3D PRINTED SILICON CARBIDE SCALABLE TO METER-CLASS SEGMENTS FOR FAR-INFRARED SURVEYOR

2018 Mirror Technology Days

NASA Phase II Results

Contract #80NSSC18C0077

An ACTIVE Participant in STEM
“You have to give it away to keep it”
Gondola for High Altitude Planetary Science (GHAPS)

Preliminary Design Review (PDR)
Optical Telescope Assembly (OTA)

Courtesy of Monica Hoffman (TPOC) and Roy Young (Deputy)
OVERVIEW

- NASA Priority Technology Gaps
- GHAPS Requirements
  - GHAPS OTA Overview
  - OTA Characteristics
  - Primary Mirror Mechanical Requirements
  - Primary Mirror Design
- Phase II Goals
- Phase II Progress Report
- Full-Scale Mirror Analysis Results
- 1/4th scale mirror design
- 1/4th scale mirror analysis
- Alternate design for 1/4th scale mirror
NASA PRIORITY TECHNOLOGY GAPS
Phase II Addresses Technology Development/Demonstration of Segments Traceable to Origins Space Telescope (OST)

Cosmic Origins (COR) Program Annual Technology Report (PATR)

<table>
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<th>Priority</th>
<th>Technology Gap Name</th>
<th>Science Addressed</th>
<th>Submitted By</th>
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<td>Priority 1</td>
<td>Heterodyne Far-IR detector arrays and related technologies</td>
<td>Far-IR</td>
<td>OST STDT</td>
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<td></td>
<td>Cryogenic readouts for large-format Far-IR detectors</td>
<td>Far-IR</td>
<td>OST STDT</td>
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<td>Warm readout electronics for large-format Far-IR detectors</td>
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<td>OST STDT</td>
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<td>Large cryogenic optics for the Far IR</td>
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<td>Large-format, low-noise and ultralow-noise Far-IR direct detectors</td>
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<td>OST STDT</td>
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<td>High-performance, sub-Kelvin coolers</td>
<td>Far-IR/X Ray</td>
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<td>Large-format, high-dynamic-range UV detectors</td>
<td>UV/Far-UV</td>
<td>LUVOIR STDT</td>
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<td>High-reflectivity broadband Far-UV-to-Near-IR mirror coatings</td>
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<td>LUVOIR STDT</td>
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<td>Lightweight, large-aperture, high-performance telescope mirror systems for Far-IR</td>
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<td>General Community</td>
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<td>Compact, integrated spectrometers for 100 to 1000 µm</td>
<td>Far-IR</td>
<td>OST STDT</td>
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<td>Advanced cryocoolers</td>
<td>Far-IR/X Ray</td>
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<td>Mid-IR detectors</td>
<td>Mid-IR</td>
<td>OST STDT</td>
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<td>Cryogenic deformable mirror</td>
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<td>OST STDT</td>
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<td>High-efficiency UV multi-object spectrometers</td>
<td>UV</td>
<td>General Community</td>
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<td></td>
<td>Lightweight, large-aperture, high-performance telescope mirror systems for UVOIR</td>
<td>UVOIR</td>
<td>General Community</td>
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</table>
GHAPS REQUIREMENTS
GHAPS OTA Overview

BIRC-IR
UV-VIS
Motorized Trim Weights***
Avionics Functional Groupings
OTA Avionics Plate
WASP Flight Computer Plate
LN251Plate
Ethernet Hub Plate

OTA to Wallops Arc Second Pointer (WASP) Interface
Interface from WASP to pointed mass

Secondary Mirror
Head Ring
Sun Shade
Secondary Metering Shroud
Primary Mirror Cell
Primary Metering Shroud
OTM Characteristics

