3D Printed Submillimeter Reflectors: a New Design and Manufacturing Methodology

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***Abstract*—Submillimeter wavelength (1mm > λ > 0.1mm) reflectors are being utilized to an increasing degree in NASA missions due to their ability to observe phenomena in disciplines ranging from climatology to astrophysics. Due to the inherent form factor of reflectors and the need for stiffening backing structures, production is often limited by manufacturing restrictions that can lead to mass, cost, and/or schedule issues. To address these issues, we have developed a new manufacturing technique based on additive manufacturing and the use of light weight structures to enable a new class of low cost, high performance submillimeter reflectors.**

Keywords—submillimeter antenna, additive manufacturing, 3D printing, lattice, topology optimization

I. Introduction

Submillimeter wavelength (1mm>λ>0.1mm) reflectors are being utilized to an increasing degree in NASA missions. For example, in astrophysics, the ASTHROS mission will study how new stars are formed by observing fine structure lines of ionized nitrogen at 0.21 and 0.12 mm wavelengths [1]. In climatology, the Earth Observing System Microwave Limb Sounder (EOS MLS) instrument on the Aura Satellite has been studying the Earth's atmosphere through observation of 0.47 mm and 0.12 mm spectral lines [2].

Due to the inherent form factor of reflectors and the need for stiffening backing structures, production is often limited by manufacturing restrictions that can lead to mass, cost, and/or schedule issues [3], [4]. Small reflectors (cm scale) are now generally made by direct machining, but are relatively heavy due to limitations on minimal wall thicknesses. For larger (meter scale) reflectors, the reflecting surface is often electroformed in sections on a glass mold and then bonded to a stiffening backing structure (such as an aluminum honeycomb). The glass molds used in these processes are usually expensive (>$100k) and long-lead (6 months to a year), not only impacting project budgets, but also limiting design flexibility and agility to incorporate changes. In the case of off-axis antennas, as are increasingly desired, the cost further increases as a single mold cannot be used for as many panels as for a symmetric reflector. From a performance standpoint, the mismatched Coefficients of Thermal Expansion (CTE) found in these bonded structures can lead to thermal related performance issues. A new and fast manufacturing technique capable of producing light, monolithic reflectors is therefore highly desirable.

To address these manufacturing issues and enable a new class of low cost, high performance submillimeter reflectors, we developed a new methodology based on Additive Manufacturing (AM). AM is a relatively new manufacturing technique that builds a structure through a layer-by-layer process, allowing for the production of highly complex parts at a low cost. In the context of reflectors, this allows for rapid development and production of symmetric or off-axis parabolas with a fully integrated backing structure without the need for complicated molding/bonding procedures or CTE mismatches within the structure.

II. Manufacturing

Although Additive Manufacturing (AM) has the potential to overcome many of the issues associated with conventional manufacturing methodologies, features inherent to the process could cause performance issues. Of particular concern are thermal distortions due to the complex thermal history of the part and subsurface defects that result from the melt pool dynamics inherent to the process (such as keyholing and voids), both of which could negatively impact achievable surface profile accuracy of the reflector [5]. Furthermore, the limited length-scale resolution of modern printers could limit the areal density (projected area of the reflector divided by the mass) [6].

Due to the complexity associated with predicting manufacturing outcomes via modeling, reflectors were manufactured to verify the applicability of AM. A total of three reflector concepts were investigated, including 4x 8cm on-axis reflectors with an integrated lattice backing structure, a 20 cm off-axis reflector with an integrated lattice backing structure, and a 20 cm off-axis reflector with a topology optimized backing structure (see Figure 1). The focal lengths were half the nominal reflector diameter (4 cm and 10 cm) and the targeted wavelength range was 0.6 mm (500 GHz). All reflectors were manufactured from Aluminum A6061-RAM2 -- a printable version of the commonly used aerospace material Al 6061 -- using Laser Powder Bed Fusion (LPFB) due to its overall process maturity and feature resolution; all parts were printed on an EOS M290. Due to surface finish limitations in the LPFB process, and to help compensate for potential thermal distortions, the reflector surfaces were overbuilt in thickness by 3 mm, which was subsequently removed in a post machining step. To minimize the potential for thermal distortions and subsurface defects, the parts were Hot Isostatic Pressed (HIPed) at 510°C for 120 min at 101.7 MPa per ASTM B998. To improve strength, they were then solution heat treated at 529°C for 120 minutes, quenched in a 20% Glycol solution and subsequently aged at 160 °C for 18 hrs (which is equivalent to the commonly used T6 heat treatment as per Ams2770 for wrought Al 6061). Lastly, the reflector surfaces were post machined on a 3-axis mill to achieve the desired profile accuracy.

