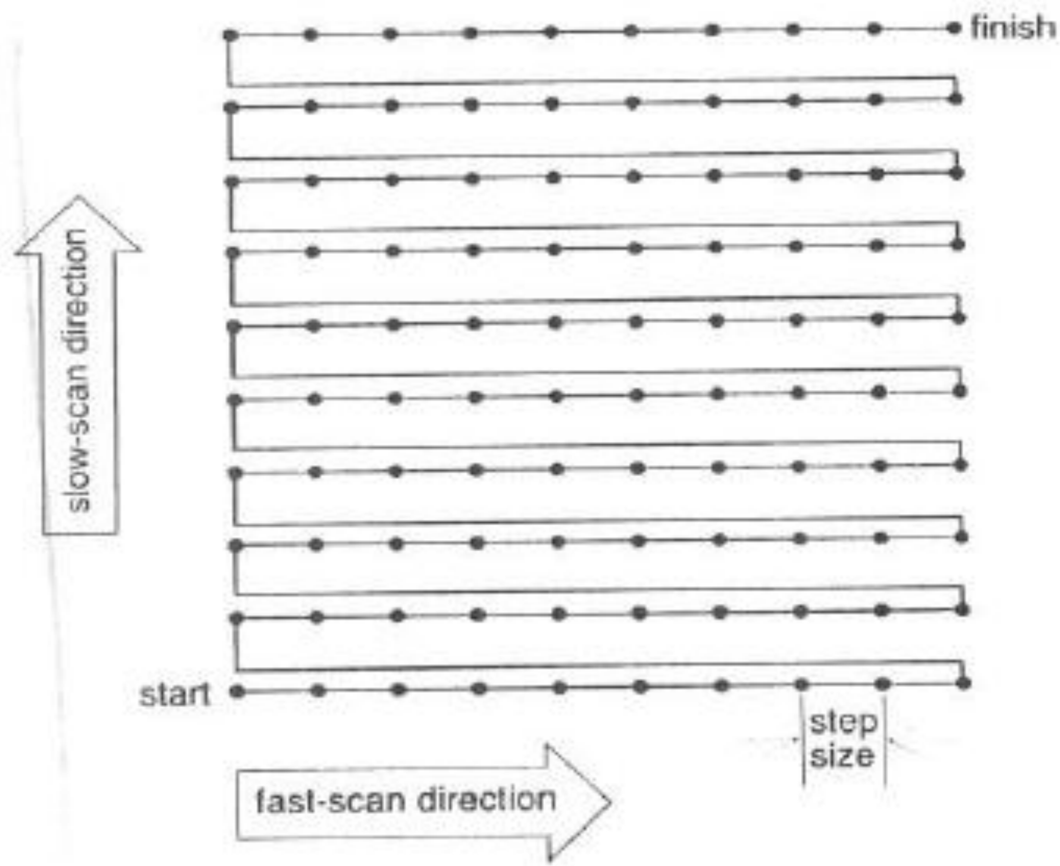


Figure 1- Scanner motion during SPM data acquisition.

The Scanner

Piezoelectric scanner is used as an extremely fine positioning stage to move the probe over the sample (or the sample under the probe).

SPM electronics drive the scanner in a type of raster pattern [see Figure 1].

The scanner moves across the first line of the scan and back. Then steps in the perpendicular direction to the second scan line moves across it and back, then to the third line and so forth.

The path differs from a traditional raster pattern in that alternating lines of data are not taken in opposite directions. SPM data are collected in only one direction, commonly called the fast-scan direction.

The perpendicular direction, in which the scanner steps from line to line, is called the slow-scan direction.

While the scanner is moving across a scan line the image data are sampled digitally at equally spaced intervals. The data would be the height of the scanner in z for constant-force mode (AFM) or constant-current mode (STM).

For constant-height mode, the data would be the cantilever deflection (AFM) or tunneling current (STM).

The spacing between the data points is called the step size. The step size is determined by the full scan size and the number of data points per line. In a typical SPM scan sizes run from tens of angstroms to hundreds of microns.

The number of lines in a data set usually equals the number of points per line.

Since the data are displayed as a square array on the computer screen the image will be distorted laterally unless the measurement grid is perfectly square.

1- Design and Operation

Piezoelectric materials are ceramics that change dimensions in response to an applied voltage.

Piezoelectric scanners for SPM are usually fabricated from lead zirconium titanate or PZT with various dopants added to create specific materials properties.

2- Nonlinearities and their effects

In first approximation the strain in a piezoelectric scanner varies linearly with applied voltage.

Strain is the change in length divided by the original length, $\Delta l/l$.

The ideal relationship between the strain and an applied electric field is: $\boldsymbol{s = d \cdot E}$, where $\boldsymbol{s}$ is the strain in Å/m, $\boldsymbol{E}$ is the electric field in V/m and $\boldsymbol{d}$ is the strain coefficient in Å/V.

The strain coefficient is characteristic of a given piezoelectric material. In practice, the behavior of piezoelectric scanners is not so simple; the relationship between strain and electric field diverges from the ideal linear behavior.

i- Hysteresis

To complicate matters piezoelectric ceramics display hysteretic behavior. Suppose we start at zero applied voltage gradually increase the voltage to some finite value and then decrease the voltage back to zero. If we plot the extension of the ceramic as a function of the applied voltage, the descending curve doesn't retrace the ascending curve, it follows a different path as shown in Figure 2.

