How to Recognize and Avoid AFM Image Artifacts

Paul West and Natalia Starostina
Pacific Nanotechnology, Inc.
pwest@pacificnanotech.com

Images produced by an atomic forces microscope (AFM) often contain spurious features and image distortion that can render accurate imaging and metrology suspect. These "artifacts" are caused by the manner in which the image is produced. Artifacts can originate from the probe tip geometry, scanner non-linearity, image processing software, vibration, sample contamination, electronic noise, and poor sample stability. This article describes and illustrates common AFM image artifacts and suggests means to eliminate or minimize them.

Artifacts Caused by the Probe Tip

Images produced by an AFM are always a convolution of the probe tip shape and the shape of the feature being imaged (Figure 1). This can result in the feature images appearing too large, too small, or even strangely shaped. These types of artifacts can be avoided by matching the probe size and shape to the sample geometry. The probe tip should be narrow enough and long enough to be able to accurately trace the image shape. A pyramidal probe tip scanning across a spherical feature of similar size will produce a broadening of the surface feature (Figure 1a). In Figure 1b, the probe tip is wider than the surface depression and cannot reach the bottom. In this case, the line profile is that of the probe tip itself and the measured depth will not be accurate. However, measurements of the width of a hole or depression or the pitch of a repeating pattern will be accurate.

Often the size of an extremely small sample such as a nanotube or nanosphere will look larger than expected. However, the height of the feature as measured by a line profile will be correct. This is illustrated in Figure 2, where the image of an 8-nm-diameter sphere is broadened to 92 nm, while the height is accurately represented. If depth is to be measured accurately, the probe tip must be able to touch the lowest point of the feature. Figure 3 is an example of this problem.

Even if the features being imaged are smaller than the probe diameter, if the probe tip is not perpendicular to the feature, the leading edge profile can be distorted and a raised feature widened (Figure 4). Some AFMs have the probe-to-sample angle fixed at 12 degrees and some AFMs do not have an adjustment to set the probe angle.

A damaged probe can also cause image distortion and produce strangely shaped objects that mimic the effect of a tilted probe. Figure 1c illustrates the effect of a damaged or asymmetric probe tip that is too large relative to the feature topography. The image will be significantly distorted. This is illustrated in the image and line profile of Figure 5. Although, this artifact could be caused by a large angle between the probe and the sample surface, the angle as indicated by the line profile is too large (height = 0.16 µm; width =10 µm). In this case a damaged tip caused the distortion.

If the features on a surface are much smaller than the probe tip, it is possible to see large numbers of repeating patterns in the image. These patterns may reflect the shape of the tip rather than the geometry of the sample. For example, if a pyramidal silicon probe tip is used, the spurious image patterns often appear as triangles. Figure 6 shows how a damaged tip distorts the images of perfect nanospheres.

Artifacts Caused by the Scanner

In an AFM the probe is positioned and scanned in three dimensions (x, y and z) by a ceramic piezoelectric element or "piezo." Piezo elements are electromechanical transducers that can move a probe very small distances but the relation between the voltage signal applied to the piezo and the amount of movement is generally non-linear. In addition, self-heating of the piezo causes hysteresis in the scanner

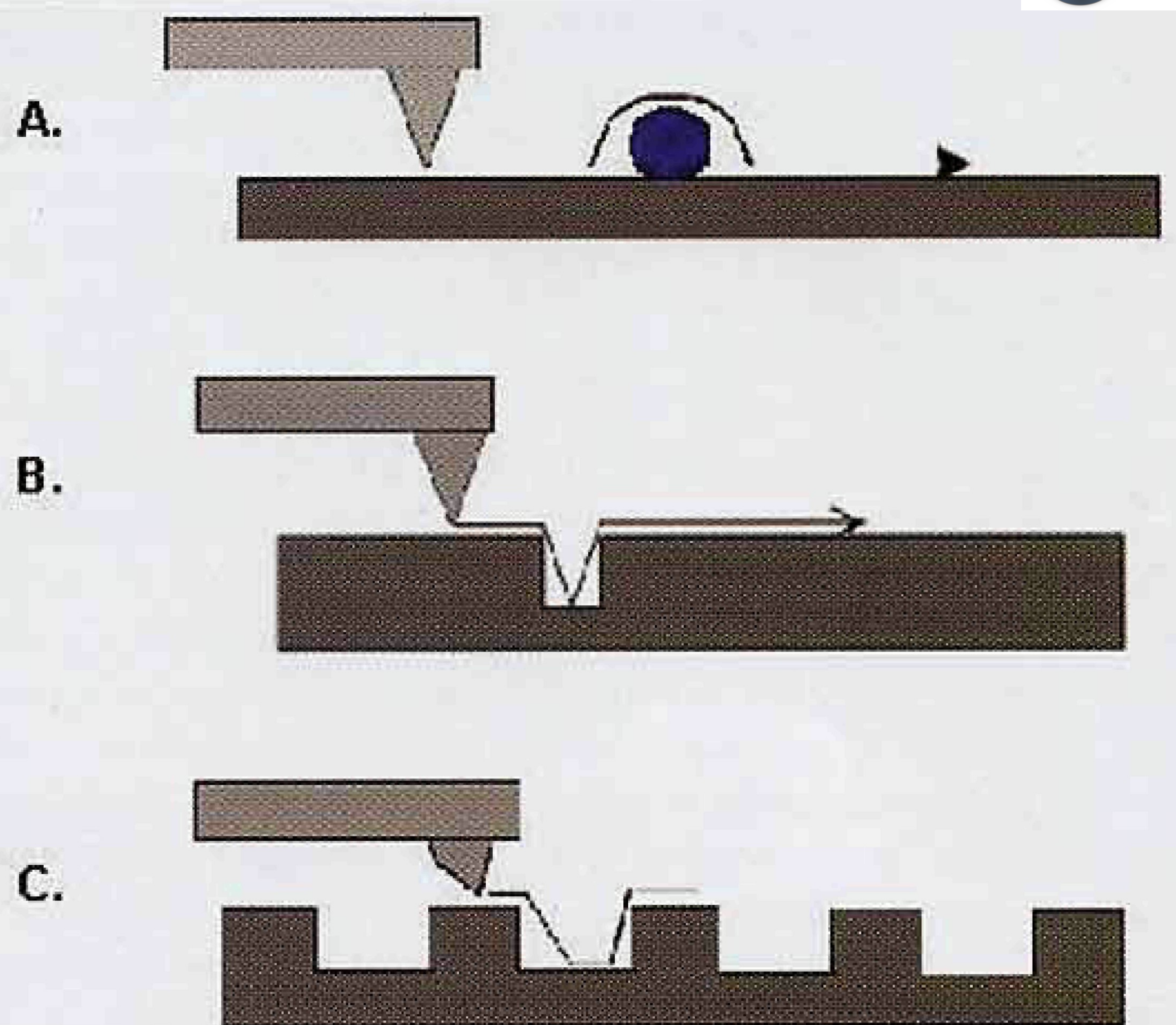

Figure 1. A. The trace of a pyramidal-shaped probe tip scanning over a spherical surface feature. The image will be broader than the feature. B. The trace of a probe tip scanning over a surface feature narrower than the probe width. The image will be smaller than the feature. C. The motion of a chipped or damaged probe tip over a surface can create an image artifact.

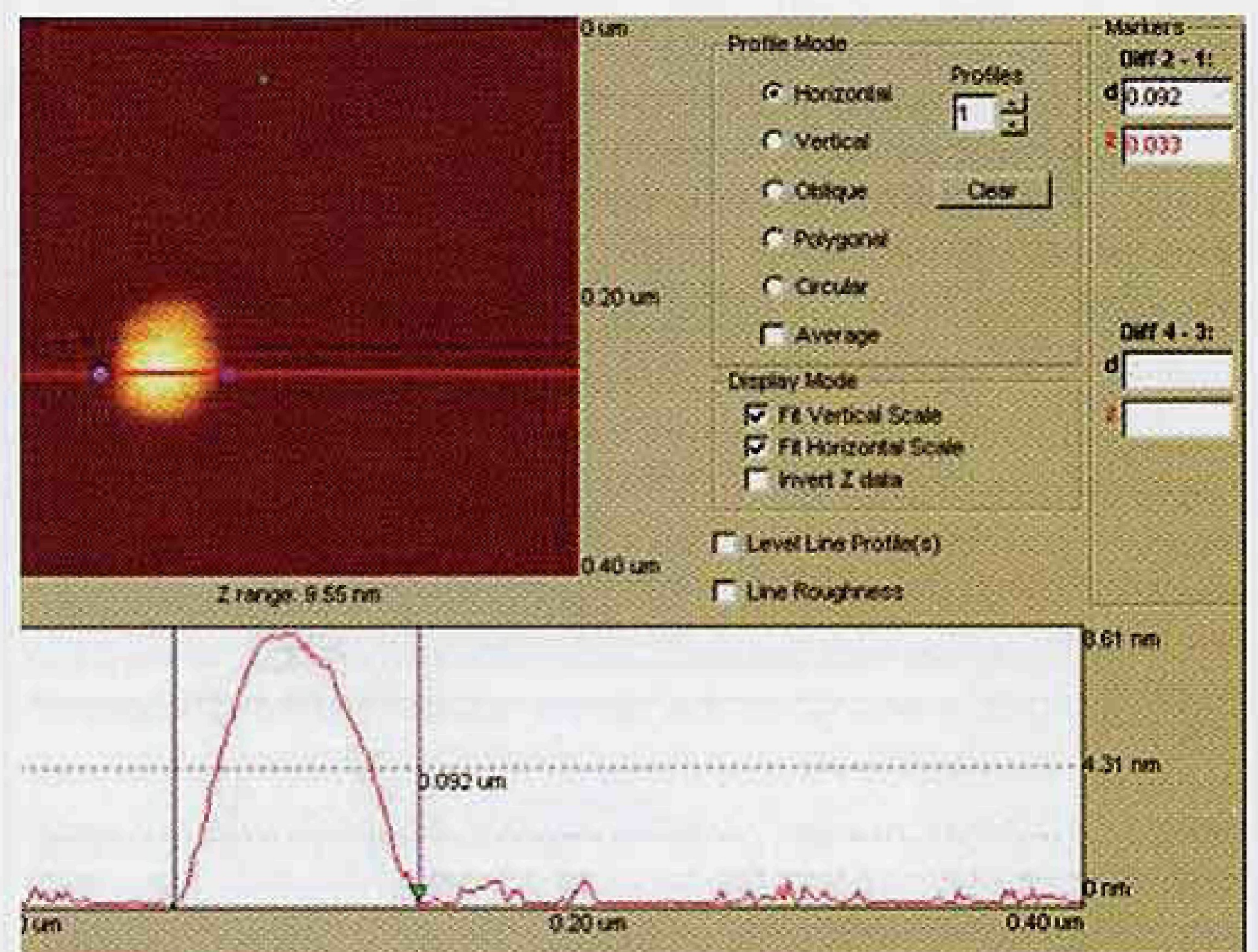

Figure 2. The image (top) of an 8-nm-diameter sphere (field: 400×400 nm) and the resultant line profile (bottom). This probe tip was larger than the feature (Figure 1a) the image shows an incorrect diameter of 92 nm and a height of 8 nm.

