Defining and Describing Surface Error

Mark Malburg and Mike Zecchino

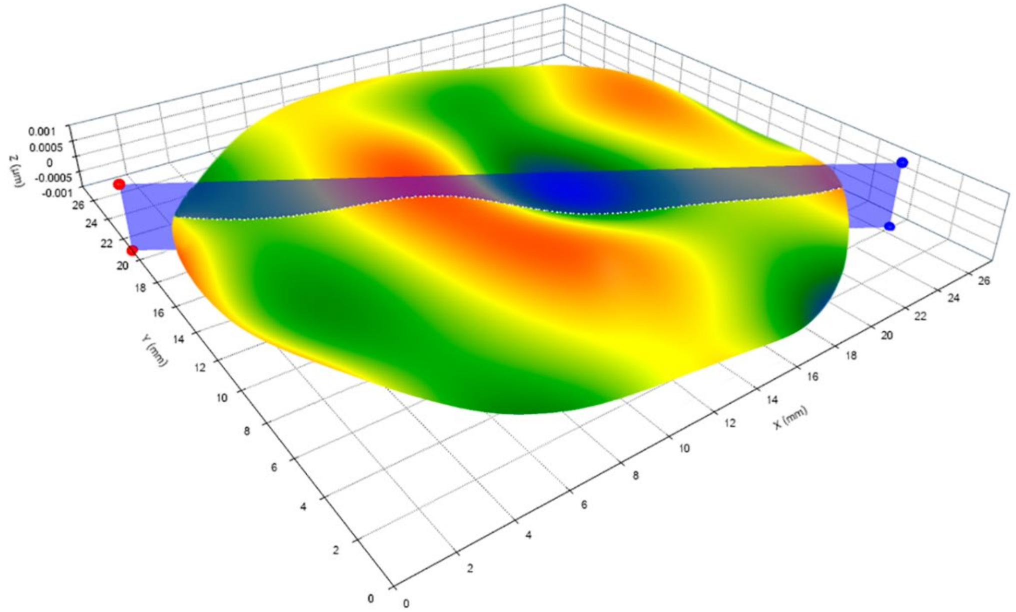


Figure error on an optical surface. The false colors in this 3D map represent surface heights. The blue plane provides a cross section through the data; the white dots along the plane represent the lateral resolution limit of the instrument that made the measurement. (OmniSurf3D software, courtesy Digital Metrology Solutions)

Controlling the performance of optical components requires well-defined processes for measuring shape and surface texture. The measurement and description of a *shape* is not a trivial task: differences between instruments, techniques, calculations and interpretation can all contribute to errors in the data. These errors in turn can lead to incorrect decision making and, ultimately, to significant costs.

Today’s metrology instruments provide increasingly high resolution, and software packages offer more and more analysis options. Yet, this improved technology can paradoxically lead to an increase in variability, and even an increase in scrap rate due to higher sensitivities.

To benefit from metrology advances, the measurement process must address some basic fundamentals to ensure repeatable results. Specifically, processes must agree in how they:

- compare the measured shape data to the nominal geometry
- filter the data to explore the deviations that matter for an application
- select numerical results (parameters) to describe the deviations
- standardize measurements across process steps, facilities and vendors.

We will begin with an example and then examine each of these analysis steps in turn.

Advances in Measurement Can Seem to Reveal New Error

In the not-so-distant past, a digital 640x480 image interferogram of an optical surface was considered a breakthrough for measuring and describing surface error. Today, we have improved that resolution many thousands of times over. 2D and 3D measurement instruments now give us the ability to resolve lateral spacings at the submicron level.

This increased resolution, however, poses an interesting challenge. Surfaces that historically exhibited smaller surface errors can now show higher error numbers, simply due to the higher resolution of the measuring instruments. Consider the 3D (areal) measurements of a diamond-turned surface shown in Figure 1. Diamond-turning creates a texture that is made up of relatively short wavelength (high spatial frequency) shapes. In some cases, the spacing of these features can be less than a micron. Earlier optical measurement systems lacked the lateral resolution to sense these fine details. When a surface such as this was measured it appeared smooth, as in Figure 1a. Today, however, many measurement technologies can detect such fine details, resulting in the "rougher" surface shown in Figure 1b. These short wavelength shapes will be reported as error with the higher resolution system.

The component's surface has not grown worse over time—the measurement system is simply able to sense, and report, smaller wavelength error.