Quantitatively the hysteresis of a piezoelectric scanner is the ratio between the maximum divergence between the two curves and the maximum extension which a voltage can create in the scanner, ÅY/Y_{max}. Hysteresis can be as high as 20% in piezoelectric materials.

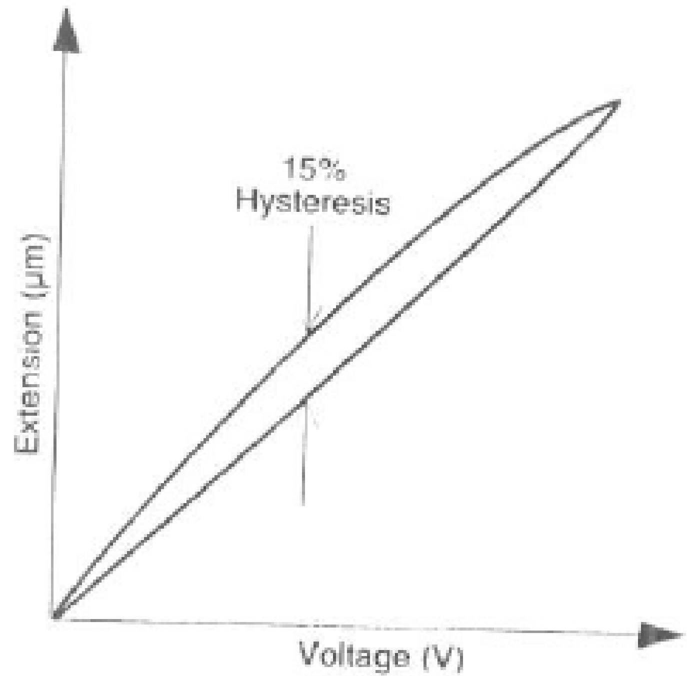


Figure 2- Hysteresis in a piezoelectric scanner: the extension of the scanner differs depending upon whether it is extending or contracting.

ii- Creep

When an abrupt change in voltage is applied, the piezoelectric material does not change dimensions all at once. Instead, the dimensional change occurs in two steps: the first step takes place in less than a millisecond, and the second on a much longer time scale. The second step (Δx_c in Figure 3) is known as creep.

Quantitatively creep is the ratio of the second dimensional change to the first $\Delta x_c/Ax$. Creep is expressed as a percentage and usually quoted with the characteristic time interval Tcr over which the creep occurs. Typical values of creep range from 1% to 20% over times ranging from 10 to 100 seconds.

The times involved during typical scans place the lateral motion of the scanner in the curved part of the response curve in Figure 3.

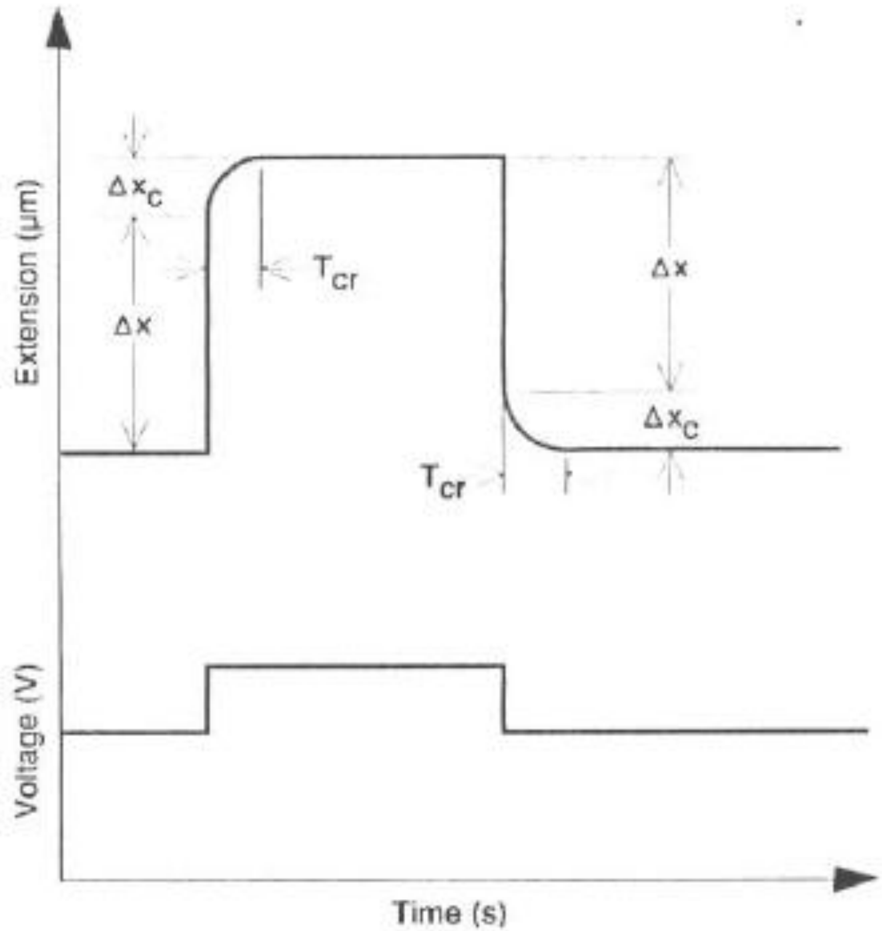


Figure 3- Creep in a piezoelectric scanner: delayed response of the scanner to an abrupt change in voltage.

iii- Cross Coupling

The tern cross coupling refers to the tendency of x-axis or y-axis scanner movement to have a spurious z-axis component (Figure 4). It arises from several sources and is fairly complex. For example the electric field is not uniform across the scanner. The strain fields are not simple constants but actually complex tensors. Some "cross talk" occurs between x, y and z electrodes. But the largest effect is geometric. Geometric cross coupling has its basis in the way piezoelectric scanners are constructed, usually as segmented tubes or as tripods.

