

Application Note #548

AcuityXR Technology Significantly Enhances Lateral Resolution of White-Light Optical Profilers

White light interferometry is firmly established as being among the fastest, most accurate, and most versatile surface measurement techniques available to researchers and manufacturers. Traditionally, interferometric technology does have a well-known limitation in lateral resolution compared to a couple of other techniques. This application note details Bruker's development of an interferometric measurement mode, AcuityXR™, that effectively overcomes this optical diffraction limit, resolving greater detail in many surfaces without compromising the many other benefits of white light interferometry.

Optical Interferometry and Lateral Resolution Limits

Interferometric methods provide among the fastest, most accurate, and most versatile surface measurements.^{1,2} The measurement principal is relatively simple: split a single beam of light into two parts; reflect one part off a high-quality reference surface and one part from the test surface; recombine the light and measure either the phase of the resulting signal or its contrast as the test object moves through focus. The result is a series of optical fringes that correspond to the topography of the sample surface, much like a topographic map for geographic areas. Using this

technique, vertical noise floors less than 0.01nm may be readily achieved using a standard commercial system, with measurement times on the order of a few seconds and virtually no setup time.

One drawback of interferometry in certain situations, however, is a more limited lateral resolution as compared to atomic force microscope (AFM) or scanning electron microscope (SEM) systems. There are two potential limits on the lateral resolution of an optical system. The first is pixel-limited resolution, where two adjacent features are imaged into a single camera pixel, and thus there is no way to distinguish between the features in the final digitized image (see figure 1). The black lines represent camera pixels and the red curves are the images of perfect lines as spread out by the optical system. Since both the red curves are imaged onto the same pixel, only one bright spot would be observed rather than one for each feature. In this case, resolution may be increased by increasing the number of pixels in the imaging camera, though this is not always practical. Pixel-limited resolution is typically encountered at low microscope magnifications, such as 2.5X, 5X, or 10X where the optical resolution often exceeds the pixel resolution of the system.

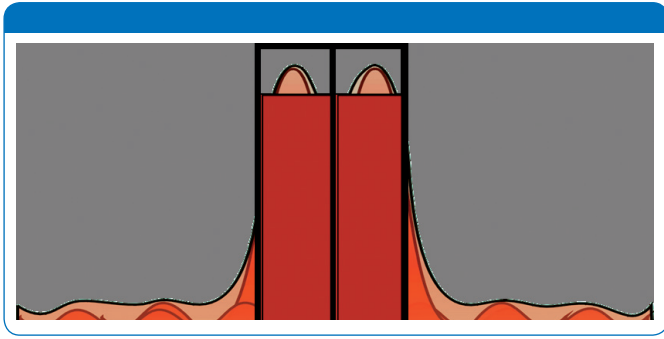


Figure 1: Illustration of pixel-limited resolution. The red bars represent the overall light collected in each pixel. The two adjacent features will not be distinguished because of inadequate camera pixel spacing.

Another possible limitation to lateral resolution is an optics-limited one, where there are at least two camera pixels for each feature but where multiple features are so blurred by the optics that they still cannot be readily distinguished from each other (see figure 2). This is known as diffraction limited resolution. The diffraction-limited resolution δ is typically defined using the Sparrow criterion formula $\delta = 0.47\lambda/NA$, where λ is the wavelength of light and NA is the numerical aperture of the optical system used to image the feature. For visible-light microscope systems, including white-light interferometers, this limit is usually about 350 to 400nm. High-magnification objectives, such as 20X, 50X, and 115X typically produce diffraction-limited images. Often resolution may be increased by moving from a smaller magnification to a larger magnification. However, high-magnification objectives are both expensive and limited in the size of objects that can be imaged in a single field of view, making them less than ideal for many applications.

