Manufacturing Large Mirrors – The challenge

Large mirrors are a critical aspect of numerous optical systems and are used in a wide variety of important applications. For the production of high performance large mirrors, optical manufacturers are tasked with the challenge of meeting a strict set of requirements

When it comes to long range multi-spectral optical systems, large mirrors play an integral role. Such optical systems are used for defense applications, surveillance and monitoring, as well as for certain commercial applications. For example, large mirrors may be integrated in the optical systems of aircraft like large UAVs. An interesting commercial application is the long distance aerial monitoring of agricultural field temperature using infrared. The most commonly recognized applications of large mirrors are in the aerospace industry – for satellites and telescopes.

Reflective systems are commonly of long focal length and meant for long distance surveillance, possibly tens of kilometres. Reflective telescopes may use one or more on-axis or off-axis mirrors to produce high resolution images. Many telescopes, as well as other optical systems using large mirrors, are catadioptric systems that use a combination of lenses and curved mirrors – this maximizes error correction, allowing for a wider field of view.

Large mirrors take many shapes, from spherical to aspheric, parabolic, or free-form. They are used for a wide spectrum of light– including visible, UV, and IR. Mirrors are fabricated from materials such as Aluminum (Al), Silicon (Si), Germanium (Ge), and Copper (Cu).

The production of such mirrors presents a unique set of challenges for optical manufacturers. Firstly, there is accuracy of surface form – whether it is spherical, aspheric, parabolic, or free form. Tolerance requirements of the order of 0.2 fringe of HeNe light are not uncommon. The off-axis form is specified in systems that cannot tolerate the central obscuration. These off-axis mirrors are substantially more challenging in terms of mirror fabrication, testing, and system assembly.

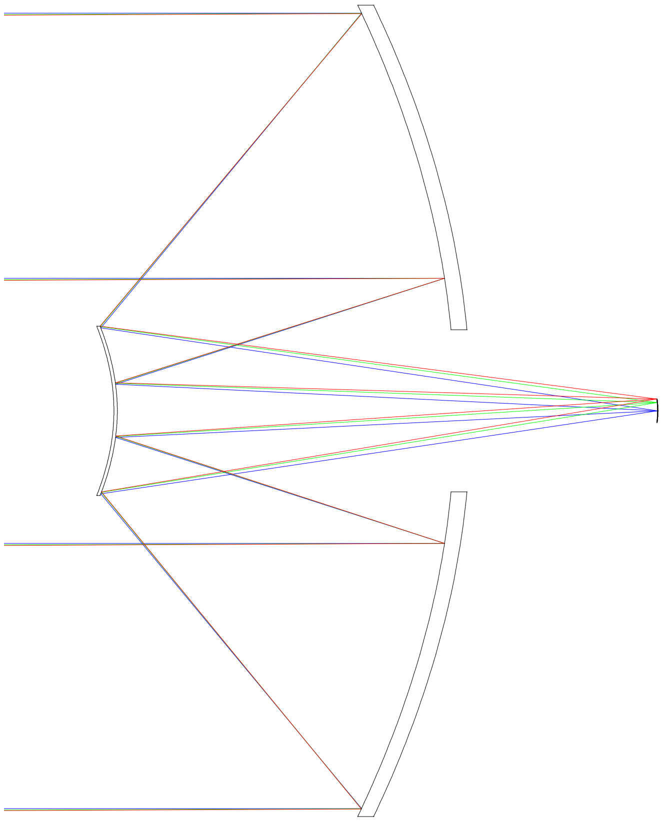
As large mirrors are often used for multispectral applications, they must perform to a high level across a wide range of wavelengths. This means that the mirrors must have minimum roughness, especially when they are used in VIS wavelength, under 40Å RMS, to prevent light from scattering. Additionally, as detectors are increasing in resolution, there has been growth in the demand for mirrors with increasingly accurate surfaces.