Cross coupling can cause an SPM to generate a bowl-shaped image of a ft sample. A profile of such an image is shown in Figure 5 with our familiar example of a step.

This example shown only a single step to demonstrate hysteresis creep and cross coupling in the vertical direction. To show a single image in the laboratory that illustrates each of these effects in isolation is virtually impossible. Figure 6 shows the sum of the effects of hysteresis, creep and cross coupling on the image of a single step. The aspect ratio of the tip may also contribute to the shape of the sidewalls.

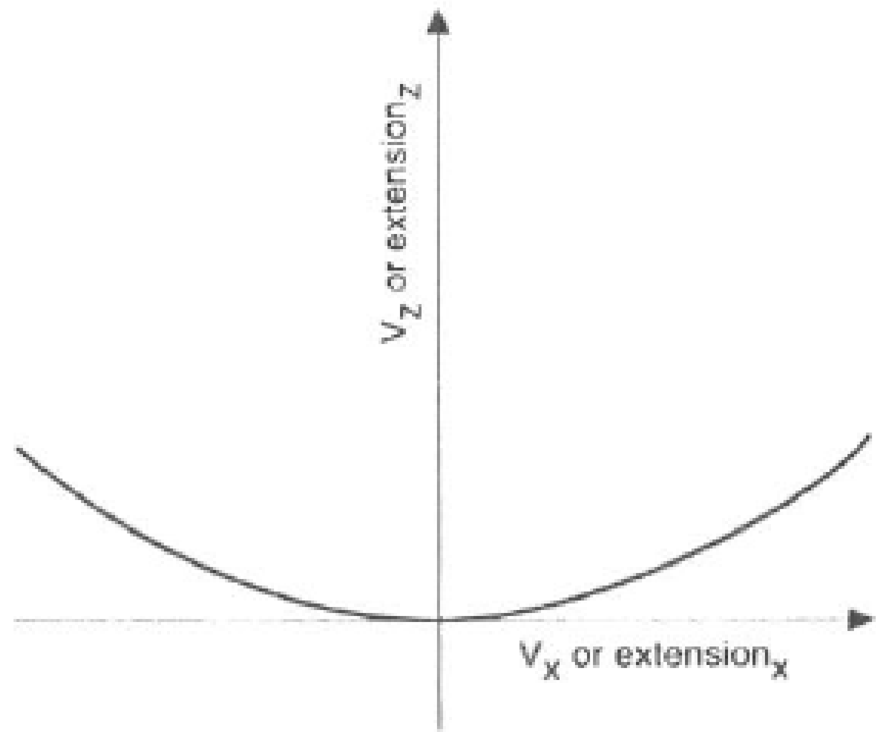


Figure 4- Cross coupling in a piezoelectric scanner: a voltage applied along one axis causes deflections along other axes.

