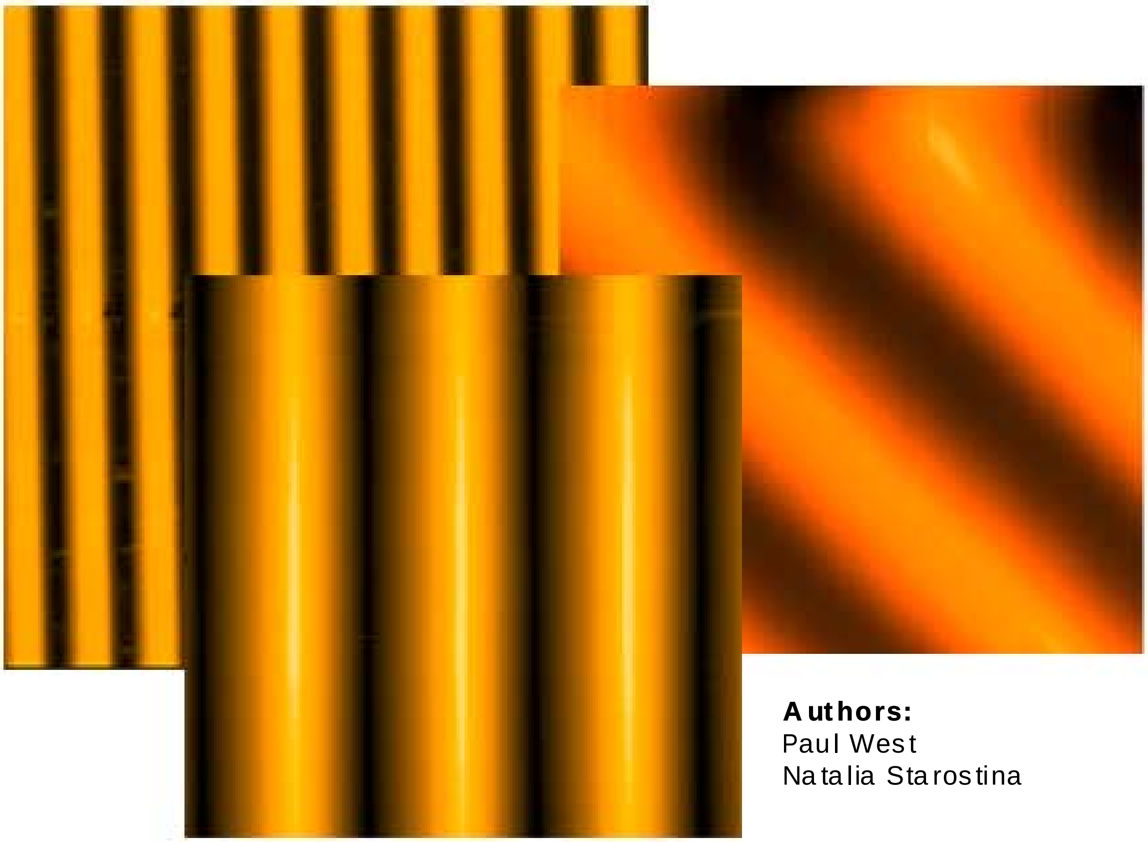
A Guide to
AFM Image Artifacts



Authors:
Paul West
Natalia Starostina

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Introduction

All measurement instrumentation used by scientists and engineers for research development and quality control generates results that may have artifacts. This paper serves as a guide to identify common artifacts that occur in AFM images. This guide is organized in sections that are divided by the sources that generate the image artifacts.

There are four primary sources of artifacts in images measured with atomic force microscopes. They are:

- Probes
- Scanners
- Image Processing
- Vibrations

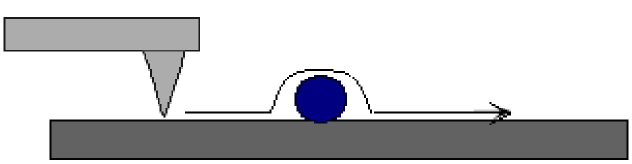
1.0 Probe Artifacts

Images measured with an atomic force microscope are always a convolution of the probe geometry and the shape of the features being imaged. If the probe is much smaller than the features of the images being measured, then the probe-generated artifacts will be minimal and the dimensional measurements derived from the images will be accurate.

Avoiding artifacts from probes is achieved by using the optimal probe for the application. For example, if the features that are being imaged have feature sizes of interest in the 100 nanometer range, a probe as large as 10 nanometers in diameter will be adequate for getting good images with no artifacts. In some cases, even if the probe is not as sharp as the object being imaged, it is still possible to get accurate information from the image. Common artifacts are:

1.1. Features on a surface appear too large:

Figure 1



Motion of an AFM probe as it goes over a sphere that is attached to a surface. In such a measurement the side of the probe will cause a broadening of features in the image.

Often the size of features on the surface such as nanotubes or nanospheres look larger than expected. However, the height of the feature when measured by a line profile is correct.

