A new mirror manufacturing technology for free space optical communication

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ABSTRACT

A manufacturing technology of mirrors for free-space optical communication is presented: a thin layer of Nickel is deposited on a master and bonded on a light-weighted structure by adhesive. After separation, the master is ready for another cycle. The process is cost-effective because only the master needs to be of optical quality. The structure is machined by traditional tooling, with figure errors compensated by the adhesive. Its curing time defines the process throughput to one mirror per day per master. Several 200 mm-aperture Ritchey-Chrétien telescopes have been manufactured and tested.

Keywords: Mirror manufacturing, Free space optical communications, Mass production, Telescope manufacturing

1. INTRODUCTION

Free space optical communications for inter-satellite and satellite-to-ground communication is getting momentum as the demand for large bandwidth connections is steeply raising. This includes both downlink data transfer from scientific Space missions and commercial applications to sustain the Word Wide Web services. In the latter case, constellations of several tens of satellites are planned by different initiatives

For satellites in low Earth orbit (LEO), the specifications of the optics are not particularly stringent, in particular in terms of dimensions and field of view [1], [2]. In typical configurations, the optics is used for both transmission and reception of the modulated data beam. Large diffraction limited apertures are not a definite advantage because narrow-divergence beams would be difficult to steer and control with the required tight angular accuracy. In reception, for LEO-to-ground applications, small apertures are not challenging since adequate power levels can be easily reached at the transmitter station on ground. Typical apertures range in the order of 100 mm to 200 mm.

Large fields of view are also not a specific requirement. At reasonably large data rates, the received beam must be focused on the core of a fiber optics or directly onto a small detector. Similarly, the transmitted beam must illuminate the receiver station on ground. Assuming a reference wavelength of 1550 nm and an aperture of 150 mm, the half-beam divergence is about 13 µrad. Thus, what is needed is a dynamic pointing capability of keeping the optical alignment within few microradians during the satellite motion along its orbit. The steering capability must also be fine and fast enough to compensate for the mechanical vibrations onboard the satellite platform.

Finally, the figure accuracy of the optics is somewhat relaxed since most initiatives are planning to operate in C-band (1530 nm – 1565 nm) or L-band (1565 nm – 1625 nm) in order to benefit from the vast technological developments offered by the ground fiber optics communication industry.

In this technical framework and in a commercial scenario of strong competition, there is and there will be an increasing demand for volume production of mid-size of quality mirrors for free space optical communication telescopes. A new cost-effective mirror manufacturing technology (patent pending) has been developed to address this need. The process consists in depositing a thin layer of Nickel of the order of 0.1 mm on a negative master and then bonding a supporting light-weighted structure on the Nickel layer by means of an adhesive. After curing, the mirror is separated from the master, which is ready for a new manufacturing cycle. By the nature of the process, the mirrors come with an integrated Gold reflective coating. However, additional optical coatings, for example protected aluminum or silver, can be added to enhance the optical reflectivity in the operational wavelength band.

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The process allows producing precision, highly aspheric mirrors at a fraction of the cost of conventional technologies because only the master needs to be of optical quality in terms of both shape accuracy and roughness. Instead, the supporting structure can be machined by traditional tooling at about 10 µm rms figure error, which is compensated for by the adhesive. Moreover, the cycle time of the manufacturing process is very short in comparison to traditional approaches and is essentially limited by the curing time of the adhesive. This leads to a production throughput of one mirror per day per master, making this process suitable for precision and cost-sensitive applications such as optical communication terminals for satellite constellations.

Several complete Ritchey-Chrétien telescopes with 200 mm aperture and 500 mm focal length have been manufactured and optically tested.

2. TELESCOPE DESIGN

The Ritchey-Chrétien telescopes have a focal length of 500 mm and an aperture of 200 mm, resulting in an F-number of 2.5. The design is rather compact, with a primary-to-secondary distance of only 120 mm. The obscuration ratio is 0.26 mm. The nominal spot diagram and the modular transfer function (MTF) curves at 1550 nm are shown in Figure 1 for 3 fields at 0, 0.1° and 0.2° from the axis. The focal plane position is optimized over these three fields. The diameter of the Airy disk is 9.45 µm at a wavelength of 1550 nm.

The mechanical design of the telescope is also rather simple and compact (see Figure 2). The main structural element is the primary mirror. The secondary is mounted on a three-structs wheel, which is coupled to the primary mirror by means of a tubular structure. The three elements – primary mirror, secondary wheel, and tube – are assembled and fixed together by an adhesive. The alignment of the secondary mirror can be adjusted using a three-screw interface to the secondary wheel. Finally, the telescope can be interfaced to an external structure by means of three brackets attached to the body of the primary mirror (see Figure 3). All elements described above and including both the optics and the structural parts are made of the Aluminum, except for the brackets (in stainless steel) and coating of the mirrors (in Nickel, see Section 3 for more details). This choice considerably improves the thermal stability of the telescope. The total mass of the telescope is 2.61 kg, which includes a mild light-weighting of the primary mirror of 33%.