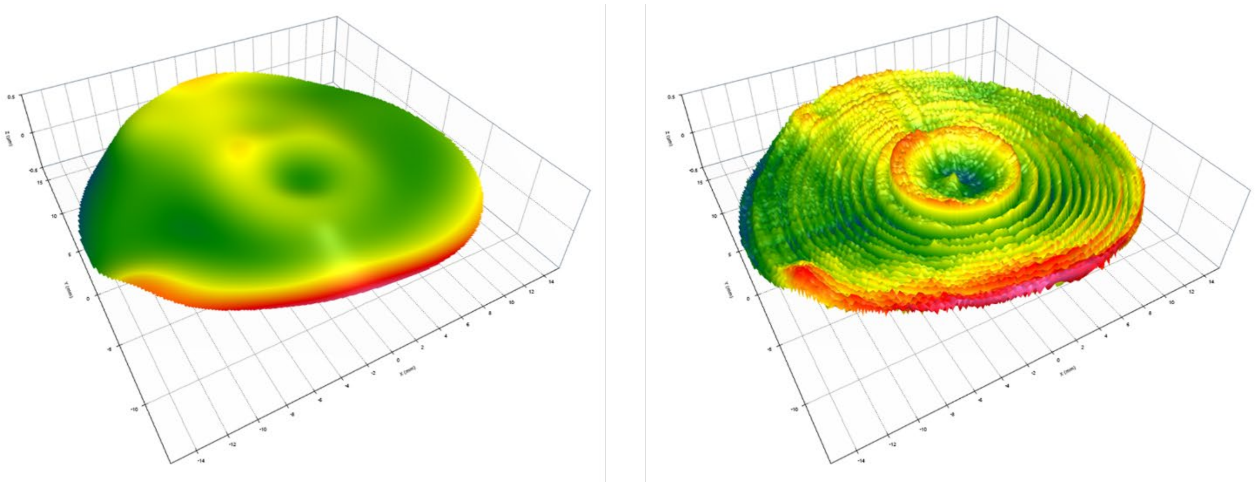


Figure 1. Differences in reported error based on the lateral resolution of the measurement system. These false-color, 3D maps are shown in OmniSurf3D analysis software.

Other technology advances also introduce potential variability. Some new optical designs, for example, feature extreme geometries that may produce curvatures that cannot be accounted for by certain sensors and software packages. The abundance of measurement parameters available in measurement software may lead designers to overly constrain a process or may create confusion in determining a good part from bad.

A well-designed measurement process can take advantage of metrology advances. Measurement software can help, by guiding users through the process and making it simple to view how various options affect results. Software can guide a "recipe-driven" approach to analysis by leading the user through the steps (geometry removal, filtering and choosing parameters).

Geometry — Comparing a Measured Surface to the Design

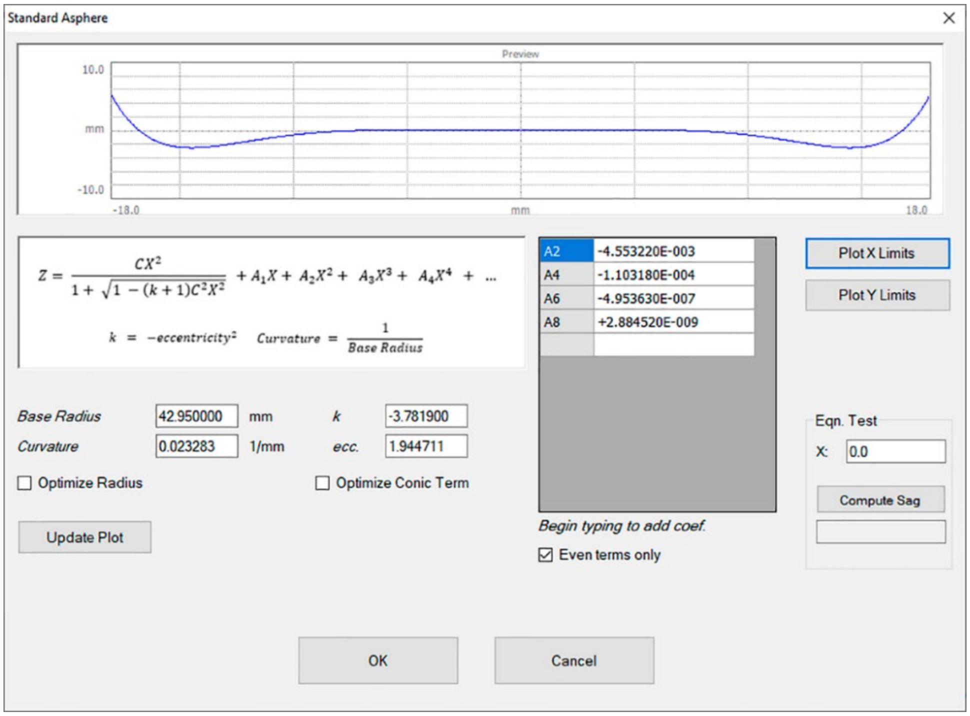
A component's geometry is designed to achieve a set of optical and mechanical properties. To verify the quality of a produced surface we measure points on that surface and then subtract the designed shape from the measured data. The resulting data set represents the errors, or "residuals," in the produced surface. This deviation from the expected shape can be used to guide further processing or adjustment, or it can be fed back into an optical analysis package to determine whether the error is acceptable.

Traditionally, optical surface shapes could be approximated by basic geometries, such as cylinders or spheres. Today, however, optical surfaces vary widely in shape, including "aspheric" surfaces, and free-form optics with shape that cannot be defined strictly by mathematical equations.

Regardless of the geometry, analysis software must provide for the following:

- the input of the design/model geometry
- the fitting method, and
- the orientation of the residual errors.

The input of a geometry is typically equation based. Figure 2 gives an example of the input for an aspheric surface:



$$Z = \frac{CX^2}{1 + \sqrt{1 - (k+1)C^2X^2}} + A_1X + A_2X^2 + A_3X^3 + A_4X^4 + \ldots$$