Figure 2

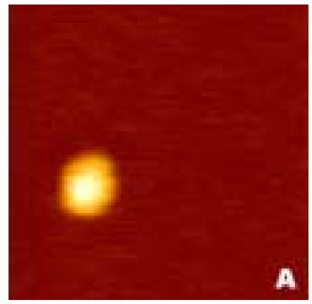
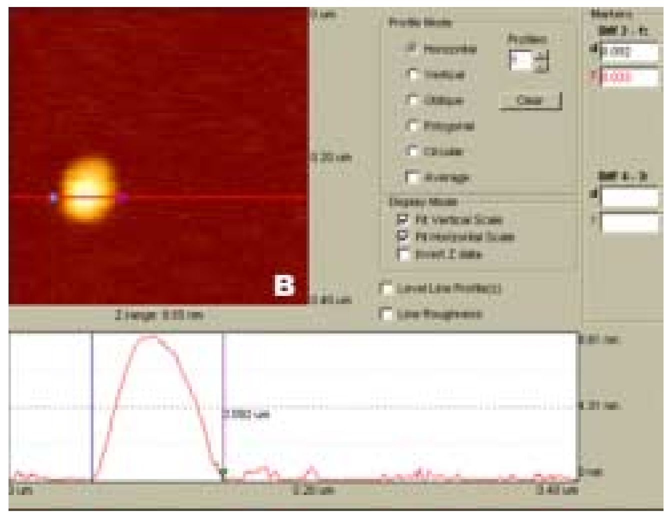
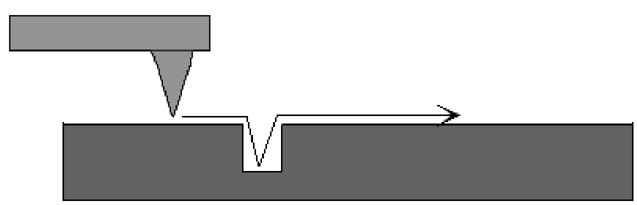


Figure 2A-B: 400 X 400 nm AFM image of an 8 nm diameter sphere (A) The line profile of the image shows a diameter of 92 nm and a height of 8 nm. (B). The broadening in the image is caused by the shape of the probe used for measuring this AFM image.



1.2. Features in an image appear too small:

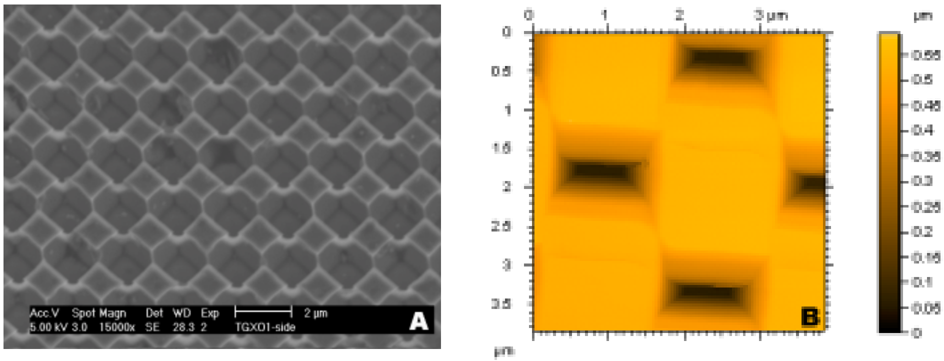
Figure 3



The motion of an AFM probe as it moves over a hole in a surface. Because of the width of the probe, it does not reach the bottom of the hole.

If the probe needs to go into a feature that is below the surface, the size of the feature can appear too small. The line profile in these cases is established by the geometry of the probe and not the geometry of the sample. However, it is still possible to measure the opening of the hole from this type of image. Also, the pitch of repeating patterns can be accurately measured with probes that don't reach the bottom of the features being imaged.

Figure 4

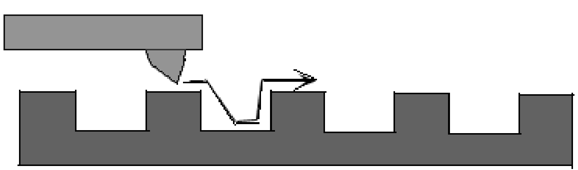


Scanning electron microscope image of a test pattern of squares (NT-MDT TXO1) (A) The sides of the squares are all equal. (B) AFM image of the test pattern. Because the probe is not sharp, the test pattern squares appear much smaller than they should. The features in the AFM image appear as rectangles and not as squares.

1.3. Strangely shaped objects:

If the probe gets broken or chipped before an image is measured, strangely shaped objects may be observed that are difficult to explain. For example, when scanning a semiconductor test pattern, it can appear as though the tip is at a large angle to the surface as described in section 2.1. However, the probe to sample angle would have to be extreme to explain the image artifact.

Figure 5



This "chipped" AFM probe follows the geometry of the sample surface and creates an image with a substantial artifact.

