Application and Testing of SupremEX® 640XA and AyontEX™ 13 for Mirrors and Precision Structures

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Abstract

SupremEX® 640XA Al-SiC MMC and AyontEX™ 13 Al-Si alloy are advanced aluminum-based materials developed by Materion Corporation that are under consideration for mirrors and related precision structures for high performing land, sea, air, and space applications. SupremEX® 640XA is a Metal Matrix Composite (MMC) with a 6061B aluminum alloy matrix reinforced with 40vol.% ultrafine Silicon Carbide particles and is harder, lighter, and stiffer than Titanium 6Al4V with excellent fracture toughness and fatigue resistance. AyontEX™ 13 is a hypereutectic Aluminium-Silicon alloy and is both lighter and stiffer than aluminum alloy 6061-T6. Both materials also have CTEs that are well matched to that of electroless nickel plating (13 ppm/°C) commonly used for mirror applications. Our investigations demonstrate that these materials can sustain requisite properties of finished mirrors operating at visible wavelengths and over broad ranges of operational temperature.

A 150 mm aperture finished light-weighted concave spherical test mirror was designed and manufactured according to developed manufacturing guidelines for both materials and is representative of design forms for airborne and space applications. Optical finishing operations included diamond point turning (DPT) and loose abrasive polishing. By use of laser interferometry, mirror figure stability was verified after multiple thermal cycles. Similar interferometric measurements were then repeated when subjecting the test mirrors to hot and cold temperature excursions under vacuum. These experiments were also performed both before and after the application of electroless nickel plating. Also considered were concepts for precision structures that are best fitted to the unique manufacturing-related characteristics of these materials.

Introduction:

CMM Optic, in Rochester Hills, MI designs and builds reflective metal mirror components, telescopes, polygon scanners, and fast steering mirror assemblies for a variety of military, commercial, and scientific applications. CMM Optic designed the test mirror and performed thermal cycling and temperature excursion experiments monitored with laser interferometry for this study.

Materion, in Elmore, OH, specializes in development of a broad array of high performing materials and related processes and products. Materion is introducing AyontEX 13 and SupremEX 640XA to the market along with extensive material property qualification required for high end optical instrument and defense applications.

Outpost Technologies, in Huntsville, AL contributed conventional machining of the AyontEX test mirrors.

The University of Alabama, Huntsville (UAH) contributed diamond point machining of the test mirrors both before and after electroless nickel plating with assistance from Outpost Technologies personnel.

Comparative Material Property Table

Redefining What Is Possible

Property		Aluminium 6061 T6	Stainless Steel 416	Titanium Ti-6Al-4V	Beryllium I-70H	AlBeMet® 162H	SupremEX® 640XA=PGQ	AyontEX™ 13-T1	Fused Silica	SiC (RB)	SiC (CVD)	Si	Zerodur
Density g/cm^3 (lb/in^3)	ρ	2.69 (0.098)	7.75 (0.280)	4.43 (0.160)	1.85 (0.067)	2.10 (0.075)	2.90 (0.105)	2.54 (0.092)	2.19 (0.080)	2.95 (0.107)	3.21 (0.112)	2.33 (0.084)	2.53 (0.091)
Modulus of Elasticity GPa (msi)	E	69 (10)	200 (29)	114 (17)	303 (44)	192 (28)	140 (20)	103 (15)	72 (10)	311 (45)	420 (61)	160 (23)	90 (13)
Thermal Conductivity W/m·K (BTU/hr·ft·°F)	k	167 (97)	25 (14)	7 (47)	216 (125)	210 (121)	150 (87)	134 (78)	1.4 (0.8)	152 (88)	220 (127)	160 (93)	1.5 (0.8)
CTE ppm/°C (ppm/°F)	α	22.9 (12.7)	9.9 (5.5)	8.6 (4.8)	11.4 (6.3)	13.9 (7.7)	12.9 (7.2)	13.2 (7.3)	0.5 (0.3)	2.52 (1.40)	2.52 (1.40)	2.6 (1.44)	0.0 (0-100°C)
Specific Heat J/g·K (BTU/lb·°F)	C_p	0.90 (0.21)	0.46 (0.11)	0.53 (0.13)	1.93 (0.46)	1.47 (0.35)	0.82 (0.19)	0.85 (0.20)	0.75 (0.18)	0.67 (0.16)	0.66 (0.16)	0.71 (0.17)	0.80 (0.1)
Specific Stiffness $GPa/g{\cdot}cm^{-3}$ $(msi/lb{\cdot}in^3)$	E_ρ	25 (102)	25 (104)	26 (106)	164 (660)	91 (373)	48 (193)	41 (162)	32.9 (132)	105 (421)	131 (545)	69 (274)	35.7 (146)
Thermal Diffusivity $10^{-2}\ cm^2/s$ $(10^{-2}\ in^2/s)$	$k/\rho C_p$	69 (10.7)	7 (1.1)	3 (0.5	60 (9.3)	66 (10.3)	63 (9.8)	62 (9.6)	0.9 (0.1)	77 (11.6)	104 (16.1)	97 (16.1)	0.7 (0.1)
Yield Strength MPa (ksi)	σ_y	276 (40.0)	275 (39.9)	880 (127.7)	207 (30.0)	193 (28.0)	455 (66.0)	300 (43.5)	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
Ultimate Strength MPa (ksi)	σu	310 (45.0)	515 (74.7)	950 (137.8)	345 (50.0)	262 (38.0)	540 (78.3)	325 (47.1)	152 (22.0)	250 (36.2)	470 (68.1)	165 (23.9)	100 (14.5)
Poission's Ratio	v	0.33	0.20	0.34	0.03	0.17	0.3	0.3	0.17	0.18	0.14	0.27	0.24
Vibrational Loss Factor 10^{-4}	η	0.7	4.0	3.7	29.0	12.0	1.3	Pending	Not Available	Not Available	Not Available	Not Available	Not Available

