How to manufacture low-cost freeform optics for high-volume imaging applications

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Introduction

Since the 1970s, freeform optics have been used in optical systems with some commercially available options available. However, this practice was typically limited to highly specialized applications. More recently, freeform optics have been utilized in low-volume imaging applications for R&D, aerospace, and government-supported projects.

However, the widespread, commercial adoption of freeform optics in high-volume imaging applications was constrained by the cost implications, long lead times, and other technical and manufacturing limitations associated with traditional direct manufacturing techniques.

Yet, the benefits of implementing freeform optics are clear. They allow for custom aberration correction, redistribution of optical/mechanical tolerances, and even allow for a reduction in component count and system volume. These benefits are achievable because each freeform optic is uniquely designed around each system's requirements. The design freedom allowed provides many options to optimize an optical system allowing for a more compact instrument.

In this whitepaper, we introduce a novel optical replication manufacturing method from Spectrum Scientific, Inc. We investigate the manufacture and measurement of freeform optics, explain how this high-precision replication manufacturing method works, and outline the benefits this manufacturing solution brings to OEMs and any organisation who wants to benefit from the inclusion of freeform optics at cost and at scale across their imaging applications.

Manufacturing freeform optics

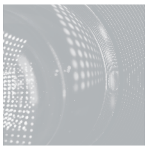
As with any optical system, the application, environment and system requirements determine the best manufacturing and measurement method for an individual project.

Moving to manufacturing

When moving from the design to manufacturing stages, communication with the manufacturer is critical. The optical surface verification needs to be confirmed by both designer and manufacturer and can be done through a variety of methods.

The designer must supply the surface equation and performance criteria to the manufacturer. We also recommend both parties generate and compare SAG tables as this information is used as a reference throughout





the manufacturing and measurement processes. This data is also used throughout the metrology stages. The optical component should meet all final performance criteria outlined including optical requirements, mechanical requirements, and environmental requirements. Alignment fiducials should also be clearly marked. If possible, the system designer and manufacturer should reference the same mechanical fiducials to ensure a smoother transition between manufacturing, metrology, and system alignment.

To summarise, we would recommend the following freeform surface requirements are communicated:

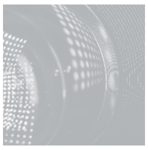
- Alignment fiducials and reference datums
- Surface equation and number of coefficients
- Optical and mechanical performance metrics
- SAG table

When it comes to the available manufacturing methods, OEMs can choose between direct manufacturing of original components (using methods including diamond turning, grind and polish, MRF, and hand-figured), moulded optics (both injection and glass moulding), nickel electroforming, and optical replication. A comparison of these methods is presented in Table 1.

MFG Method	Unit Cost	Up Front Tooling Costs	Scalability Ramp up	Surface Figure	Material Choice	
Diamond Turning	$$$$	$	★	★ ★ ★	★ ★	Originals
Glass MRF	$$$$	$	★	★ ★ ★	★	
Plastic Injection	$	$$$	★ ★ ★	★	★	Copies
Nickel Electroform	$$	$$	★ ★	★	★	
Optical Replication	$$	$$	★ ★ ★	★ ★ ★	★ ★ ★	

Table 1: Comparison of Aspheric Optic Manufacturing Methods





Direct manufacturing methods are expensive options where each component is usually produced one at a time, requiring many hours of operation to produce a single part. While these processes allow for a wide range of flexibility, long lead times and high costs make direct manufacturing unfeasible from both a cost and time perspective for high-volume imaging applications.

High volume production is feasible for plastic injection and nickel electroform from a cost perspective and both methods can reduce the variability between batches. However, these methods offer less flexibility due to size and optical surface quality limitations, making them unsuitable for demanding imaging applications.

The Spectrum Scientific optical replication process provides the only viable alternative to these traditional manufacturing techniques. Using a process similar to nanoimprint lithography, it faithfully transfers the shape of a master optic to low cost substrates. This is the most precise manufacturing method available that accommodates material choices, optical surface design, and production scalability all while being financially viable for high-volume production imaging systems.