Figure 6

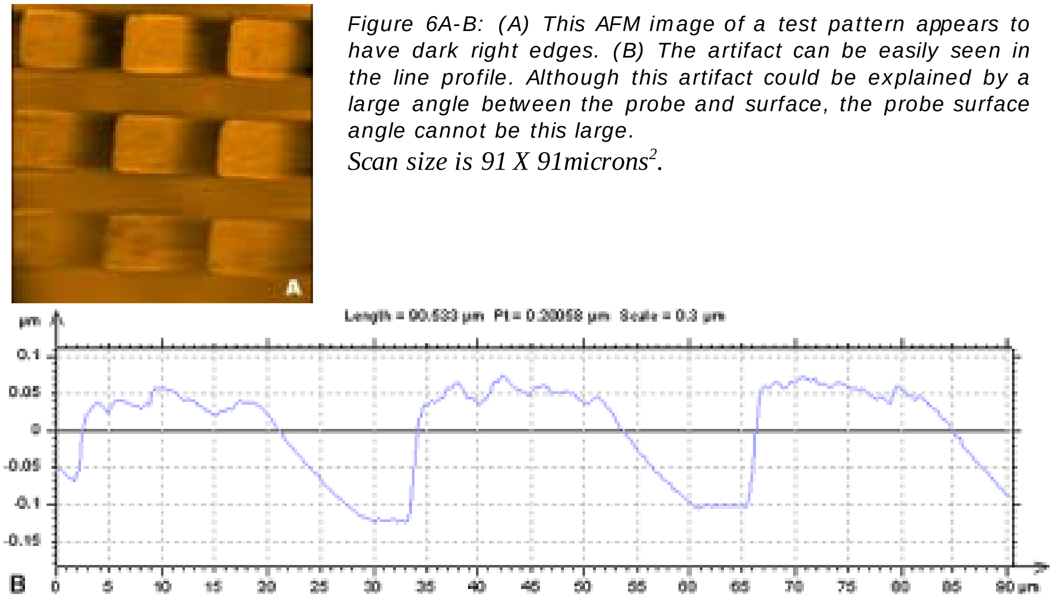


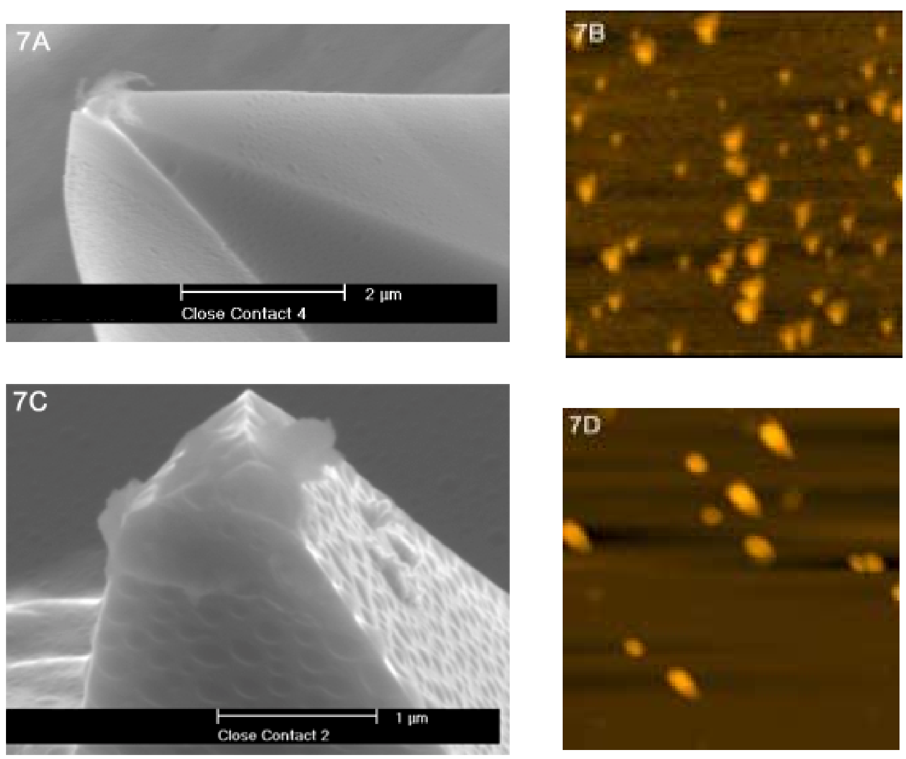
Figure 6A-B: (A) This AFM image of a test pattern appears to have dark right edges. (B) The artifact can be easily seen in the line profile. Although this artifact could be explained by a large angle between the probe and surface, the probe surface angle cannot be this large.
Scan size is 91 X 91microns^2.

1.4. Repeating Strange Patterns in an Image

If the features on a surface are much smaller than the probe, then it is possible to see large numbers of repeating patterns in an image. The patterns will often appear as triangles, especially if silicon probes are used for imaging.

Example: Images of colloidal gold particles reflect the shape of the tip rather than their own geometry. Compare the SEM images of tips and related AFM images of spheres in the figures to the right.

Figure 7



The AFM images at the right, B (5 nm in diameter) and D (28 nm in diameter), are of nanospheres that are supposed to be perfect spheres. At the right, A and C, are scanning electron microscope images of the AFM probes used for getting the images of the spheres. Because the chipped probes are much larger than the spheres, the AFM images reflect the probe's geometry. The scan size is 700nm X 700nm.

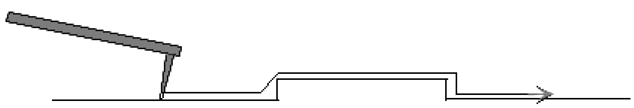
2.0 Scanner Artifacts

Scanners that move the probe in an atomic force microscope in the X, Y and Z directions are typically made from piezoelectric ceramics. As electromechanical transducers, piezoelectric ceramics are capable of moving a probe very small distances. However, when a linear voltage ramp is applied to piezoelectric ceramics, the ceramics move in a nonlinear motion. Further, the piezoelectric ceramics exhibit hysteresis effects caused by self-heating. Artifacts can also be introduced into images because of the geometry of the scanner. The positioning of the scanner relative to the sample can also create artifacts.

