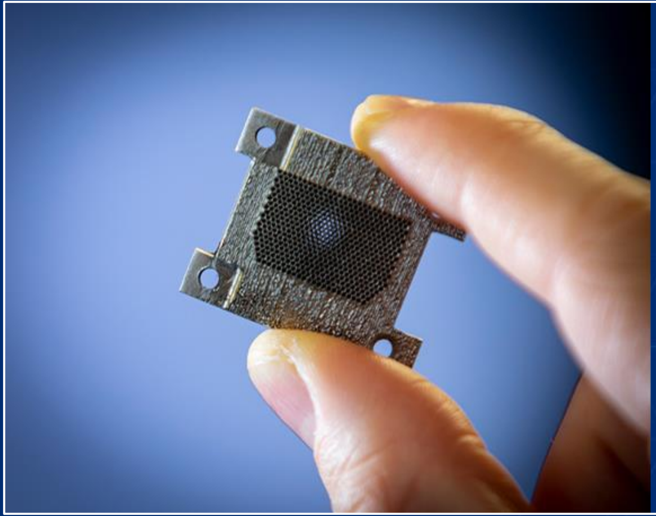
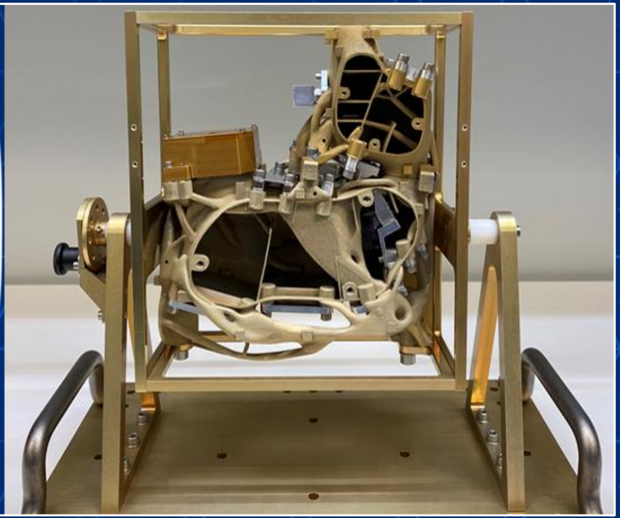




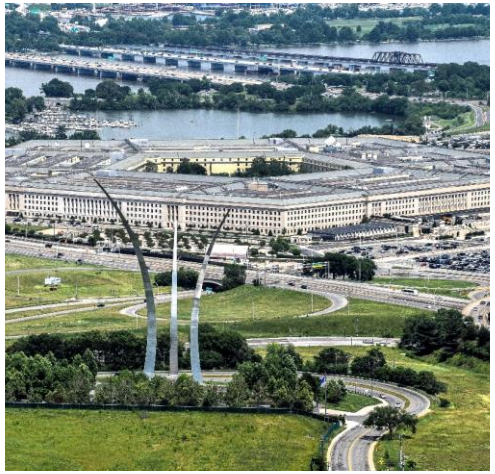
High Strength Aluminum Alloy for Additive Manufactured Space Optical Instruments

2023 Contamination, Coatings, Materials, and Planetary Protection Workshop

Authors: Walter Zimbeck[1], Zach Post[1], Steven Storck[1], Robert Mueller[1], Salahudin Nimer[1], William Swartz[1], Benjamin Stewart[1], Frank Morgan[1], Floris van Kempen[2], Gerard Otter[2], S.J. van den Boom[2]

[1]Johns Hopkins University Applied Physics Laboratory
[2] The Netherlands Organisation for Applied Scientific Research (TNO)

APL in Brief



What are we?

- Research division of Johns Hopkins University
- University affiliated research center

Who are we?

- Technically skilled and operationally oriented
- Objective and independent

Who are our sponsors?

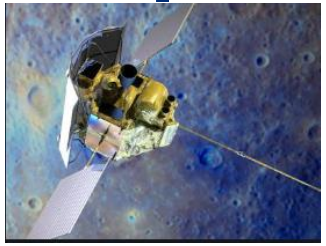
- Department of Defense
- NASA
- Department of Homeland Security
- Intelligence Community

What is our purpose?

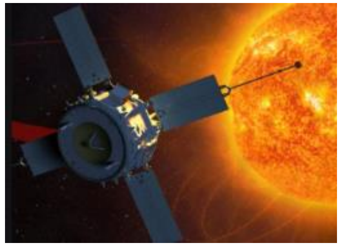
- Critical contributions to critical challenges