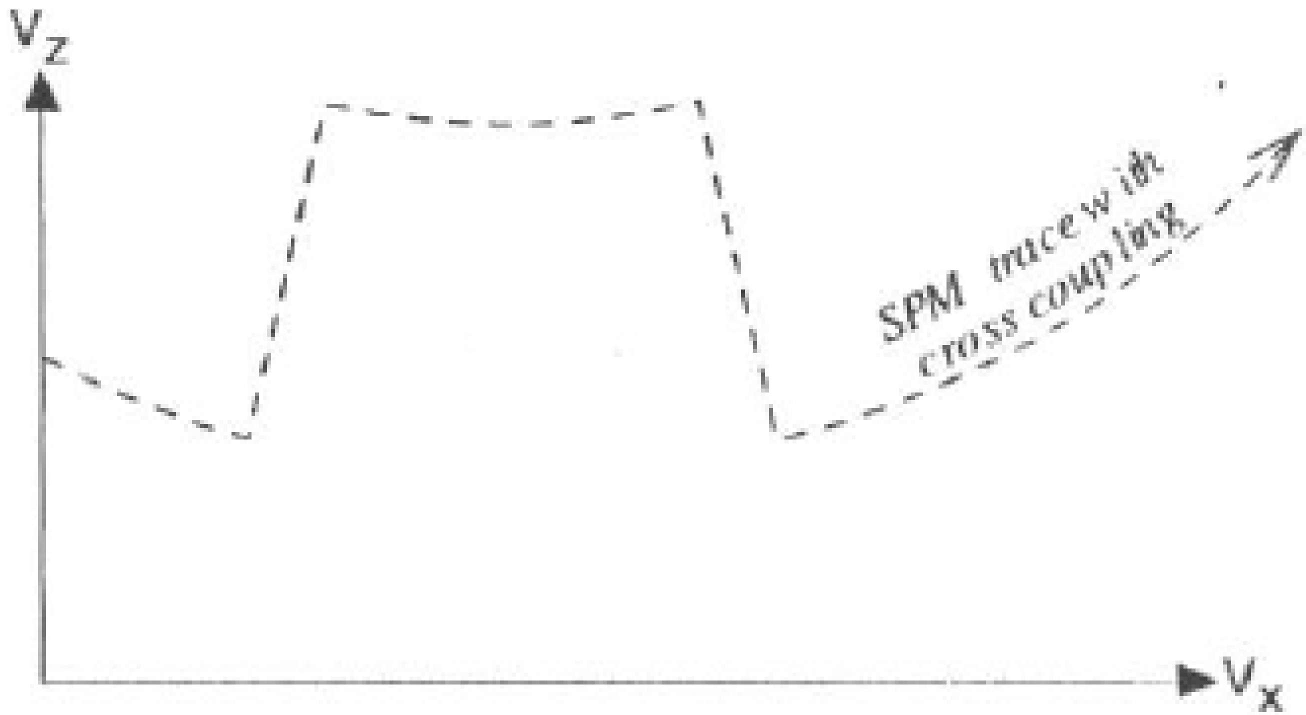


Figure 5- The effects of cross coupling on an SPM image of a step.

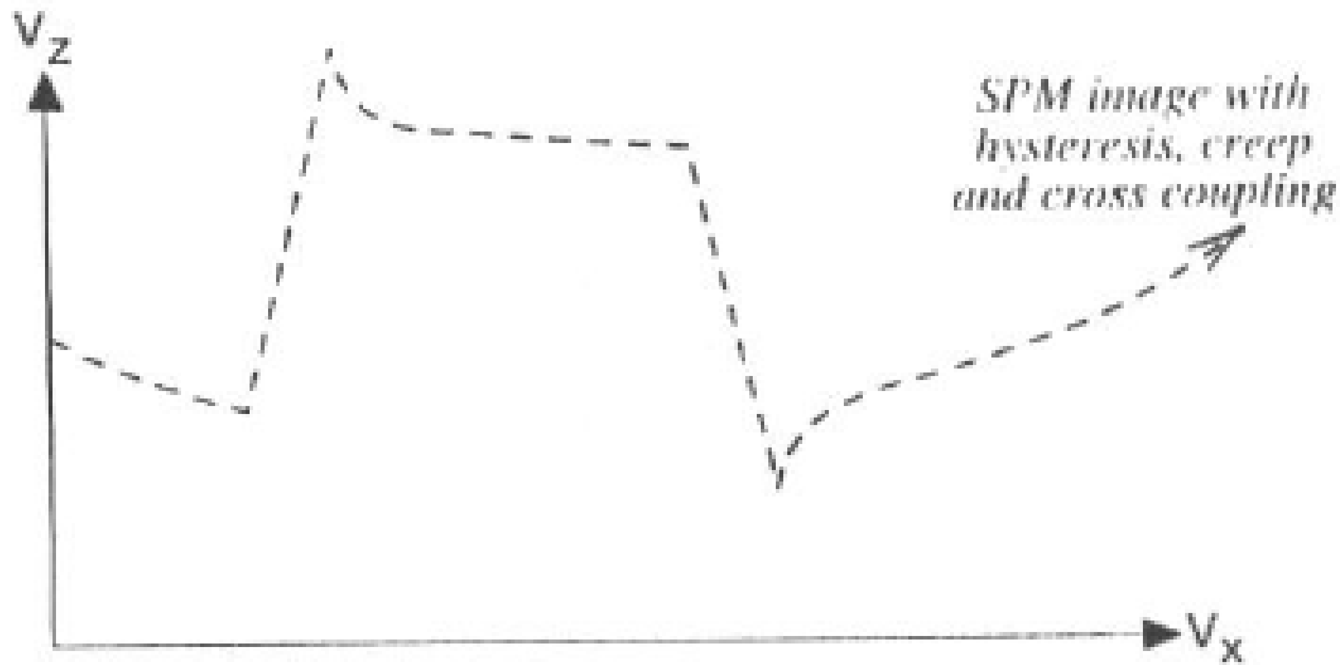


Figure 6- The combined effects of scanner hysteresis, creep and cross coupling on an SPM image of a step.

3- The AFM Cantilever and Tip

Cantilevers and tips are critical components of an AFM system because they determine the ultimate lateral resolution of the system and the force applied to the sample. Integrated tip and cantilever assemblies can be fabricated from silicon or silicon nitride using photolithographic techniques.

i- Properties of Cantilevers and Tips

Atomic force microscopes require not only sharp tips but also cantilevers with "soft" spring constants – lower than the spring constants between atoms in a solid which are on the order of I0 N/m. The spring constant of the cantilever depends on its shape, dimensions and the material from which it is fabricated. As you might think thicker and shorter cantilevers tend to be stiller and have higher resonant frequencies. The spring constants of commercially available cantilevers range over four orders of magnitude from thousandths of a Newton per meter to tens of Newton per meter. Resonant frequencies range from a few kilohertz to hundreds of kilohertz providing high speed response and allowing for non-contact AFM operation.

ii- Selecting an Appropriate Cantilever

The desirable properties for a cantilever depend on the imaging mode and the application. In contact mode soft cantilevers are preferable because they deflect without deforming the surface of the sample. In non-contact mode, still cantilevers with high resonant frequencies give optimal results.

iii- Tip Shape and Resolution

The lateral resolution of an AFM image is determined by two factors: the step size of the image (Figure 1) and the minimum radius of the tip.

The sharpest tips available commercially are specified with a minimum radius of about 50 Å. Because the interaction area between tip and sample is a fraction of the tip radius, these tips typically provide a lateral resolution of 10 to 20 Å.