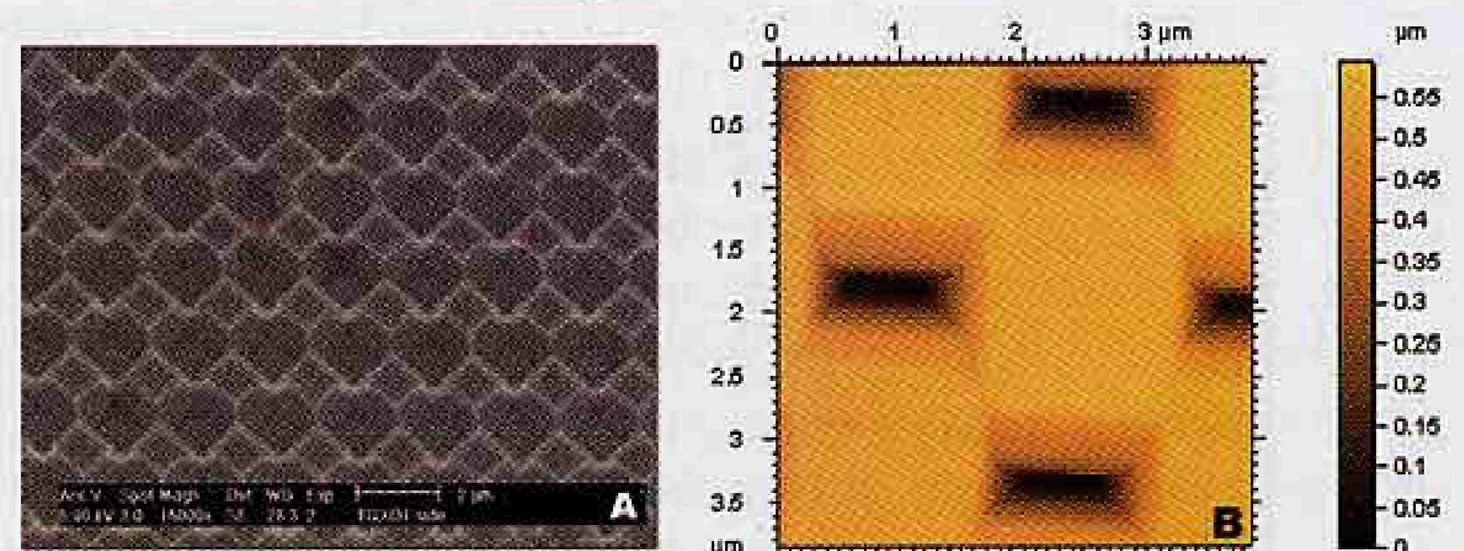

Figure 3. A. Scanning electron microscope (SEM) image of a chess-board array of square pillars with sharp edges; pitch = 3.0 µm (MikroMasch TX01 silicon grating). B. AFM image of the same test pattern. Because the probe diameter is too wide (Figure 1B), the spacing between the pillars appear narrower than it should and the pillars are rectangles rather than squares.

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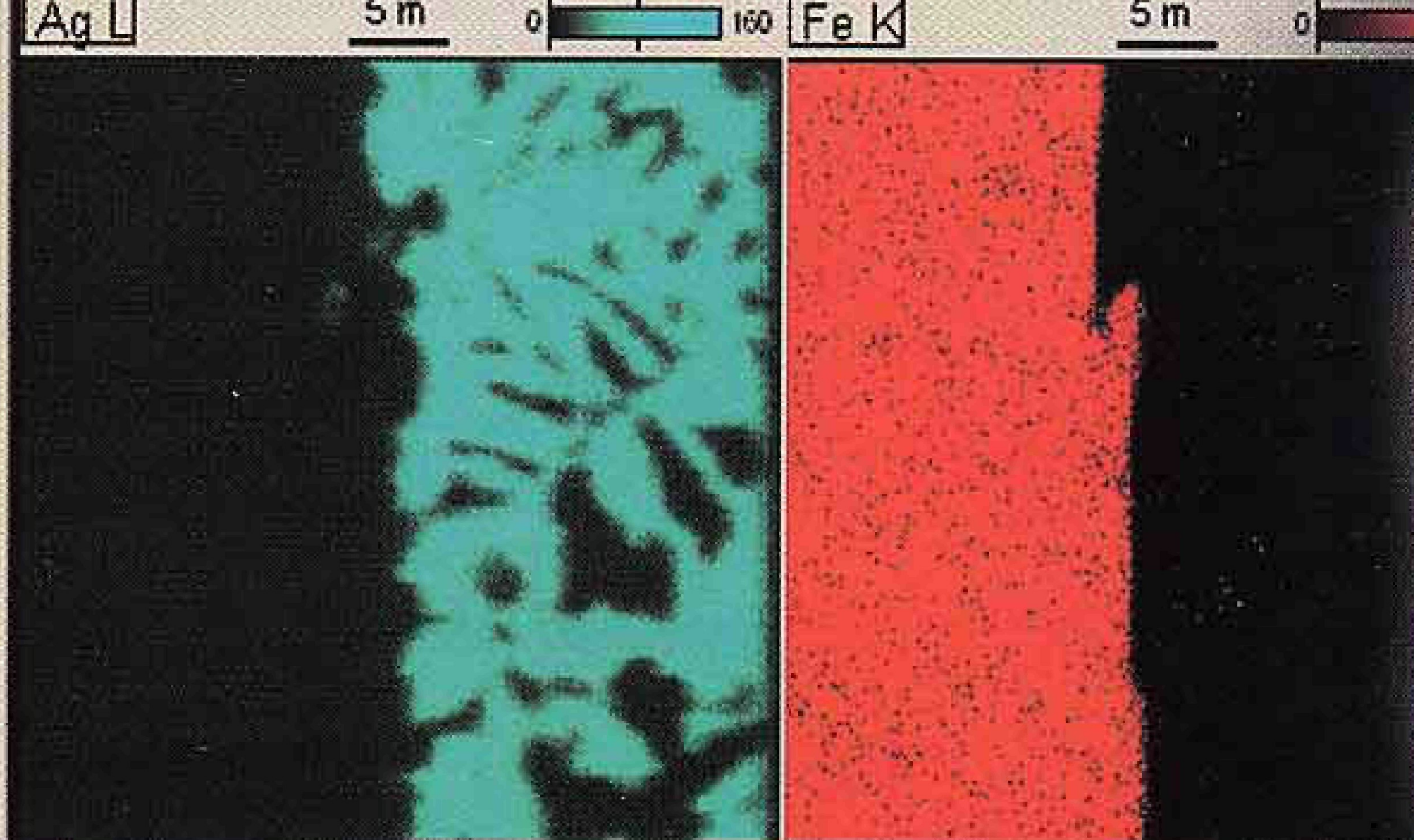

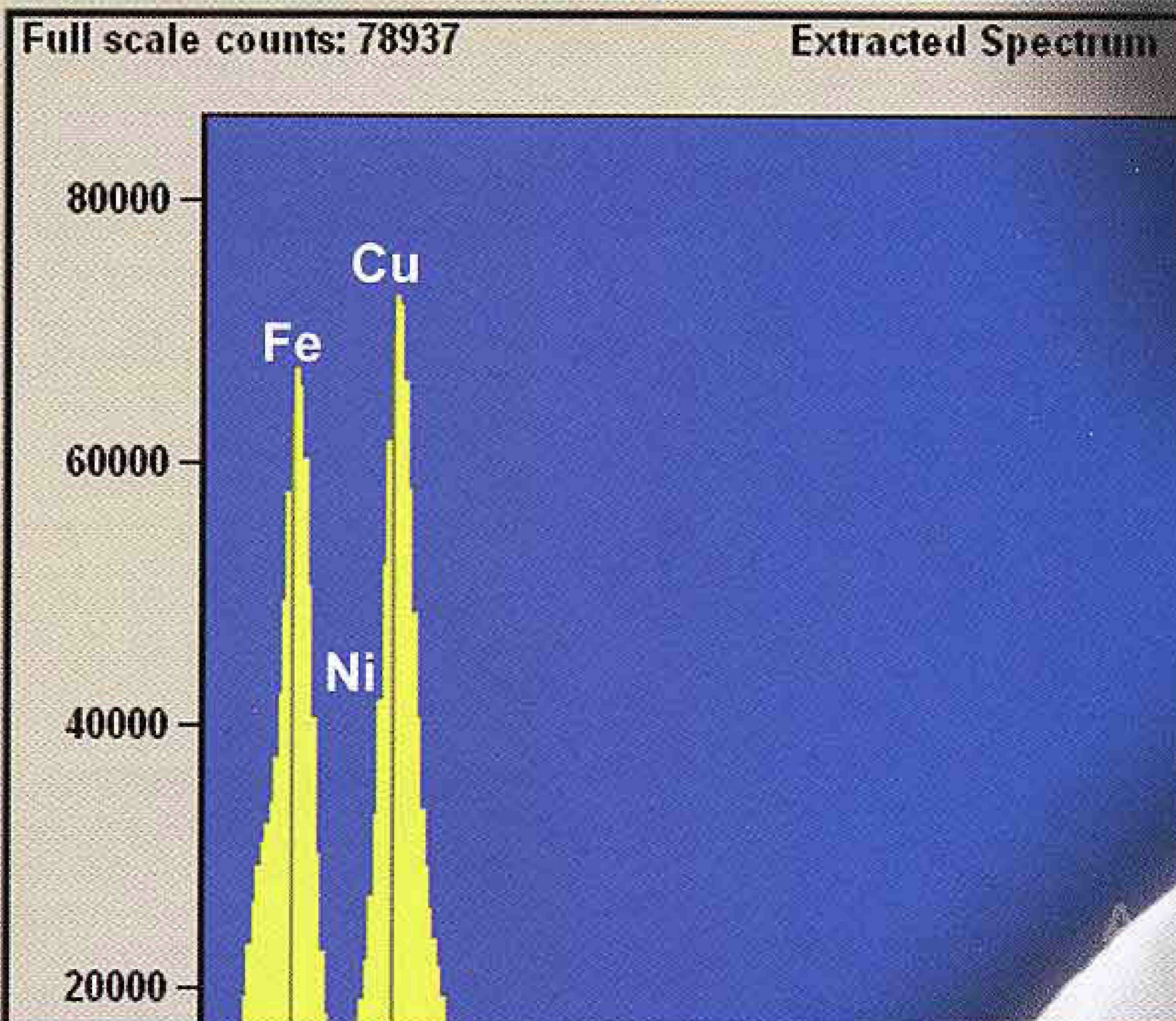

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motion. Non-linearity and hysteresis introduce error in both positioning and scanning that are exhibited as distortions of the AFM image.