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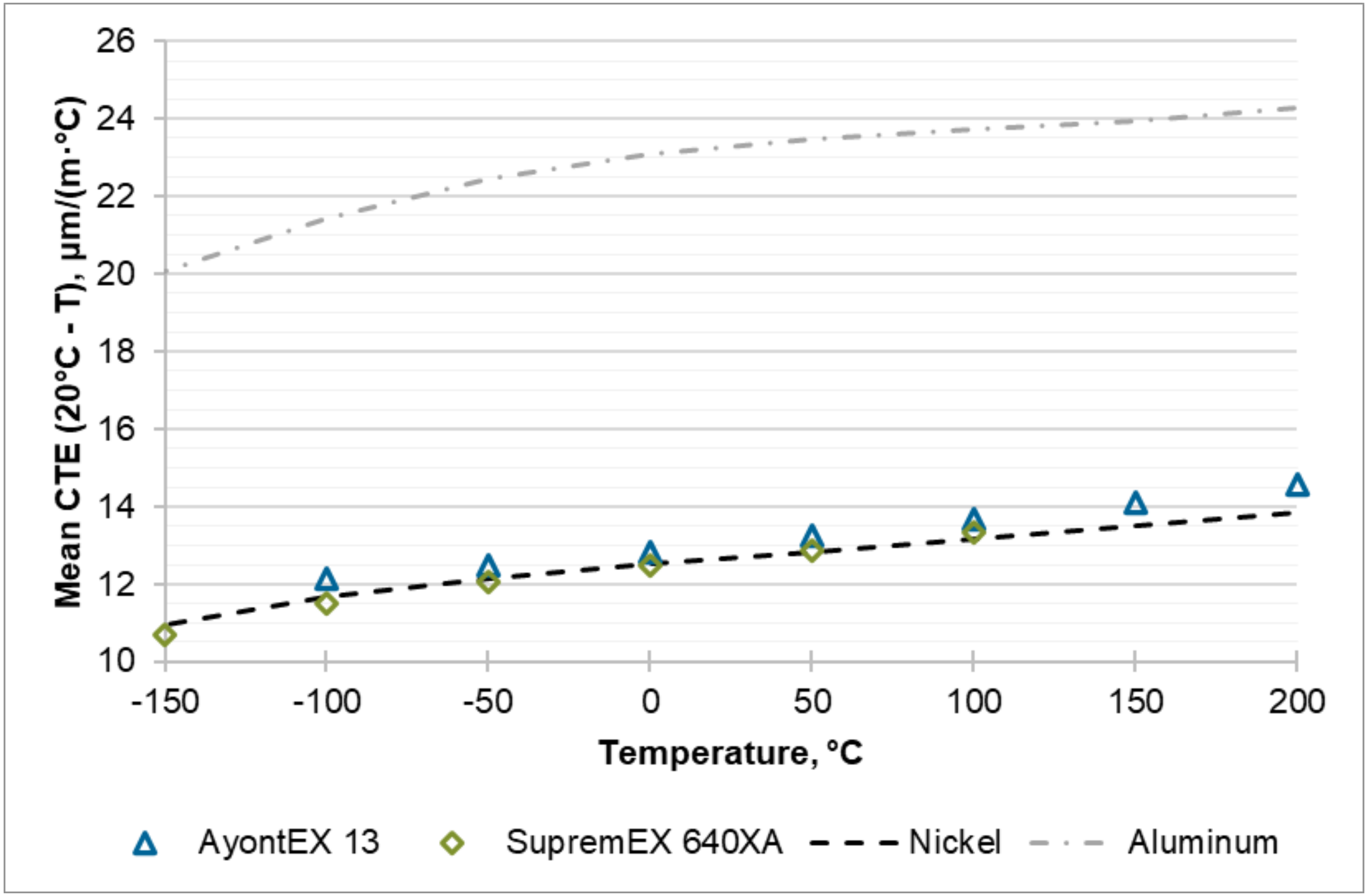
Relative CTE match to nickel plating



The graph above shows the CTE match of SupremEX 640XA and AyontEX™ 13 to commercially pure nickel, with comparison to aluminum. Also, increased modulus of elasticity further reduces the relative bi-metallic bending effects.

Key Takeaways: Material Properties

Fine, highly dense, randomized particle distribution relates well to strength and isotropic CTE.

Both materials generally abide by the rule of mixtures to obtain the best compromise of properties.

SupremEX® 640XA and AyontEX™ 13 are stronger and stiffer than Al6061-T6

The CTE match to electroless nickel is about 25-30X better than Al6061-T6

Modal frequency is improved by (specific stiffness ratio)^0.5 compared to Al6061-T6

Microyield is pending but is expected to be dominated by the Al6061 matrix.

SupremEX has notable lubricity and wear resistance for sliding contact applications

Both materials can be nickel plated, conversion coated, and black anodized

AyontEX™ 13 can be CNC milled and turned similar in cost to Al6061-T6, SupremEX® 640XA can be machined to similar complexity but polycrystalline tools are required, and machining cost is estimated at about +3X.

SupremEX® 640XA can be cut on diamond point turning machine to a non specular condition but having sufficient form and finish accuracy for application of electroless nickel. AyontEX™ 13 can be diamond point machined to 120-160 Angstroms RMS.

Thermal Cycling

Residual stress is a critical consideration in the manufacture of optics. Metal optics may be stress relieved by thermal cycling.

Episodes of hot and cold thermal cycles are known to release unstable metallurgical stress conditions. Other remaining internal stresses are expected to remain stable on a long-term basis unless activated by further material removal sequences.

Repeatable optical figure before and after thermal cycle is essential.

Mounting of optics is paramount to the success of an optical instrument. Tests for repeatability of optical figure and alignment registration must be performed throughout the manufacturing process to ensure satisfactory performance.

CMM Optic employs thermal cycle chambers that are fully programmable for ramp rates and dwell times at hot and cold temperature settings. Typical profiles for aluminum are +200-+325F and -100F-300F. Ramp rates and dwell times are determined by maximum wall thickness of the loaded parts to minimize thermal shock and to ensure that equilibrium is achieved at dwell temperatures.

Test Mirror Design

In order to evaluate these new materials for optics in the aerospace and precision instrumentation markets, the following attributes for a representative test mirror were embodied as follows:

- 6” size is small enough for reasonable cost while large enough to be of interest to EO systems engineers.
- Isogrid light-weighting pocket structure will reveal stress release and bi-metallic print-through issues during optical testing and also demonstrates ease of ball end mill contour machining.
- Relatively fast concave spherical surface simulates an aspheric surface and is readily generated by DPT and tested by laser interferometry. A 3D spherical contour is also effective at differentiating global and localized transverse and longitudinal changes in optical figure over temperature both before and after application of electroless nickel plating.
- Three-point integral mounting tangs typical for snap together optical alignment and diamond point turning.
- Demonstration of successful application of electroless nickel plating conducive for optical finishing and test for minimized bi-metallic change over temperature when plated on the mirror side only.