Laboratory Employees: ~8,100 staff members

APL Space Missions Legacy

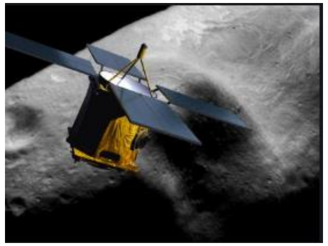


MESSENGER
Launched: 1996

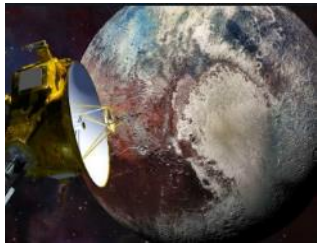


ACE
Launched: 1997

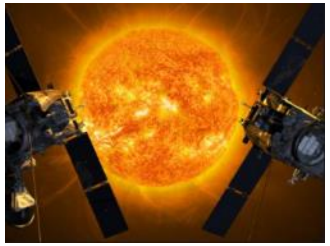
TIMED
Launched: 2001



NEAR
Launched: 2004

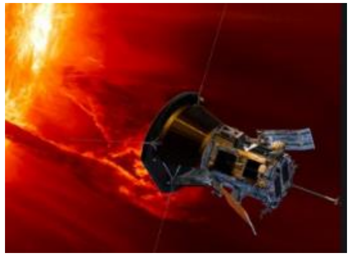


New Horizons
Launched: 2006

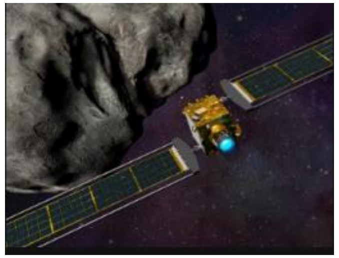


STEREO
Launched: 2006

Van Allen Probe
Launched: 2012

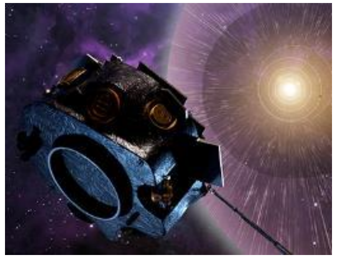


Parker Solar Probe
Launched: 2018



DART
Launched: 2021
Impact: 2022

JUICE
Launched: 2023



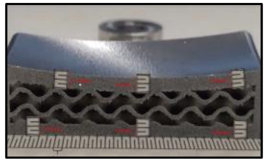
IMAP
Launch: 2025

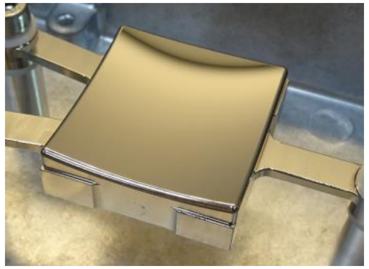
Dragon Fly
Launch: 2027

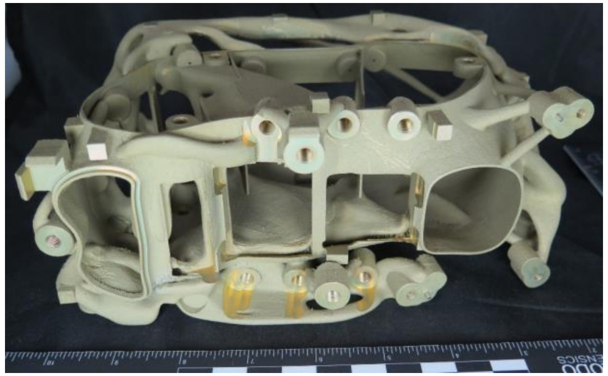
Includes metal AM hardware

CHAPS-D Innovations

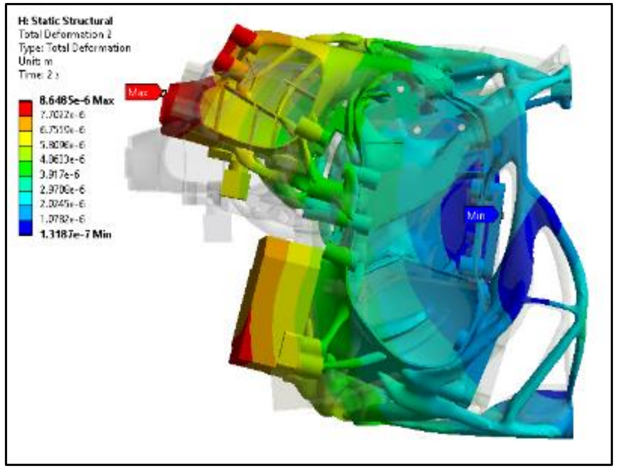
CHAPS-D
COMPACT HYPERSPECTRAL AIR POLLUTION SENSOR



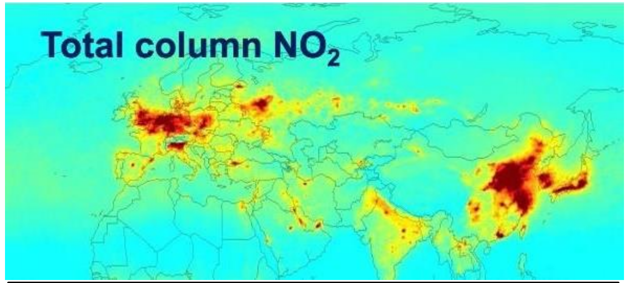


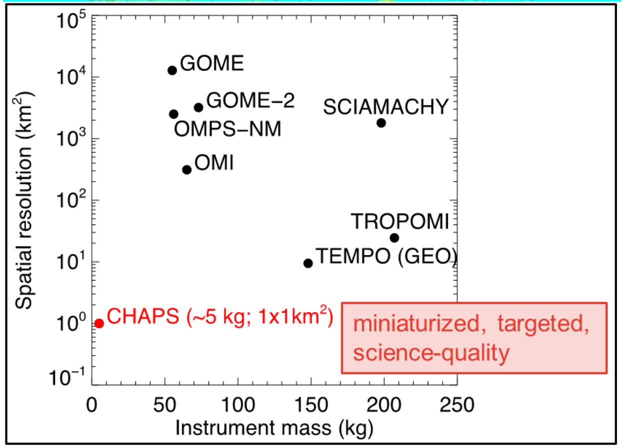


Metal Additive Manufacturing
- **Optical housings w/ integrated baffles**
- **Lightweight latticed mirror**