To compensate for x-y non-linearity in the plane of the scan AFMs must be calibrated. Figure 7 illustrates the difference between a square array test pattern and the image generated by an un-calibrated AFM due to non-linearity. With no correction the features on one side of an image will appear smaller than on the opposite side. Correction for non-linearity (linearization) is typically done by software. For accurate metrology the AFM must also be calibrated using a standard test structure [1] or standard 3D objects such as nanospheres of known diameter. Accurate height measurements also require that the AFM be linearized and calibrated in the z-axis. Non-linearity and calibration can also be accomplished in AFMs that have calibrated position sensors that correct the AFM output in real time.

The scanner motion can introduce two types of background artifacts: bow and tilt. A bow in the AFM image is the appearance of a convex background across the scanned field. Figure 8 illustrates the origin of bow and Figure 9 shows an AFM image and line scan showing the effect. Although some bow is expected in AFM images the extreme bow shown in Figure 9 indicates that the scanner is damaged.

An apparent tilt in the image background occurs when the probe tip is not perpendicular to the sample surface. In many cases, background bow and tilt can be subtracted from the image by using the "flattening" or "leveling" feature of image processing software.

Hysteresis in the piezo element that controls the z-motion of the probe can cause overshoot at the edges of a structure (Figure 10). This is often observed when imaging steps in fabricated microstructures such as patterned silicon wafers or compact disks. The effect is misleading because it can make the image look sharper with no noticeable artifacts. However, the line profile shows the errors as a bump in the leading edge and a dip after the trailing edge of the scan.

Distortion of AFM images can occur because of thermal drift of the piezo element and because the AFM instrument is susceptible to external temperature changes. The most common type of drift occurs at the start of a scan of a zoomed-in region of an image. Drift in the piezo element can cause image distortion, e.g. curvature of a straight test pattern, at the beginning of the scan (Figure 11, *page 24*). Rescanning without changing the magnification will usually remove drift distortion.

Another type of image distortion is introduced when the motions generated by the x-y scanner are not orthogonal. This can be due to cross-talk between the x- and y- motion signals. In such a case there will be errors in the horizontal measurements of the image. This error can best be detected by imaging a square array standard test pattern. The horizontal and vertical rows of the image should be exactly perpendicular.

The images of sidewalls of surface structures can be distorted and show incorrect sidewall angles due to mechanical cross-talk between the z- piezo element and the x-y piezo elements. This type of error can be detected by scanning a test sample with repeating triangular surface structure. The line profile should show equal sidewall angles (Figure 12). This may indicate a damaged or improperly designed scanner system.

Image Processing Artifacts

Image-processing software converts raw line scan data into 3D images that can be printed or viewed on a monitor screen. Most AFMs are supplied with versatile image analysis and display software. For example, depth information can be displayed as gradations in color (the images in this article indicate low-to-high regions on the sample by dark to light gradation). Any portion of the image can be selected and a line-scan profile displayed. Properly used, image-processing software will not introduce artifacts or distortions. Improper use can cause strange effects and even make the image look too good. Imaging processing procedures include leveling, flattening, high-pass filtering, matrix filtering, and Fourier filtering.

As previously mentioned, most images have some tilt and bow introduced by the scanner or stage. Image processing software offers several possible background subtraction options for line-by-line leveling and plane leveling. Figure 13 illustrates the use of image leveling.

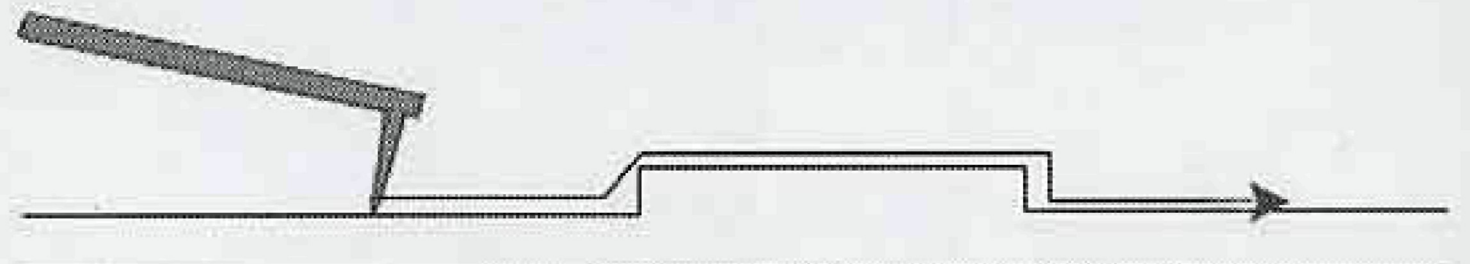

Figure 4. Although a probe tip is sharper than the feature, a tilted probe can introduce image distortion such as a shallower leading edge slope and a widening of the feature.

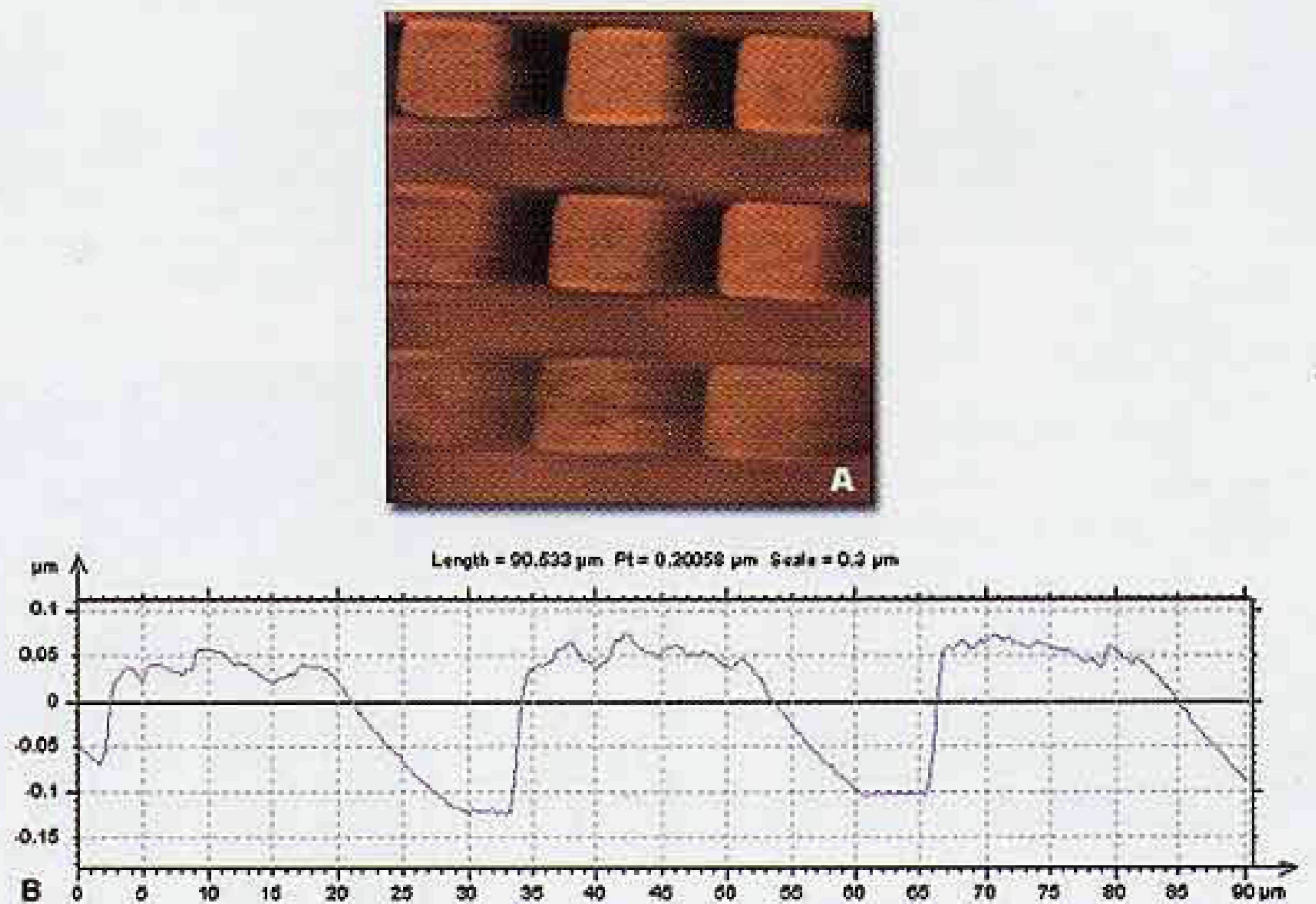

Figure 5. Image distortion caused by a damaged probe tip. A. The image of the functional surface has dark right edges indicating a slope (field: 91×91 µm). B. The line profile shows the degree of the slope to be too great to be due to a tilted probe.

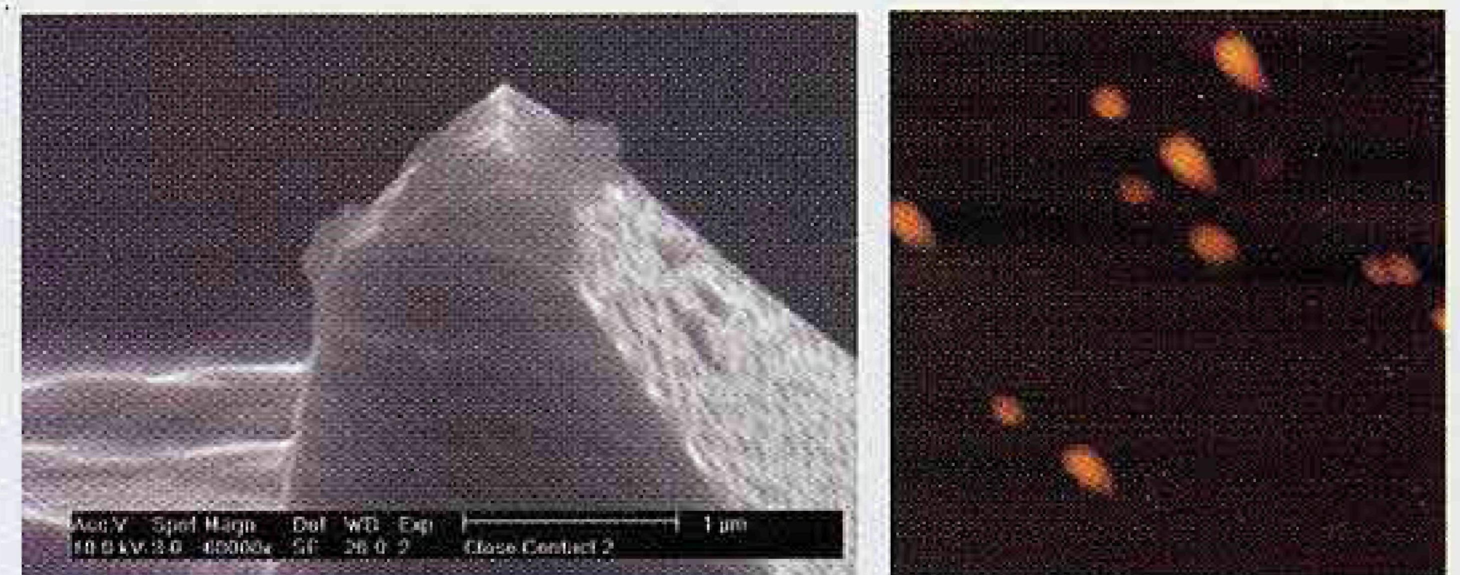

Figure 6. A damaged tip (Figure 1C) can cause image distortion. SEM image of a chipped tip (left) used to produce the AFM image (right) of 28-nm-diameter colloidal gold spheres (TedPella). The AFM image reflects the tip geometry.