Test Mirror Design

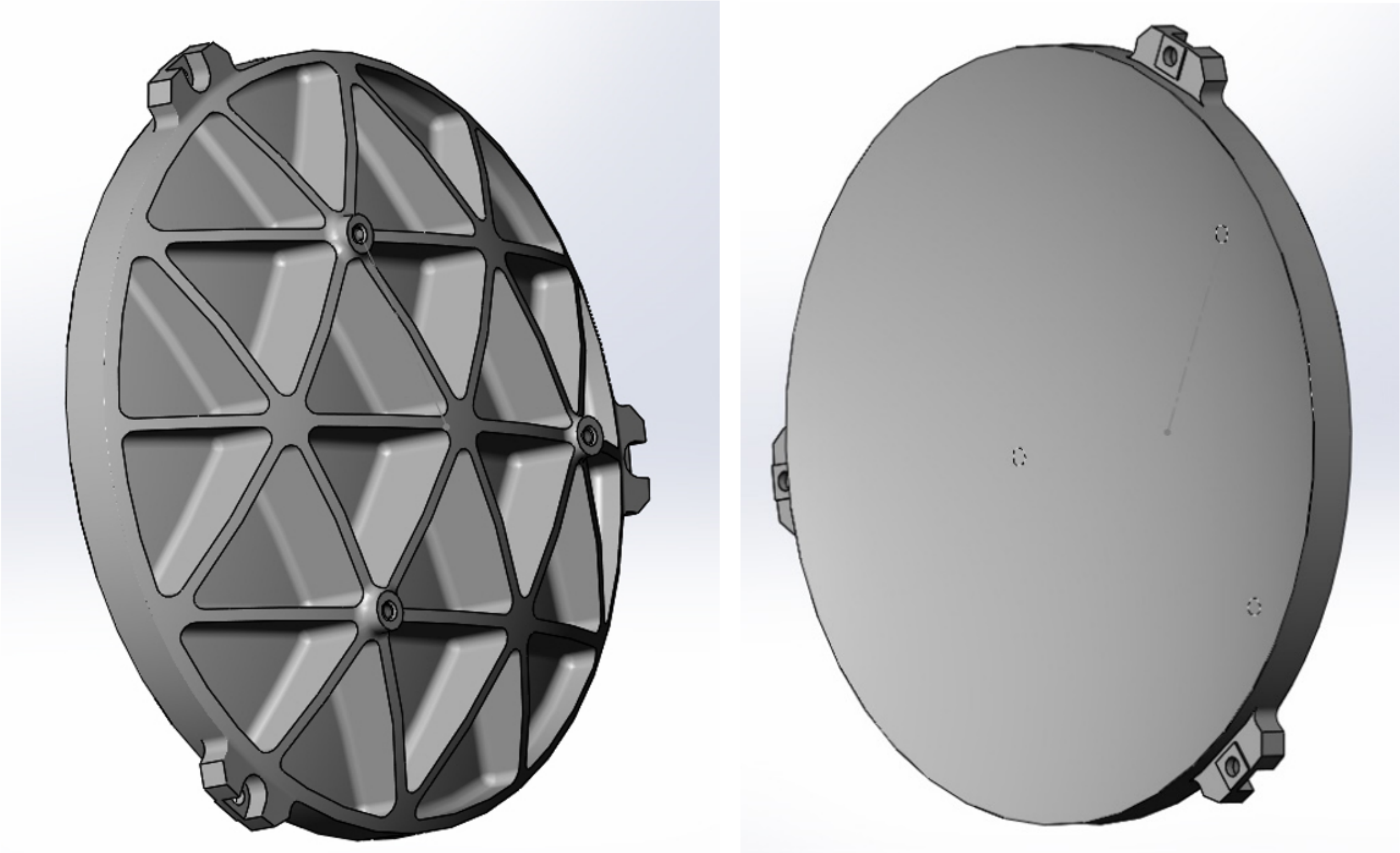
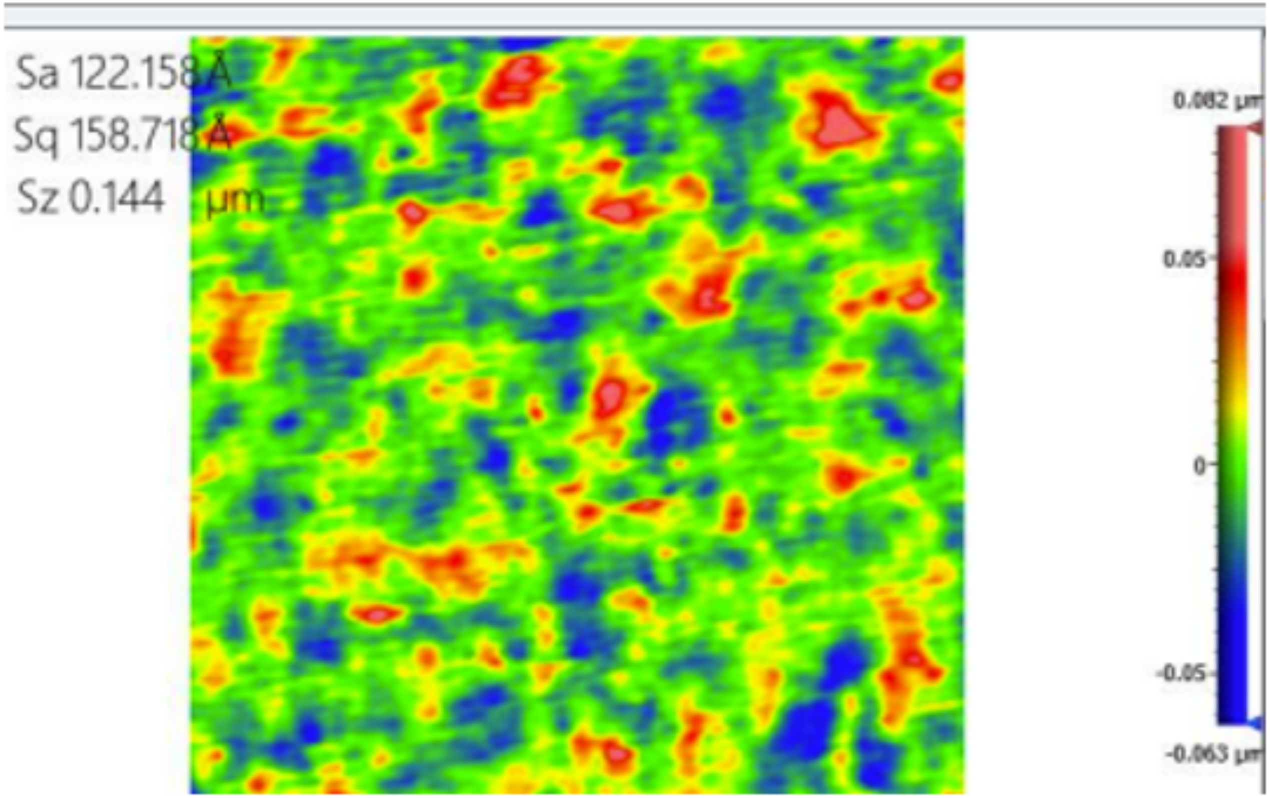


Figure 1: Resulting 6.00” diameter (152 mm) concave spherical test mirror design. All interferometric testing was conducted when resting face up in a free state of constraint for vertical testing or mounted for horizontal testing under light fastening spring pressure to the three raised pads on the back side.

Diamond point turning results: AyontEX-13



Results are consistent from part to part and location to location on each part.