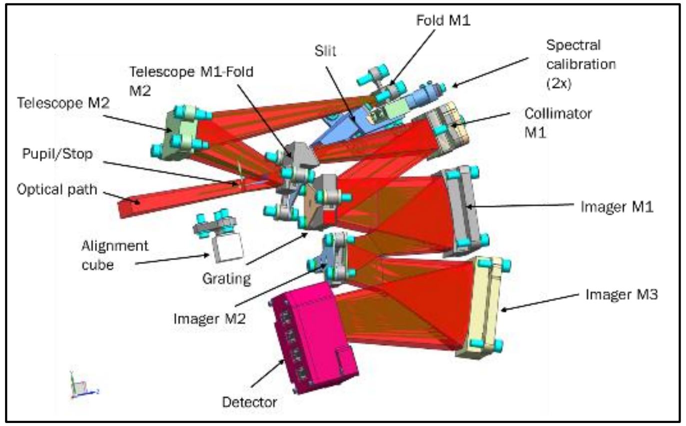


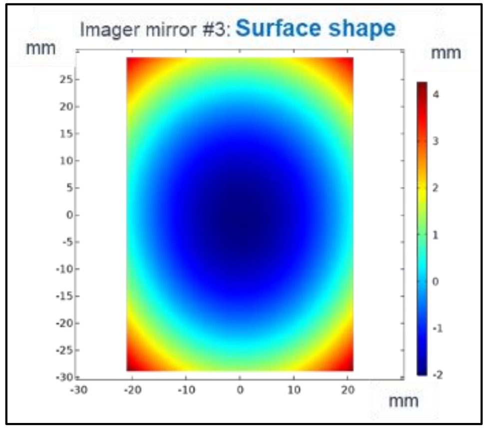
Topology Optimized Structures





High Resolution, Science Quality Trace Gas Measurement from a small platform



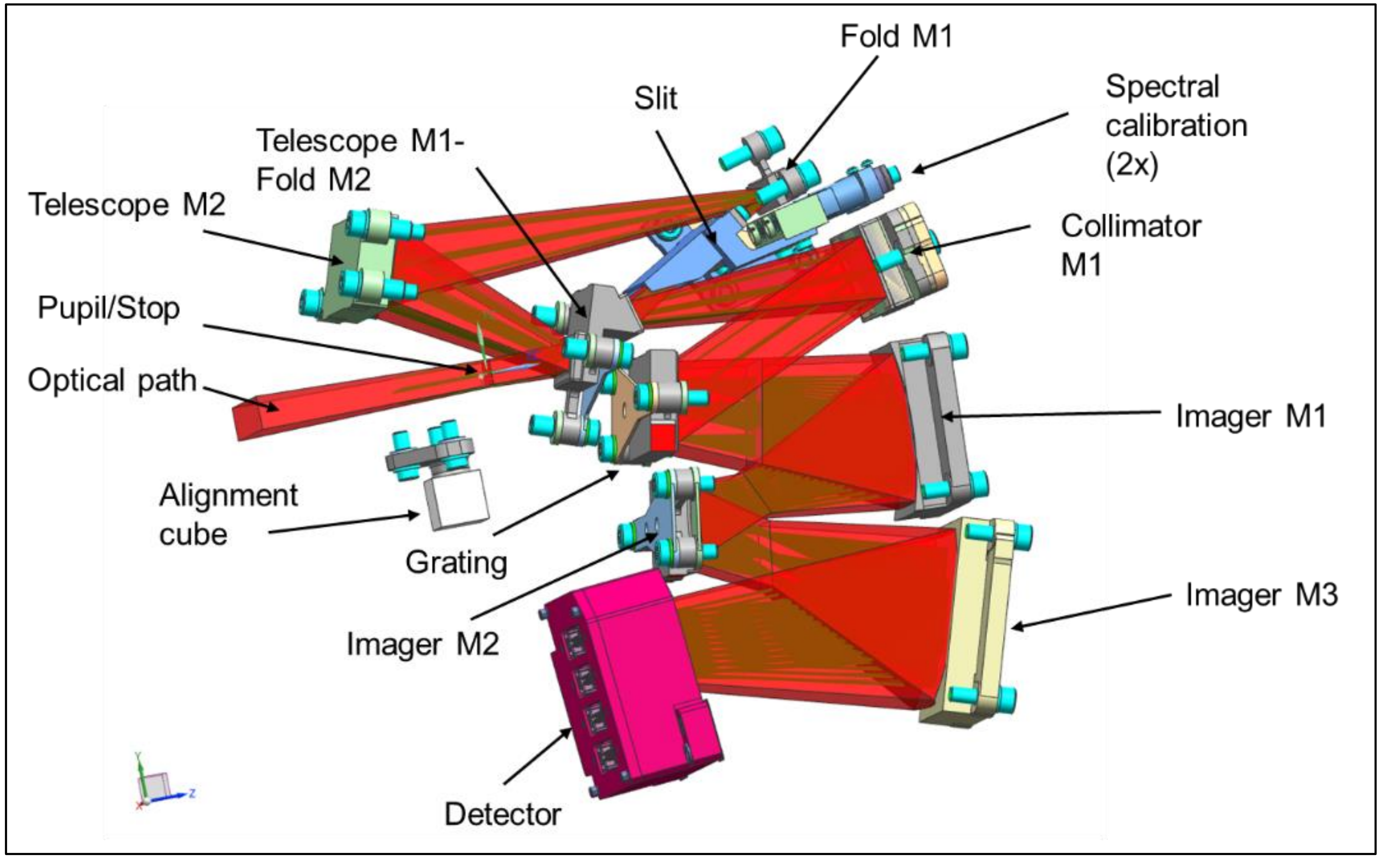


Freeform Optics

Funding: NASA ESTO IIP-19 (80NSSC20K0323)

CHAPS Optical System Design & Requirements

- Freeform optics
- A-thermal design
- Optical elements mounted directly on assembly tolerances
- Alignment of the detector in 6 DoF as compensator
- Two part integrated housing: Telescope & Spectrometer
- Optical components stable within ±15 µm in x-, y-, or z-direction under gravity release and a 10K thermal gradient



Funding: NASA ESTO IIP-19 (80NSSC20K0323)

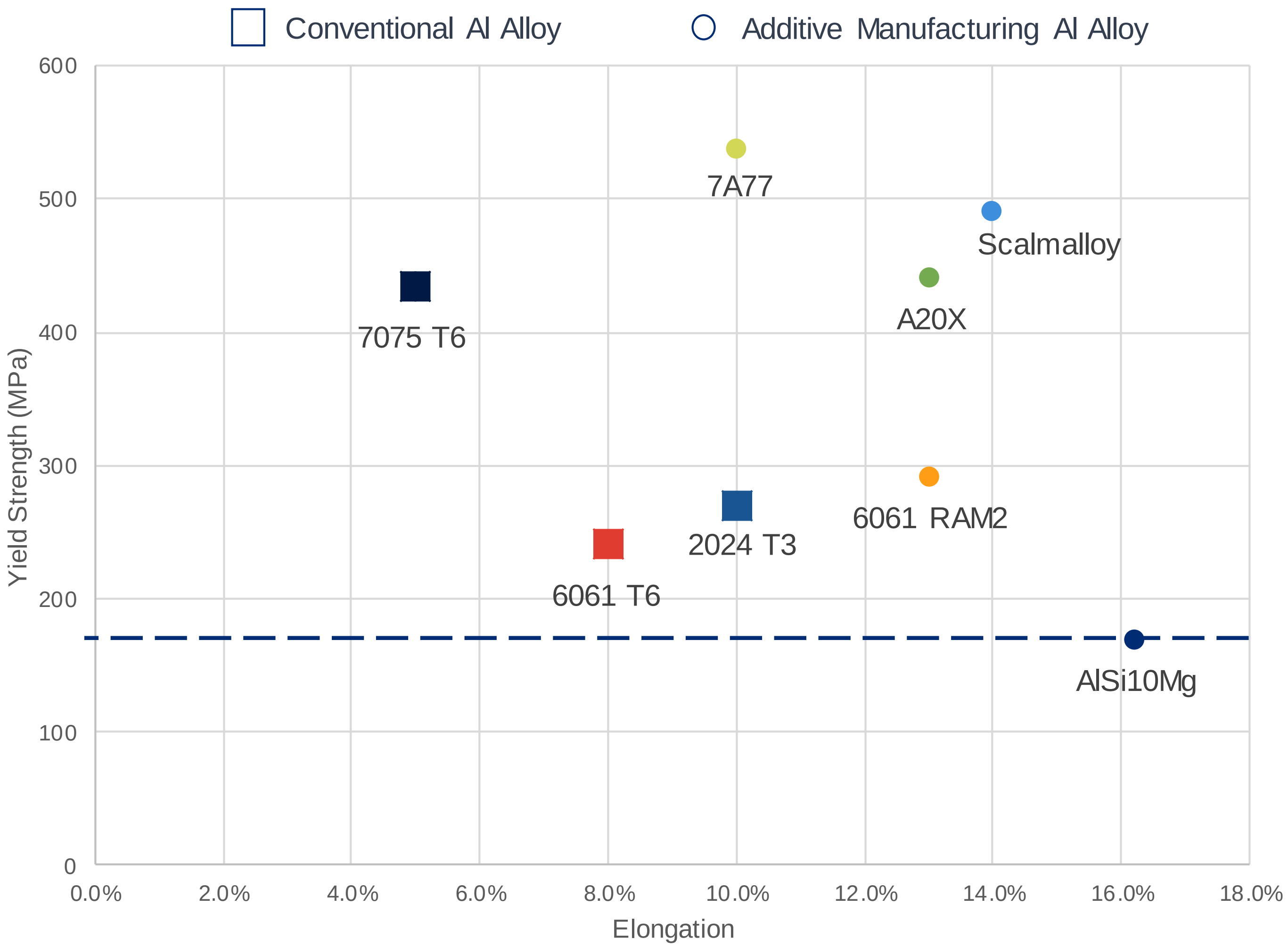
CHAPS-D Material Requirements

	Property	Method	Weight	Notes
Mechanical	Tensile Ultimate Strength (MPa)	Mini-Tensile Bars, ASTM E8	7	> 450
	Tensile Yield Strength (MPa)		3	> 400
	Tensile Modulus (GPa)		3	> 70
	Tensile Elongation (%)		2	> 5
Print Quality	Minimum Wall Thickness (undistorted)	Test plate	3	Integrated baffles
	Thermal Stress (mm deflection)	Stress combs	3	Distortion concerns in TO structure
	Down-facing Surface Accuracy	Calipers	3	Reduced accuracy
	Surface Roughness (vertical wall)	XCT	2	Effects clean-ability and strength
	Minimum Hole Diameter (mm)	Pin Gauge	2	Small holes for venting, fiber optics
Post Processing	Compatibility with NiP Plating & SPDT	NiP Plating & SPDT	7	Mirror coating compatibility
	Compatibility with Chrome Conversion Coating and Optical Black Paint	Coating and Paint adhesion tests	4	Housing coating compatibility
Thermal	CTE (µm/m/K)	ASTM E228, Dilatometer	10	Similar to Al 6061 cubesat structure
	Thermal Conductivity (W/mK)	ASTM E1461 Flash	4	High conductivity minimizes gradients