Concerning metrology

The measurement process is important to guarantee the desired functional performance of the component. There are a number of contact and non-contact metrology techniques available.

Contact probes, for example, are common forms of measurement. Depending on how precise of a measurement is required, the contact probes may not have a high enough resolution to provide an accurate measurement. An example of this can be a diffraction grating with a very high groove density. Furthermore, the probe must be in contact with the optical surface, potentially damaging it in the process.

Non-contact methods include optical probes or laser interferometry, which provide higher precision, compared to contact methods, but may require stitching or a phase mark to be used as a null corrector.

The choice of metrology is independent of the manufacturing process. Instead, the surface profile requirements of the freeform optic in question will determine the measurement methods used.

For optical replication and plastic injection methods, the master moulds are measured to a very high level of detail, using nanometre-level precision. However, not all these measurements may be necessary during the final production stages.

Freeform optics are more susceptible to alignment errors, compared to conventional optics. Whereas most aspheric surfaces are measured using interferometry using first-principal methods where point sources and plane wave interferometry can be used in all the wavefront, freeforms do not have this advantage.

Therefore, fiducials and reference datums are critical for angular and linear coordinates, where the manufacturer will use these for production and test purposes, while the end user will rely on fiducials for system integration.

Introducing the replication process

Spectrum Scientific, Inc. can deliver low-cost freeform optics with aspherical profiles in high volumes and to exacting specifications, offering significant benefits and cost savings for today's optical systems.

Essentially, Replication is the process of manufacturing optics by transferring the optical surface of one original optical surface onto other surfaces, thus creating copies of the original. Using this process, the profile of the original optic is faithfully preserved and transferred, producing a replicated optic that's virtually indistinguishable in performance from the original master with excellent reflected wavefront and low surface scatter. This process is repeated numerous times to support volume requirements. Each replicated optic is almost identical to the original optic, allowing for a high degree of batch-to-batch repeatability.