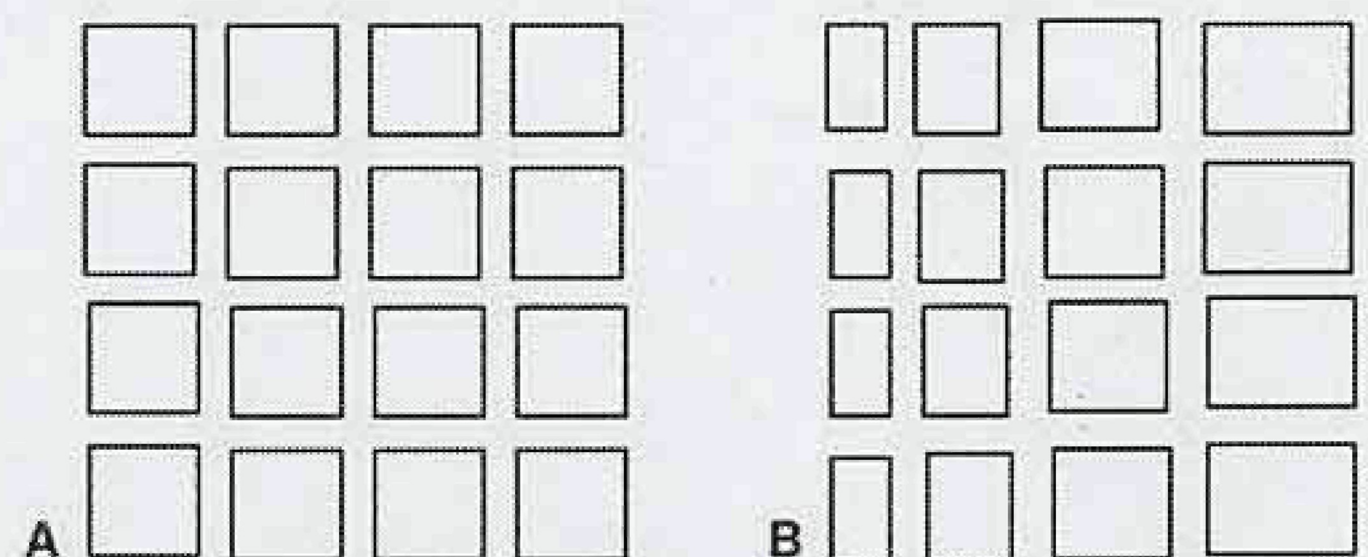

Figure 7. Linearity and x-y calibration. A. Test pattern. B. Image with distortion caused by non-linearity in an uncalibrated AFM.

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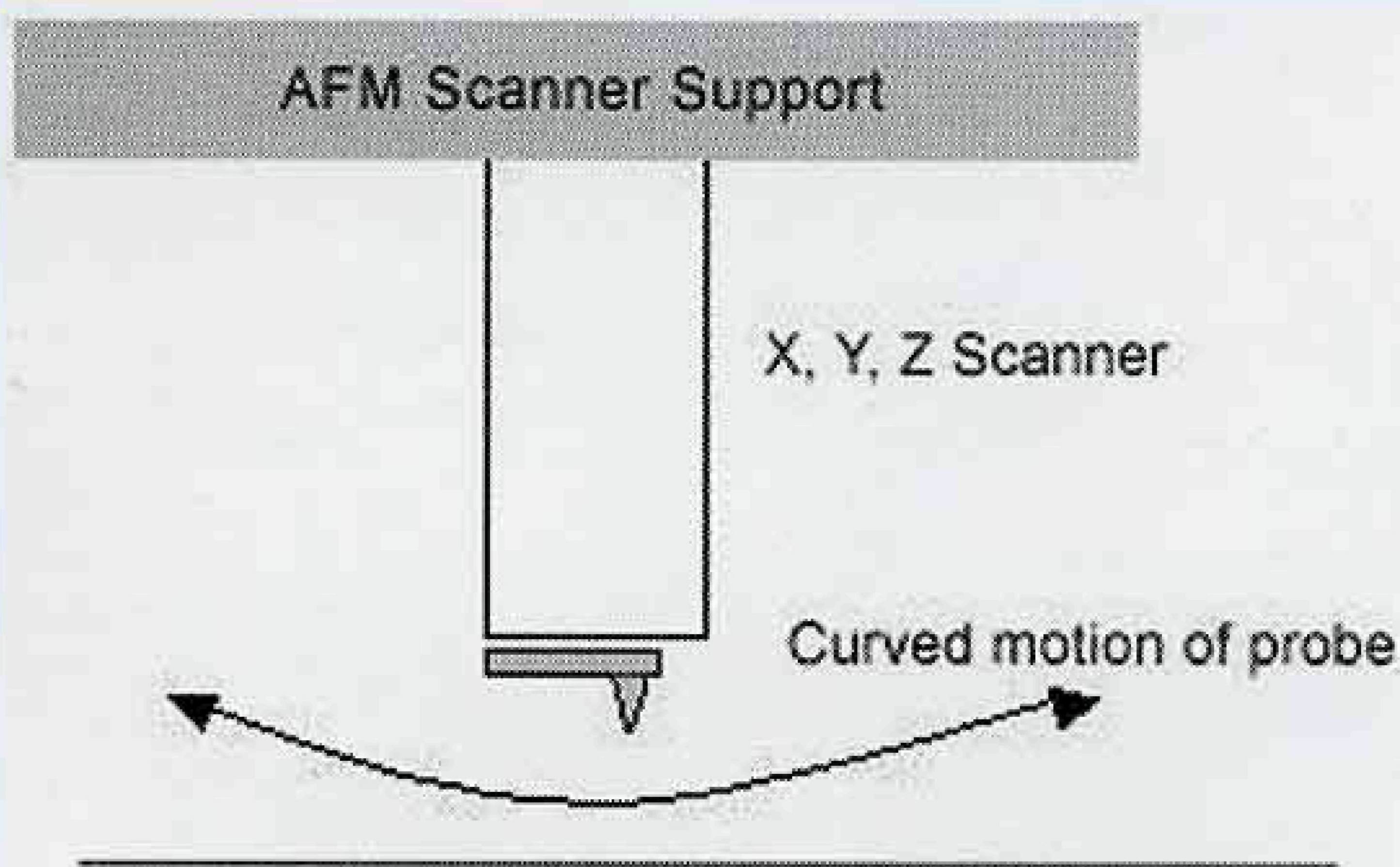

Figure 8. A mechanical assembly often supports the AFM piezo and the motion of the probe tip describes an arc as it scans the surface. The motion can be spherical or parabolic depending of the type of piezo.

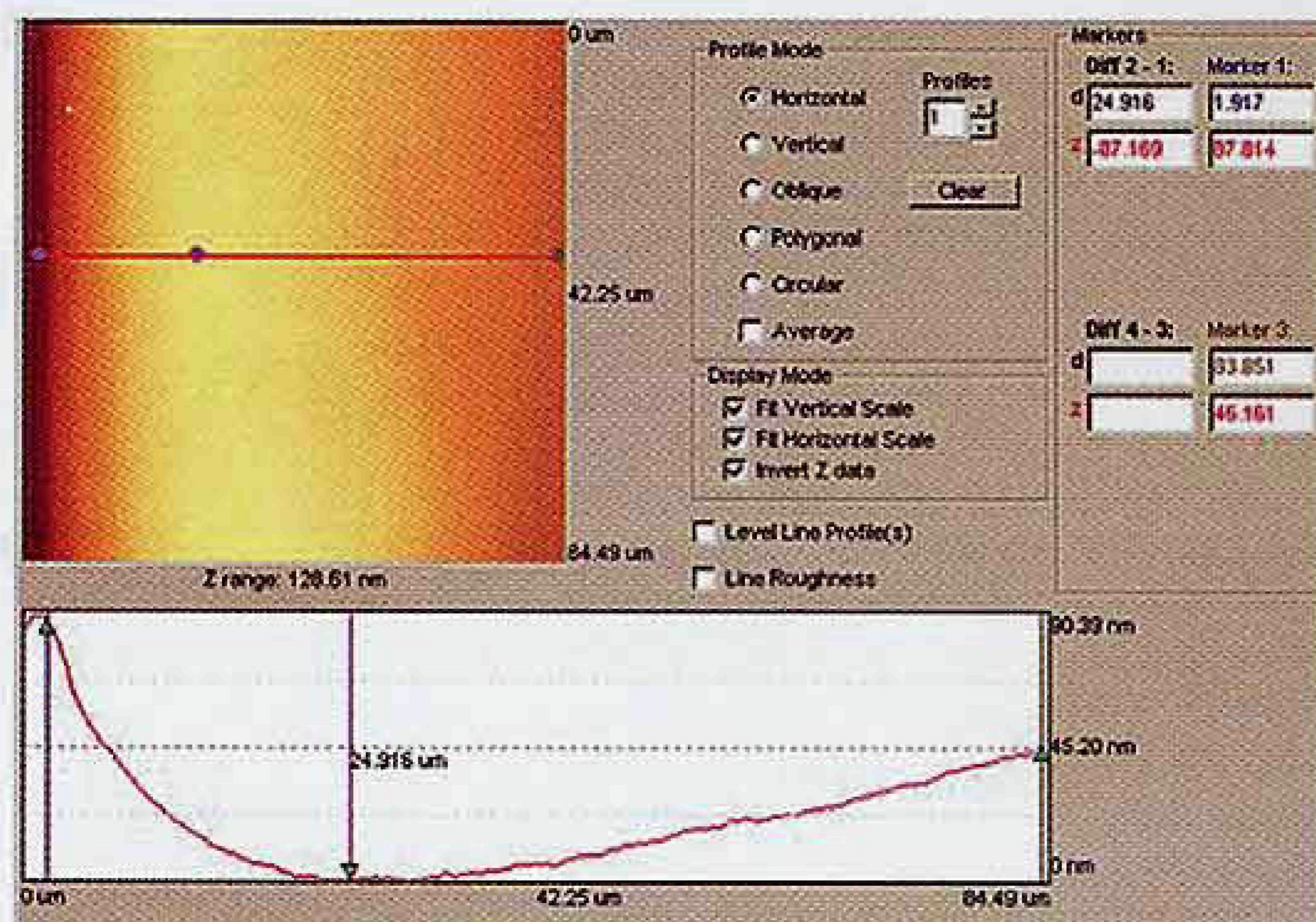

Figure 9. AFM image (field: 85×85 μm) and line scan of a flat silicon surface. Bow is evident at the edges of the image. A line profile shows the magnitude of the bow. This large amount of bow indicates a damaged scanner.