$$k = -eccentricity^2 \quad Curvature = \frac{1}{Base\ Radius}$$

Base Radius 42.950000 mm

Curvature 0.023283 1/mm

k -3.781900

ecc. 1.944711

☐ Optimize Radius

☐ Optimize Conic Term

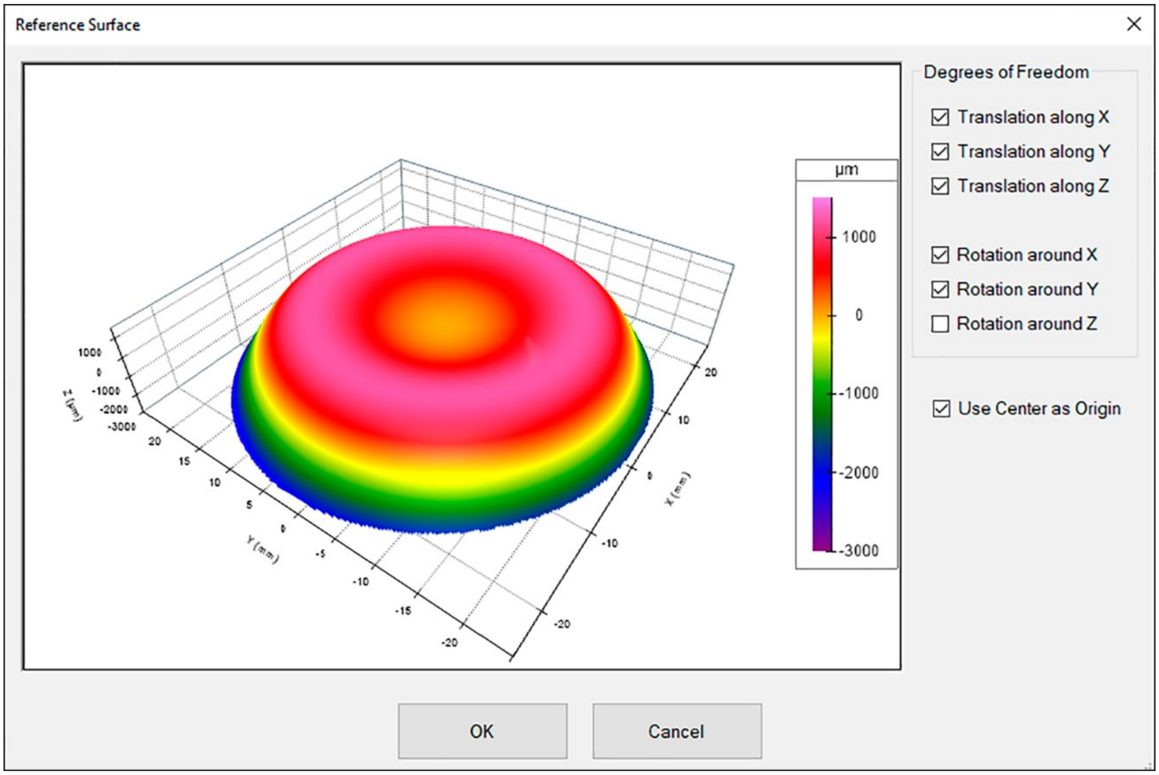
A2	-4.553220E-003
A4	-1.103180E-004
A6	-4.953630E-007
A8	+2.884520E-009

☑ Even terms only

X: 0.0

Figure 2. Configuring a standard asphere in OmniSurf3D.

When a nominal geometry cannot be described by standard equations, a CAD model or nominal point cloud (STL data, for example) can be used as the input (Figure 3).



Degrees of Freedom

☑ Translation along X
☑ Translation along Y
☑ Translation along Z

☑ Rotation around X
☑ Rotation around Y
☐ Rotation around Z

☑ Use Center as Origin

Figure 3. CAD Model Input into OmniSurf3D. Note the degrees of freedom that can be independently controlled.

The analysis software must also fit the designed geometry to the measured data. Various methods exist for "associating" the measured and nominal geometry. The most common method for optical components is a least squares fit.

Sometimes constraints are applied to limit the allowed fitting motions. The ability to lock the degrees of freedom in this fashion is very important in the analysis of optical surfaces such as off-axis aspheres (Figure 3).

Once the fitting operation is complete, the residual error is recorded across the surface. Defining the direction of these errors is a very subtle yet extremely important aspect of this analysis step. For example, reporting the errors along the optical axis versus perpendicular to the nominal surface, results in very different results (Figure 4).

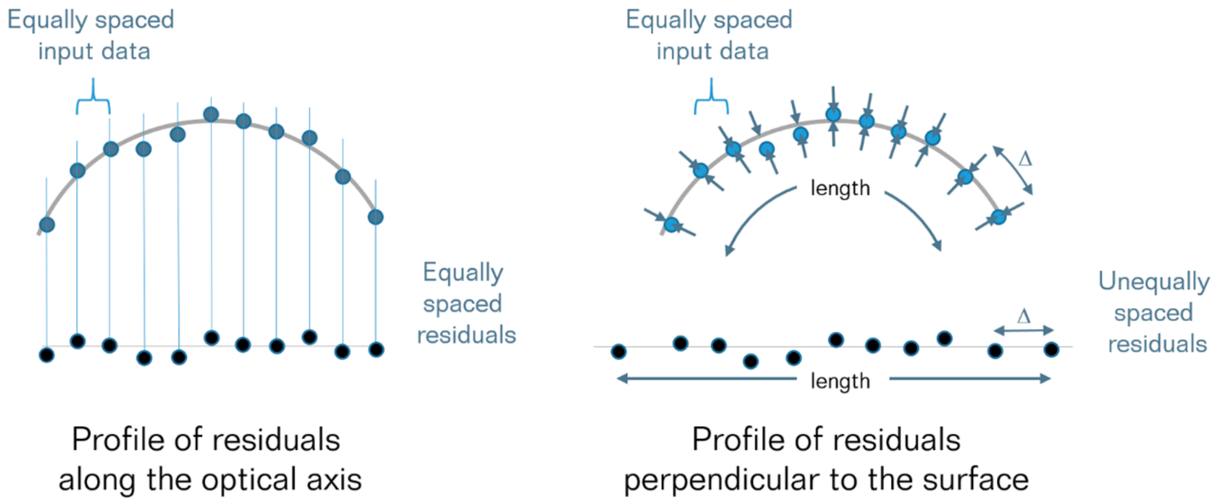


Figure 4. Measuring residual errors along the optical axis produces different results than measuring errors perpendicular to the surface.

