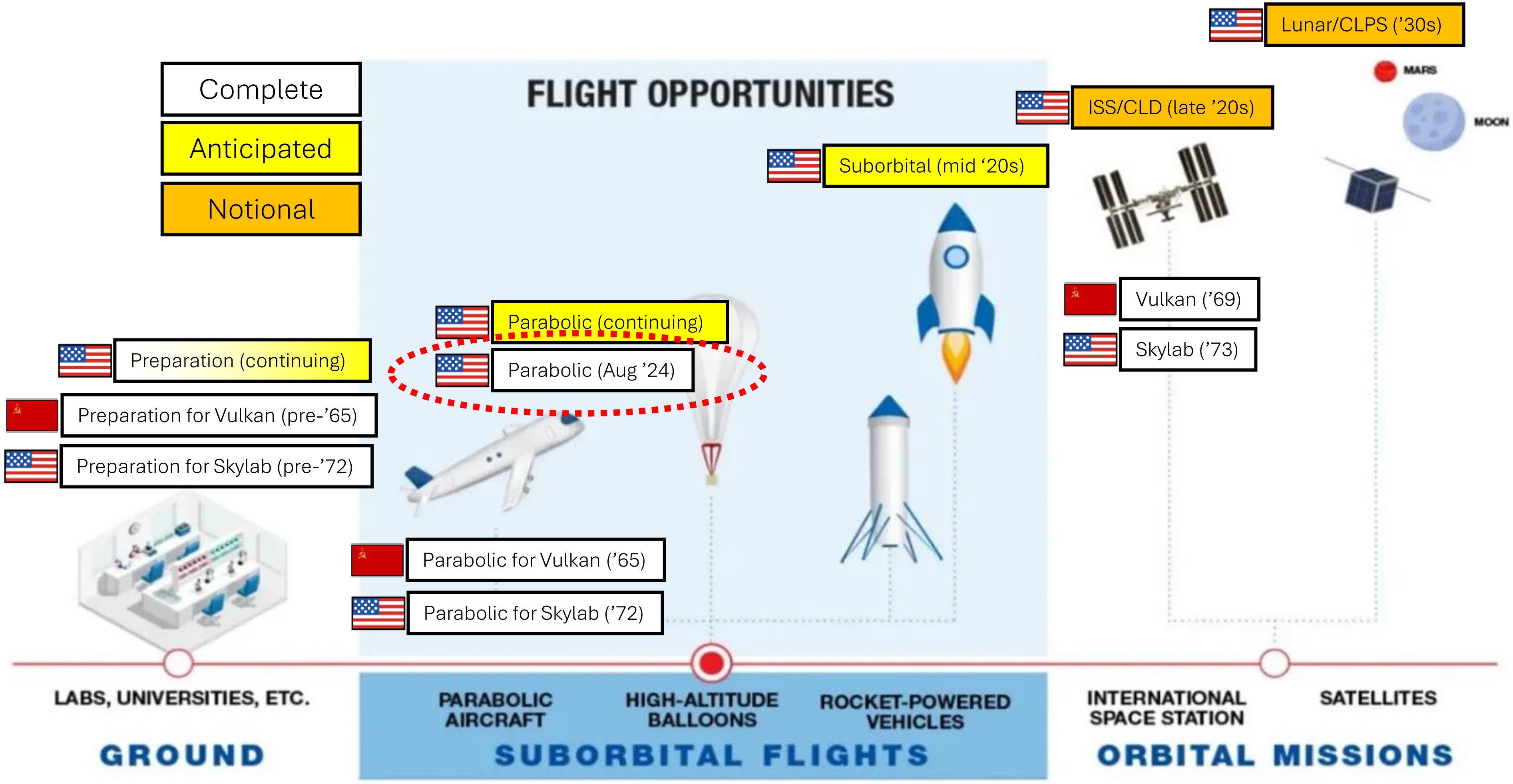
Structured light scan of joint fit-up on Flat Floor

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

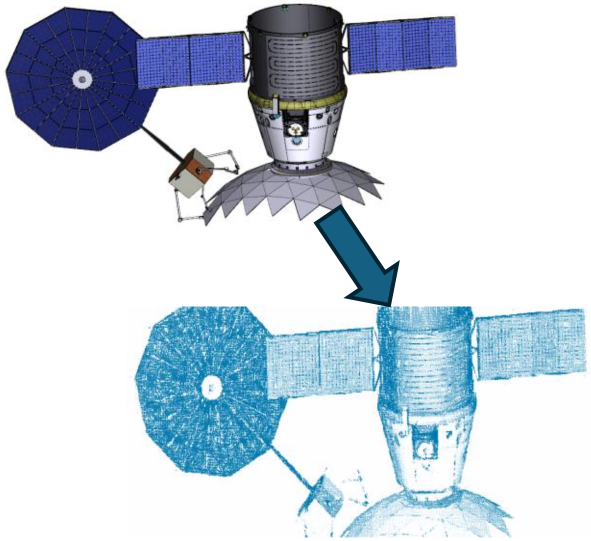


Ongoing:
Glovebox capable of variable composition atmosphere and with regolith simulant (Lunar, Martian, etc.) via handheld LBW

Progression of flight experiments



Concurrent development of Digital Twin using collected data



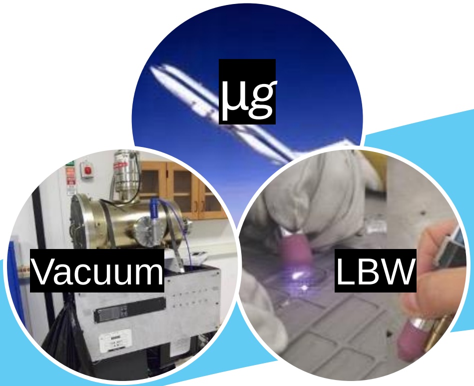
Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Collaboration with the Ohio State University on parabolic flight

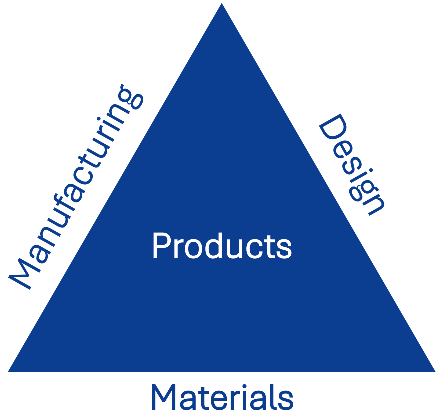
Integration and Ground Demonstration of Self-contained Laser Welding System for Parabolic Microgravity Experiments.

- 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.

Generate Model Calibration Data



OSU-NASA CAN



Integrated Computational Materials Engineering (ICME)

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)

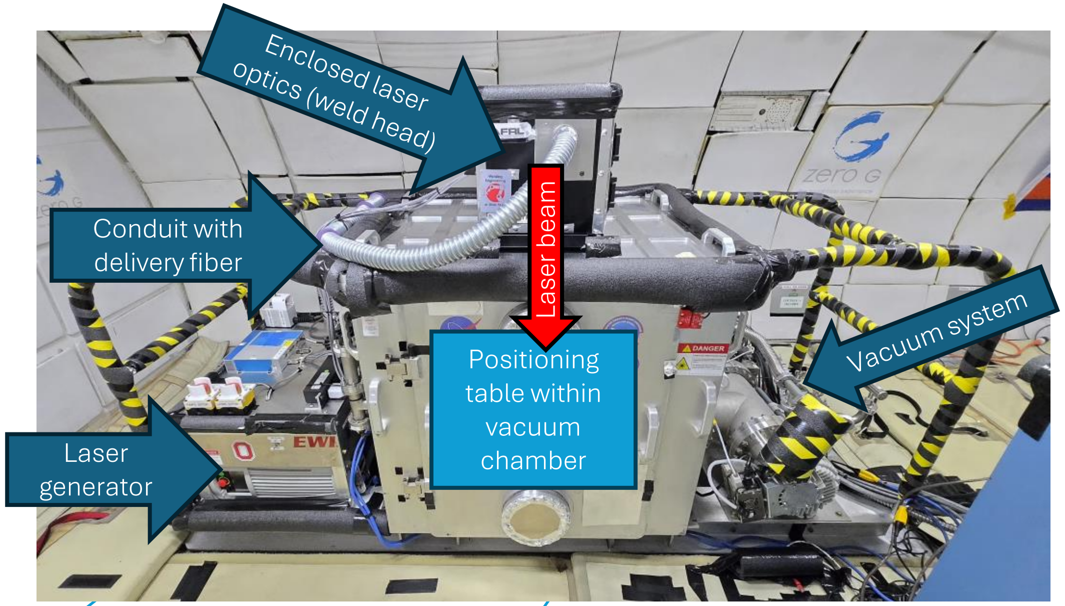
Leverage LBW expertise and workforce development at OSU

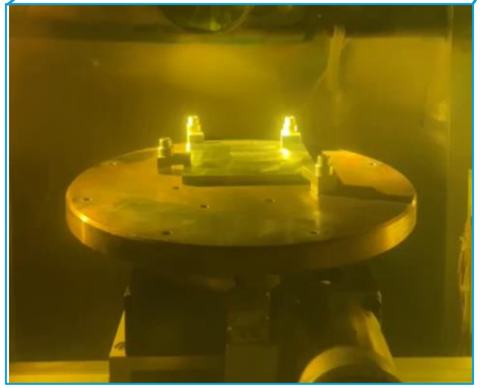
Retrofitted vacuum chamber in flight on Zero-G 727 aircraft

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

Post-flight data analysis ongoing and preparing for re-flight

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING





in situ thermal data and videography

Successfully welded during 69 out of 70 total parabolas – including both Lunar and microgravity profiles

