A STUDY OF HEIGHT MEASUREMENTS USING THE Z_SENSE AND Z_DRIVE SIGNALS

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1. Introduction

In this note, a study of height measurements using the Z_DRIVE and Z_SENSE signals is presented. Two problems are presented.

(1) The Z_DRIVE signal suffers from piezo hysteresis. Therefore the measured height depends on the history of the scan. This was documented in a previous note. This can be observed as what appear to be height variations of what should be a uniform background in grid patterns. Here we add that the height measurements vary across the image.

(2) In some cases, the Z_DRIVE signal produces a valid image while the Z_sense image shows loss of signal. It si possible that he piezo feedback has more range than the strain gauge.

2. Materials and Methods

2.1. AFM Configuration. The data presented in this document were taken with a TT2-AFM (AFMWorkshop). Images were acquired over 256 lines with a scan rate of 0.5 Hz, in vibrating mode. The extension factor as set to 0.7, but when the Z_SENSE signal lost contact, the extension factor was reduced to 0.65.

2.2. Samples. The following height standards were used:

(1) A BudgetSensors HS-100MG 100nm height standard, with a specified height of 114 nm.

(2) BudgetSensors HS-20MG 20nm height standard, specified to be 21.4 nm.

2.3. Image Processing. The open source Gwyddion software package was used to process the data, unless otherwise stated.

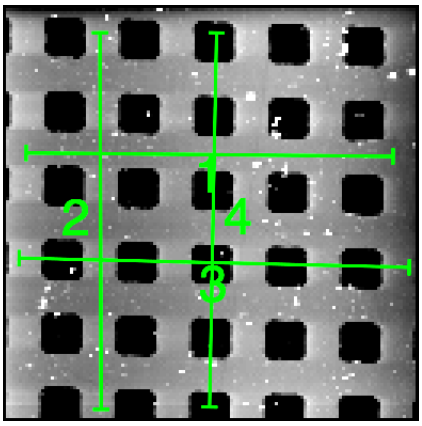
3. Artefact in measurement of height standard grids

Here we demonstrate a problem in using two height standards: AppNano SHS-0.1 and Budget Sensors HS100MG. Our SHS-0.1 is specified to be 104 nm and both of our HS-100MG targets are specified to be 113 nm.

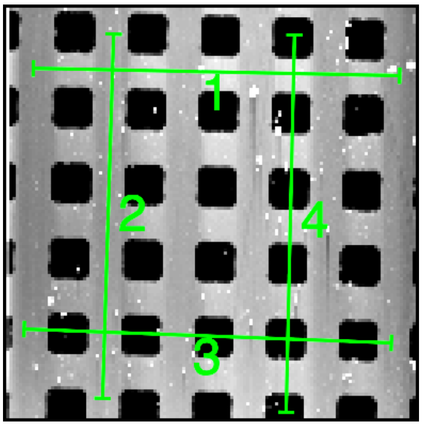
3.1. SHS-0.1. Figure 1 shows two images, acquire sequentially, where the only difference is the scan rotation. Figure 1(A) was acquired with scan rotation of 0°, while Figure 1(B) was acquired with scan rotation set to 90°. These images were levelled using Gwyddion's Flatten Base method. This is not the best levelling method, but it is adequate for our purpose.

Let us focus on profiles 1 and 2 in each image. These profiles run along the background, and do not enter wells. They should be flat. Since the levelling method not ideal, they have some polynomial distortion.

Figure 2 shows the profiles for Figure 1(A). Profile 1 is as expected, but Profile 2 has a periodic component of about 10 nm However, in the profiles for the image in Figure 1(B), shown in Figure 3, Profile 1 has the periodic component, and Profile 2 is smooth to within the polynomial distortion of the background. The only different here is the scan rotation. The target has not moved. Therefore, this spurious component must be a function of the scanner, not the target. SInce the target is a 100 nm standard (Appnano



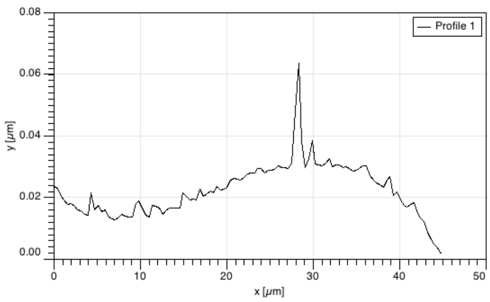
(A)