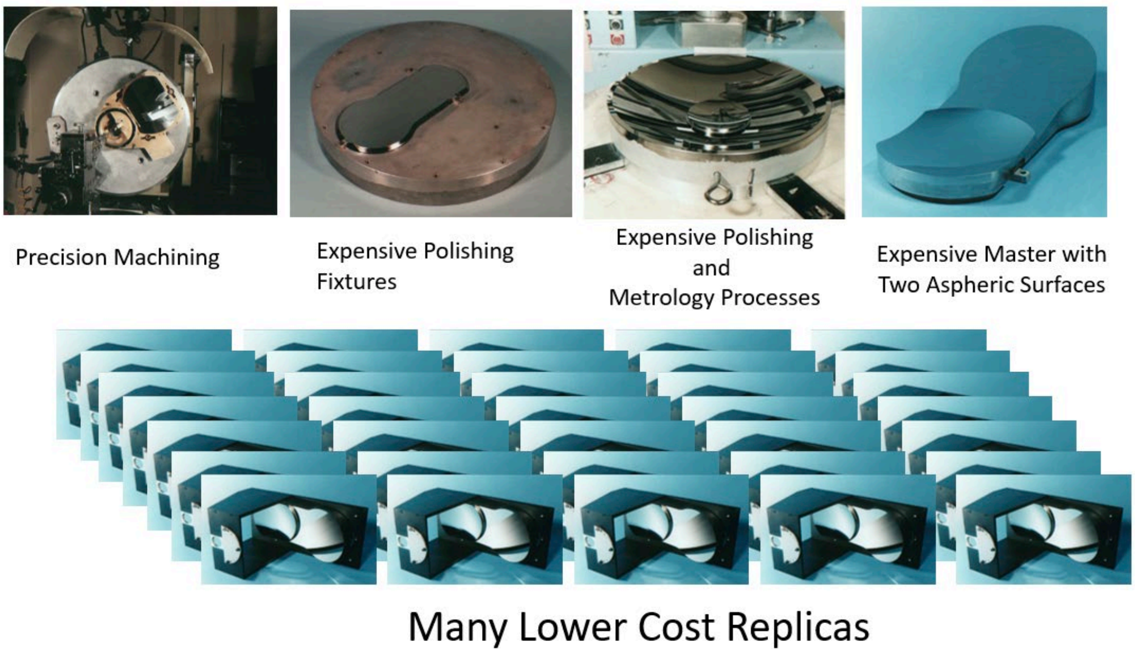


Figure 1: How low-cost replicas are created from complex, expensive components

The processing time for manufacturing replicated optics is a fraction of traditional direct techniques which allows for aggressive ramp schedules and lower costs. Some white light interferometric examples of replicated optics are given in Figures 2 to 5.