These two residual types can result in significantly different error maps. For example, the error map (or error profile) based on axial residuals will have the same area (or length) as the input data. This may be of interest when considering the optical axis or in some machine compensation applications. The error map based on perpendicular residuals is larger laterally, as it represents the "unrolling" of the surface. This map is often more important in modelling where an error surface is applied to (or "wrapped around") a nominal geometry. In either case, the software package must specify which method is employed and, if possible, should make both options available for the user.

Filtering — Defining the Surface Shapes of Interest

Once we have obtained the surface data and removed the nominal geometry we can then begin analyzing the residual error. Surface error, or surface texture, is rarely random variation from the expected surface; rather, it consists of a spectrum of wavelengths, ranging from the short-wavelength roughness through long-wavelength form. The spectrum is also often described by frequency (1/wavelength).

In order to more completely describe, and control, the surface errors we must specify the regions of the wavelength spectrum that are important for the application. Controlling short-wavelength roughness may be critical for components that transmit high energy, whereas controlling longer wavelength shape may be paramount for focal systems. Most components require some independent degree of control over both regions of the spectrum.

Using Filters to Isolate Features of Interest

To define these wavelength/frequency regions of interest, we use filtering—applying "cutoff wavelengths" or "cutoff frequencies." Doing so lets us analyze the surface roughness and form independently so that we can assign parameters to control each domain. For example, a short filter can be used to suppress (filter out) short-wavelength, high-frequency features (e.g., noise). A long filter can be used to remove long wavelengths (low frequency) influences in the data.

As an example, consider the raw, unfiltered surface in Figure 5:

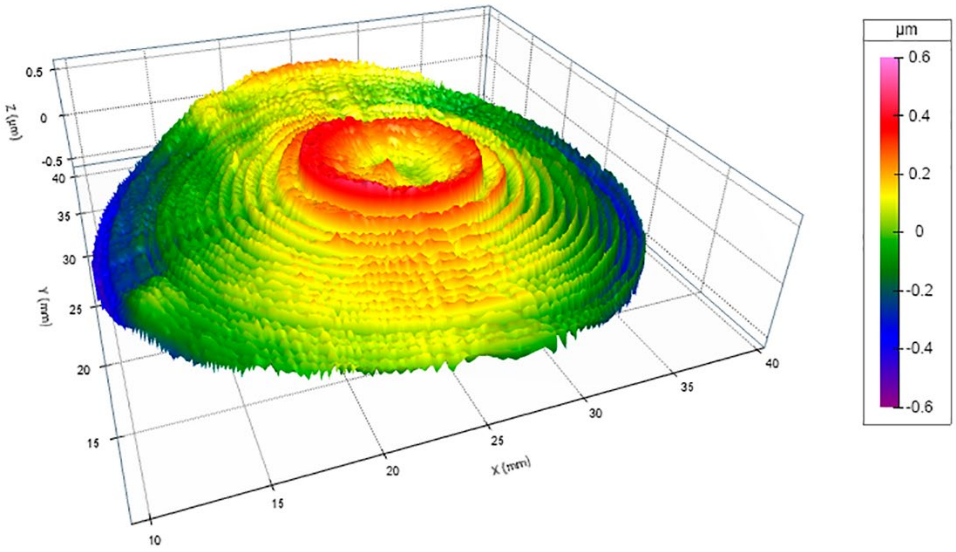


Figure 5. A surface consisting of prominent features in several wavelength regimes.

This surface can be decomposed into different wavelength domains by choosing appropriate filter cutoff values in the analysis software. For example, setting the short cutoff to 0.25 mm and the long cutoff to 2.5 mm isolates the tool marks on this example surface (Figure 6). The short (0.25 mm) filter suppresses short wavelength (e.g., "surface noise") and the long (2.5 mm) suppresses the wider features.

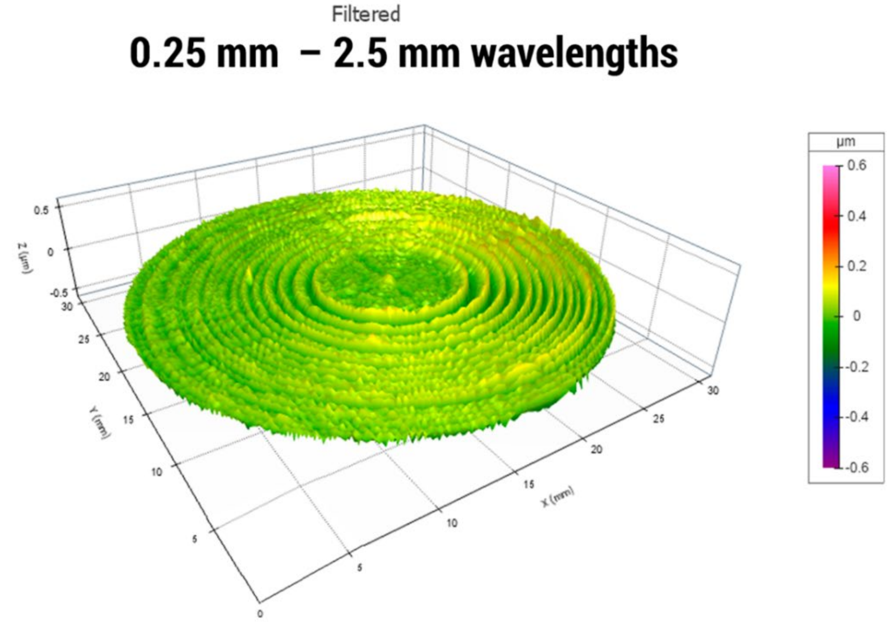


Figure 6. The tool marks are visible with appropriate filtering.