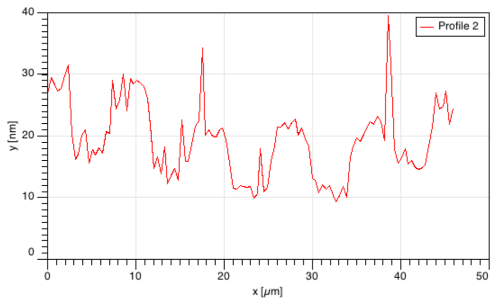
(B)

Figure 1. (A) AFM image of SHS-0.1 area B (10 µm pitch grid) acquired with scan rotation set to 0°. (B) Same target rescanned with scan rotation set to 90°. All other parameters were unchanged. Height profiles were acquired along the green lines.

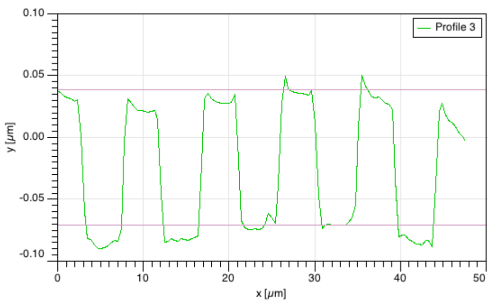
labeled it as 104 nm), there is a significant difference if the height is measured with Profile 3 or Profile 4.



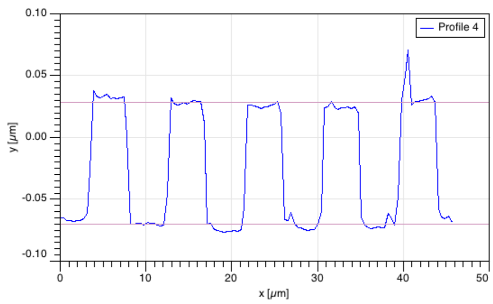
(A)



(B)



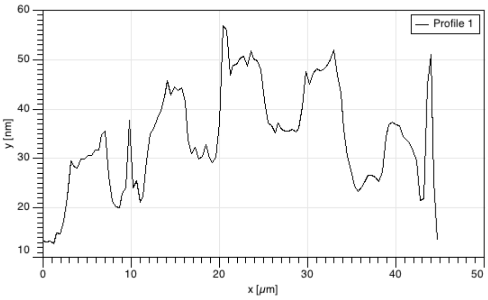
(C)



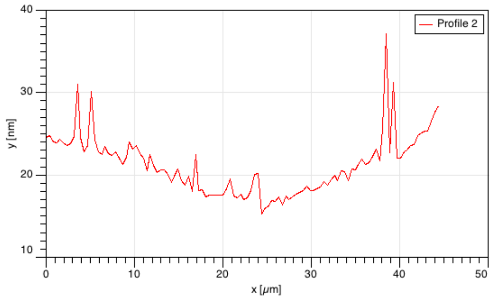
(D)

Figure 2. Line height profiles of the image in Figue 1(A) (0°rotation). (A) Profile 1 (B) Profile 2,(C) Profile 3 (D) Profile 4

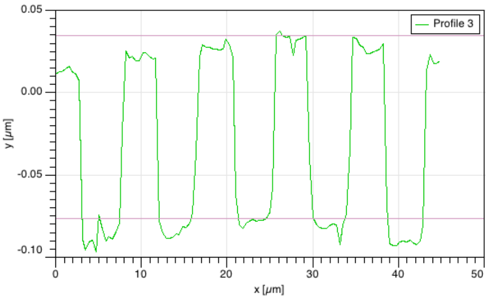
3.2. HS100MG. Figure 4 shows two images, acquire sequentially, where the only difference is the scan rotation. Figure 4(A) was acquired with scan rotation of 0°, while Figure 4(B) was acquired with scan rotation set to 90°. As for the SHS images above, these images were levelled using Gwyddion's Flatten Base method.