In the microscopy community, two asperities (peaks) are considered resolved if the image satisfies Rayleigh´s criterion. In this application Rayleigh´s criterion requires that the height of the image must dip at least 19% between the asperities (Figure 7). To determine the lateral resolution of an SPM experimentally, we would bring the asperities closer and closer together until the image no longer dips by 19% between peaks. The minimum separation between resolved asperities determines the best lateral resolution of the system. Using this definition, the lateral resolution of an AFM with the sharpest tips commercially available is 10 to 20 Å.

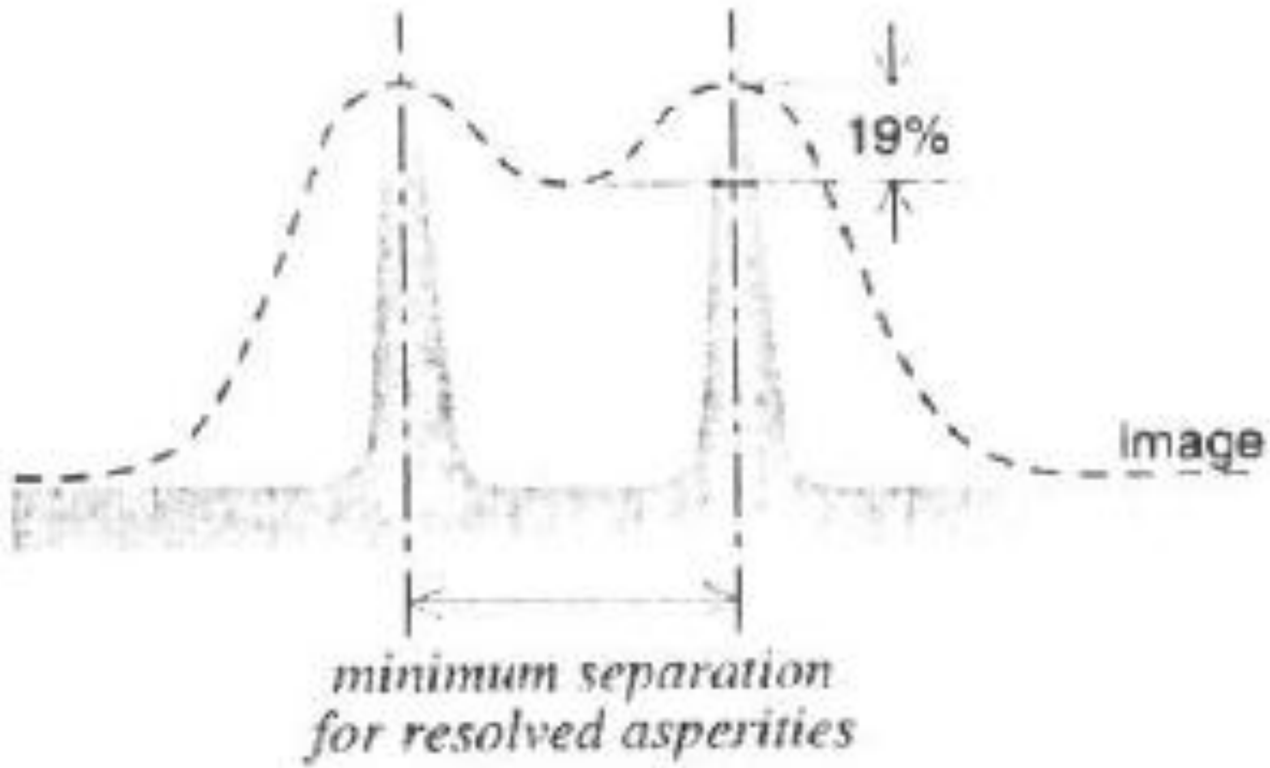


Figure 7- Definition of lateral resolution using Rayleigh's criterion. In this example the two asperities are resolved because the height profile dips 19% between the peaks.

At first glance, the figure of 10 to 20 Å resolution seems to conflict with the ubiquitous images of atomic lattices in AF M brochures. The distinction between imaging atomic-scale features with accurate lattice spacing and symmetry and true atomic resolution bears some comment.

In an AFM the dependence of cantilever deflection on tip-to-sample separation is weaker. The result is that several atoms on the tip interact simultaneously with several atoms on the sample (Figure 8).

In an AFM each atom from the tip that participates in the imaging (each shaded atom in Figure 8) "sees" the sample as a periodic lattice. But because the atoms of the tip are in different lateral positions the lattice that each atom sees is shifted from the lattice seen by its neighbors (Figure 9). Each atom in the tip is also at a different height with respect to the sample. The strength of the signal seen by each lip atom weakens with its distance from the sample. When the contributions from all of the participating atoms in the tip arc combined at each snapshot in time and the result is summed over time as the tip is scanned across the periodic surface, the final image is periodic with the correct symmetry and spacings. However, if one atom were missing the hole left behind would not be detected because the image represents a superposition of many images.