In order to meet the strict specifications required, optical manufacturers must employ cutting edge technologies. Here at Ophir, we use advanced CNC grinding and polishing, as well as diamond turning – for the production of highly accurate, precise surfaces. Ophir can produce spherical, aspherical, parabolic, and free form mirrors up to 700mm in diameter, whether on-axis or off-axis. Ophir's large mirrors have an impressive radius tolerance of 0.05%, irregularities less than 0.5Fr P-V, 0.1Fr RMS at 0.633μ, and a roughness of less than 40Å RMS – resulting in high accuracy and low scatter. Ophir has several proprietary reflective coatings, each designed for spectral performance and surface durability.

Optical design

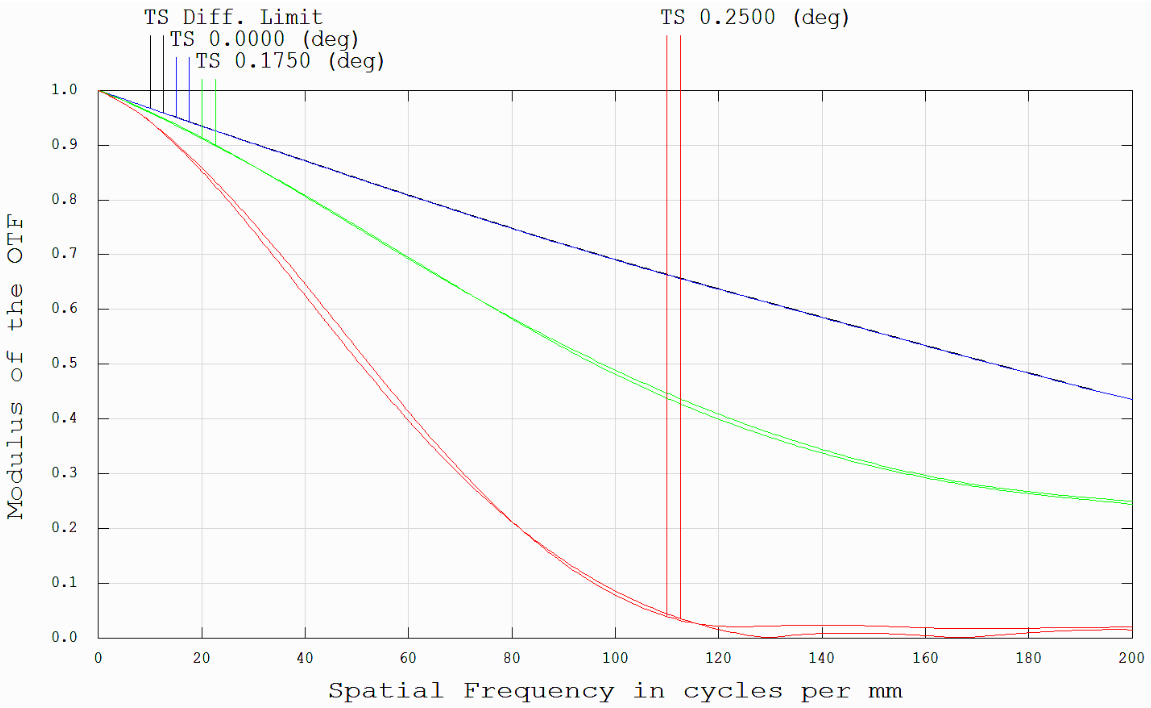
The effect of surface figure on performance – a simple example

We consider an all reflective design, similar to the classic Cassegrain telescope, with an f-number of f/3.4.



Reflective systems of this type are most advantageous in cases where there is a large ratio of effective focal length (EFL) to physical length. In our example, the EFL is 1000mm, whereas the overall length of the optics alone is 200mm. Such a ratio of 5 to 1 is uncommon in the case of refractive systems.

The MTF of this system at 100 lines per mmm (lpmm) is 0.7 for the wavelength 500 nm. This corresponds to the diffraction limit.