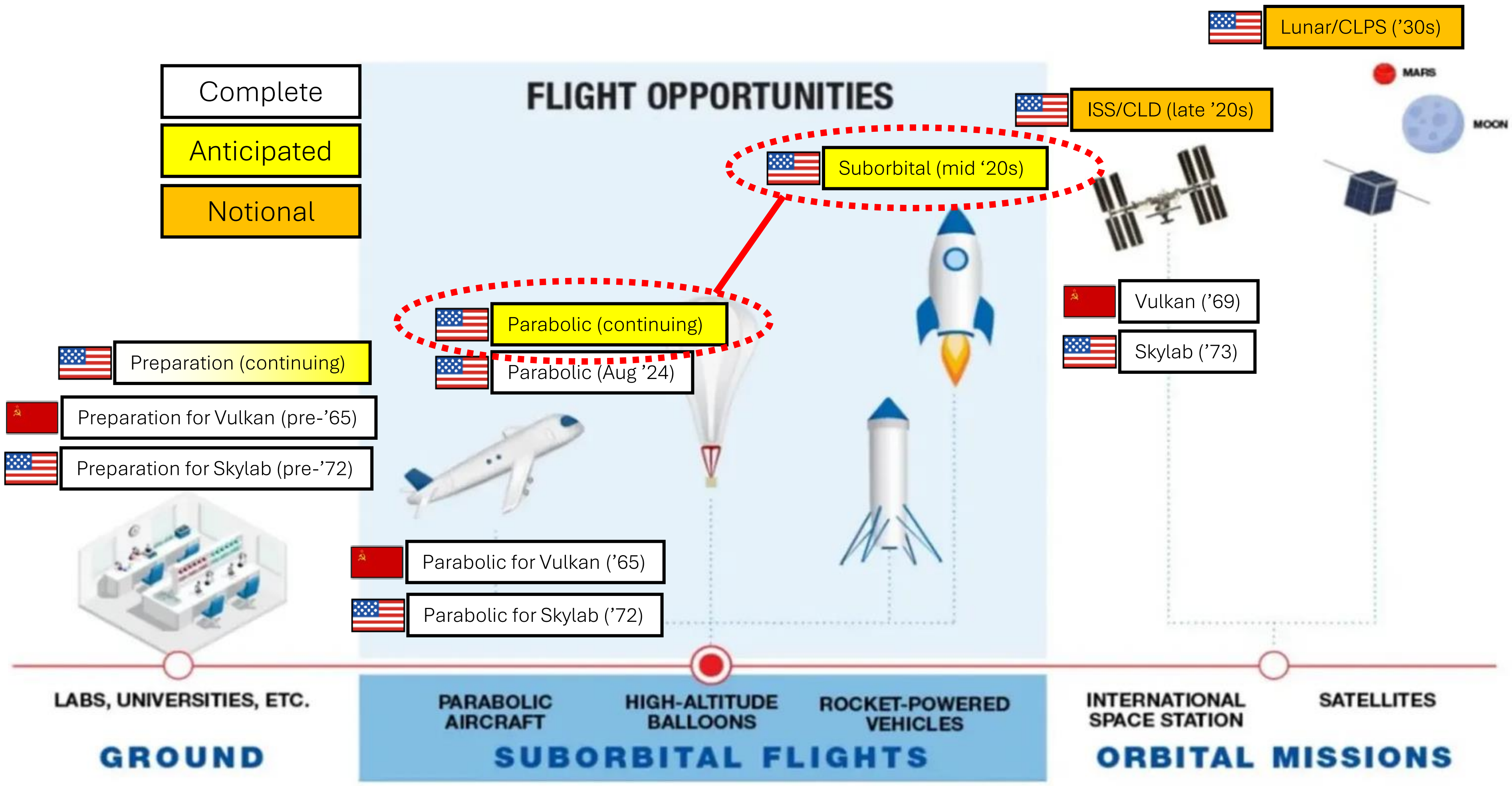
Characterization in progress:

- X-ray radiography, micro-CT scans
- Metallography and hardness testing

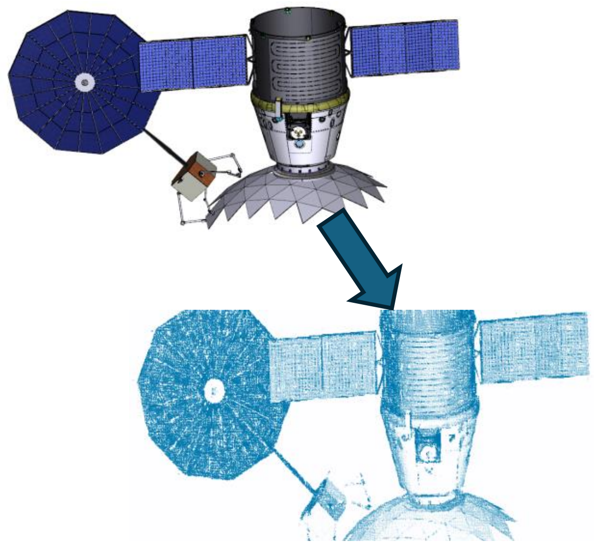
Upcoming flight tentatively scheduled for May 2025:

- Hermetic welds (pressure vessels, etc.) and realistic joints (lap, butt-lap, etc.)
- Continuous melt pools established and maintained through gravity transitions
- Reduced order alloys (*e.g.* Al-Cu for Al 2219) to ease computational modeling

Progression of flight experiments



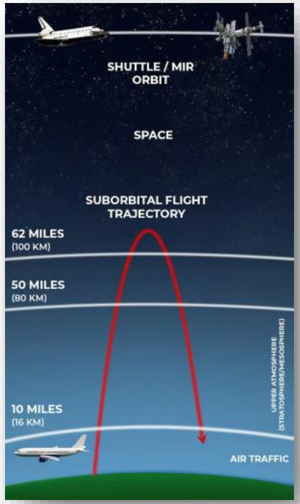
Concurrent development of Digital Twin using collected data



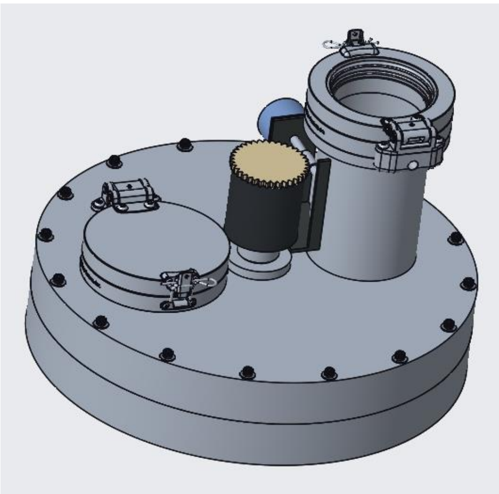
Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

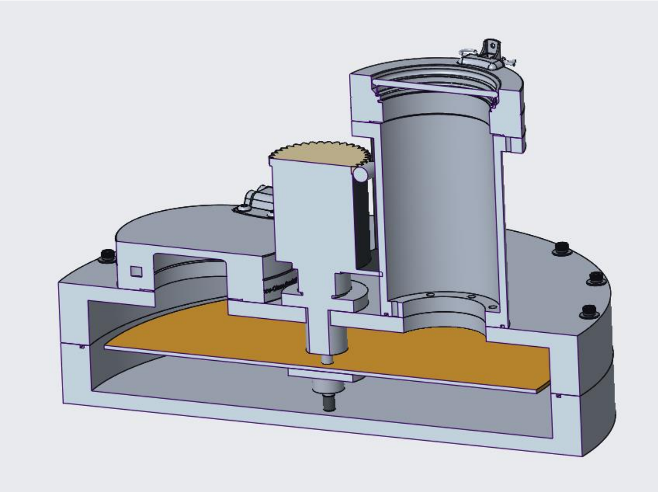
Evolve from parabolic to suborbital flight experiments

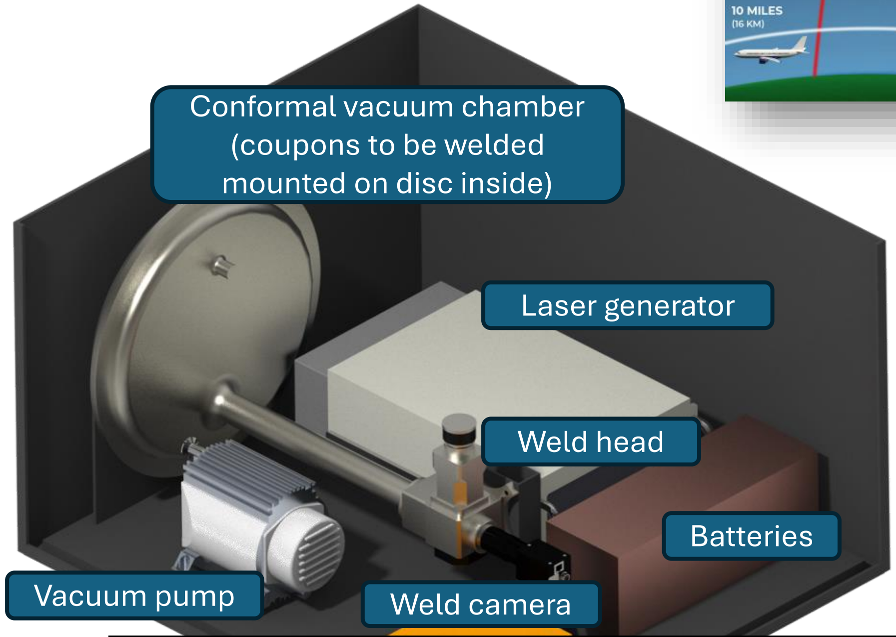
Parabolic	Suborbital
Tens of seconds in reduced or μg	Minutes in reduced or μg
Two-*g* during pull out (weld solidified?)	Hi-*g* only before welding (launch)
g-jitter complicates effect of gravity	Reduced *g*-jitter