The optical and mechanical design of the telescope has been validated through finite element analysis. The list of applied load cases is reported in Table 1 and a summary of the corresponding results in Table 2. In all cases the margin of safety (MOS) is positive. The latter is defined by

$$\text{MOS} = \frac{\text{allowable load}}{\text{applied load} \times FOS} - 1$$

where the allowable load is a measure of the load capability of the material for the relevant failure mode (276 MPa for yield and 310 MPa for ultimate stress); the applied load is calculated by finite element analysis as equivalent von Mises stress; the factor of safety (FOS) is 1.25 for yield and 1.5 for ultimate stress.

![Figure 1](image1.png)

Figure 1. Spot diagram (left) and MTF at 1550 nm (right) of the telescope optical design. The Airy disk (9.45 µm in diameter) is shown as a solid circle in the spot diagrams.
The uniform temperature change of 10 °C and 1g gravity are operational load cases, the latter as gravity release in orbit. It is then important to assess not only the structural integrity of the telescope but also its optical performance. This is done by fitting the calculated deformation by the first 21 Zernike polynomials and using the results for optical analysis. Gravity along X, i.e. orthogonal to the optical axis, has negligible optical effect. The calculated MTF curves for gravity along the optical axis (Z axis) and for 10 °C uniform temperature change are shown in Figure 4. Although some degradation of the MTF occurs, the telescope remains fully functional. It should also be noted that no refocusing has been applied to obtain the plots in in Figure 4.
Table 1. Load-case definition for the finite element analysis; the Z-axis is the optical axis of the telescope.

<table>
<thead>
<tr>
<th>Load-case</th>
<th>Specification</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi static load – Z axis</td>
<td>40 g</td>
<td>Interface brackets</td>
</tr>
<tr>
<td>Quasi static load – Radial</td>
<td>40 g</td>
<td>Interface brackets</td>
</tr>
<tr>
<td>Modal analysis</td>
<td>&gt; 170 Hz</td>
<td>Interface brackets</td>
</tr>
<tr>
<td>Uniform temperature change</td>
<td>10 °C</td>
<td>Isostatic constraint (radial free)</td>
</tr>
</tbody>
</table>

The first eigenfrequency of the telescope is 250 Hz and is due to oscillation of the secondary mirror subassembly along the optical axis. Although the specification of 170 Hz limit for the lowest eigenfrequency is well below this value, it can be easily improved, if necessary, by increasing the stiffness of the three struts of the secondary wheel, for example by increasing their thickness along the direction of the optical axis. The second lowest mode is a transversal bending of the tubular structure of the telescope and has a resonance frequency of 357 Hz.

3. MIRROR MANUFACTURING APPROACH

Mirror manufacturing based on electroforming was developed in the late 20th century for application to Space-based X-ray telescopes. Missions like Beppo-SAX, XMM-Newton, Swift, eRosita [4]-[7], all exploit optics based on this technology. The essence of the manufacturing flow consists in the galvanic deposition of a metal, typically Nickel, on an Aluminum master with a shape that is the negative of the final desired geometry. The master is usually coated with few tens of micrometers of Nickel-Phosphorous to allow reaching the low level of roughness required by the optics, especially in the X-ray waveband. After figuring and polishing, the master is coated with a thin layer of Gold, which serves as separation layer. Nickel is then deposited on the master with thickness ranging from a fraction of millimeter to 1-2 mm, depending on the structural requirements of the application. Once the Nickel deposition has reached the desired thickness, the mirror is separated from the master by exploiting the different coefficient of thermal expansion between Aluminum and Nickel. Upon separation, the Gold layer sticks on the surface of the Nickel mirror, in many applications serving as a reflecting layer. If needed, however, other optical coatings can be deposited, including protected Aluminum.

Table 2. Summary of results of finite element analysis (FEA). Yield is at 276 MPa with a factor of safety 1.25; ultimate stress is at 310 MPa with a factor of safety 1.5. For random vibration, the maximum FEA stress is the 3σ value.

<table>
<thead>
<tr>
<th>Load-case</th>
<th>Maximum FEA stress</th>
<th>Location</th>
<th>Failure mode</th>
<th>Margin of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi static load – Z axis</td>
<td>20.0 MPa</td>
<td>Secondary wheel</td>
<td>Yield</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ultimate stress</td>
<td>9.3</td>
</tr>
<tr>
<td>Quasi static load – Radial</td>
<td>20.4 MPa</td>
<td>Bracket</td>
<td>Yield</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ultimate stress</td>
<td>9.1</td>
</tr>
<tr>
<td>Random vibration – Z Axis</td>
<td>112.7 MPa</td>
<td>Secondary wheel</td>
<td>Yield</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ultimate stress</td>
<td>0.83</td>
</tr>
<tr>
<td>Random vibration – Radial</td>
<td>131.3 MPa</td>
<td>Bracket</td>
<td>Yield</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ultimate stress</td>
<td>0.57</td>
</tr>
<tr>
<td>Uniform temperature change</td>
<td>54.6 MPa</td>
<td>Bracket</td>
<td>Yield</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ultimate stress</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Figure 5. Primary and secondary mirrors at different stage in the production flow: above, just after machining of the light-weighted Aluminum supporting structure; below, after release from the master, with the Gold separation layer visible.

and Silver. After separation, the master is cleaned and ready for a new manufacturing cycle. The advantage of this process is evident: the figuring and polishing effort is spent only once, for the master. The replication process takes care to transfer shape and roughness from the master to the mirror.