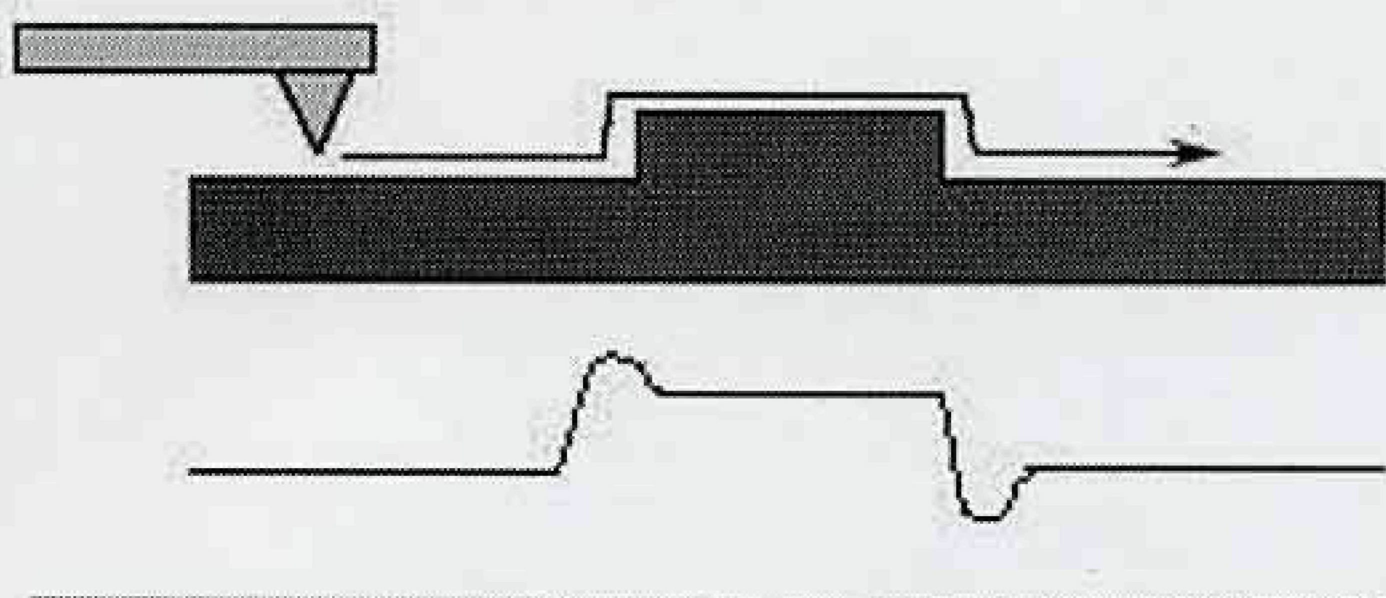

Figure 10. Z-axis hysteresis. Top: As the probe scans from left to right over a step, overshoot occurs in the line profile and the leading and trailing edges. Although the SPM image of the test pattern (A) appears to have no artifacts, the line profile (B) shows overshoot at the top of each line.

The degree of leveling can be from zero order to fourth order. Selected areas can be excluded from leveling and not used to calculate the image background (Figure 13c).

A high-pass filter sharpens data prior to display but can distort the images of features such as steps. Figure 14 illustrates this effect. The leading edge of a step is sharpened and the trailing edge is rendered as slope. The amount of distortion depends on the degree of filtering applied. Images that have significant high-pass filtering will have distorted dimensions and a false increase in sharpness at the edge of steps.

Matrix filtering is very effective at "smoothing" images and removing noise. However, this filtering process reduces image resolution. As a rule, if the image has no noise in it, then the data has probably been compromised.

Fourier filtering is another filtering algorithm technique that should be used with caution. Phantom periodic structures can easily be introduced with this technique. For example, images containing only white noise can be filtered to produce an image that looks like surface atomic structure.

Filtering can produce an image that looks too good. As all AFM images are electronic and have inherent noise it is possible to use image enhancement to alter it to create a beautiful, but inaccurate, picture. For example, Figure 15 is a processed image of a carbon nanotube. The fine nodular structure on the nanotube was added by the filtering process and does not actually exist. Recognizing this type of artifacts requires experience and knowledge of what the sample should "really" look like.

Effect of Vibration

Vibrations in the room where the AFM is located can cause the probe to vibrate and produce image artifacts that appear as oscillations in the image. The source of the vibrations can be mechanical or acoustic. The building floor itself can vibrate up and down several micrometers at frequencies below 5 Hz. Floor vibrations can cause spurious periodic structures in an image, especially when very flat samples are imaged. Floor vibrations can be caused by an event such as an elevator, a train going by, or even people passing by in a hallway outside the room.

Even acoustic vibrations such as an airplane passing overhead or loud talking can cause artifacts in AFM images. Figure 16 shows the effect of a person talking while the AFM image was being acquired. A quiet vibration-free environment will ensure a clean, noise-free image.

Electronic Noise

Faulty electronics can introduce electrical noise into an AFM image that most often appears as periodic oscillations or repeating patterns. Ground loop currents due to improper electrical grounding of the stage or defective electronic components are the usually sources of electronic noise. Figure 17 illustrates noise introduced by a faulty ground connection to the sample stage. Check that all ground connections are tight and free of corrosion or insulating films.

Contamination

Obviously any contamination on the sample surface will introduce image artifacts. Fingerprints or environmental contamination such as an oil film can cause streaks in the image especially at sharp features and steps edges on the sample surface. The remedy is to clean the sample with an appropriate high-purity solvent.

Vacuum Chuck

Many AFMs that are used to examine semiconductor wafers or recording media disks often have a vacuum chuck that holds the sample while scanning. A leak in the vacuum seal caused by debris between the sample holder and the sample can result in sample instability produce loss of resolution in the image. Cleaning the vacuum chuck surface and the back of the sample often can eliminate the problem.

Summary

The following table *(page 26)* summarizes common image artifacts and their possible causes. By learning to recognize these artifacts, microscopists can take preventative action to avoid them. ■

Reference

1. Absolute calibration requires a standard AFM Calibration Standard such as those available at www.probestore.com. Less expensive AFM Reference Samples can be used to verify the performance of AFM scanners and assure the repeatability of an AFM.

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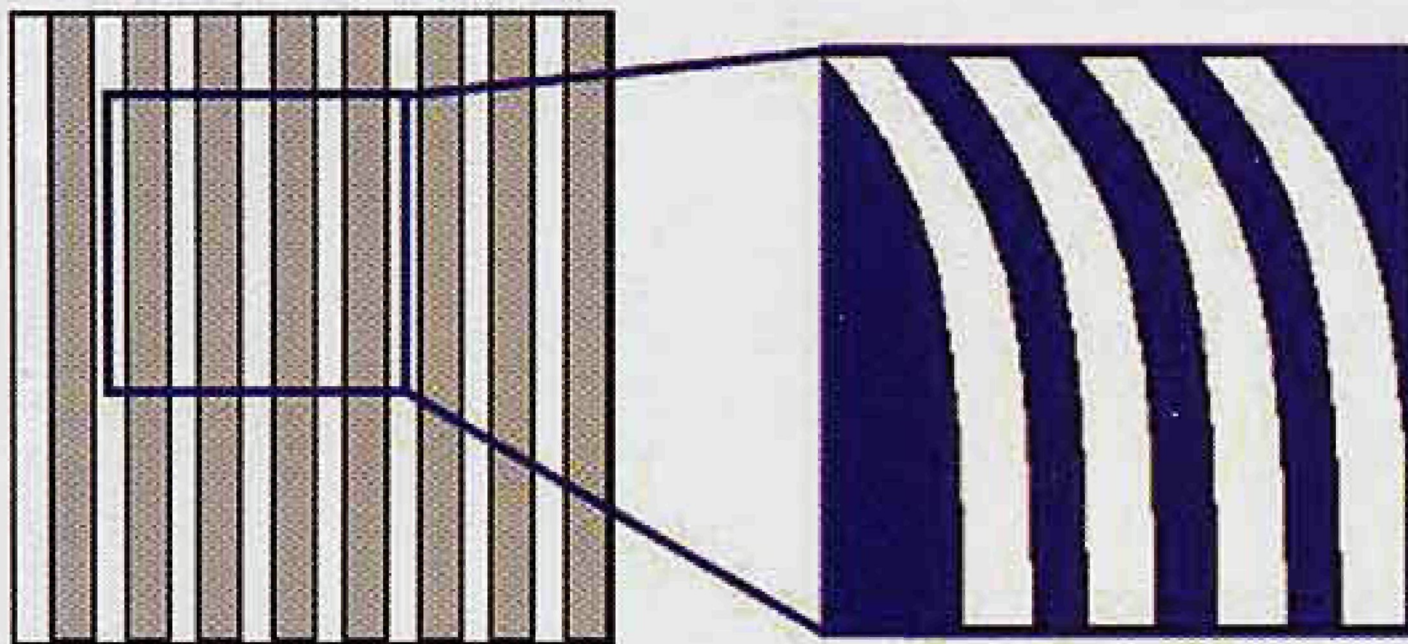


Figure 11. After a particular region of the sample is scanned it is common to zoom in to a smaller area at a higher magnification. Drift in the piezo element can distort the pattern.

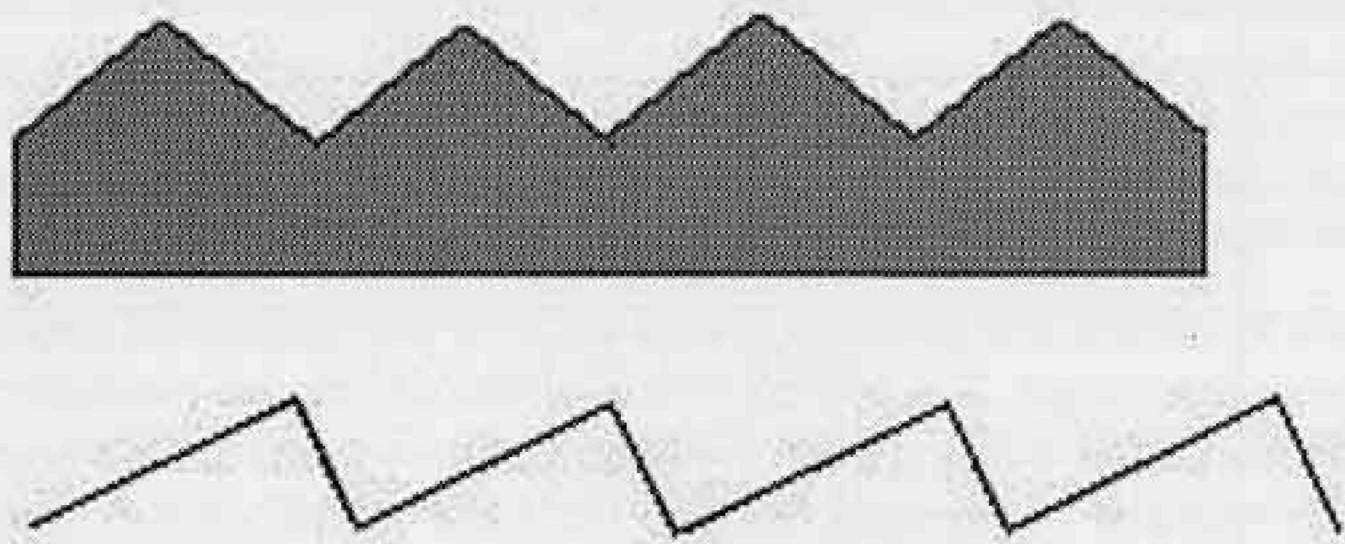


Figure 12. Top: Cross section of test sample used to detect sidewall measurement errors. Bottom: Line profile of sample shows measurement distortion and non-symmetric profile.