Beating the Diffraction Limit

Overcoming this diffraction limit would provide great advantages to the user of such an optical system. For instance, smaller features could be distinguished for any given microscope magnification, so that the field of view could be larger and the need for stitching together multiple images to fully characterize a surface would be less. Also, for the highest magnifications, where simply moving to a larger NA objective is not possible, interferometric techniques could continue to be used without resorting to the more difficult and costly AFM or SEM methods. Some of the primary applications where such a technique would be useful include:

- Defect detection on glass, silicon, plastic, or other substrates
- Examination of micro-scratches from polishing processes, such as for orthopedics or other finely ground surfaces
- Linewidth measurements of very small features
- Nanoscale roughness determination of smooth surfaces

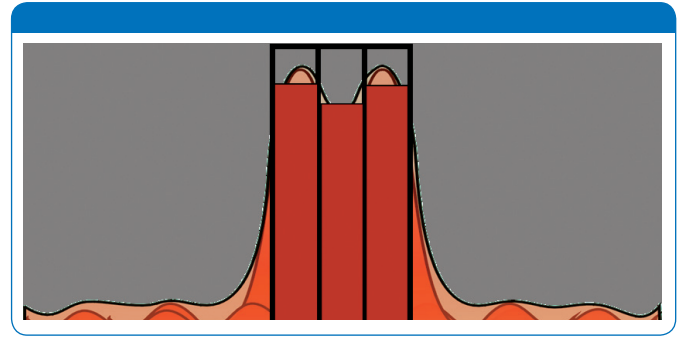


Figure 2: Illustration of diffraction-limited resolution. Features are wider than the camera pixel spacing but are blurred due to the optics of the system and in this case are barely separated.

- Distinguishing fine features and determining precise motions of MEMS devices
- Nanoscale quality control for medical implants, including optics, orthopedics, and monitoring devices
- Imaging of sub-cellular structures in biological applications

In theory, one can reconstruct the object that has been imaged by an optical system. However, this requires that the optical system be perfectly known and that either no noise is present or it is perfectly characterized. Such knowledge of the system is generally impossible to obtain. In addition, such a reconstruction works only on a single image, and does not readily translate to a surface map generated by many such images, such as is the case for surface measurements using white light interferometry.

Various methods have been proposed to overcome the limited lateral resolution of optical systems.^{3,4} However, such methods have only been commercially successful in improving resolution when it is camera-pixel limited, such as is generally the case for satellite imagery or for reconstruction of scenes taken with a video camera. For improving diffraction-limited resolution, only a few very specific, well-controlled cases have been described in the literature.^{5,6} To date, no commercially available system has solved this problem to provide real-time improvements in lateral resolution for a broad range of surfaces. A primary limitation of other proposed solutions has been the inability to enhance the signal from the small features without also enhancing noise in the system in such a way that it dominates the final results.

Through extensive research and a novel combination of hardware and software techniques, Bruker's Nano Surfaces Business has overcome these challenges and has implemented a revolutionary measurement mode, AcuityXR, that can significantly enhance the lateral resolution for a broad class of measurements. AcuityXR works on any smooth surface in which the phase of the light is examined and used to calculate the surface from the white-light-interferometric signal.

AcuityXR Enhanced-Resolution Microscopy Technology

Through advanced system modeling and the combination of multiple scans, AcuityXR produces a measurement with twice the number of pixels in the X and Y directions than is possible with a standard interferometric measurement. Greater detail is achieved for fine features in the measurement, such as more separated lines and sharper scratches or defects. There may be slight ringing near the edges of the field of view or near areas of missing surface data from the processing required to improve resolution, but this is a normal consequence of the mathematical algorithms used to enhance the resolution. The examples below detail several use cases where AcuityXR measurements provide significant benefits in detection capability or in quantification of key surface features.

Case 1: Improved Metrology of Narrow Linewidths

One obvious application of enhanced lateral resolution is to achieve superior measurement of narrow linewidth features. To test this, a sample with two 350nm lines, separated by 350nm were measured on a Bruker ContourGT X8 Optical Profiler System using standard Phase Shifting Interferometry (PSI) and AcuityXR PSI measurement

modes. Figure 3 shows one measurement from each technique. First, one can clearly see that using the AcuityXR measurement, enough resolution is gained to reveal the full separation between the lines, whereas for the PSI image they are blurred enough that the surface height between the lines is not the same as the rest of the substrate. Also, fine details of the linewidth variation along the line are visible in the AcuityXR result and not apparent in the standard PSI result. The average linewidth calculated using PSI was just 300nm. Using AcuityXR mode, the average linewidth was 320nm. Though the AcuityXR result is still slightly smaller than listed on the standard, it can be adjusted based on exactly where the width is taken vertically along the line.