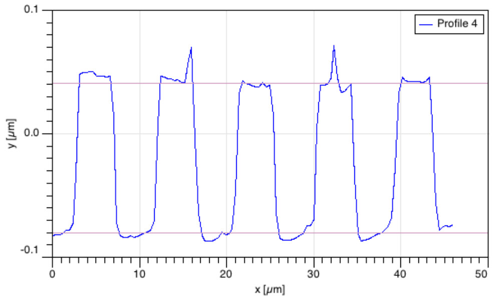
(A)



(B)

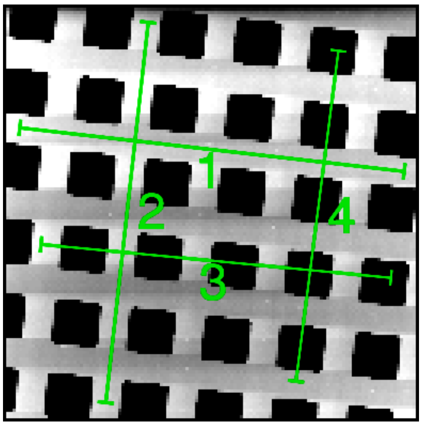


(C)

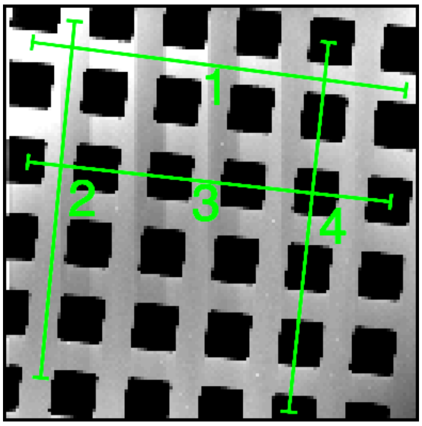


(D)

FIGURE 3. Line height profiles of the image in Figure 1(B) (90°rotation). (A) Profile 1 (B) Profile 2,(C) Profile 3 (D) Profile 4



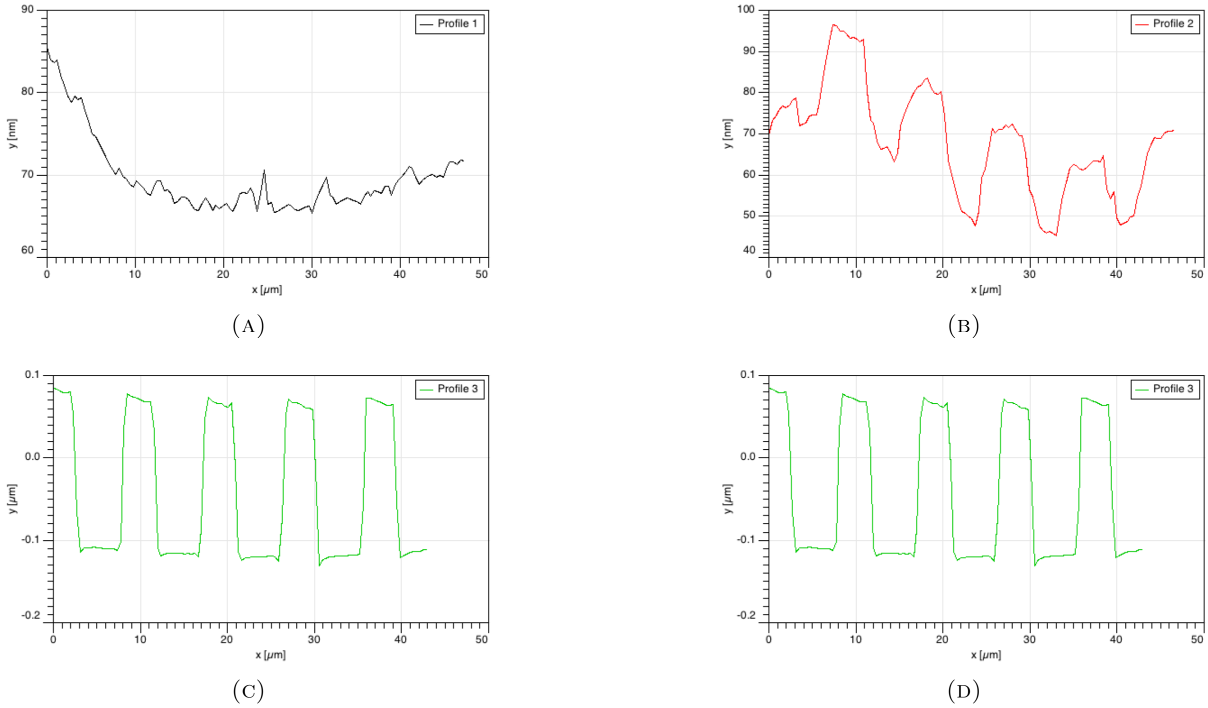
(A)



