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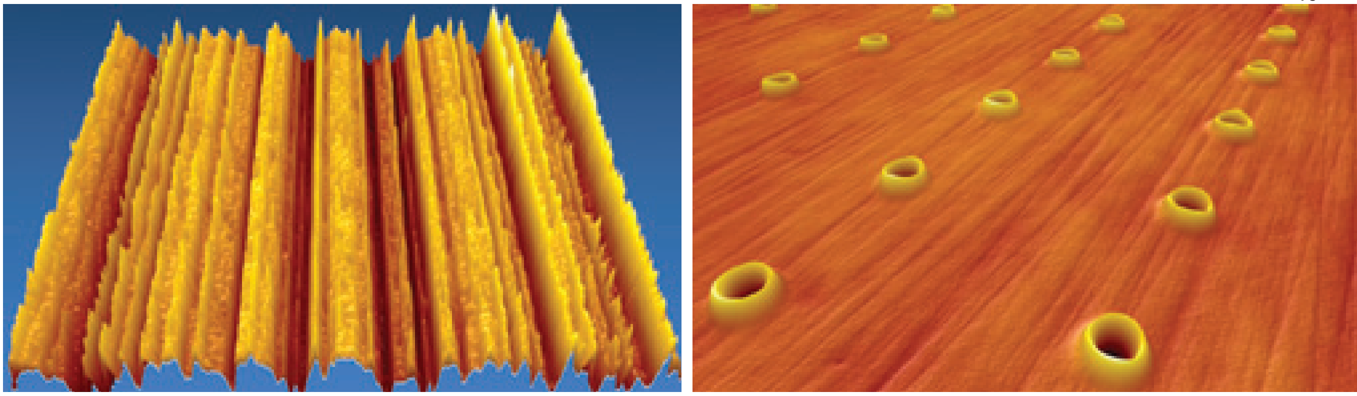

The Meaning and Measure of Lateral Resolution for

Surface Profiling Interferometers

Peter de Groot, Xavier Colonna de Lega, Daniel Sykora and Leslie Deck

Optical interferometers for surface characterization provide detailed information about surface topography, and they carry specifications related to the ultimate resolving power for 3-D imaging. It is worthwhile for engineers to understand the meaning of these specifications and the methods for validating them.

Lateral resolution quantifies our ability to separate individual features from each other in an image. Traditional specifications for resolving power employ either single numbers, such as Rayleigh or Sparrow criteria, or detailed response information as a function of spatial period or frequency, as in the modulation transfer function (MTF). For straightforward incoherent imaging of light and dark or contrasting colors, as in a camera or a telescope, these definitions are clear and have well-known procedures for specification confirmation.

However, it is less clear how to define resolving power for instruments that measure surface shape. Interferometry, for example, relies on the light wave phase as the fundamental metrology principle. The phase is tucked inside a sine or cosine function and must be extracted by a process that is more complex than simple intensity imaging—for example, by shifting the phase in a controlled way and recording what happens.

As a practical reality, metrology instruments report 3-D surface profiles that may differ from the feature's shape, depending on its heights and separations. Consequently, surface profilers do not have generally applicable lateral resolution specifications that are valid for all surface shapes. Although there are published drafts of international standards, there is not complete agreement among engineers on a definition for the resolving power for a real measurement of surface topography.

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In spite of this, users of 3-D optical profiling tools insist on lateral resolution specifications and manufacturers are compelled to generate them. The good news is that it is possible to develop meaningful specifications for comparison and evaluation, provided that we take special care to define applicable measurement conditions. Chief among these conditions is that the surface height deviations should be small with respect to the wavelength—less than 50 nm for visible light, especially if features are close to each other. If we respect this limitation, we can leverage traditional and familiar 2-D imaging definitions to describe the 3-D topographical measurement properties.

Specifying and verifying lateral resolution

The most common lateral resolution specification for interferometers is a single number, expressing the smallest separation between features that can be distinguished in an image. For generations this was the Rayleigh criterion, whereby two image points are considered resolved if the distance for the diffraction maximum of one point image coincides with the first minimum of the other. The more generous Sparrow criterion corresponds to the separation between points at which the instrument fails to separate the two images. For a high quality, diffraction-limited microscope with an incoherent light source, the Sparrow limit is: $D = \lambda/2NA$, where λ is the mean wavelength and NA is the numerical aperture of the microscope objective. In order for one to take advantage of this diffraction-limited resolution, the camera pixel size in object space must be much smaller than D; otherwise the resolution is said to be camera-limited.

