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# Standard Guide to Scanner and Tip Related Artifacts in Scanning Tunneling Microscopy and Atomic Force Microscopy[1]

This standard is issued under the fixed designation E2382; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 All microscopes are subject to artifacts. The purpose of this document is to provide a description of commonly observed artifacts in scanning tunneling microscopy (STM) and atomic force microscopy (AFM) relating to probe motion and geometric considerations of the tip and surface interaction, provide literature references of examples and, where possible, to offer an interpretation as to the source of the artifact. Because the scanned probe microscopy field is a burgeoning one, this document is not meant to be comprehensive but rather to serve as a guide to practicing microscopists as to possible pitfalls one may expect. The ability to recognize artifacts should assist in reliable evaluation of instrument operation and in reporting of data.

1.2 A limited set of terms will be defined here. A full description of terminology relating to the description, operation, and calibration of STM and AFM instruments is beyond the scope of this document.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1813 Practice for Measuring and Reporting Probe Tip Shape in Scanning Probe Microscopy

## 3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *artifact*—any feature of an image generated by an AFM or STM that deviates from the true surface. Artifacts can have origins in sample preparation, instrument hardware/software, operation, post processing of data, etc.

3.1.2 *image*—surface topography represented by plotting the z value for feature height as a function of x and y position. Typically the z height value is derived from the necessary z voltage applied to the scanner to allow the feedback value to remain constant during the generation of the image. The "image" is therefore a contour plot of a constant value of the surface property under study (for example, tunneling current in STM or lever deflection in AFM).

3.1.3 *tip*—the physical probe used in either STM or AFM. For STM the tip is made from a conductive metal wire (for example, tungsten or Pt/Ir) while for AFM the tip can be conductive (for example, doped silicon) or non-conductive (for example, silicon nitride). The important performance parameters for tips are the aspect ratio, the radius of curvature, the opening angle, the overall geometrical shape, and the material of which they are made.

3.1.4 *cantilever or lever*—the flexible beam onto which the AFM tip is placed at one end with the other end anchored rigidly to the microscope. The important performance parameters for cantilevers are the force constant (expressed in N/m) and resonance frequency (expressed in kHz typically). These values will depend on the geometry and material properties of the lever.

3.1.5 *scanner*—the device used to position the sample and tip relative to one another. Generally either the tip or sample is scanned in either STM or AFM. The scanners are typically made from piezoelectric ceramics. Tripod scanners use three independent piezo elements to provide motion in x, y, and z. Tube scanners are single element piezo materials that provide coupled x,y,z motion. The important performance parameters for scanners are the distance of movement per applied volt (expressed as nm/V) and the lateral and vertical scan ranges (expressed in microns).

3.1.6 *scan angle*—the angle of rotation of the x scan axis relative to the x-axis of the sample

3.1.7 *tip characterizer*—a special sample used to determine the geometry of the tip. The tip in question is used to image the characterizer. The image then becomes an input to an algorithm for determining the tip geometry.

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[1] This guide is under the jurisdiction of ASTM Committee E42 on Surface Analysis and is the direct responsibility of Subcommittee E42.14 on STM/AFM.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2 *Abbreviations:*

3.2.1 *AFM*—atomic force microscopy (microscope). We refer here to contact mode AFM as opposed to non-contact techniques.

3.2.2 *STM*—scanning tunneling microscopy (microscope).

## 4. Significance and Use

4.1 This compilation is limited to artifacts observed in scanning tunneling microscopes and contact-mode atomic force microscopes. In particular, this document focuses on artifacts related to probe motion and geometrical considerations of the tip and surface interaction. Many of the artifacts described here extend to other scanned probe microscopies where piezoscanners are used as positioning elements or where tips of similar geometries are used. These are not the only artifacts associated with measurements obtained by STM or AFM. Artifacts can also arise from the following: control electronics (for example, improper feedback gains); noise (mechanical, acoustic, or electronic); drift (thermal or mechanical); problems unique to signal detection methods (for example, laser spillover in optical lever schemes); improper use of image processing (real time or post processed); sample preparation, environment (for example, humidity) and tip-surface interaction (for example, excessive electrostatic, adhesive, shear, and compressive forces). It is suggested that these other types of artifacts form the basis of future ASTM guides.