2.1. Probe/Sample Angle

If the features that are being imaged by the AFM are much smaller in profile than the probe, and the image does not seem "correct", the artifact may be caused by a non-perpendicular probe surface angle. Ideally, the probe of the microscope should be perpendicular to the surface.

Figure 8



In this example the probe is much sharper than the feature it is scanning across and should give a correct image. However, because of the extreme probe sample angle, the line profile will show an artifact at the left edge of the feature.

Solving this problem is achieved by adjusting the angle between the probe and the sample so that they are perpendicular. In some microscopes the probe is designed to be at a 12 degree angle with respect to the sample. Also some AFM microscopes do not have mechanical adjustments to control the probe/sample angle.

2.2. X-Y Calibration/Linearity

All atomic force microscopes must be calibrated in the X-Y axis so that the images presented on the computer screen are accurate. Also the motion of the scanners must be linear so that the distances measured from the images are accurate. With no correction, the features on an image will typically appear smaller on one side of the image than on the other.

Figure 9

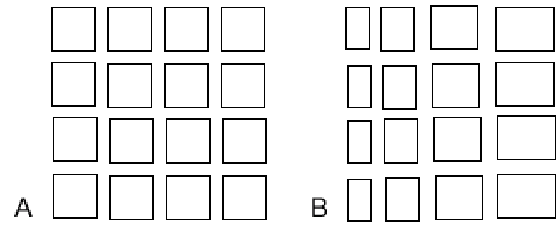
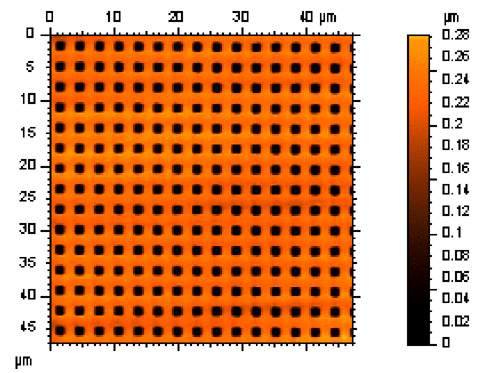


Figure 9A-B: A test pattern with squares, shown in figure 9A, will appear severely distorted if the piezoelectric scanner in the AFM is not linear as in 9B.

Once the scanner is properly linearized, it is also critical that the scanner be calibrated. For example it is possible for the scanner to be linear but not calibrated. If the calibration is incorrect, then the X-Y values measured from line profiles will be incorrect.

Figure 10



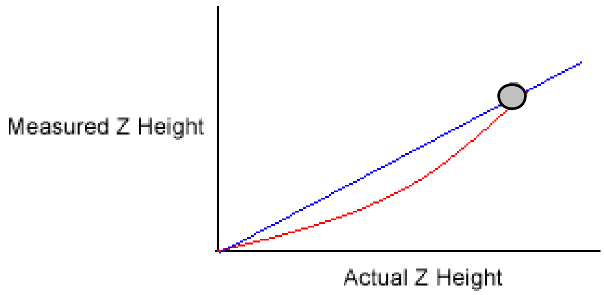
This AFM image of a test pattern is very linear. The spacing of the squares at the top, bottom, left and right sides are all the same distance apart. It appears as it should.

A common method for correcting the problems of X-Y non-linearity and calibration is to add calibration sensors to the X-Y piezoelectric scanners. These sensors can be used to correct the linearity and the calibration in real time.

2.3. Z Calibration/Linearity

Height measurements in an AFM require that the piezoelectric ceramics in the Z axis of the microscope be both linear and calibrated. Often the microscope is calibrated at only one height. However, if the relationship between the measured Z height and the actual Z height is not linear, then the height measurements will not be correct.

Figure 11



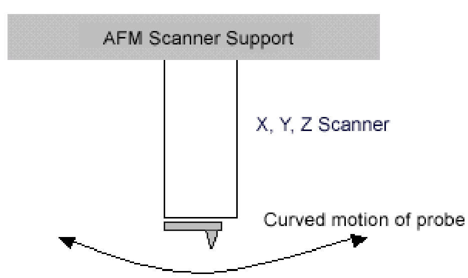
This graph shows the relationship between an actual Z height and a measured Z height in an atomic force microscope. Often only one calibration point is measured as shown by the grey circle, and the Z ceramic is assumed to be linear, as shown by the blue line. However, as is often the case, the ceramic is nonlinear, as shown by the red line. In such cases incorrect Z heights are measured with the microscope unless the feature being measured is close to the calibration measurement.

2.4. Background Bow/Tilt

The piezoelectric scanners that move the probe in an atomic force microscope typically move the probe in a curved motion over the surface. The curved motion results in a "Bow" in the AFM image. Also, a large planar background or "Tilt" can be observed if the probe/sample angle is not perpendicular.

Often the images measured by the AFM include a background "Bow" and a background "Tilt" that are larger than the features of interest. In such cases the background must be subtracted from the image. This is often called "leveling" or "flattening" the image. After "leveling" the desired features are typically directly seen in the image.