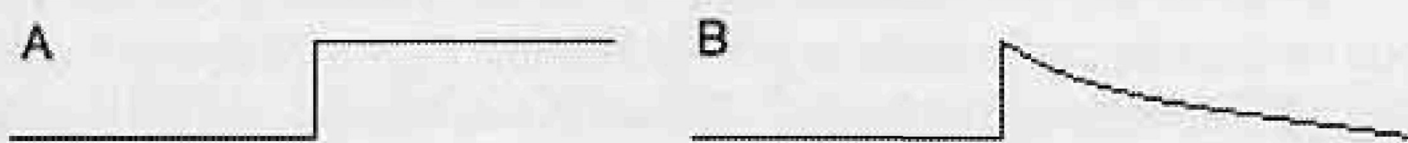


Figure 14. Effect of high-pass filtering on the image of a step (A). The leading edge of the step is sharpened and the trailing edge is rendered as slope (B).

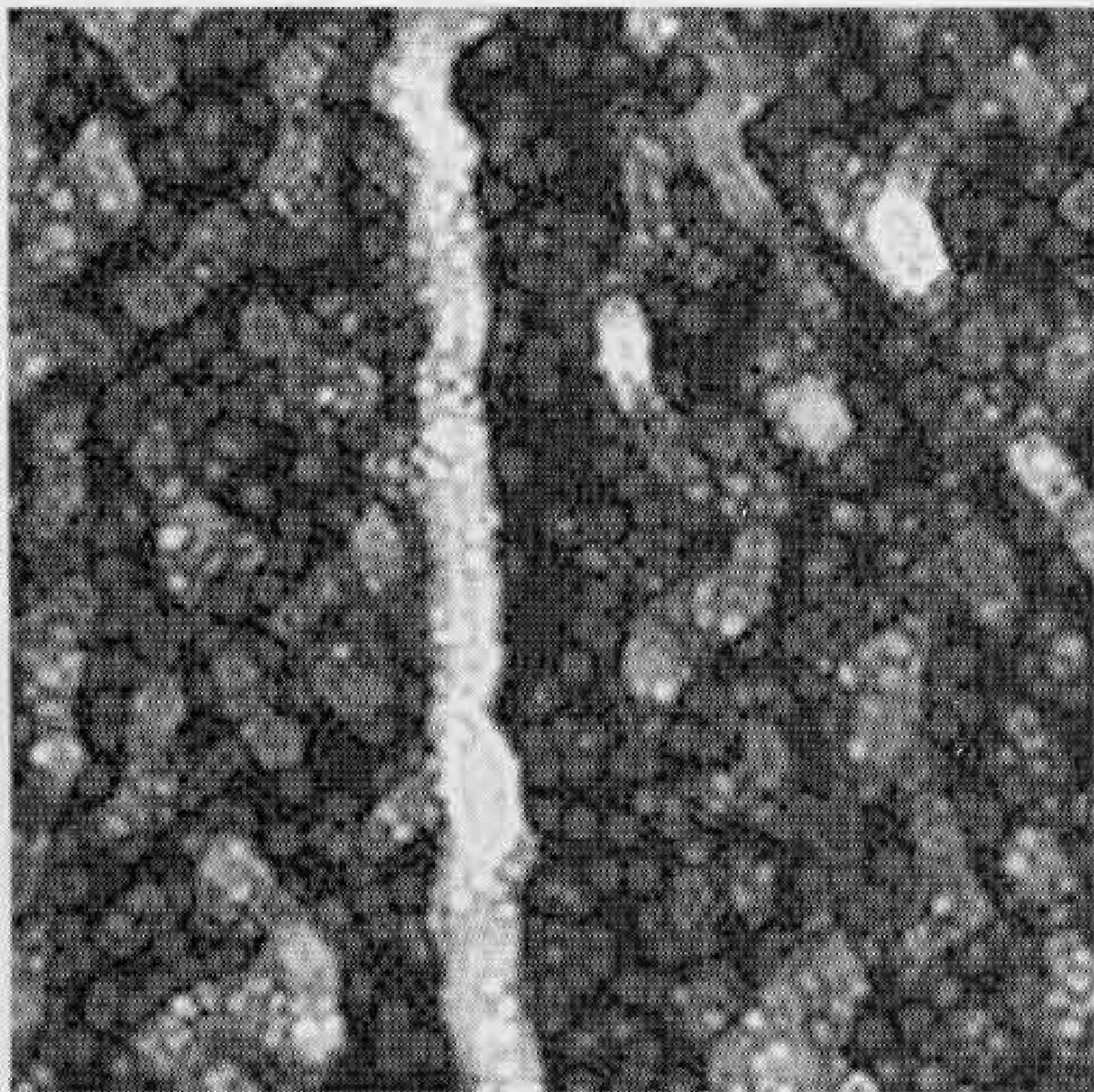
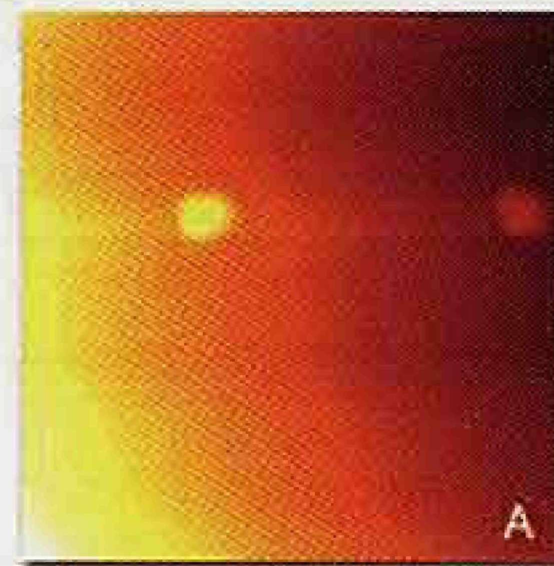
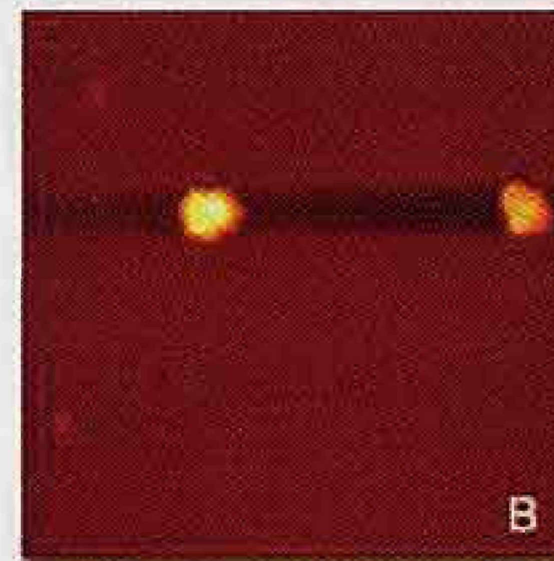


Figure 15. An image of a carbon nanotube that is too good to be true (field: 850×850 nm). The apparently highly-resolved "nodules" on the nanotube are bogus and were added by the filtering process.





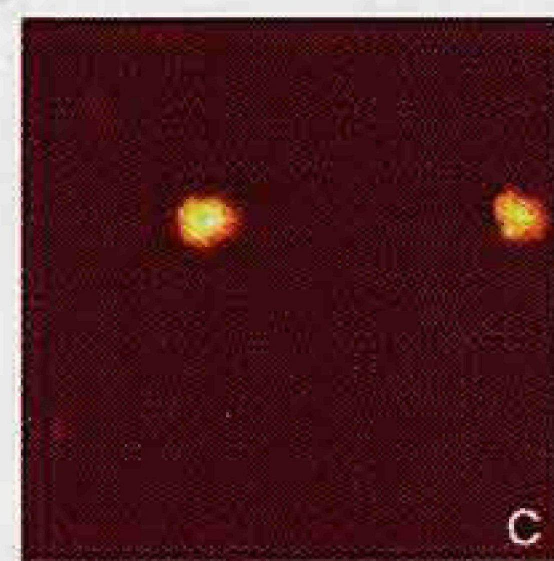


Figure 13. Leveling of an image of colloidal gold spheres (TedPella) on mica (field: 1.6×1.6 μm). A. Original image before leveling. The grading from light to dark indicates tilt. B. Image after line-by-line leveling with a first-order background correction. The dark band bisecting the nanospheres is an image-processing artifact. C. Particles were excluded from the background subtraction to derive this image.

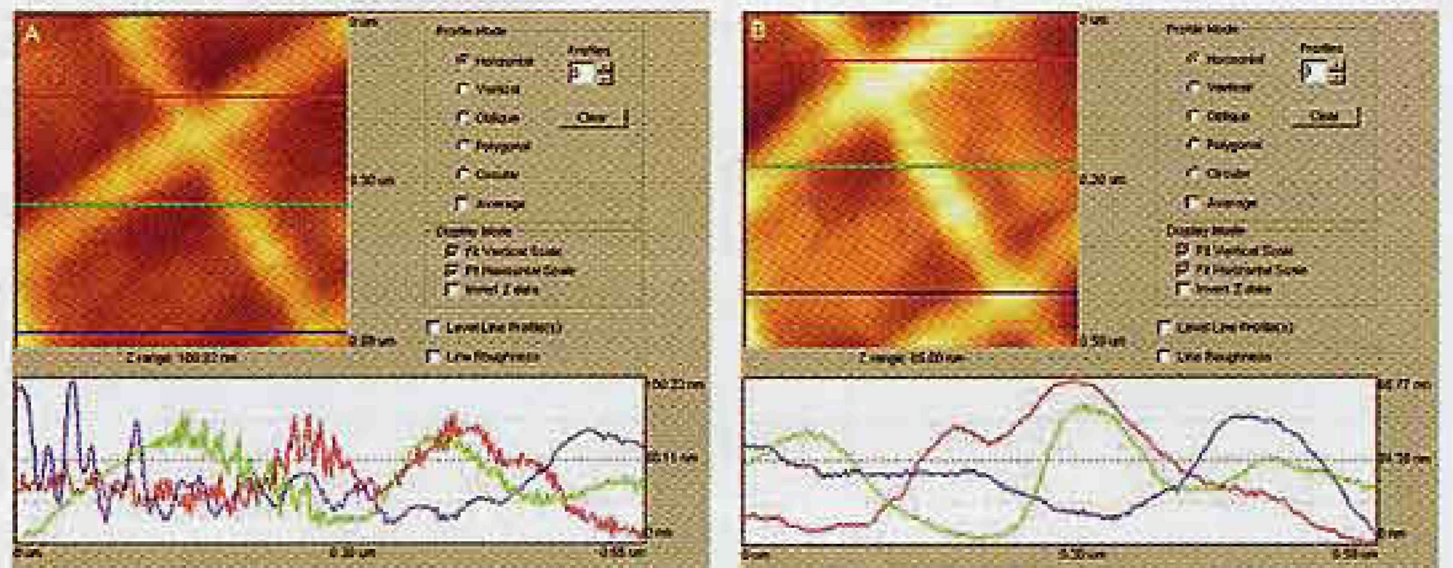


Figure 16. Effect of acoustic noise on a high-resolution image (top) and line scans (bottom) of a diffraction replica AFM standard (TedPella). Left. Noise present. Right. Noise eliminated.