In terms of numerical measurement performance, the standard deviation of linewidth for the PSI measurements was 35.1nm. For the AcuityXR PSI results, the standard deviation drops by nearly a factor of 7, to just 5.2nm. Similarly, when calculating the volume of the lines, the standard deviations for PSI and AcuityXR PSI measurements are $.005\mu\text{m}^3$ and $0.001\mu\text{m}^3$ respectively, which is a factor of 5 improvement. Thus, significant gains in metrology capability are possible through the enhanced lateral resolution offered by AcuityXR.

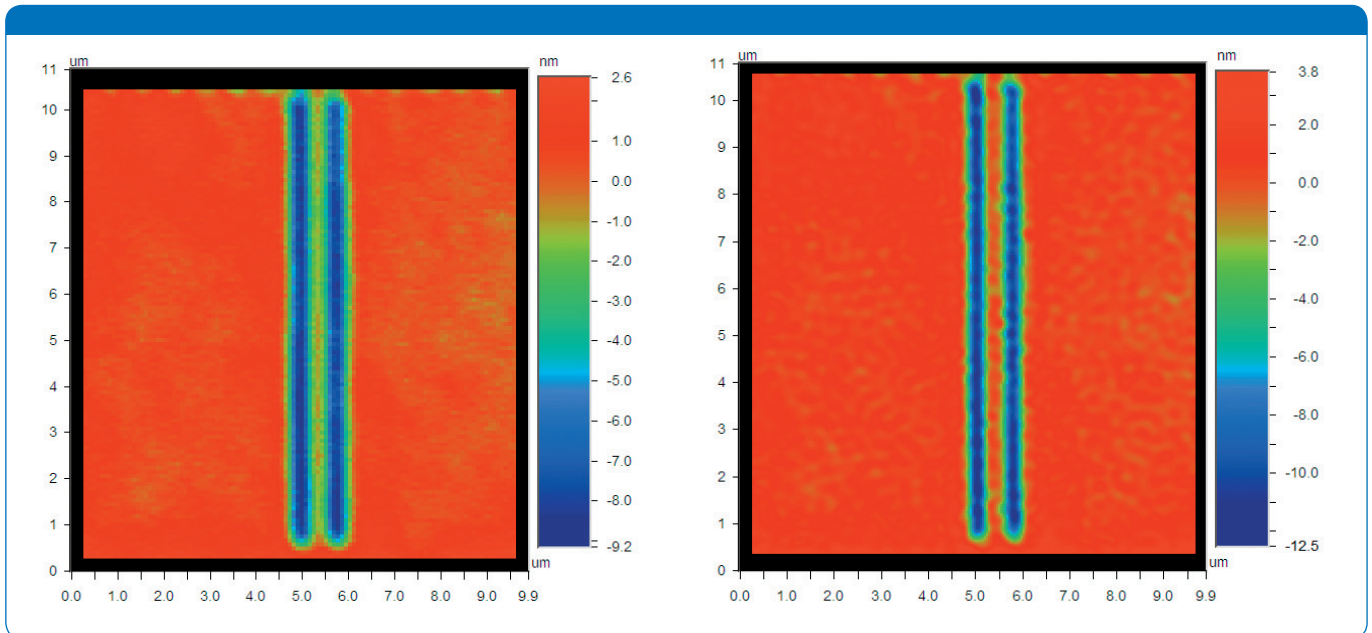


Figure 3: 350nm linewidth measurements taken with Standard PSI (left) with little feature separation and AcuityXR PSI (right), showing high levels of feature differentiation.