Figure 12



An AFM piezoelectric scanner is often supported at the top by a mechanical assembly. Thus the motion of the probe is nonlinear in the Z axis as it is scanned across a surface. The motion can be spherical or even parabolic depending on the type of piezoelectric scanner.

Figure 13

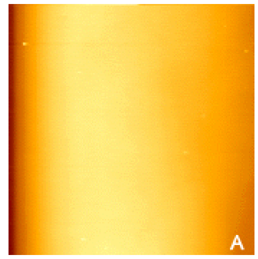
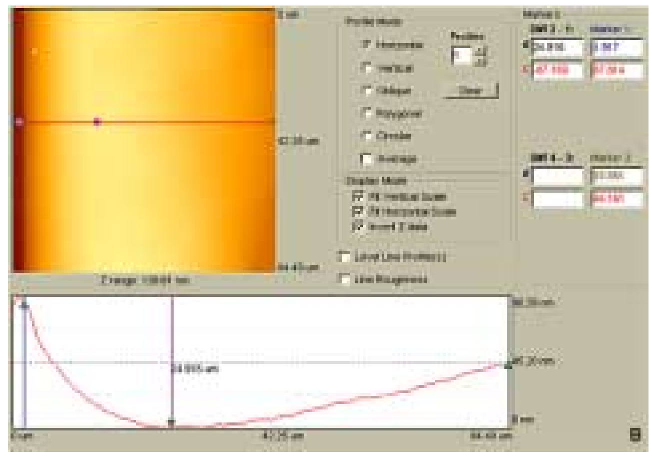


Figure 13A-B: Image (A) is an 85 X 85 micron image of a flat piece of silicon. The bow introduced into the image is seen at the edges. (B) A line profile across this image shows the magnitude of the bow.



2.5. Z Edge Overshoot

Hysteresis in the piezoelectric ceramic that moves the cantilever in the perpendicular motion to the surface can cause edge overshoot. This problem is most often observed when imaging micro-fabricated structures such as patterned Si wafers or compact discs. The effect can cause the images to be visually better because the edges appear sharper. However, a line profile of the structure shows errors.

Figure 14

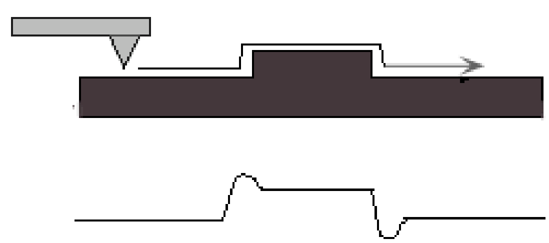


Figure 14A-B: (A) The probe is scanned from left to right across a feature on a surface. (B) Overshoot may be observed in the line profile at the leading and trailing edge of the structure.

Figure 15

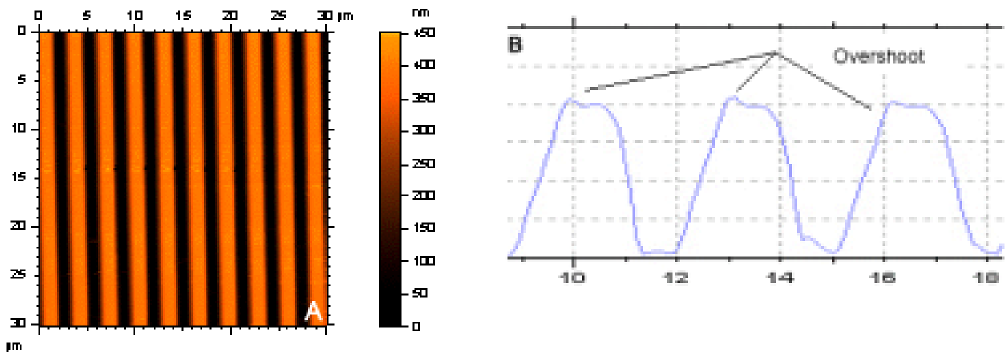
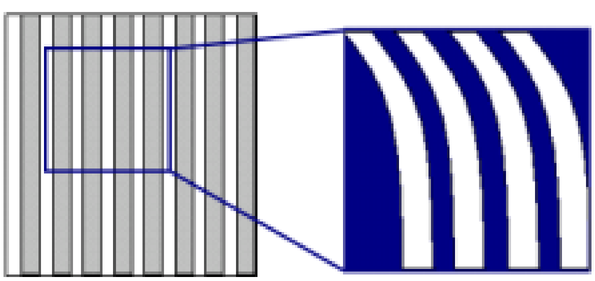


Figure 15 A-B: (A) The AFM image of a test pattern appears to have no artifacts. (B) However, a line profile of the test pattern shows overshoot at the top of each of the lines.

2.6. Scanner Drift

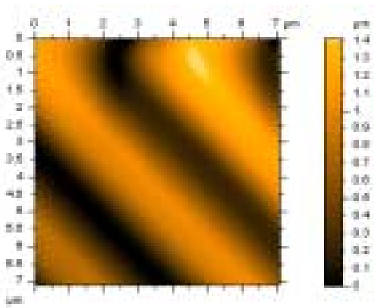
Drift in AFM images can occur because of thermal drift in the piezoelectric scanner and because an AFM can be susceptible to external temperature changes. The most common type of drift occurs at the beginning of a scan of a zoomed-in region of an image. This artifact causes the initial part of a scan range to appear distorted. Drift artifacts are most easily observed when imaging test patterns. Drift will cause lines that should appear straight to have curvature.