- **Key Features of OTA**
  - 14.052 m effective focal length (EFL) Ritchey-Chretien (RC) design
  - **Hyperbolic primary** and secondary
    - Primary will be a contracted item – size exceeds in-house fabrication capabilities
    - Secondary will be fabricated in-house
  - Design influenced by existing legacy UV-visible and IR instruments
    - OTA focal length is a compromise between short focal length desired for IR instrument and long focal desired by UV-visible instrument
  - **1.0 m clear aperture, F/2.5 focal ratio**
    - Physical diameter of mirror 1030 mm to include rolled bevel edges
    - Edge thickness 125 mm
  - **Mirror Material:** Zerodur Tailored CTE
  - Open back configuration with iso-grid light weighing pattern
    - Current weight 78.7 kg, Light weighting fraction ~ 68%
    - Compromise between weight reduction and mirror robustness (i.e., crash survival)
PRIMARY MIRROR MECHANICAL REQUIREMENTS

- **Optical System Performance:**
  - Operating Temperature Range: -50°C to 20°C
  - Gravity release

- **Fundamental Frequency:**
  - 10 Hz Minimum for Optical Telescope Assembly.
  - Zerodur Primary Mirror estimated 378.5 hz

- **Adequate Strength**
  - +/-10g (X, Y, and Z directions, independently)

- **Drawing Requirements**
  - Aspheric Optical Surface
  - 1080 Diameter, Center Hole
  - Whiffletree and Tangent bar Mounting Interfaces
(M1) Primary Mirror

- **Primary Mirror**
  - 1030 mm OD
  - 125 mm Thick
  - Schott Zerodur (0±0.02 PPM/K CTE)
  - 65% Light-Weighted Open Back

- **Support Bond Pads**
  - 3 Tangent Bar Mirror Mount
  - 18-Point Whiffle Tree Axial Mount

- **Drawings**
  - MEE00532: Pre-Polished, Light-Weight Blank
  - MEE00531: Bonded/Polished, Primary Mirror

- **Total Weight:** 171.5 lbs (77.8 kg)
- **Potential Weight Savings**
  - No Opportunity

40.55 inch OD
4.92 inch thick
MEE00532-001, REV C. GHAPS PRIMARY MIRROR PREPOLISHED BLANK

Note 2 different Rib Thicknesses 8.6 (0.34 in) and 5.6 mm (0.22-in)
(M1) Whiffle-Tree & Tangent Bar Mirror Mount

- 6X Rockers
- 3X Yokes
- Simultaneous 1D Athermal
  - Inner Bond Path
  - Outer Bond Path

- 3X Tangent Bar Assemblies
  - Bond Pad Flexure (Titanium)
  - Composite Tubes (IM7/8552)
  - Switch Back (6061 Aluminum)
  - Expendable Flexure (Titanium)
  - Differential Screw (Inner, Outer)

- 1D Athermal
  Axial Position Datum A
  Tangential Line of Action
FULL SIZE GHAPS PRIMARY LEGACY ISOGRID DESIGN
FINITE ELEMENT MODEL DESCRIPTION

18 Whiffle Tree Support Areas
PHASE II GOALS

- Use 3D printing and additive manufacturing processes to produce the greenbody components, that when assembled and ceramized, will yield a large meter-class silicon carbide primary mirror substrate suitable for GHAPS, and is traceability to future missions that require large mirrors.
- Print four OAP parts and then AM to make a monolith primary mirror at quarter scale.
Reviewed NASA GHAPS Requirements
- Requirements Document
- Primary Mirror Drawings and STEP file model

Performed Full Size Isogrid Primary Mirror Analysis, Zerodur® vs RoboSiC™
- Fundamental Modes
- Gravity Sag (X,Y, and Z directions)
- Thermal Soak (20°C to -50°C)

Created 1/4 “Scale” Primary Mirror Design, Isogrid (legacy)
- Design Model and Drawing

RoboSiC™ design and manufacturability for ¼-Scale Pathfinder
FULL SCALE MIRROR ANALYSIS RESULTS
The superior specific stiffness to weight ratio of RoboSiC™ will allow a thinner, lighter mirror. But how much thinner Dr. Bill?
### Potential Weight Improvement at Constant 1st Mode