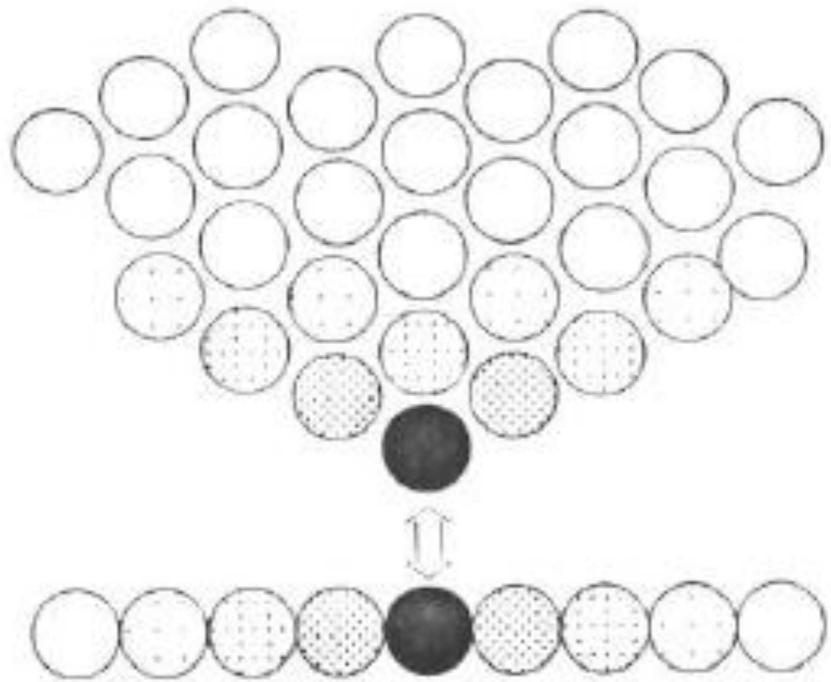
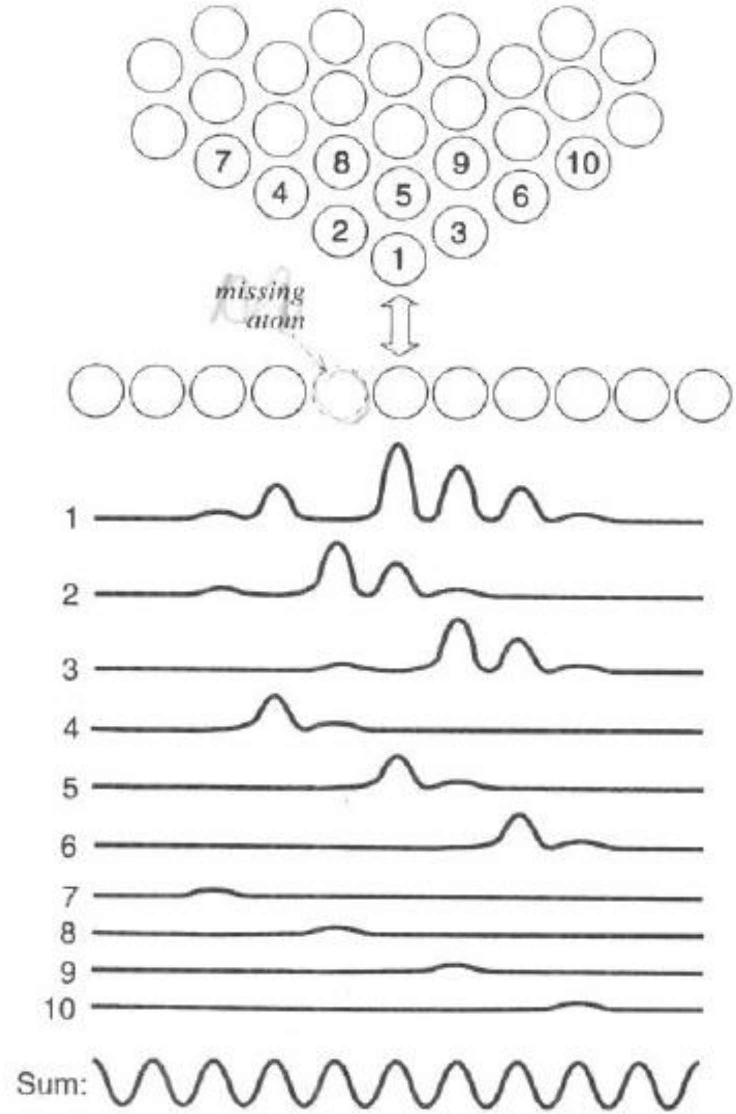


Figure 8- Interatomic interaction in AFM. For AFM, the interaction has weaker distance dependence, so more atoms in the tip and sample are involved. Shading denotes interaction strength.

Figure 9- AFM imaging of an atomic-scale periodic lattice. The profiles below the schematic are numbered to correspond to the image from the associated tip atom, as the sample scans under the tip. The profile labeled sum obtains by summing the contributions from each atom at each instant in time and also summing over time as the sample is scanned under the tip.



4- Common Artifacts

i- Tip Convolution

Most imaging artifacts in SPM arise from a phenomenon knows as tip convolution or tip imaging. Every data point in an image represents a spatial convolution (in the general sense, not in sense of Fourier analysis) of the shape of the tip and the shape of the feature imaged. As long as the tip is much sharper than the feature, the true edge profile of the feature is represented. However, when the feature is sharper than the tip, the image will be dominated by the shape of the tip. Figure 10 demonstrates the origin of tip convolution.