To validate a single-number lateral resolution specification, one must identify an artifact with two topographical features, such as etched lines that are not too high (or deep) compared to the surrounding area, as required to stay within the linear regime of the measuring instrument. Suitable artifacts have a selection of line pairs to establish the distance at which the line images merge. Some line width artifacts can serve this purpose, although it is essential to confirm the actual pitch or spacing so as not to confuse the width of individual lines with feature separation. Optical resolution refers to the smallest center-to-center feature separation, not the smallest or thinnest object that we can see. From this perspective, it is often more reliable to measure gratings or arrays of multiple lines at a calibrated spatial period rather than to examine isolated line pairs.

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Instrument transfer function

Even though topography features may fully separate in a 3-D image, the reported heights are not necessarily correct. Closely spaced features will generally appear to have progressively smaller height differences as the spacing approaches the lateral resolution limit. We turn to the instrument transfer function (ITF) to characterize this phenomenon. ITF catalogs the response of an interferometric profiler as a function of the object's spatial frequency content. The modulus of the ITF for interferometers is the analog of the MTF in imaging instruments.

The ITF comes in two flavors. The incoherent ITF—typical of microscopes with LED illumination—has a gradual, monotonic decline in response from zero frequency to the Sparrow frequency, $1/D$. The coherent ITF—often associated with laser Fizeau interferometers for optical testing—has a more uniform response but falls off more quickly at an inferior resolution limit. Most instruments are to some extent partially coherent, resulting in measured or apparent ITF that is a balance somewhere between coherent and incoherent.

ITF validation requires measurement of the instrument response over a range of spatial frequencies. An intuitive way to do this is to use a specialized artifact with an assortment of sinusoidal grating patterns, fabricated by photolithography. Another approach is to measure the profile of a sharp step feature, in analogy with the traditional MTF

[An interferometer validates sufficient lateral resolution]

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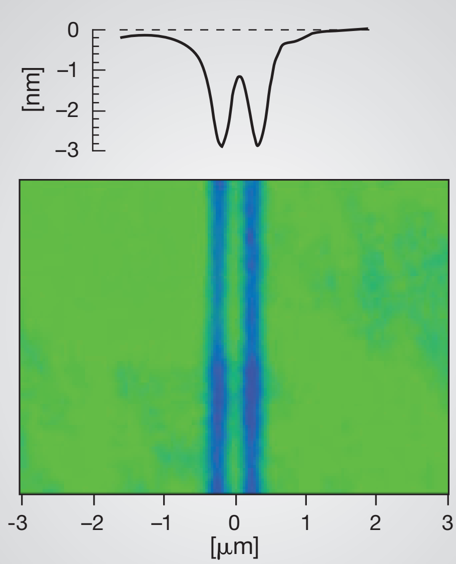

A ZYGO NewView white light interference microscope resolves parallel trenches on this 200-nm line width standard. The separation of the trenches is 480 nm. The Sparrow criterion lateral resolution is 320 nm at a numerical aperture of 0.85.

[Instrument transfer function validation]

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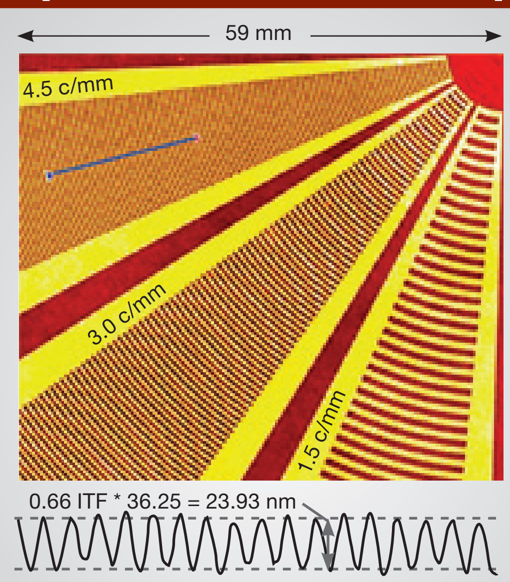
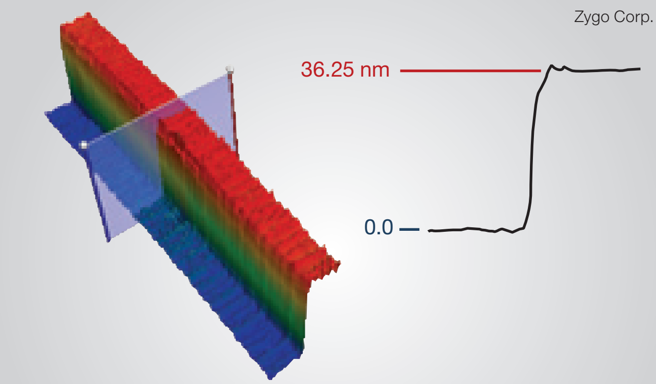