Funding: NASA ESTO IIP-19 (80NSSC20K0323)

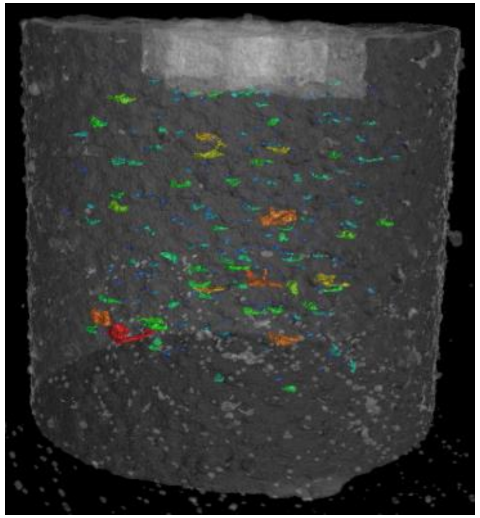
Additive Aluminum Alloy Candidates

Alloy	Pros	Cons
AlSi10Mg	Widely used AM alloy	Low YS, high Si (plating?), stability?
6061 RAM2	Compatible with 6061 cubesat, low roughness	Minor increase in YS
A20X	High tensile properties	Unknown other properties
Scalmalloy	High tensile properties	Unknown other properties
7A77	Highest tensile properties	HIP recommended, Unknowns

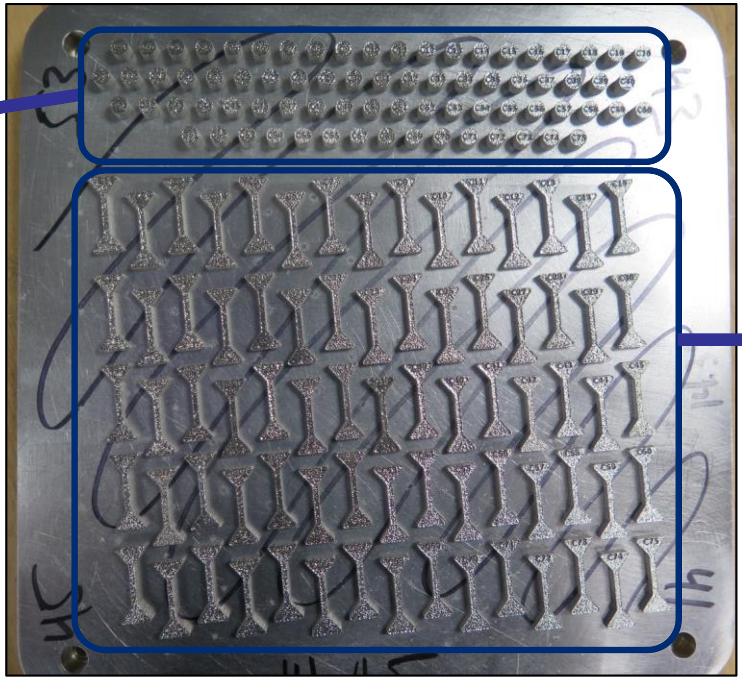


Test Plan Step 1: Laser Parameter DOE of Each Material

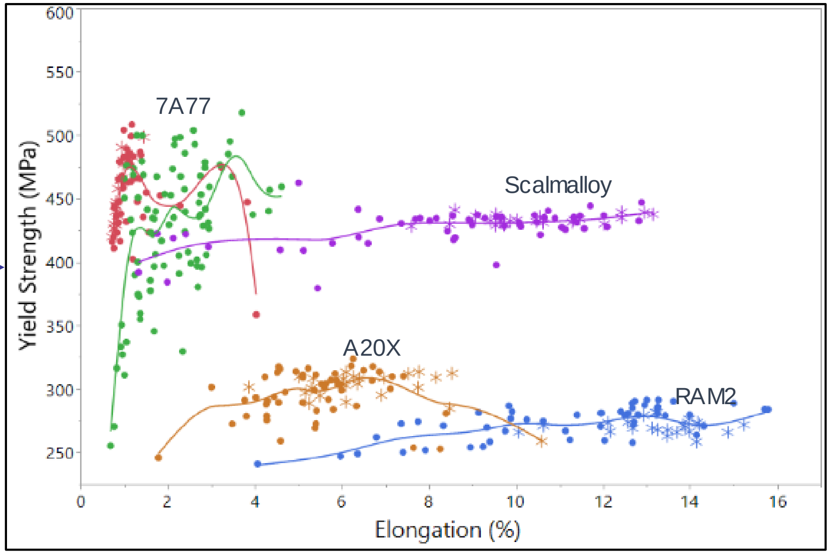
- 75 Laser Parameter Sets
  - Variables: laser power, exposure time and point distance (scan speed), hatch spacing
  - X-ray Computed Tomography (XCT): porosity and surface roughness (vertical wall)
  - Mini-Tensile Bars (2mm gauge section): YS, UTS, elongation
  - Select 7 best parameter sets for Step 2.