The surface profiles for 2x 8 cm and 1x 20 cm reflectors were measured and found to meet common specifications for operation at wavelengths (λ) of 0.6 mm and higher. The influence of profile accuracy on antenna gain is approximated by

$$\frac{G}{G_0} = \mathrm{e}^{-\left(4\,\pi\frac{e}{\lambda}\right)},$$

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where e is RMS surface profile error, and G/G_0 is the normalized gain loss [7]. In line with common requirements for spacecraft reflectors, the target gain efficiency here is at least 67% (-1.7 dB). The required surface profile error must therefore be $\lambda/20$ RMS or less, which corresponds to 30 µm RMS when operating at 500 GHz. A Mitutoyo AVANT Formtrace profilometer was used to measure each reflector, measuring multiple linear traces at a fixed spacing across the geometry (see Figure 2 a-b). To measure the pointwise surface accuracy, the nominal parabolic surface was fit to the measured point cloud and the difference between expected and measured position was calculated. In the case of the 8 cm diameter reflectors, the surface profile tolerances were measured to be 10.3 µm RMS (SN002) and 12.7 µm RMS (SN001), while the larger 20 cm reflector was measured at 16.2 µm RMS, all of which are lower than the 30 µm RMS requirement.

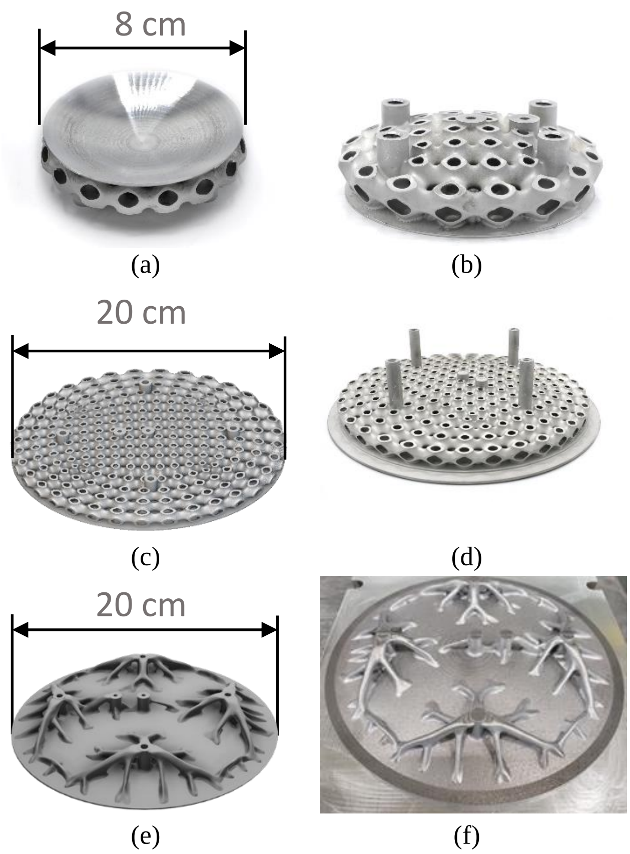


Figure 1: To demonstrate the manufacturing precision requirements for reflectors, three AM reflectors geometries were manufactured: (a, b) an on-axis 8 cm diameter subscale geometry used for process development (areal density of 13.4 kg/m^2), (c, d) an off-axis 20 cm diameter geometry with a lattice backing structure (areal density of 8.1 kg/m^2), and (e, f) an off-axis 20 cm diameter geometry with a topology optimized backing structure (areal density of 6.3 kg/m^2).

To overcome the feature resolution limitations associated with LPBF (predominantly minimum thickness) and the corresponding need for light weight aerospace structures, a chemical etching process was developed to refine the reflector backing structure (see Figure 3). For the reflector size range examined here (< 20 cm in diameter), state of the art reflector areal density is on the order of 14 kg/m^2 [8] In the case of the 8 cm on-axis geometries, when running the printer at its minimum printable thickness of approximately 1 mm, the as-printed areal density was 19.2 kg/m^2; however, removing 165 µm off the backing structure surfaces via chemical etching reduced the areal density down to 13.4 kg/m^2. It should be noted that this 8 cm geometry was not originally optimized for mass or performance, but rather as a unit to aid in process development. These results therefore indicate the ability to refine feature size rather than the ability to achieve a specific areal density.