## 5. Artifacts in STM and AFM

5.1 *Artifacts arising from Scanner Motion*—Scanners are made from piezoelectric ceramic materials used to accurately position the tip relative to the surface on the nanometer scale. They exhibit an inverse piezoelectric effect where the material will undergo dimensional change in an applied electric field. Ideal behavior is often assumed when using these devices in STM or AFM microscopes. Ideal behavior implies: (*1*) linear response in dimensional change per applied volt; (*2*) no dependence of the dimensional response on the direction of the voltage change, the magnitude of the voltage change, or the rate of the voltage change (Fig. 1). The motions of these devices are subject to deviations that include non-linearity, hysteresis, and creep (**1-5**).[3] In addition to these non-ideal motions which are characteristic of independent scanner axes, artifacts may arise as a consequence of coupling between the axes.

5.1.1 *Non-Linearity*—Non-linearity means that the response of the scanner in nm/V changes as a function of applied voltage. Typically the response deviates more at larger positive or negative voltages than near zero applied volts (**2**) (Fig. 2). Non-linear effects in the lateral direction (x,y) can be observed most clearly when scanning a periodic structure with known spatial frequencies such as a diffraction grating . Since the scanner does not move linearly with applied voltage, the measurement points will not be equally spaced. The observed spacings will vary over the image and some linear features will appear curved. While obvious for test structures, this effect could go unnoticed on other samples that do not have evenly spaced surface features. This effect can be compensated for in software by applying a non-linear voltage ramp during scanning based on prior calibration (open loop method) or by independently measuring the position of the scanner using an additional position sensor such as a capacitor plate (closed loop method) (**5**). An example of the open loop correction method is given in Fig. 3. Non-linear effects in z or height measurements are less obvious but can be detected using vertical height

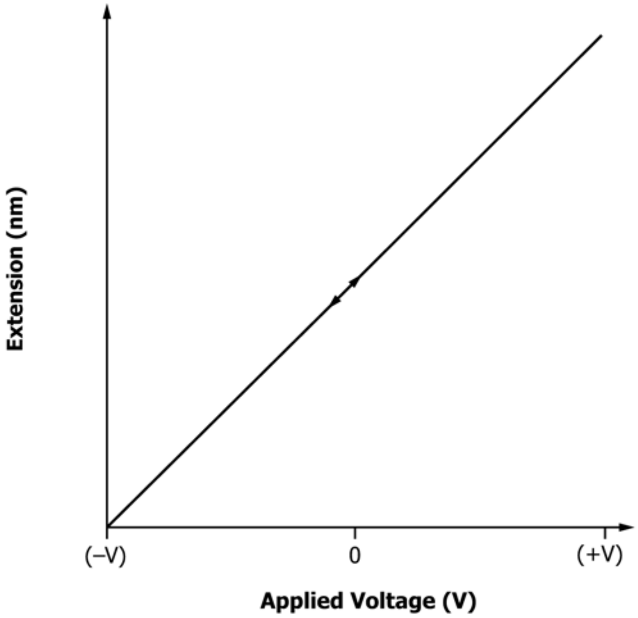
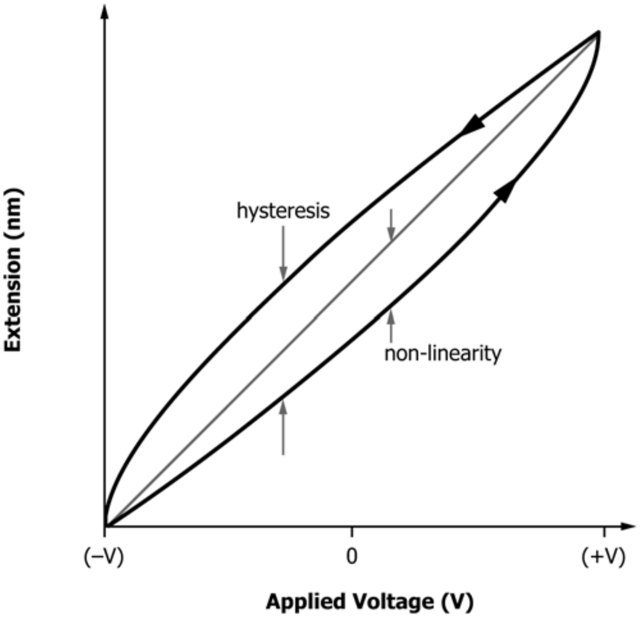


FIG. 1 Ideal Behavior of a Piezoelectric Scanner in One Dimension (Either *x, y,* or *z*)



NOTE 1—Non-linear extension in response to linear applied voltage and hysteresis where the sensitivity varies depending on direction of applied voltage.