Case 2: Feature Separation Capability

To truly test the limits of AcuityXR and its ability to distinguish fine features, a linewidth standard of successively smaller lines, from 1 μ m to 100nm, was obtained. Bruker's exclusive 115X, 0.8NA microscope objective was used to provide maximum resolution on the linewidth standard. The lateral resolution of the optical system as determined by the Sparrow criterion is 314nm. Features down to 200nm can be easily distinguished both using PSI and AcuityXR PSI modes (see figure 4). However, greater detail and a better separation are clearly seen using the AcuityXR mode.

The 150nm lines that can barely be distinguished using normal measurements are quite clearly separated using AcuityXR. Ultimately, at 130nm there was no separation at all visible using normal PSI measurement, while AcuityXR mode was able to show two distinct features. This apparent limit of the lateral resolution capability of AcuityXR enhanced measurements is approximately 2.5 times smaller than the lateral resolution expected from the Sparrow calculation.

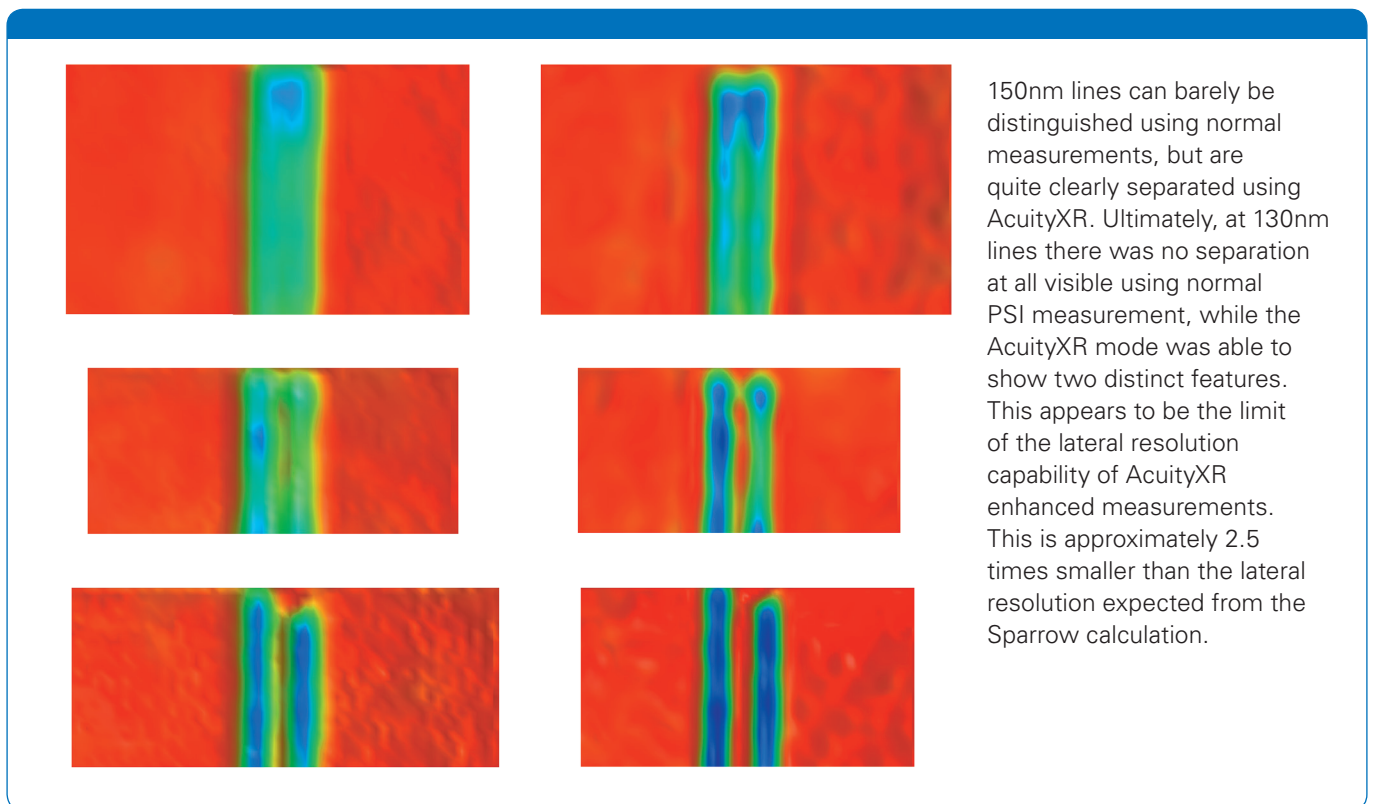


Figure 4: All the images have the same vertical scale of 2nm (red) to -8nm (blue). Standard PSI Measurements (left) and AcuityXR PSI Measurements (right) of 200, 150, and 130nm linewidth features. The two 130nm lines are indistinguishable in standard PSI measurements, but AcuityXR PSI is able to separate the two features.