Similarly, we can choose a different band of filtered wavelengths to isolate mid-spatial features that may be related to tool chatter or machine vibration during manufacturing. Uncontrolled mid-spatial errors can lead to hazing, blur and other imaging issues. In this example, a 2.5 mm short filter and a 25 mm long filter will give the residuals as show in Figure 7.

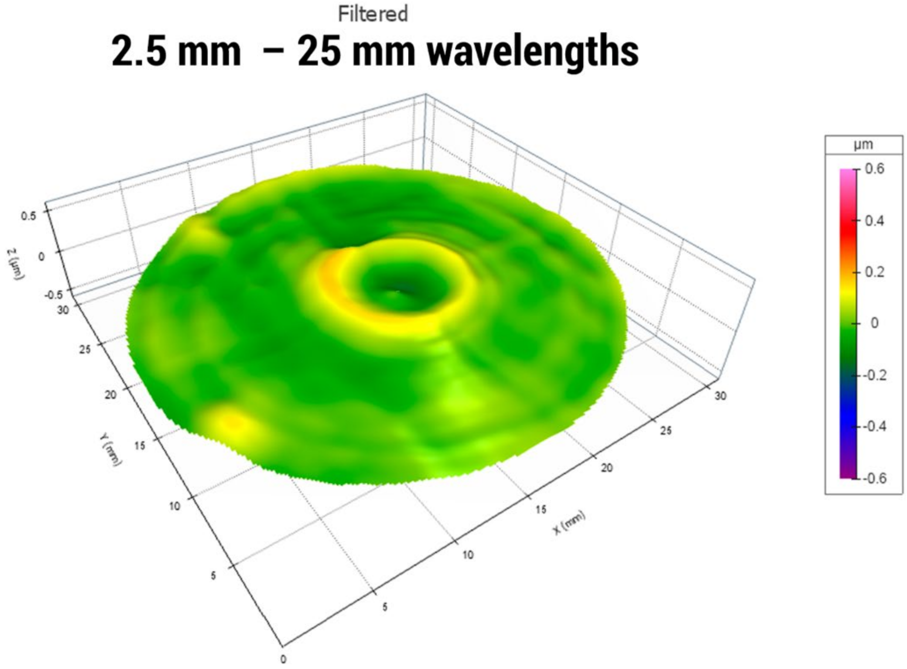


Figure 7. Tool chatter and vibration become visible by choosing different filter settings.

Finally, if we filter to isolate the long wavelengths we can see the underlying surface trends. For this data, a 25 mm short filter with no long filtering will give the shape in Figure 8.

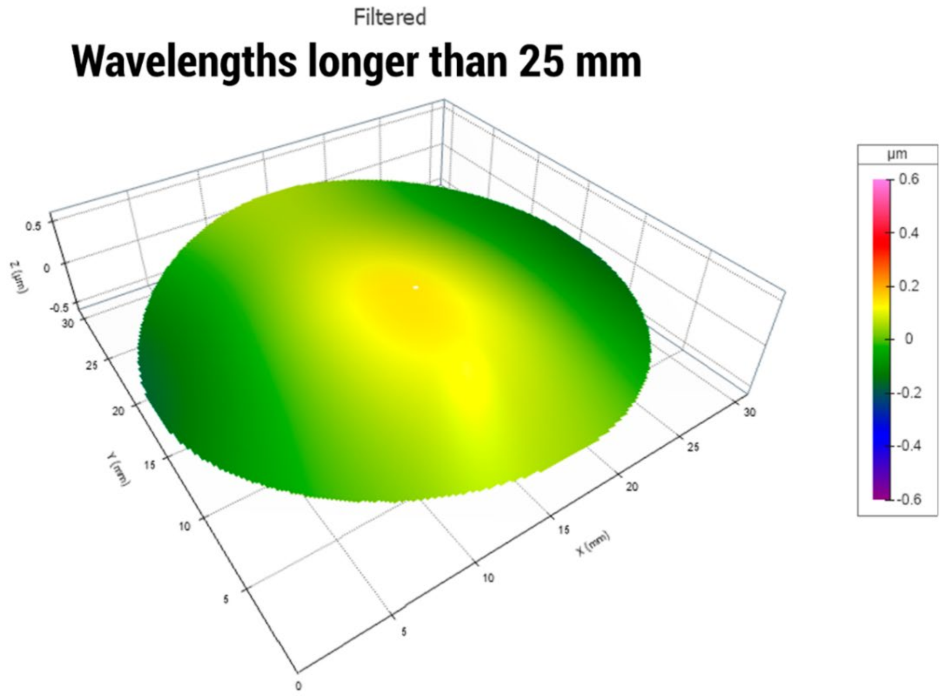


Figure 8. The application of only a short filter shows the underlying surface trends.

Using Filters to Standardize Measurements Between Instruments

Filtering can also help standardize measurements between instruments, addressing variability as we saw in Figure 1. International standards such as the ISO 25178 series of standards describe the measurement of surface shapes and provide tools for specifying the surface wavelength regime of interest. The cutoff wavelengths are defined mathematically rather than based on a particular measuring instrument or a particular sensor resolution. Thus, these standards present a portable approach that can be applied to many different instruments.

As we saw in Figure 1, improved resolution in the measuring instrument can sense short surface wavelengths (high surface frequencies), resulting in higher reported values for surface errors (Figure 9).