(B)

FIGURE 4. (A) AFM image of HS100MG (10 µm pitch grid) acquired with scan rotation set to 0°. (B) Same target rescanned with scan rotation set to 90°. All other parameters were unchanged. Height profiles were acquired along the green lines.

Figure 5 shows the profiles for Figure 4(A). Profile 1 is as expected, but Profile 2 has a periodic component of about 10 nm However, in the profiles for the image in Figure 4(B), shown in Figure 6, Profile 1 has the periodic component, and Profile 2 is smooth to within the polynomial distortion of the background. The only different here is the scan rotation. The target has not moved. Therefore, this spurious component must be a function of the scanner, not the target. Since the target is a 100 nm standard (Budget Sensors labeled it as 113 nm), there is a significant difference if the height is measured with Profile 3 or Profile 4. Notice that the artefact is either vertical or horizontal. Unlike the SHS images above, the HS100MG was not positioned with its grid aligned with the scan directions. Yet we see that the artefact is aligned with the scan directions, and follows the scan rotation reproducibly.



(A) (B) (C) (D)

FIGURE 5. Line height profiles of the image in Figure 4(A) (0°rotation). (A) Profile 1 (B) Profile 2,(C) Profile 3 (D) Profile 4

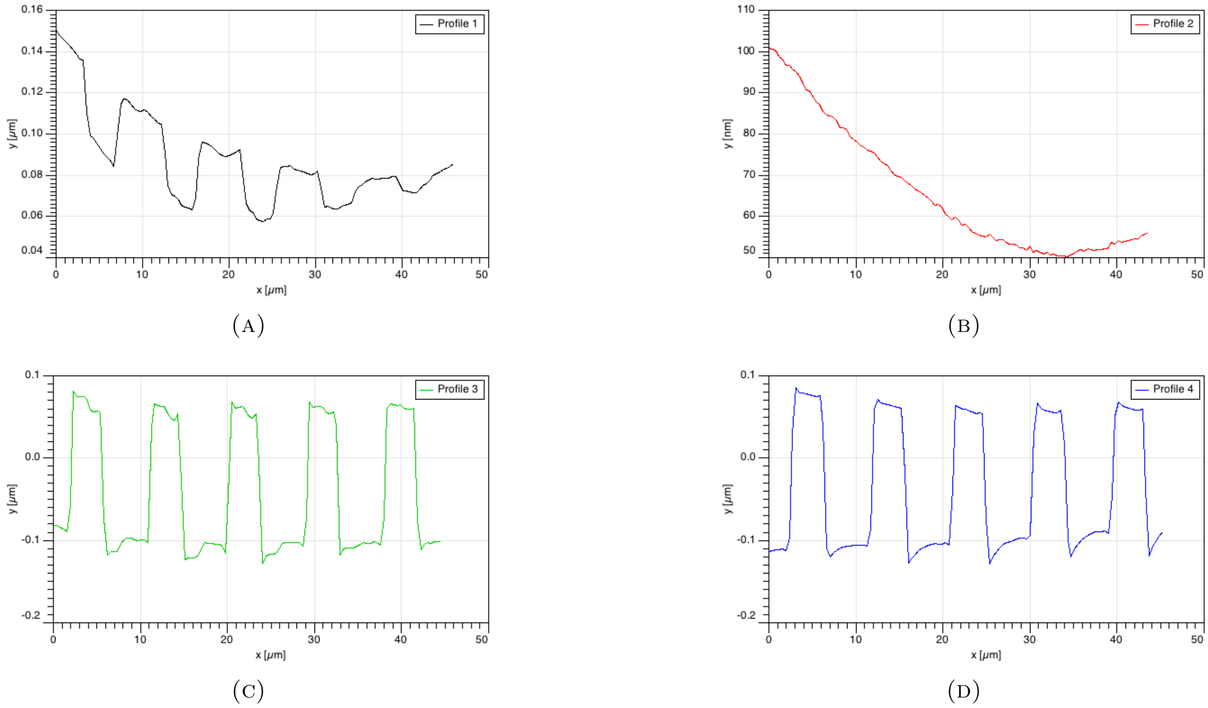


FIGURE 6. Line height profiles of the image in Figure 4(B) (90°rotation). (A) Profile 1 (B) Profile 2,(C) Profile 3 (D) Profile 4