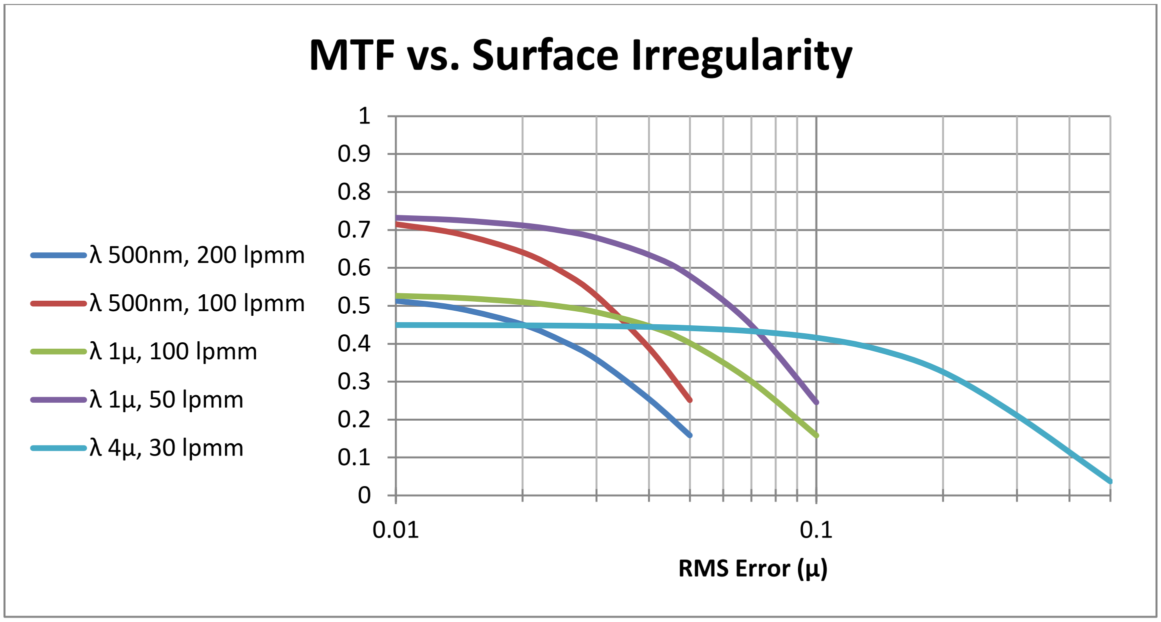
In this simple all reflective case, with the 5:1 ratio of EFL to length, the field curvature is substantial, and there is significant astigmatism at field positons off axis. This can be seen in the MTF plot, where the performance of the 0.25° field is much degraded. For this reason, our simple example is for illustration only and should not be considered a practical design.

In general, refractive elements are needed in order to flatten the field. The classic solution is the Schmidt corrector plate, which is placed in front of the primary mirror, roughly in the same axial position as the secondary mirror. Alternatively, refractive elements between the secondary mirror and the image can simultaneously correct the field and change the EFL. The disadvantage of refractive elements in the system is that they limit the wavelength spectrum and introduce chromatic aberration.

The surface figure of reflective elements is extremely important for high-resolution systems. The amount of wavefront error caused by a given surface irregularity in reflection is more than double that caused by the same surface in refraction. To model the relationship between surface irregularity and imaging resolution performance, we apply Zernike Standard term 11 on the primary mirror:

$$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$$

Then, the MTF of the center field is plotted against RMS surface error for five representative cases.



RMS errors as little as 0.02µ can be significant in high-resolution visible light systems; this is equivalent to 0.03λ RMS at λ=633nm test wavelength. For IR systems in the region of 4µ wavelength, the diffraction limit of resolution is much lower, and so, RMS errors as high as 0.1µ can be tolerated.

Manufacturing

The production of large, precision mirrors presents its own challenges. Whenever possible, Ophir works in conjunction with designers to deliver the best options available. Firstly, the choice of raw material is crucial, especially for diamond turned aluminum mirrors. We often recommend the utilization of RSA 6061, the proprietary super aluminum alloy, for multispectral applications. This material allows low levels of surface roughness, unattainable by conventional Al 6061. While higher roughness usually has no consequence in IR systems, a low surface roughness is vital for visible and SWIR applications. RSA 6061 has the added advantage of being somewhat stronger than conventional Al 6061.