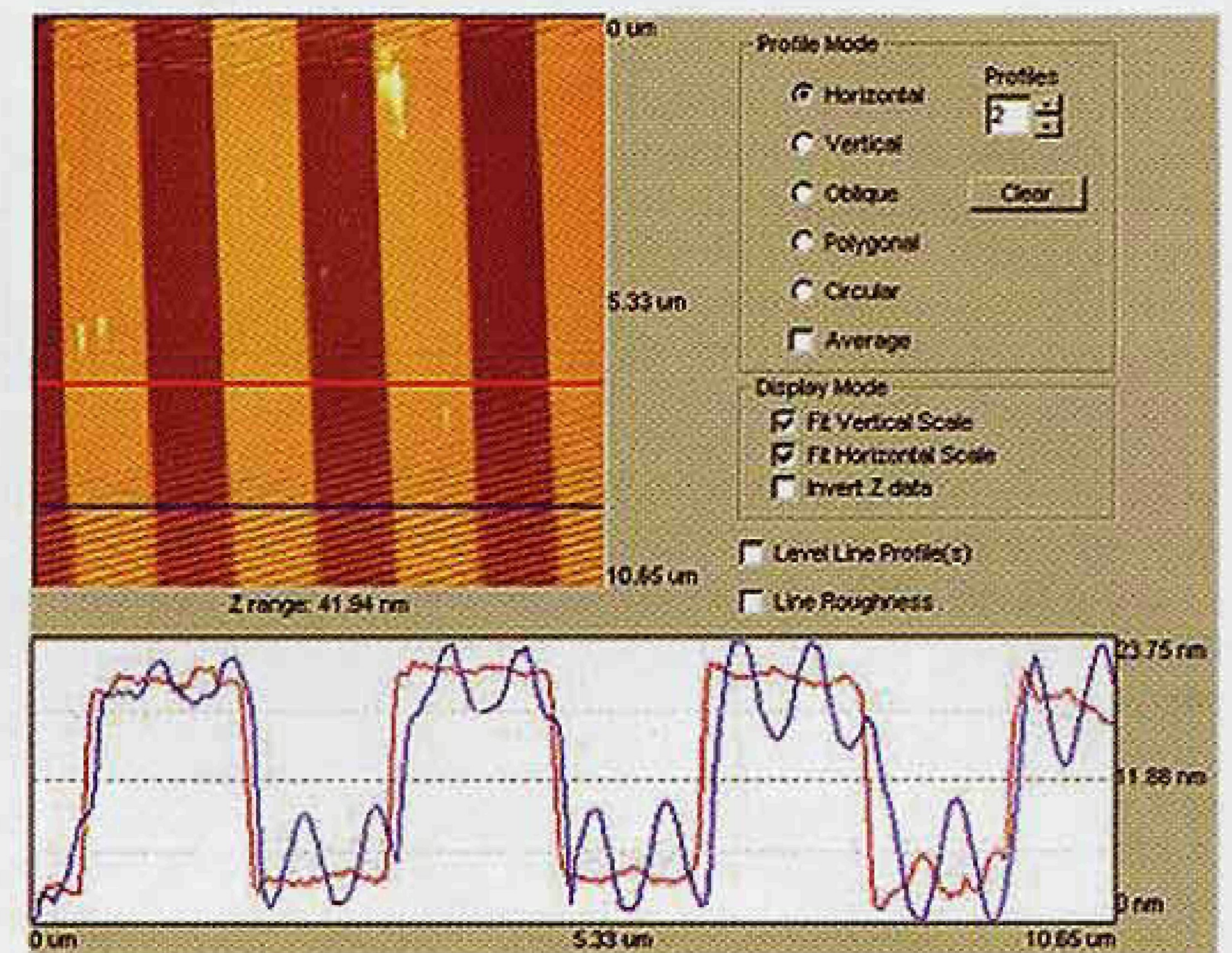


Figure 17. Effect of electronic noise. The effect can be seen in the lower part of the image and in the blue line profile.

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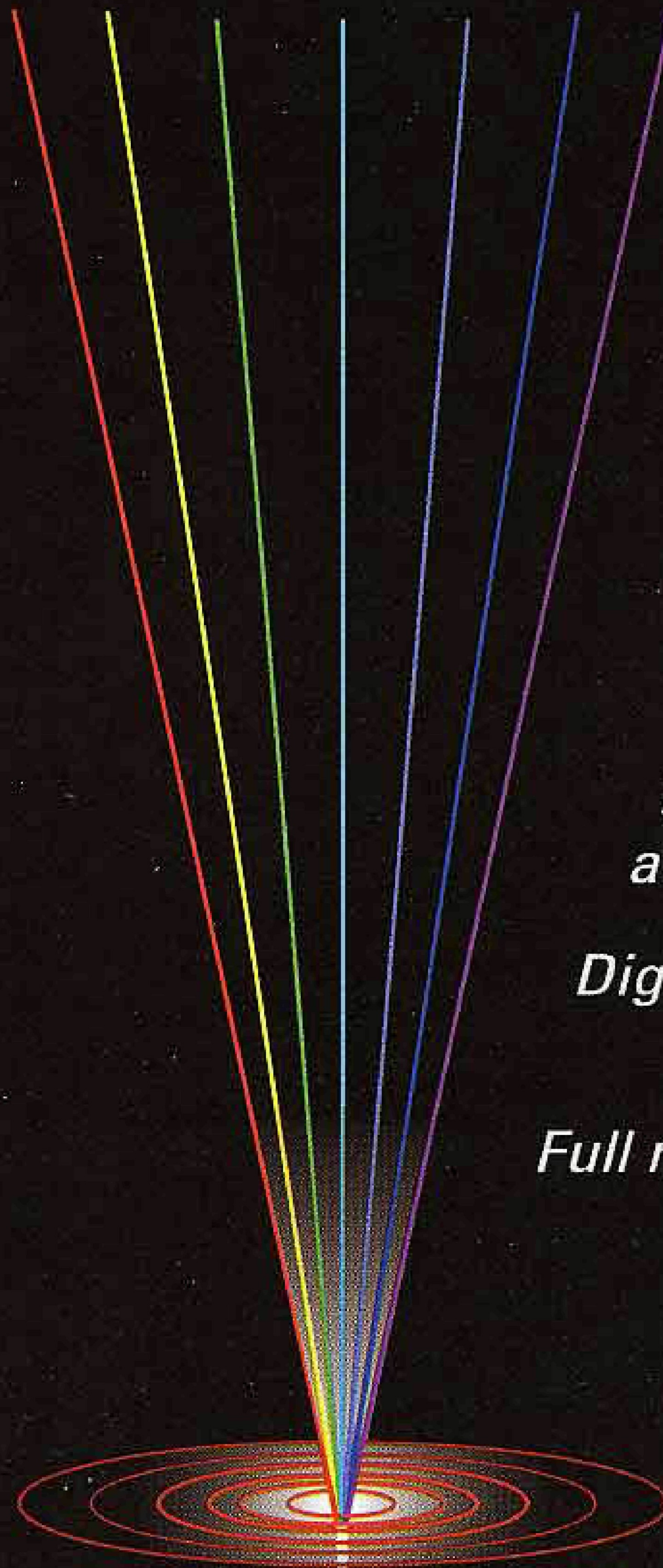

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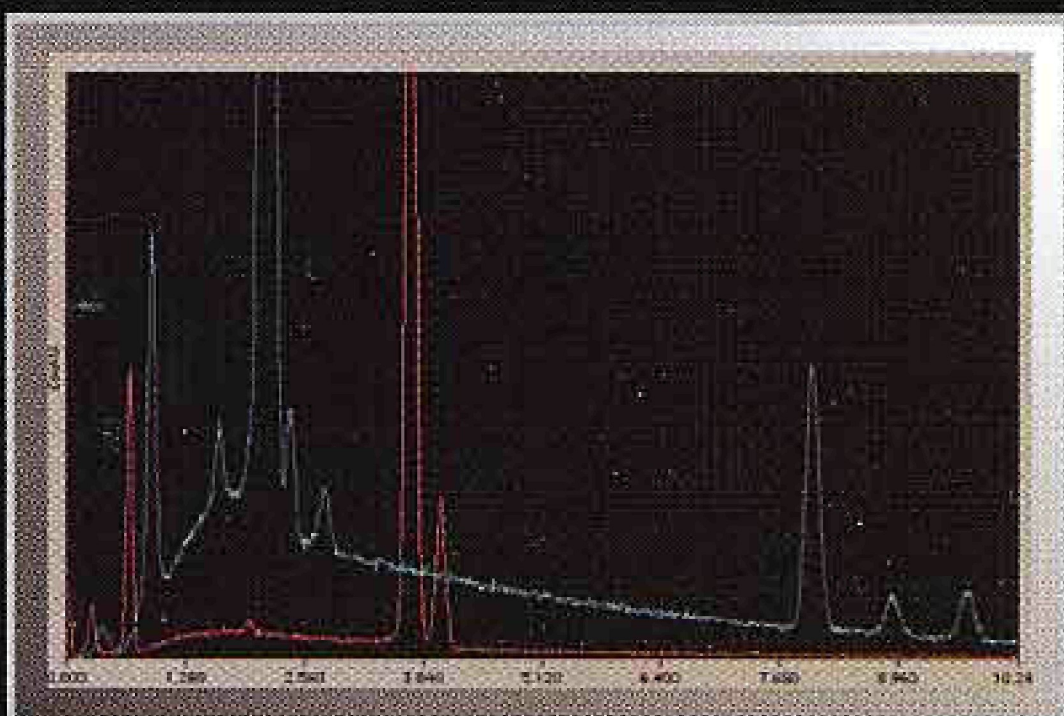