Initial protoflight hardware design

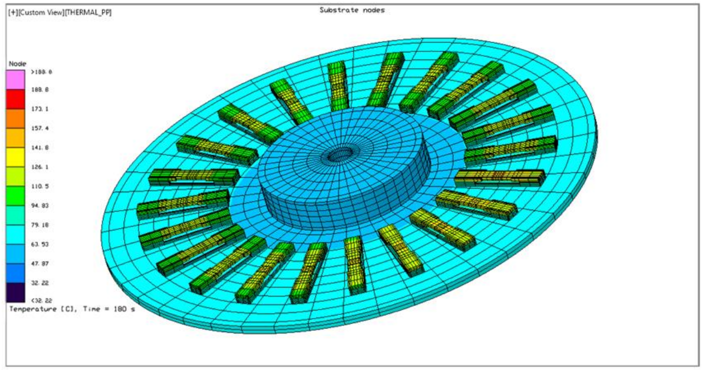


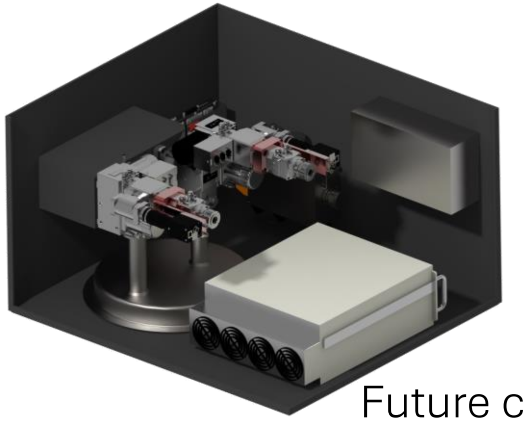




Conceptual design developed with MSFC Advanced Concepts Office

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:

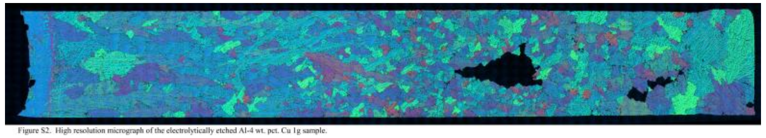
- Vapor deposition and spatter on vacuum window
- Loss of vacuum due to offgassing

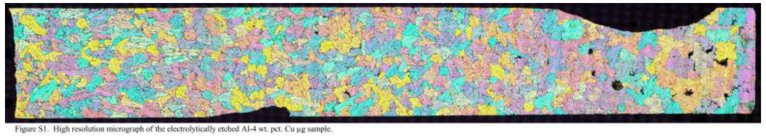
Courtesy: IPG Photonics

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 μ*g* shown below)





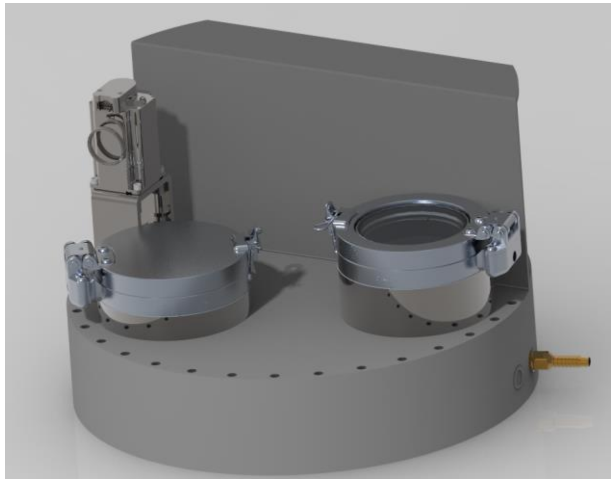
Beckermann, C, "Solidification Using a Baffle in Sealed Ampoules Effect of Convection on the Columnar-to-Equiaxed Transition in Alloy Solidification" NASA Physical Sciences Informatics (PSI). https://psi.ndc.nasa.gov/app/record/204999

Data collection to anchor computational models

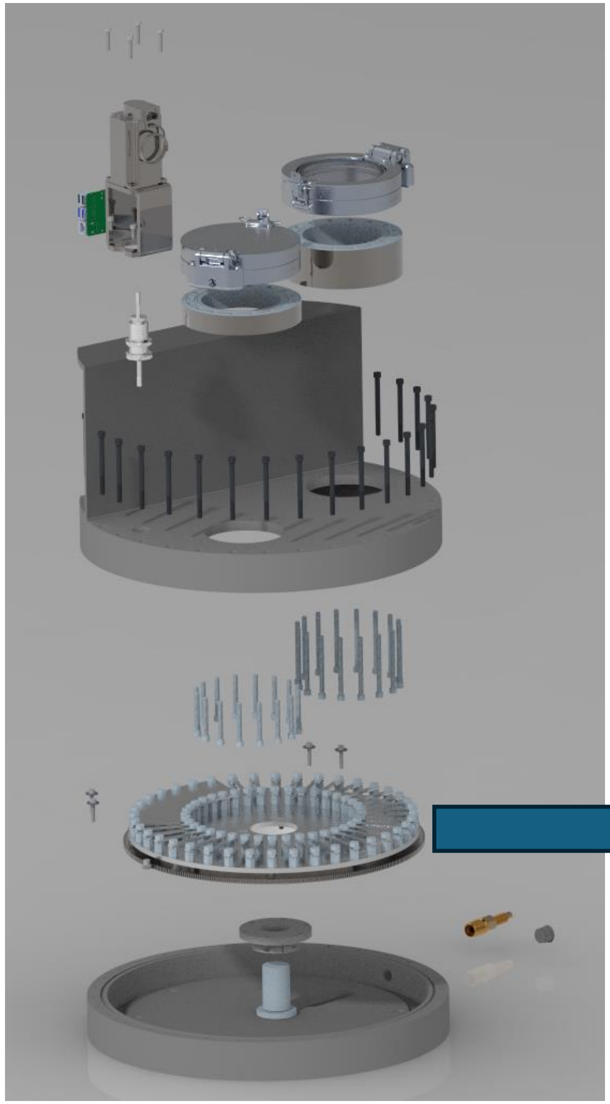
- Weld camera: 140+ dB HDR imaging for weld bead size & morphology
  - Coxial mount onto weld head for on-line alignment with specimens
- Thermal/weld camera: short-wave infrared (InGaAs) thermography of weld
  - Reduced effect of emissivity shifts on thermal data
  - Enhanced view through weld fumes
- 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, mid-wave infrared or Schlieren for morphology

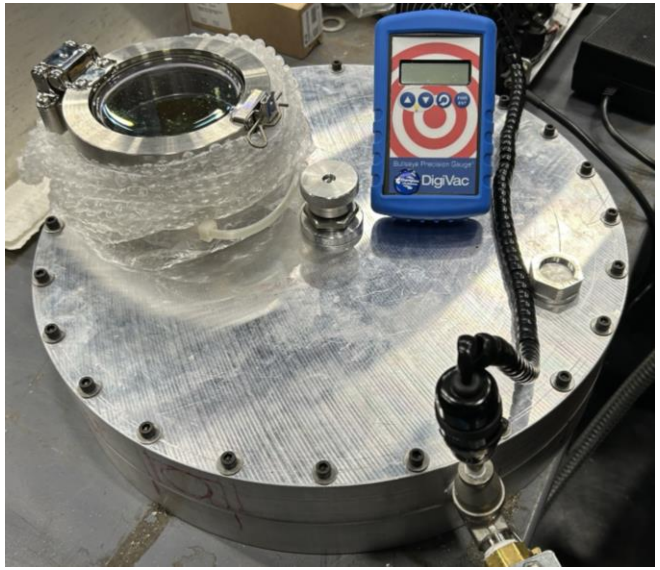
Latest prototype status – design and fabrication

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

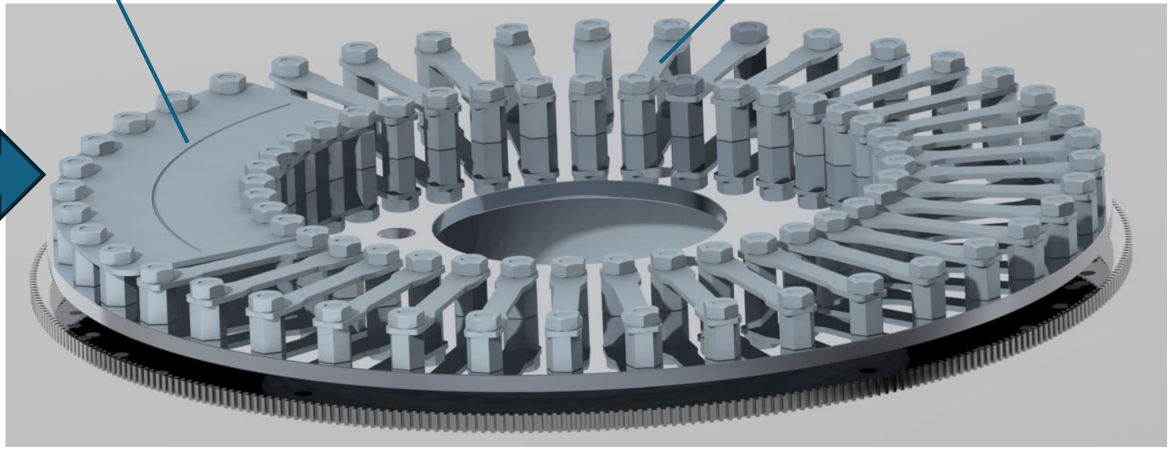


- Switched from central spindle to turntable driven by belt (o-ring)
- Added additional access door
- Reduced length of “stovepipe”
- Provided mounting plane for weld head, etc.