Case 3: General Feature Clarity

Often when examining surfaces, one wishes to identify scratches, defects, or other fine features without necessarily needing to perform gage studies or otherwise quantify each individual feature. For instance, this would be a nonsensical laboratory requirement when examining surface finish in orthopedics, medical implants, plastic substrates, or optics. We measured a variety of surfaces

quickly using PSI measurement mode and AcuityXR PSI mode (see figure 5). In each case, the AcuityXR measurement demonstrates sharper features on the gratings and other small defects present in the images. This allows not just superior visual identification, but also a better capability for automatically locating, counting, and quantifying features based on width or height with Bruker's Vision® software.

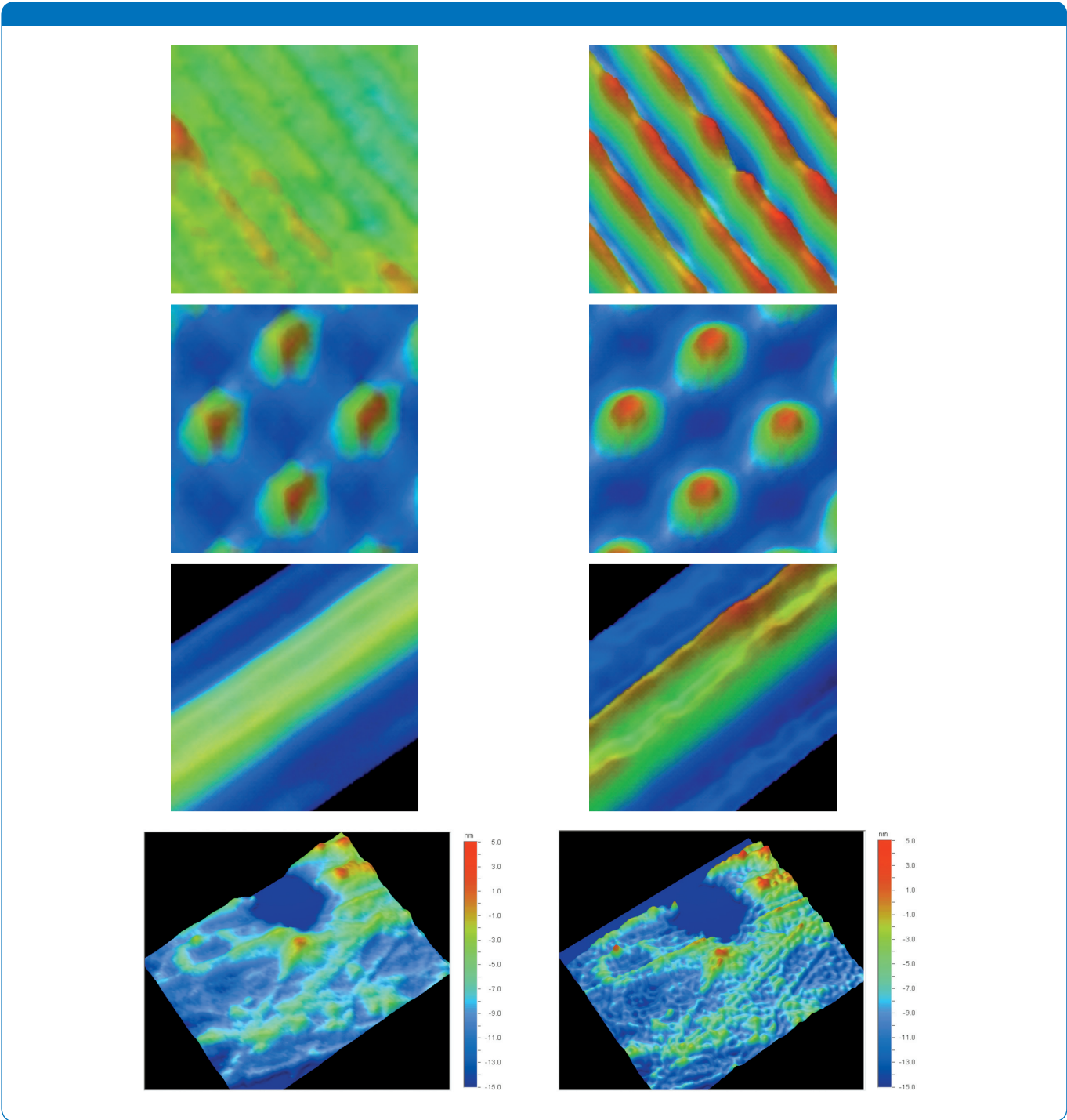


Figure 5: Images taken with Standard PSI (left) and AcuityXR PSI (right) shows vast improvement in AcuityXR PSI in the ability to make images less pixelated while showing the proper structure on the sample.

Limitations of AcuityXR Mode

While AcuityXR can measure many surfaces, it is limited to surfaces with local roughness less than approximately 20nm, where PSI or HDVSI measurement modes can measure the surface without problems. Rough surfaces, such as paper, roughly machined metal, or foams are not appropriate for AcuityXR. The additional noise caused by the rougher surfaces overwhelms the ability to accurately model the optical system's behavior. Also, surfaces with large amounts of missing data may suffer some ringing near the edges of the valid data when using AcuityXR, since the mathematics involved require contiguous surfaces for proper calculation. In general though, if PSI or HDVSI may be used to measure the surface, AcuityXR should show significant enhancement of fine features on the surface.

Conclusions