After the successful application of electroforming to X-ray astronomy, spin-offs to other branches of optics have been developed. This includes large panels for sub-millimeter radio-frequency telescopes [8], [9], collectors for extreme ultraviolet lithography [10], and payloads for visible and infrared applications [11]. However, dimensions and figure accuracy of imaging optics in the visible waveband are limited by both technological and practical considerations. The deposition of Nickel on the master in the galvanic bath is accompanied by the building up of internal stresses in the material that, upon separation from the master, produce deformations in the optics. Moreover, the mirrors obtained by electroforming are thin membranes that require dedicated supporting structures. As the dimension of the optics increases and their quality is pushed to the limit, the design, engineering, and integration of these structures become more and more challenging. Although design solutions exist that alleviate the problem – for example exploiting optical designs with high sag-to-diameter ratio to increase the mirror stiffness –, we developed a new process (patent pending) aimed to get rid of the self-standing thin-membrane issue.

The very first part of the process is identical to the standard electroforming manufacturing sequence. The master, with the negative of the desired geometry is machined, figured, and polished. Again, a thin layer of Gold is deposited by vapor deposition techniques on the master and Nickel is galvanically laid down on it. At this point the manufacturing sequence deviates from traditional electroforming. Instead of aiming to a self-supporting layer of Nickel, the galvanic process is stopped after a thin layer of the order of 0.1 mm is deposited on the master. Since the typical deposition layer
is of the order of 10 µm/h, this means that the electroforming step lasts for few hours instead of half a week or more. After deposition, the Nickel layer is not immediately separated from the master, but a previously prepared supporting structure is bonded on top the Nickel layer by an adhesive. Only after the latter is completely cured, the mirror is released from the master, which is again available for a new manufacturing cycle.

The advantage of this approach consists in that the high accuracy figure and low roughness of the master is “frozen” into the thin Nickel layer by the adhesive. The internal stress in the Nickel deposit becomes irrelevant due to its limited thickness. Moreover, the adhesive serves as a buffer layer between the Nickel layer and the supporting structure. This means that the latter does not need to be accurately machined: standard lathing or milling with typical accuracy of 10 µm is sufficient. If necessary, the supporting structure can also be light-weighted and interface featured easily machined on it. Figure 5 shows both supporting structures and finished mirrors with the Gold separation layer on them.

4. PRODUCTION AND TESTS

A total of 16 telescopes has been produced up to now for LIDAR applications (see Figure 6). Both the primary and the secondary mirrors were coated with protected Aluminum to increase the reflectivity at the operating wavelength, as shown in Figure 6.

The optical qualification of the telescopes has been done by measuring the 50% and the 90% encircled energy diameter on the focal plane upon illumination by a plane wavefront generated by a parabolic collimator mirror. The average 50% encircled energy of the 16 telescopes is 29.7 µm with a standard deviation of 5.4 µm. Assuming a 2-dimensional Gaussian distribution for the point spread function, the 50% encircled energy is also equal to the FWHM. Thus, the average value of the angular FWHM of the point spread function is 57.4 µrad with a standard deviation of 10.8 µrad.

The measured FWHM of the point spread function is partially due to the figure error of the master of the primary mirror – estimated in the order of about 40 µrad – but it is in line with the technical specification for the field of application of the produced telescopes.

A measurement of the wavefront of an assembled telescope has also been performed in autocollimation with an interferometer at the focus of the telescope and a plane mirror at the entrance aperture of the telescope. The measured wavefront error is shown in Figure 7 and amounts to 287 nm rms.

5. CONCLUSIONS

A new manufacturing process has been developed for the production of mirrors for non-imaging applications, like LIDAR and free space optical communications. The process relies on the replication from a high-accuracy negative master and the use of an adhesive to make the optical surface compliant with the low-accuracy substrate. As a result, the
optical quality mirrors can be produced at reduced costs and short time. More than a dozen 200 mm Ritchey-Chrétien telescopes have been realized with both the primary and the secondary mirror manufactured with this technology. The process has proved to be reliable and the optical quality has been measured to be less than 300 nm rms in wavefront error.

Thermal and mechanical environmental characterization, including thermal cycling, outgassing measurements, random vibration, and sine sweep is in progress. Based on the structural analysis, dynamical tests are not expected to induce any permanent deformation or damage to the telescope. Thermal tests are mainly aimed to verify the stability of the adhesive and define a reliable operational temperature range. It should be noted that bimetallic effects due to difference in the coefficient of thermal expansion (CTE) between Nickel and Aluminum is mitigated by the presence of the adhesive. Moreover, Aluminum-Silicon alloy, CTE-matched with Nickel, can possibly be used for the mirror structure if the bimetallic effect is not sufficiently suppressed by the adhesive layer.

REFERENCES