XCT reconstruction showing porosity in 6mm dia. x 10mm tall cylinder



Build Plate with 75X each XCT cylinders and mini-tensile bars

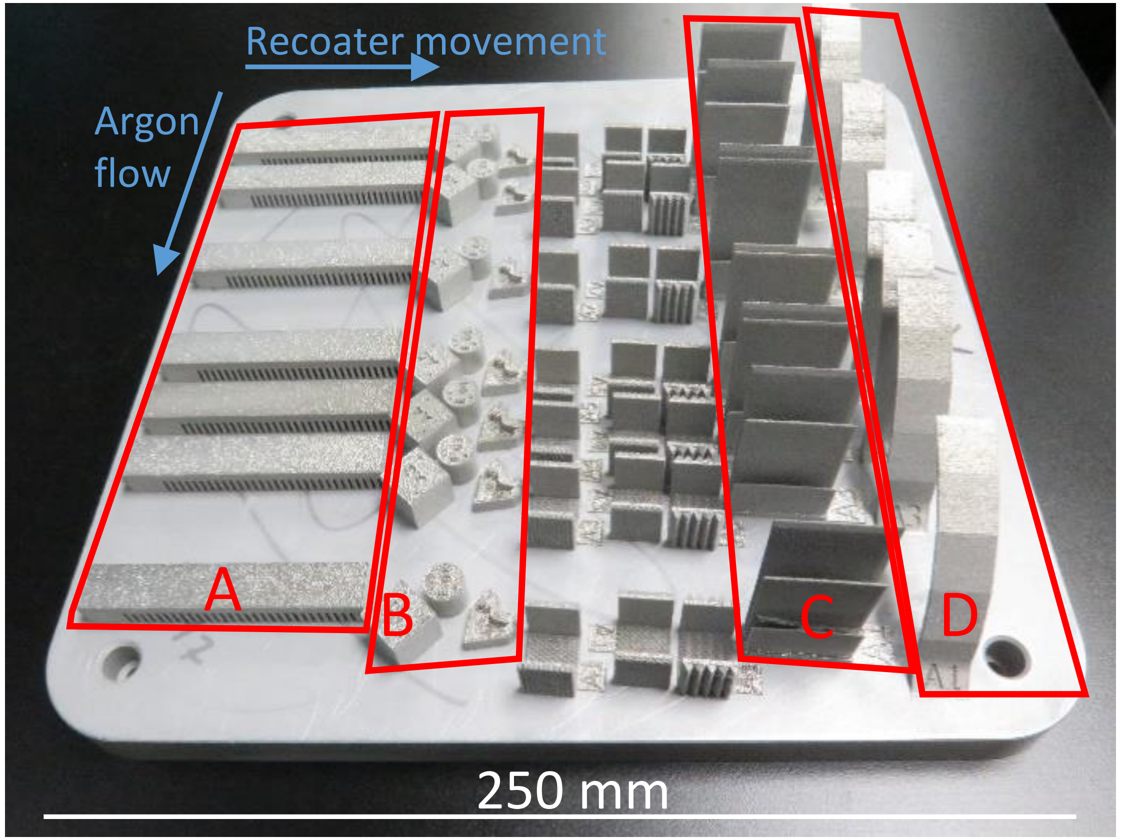


Tensile Yield Strength vs Elongation Results

Test Plan Step 2: Printability Assessment

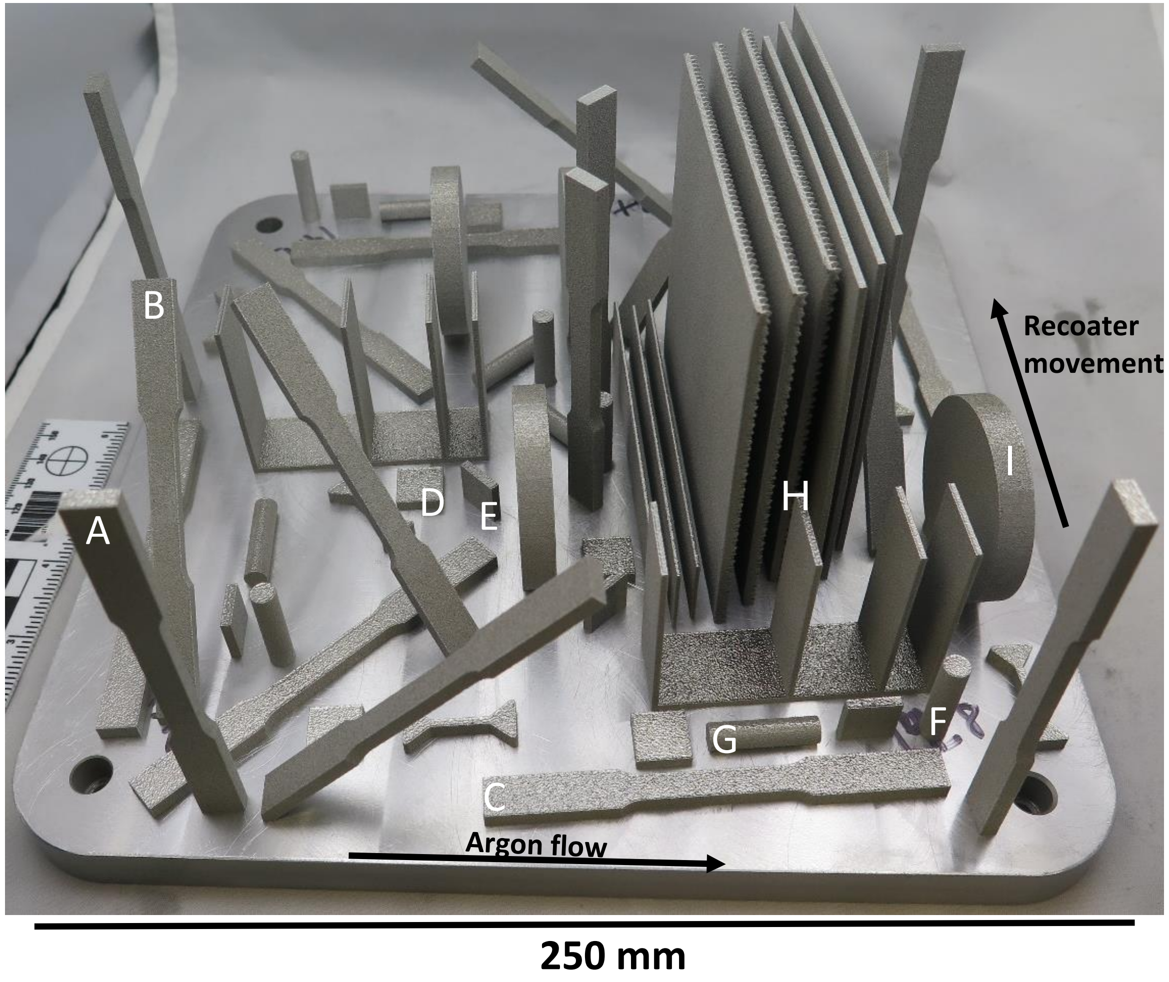
- Using Best 7 Parameter Sets from Step 1
    A. Stress combs (residual stress)
    B. Minimum hole diameter
    C. Thin wall distortion
    D. Down-facing surface quality

- Down select best parameter set for each material



Test Plan Step 3: Mechanical & Thermal Properties

- Test Best Parameter Set for each material.
  - Quantity 6 of each test sample type
- Tensile Properties
  - ASTM E8 flat specimens
  - Vertical (A), 45° (B), Horizontal (C)
- Thermal Conductivity (ASTM E228, Flash Diffusivity)
  - 10mm squares x 1.5mm thick
  - Vertical (D), Horizontal (E)
- Coefficient of Thermal Expansion (CTE, ASTM E1461)
  - Rods 3mm dia x 10mm long
  - Vertical (F), Horizontal (G)
- Paint Adhesion Test
  - 100mm x 100mm x 1.5mm plates (H)
- NiP and Single Point Diamond Turning (SPDT)
  - 50 mm dia. x 10 mm thick disks
  - Mirror post-processing compatibility (I)