<table>
<thead>
<tr>
<th>Room Temperature Property:</th>
<th>Density</th>
<th>Young’s Modulus</th>
<th>Specific Stiffness</th>
<th>Tensile Strength</th>
<th>Specific Strength</th>
<th>Thermal Conductivity</th>
<th>Thermal Expansion</th>
<th>Specific Thermal Contraction</th>
<th>Thermal Diffusivity</th>
<th>Steady State Thermal Stability</th>
<th>Transient Thermal Stability</th>
<th>Poisson’s Ratio</th>
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</thead>
<tbody>
<tr>
<td>Units:</td>
<td>kg/m³</td>
<td>GPa</td>
<td>MPa-m²/kg</td>
<td>Mpa</td>
<td>MPa-m²/kg</td>
<td>W/m-K</td>
<td>10⁶/K</td>
<td>W/m-K</td>
<td>j/kg-K</td>
<td>10⁶/m²/s</td>
<td>W/μm</td>
<td>m²-K/s</td>
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<tr>
<td>Preferred Value:</td>
<td>Small</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
</tr>
</tbody>
</table>

- **Zerodur**
  - ρ: 2530 kg/m³
  - E: 90.3 GPa
  - E/ρ: Large
  - σ: Large
  - σ/ρ: Large
  - α: Large
  - k: Small
  - Cp: Large
  - D=k/ρCp: Large
  - k/α: Large
  - D/α: Large
  - ν: 0.24

- **SiC: Sintered (alpha)**
  - ρ: 3100 kg/m³
  - E: 410 GPa
  - E/ρ: Large
  - σ: Large
  - σ/ρ: Large
  - α: Large
  - k: Small
  - Cp: Large
  - D=k/ρCp: Large
  - k/α: Large
  - D/α: Large
  - ν: 0.14

- **SiC: Reaction Bonded**
  - ρ: 2950 kg/m³
  - E: 364 GPa
  - E/ρ: Large
  - σ: Large
  - σ/ρ: Large
  - α: Large
  - k: Small
  - Cp: Large
  - D=k/ρCp: Large
  - k/α: Large
  - D/α: Large
  - ν: 0.18

- **RoboSiC-Optical**
  - ρ: 3210 kg/m³
  - E: 460 GPa
  - E/ρ: Large
  - σ: Large
  - σ/ρ: Large
  - α: Large
  - k: Small
  - Cp: Large
  - D=k/ρCp: Large
  - k/α: Large
  - D/α: Large
  - ν: 0.21

**Improvement:** 5.09 4.02

- **Thickness for Equivalent Stiffness cm**
  - **Relative Areal Density kg/m²**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness for Equivalent Stiffness</th>
<th>Relative Areal Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zerodur</td>
<td>3.66</td>
<td>93</td>
</tr>
<tr>
<td>SiC: Sintered (alpha)</td>
<td>0.81</td>
<td>25</td>
</tr>
<tr>
<td>SiC: Reaction Bonded</td>
<td>0.91</td>
<td>27</td>
</tr>
<tr>
<td>RoboSiC-Optical</td>
<td>0.72</td>
<td>23</td>
</tr>
</tbody>
</table>

**Improvement:** 5.09 4.02

- If the mirror were a solid “Hockey Puck” the RoboSiC would be 1/5 the thickness.
- It can be ¼ the areal density (mass 19.875 kg)
- Print in microgravity and you only need a facesheet with attach points (2-3 kg)
- Also get 10X BETTER Thermal Stability with RoboSiC™
FULL SIZE GHAPS PRIMARY

DESIGN: LEGACY ISOGRID

LOAD: 1G GRAVITY, Z DIRECTION

RESULTS: TOTAL DISPLACEMENT (PV IN INCHES, MICRONS)