Another key design aspect is that the mirror's back surface must permit stress-free mounting. Upon assembly, the mirror must not permit stress to bleed through to the optical surface. Often, we encounter bore threads in sketches near the mirror surface, which almost certainly lead to image distortion. There must also be ample surface area to hold the mirror onto the cutting machines.

The production environment is another core concern. Aluminum has a relatively high coefficient of thermal expansion (α_L=~26 *m/m°C*) compared to other diamond turned materials, such as Germanium. Therefore, production areas must be temperature controlled and seismically isolated.

When designing aluminum mirrors, designers must take advantage of the fact that the diamond turning

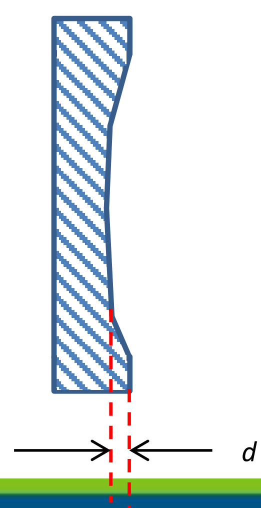


Figure A

machine is actually a very sophisticated CNC lathe. Therefore, one can attain critical **mechanical** dimensions, to very demanding tolerances. For instance, the distance *"d"* in figure A, which may be the distance between the center of the concave mirror and a flat mounting surface, can be within a few microns, as both surfaces can be generated with the same tool. Surfaces like these allow precision and no-nonsense assembly, because of their high degree of flatness and roughness.

Cleaning the mirrors is another important part of the production process. In general, cleaning aluminum is not a trivial procedure, and preparing mirrors for testing and coating is an essential skill. We ensure that all mirrors are thoroughly and carefully cleansed immediately after the diamond turning has finished, removing cosmetic blemishes.

Perhaps the most critical aspect of the production process is the ability to measure accurately and reliably. Optical shops have many options for measuring such surfaces. Historically, parabolas have been the preferred shape of large mirrors, and this special conic contour is readily measured using the auto-collimation method. In theory, parabolas by themselves also promise low spherical aberration. A typical auto-collimation system consists of a commercial interferometer, a transmission sphere, and a large flat mirror with a central hole. Inherent aberrations, however, from each of these systems' components, add to the overall error. Often, built-in errors can be compensated for by performing rather complicated calibration and nulling. Instead, Ophir utilizes precise Fizeau transmission spheres to reduce these built-in errors. Another disadvantage of the auto collimation system is that measuring the radius of curvature is awkward and rough. This is especially magnified for mirrors with no centers.

In recent years, designs have shifted away from pure parabolas, and the use of various aspheres has increased. Optical shops must therefore be equipped with versatile tools for measuring a wide assortment of aspherical mirrors. Here at Ophir, we have a Zygo VFA Asphere at our disposal, enabling us to precisely measure the majority of large aspheric mirrors. When measuring mirrors that have no center, the Zygo VFA requires an artificial center plug, which adds some more uncertainty to the equation. Nevertheless, the radius of curvature can be acquired with a high degree of accuracy and low uncertainty.

For very demanding requirements, we regularly utilize either a CGH (Computer Generated Hologram) or a DFNL (Diffractive Fizeau Null Lens). Both of these allow for the extremely accurate measurement of aspheric mirrors. These tools often add extra features, allowing the measurement of the radius of curvature and surface irregularity in tandem. A distinct advantage of the DFNL over other aspheric methods of measurement, for surfaces with F#>1, is that the DFNL itself is the only component needed to check the asphere. For these surfaces, the DFNL is able to bend and collimate the light and create a null.