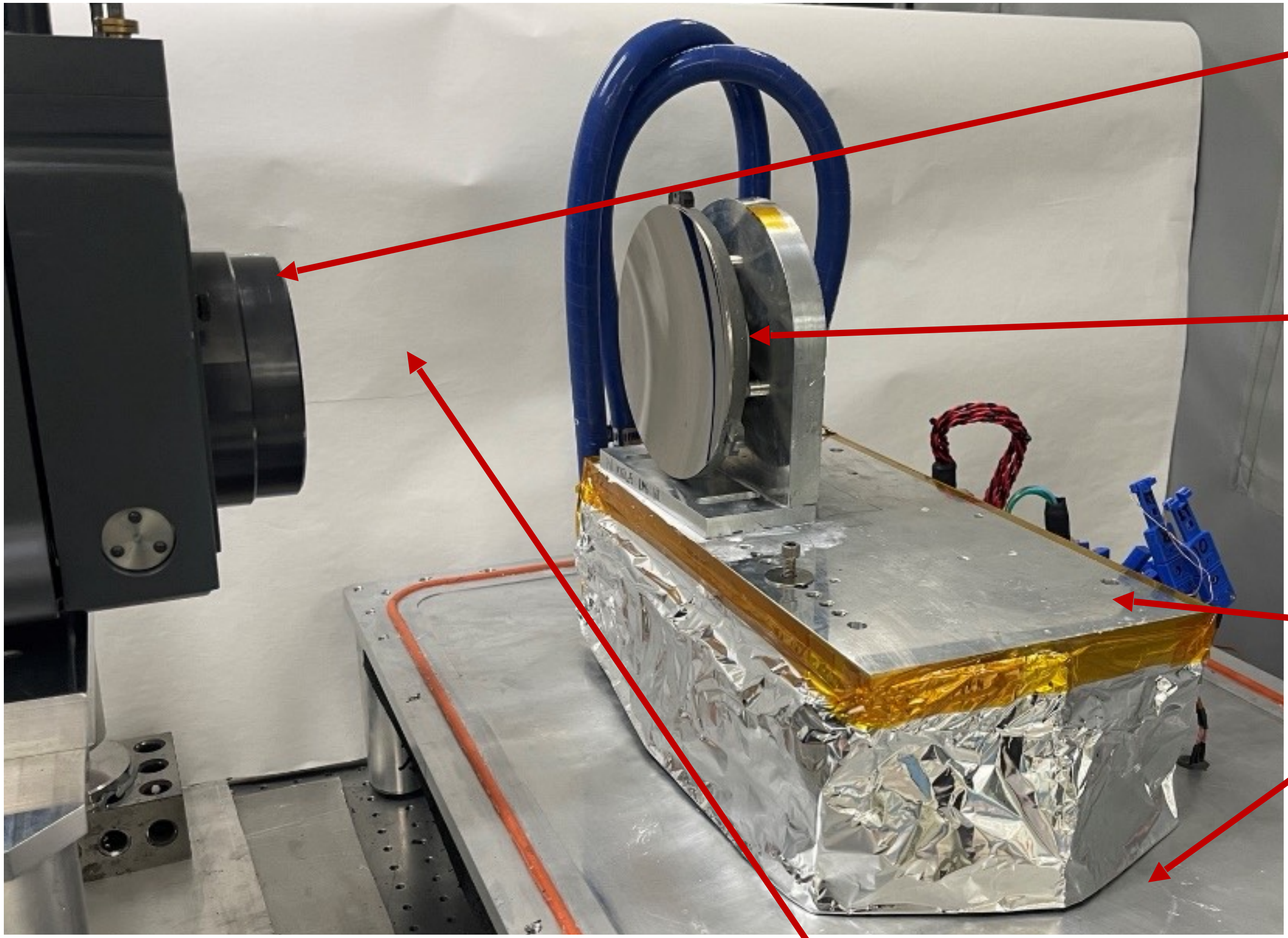
120-160 Angstoms RMS

Density is excellent No voids from pull out or porosity evident in any of the scans.

Surface finish is dominated by material grain structure and not DPT artifacts. Grain structure is random and regular DPT grooves not readily evident.

By comparison, diamond turning of aluminum 6061-T6 will result in 40-100 Angstroms RMS and electroless nickel plating 20-40 Angstroms RMS

Thermal Vacuum Testing



3-axis adjustable Zygo phase measuring interferometer fitted with F/0.75 transmission sphere

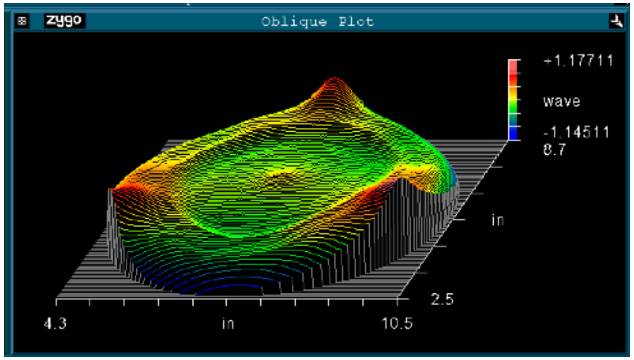
Concave spherical test mirror attached via three tapped holes in the back side to tombstone shaped mount bolted onto heat exchanger

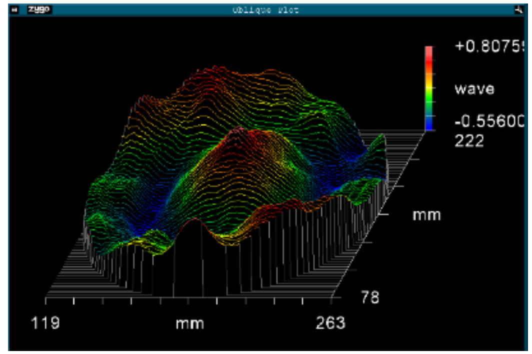
Anti-freeze liquid hot and cold heat exchanger

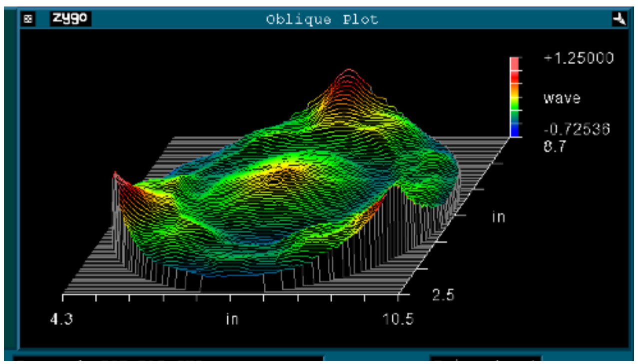
Base plate of thermal vacuum chamber

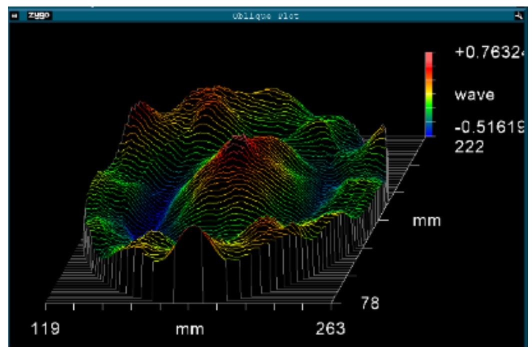
Thin window in vacuum cover minimizes spherical aberrations