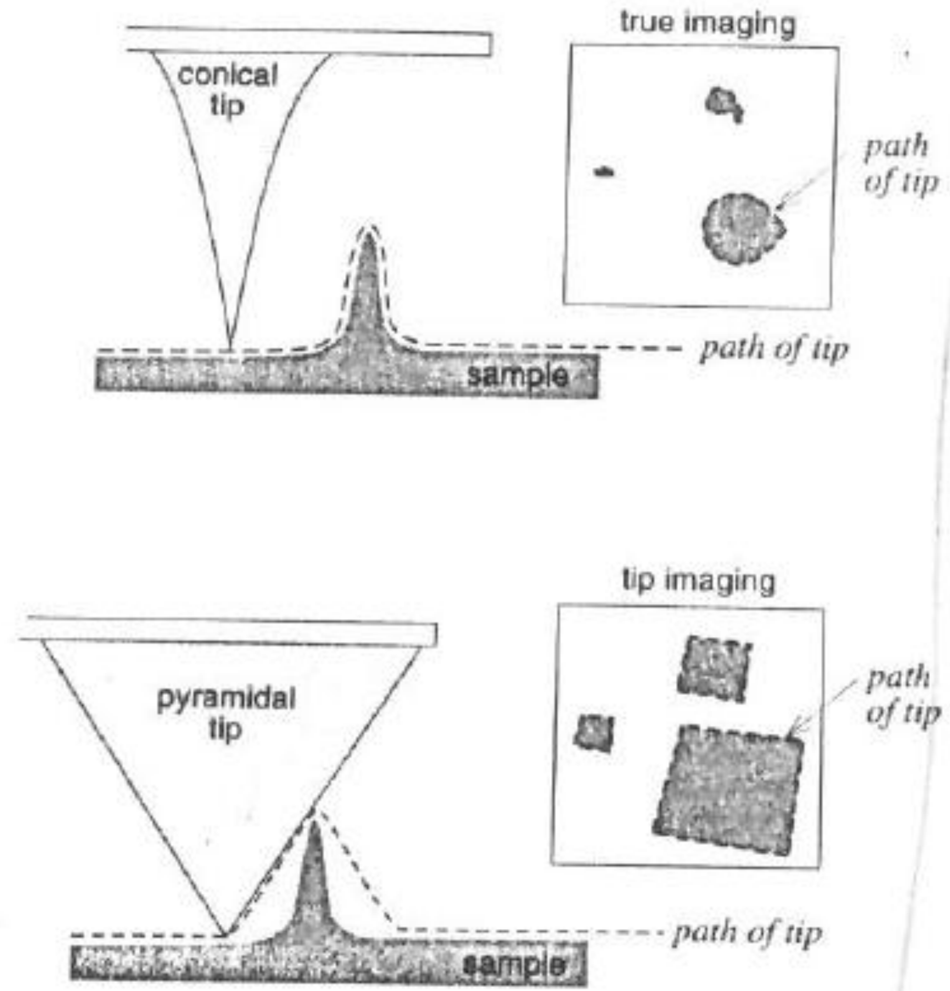


Figure 10- Comparison between true images of feature: imaged by sharp conical tip and tip-dominated image, generated by square-pyramidal tip. Insets show top-down view of 3D SPM image, imaged true and imaged with large, square-pyramidal tip.

ii- Feedback Artifacts

If the feedback loop of the SPM is not optimized the SPM image can be affected. When feedback gains are too high the system can oscillate, generating high frequency periodic noise in the image. This may occur throughout the image or be localized to features with steep slopes.

On the other hand when feedback gains are too low the tip cannot track the surface well. In the extreme case, the image will be losing detail, appearing smooth or "fuzzy". A less obvious effect is "ghosting". On sharp slopes, overshoot can appear in the image as the tip travels up the slope, and an undershoot can appear as the tip travels down the slope. This feedback artifact commonly appears on steep features represented as bright ridges on the uphill side and/or dark shadows on the downhill side of the feature.