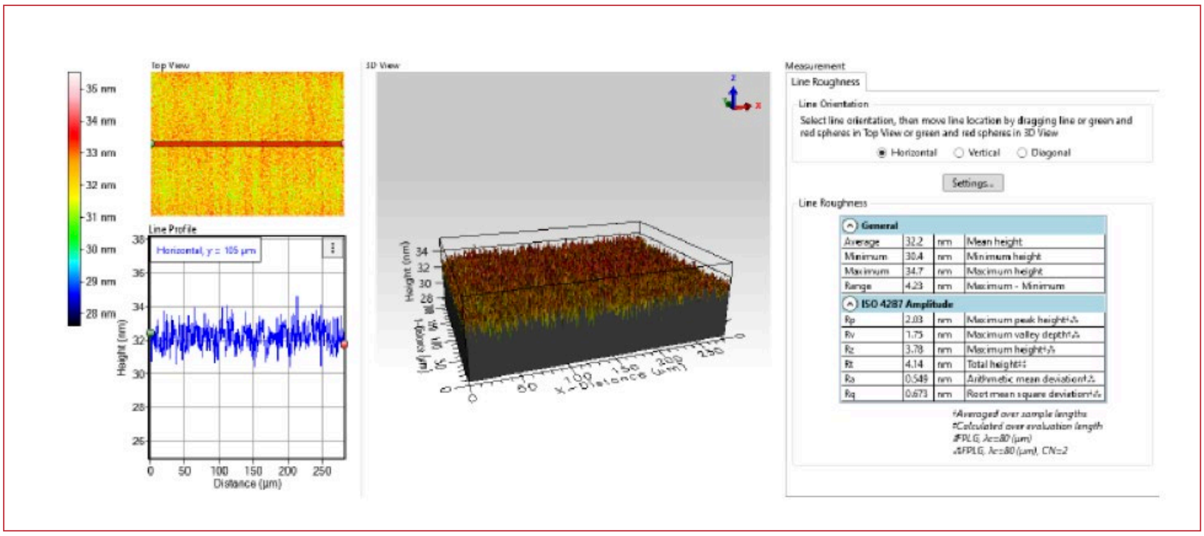


Figure 2: Master-to-replica precision

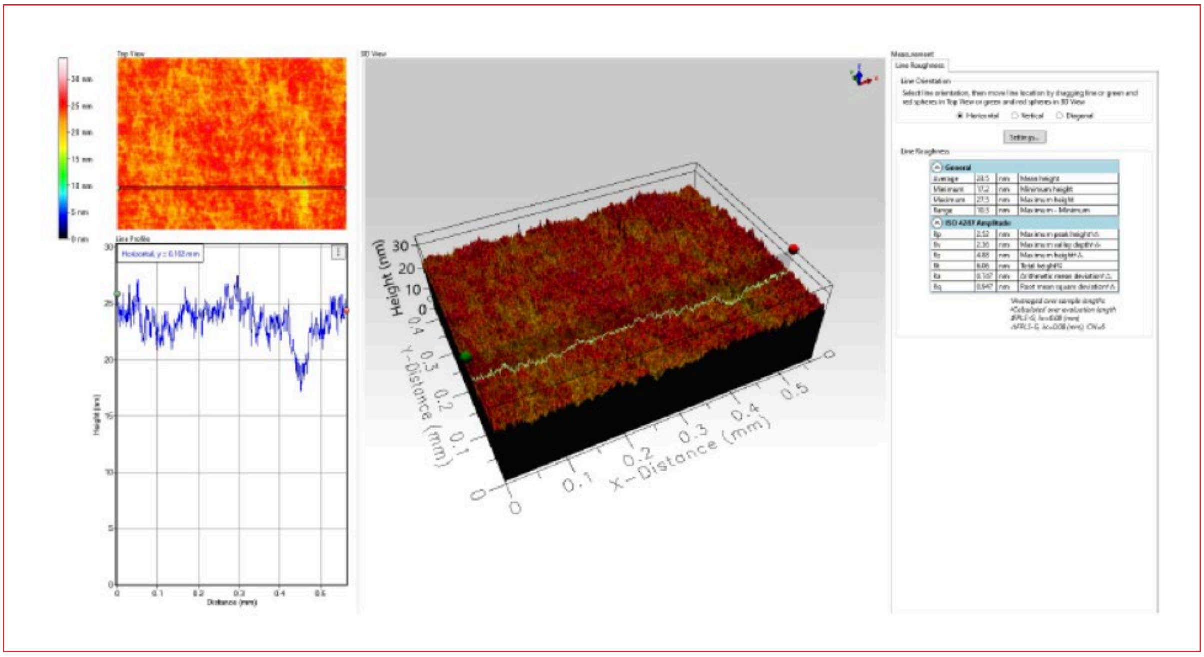
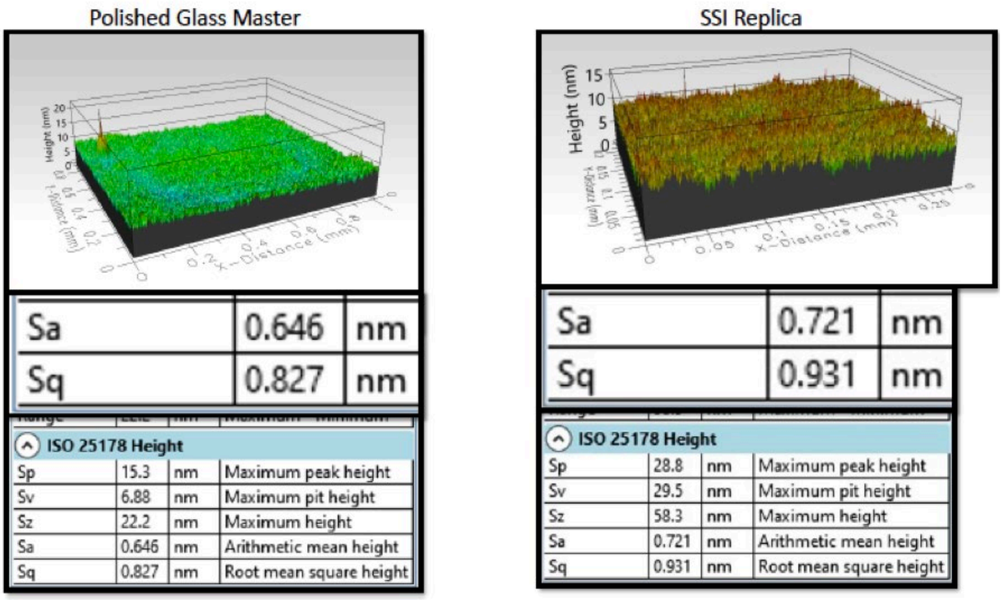