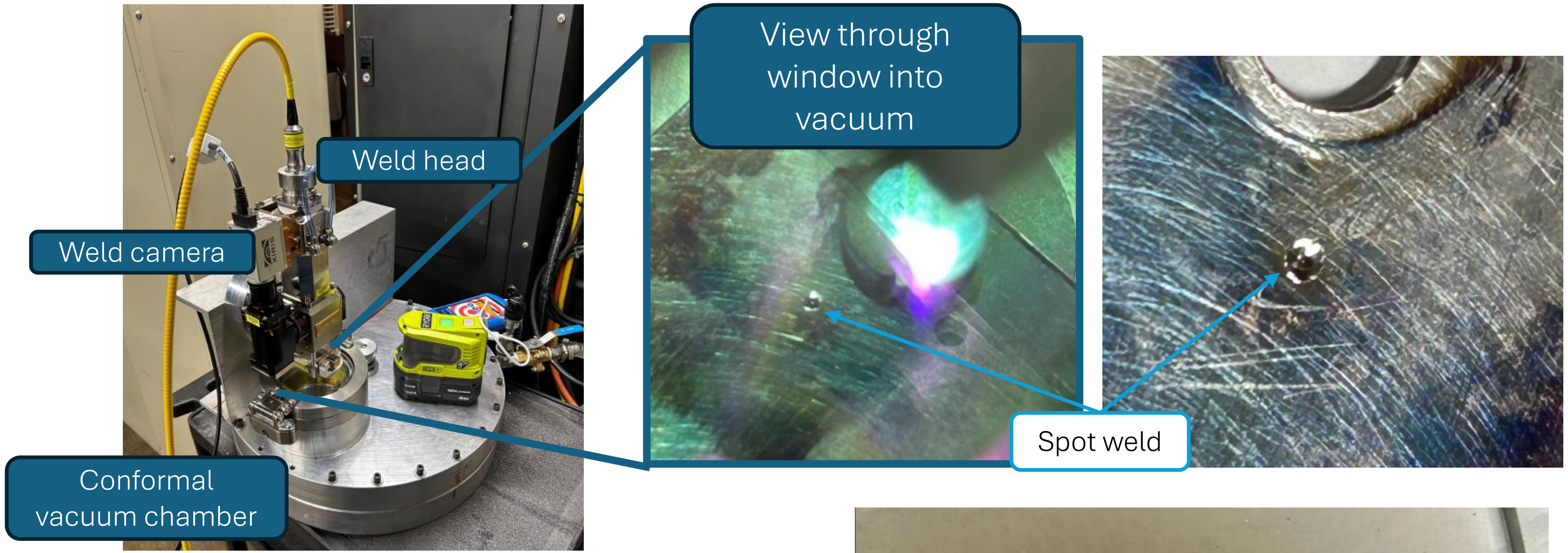




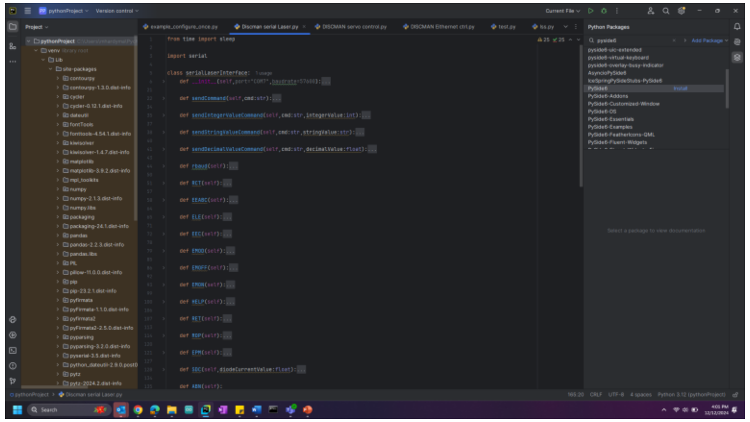
- Vacuum chamber robust and maintains <100 Pa
- Initial operating capability (spot welds without thermography) achieved



Latest prototype status – initial operating capability

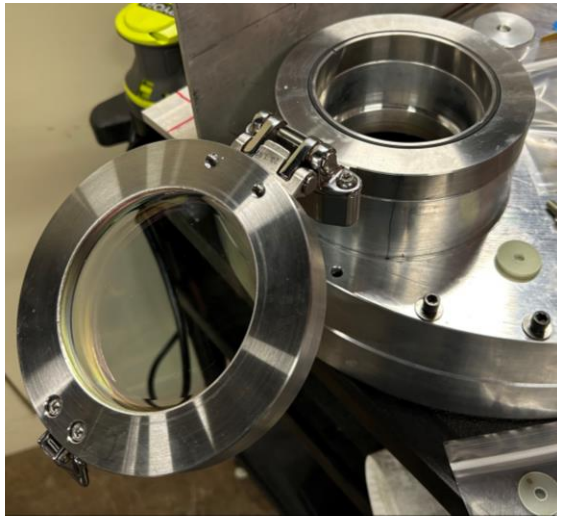


Programmatic control of coupon positioning/movement and laser expected shortly



Coaxial weld camera in operation; thermal to follow

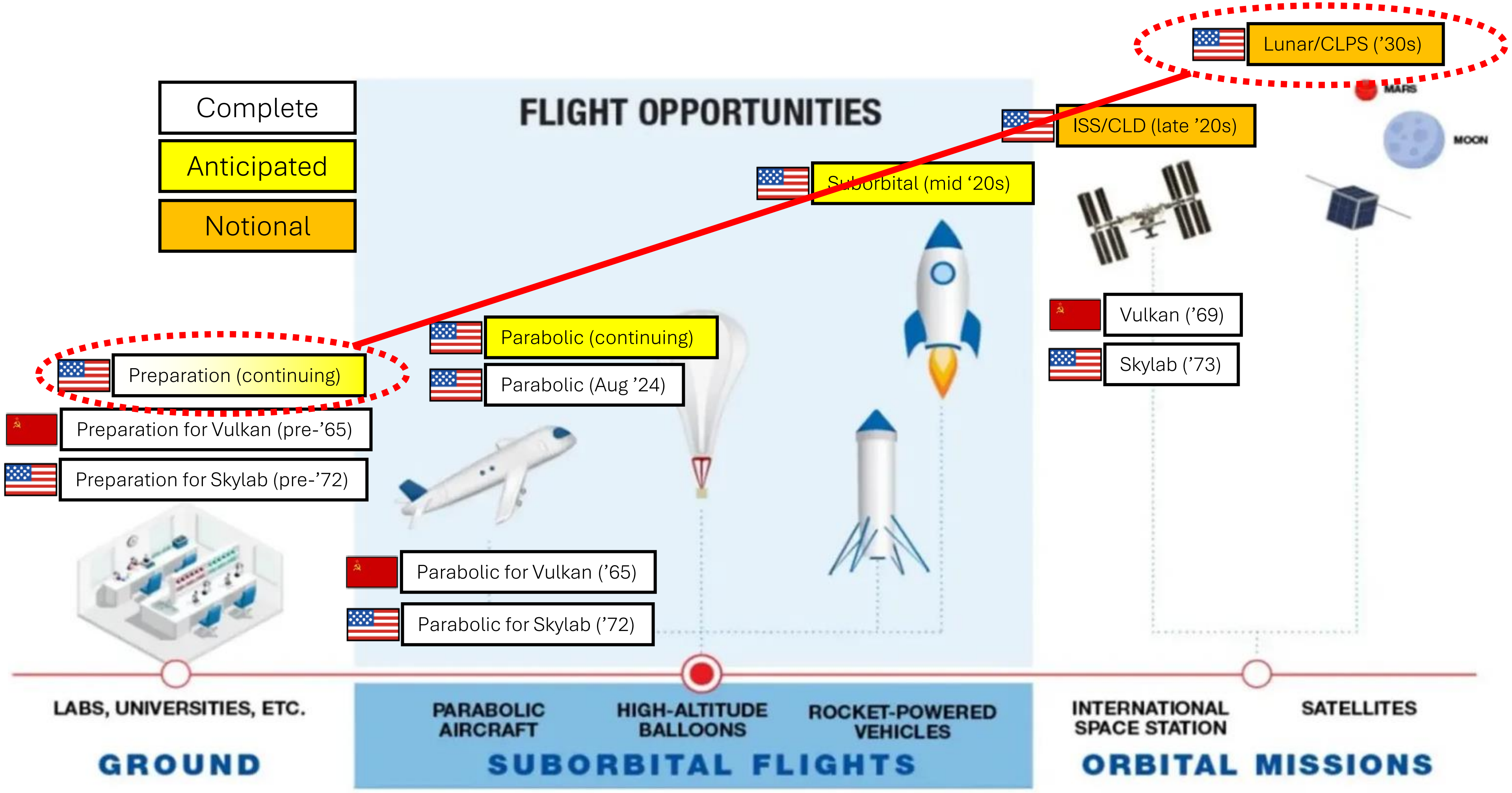
Rapid access to coupons



Concern: metal vapor coating, also spatter
Current mitigation: cover glass (sacrificial)

FY25 SBIR Pre-release – “Space-Capable Laser Beam Welding Component and Subsystem Development”

Progression of flight experiments



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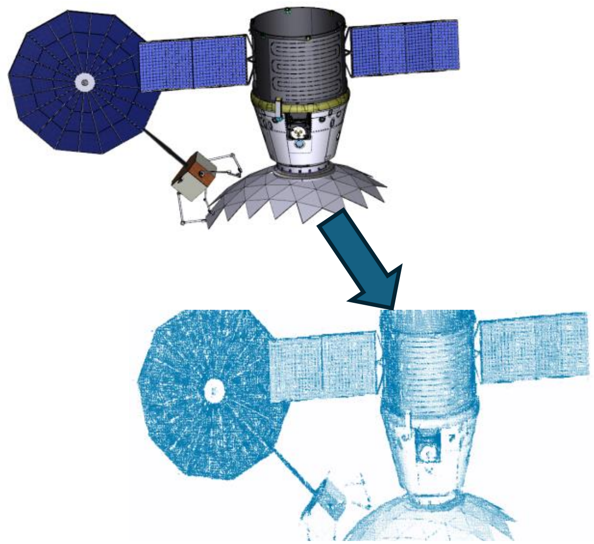
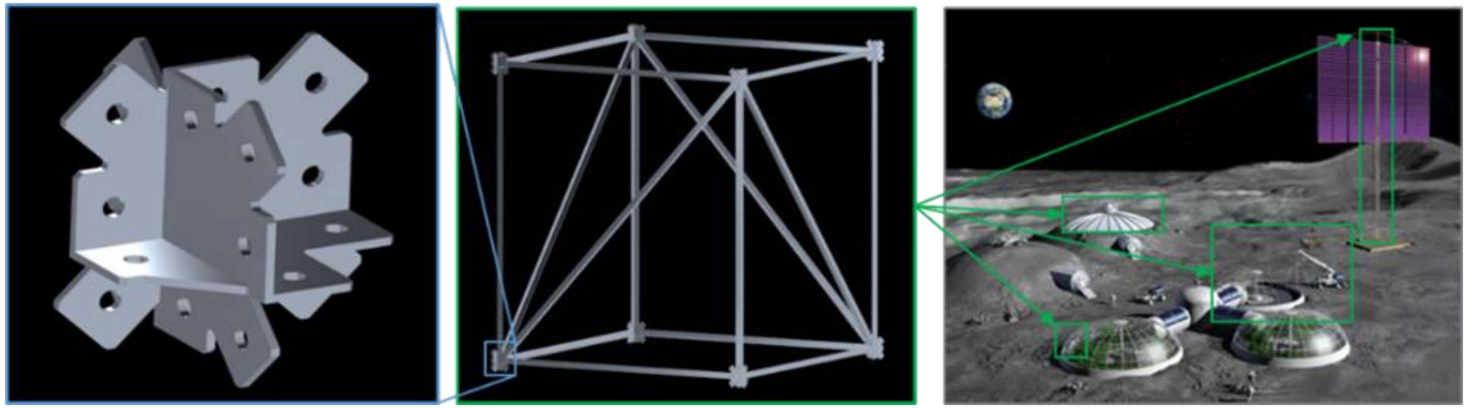