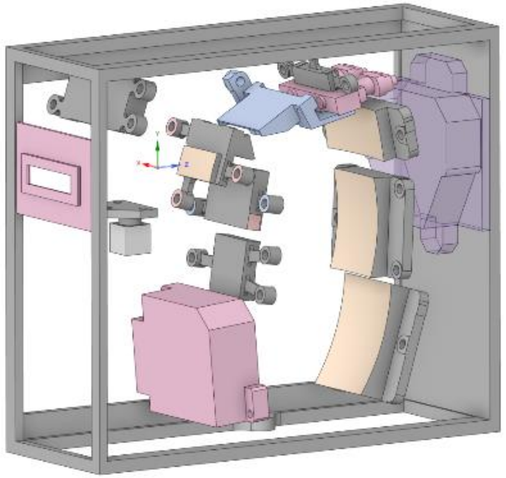
Test Results

Pass
Fail (Marginally)
Fail

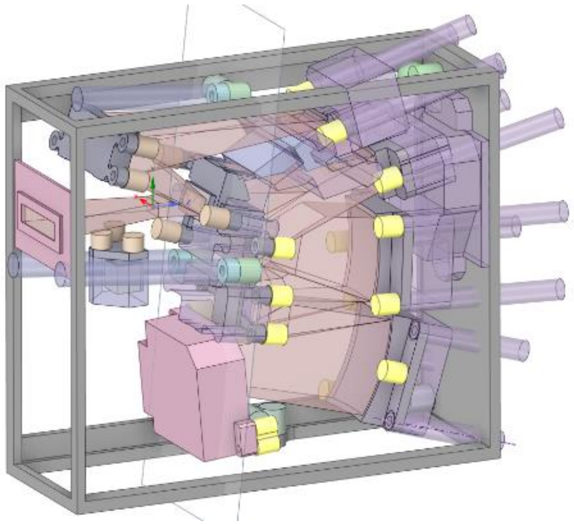
	Property	Weight	Target	A20X	Scalmalloy	7A77	6061 RAM2
Mechanical	Tensile Ultimate Strength (MPa)	3	> 450	410	477	478	317
	Tensile Yield Strength (MPa)	7	> 400	324	439	466	291
	Tensile Modulus (GPa)	3	> 70	110	70	74	90
	Tensile Elongation (%)	2	> 5	6.2	12.4	1.3	9.0
Print Quality	Minimum Wall Thickness (mm)	3	0.5	0.5	0.5	1	--
	Thermal Stress (mm deflection)	3	< .08	.067	.078	.097	--
	Down-facing Surface Accuracy (mm)	3	< +.50	+.57	+.51	+.64	+.35
	Surface Roughness (Ra, µm)	2	< 20	17.7	19.2	33.5	--
Post Processing Compatibility	Compatibility with NiP Plating & SPDT	7	PASS	PASS	PASS	FAILED	--
	Compatibility with Chrome Conversion Coating and Optical Black Paint	4	PASS	PASS	PASS	PASS	PASS
Thermal	CTE (µm/m/K)	10	22 - 25	23.0 +/- 1.3%	24.5 +/- 1.0%	--	--
	Thermal Conductivity (W/mK, 25C)	4	> 70	101	81.5	--	--

Post, Z.J. *et al.* (2023). Material Evaluation Framework of Additive Manufactured Aluminum Alloys for Space Optical Instruments. In: Broek, S. (eds) Light Metals 2023. TMS.

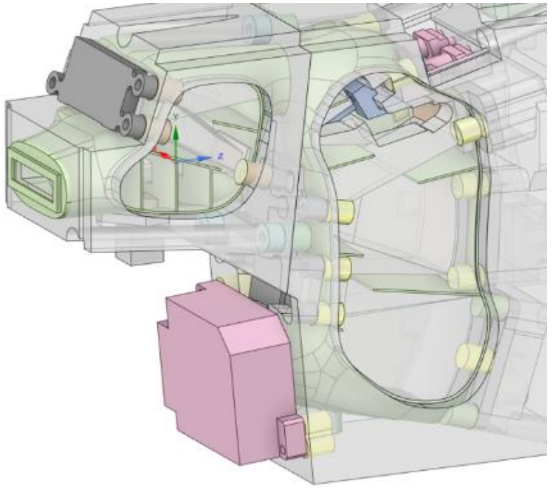
Topology Optimized Design Flow



Optical system in cubesat frame

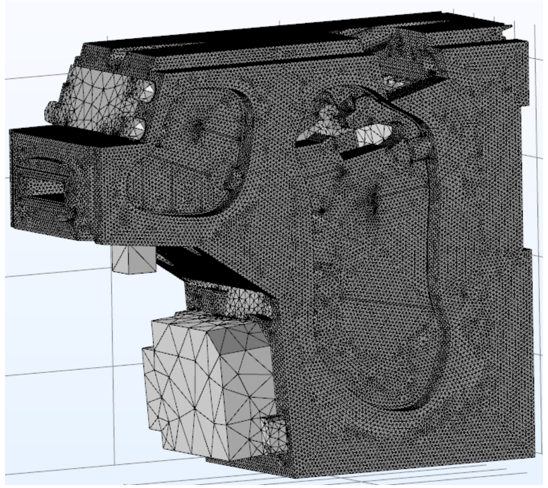


Add keep-free zones, interfaces to frame

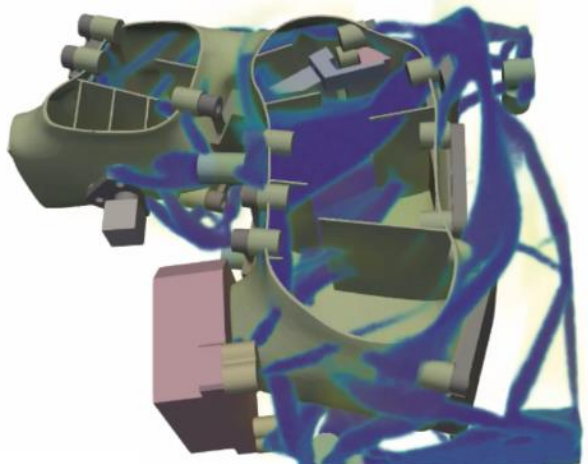


Iteration 0

Add light-tight shell, baffles, and access openings

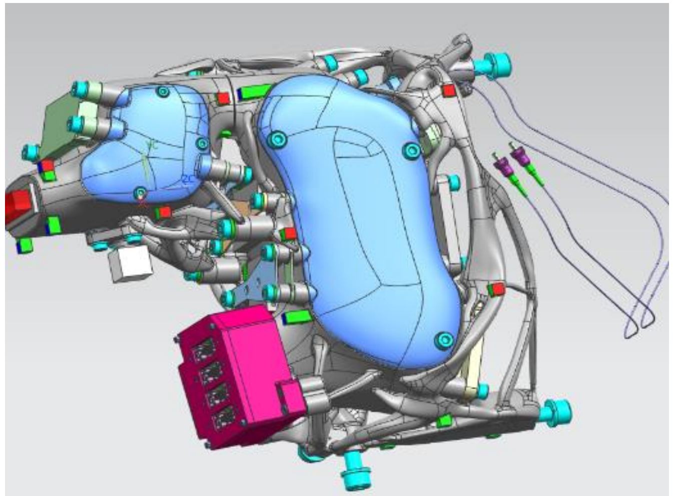


4.8M element mesh (1mm resolution)



Iteration 50

Minimize mass against 9 Load Cases. 5.5kg → 1.9kg



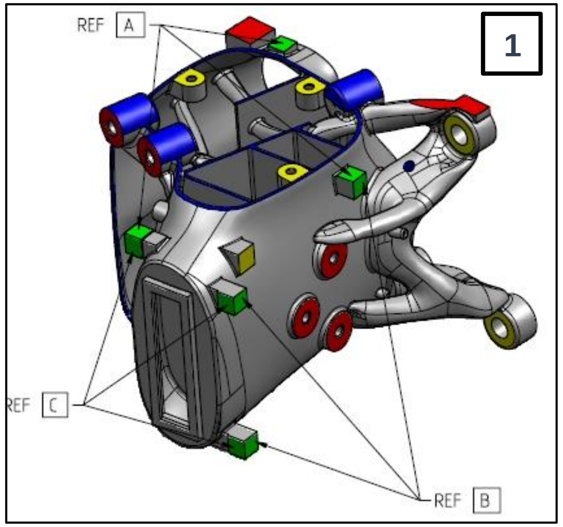
Add design details (reference cubes, lids, etc.)