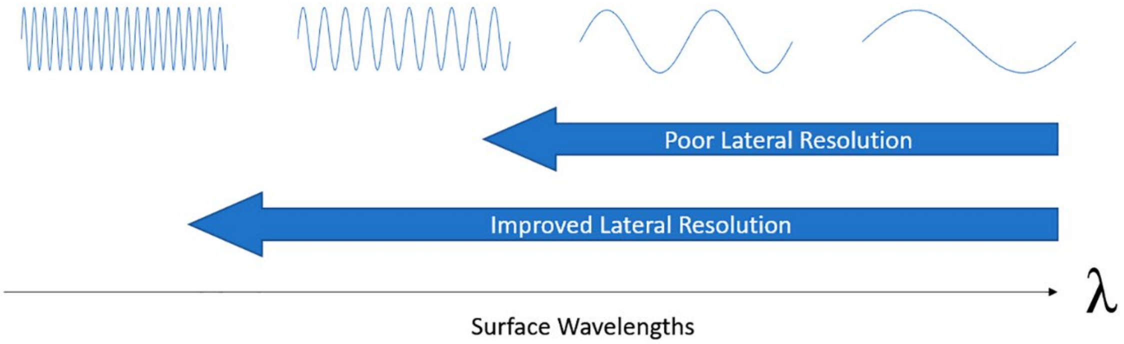


Figure 9. Differences in surface wavelengths acquired by measurement instruments.

By using a short filter to smooth the data we can often improve the agreement between measurement systems. If two instruments can be filtered to the same (mathematical) limits we have a better opportunity to attain agreement. The short filter's cutoff wavelength controls the amount of smoothing. Figure 10 demonstrate various short filter cutoff wavelengths applied to the high-resolution data in Figure 1. Figure 10 demonstrates that increasing the cutoff wavelength increases the degree of smoothing.

Note that this example differs from the bandpass filtering series shown in Figures 6–9. In Figure 10 only a short filter is being altered.

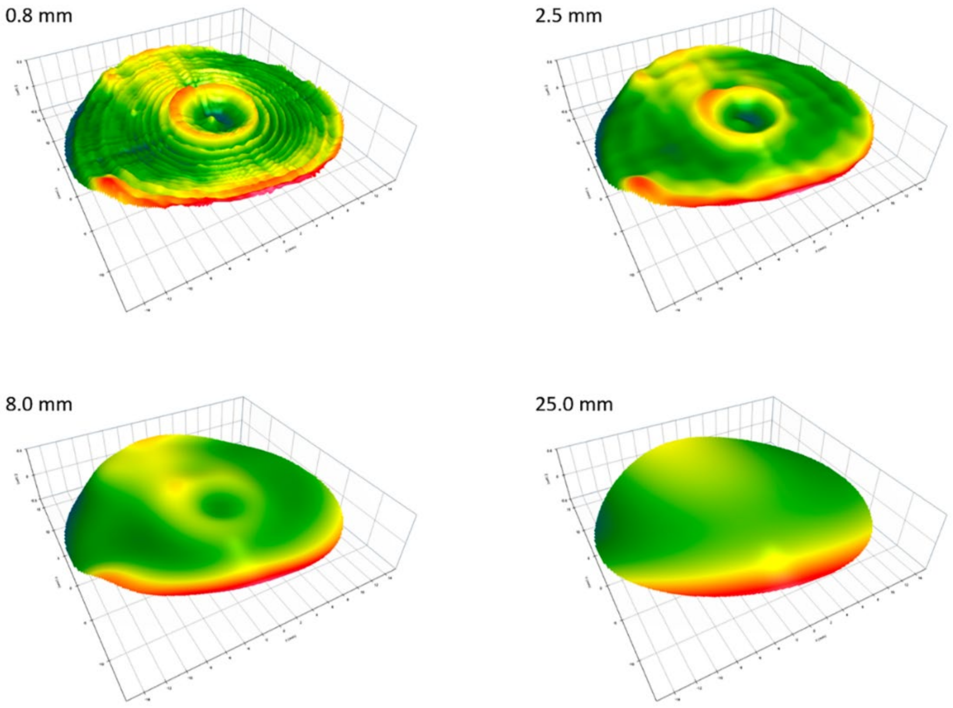


Figure 10. Increasing the cutoff wavelength of the short filter increases the amount of smoothing.

Figure 11 gives an example of how a particular short wavelength limit (referred to as the "short filter") can be used to achieve comparable results between two different instruments. The two different instruments inherently report different surface wavelength ranges. However, if both are filtered back to the same cutoff wavelength, agreement is possible.