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Lunar Assembly and Servicing by Autonomous Robotics (LASAR)

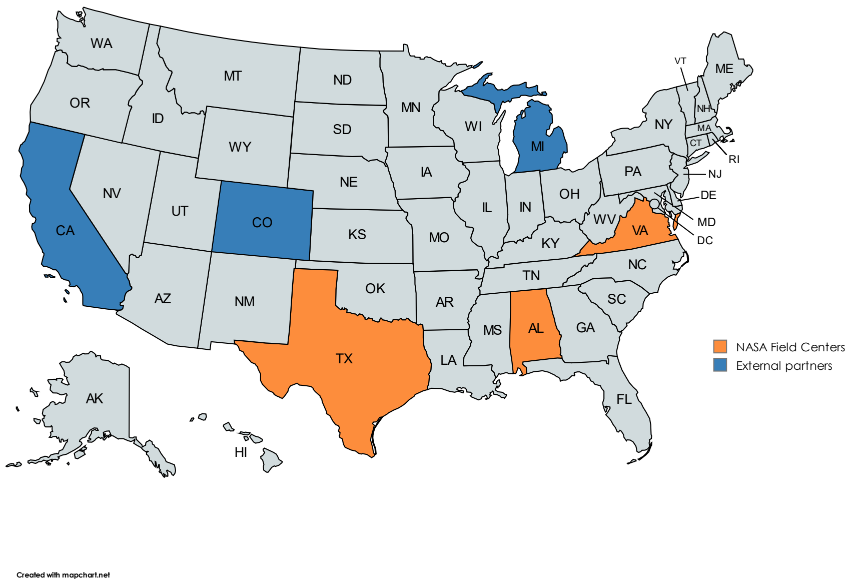
NASA-funded Early Career Initiative project: Mature LBW and associated robotics & NDE (non-destructive evaluation) for Lunar infrastructure applications

- Ruggedized laser optics and robotic arm suitable for thermal vacuum
- Supervised autonomous LBW of innovative “Snowflake” joint geometry
- Non-contact NDE of welds



Visualization of innovative “snowflake” joint geometry constructing Tall Lunar Tower

PI: Andrew O’Connor; PM: Zach Courtright (both NASA/MSFC)



NASA Core Team Members

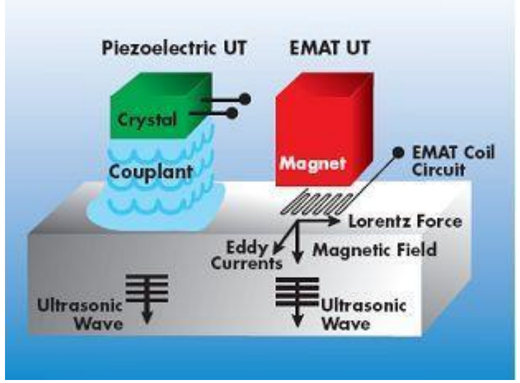
Name	Center
Emma Jaynes	NASA/MSFC
Alex Sowell	NASA/JSC
Raju Subedi	NASA/MSFC
Brace White	NASA/LaRC
Supported by:	
William Evans	NASA/MSFC
Matthew Mahlin	NASA/LaRC
Parker Shake	NASA/MSFC

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

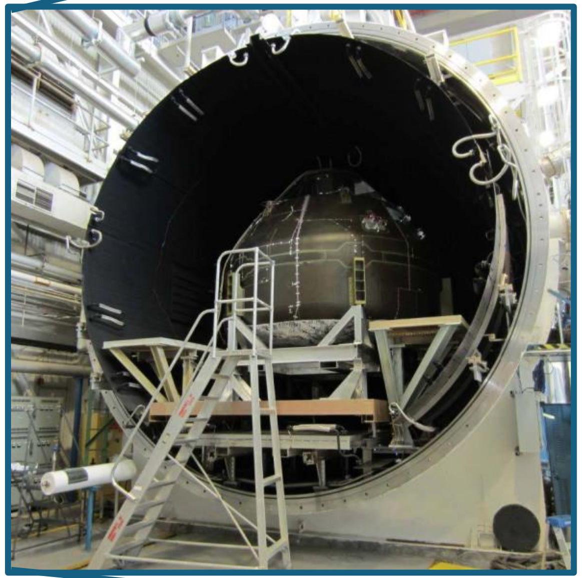
LASAR: Laser Processing sub-team

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

Initial mounting and welding trials on UR10e robotic arm in ambient conditions

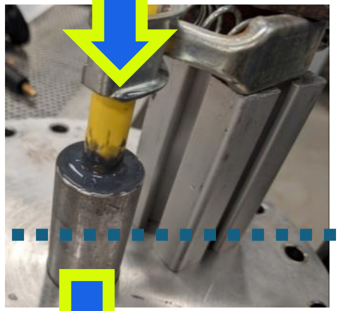
Laser optics and delivery fiber to be placed within thermal vacuum representing Lunar surface

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



Laser generator, diode (outside TVAC)*

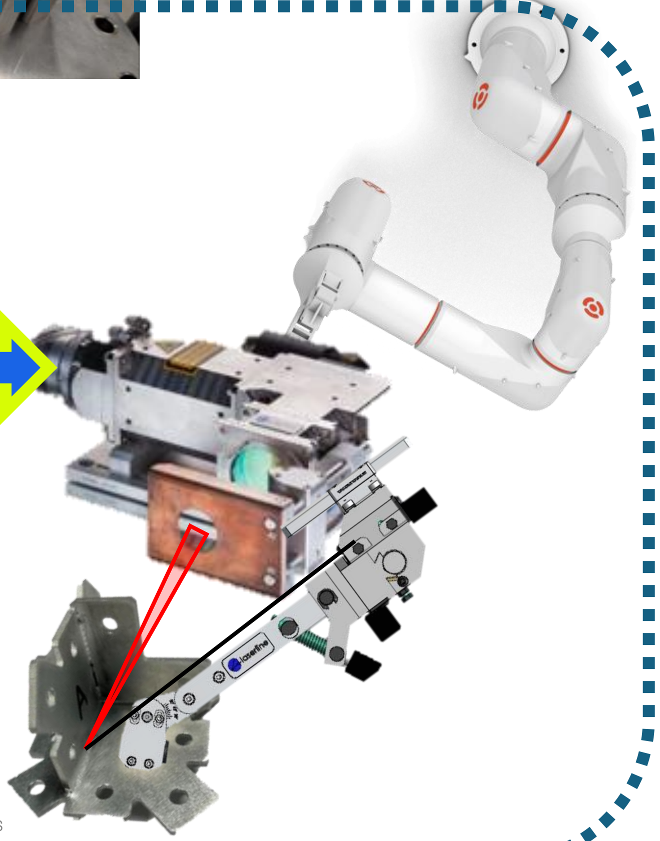
*Future opportunity: ruggedization of laser generator



Post-weld characterization:

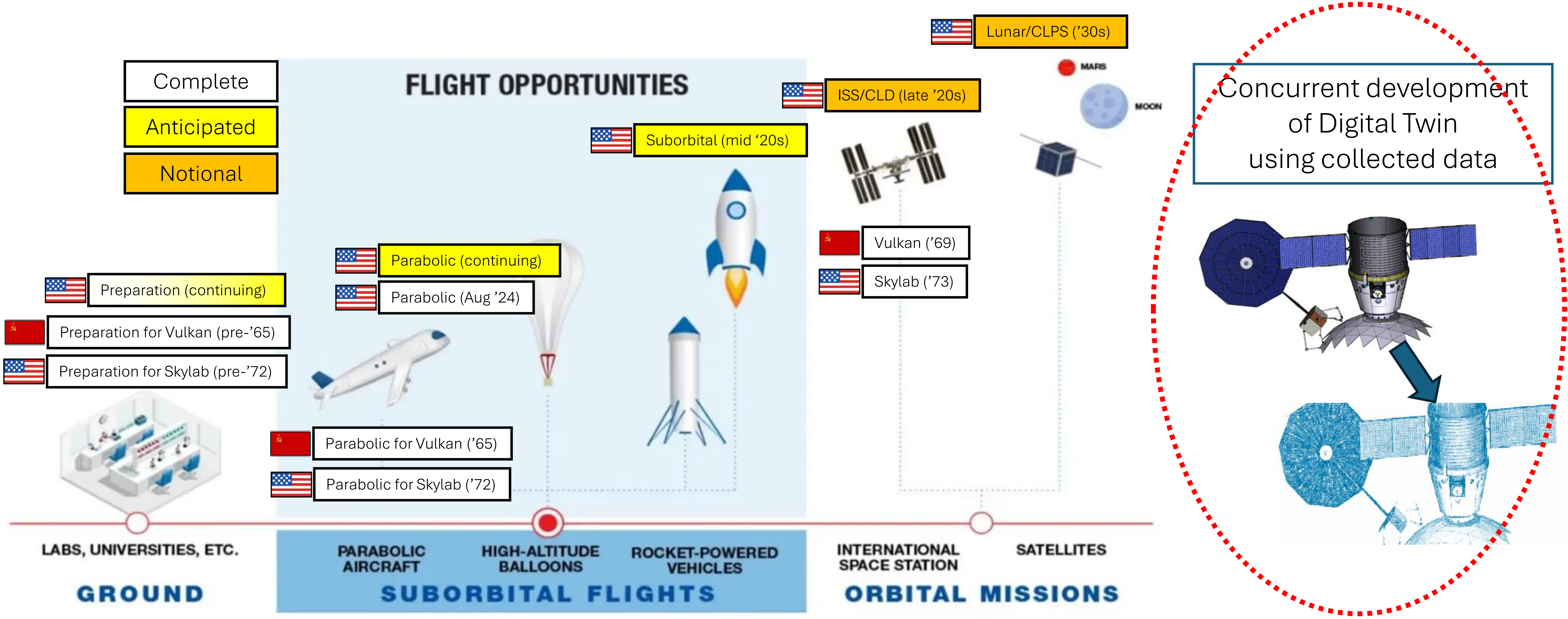
- Metallography and chemistry
- Mechanical testing
- TVAC compatibility