Our skilled operators are then able to use interferometric output data to create feedback correction programs. These operations depend on highly accurate processes, with very high certainty. The "Measurement Correction" feature is one of the most powerful weapons in Ophir’s arsenal. This feature is only as successful as the accuracy and uncertainty of the measurement process. In general, measurement correction features only correct symmetrical errors. Due to this, asymmetrical problems, such as mounting stress or thermal issues, cannot be fixed.

In figure B, we can see the results of a Φ190mm aluminum mirror. The low results show spherical aberration of less than 0.02λ RMS, achieved using our advanced tools and equipment. Often, the coating process can degrade the results. In these cases, we must consider such effects in our calculations.

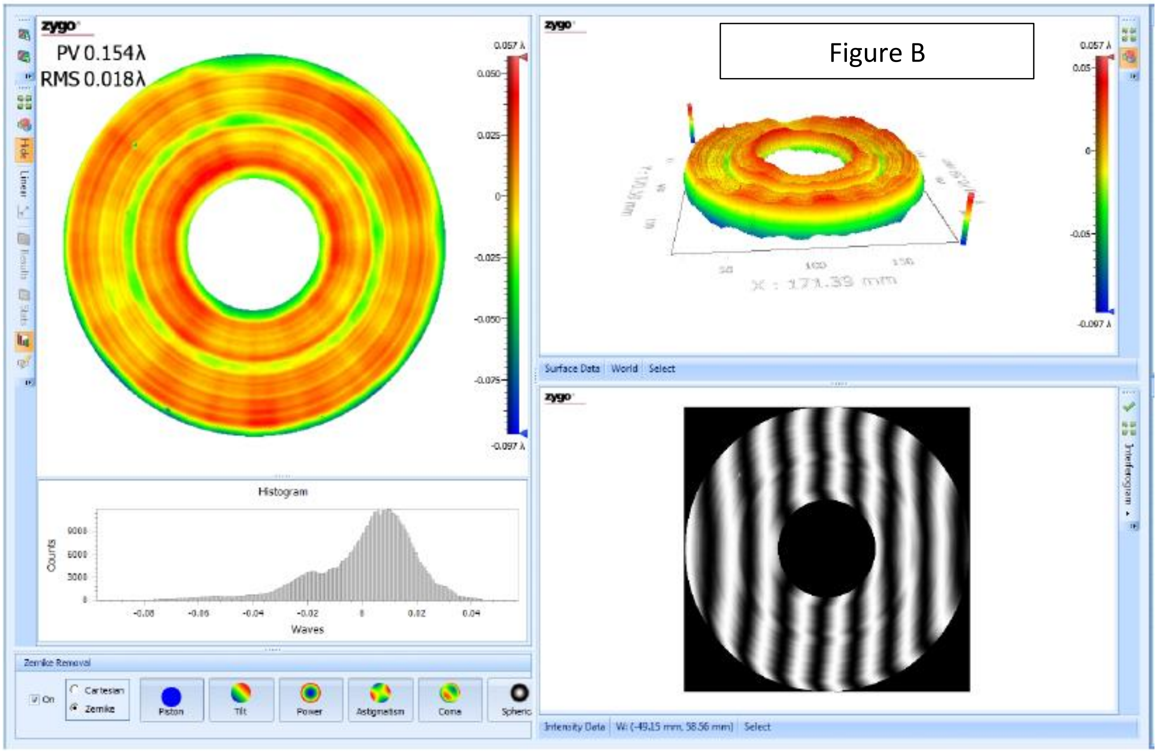


Figure B
PV 0.154λ
RMS 0.018λ
Histogram
Counts
Waves
Zernike Removal
On
Cartesian
Zernike
Piston
Tilt
Power
Astigmatism
Coma
Surface Data
World
Select
Intensity Data
Select