AcuityXR is a breakthrough technology available for most models of Bruker's optical profilers. It employs system modeling, low-noise measurements, and the combination of multiple surface scans. With this combination, the blur caused by the optical elements can be reduced and lateral resolution significantly enhanced. Greater detail can be seen in many surfaces. For narrow features, AcuityXR also offers significantly enhanced quantification of variations, making process control possible even on small structures. While AcuityXR is not suitable for all surfaces, for smooth, fine features it greatly enhances the measurement capability of the optical profiler.

References

1. P. Caber, "Interferometric Profiler for Rough Surfaces," *Appl. Opt.* 32: 3438–41 (1993).
2. J. Schmit and A. Olszak, "High-Precision Shape Measurement by White-Light Interferometry with Real-Time Scanner Error Correction," *Appl. Opt.* 41: 5943–50 (2002).
3. S. Park, M. Park, and M. Kang, "Super-Resolution Image Reconstruction: A Technical Overview," *IEEE Signal Processing Magazine*, May: 21–36 (2003).
4. Y. Eldar and T. Michaeli, "Beyond Bandlimited Sampling," *IEEE Signal Processing Magazine* 48: 48–68 (2009).
5. G. van Kempen et al, "Comparing Maximum Likelihood Estimation and Constrained Tikhonov-Miller Restoration as Applied to Confocal Microscopy," *IEEE Engineering in Medicine and Biology* Jan/Feb: 76–83 (1996).
6. Z. Zalevsky, "Spatial Information Transmission Using Orthogonal Mutual Coherence Coding," *Optics Letters* Vol. 30, No. 21: 2837–39 (2005).

Authors

Erik Novak, Bruker Nano Surfaces Business, Stylus and Optical Metrology (erik.novak@bruker-nano.com)

Florin Munteanu, Bruker Nano Surfaces Business, Stylus and Optical Metrology (florin.munteanu@bruker-nano.com)

● Bruker Nano Surfaces Business

Tucson, AZ · USA
+1.520.741.1044 ext. 3/800.366.9956 ext. 3
productinfo@bruker-nano.com
www.bruker-axs.com