Material: Zerodur®

1/4 Sag with RoboSiC™, 75% Improvement

Material: RoboSiC™

1.7E-05 inch
0.433 micron

4.25E-06 inch
0.108 micron
FULL SIZE GHAPS PRIMARY

DESIGN: LEGACY ISOGRID

LOAD: 1G GRAVITY, Y DIRECTION

RESULTS: TOTAL DISPLACEMENT (INCHES, MICRONS)

Material: Zerodur®

6.6E-05 inch
1.674 micron

5.3E-05 inch
1.346 micron

Material: RoboSiC™

1.64E-5 inch
0.417 micron

1.31E-5 inch
0.333 micron

1/4th deflection with RoboSiC™, 75% Improvement
FULL SIZE GHAPS PRIMARY
DESIGN: LEGACY ISOGRID
LOAD: 1G GRAVITY, X DIRECTION
RESULTS: TOTAL DISPLACEMENT (INCHES, MICRONS)

Material: Zerodur®
- 7.0E-05 inch (1.78 micron)
- 5.66E-05 inch (1.438 micron)

Material: RoboSiC™
- 1.74E-5 inch (0.442 micron)
- 1.4E-5 inch (0.356 micron)

1/4th deflection with RoboSiC™, 75% Improvement
FULL SIZE GHAPS PRIMARY

**DESIGN:** LEGACY ISOGGRID

**LOAD:** 20°C TO -50°C THERMAL SOAK

**RESULTS:** TOTAL DISPLACEMENT (INCHES, MICRONS)

Material: Zerodur®

- 5.43E-3 inch 137.9 micron
- 6.99E-04 inch 17.75 micron

Material: RoboSiC™

- 1.49E-3 inch 37.85 micron
- 3.18E-4 inch 8.08 micron

**Thermal Soak Optical Surface Deformation (72% Improvement with RoboSiC™)**
1/4TH SCALE MIRROR DESIGN
1/4 SCALE PRIMARY MIRROR – LEGACY DESIGN
1/4 SCALE PRIMARY MIRROR – LEGACY DESIGN
### 1/4 SCALE PRIMARY MIRROR - DIMENSIONS COMPARISON

<table>
<thead>
<tr>
<th>Description</th>
<th>Full Size PM</th>
<th>1/4 Scale PM</th>
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<tbody>
<tr>
<td>Optical Surface Spherical Radius</td>
<td>5012.7</td>
<td>5012.7</td>
</tr>
<tr>
<td>Physical Diameter</td>
<td>1030</td>
<td>257.5</td>
</tr>
<tr>
<td>Mirror Depth</td>
<td>125.5</td>
<td>31.375</td>
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<tr>
<td>Faceskin Thickness</td>
<td>13.5</td>
<td>3.375</td>
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<tr>
<td>Rib Spacing</td>
<td>127.5</td>
<td>31.875</td>
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<tr>
<td>Rib Thickness</td>
<td>5.6</td>
<td>1.4</td>
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<tr>
<td>Thicker Rib Thickness</td>
<td>8.6</td>
<td>2.15</td>
</tr>
<tr>
<td>Fillet Radius</td>
<td>11.8</td>
<td>2.95</td>
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<tr>
<td>Mass (ULE)</td>
<td>75.2</td>
<td>1.2136</td>
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</table>

Areal Density = 90.25 kg/m²  Areal Density = 23.30 kg/m²
1/4\textsuperscript{TH} SCALE MIRROR ANALYSIS
QUARTER SIZE GHAPS PRIMARY DESIGN: 1/4 LEGACY ISOGRID RESULTS: FIRST MODE

<table>
<thead>
<tr>
<th>Design</th>
<th>Material</th>
<th>Weight</th>
<th>Free-Free 1st Mode</th>
<th>WT/TB BC 1st mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 GHAPS Primary Ø257</td>
<td>Zerodur</td>
<td>2.7</td>
<td>1838.6</td>
<td>2417.6</td>
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<tr>
<td>1/4 GHAPS Primary Ø257</td>
<td>RoboSiC-Optical</td>
<td>3.5</td>
<td>3689.6</td>
<td>4856.7</td>
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</table>