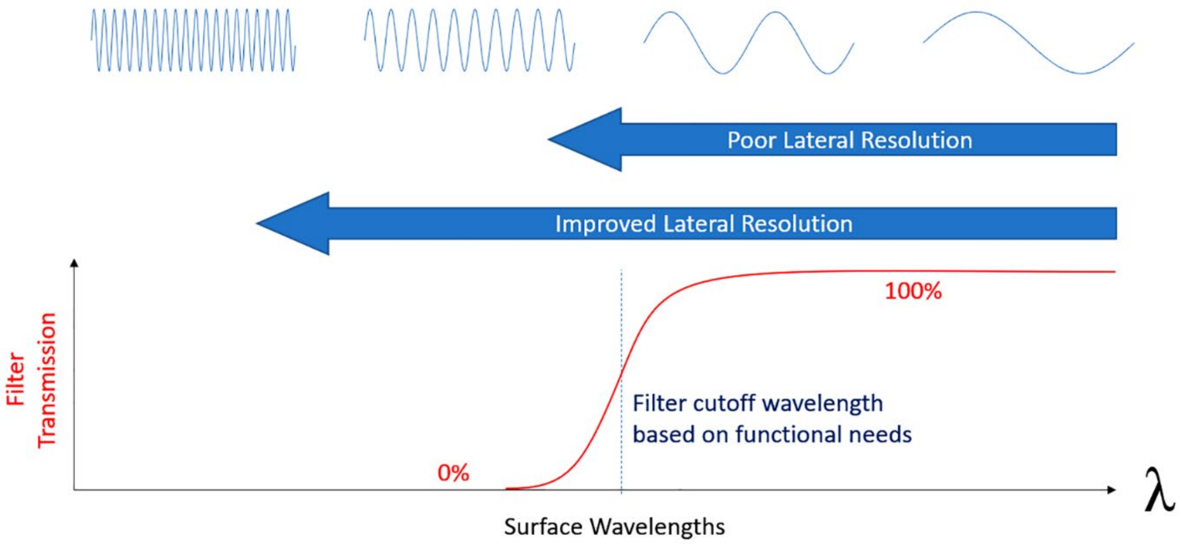


Figure 11. A short wavelength limiting filter.

Analysis software can present a vast array of filtering options. In most applications, the short filter is a Gaussian filter (as represented by the red curve in Figure 11), which provides the sharpest (steepest) possible transmission curve while not introducing digital artifacts into the surface data. Recent advances in filtering put forth in the ISO 16610 series of standards includes an option for a 2nd order Gaussian filter which improves a filter's ability to follow underlying curvatures. This can be useful on geometries with sharper curvatures and can therefore be beneficial in many of today's applications.

At the end of the day, the application of filtering must provide insight into surface texture rather than suppressing vital information. Analysis software should not just provide filter options: it should also make the effects of filtering clear. Figure 12 shows a linked, side-by-side view of unfiltered and filtered data in Digital Metrology's OmniSurf3D software. These kinds of visuals provide a "sanity check" to ensure that the filters are not only adhering to standards but are also leading to meaningful data.

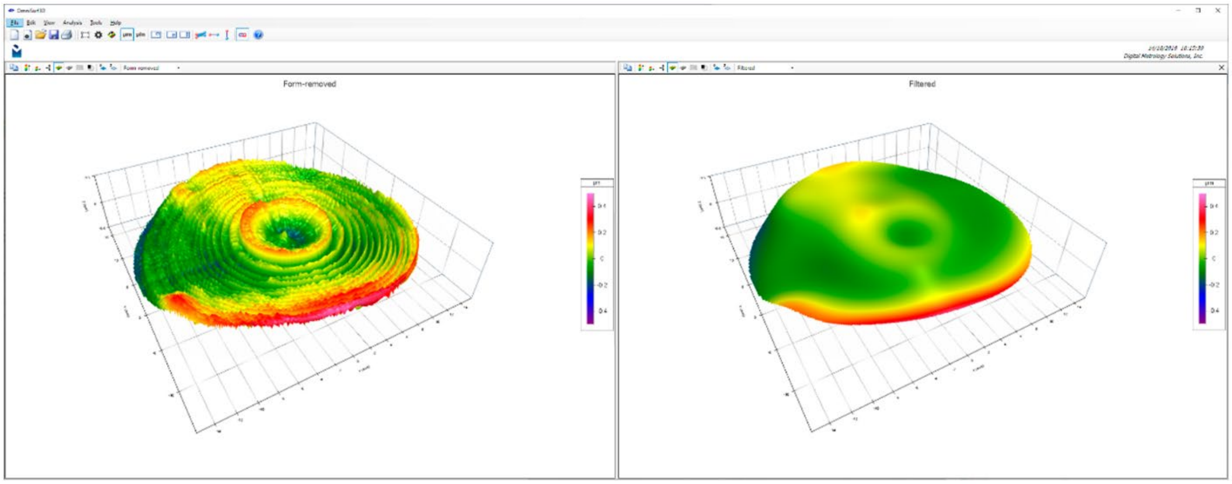


Figure 12. Synchronized views for exploring the effects of filtering, etc., as shown in OmniSurf3D.

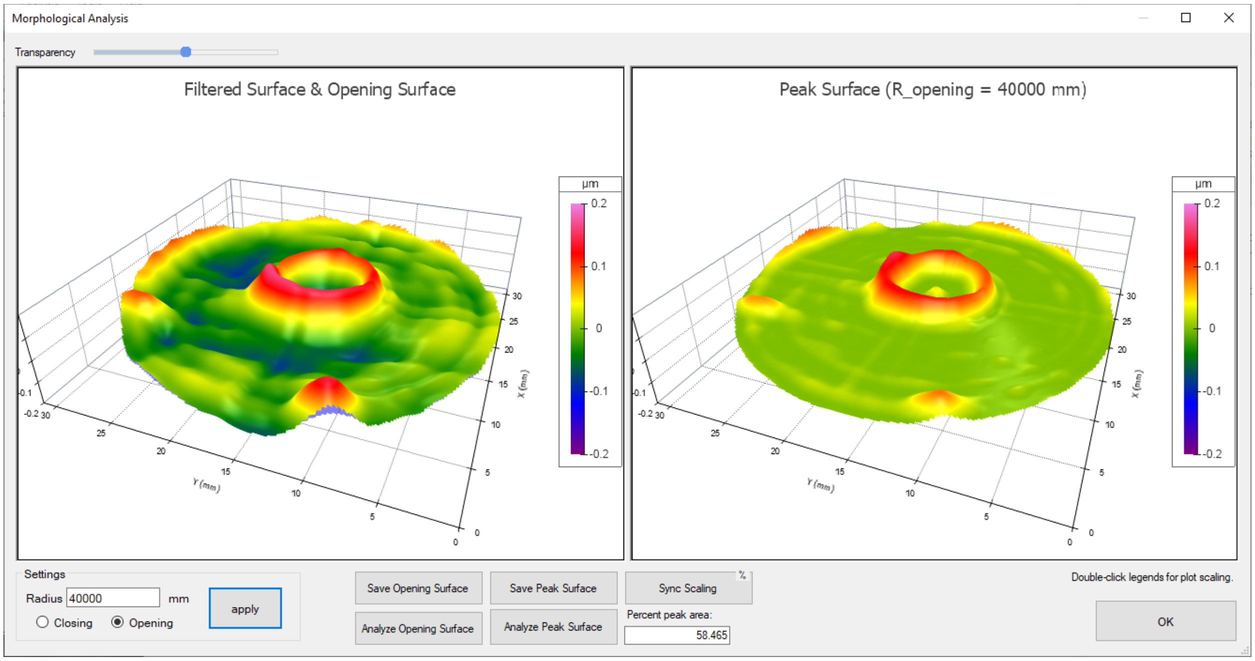
Parameters — Describing Error with Numbers