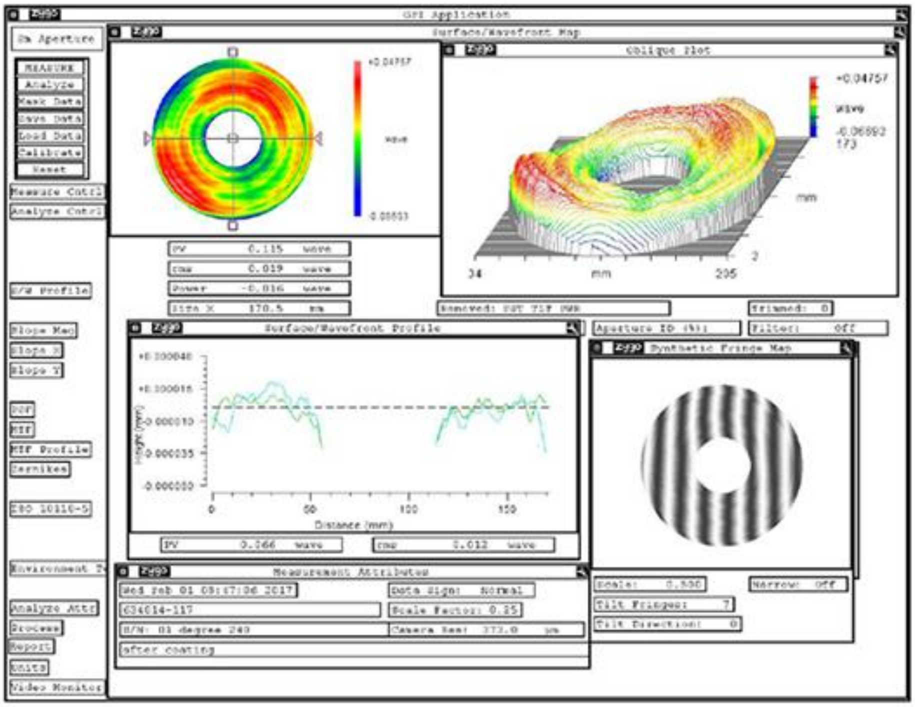


Figure 1.0: Interferogram of a primary mirror with a central obscuration. Measured surface error: 0.115λ P-V, 0.019λ RMS at λ=0.633nm

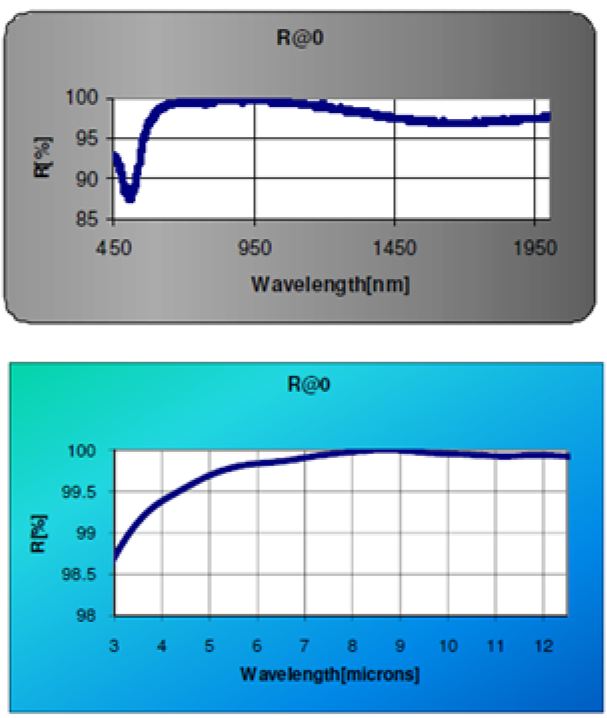


Figure 2: Spectral performance of wide band protective silver coating on Aluminum substrate

Ophir’s turnkey solution – from design through to manufacturing, ensures quality is maintained throughout the production process, with vigorous inspection and testing to ensure our mirrors meet the high standards expected.

The long range, multi-spectral nature of optical systems with large mirrors presents a challenge for optical manufactures. However, using advanced technologies, these mirrors can be produced to meet the requirements, with sufficiently high accuracy to meet today's performance specifications.

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