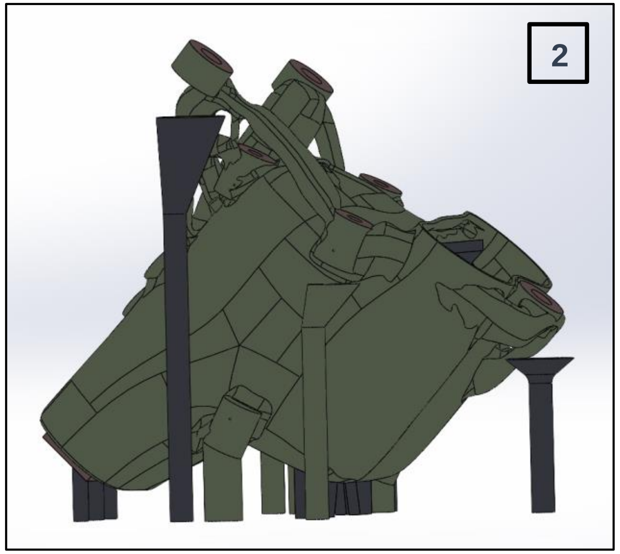
Funding: NASA ESTO IIP-19 (80NSSC20K0323)

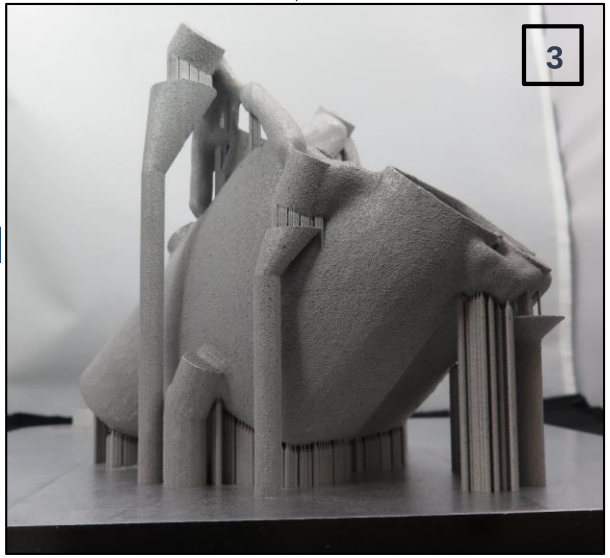
van Kempen et al, Small Optical instruments designed by Topology Optimization, ECSSMET, 2023

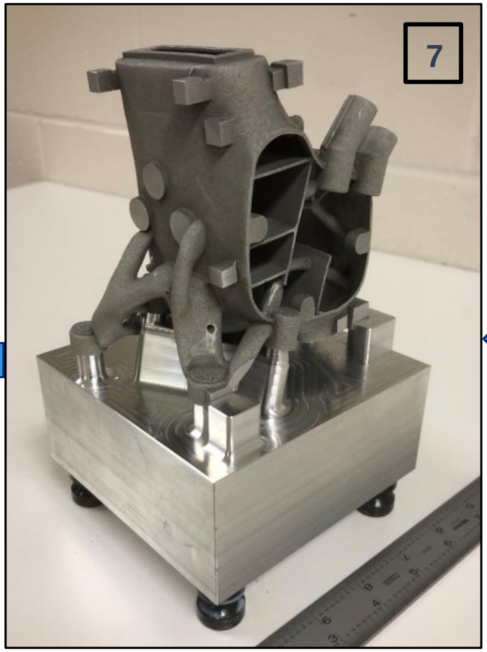
CHAPS-D Breadboard Fabrication

1. Add machining stock to precision surfaces in CAD model
2. Choose build orientation and generate support structure
3. 3D Print
4. Heat Treat
5. Remove Parts from Build Plate & Remove Supports from Part
6. Thermal Stabilization Treatment
   - -70C to 100C, 8X cycles
7. Machine Precision Surfaces
8. Chromate Conversion Coating
9. Breadboard Assembly
10. CMM Inspection (pre-test)
11. Vibration Testing & CMM
12. Thermal Testing & CMM





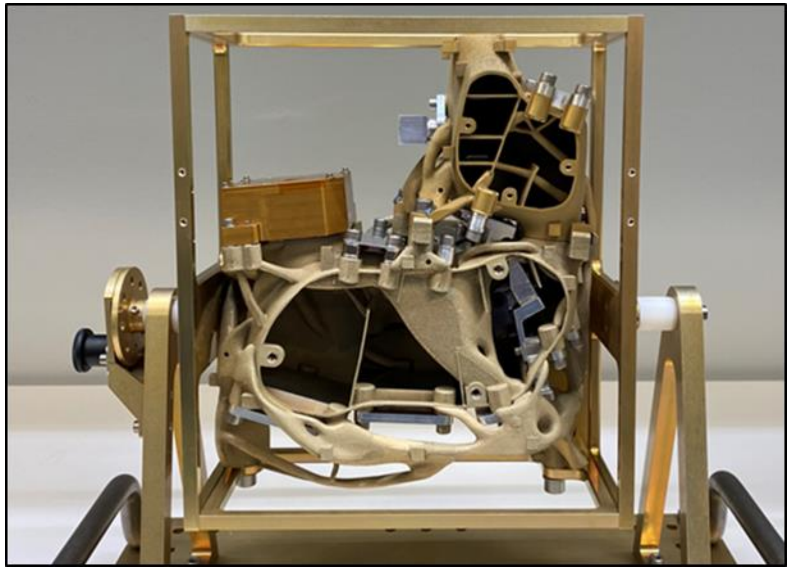




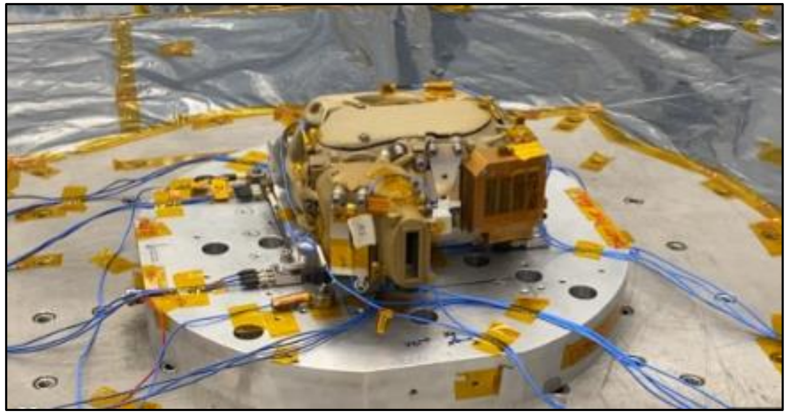
Funding: NASA ESTO IIP-19 (80NSSC20K0323)

CHAPS-D Breadboard Assembly & Testing

- Vibration tested to GEVS levels
  - No visible damage to housing
  - No changes to resonant frequency
  - Some mirrors shifted during vibration testing, 30–60 μm
    - Larger than expected, but analysis suggests no significant impact on performance
- Thermal cycled
  - -20°C to +60°C for 6 cycles
  - Post-Test CMM showed maximum shifts < 3 microns



units		Pre TC avg	Post TC avg	Pre-Post TC
	IM1			
deg	IM1 clocking	-0.06405	-0.064	-5E-05
deg	IM1 Backside Proj Ang 1	-2.60305	-2.60305	0
deg	IM1 Backside Proj Ang 2	-0.08185	-0.08195	1E-04
mm	IM1 X	135.1242	135.1271	-0.0029
mm	IM1 Y	-98.5006	-98.5028	0.0022
mm	IM1 Z	-12.70845	-12.70755	-0.0009

