Lateral Resolution in Scanning Force Microscopy

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Two particular questions keep coming up regarding Atomic Force Microscopy (AFM), and we would like to address them here.

What exactly is the definition of "lateral resolution" of atomic force microscopy?

The lateral resolution of AFM is a parameter that currently has no accepted definition. The definition used in our lab is "the minimum distance between objects at which you can distinguish distinct objects." In other words, imagine a surface with two sharp features: upon bringing the two features closer and closer together, at some point only one object is seen. That distance is the resolution limit. It is useful to define "see" as having a dip in height greater than the noise level in the image.

In optics, this is analogous to the Rayleigh criterion (aka the Abbé diffraction limit). In this case, a hole in an optically opaque plane with a size near the wavelength of light causes a pattern to appear on the focal plane that consists of a series of concentric rings. The intensity of the rings as a function of radial distance away from the center of the pattern varies as sinc(r). The Abbé diffraction limit is the r value where the first minimum of the pattern from one hole matches up with the first maximum of the second hole. This is a nicely defined distance that can be arrived at because the light interaction with the hole is well described as a convolution and because everybody tries (and can almost) make their light intensity profile look Gaussian (especially when using laser light). It is interesting to note that with modern equipment, it is easy to exceed the Rayleigh criterion. That is, the noise in the profile between two scattering objects is often much less than the dip described by the limit. Thus, it is easy to distinguish two objects that are substantially closer together than the conventional limit. The limit we apply to AFM is analogous to an optical resolution limit much less conservative than the typical Rayleigh criterion. In AFM, resolution is trickier because the probe shape (which takes the place of the light intensity profile) is not so easy to make regular. As a general rule, the shape will be different along every line drawn through the apex of the probe. In addition, the width of the probe varies as a function of height up from the apex. Thus, AFM resolution will depend on the height of the objects measured and the geometry of the specific probe used. For imaging atoms that protrude less than an Ångstrom above the image plane, the lateral resolution of AFM can be below 1 Ångstrom. For objects that are a nanometer or two tall, this resolution limit quickly jumps up to several nanometers and is strongly dependent on the geometry of the particular probe in use.

All of the papers that deal with these issues that we are aware of address accuracy but not resolution.

What is the difference between the "radius of curvature" of an AFM tip, and the "tip radius"?

The term "curvature" is a well defined mathematical concept found in most analytic geometry textbooks and it is:

$$\kappa = \frac{\left|\frac{d^2y}{dx^2}\right|}{\left(1+\left(\frac{dy}{dx}\right)^2\right)^{\frac{3}{2}}}$$

So, if one has an AFM tip and takes a cross section through the tip, there is a well defined curvature at each point along that line. There is another object called the "circle of curvature" which is the circle tangent to the function at the point of interest and having a curvature equal to the function. It turns out that the radius of this circle is $1/\kappa$. People often talk about the "radius of curvature" of their AFM tips, which is an offshoot of this rigorous mathematical concept. What they do is to fit the best possible circle to a cross section taken near the apex of their tip. They then call the radius of this best fit circle the "radius of curvature."

A more cavalier use of the term "tip radius" is used when thinking about the tip as a cylindrically symmetric object. Then, at each position up from the tip apex, the distance from the z-axis of the tip to its surface is reported as the "tip radius."

Some examples of sphere and parabola fits to reconstructed nanosensor SFM probes are at: http://home.cwru.edu/~bat5/research/sfm_probes/nanosensors.html The tip radius for the sphere fit and the radius of curvature for the parabolic fit are generally pretty comparable. ■