Figure 3: Replica of conventionally polished glass parabola



Polished Glass Master

Sa	0.646	nm
Sq	0.827	nm

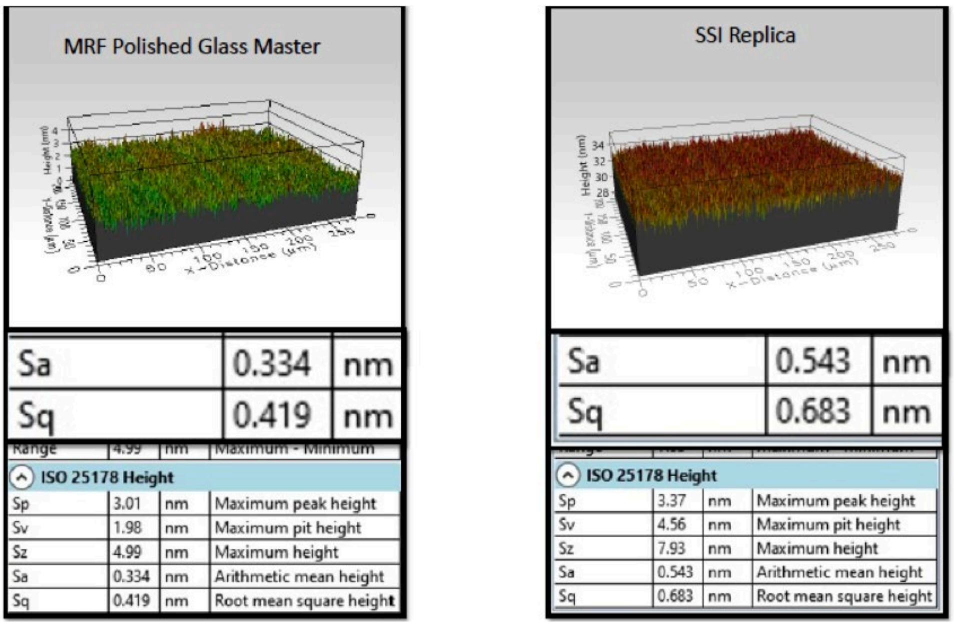
ISO 25178 Height			
Sp	15.3	nm	Maximum peak height
Sv	6.88	nm	Maximum pit height
Sz	22.2	nm	Maximum height
Sa	0.646	nm	Arithmetic mean height
Sq	0.827	nm	Root mean square height

SSI Replica

Sa	0.721	nm
Sq	0.931	nm

ISO 25178 Height			
Sp	28.8	nm	Maximum peak height
Sv	29.5	nm	Maximum pit height
Sz	58.3	nm	Maximum height
Sa	0.721	nm	Arithmetic mean height
Sq	0.931	nm	Root mean square height

Figure 4: Replica of Conventionally Polished Parabola



MRF Polished Glass Master

Sa	0.334	nm
Sq	0.419	nm

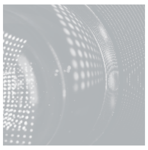
ISO 25178 Height			
Sp	3.01	nm	Maximum peak height
Sv	1.98	nm	Maximum pit height
Sz	4.99	nm	Maximum height
Sa	0.334	nm	Arithmetic mean height
Sq	0.419	nm	Root mean square height

SSI Replica

Sa	0.543	nm
Sq	0.683	nm

ISO 25178 Height			
Sp	3.37	nm	Maximum peak height
Sv	4.56	nm	Maximum pit height
Sz	7.93	nm	Maximum height
Sa	0.543	nm	Arithmetic mean height
Sq	0.683	nm	Root mean square height

Figure 5: Master-to-replica precision



Core values and benefits

The Spectrum Scientific optical replication manufacturing method allows multiple replicas to be created from one precision part. This process offers many significant advantages over traditional manufacturing techniques, especially for high-volume production. These benefits are highlighted in Table 2 and the considerations associated with this technique are presented in Table 3.