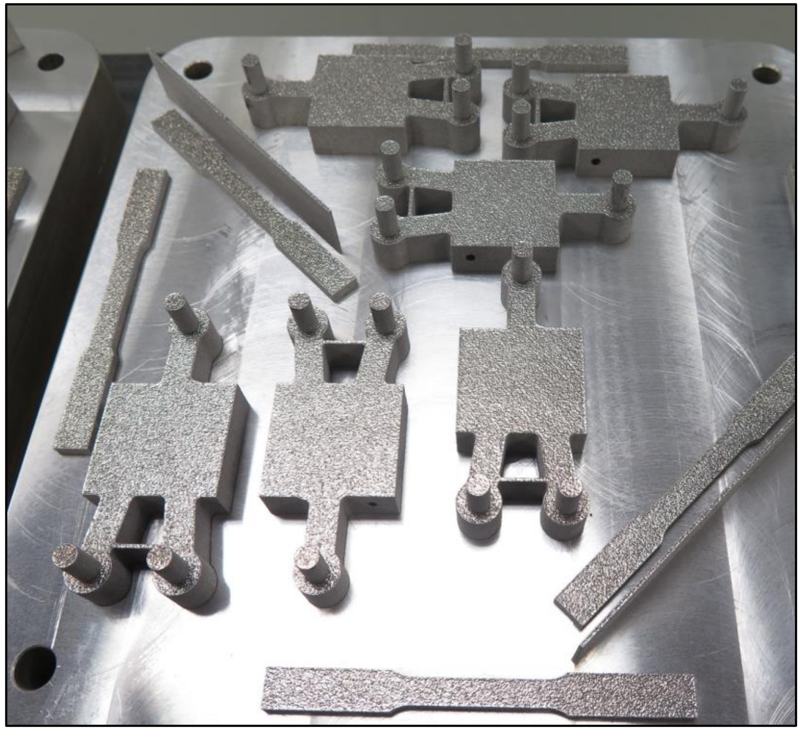


Scalmalloy AM Alloy Meets Environmental Stability Requirements for Optical Instruments

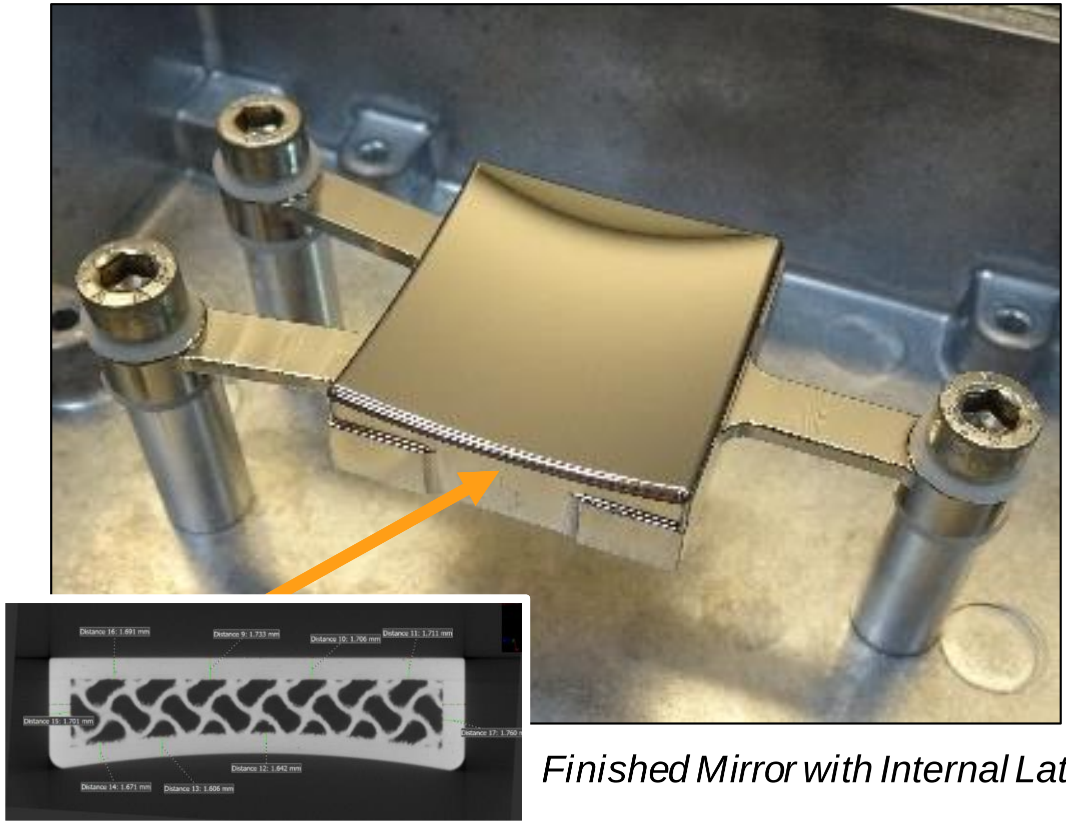
Funding: NASA ESTO IIP-19 (80NSSC20K0323)

Scalmalloy Mirrors

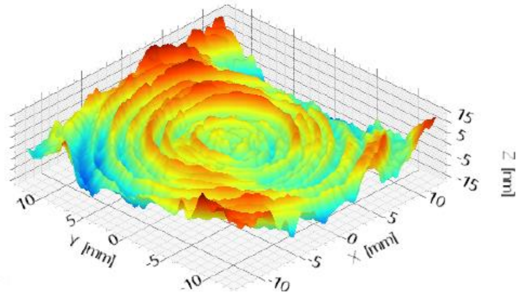
- Solid and lightweighted mirrors printed, heat treated, and pre-machined at APL
- TNO completed final machining, NiP plating, single point diamond turning, magneto rheological polishing and inspection



As-Printed Mirror Blanks



Finished Mirror with Internal Lattice



Fit results:

RMSi	=	4.6	nm
PV	=	34	nm
dx	=	15.95	µm
dy	=	-19.47	µm
dz	=	-119.82	µm
dRz	=	5825	µrad
Power	=	-99	nm

Scalmalloy AM Alloy Compatible with Mirror Fabrication Process

Funding: NASA ESTO IIP-19 (80NSSC20K0323)

Conclusions and Next Steps

- A Quantitative Material Selection Framework was developed and utilized to determine the best AM aluminum alloy to use for space optical instruments
  - Framework consists of weighted factors in four categories
    - Mechanical
    - Thermal
    - Print quality
    - Compatibility with post processing steps
  - Scalmalloy selected from four candidates
- Scalmalloy used to 3D Print CHAPS-D Housings and Mirrors
  - Environmental testing of breadboard assembly proved Scalmalloy optical stability
  - 3D Printed mirror blanks compatible with mirror processing steps
- Next Steps
  - Minor updates to housing designs and fabricate flight hardware
  - Aircraft flight test planned for Summer 2024

Funding: NASA ESTO IIP-19 (80NSSC20K0323)

JOHNS HOPKINS

APPLIED PHYSICS LABORATORY