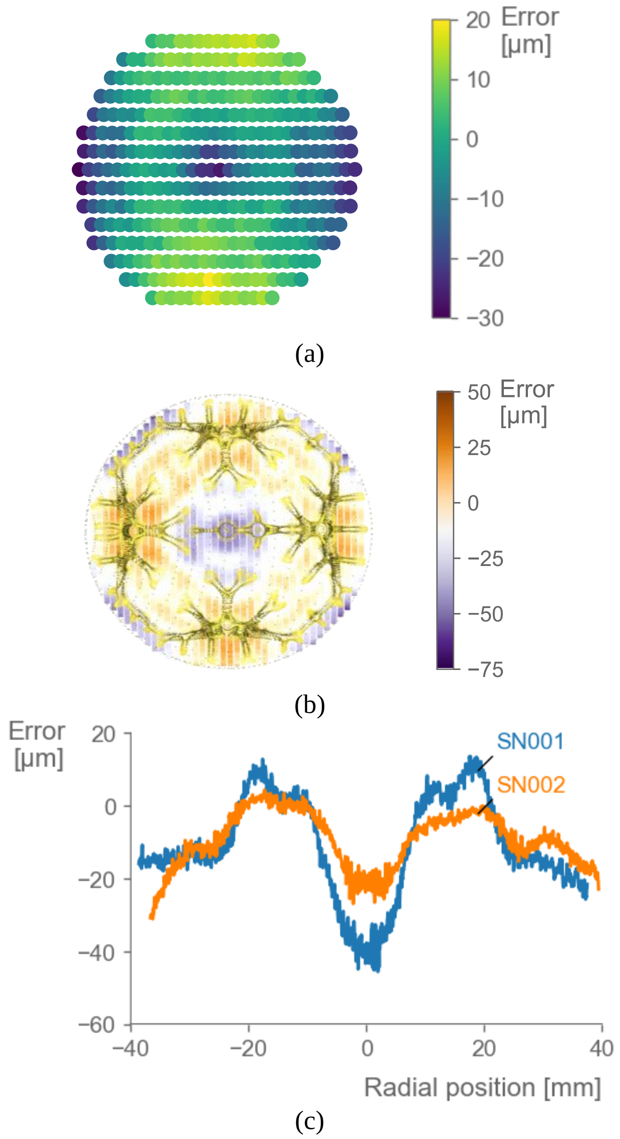
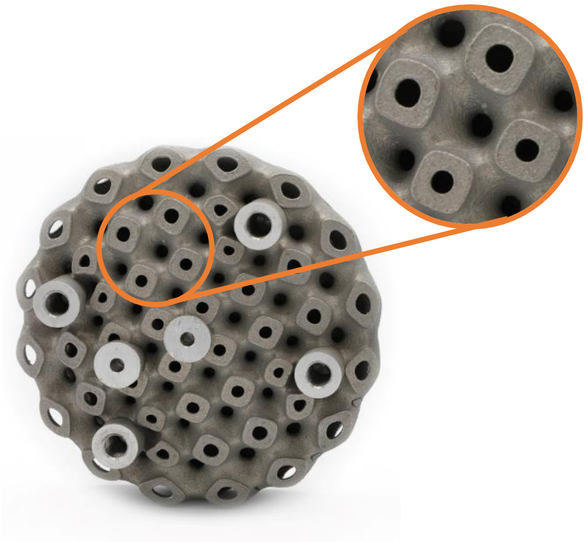


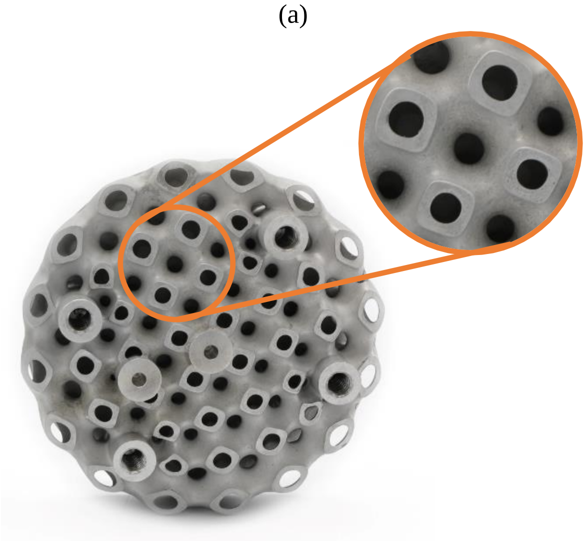
Figure 2: The reflector profile tolerance of 30 µm RMS was verified through profilometry, taking multiple line scans over the reflector surface and comparing the data to the nominal geometry: (a) 10.3 µm RMS for 8 cm reflector SN002 and (b) 16.2 µm RMS for the 20 cm topology optimized reflector (noting that the overlay illustrates the backing structure layout). (c) The consistency of the manufacturing process was verified through the measurement of two 8 cm reflectors, with a single radial trace shown to illustrate surface roughness and part to part variation.