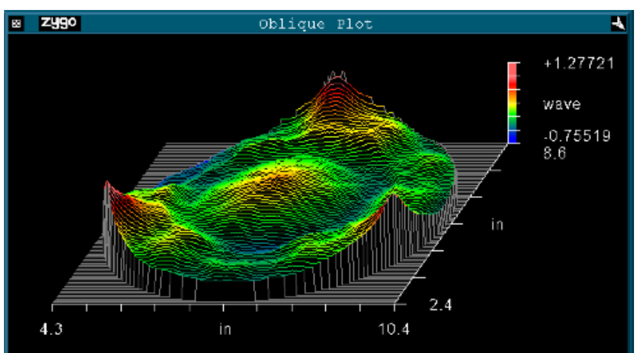
Interferometric Testing

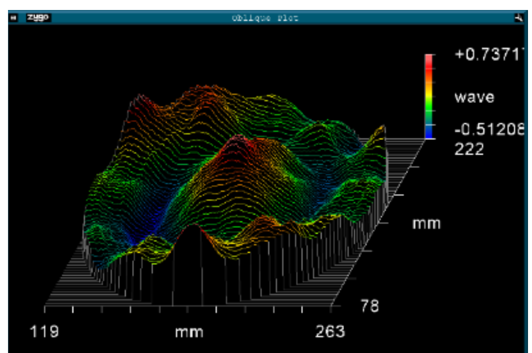








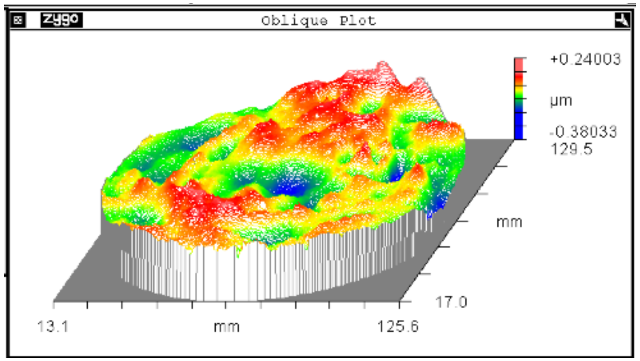


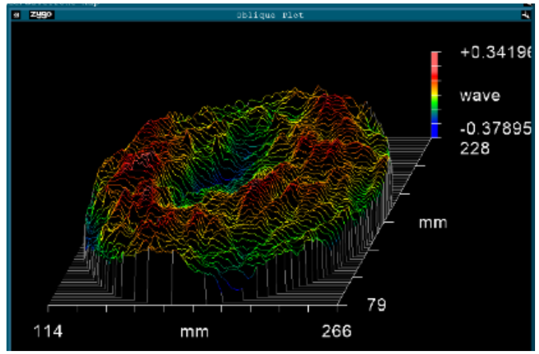


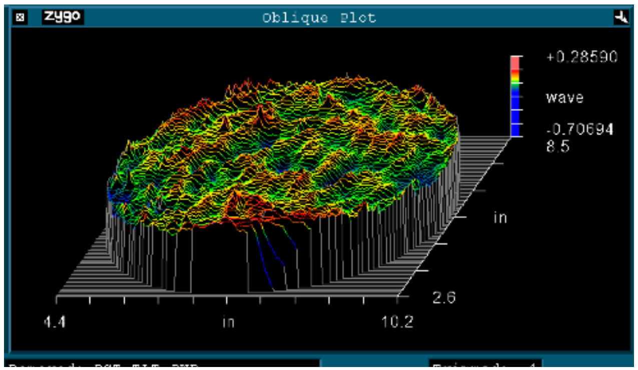
AyontEX™ 13 SN002
Top Left 70F Post diamond machine/pre-cycle P-V: 2.312 waves @632.8 nm
Middle Left 70F Post cycle #1 (3X -100F to +325F) P-V: 1.975 waves @632.8 nm
Bottom Left 70F Post cycle #2 (3X -100F to +325F) P-V: 2.032 waves @632.8 nm

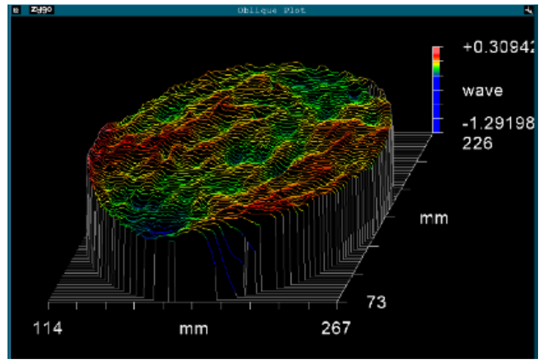
AyontEX™ 13 SN004
Top Right 160F Thermal Vacuum Test P-V: 1.364 @632.8 nm
Middle Right 7F Thermal Vacuum Test P-V: 1.279 @632.8 nm
Bottom Right 70F Thermal Vacuum Test P-V: 1.249 @632.8 nm

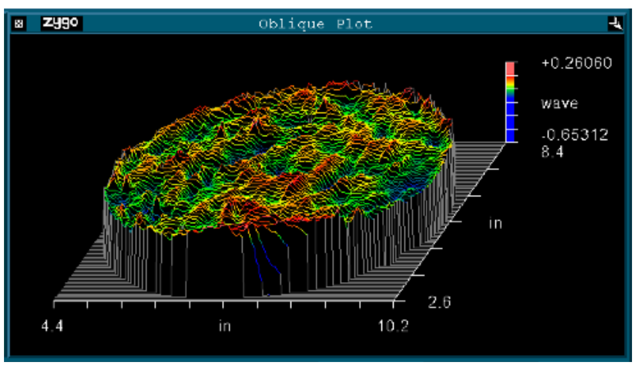
Interferometric Testing

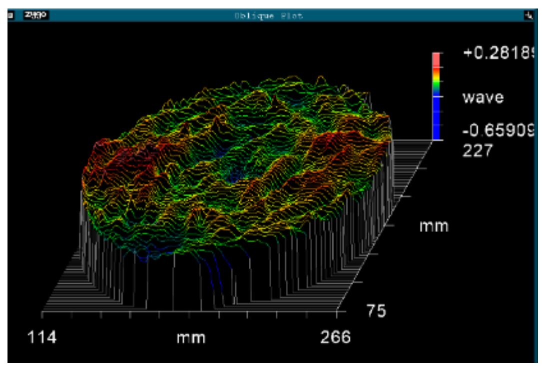












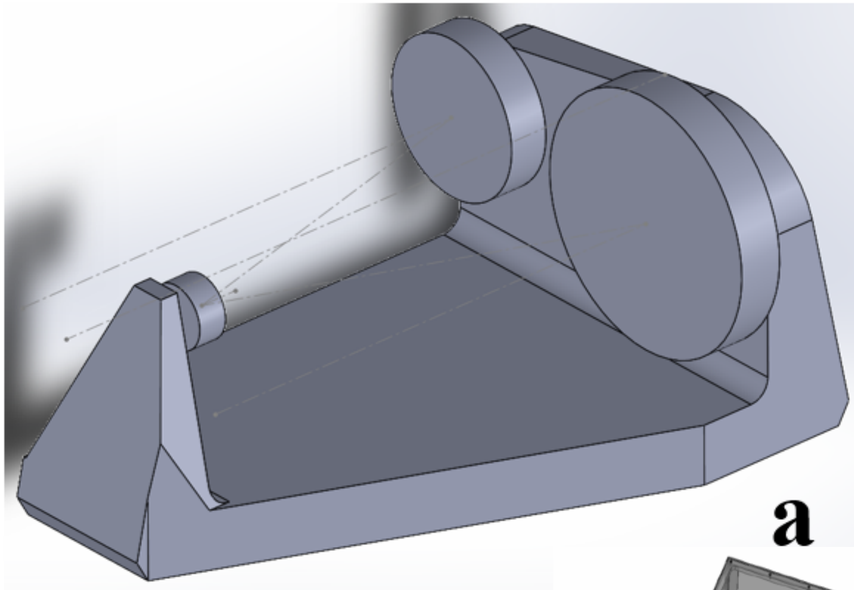
SupremEX® 640XA SN001
Top Left 70F Nickel plated and polished in 2021 P-V: 0.980 @632.8 nm
Middle Left 70F Re-tested pre-cycle P-V: 0.993 @632.8 nm
Bottom Left 70F Post cycle #1 (3X -100F to +325F) P-V: 0.914 @632.8 nm

SupremEX® 640XA SN001
Top Right 160F Thermal Vacuum Test P-V: 0.725 @632.8 nm
Middle Right 15F Thermal Vacuum Test P-V: 0.925 @632.8 nm
Bottom Right 70F Thermal Vacuum Test P-V: 0.943 @632.8 nm

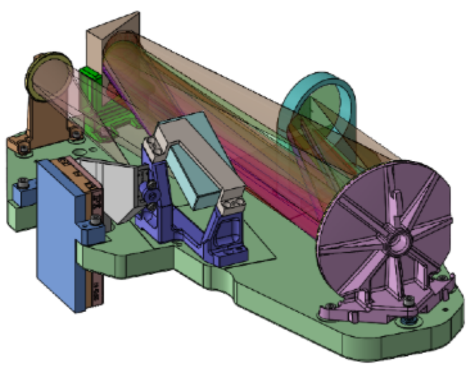
Typical Metering Structure Design Goals:

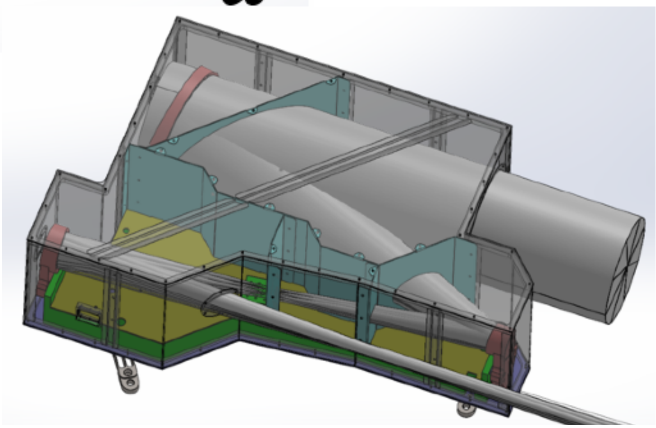
- Compact design form, particularly for airborne and space applications.
- Matching CTE to mirrors for athermalized design
- Accuracy of location for integrated optical elements
- Stiff enough to sustain manufacturing forces and operational load cases. High vibration mode frequencies.
- Higher stiffness and structural damping are bonus properties compared to aluminum.
- Manufacturing Producibility.
- Generally, avoid un-improved surfaces from sinker or wire EDM manufacturing methods due to re-cast concerns