FIG. 2 Non-Ideal Behavior in a Piezoelectric Scanner

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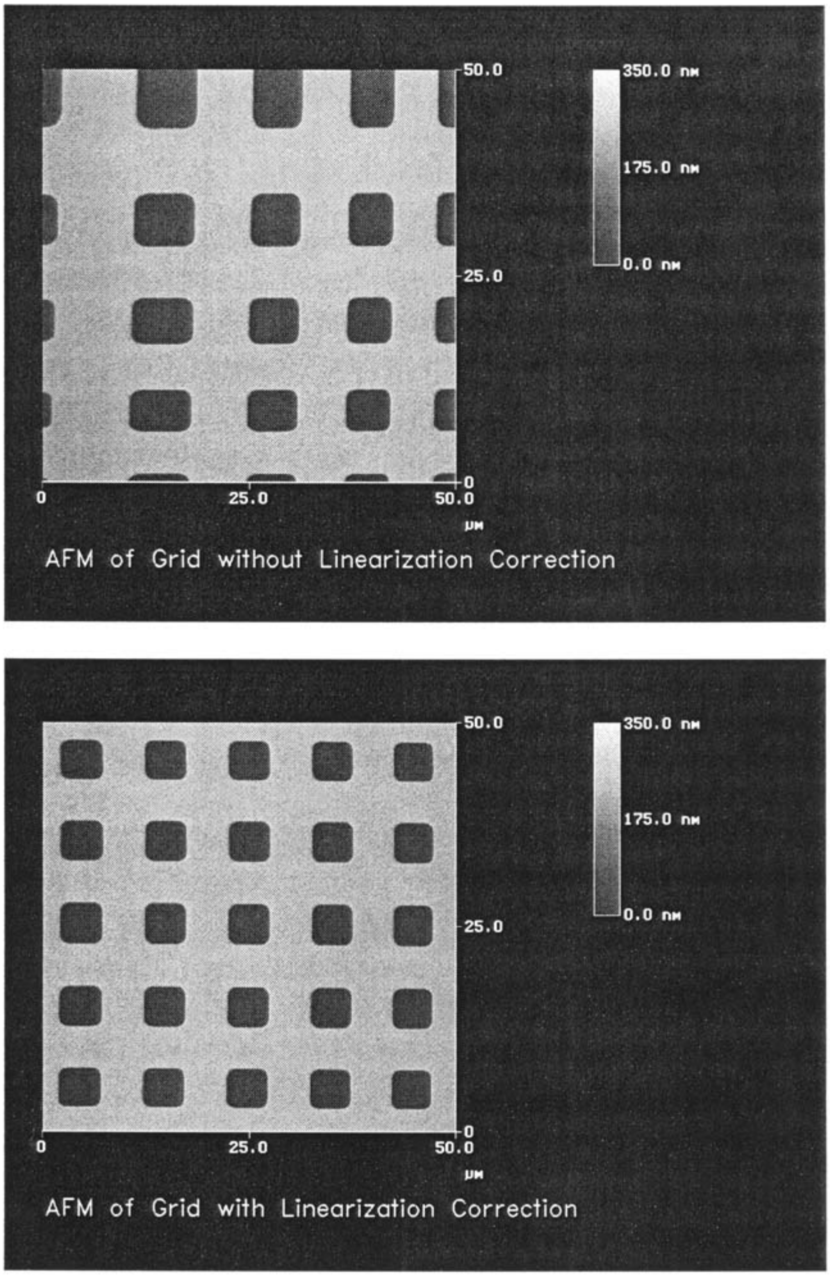
[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.



NOTE 1—(Images courtesy of G. Meyers. Used with permission of The Dow Chemical Company.)

**FIG. 3 AFM of a Two-Dimensional Grating (Top) without Software Linearity Correction and (Bottom) with the Open-Loop Correction**

standards (**4**). They are most noticeable when trying to measure small features (small changes in V) and large features (large changes in V) within the same scan. They are also more difficult to correct for due to the complex coupling of motion of x and y to z, in say, a tube scanner.

5.1.2 *Hysteresis*—Hysteresis occurs in piezoelectric materials when the response traces a different path depending on the direction of the voltage change (Fig. 2). The magnitude of the effect will depend on the DC starting voltage, the size of the voltage change, the rate of the voltage change, and the scan angle. The effects of hysteresis can be compensated for by means of a software correction. However, the accuracy of the correction is limited by the need to create a model with a large number of variables. In the case where voltage ramps are applied to the scanners, such as in rastering in x,y for STM or AFM imaging or for ramping in z for generating a force versus distance curve in AFM, the tip or sample will move nonuniformly. Hysteresis could explain why the distance between the same features in an image might differ depending on the direction of scan (trace versus retrace), the size of the scan, or