III. Design

The added design flexibility of AM allows for the possibility of reconceptualizing the design of reflectors; in particular, the stiffening backing structure. A reflector backing structure provides two primary functions: sufficient stiffness to survive the spacecraft launch environment and sufficient stiffness to alleviate the need for gravity compensation during ground handling and calibration (i.e., negligible gravity sag). This is conventionally achieved through an isogrid (triangular webbing pattern) that is machined into the reflector or hexagonal honeycomb that is bonded on to the back of a reflector [3], [4], [9]. In the context of AM reflectors, these stiffening concepts can be generalized into a broader range of lattice structures or directly optimized using topology optimization.



(a)



(b)

Figure 3: Chemical etching was demonstrated to be an effective geometry refinement technique, reducing the areal density of the as-printed 8 cm reflector from (a) 19.2 kg/m^2 down to (b) 13.4 kg/m^2.

The use of a lattice structure (such as an isogrid or honeycomb) as the backing of a reflector leverages a similar concept as an I-beam: it acts as webbing to support shear forces while pushing the majority of the material away from the bending neutral axis to increase area moment of inertia and thus bending stiffness [4]. The primary design driver is to therefore identify a lightweight lattice geometry with a high shear stiffness. Of the many possible lattice candidates, a Schwarz Triply Periodic Minimal Surface (TPMS) structure was identified as an ideal lattice geometry for not only its high shear stiffness, but its self-supporting, printable geometry and the easy flowability of etchant throughout the structure. This design methodology was implemented for both the on-axis 8 cm reflectors (see Figure 1 a-b) and the off-axis 20 cm diameter reflector with the lattice backing structure (see Figure 1 c-d), resulting in areal densities of 13.6 kg/m^2 and 8.1 kg/m^2, respectively. When compared to a conventionally isogrided reflector with equivalent mass and geometry (cell size and height), the corresponding stiffness and fundamental frequency are similar. Further study into alternative lattice unit cells may yield better performance, but were not investigated here.

Designing a reflector via Topology Optimization (TO) moves beyond the engineering intuition of lattice structures and directly optimizes for the desired end behavior: high bending stiffness. TO is a computational design framework that relies on physics-based simulations (typically via the Finite Element Method) to inform the layout of a structure based on governing design objectives and requirements. In the case of aerospace reflector design, the ideal optimization problem is to minimize structural mass given requirements on fundamental frequency (which relates to stiffness), gravity sag, and material strength; however, in practice, this problem formulation is challenging to solve with existing commercial tools and therefore requires some reformulation. A better behaving optimization is to maximize stiffness given mass and stress constraints. Using the same off-axis reflector profile as the 20 cm reflector with the lattice backing structure, the stiffness was optimized with respect to pressure loading on the surface of the reflector with a mass constraint of 0.2 kg (which corresponds to an areal density of 6.3 kg/m^2). Additionally, the design is restricted to have one plane of symmetry and overhangs limited to 45° (which is required for AM). The final optimized design is shown in Figure 1 (e-f) and was generated using Autodesk's Fusion 360 software tool.

For the design case examined here, the TO backing structure resulted in a lighter and stiffer design than the lattice backing structure. Under pressure loading across the reflector surface, the TO design has 1.75x higher specific stiffness (which is defined by the inverse of total strain energy -- a measure of stiffness -- divided by mass); additionally, the TO design has 1.83x higher specific fundamental frequency (which is defined by the fundamental frequency divided by mass).

IV. Conclusions

Additive Manufacturing (AM) of aerospace reflector structures was demonstrated as a proof-of-concept for submillimeter applications. In the case of reflector structures, the primary limitation of AM is its minimum feature resolution, affecting the potential mass efficiency and reflector profile accuracy. To overcome this limitation, a thick version of the reflector was printed and then refined to the desired final geometry through chemical etching of the backing structure and post machining of the reflector profile. This process methodology was implemented on on-axis 8 cm diameter and off-axis 20 cm diameter reflector geometries, demonstrating areal densities ranging from 6.3 kg/m^2 to 13.4 kg/m^2 and surface profile accuracies ranging from 10.3 μm RMS to 16.2 μm RMS (which corresponds to diffraction limited observations on the order of 500 GHz). AM therefore has the potential to reduce cost and lead time of reflectors while maintaining the mass and geometric tolerances required for aerospace operations.

The added design flexibility of AM allows for the possibility of reconceptualizing the design of reflectors. Through the use of generalized lattice structures and computational design tools such as Topology Optimization (TO), lightweight, yet stiff geometries are possible. A Schwarz Triply Periodic Minimal Surface (TPMS) lattice was found to have comparable stiffness to conventional isogridding approaches; however, topology optimization improved stiffness by approximately 1.75x. AM therefore has the potential to significantly increase the specific stiffness (stiffness-to-mass ratio) or reflectors, resulting in lighter weight structures.

V. Acknowledgements

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VI. References

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