Metal Telescope Design: Mini-bench



a





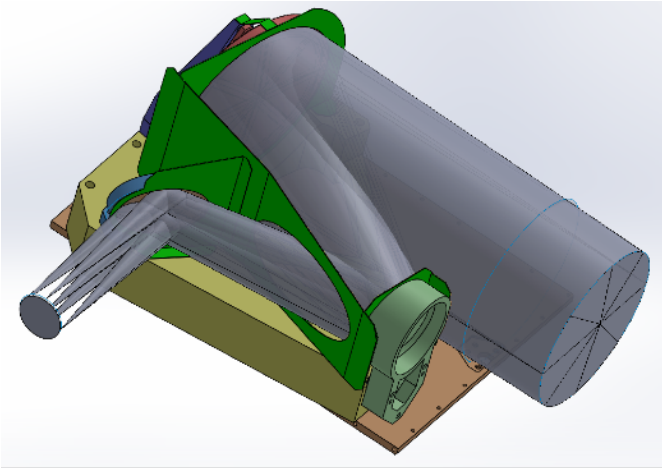
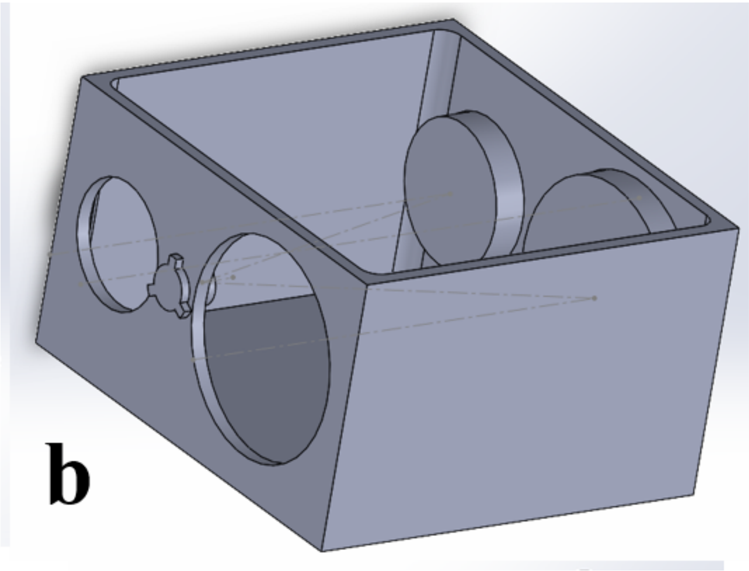
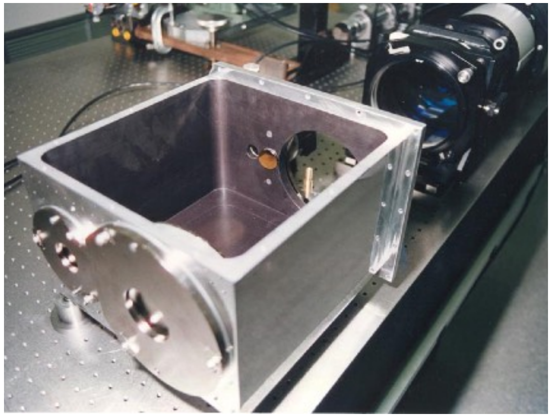
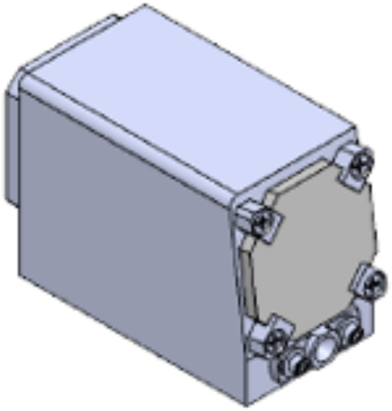


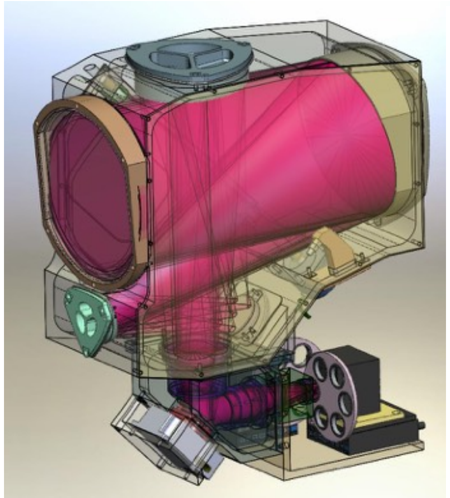
Figure “a” is a “mini-bench” with three off axis mirrors mounted from the back side and generally integrated into an enclosure at a higher level of assembly.

Metal Telescope Design: Box









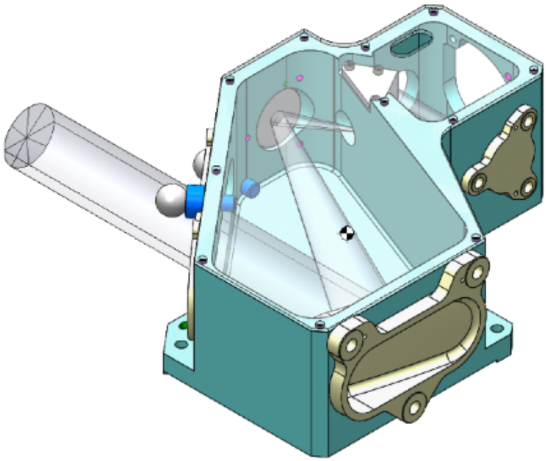
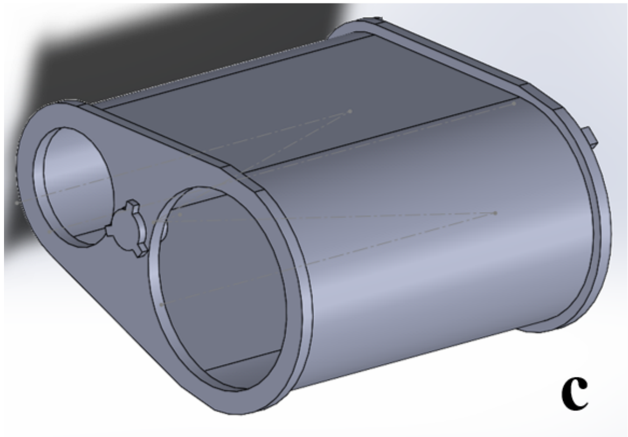
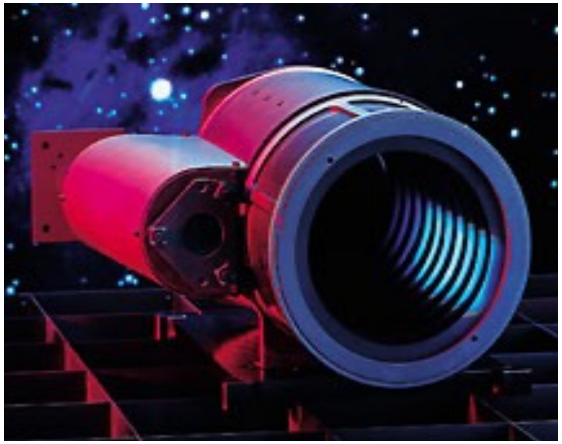
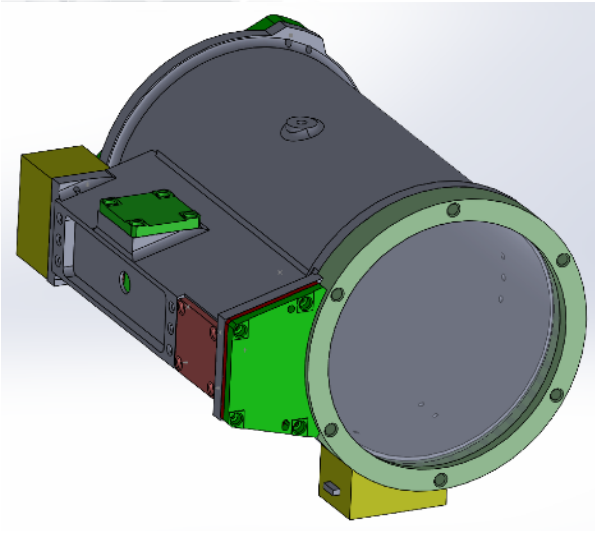