Once we have eliminated the variability in the measurement acquisition, shape removal and filtering we can then specify the parameters to describe the geometries and extent of the surface errors. Most software packages give access to a vast range of parameters; however, knowing which to specify and control can be a complex question.

The most commonly-used measure of figure error is the total, peak-to-valley height of the error map. In the context of the ISO 25178 standards this parameter is referred to as Sz (also reported as St by many instruments and software packages). Since the Sz parameter simply reports the worst deviation, it does not provide a clear description of the surface. For example, the Sz parameter cannot distinguish between an astigmatic error and an error due to a single, narrow spike on the surface.

Another common approach is to look at the root-mean-squared (RMS) value, or “standard deviation,” of the surface errors. This is the parameter Sq per the ISO standard. The Sq parameter is more indicative of the typical errors over the surface, whereas the Sz only references the two most extreme data points.

In recent years, many other parameters have been introduced that may be more descriptive and may relate more directly to the actual function of the component. Some of these parameters report surface aspects such as spacings and curvatures, while others are more indicative of directionalities or slope. Recent advances in morphological filtering have shown great promise in terms of isolating certain curvatures of interest (Figure 13). These morphological tools are of particular interest as they can highlight the mid-spatial surface errors described above.



Settings

Radius 40000 mm

○ Closing ● Opening

Percent peak area: 58.465

Figure 13. OmniSurf3D's morphological analysis tool indicating regions of sharp upward curvatures in the "peak surface" representation.

With so many parameters available there can be a tendency for designers to attempt to control more parameters than is sensible—or possible—on the manufacturing floor. Care must be taken to choose a set of parameters that is best suited to the component and its intended function, while also being attentive to the limitations of the manufacturing processes.

Standardizing Software Maximizes Consistency

As we mentioned earlier, using different measurement instruments at different facilities, or at different points in the manufacturing process, can lead to significant variability in the measurement results that control the processes. Similarly, using different analysis software throughout the process can also lead to variability. While the actual calculations in various measurement software *should* be tied to methods described in standards, other aspects of the software may not be so reliably consistent. Parameters available in one software package may not be available in another. Terminology may vary, leading to incorrect interpretations. In many cases, software used at various points in a process may simply be the software that was provided with measurement instruments in those departments. In other cases, the software in use may be based on the preference of various inspectors, or on financial decisions.

Software packages are now widely available that can analyze data from many different instruments in a standardized, recipe-driven format to reduce variability. Digital Metrology's OmniSurf3D, for example, can import and analyze data from dozens of instruments, in many file formats. Standard measurement settings can be developed for form removal, filtering and parameterization to achieve consistent results throughout processes. These settings can easily be exported and shared among users and facilities. The software's interface is designed to help users visualize how these aspects of analysis fit together, rather than just presenting numbers on a printed report.

The interface also extends the software's use beyond the manufacturing floor. The ability to visualize and interact with data is essential to understanding error. Simply stating that the surface has a figure error (Sz) of 12 microns does not convey adequate information regarding the surface errors. By making data visible and interactive, software such as OmniSurf3D makes it possible for component designers, technicians, inspectors, the warranty dept, etc., to all interact with the same 3D data throughout a facility. Having a consistent, approachable and affordable software platform provides consistency and broadens the dissemination of process information to everyone involved with a product.

In many cases, the software provided with a measuring instrument is not ideal for such broad deployment across and organization. Instrument software typically contains hardware interfacing and countless tools that relate to acquiring the measured surface. Easy-to-use, highly visual software packages are preferred for broader deployment across an organization—especially in cases where not all users of the software are experts in metrology and surface analysis. Tools such as OmniSurf3D are visually-based can help non-experts to explore surfaces and better understand the implications of the analysis tools—and sources of variability—described in this article.

About the Authors

Dr. Mark Malburg is the president of Digital Metrology Solutions. With over 30 years in surface metrology, he is the chief architect of a range of standard and custom software for surface texture and shape analysis. Dr. Malburg has consulted in numerous industries from optics to automotive engines and aerospace. He is a frequent participant in standards committees and has helped shape many of the standards that govern surface specification and control.

Mike Zecchino has been creating technical content and resources related to optical metrology, and many other industries, for over 20 years. His articles have appeared in dozens of publications, and his training materials and videos support numerous measurement instruments and technologies.

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