Boundary Condition: Free-Free Shape: Saddle

Boundary Condition: Whiffletree/Tangent Bars Shape: Perimeter Wall Bending

100% improvement with RoboSiC
QUARTER SIZE GHAPS PRIMARY – STIFFNESS EQUIVALENT ROBOSIC ISOGRID
DESIGN: 1/4 LEGACY ISOGRID, HALF HEIGHT RIBS (15MM), 2.4MM FACESHEET
RESULTS: FIRST MODE

<table>
<thead>
<tr>
<th>Design</th>
<th>Material</th>
<th>Weight</th>
<th>Free-Free 1st Mode</th>
<th>WT/TB BC 1st mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>Zerodur</td>
<td>2.7</td>
<td>1838.6</td>
<td>2417.6</td>
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<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>RoboSiC-Optical</td>
<td>2.0</td>
<td>1799.0</td>
<td>4858.0</td>
</tr>
</tbody>
</table>

25% lower mass for equivalent Free-Free 1st mode with RoboSiC
25% lower mass and 2X Whiffle Tree Support 1st mode with RoboSiC
FULL SIZE GHAPS PRIMARY
DESIGN: 1/4 LEGACY ISOGRID
LOAD: 1G GRAVITY, Z DIRECTION
RESULTS: TOTAL DISPLACEMENT (INCHES)

Material: Zerodur

75% improvement with RoboSiC

Material: RoboSiC
FULL SIZE GHAPS PRIMARY
DESIGN: 1/4 LEGACY ISOGRID
LOAD: 1G GRAVITY, Y DIRECTION
RESULTS: TOTAL DISPLACEMENT (INCHES)

Material: Zerodur

75% improvement with RoboSiC

Material: RoboSiC
FULL SIZE GHAPS PRIMARY
DESIGN: 1/4 LEGACY ISOGRID
LOAD: 1G GRAVITY, X DIRECTION
RESULTS: TOTAL DISPLACEMENT (INCHES)

Material: Zerodur

75% improvement with RoboSiC

Material: RoboSiC
FULL SIZE GHAPS PRIMARY
DESIGN: 1/4 LEGACY ISOGRID
LOAD: 20C TO -50C THERMAL SOAK
RESULTS: TOTAL DISPLACEMENT (INCHES)

Material: Zerodur

72% improvement with RoboSiC

Material: RoboSiC
# 1/4 GHAPS PRIMARY, LEGACY ISOGRID ZERODUR VS ROBOSIC ANALYSIS SUMMARY

## Mass and Fundamental Modes (2x Stiffness Improvement with RoboSiC)

<table>
<thead>
<tr>
<th>Design</th>
<th>Material</th>
<th>Weight</th>
<th>Free-Free 1st Mode WT/TB BC 1st mode</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>lbs</td>
<td>Kg</td>
</tr>
<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>Zerodur</td>
<td>2.7</td>
<td>1.2</td>
</tr>
<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>RoboSiC-Optical</td>
<td>3.5</td>
<td>1.6</td>
</tr>
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</table>

## Gravity Sag (4x Improvement with RoboSiC)

<table>
<thead>
<tr>
<th>Design</th>
<th>Material</th>
<th>Max Total Displacement</th>
<th>Max Z Direction Displacement</th>
<th>Max Total Displacement</th>
<th>Max Z Direction Displacement</th>
<th>Max Total Displacement</th>
<th>Max Z Direction Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>in</td>
<td>micron</td>
<td>in</td>
<td>micron</td>
<td>in</td>
<td>micron</td>
</tr>
<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>Zerodur</td>
<td>0.00000007</td>
<td>0.002</td>
<td>0.00000094</td>
<td>0.024</td>
<td>0.00000181</td>
<td>0.012</td>
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<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>RoboSiC-Optical</td>
<td>0.00000002</td>
<td>0.000</td>
<td>0.00000023</td>
<td>0.006</td>
<td>0.00000045</td>
<td>0.011</td>
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## Thermal Soak Optical Surface Deformation (8x Improvement with RoboSiC)