Figure “b” has the three mirrors plugging in from the outside of a box structure. This design form is common for terrestrial cryogenic instruments where mass allocation is not stringent.

Metal Telescope Design: Tubular off axis







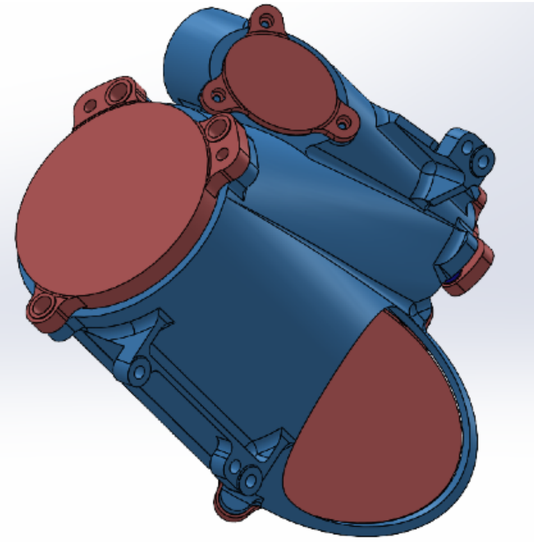
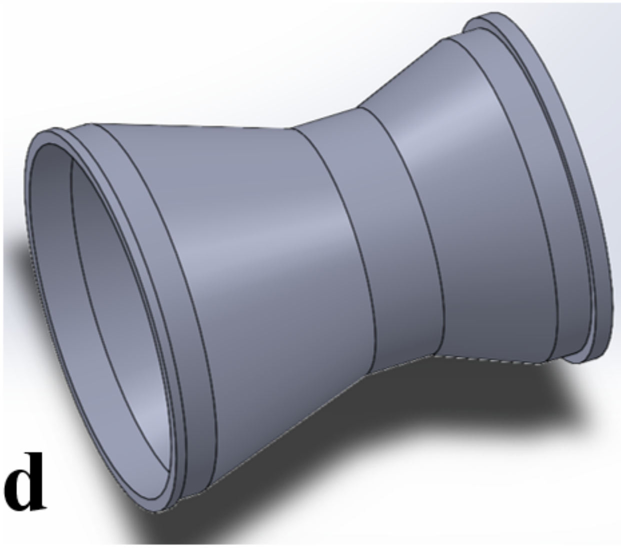
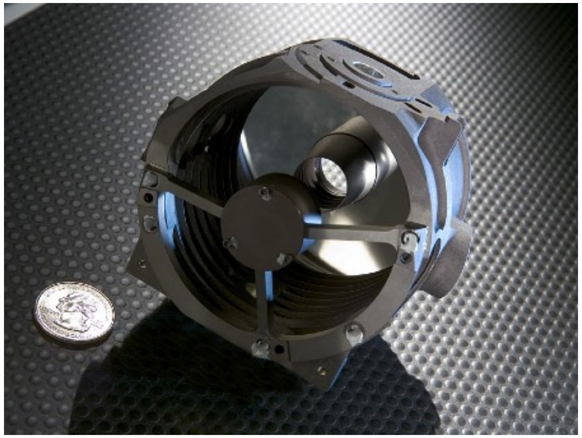
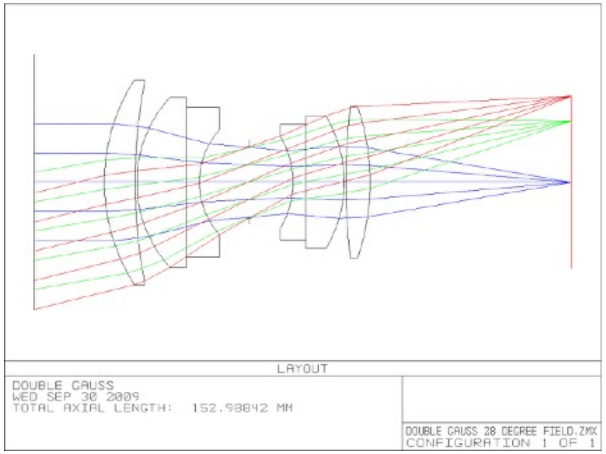


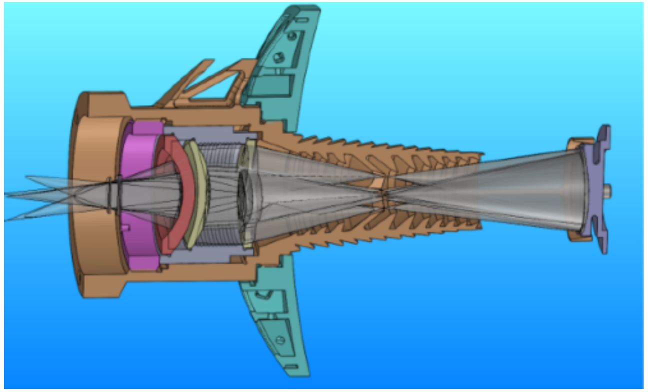
Figure "c" has the three mirrors plugging in from the outside of a flanged tubular structure that is structurally efficient and typical of airborne and space applications.

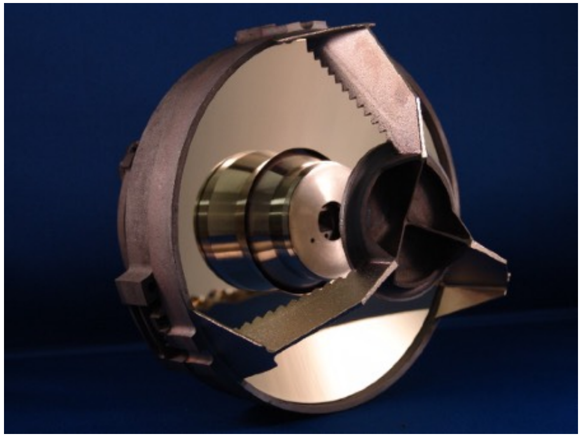
Metal Telescope Design: Tubular symmetric