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



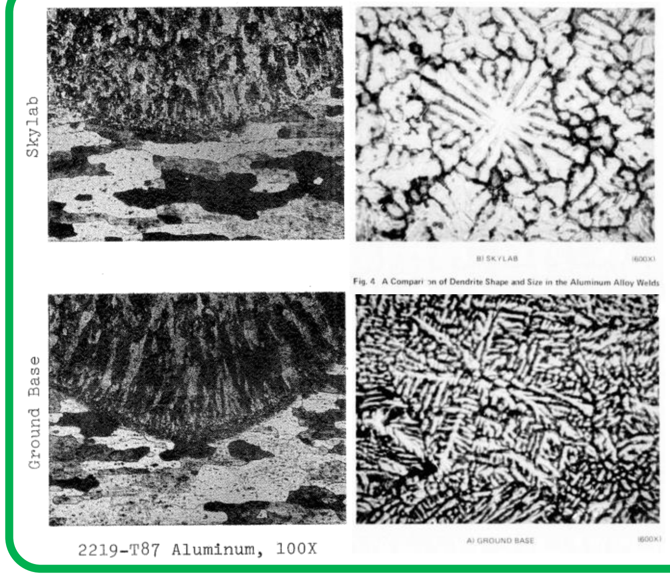
Credit: Laserline, Motiv Space Systems

Progression of flight experiments



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

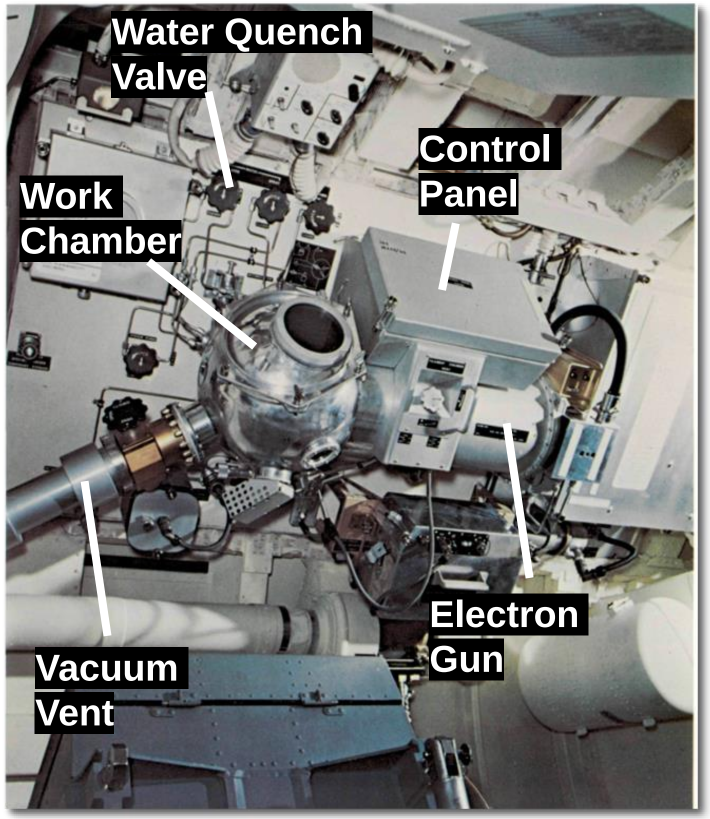
Skylab Electron Beam Welds: Structure-Property-Processing



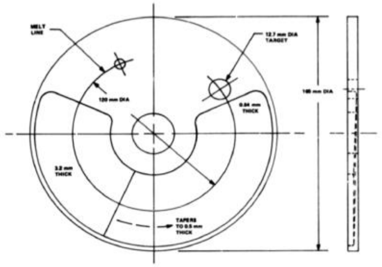
- In the ground-based samples, the dendrites are much larger at the root region than at the crown region. For Skylab samples, reduced difference in size.
- Concluded some unknown combination of ***G*** *(temperature gradient)* and ***R*** *(solidification range)* varied between ground and flight

G. Busch. Grumman Report (1976). https://ntrs.nasa.gov/citations/19770024270

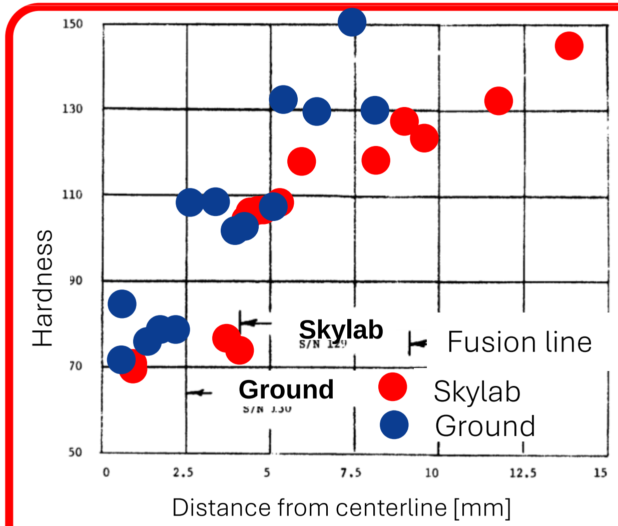
Structure



Processing



Travel speed = 1.61 cm/s, E = 20 kV, I = 50-80 mA
Alloys: Stainless Steel (304), Aluminum (2219-T87), CP Tantalum.
After 2 hr space vent, Vacuum = 10^{-4} Torr (~10^{-2} Pa)



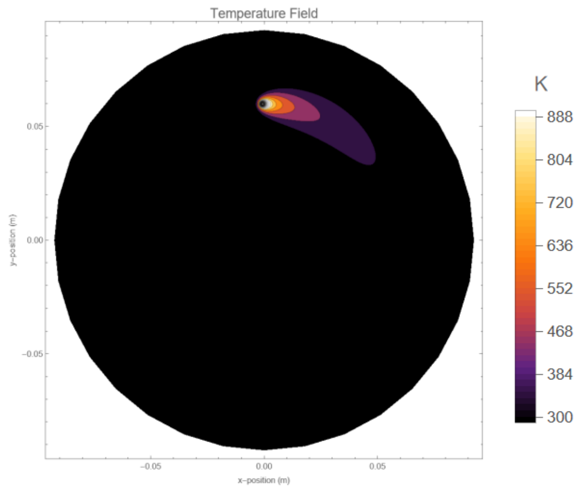
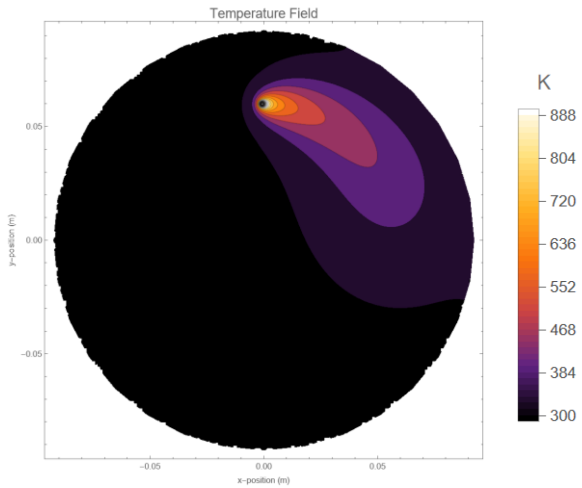
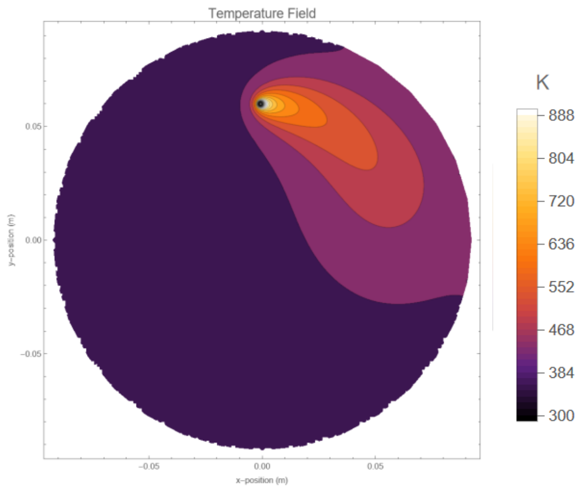
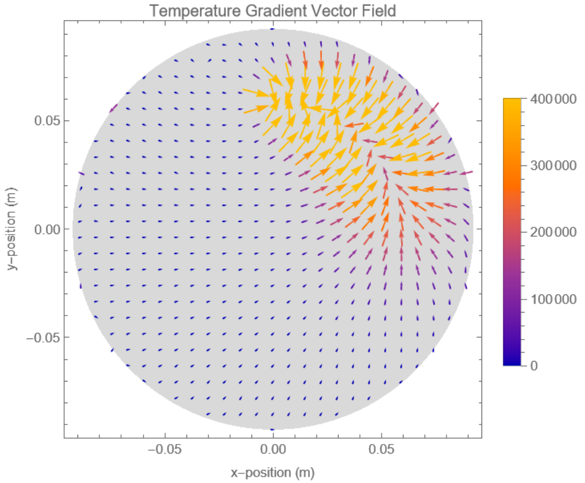
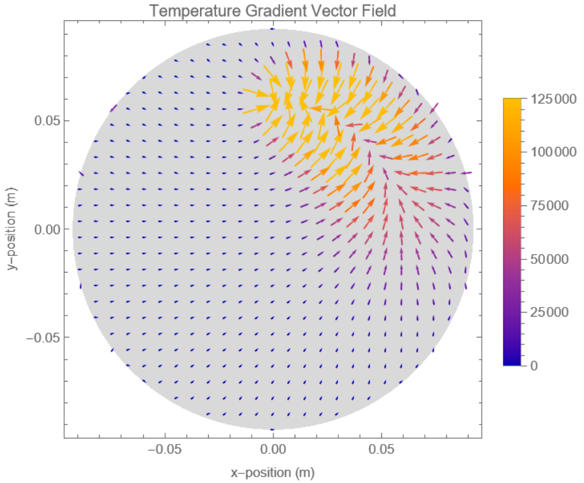
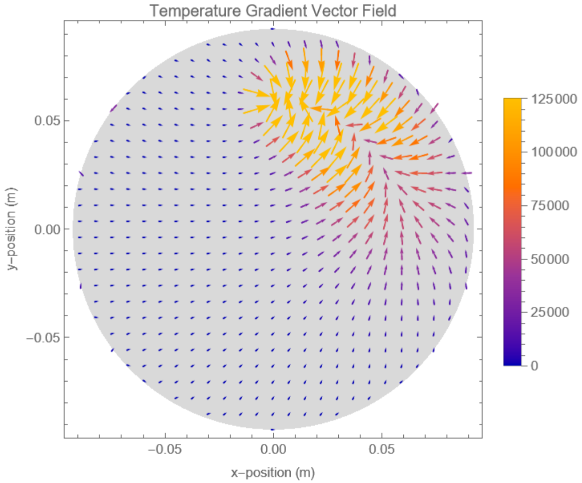
R.E. Monroe. NASA CR-129041 (1974). https://ntrs.nasa.gov/citations/19750002046