Replicated Optics	Manufacturing Method	
	Precision Replication	Other
Unit cost - low volume	◗	●
Unit cost - high volume	●	◗
Part to part repeatability	●	◗
Ability to maintain high specification at high volume	◗	◗

Table 2: Advantages of the replication process, compared to traditional manufacturing methods

Benefits	Considerations
• Production-Grade Scalability and Cost • High Fidelity Reflective Aspheric Mirrors • λ/10 reflective optics • Minimal part-to-part variation	• Upfront set-up investment for custom manufacturing • Initial production tooling lead times • Additional investment between production stages, if the system design changes

Table 3: A comparison of the benefits and considerations of the optical replication manufacturing method

The replication process is highly cost effective for high-volume imaging applications, offers batch-to-batch and part-to-part consistency and repeatability with volume production of high specification aspheric surfaces, with typical surface figures of up to λ/10 or, in some cases, even better.

This figure of λ/10 is an impressive achievement, but it depends on the size and complexity of the surface shape. Figures 7 to 10 demonstrate how a λ/10 was achieved for an off-axis parabola surface design.

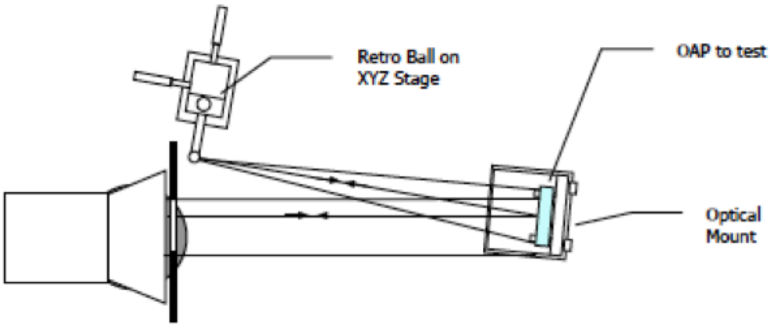


Figure 7: An example optical system, which uses a double pass set up for off-axis parabolas

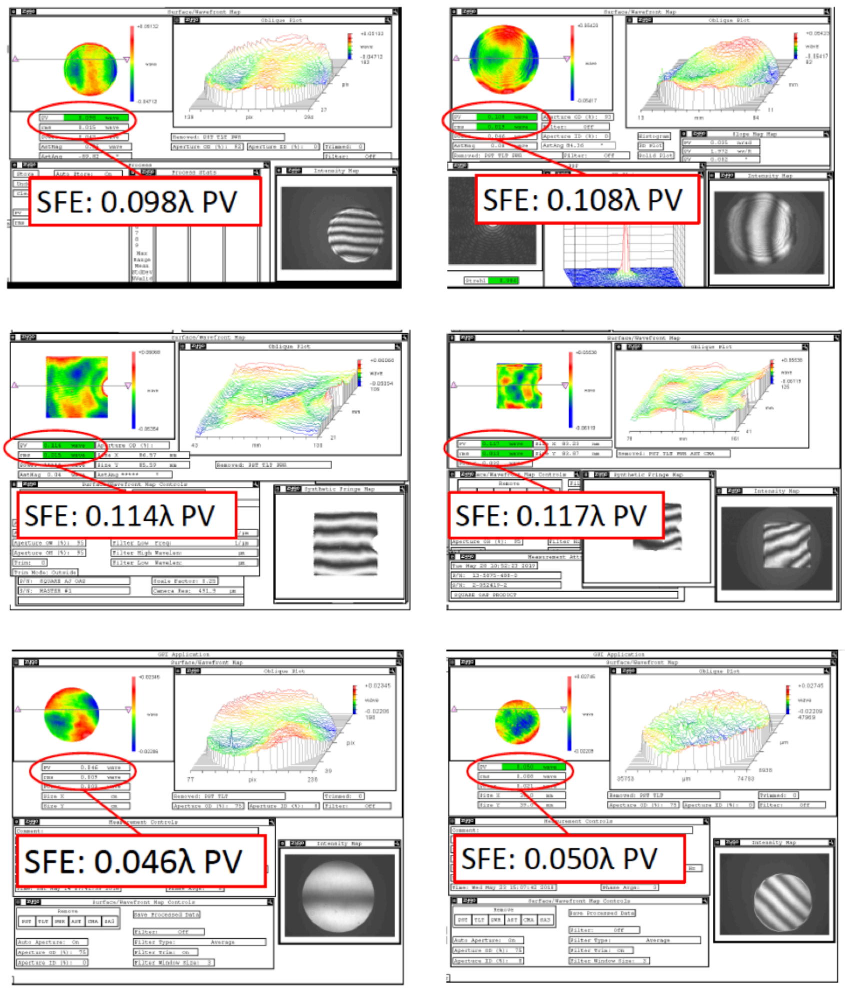


Figure 8: Interferometric examples of a variety of replicated optics ranging in size, shape, and material