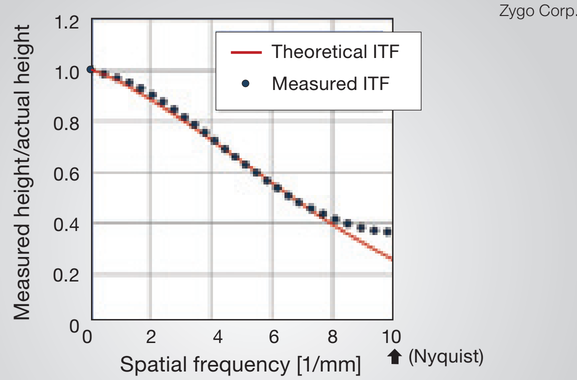
This image from a ZYGO DynaFiz instantaneous laser Fizeau interferometer illustrates an instrument transfer function response of 66 percent at a spatial frequency of 4.5 cycles/mm over a 59 mm field of view, using a specialized artifact fabricated at the National Institute of Standards and Technology, U.S.A.

[Complete instrument transfer function]



A comparison of the Fourier transform ratio of a step height measurement with the theoretical spatial frequency content of a sharp step provides a complete instrument transfer function. For small step heights, the results match those of the traditional knife-edge method for modulation transfer function.

[Instrument transfer function validation]



A 38-nm step height provides a detailed measured instrument transfer function for the ZYGO AccuFlat 100-mm aperture flatness interferometer. The 2000 × 2000 camera has a Nyquist sampling limit corresponding to a spatial period of 0.1 mm. The *NA* of this system is 0.005 and the incoherent LED illumination is at 455 nm.

measurement method using a knife-edge image. A step height generates a continuum of spatial frequencies for comparison with the known step profile using the Fourier transform ratio at each spatial frequency.

The most frequently specified ITF curve plots the modulus or absolute value of this calculation for each frequency. Averaging across multiple 2-D step height profiles in a 3-D image reduces noise. However, all resolution and ITF measurements are subject to misinterpretation. Noise, spatial sampling limitations, image distortions or image sharpening artifacts may be mistaken for high frequency resolution.

Factors that influence an optical system's effective resolving power include apertures, optical aberrations, camera pixel resolution and post-processing digital filters to reduce noise or to conform to standards. Measuring the ITF under conditions appropriate to a specific application enables methods for correcting the instrument response and improving quantitative metrology. This is most successful for derived parameters such as the measured power spectral density for a polished surface. ITF enhancement for images, like image sharpening in photography, can be effective for bringing out surface features, although the lateral resolution limitations of the instrument remain unchanged.

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Considerable research is under way to reach beyond the normally accepted limits of optical lateral resolution for 2-D imaging. Many of these techniques rely on stimulated optical fluorescence, often combined with data acquisition over time or over a range of focus positions. These explorations provide an exciting environment for pushing the boundaries of lateral resolution in all types of optical instruments, including those that measure surface shape.

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[References and Resources]

- >> R. Barakat. J. Opt. Soc. Am. **55**, 1217 (1965).
- >> P. Takacs et al. Proc. SPIE **1993**, 65 (1993).
- >> C.R. Wolfe et al. Proc. SPIE **2870**, 553 (1996).
- >> G.D. Boreman. SPIE press, Washington, U.S.A. (2001).
- >> L.L. Deck. SPIE Tech. Dig. **TD04**, paper TD040M-1 (2004).
- >> P. de Groot and X. Colonna de Lega. Proc. FRINGE 2005, W. Osten, Ed., Springer Verlag, Berlin Heidelberg (2006).
- >> D. Toomre and J. Bewersdorf. Annu. Rev. Cell Dev. Biol. **26**, 285 (2010).
- >> L.L. Deck and P. de Groot. Proc. SPIE Annual Meeting (2011).
- >> D. Sykora and P. de Groot. Proc. SPIE **8126**, 812610 (2011).
- >> Supracon AG nanoscale standard: www.supracon.com/en/nanoscale_calibration.html.