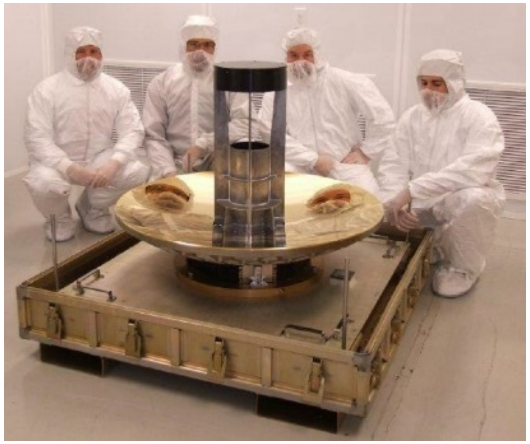


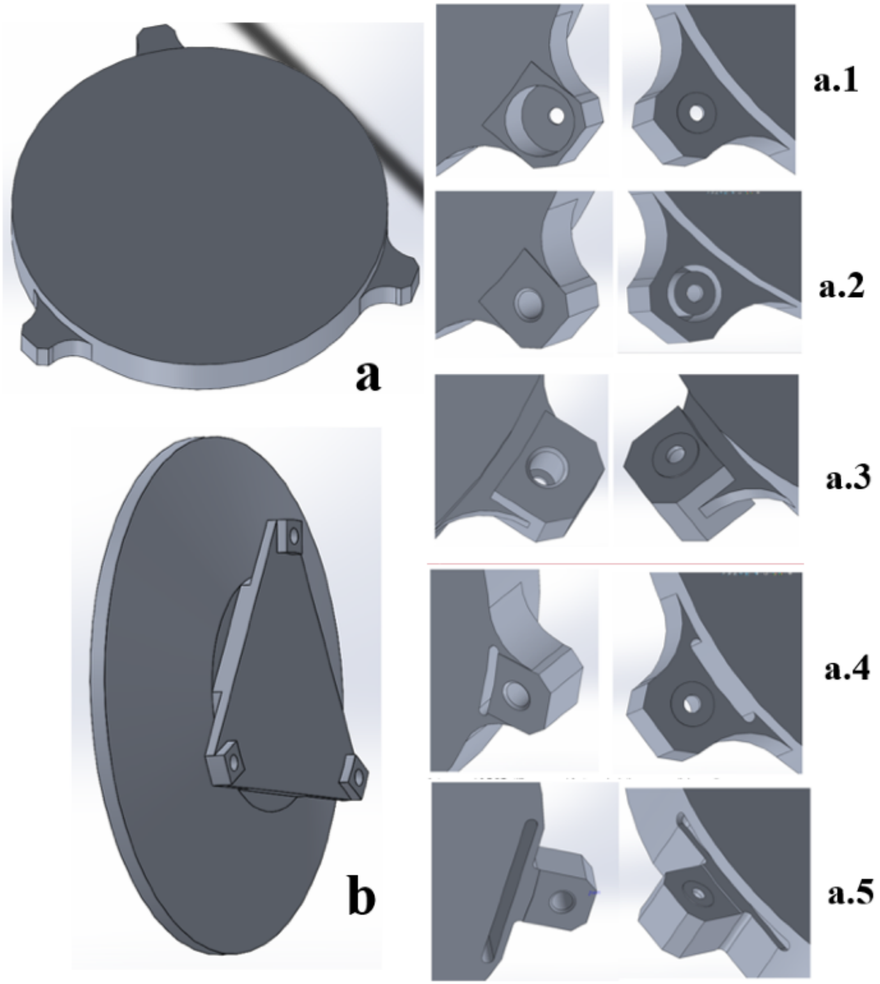
Figure “d” is typical design for a lens barrel such as for double gauss and infrared camera designs. Also can evolve into symmetric Cassegrain, Ritchey-Chretian Cassegrain, and Catadioptric designs

Mirror Flexure Design Goals

Metal mirrors typically employ integrally machined semi-kinematic mounting features. Glass mirrors typically require metal flexures that are adhesive bonded or attached to adhesive bonded metal threaded inserts

Key characteristics for metal mirror flexures include the following:

1. Integrally machined into mirror substrate.
2. Three point mounted: edge through holes in tangs, back side tapped holes.
3. Compact design form for air and space applications
4. Free state of constraint to full mounting torque of specified fasteners without distortion
5. Accuracy of location for conventional machining, DPT, and null test metrology for post polishing.
6. Pin holes close to mounting holes to minimize bending risk due to friction with pins
7. High degree of fastener strain isolation: axial, lateral, triaxial twist, delta T, self weight
8. Stiff enough to sustain manufacturing forces and operational load cases.
9. Acceptable localized stress from operational load cases. High vibration mode frequencies.
10. Manufacturing Producibility.
11. Generally, avoid sinker or wire EDM mfg methods due to re-cast concerns



Integrally machined mounting flexure designs applicable to metal mirrors in general.

- "a" illustrates generic outboard 3-point mounting tangs that can take the form of:
- a.1 diaphram flexure,
- a.2 deep standard counter bore with trepan annular isolation feature,
- a.3 deep standard counter bore with undercuts from both sides,
- a.4 deep standard counter bore with milled slot isolation feature,
- a.5 deep standard counter bore with milled slots from two directions to produce tangent flexures.
- All of the "a" mount designs are conducive for iso-grid light-weighting of the back side of the mirror,
- "b" illustrates generic back mounted, tapered back mirror design with undercut 3-point mounted delta frame attachment.

Approximate Cost Comparison: 2024

Material	Cost per lb	Machining cost
aluminum 6061-T6	$8	1.0X
AyontEX™ 13	$100	1.0X
SupremEX® 640XA	$100	3.0X
AlBeMet162	$1500	4.0X
Beryllium I-70H	$3000	6.0X

Optical processing costs consisting of diamond point machining, nickel plating, optical polishing, and optical coating can be expected to be similar among all these materials

Future Developments:

Vastly improved CTE matching of diamond point turned and highly polishable electroless nickel plating on light-weighted mirror substrates, enabled by replacement of aluminum with AyontEX™ 13 or SupremEX® 640XA, will benefit many current and future optical systems applications.

Additional material property characterization is planned to include micro-yield strength evaluation of the SupremEX® 640XA and AyontEX™ 13 materials, as well as the exploration of the damping characteristics of AyontEX™ 13.

CMM Optic will be repeating thermal test experiments on the spherical test mirrors after computer polishing of the diamond turned optical figure to a greatly improved optical figure and finish after diamond point machining

Although originally focused on opto-mechanical applications, SupremEX® 640XA and AyontEX™ 13 can also be used for high-speed semi-conductor fabrication equipment, robotics, and rotating shafts due to relative advantages of mechanical properties. These materials can also be used in light weight thermal management applications, as well as load bearing and/or wear resistant components.

Metal additive manufacturing (AM aka 3D printing) enables rapid prototyping and design forms of unprecedented structural efficiency. Since the feed stocks for the creation of both AyontEX™ 13 and SupremEX® 640XA billets are homogenous powder, additive manufacturing solutions may be on the horizon. Materion is currently investing in development of additive manufacturing at its Elmore, OH material research facility for various materials. Materion can also produce near net shapes from powders by HIP, CIP-sinter and by closed die forging.

Summary:

- These new materials occupy a unique niche between aluminum and beryllium that design engineers can now consider.
- Light weighted 6” diameter AyontEX™ 13 and SupremEX® 640XA spherical test mirrors, were designed and manufactured that have been shown to exhibit excellent density, homogeneity, dimensional stability, and isotropy of thermal expansion over temperature on the nanometer scale of measurement.
- Machining producibility was proven to be satisfactory.
- General concepts for integral mirror flexures, and optical benches and lens barrels than can be machined from AyontEX™ 13 and SupremEX® 640XA, similar to aluminum designs, have been presented.
- Overall cost comparison to aluminum is compelling when accounting for similar processing cost starting from billet and relative performance advantages.
- Further testing of material properties and thermal testing after refinements to optical figure and finish of the test mirrors is on-going.

Questions?

Thank you for your time.

Please call or email anytime if I can help with a question

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