Figure 16



After a region of a sample is scanned with the AFM it is common to "zoom" into a small section of the image to get a higher magnification of an image. Scanner drift will cause the image to appear distorted at the beginning of the scan.

Figure 17

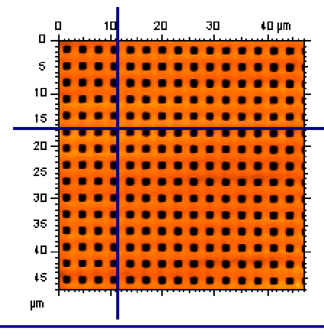


Zoomed image showing a distortion at the beginning of the scan. The scan angle is 45 degrees.

2.7. X-Y Angle Measurements

If the motion generated by the X-Y scanner is not orthogonal, then there can be errors in the horizontal measurements in an image. This error, or artifact, can best be seen when imaging a test pattern with squares. The error in orthogonality can be measured by using a straight edge to measure "orthogonal" lines in the images.

Figure 18



The blue lines drawn on this image show that the scanner has no measurable cross-talk between the X and the Y axis. The lines are orthogonal.

2.8. Z Angle Measurements

Mechanical coupling between the piezoelectric ceramics that move the probe in the X or Y directions and the Z direction can cause substantial errors when trying to measure side wall angles with the AFM. This error can best be measured with a sample that has repeating triangular structures.

Figure 19

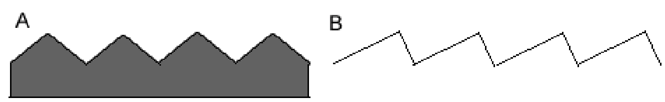


Figure 19 A-B: (A) This cross section is an ideal sample for demonstrating the ability of an AFM to measure angles. The sample has a series of repeating triangles at its surface. (B) A line profile of the sample shows that the triangles do not appear symmetric.

Figure 20

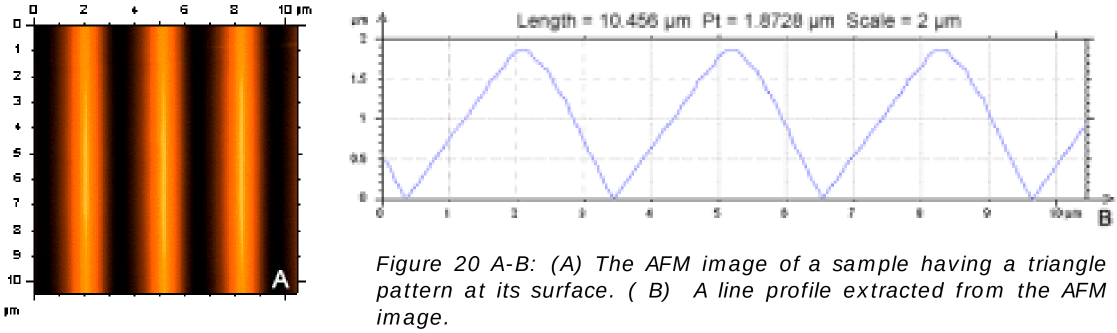


Figure 20 A-B: (A) The AFM image of a sample having a triangle pattern at its surface. (B) A line profile extracted from the AFM image.

3.0. Image Processing

Image processing is required before viewing or analyzing almost all AFM images. Most AFM products are supplied with very powerful image display and analysis software. Properly used, the image processing software will typically not introduce artifacts into an image. This section presents some of the common artifacts that can be introduced into AFM images by the image processing software.

3.1. Leveling

As mentioned in section 2.4, most images have some tilt and bow that is introduced to the images by the scanner or stage configuration. There are a number of background subtraction options that are possible. The two most common types are:

Line by line leveling - 0 to 4 (th) order
Plane Leveling - 0 to 4 (th) order

Also, software typically allows you to exclude areas from the leveling. When an area is excluded, it is not used for the calculation of the background in the image.

Figure 21

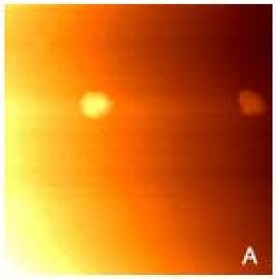
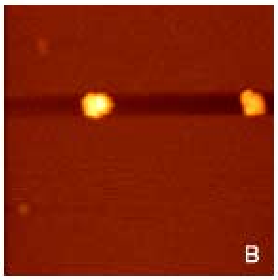
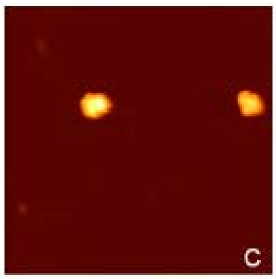


Figure 21A-C: AFM images a 1.6 X 1.6 micron image of nanospheres on a surface.

(A) The original image measured by the AFM before any image processing. Tilt is easily recognized in the image as the right side of the image appears darker than the left side of the image.



(B) The AFM image shown in "A" after a line-by-line leveling of the image with a first order background correction. The dark band in the image is caused by the image processing and is not a real structure.