Properties

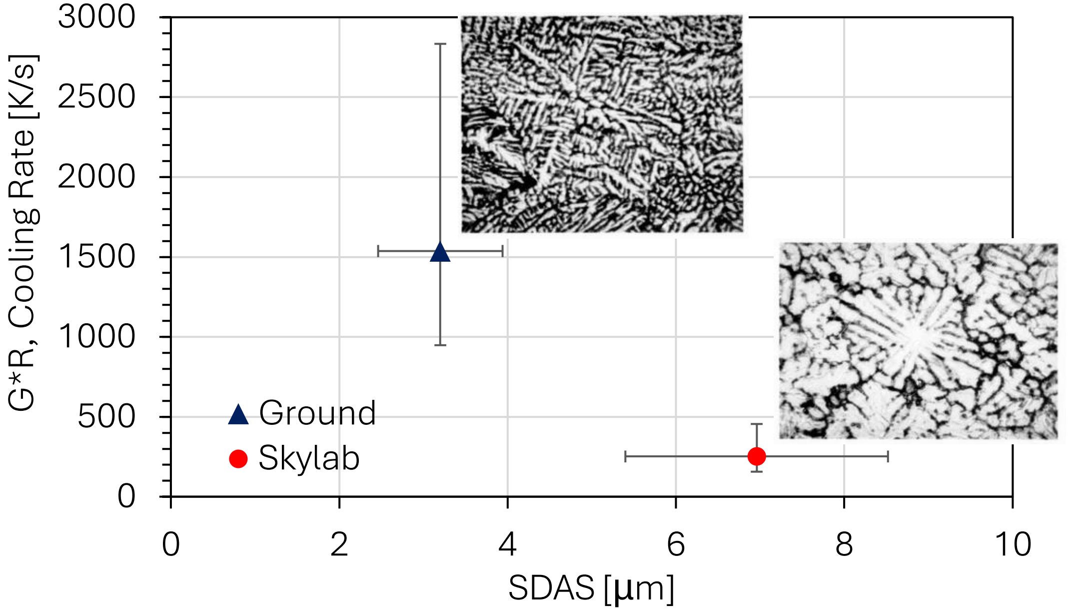
- Monroe (1974) produced hardness plots for full penetration Skylab and Ground welds.
- Li et al. (1976) concluded that no significant differences in hardness were observed between the ground-based and Skylab samples of 2219. Tantalum discs did show a significant difference, but no explanation was provided.

Computational and Physics-Based Modeling for the Development of in-Space Welding Technology - NASA Technical Reports Server (NTRS)

Temperature and gradient maps of Skylab 2219 Al disc at 100K, 293K, 400K

T_0 = 100 K	T_0 = 293 K	T_0 = 400 K
		
		

Comparison of Model and Empirical G*R



$$\lambda_2 = (143.73x^{-0.356})(G^*R)^{-0.43}$$

Brice and Dennis. *Met Trans A* 46 2015: 2304-2308.
DOI: 10.1007/s11661-015-2775-x (Wire-fed electron beam additive manufacturing process on Al-Cu)

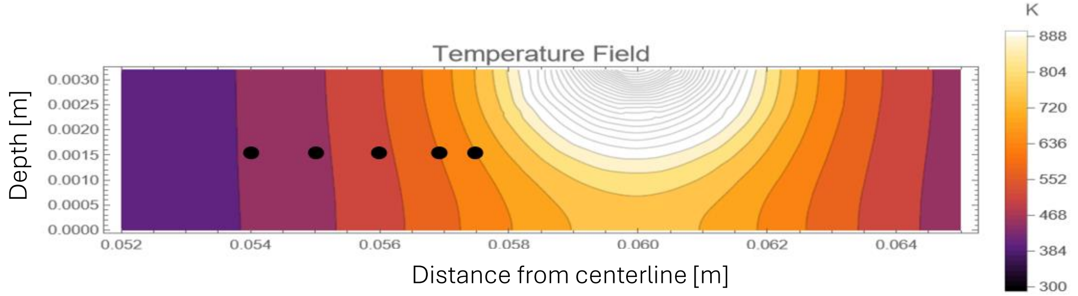
λ_2, Secondary dendrite arm spacing [µm]
x, Cu content of AA2219 Skylab discs (6.2 wt.%)
G, Thermal gradient [K/m]
R, Growth rate [m/s] (Ground ~Travel speed = 0.015 m/s)
G*R, Cooling rate through solidification interval [K/s]

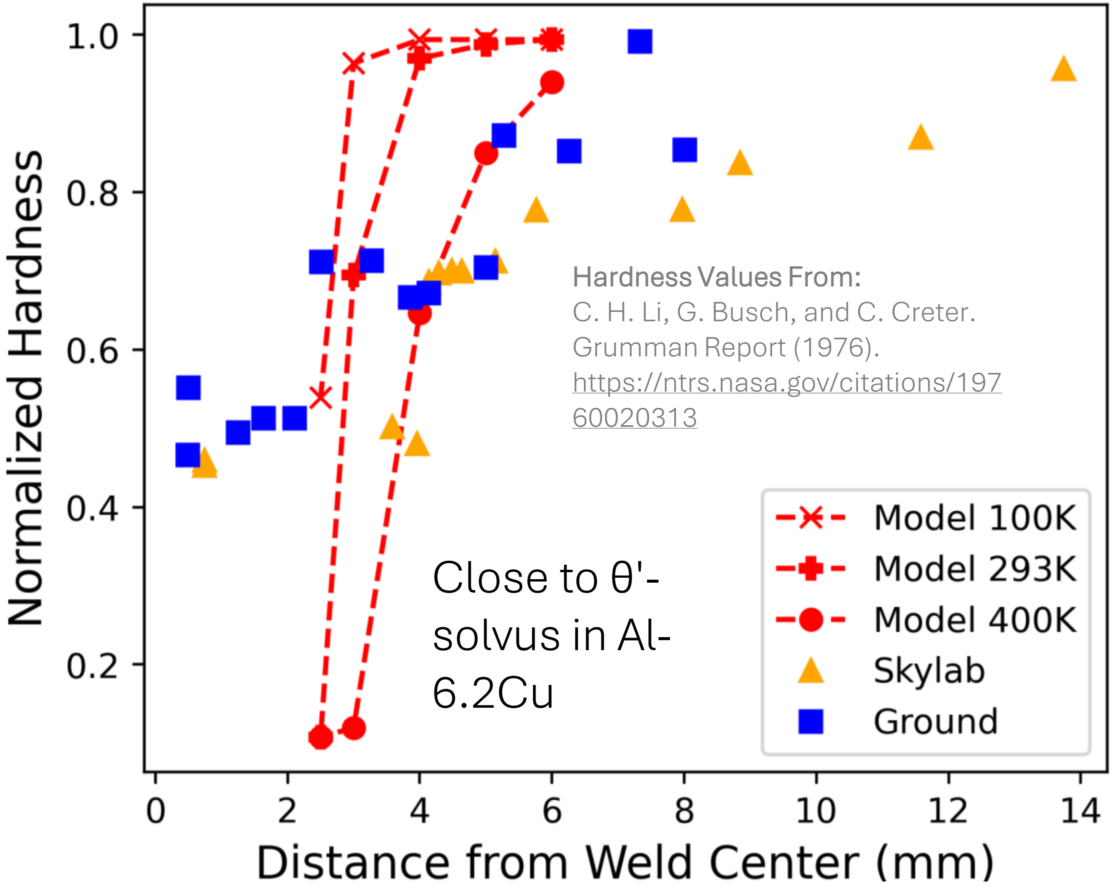
Condition	SDAS [µm]	Empirical GR [K/s] (from equation above)	Empirical G [K/m] (from equation above)	R [m/s]	Macro Gradient [K/m]
Ground	3.2 ± 0.74 (N = 26)	1537	$104 \cdot 10^3$	0.015	$125 \cdot 10^3$
Skylab	6.96 ± 1.56 (N = 22)	252	$17 \cdot 10^3$	Unknown due to microgravity solidification	Fluid transport neglected in model