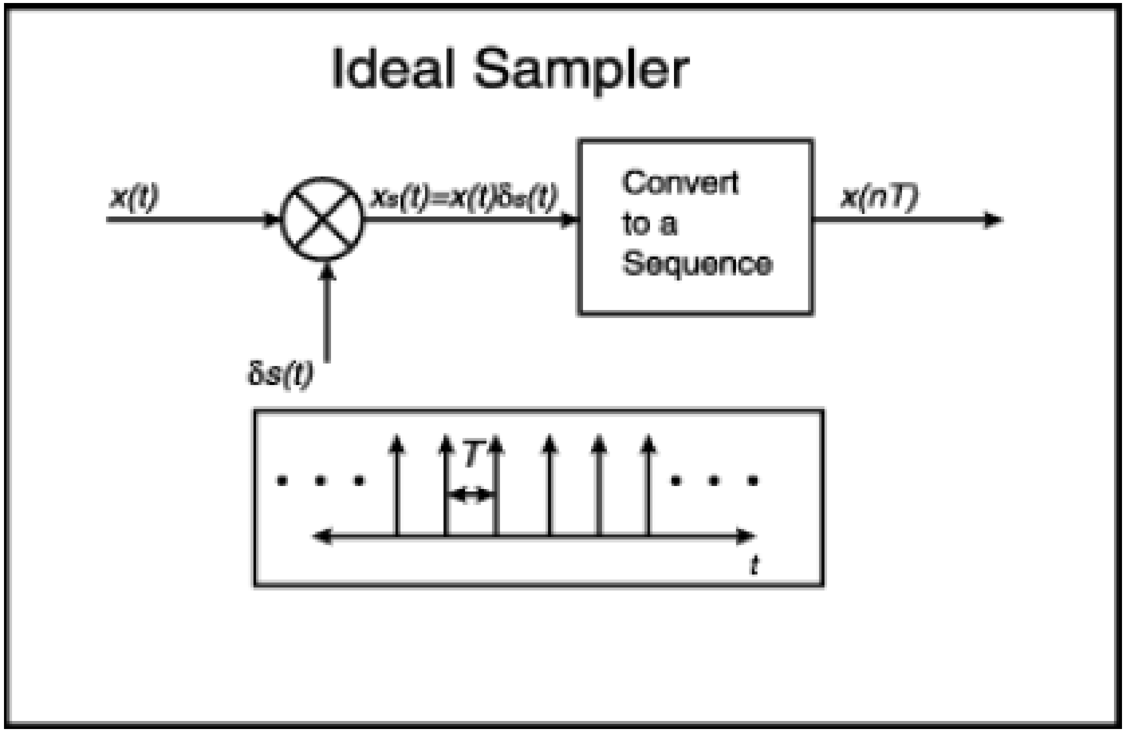


Figure 1- The ideal sampler is a conceptual tool for establishing a link between the continuous-time Fourier Transform (FT) and the Discrete Fourier Transform (DFT). The input to the ideal sampler is *x(t)* and the output consists of the sample values *x(nT).* The “analog” sampled signal, $x_S(t)$, and its FT, $X_S(f)$ are shown in Figure 2.

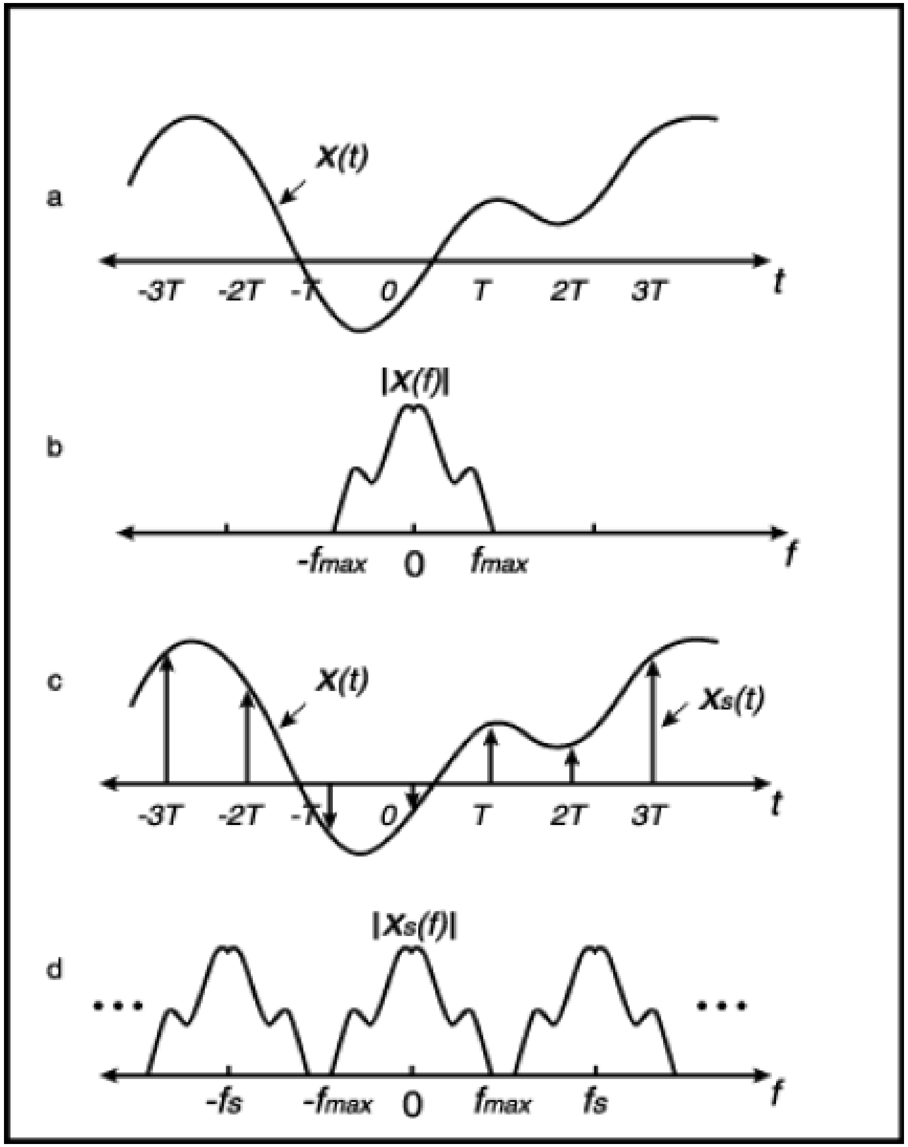


Figure 2-

a) The original continuous-time signal, x(t).

b) The FT of *x(t).*

c) The signal x_S(t) (See Fig. 1). This "conceptual" signal consists of an impulse train with each impulse weighted by x(nT) and spaced T seconds apart. Since x_S(t) is technically a continuous-time signal, it has a FT $X_S(f)$, (in part d).

d) The FT of x_S(t) provides an important conceptual link between the Fourier Transform of the signal of interest x(t) and the DFT of the sampled signal x(nT). Notice that $X_S(f)$ is formed by first multiplying X(*f*) by a constant value 1/T and then replicating X(*f*)/T at intervals spaced f_S=1/T apart (f_S is the effective sampling rate). If the sampling rate is not sufficiently large, then f_S will not be large enough to insure that the replicas of X(*f*)/T do not overlap. Aliasing occurs when the replicas of X(*f*)/T overlap.