<table>
<thead>
<tr>
<th>Design</th>
<th>Material</th>
<th>20C to -50C Thermal Soak</th>
<th>Max Total Displacement</th>
<th>Max Z Direction Displacement</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>in</td>
<td>micron</td>
</tr>
<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>Zerodur</td>
<td></td>
<td>0.00132000</td>
<td>33.528</td>
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<tr>
<td>1/4 Ghaps Primary Ø257</td>
<td>RoboSiC-Optical</td>
<td></td>
<td>0.00035300</td>
<td>8.966</td>
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## QUARTER SIZE GHAPS PRIMARY MODAL STUDY

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Facxeskin Thickness</th>
<th>Edge Thickness</th>
<th>Material</th>
<th>Mass</th>
<th>Free-Free 1st mode</th>
<th>Whiffle-Tree 1st mode</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>mm</td>
<td></td>
<td>lbs</td>
<td>kg</td>
<td>hz</td>
</tr>
<tr>
<td>1a</td>
<td>1/4 GHAPS Isogrid Design</td>
<td>3.375</td>
<td>31.38</td>
<td>Zerodur</td>
<td>2.68</td>
<td>1.22</td>
<td>1863</td>
</tr>
<tr>
<td>1b</td>
<td>1/4 GHAPS Isogrid Design</td>
<td>3.375</td>
<td>31.38</td>
<td>RoboSiC</td>
<td>3.40</td>
<td>1.54</td>
<td>3704</td>
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<tr>
<td>2a</td>
<td>Reduced Facesheet thk</td>
<td>2.4</td>
<td>31.38</td>
<td>Zerodur</td>
<td>2.46</td>
<td>1.12</td>
<td>1894</td>
</tr>
<tr>
<td>2b</td>
<td>Reduced Facesheet thk</td>
<td>2.4</td>
<td>31.38</td>
<td>RoboSiC</td>
<td>3.12</td>
<td>1.42</td>
<td>3767</td>
</tr>
<tr>
<td>3a</td>
<td>Reduced Facesheet thk and rib depth</td>
<td>2.4</td>
<td>15</td>
<td>Zerodur</td>
<td>1.50</td>
<td>0.68</td>
<td>908</td>
</tr>
<tr>
<td>3b</td>
<td>Reduced Facesheet thk and rib depth</td>
<td>2.4</td>
<td>15</td>
<td>RoboSiC</td>
<td>1.90</td>
<td>0.86</td>
<td>1799</td>
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</tbody>
</table>

- Reducing facesheet thickness from 3.375 to 2.4 does not reduce first mode stiffness (No. 2a/b compared to No. 1a/b)
- RoboSiC with 1/2 height ribs and reduced face sheet:
  - Nearly equivalent free-free mode stiffness to 1/4 GHAPS Isogrid Zerodur
  - More than 2X whiffle tree supported 1st mode

Note: Trade study for relative comparison. Results shown may not match final Nastran model results exactly because different element formulation and solver were used.
ALTERNATE DESIGN FOR 1/4TH SCALE MIRROR
Goodbye ISOGRID: Quarter Size Primary Robosic Design Concept 1

**Face Sheet**
- 2.4 mm thick
- 3 beads *0.8 mm/beam

**Minor Ribs**
- 25 mm spacing
- 2.4 mm thick (3 beads)
- +6.4 mm deep (8 beads)

**Minor Ribs and Perimeter**
- 50 mm spacing
- 2.4 mm thick (3 beads)
- +6.4 mm deep (8 beads)

Total Depth = 2.4 + 6.4 + 6.4 = 15.2 mm
Mass: 0.76 Kg (1.67 lbs)