(C) Particles are excluded from the background subtraction process to derive this image.

3.2. Low Pass Filter

A low pass filter is often used to "smooth" data before it displays. Such filters can cause steps in images to appear distorted.

Figure 22

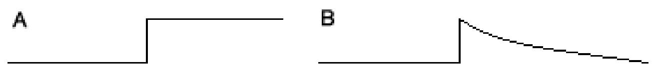


Figure 22A-B: (A) Low pass filtering of the step on the left results in the shape shown in (B). The amount of distortion depends on the amount of filtering applied to the image.

When images are viewed that have substantial low pass filtering, the dimensions in the image can appear distorted. Other artifacts can appear as a sharpness at the edge of steps in an image.

3.3. Matrix Filter/Smoothing

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

3.4. Fourier Filtering

Figure 23

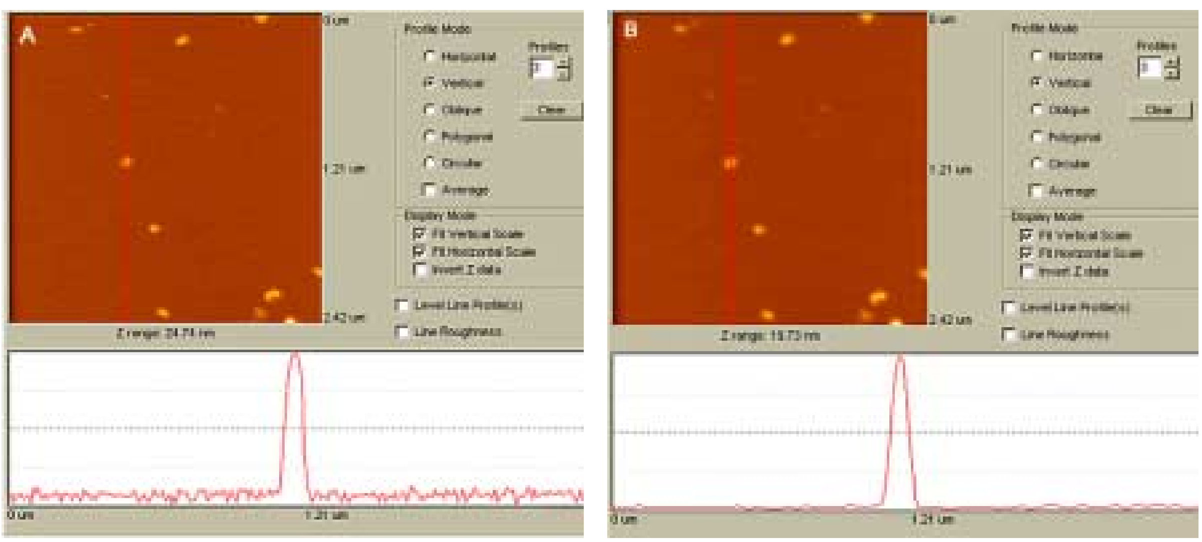


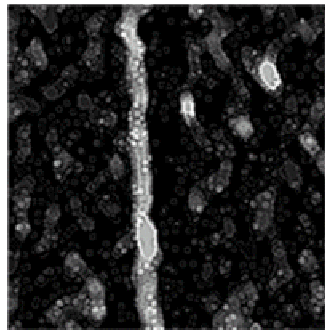
Figure 23A-B: (A) AFM image of nanospheres with no filtering. The image shows noise in the associated line profile. (B) The image generated after matrix smoothing. The line profile shows no noticeable noise and the shape of the particle is altered.

Periodic structures can easily be introduced into images with Fourier filtering. This can be used for creating "atomic structure" in images. As an example, images of "white noise" can be filtered to give periodic structure that looks like atomic structure.

3.5. Image Looks Too Good

If an AFM image looks too good to be true it probably is. All measurement techniques have some noise associated with them. Because AFM data is completely electronic, it is possible to take an image and alter it with image enhancement techniques to create a beautiful picture that does not represent the structure of the surface.

Figure 24



This 850 X 850 nm^2 image of a nanotube had substantial noise when originally measured. Filtering added the "nodules" to the image making it seem like a much higher resolution image.

4.0 Vibrations

Environmental vibrations in the room where the AFM is located can cause the probe in the microscope to vibrate and make artifacts in an image. Typically, the artifacts appear as oscillations in the image. Both acoustic and floor vibrations can excite vibrational modes in an AFM and cause artifacts.

4.1. Floor Vibrations

Often, the floor in a building can vibrate up and down several microns at frequencies below 5 Hz. The floor vibrations, if not properly filtered, can cause periodic structure in an image. This type of artifact is most often noticed when imaging very flat samples. Sometimes the vibrations can be started by an external event such as an elevator in motion, a train going by, or even people walking in a hallway.

4.2. Acoustic Vibrations

Sound waves can cause artifacts in AFM images. The source of the sound can be from an airplane going over a building or from the tones in a person's voice. Below is an image that shows the noise derived from a person talking in the same room as the microscope.