The replication process allows you to ramp up production volumes without the needs to invest in additional capital equipment, with typical ramp-up results shown in Figure 9. The cost savings are equally significant, where the unit cost be as low as a couple hundred dollars. Figure 9 is an example of a replicated freeform mirror production ramp-up.

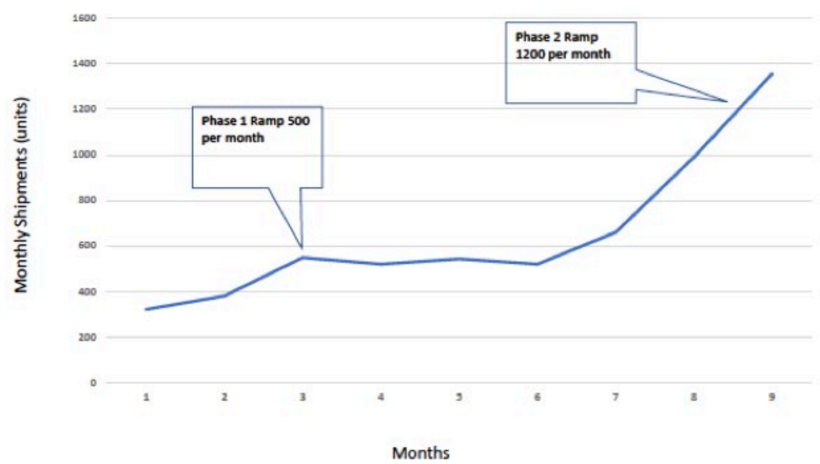


Figure 9: Replicated Freeform Mirror Ramp Up Results

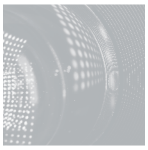
In addition, the replication process does not require demanding machining techniques. Only the master must meet a high specification. The replica substrates do not need to be so highly machined because the replication layer smooths out any imperfections. So, the optical quality of the master is faithfully transferred to the replica.

Unlike a conventional glass substrate, the optic doesn't need to be mounted or bonded to another piece of hardware. The substrate can also be machined with additional alignment mounting and registration features directly onto the replica substrate, reducing the number of parts to decrease the assembly time and likelihood of ongoing maintenance costs. By choosing a substrate with a low or high coefficient of thermal expansion, a thermalised design is also enabled.

In conclusion

The Spectrum Scientific optical replication process is ideal for OEM manufacturing of precision optics. It achieves a faithful replication of the master optic, minimal part-to-part variation and is a highly cost-efficient method for high-volume production of freeform optics.





This optical replication manufacturing method described in this whitepaper is also used to manufacture diffraction gratings, hollow retroreflectors, space-qualified optics, off-axis parabolic mirrors, ellipsoidal mirrors and, of course, freeform and aspheric mirrors.

To find out more about Spectrum Scientific and its state-of-the-art optical replication manufacturing method for freeform optics, contact one of the team at

Spectrum Scientific, Inc.
Email: sales@ssioptics.com
Website: ssioptics.com
Phone: +1 (949) 260 9900

Spectrum Scientific, Inc. (SSI) has been manufacturing high volume flat, aspheric and freeform reflective optics, hollow retroreflectors and holographic diffraction gratings since 2004. We primarily use the optical replication process in our manufacturing allowing us to supply high fidelity, high specification precision optics at a lower cost compared to traditional volume manufacturing.