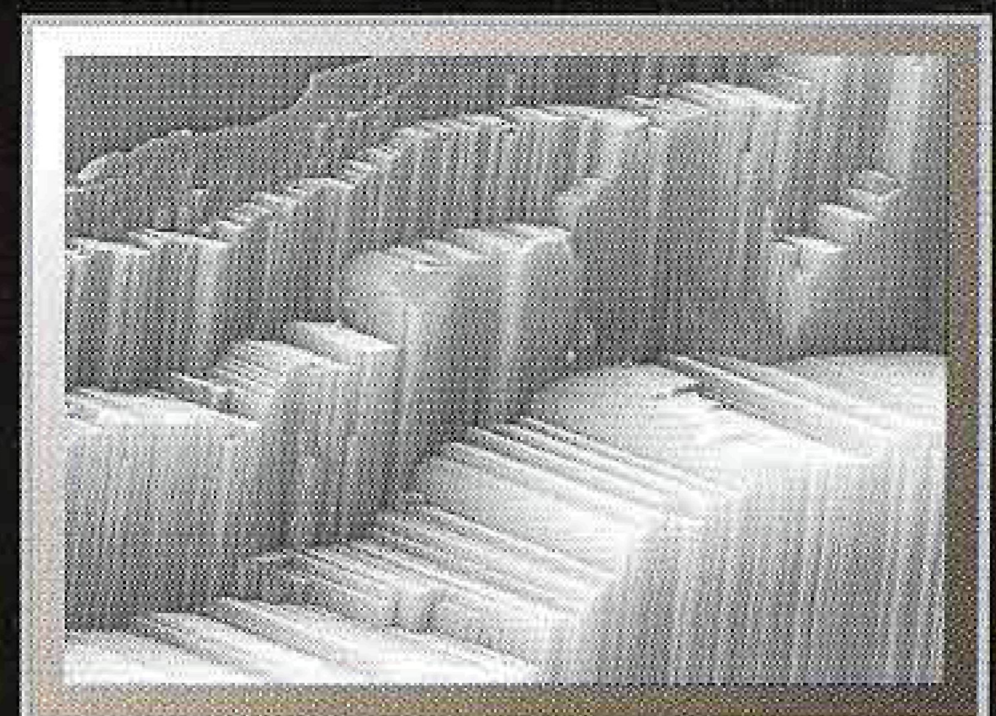

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AFM ARTIFACTS

Artifact Appearance	Possible Cause
Image features too small	Probe tip is too wide or too short
Image features too large	Probe tip shape is incompatible with the sample shape
Image distortion	Incompatible probe tip; damaged probe tip
Image background "bow"	Normal curved motion of probe tip– use background flattening image processing
Image background "tilt"	Tilted probe– use background leveling image processing
Edges of symmetrical feature not symmetrical	Tilted probe; probe tip too large
Strange repeating patterns	Tip too large relative to sample features. Damaged tip.
Image edges too sharp	Hysteresis in z-motion piezo element; over-filtering of image
Image looks too good	Over filtering of image by image processing software
Distortion after image zoom	Drift in piezo element
Random noise in line scan or image	Mechanical or acoustic vibration

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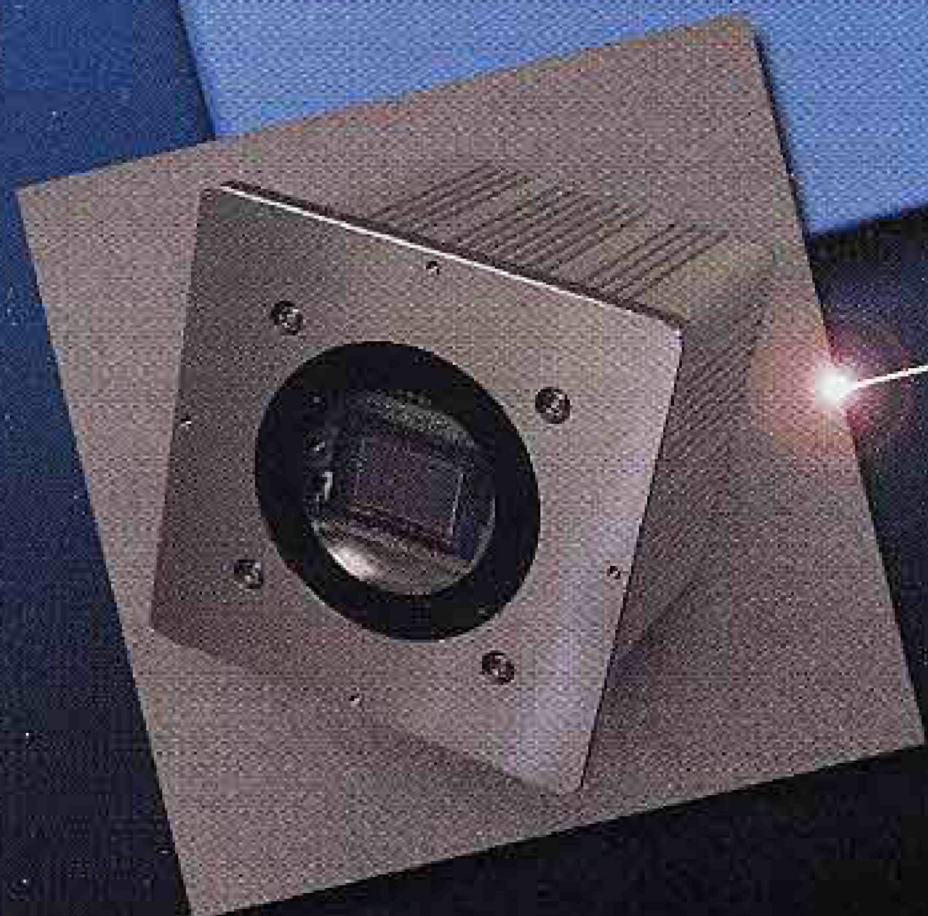

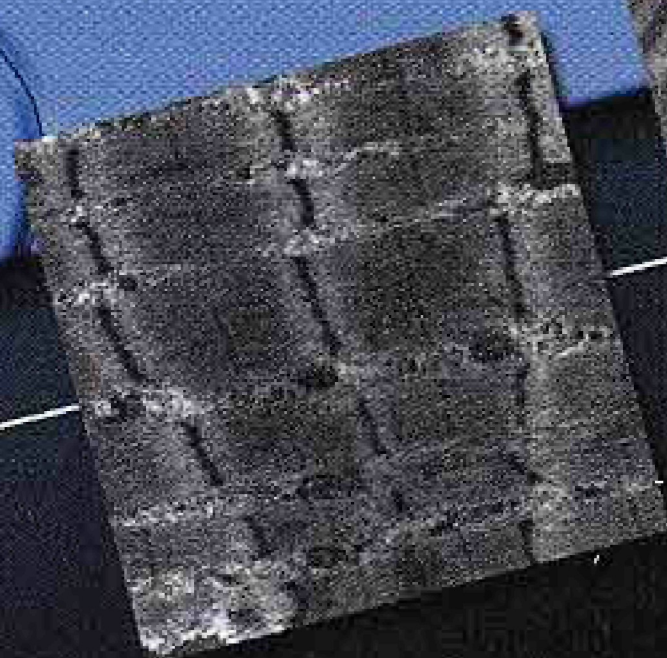

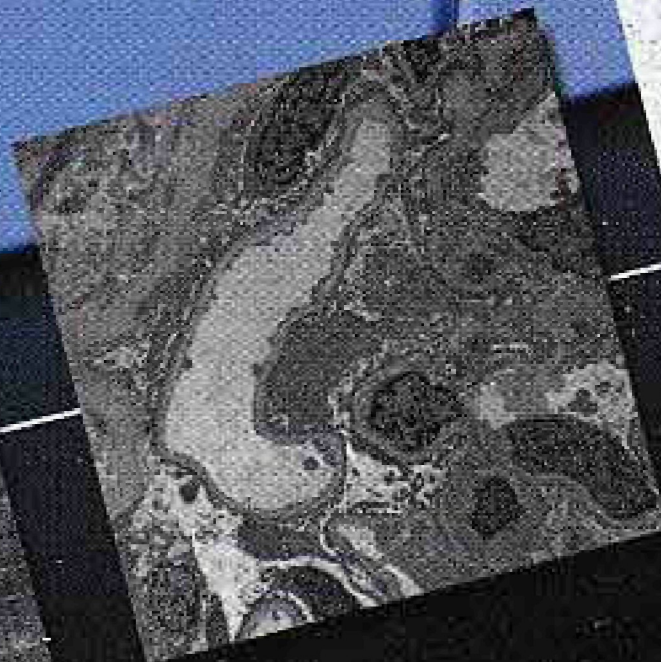

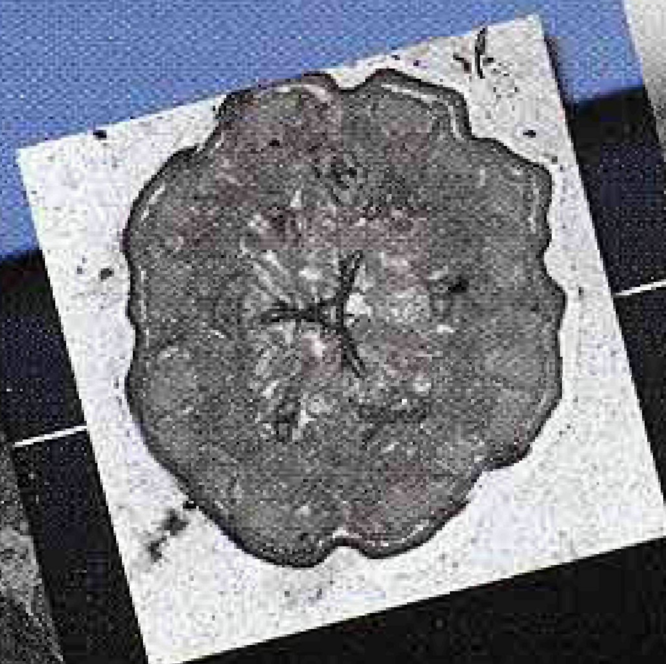

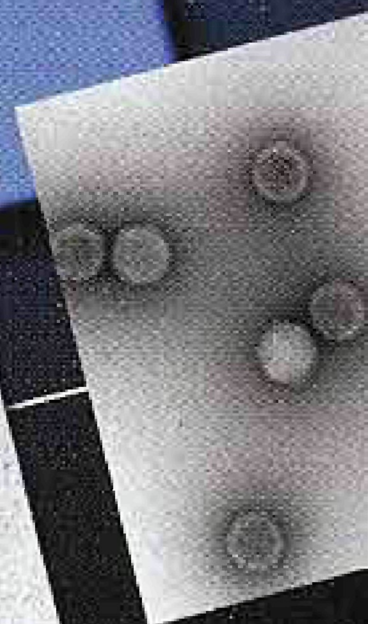

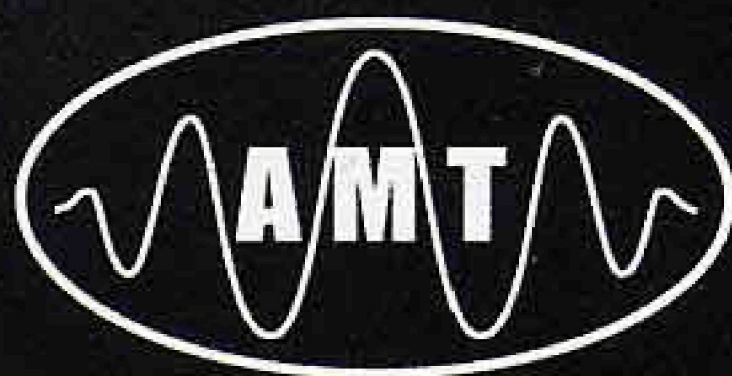

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