Figure 25

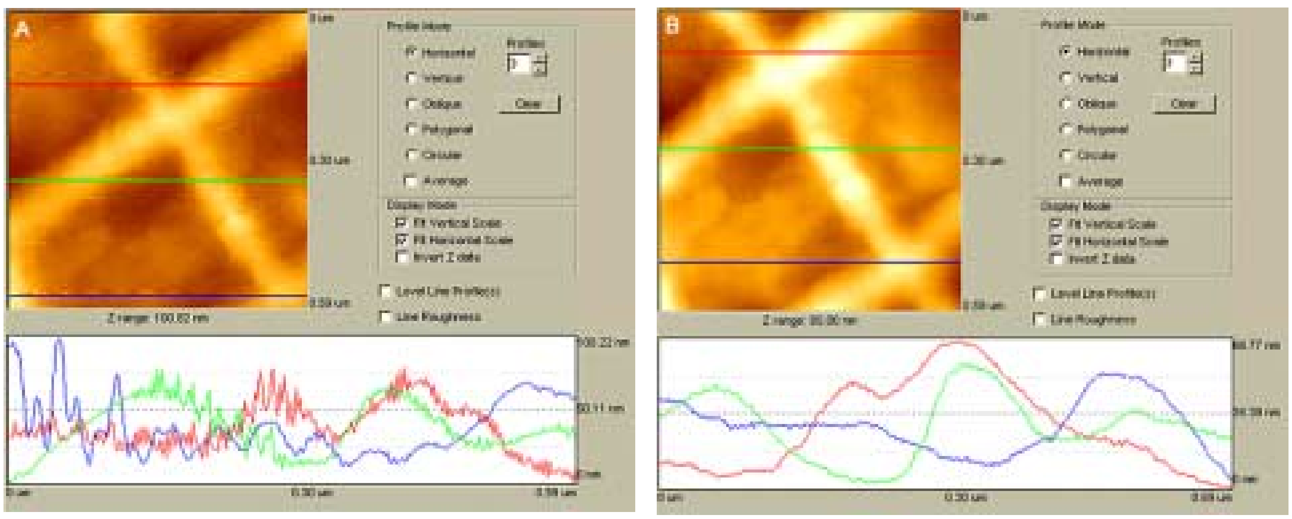


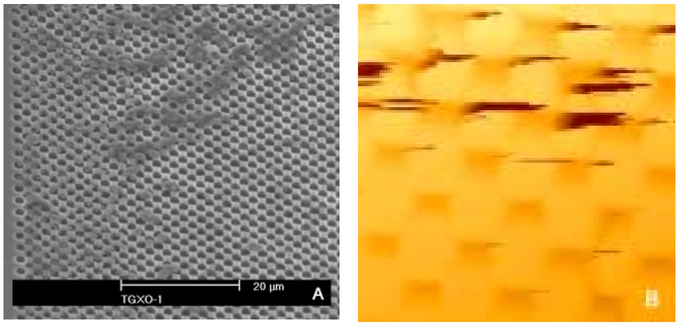
Figure 25A-B: This high resolution image of a test grid shows the effect of acoustic noise on an image. (A) Image and line profiles measured while acoustic noise was present in the room. (B) Image that was measured without the acoustic noise.

5.0. Other Sources

5.1. Surface Contamination

Substantial contamination at the surface of a sample such as a fingerprint or oil film can cause AFM image artifacts. Such artifacts appear as streaks on the image especially in locations where there are "sharp" features and edges on the sample's surface. Often the streaking can be reduced or even eliminated by cleaning the sample with a high purity solvent.

Figure 26



Figures 26A-B: (A) SEM image of a test pattern that is contaminated. (B) AFM image of the same test pattern that is covered with contamination. The contamination is identified by the streak marks at the top of the scan.

5.2. Electronics

Image artifacts can appear in AFM scans because of faulty electronics. Artifacts from electronics most often appear as oscillations or unexplainable repeating patterns in an image. Electronic ground loops and broken components are usually the source of electronic noise.

Figure 27

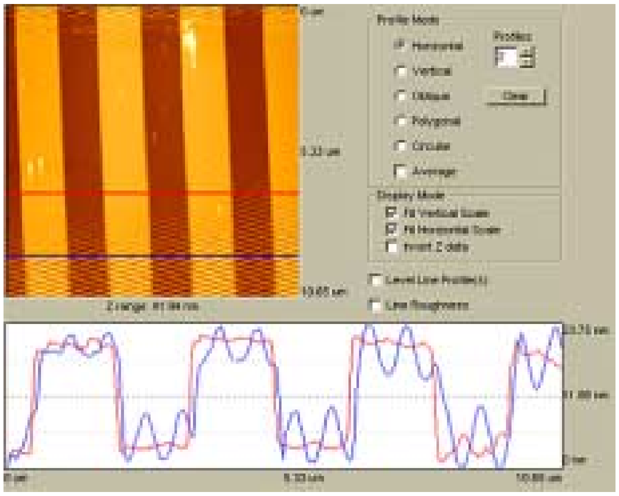


Image of a test pattern that has electronic noise at the top and bottom of the scan. The electronic noise in this case was a result of not having a ground wire attached to the stage. The artifact is identified by the oscillations.

5.3. Vacuum Leaks

Atomic force microscopes that are designed for imaging wafers and discs often use a vacuum chuck to hold the wafer/disc while scanning images. A leak in the vacuum between the specimen holder and the specimen can cause image artifacts. The artifact causes a loss of resolution in the image. Cleaning the vacuum chuck and sample often eliminates this problem.