3.3. Z_DRIVE vs Z_SENSE. These data were sent to AFMWorkshop, and they noted that the Z_DRIVE signal is affected by piezoelectric hysteresis, while the Z_SENSE signal is not affected by hysteresis. In this section, we compare the Z_DRIVE (drive signal to the piezos) and Z_SENSE (strain-gauge signal) images. We will see that the Z_SENSE image indeed has no hysteresis, but it is noisier than the Z_DRIVE signal. The Z_SENSE data are calibrated, same as the Z_DRIVE data. The TT-AFM software provides for both Z_DRIVE and Z_SENSE calibration. However, the Gwyddion software displays the Z_SENSE data in units of volts, such that the calibration is 1 nm/mV.

In this section, we will explore that effects of hysteresis by comparing the Z_DRIVE and Z_SENSE images in a number of situations that include:

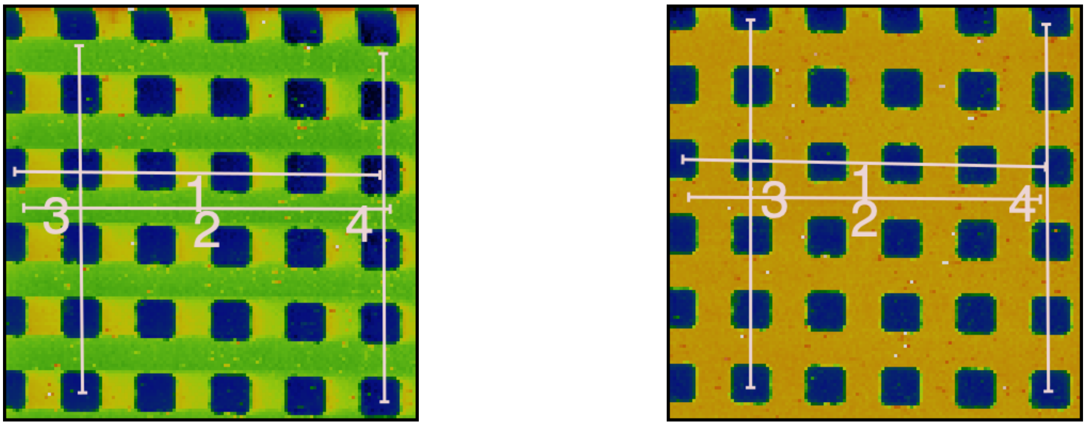
(1) Height standards that are grids (SHS-0.1 and HS20MG). In this case we have a relatively large coverage of "objects", with two different heights.

(2) Different scan speeds.

(3) 30 nm gold nano particles (GNP). These may not be observable in the Z_SENSE image due the the higher noise level of Z_SENSE. [not yet done]

3.3.1. *SHS-0.1* 100 nm *Height Standard.* Figure 7A shows the Z_DRIVE image of SHS-0.1 area B (10 µm pitch grid). The pseudo-colored image shows the measured height differences in the background between the rows of the grid squares. Figure 7B shows the Z_SENSE image of the same area. This image has a uniform background. The scan distortion observed at the top of these images will be discussed in a separate section