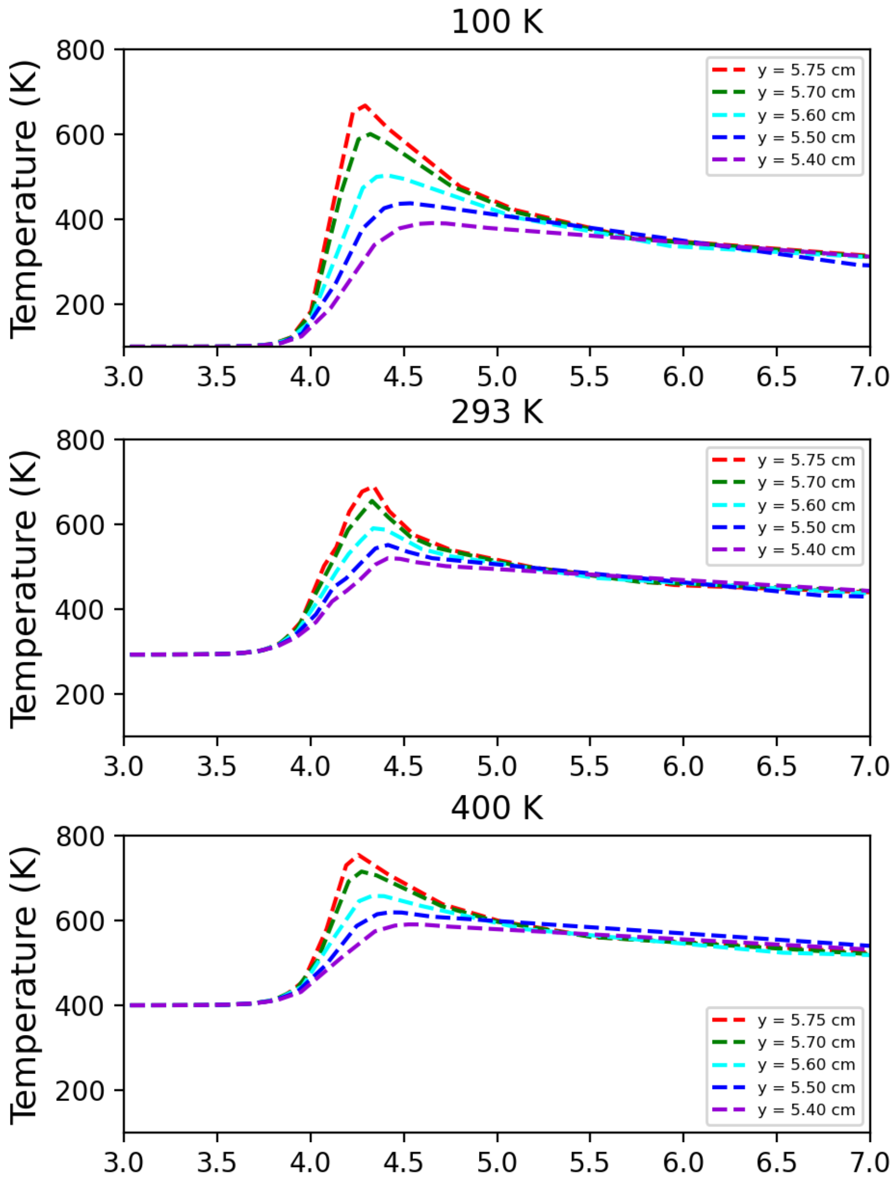
The lack of convective currents in microgravity means heat and solute are removed from the solidification front primarily by diffusion, resulting in slower growth rates and larger dendrite arms.

Glicksman, et al. (1986). Physics Today, 39(8), 60-67. Glicksman, et al. (1992). Met Trans A, 23(4), 1531–1542.

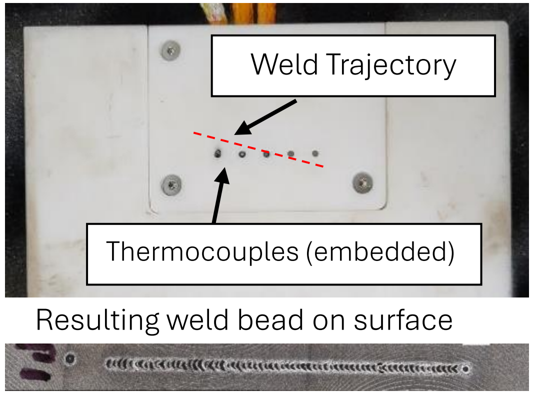
Properties: Hardness by Starting Disc Temperature

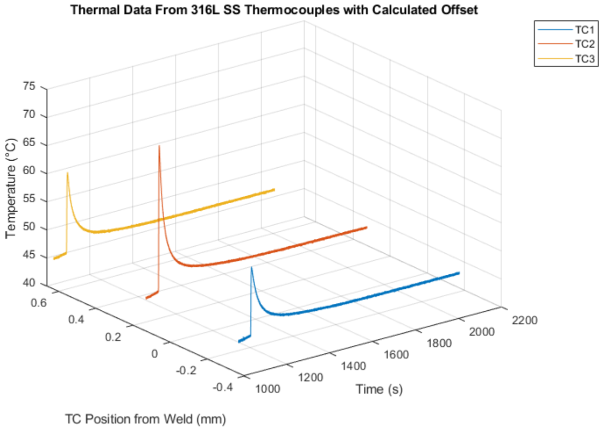


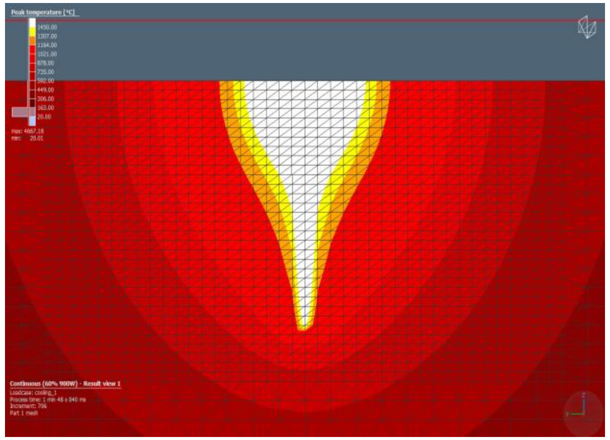


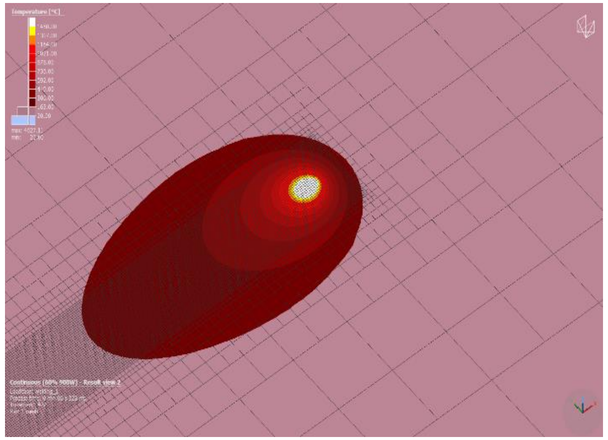


Leveraging ICME modeling to link laser absorptivity, thermophysical properties of material, laser parameters, etc.



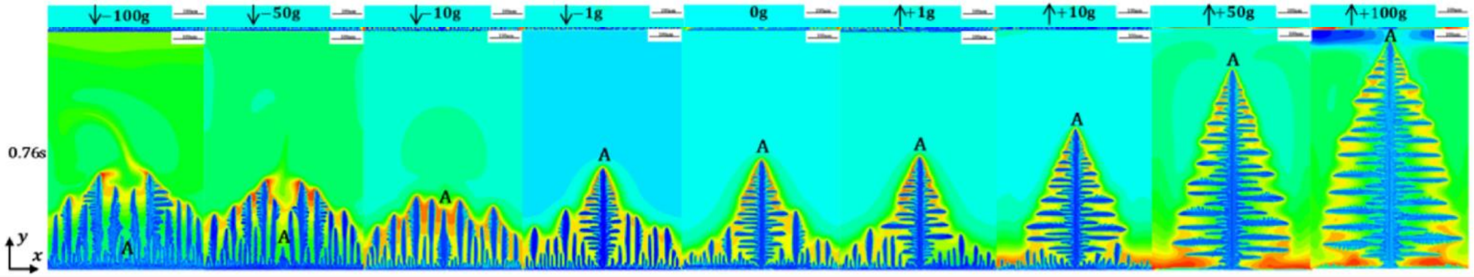






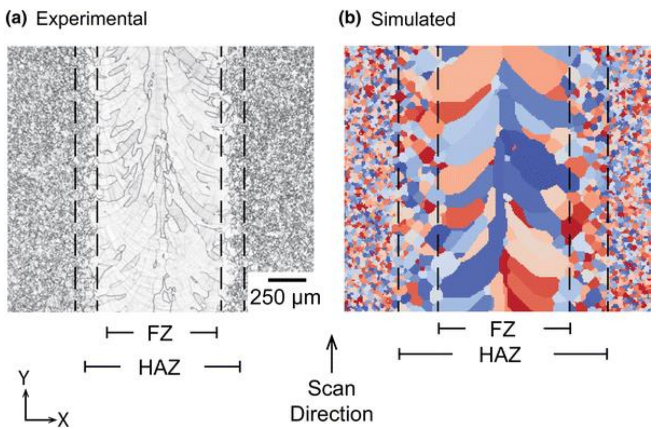
Validating LBW thermal models with thermocouples and thermography; enhances confidence in ICME approach

To do: link thermal & thermodynamic/precipitation model to solidification, fluid flow, and grain structure



Example of a phase-field lattice-Boltzmann simulation for dendritic growth during alloy solidification in negative gravity, zero gravity, Earth-normal gravity, and hypergravity

(Zhang et al., 2024, doi:10.1016/j.heliyon.2024.e27008); licensed under CC BY-NC 4.0



Example of a Monte Carlo Potts model in SPPARKS code to simulate grain growth in e-beam welding

(Rodgers et al., 2016, doi:10.1007/s11837-016-1863-8); licensed under CC BY 4.0

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 Center-directed funds, Biological and Physical Sciences Division of NASA Science Mission Directorate, NASA Space Technology Mission Directorate, 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 and upcoming re-flight support from NASA Flight Opportunities
- John Ivester (NASA/MSFC-EM42) for structured light scans of Flat Floor experiment