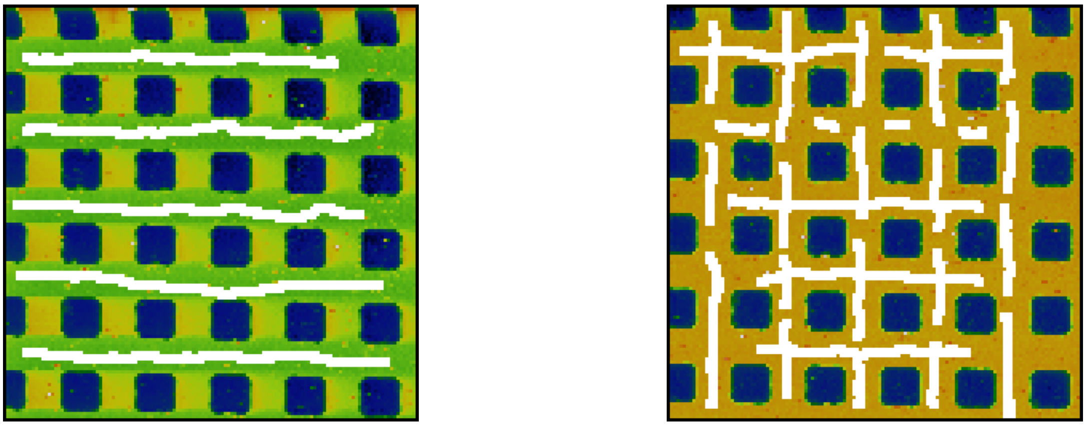
The images in Figure 7 were levelled using the *Data Process>Level>Polynomial Background...* function, with degree three in both directions, including only the masked region. Figure 8 shows the masks that were used, overlaid on the images. Notice that for the Z_DRIVE images, the mask was only drown on the uniform lines where the grid squares do not appear. The regions between the squares along the scan



(A) (B)

Figure 7. (A) Z_DRIVE image of SHS-0.1 area B (10 µm pitch grid). (B) SZ_SENSE image of SHS-0.1 area B (10 µm pitch grid). Height profiles were acquired along the pink lines. .

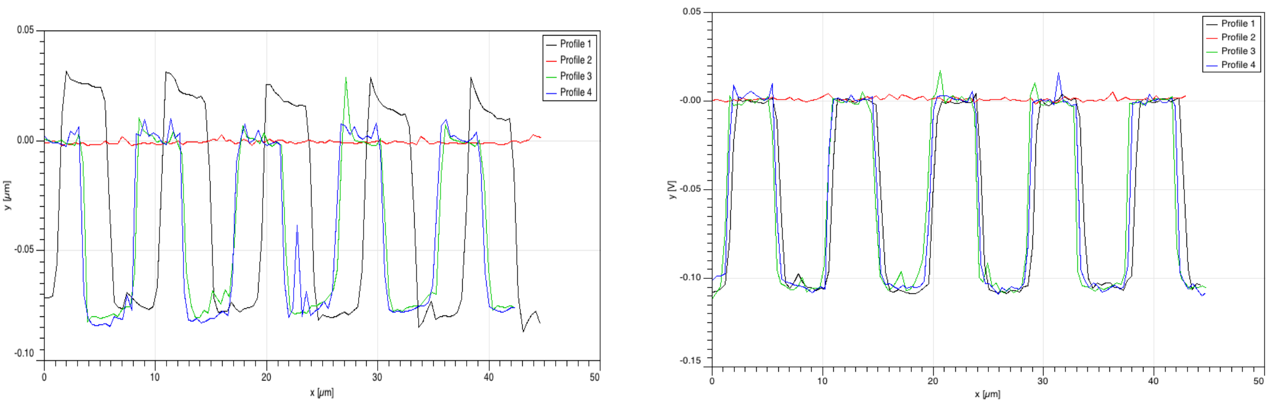
lines cannot be used because there is a non-constant hysteresis effect. That is, the background height will not appear constant.



(A) (B)

Figure 8. (A) Mask used to level the Z_DRIVE image shown in Figure 7A, overlaid on the Z_DRIVE image. (B) Mask used to level the SZ_SENSE image shown in Figure 7B overlaid on the Z_SENSE image.The mask for the Z_DRIVE image only covers the area that does not include the grid wells, and is parallel to the scan direction, so there is no hysteresis along those lines.

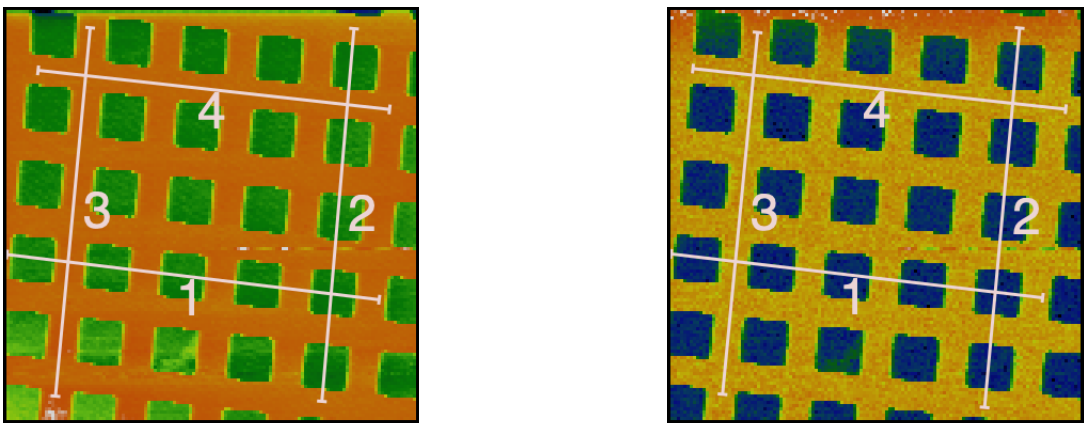
Line profiles were measured along the indicated lines, and appear in Figure 9



(A) (B)

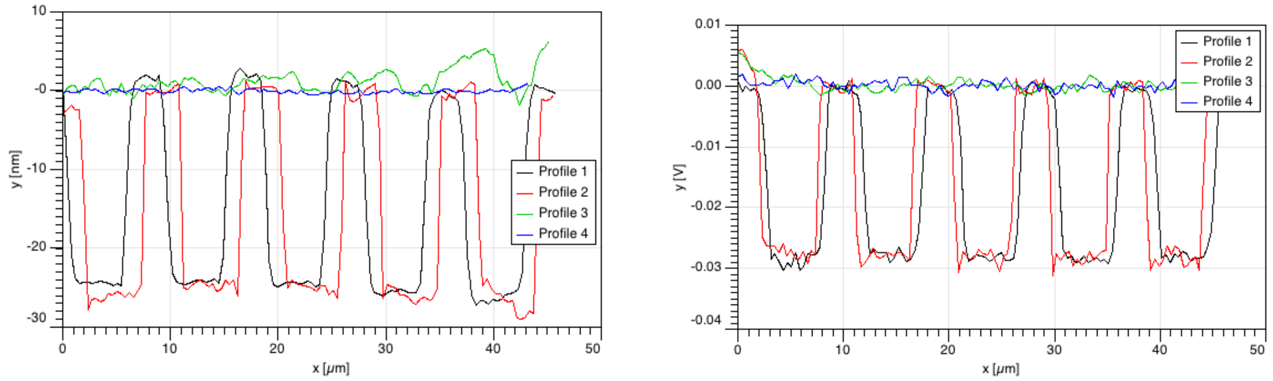
Figure 9. (A) Line profiles for the Z_DRIVE image shown in Figure 7A. (B) Line profiles for the Z_SENSE image shown in Figure 7B. The flat red profile (profile 2) hows that the background is levelled well. In the Z_DRIVE image, which was acquired at 0°scan rotation, the vertical profiles are reproducible, while the horizontal profile changes wtih distance along X. The Z_SENSE image has reproducible profiles in both directions.

3.3.2. *HS20MG* 20 nm *Height Standard.* Z_DRIVE and Z_SENSE images of the HS20MG standard (labeled by BudgetSensors as 21.6 nm) are shown in Figure 10. The hysteresis effect are greatly reduced, but can be observed near the bottom of the Z_DRIVE image, as seen in profile 3 shown in Figure 11(A).



(A) (B)

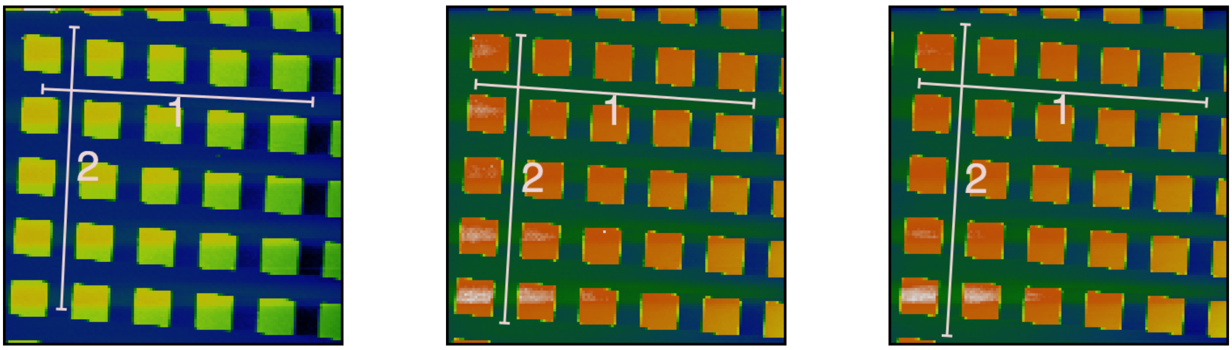
Figure 10. (A) Z_DRIVE image of an HS20MG test sample. (B) Z_SENSE image of an HS20MG test sample. These two images were acquired simultaneously as the right and left images of a single TT-AFM scan.



(A) (B)

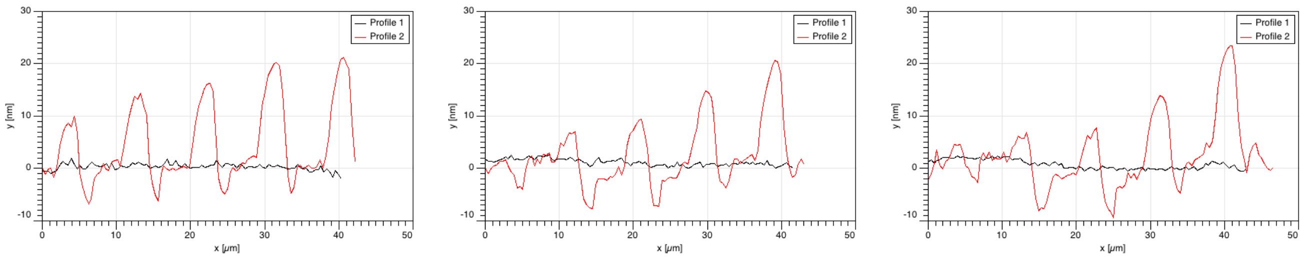
Figure 11. (A) Line profiles for the Z_DRIVE image shown in Figure 10A. (B) Line profiles for the Z_SENSE image shown in Figure 10B. In (A), some hysteresis is seen in profile 3, but the effect is much less that with the 100 nm standards.

3.3.3. *The Effect of Scan Rate.* An HS100MG was images at three scan rates: 0.5 Hz, 0.25 Hz, and 0.125 Hz. The Z_DRIVE images are shown in Figure 12. Line profiles that were acquired parallel (profile 1) and perpendicular (profile 2) to the scan direction for each of these images are shown in Figure 13. Even at slow scan rates, there is appreciable hysteresis.



(A) (B) (C)

Figure 12. Z_DRIVE images of an HS1000MG test sample with different scan rates: (A) 0.5 Hz. (B) 0.25 Hz. (C) 0.125 Hz.



(A) (B) (C)

Figure 13. Line profiles for Z_DRIVE images in Figure 12 (A) 0.5 Hz. (B) 0.25 Hz. (C) 0.125 Hz.

4. Epilogue

This document was created in two stages. First, the phenomenon was characterized and presented to AFM Workshop. The phenomenon was diagnosed by AFM Workshop to be caused by hysteresis in the piezo-scanners.This was confirmed by comparing the Z_DRIVE to the Z_SENSE images, and verifying that the Z_SENSE images did not exhibit the problem that had been documented. The conclusion is that when possible, the Z_SENSE image is preferred. However, the Z_SENSE signal is much noisier than the Z_DRIVE signal. In practice, this means that for measurements of less than about 50 nm, the Z_DRIVE signal is preferred, and certainly for nanometric measurements (for example, the SiC 1.5 nm test sample). Fortunately, for very small displacements, the hysteresis effect is reduced.

Finally, we note that at the time these data were acquired, the AFM instruments were calibrated against the AppNano SHS-0.1 100 nm height standard. We have since found that this standard is wrong, and the Budget Sensors HS-100MG standards correct.