# Keysight Technologies
# Intrinsic Contact Noise: A Figure of Merit for Identifying High Resolution AFMs

Application Note

# Introduction

Resolution and sensitivity are two important characteristics by which to judge the performance of an Atomic Force Microscope (AFM), and they are both adversely affected by noise. If the AFM is noisy, a sensitive cantilever or detector, a precisely calibrated piezoelectric scanner, and a whole host of other high-performance elements of an AFM may as well be replaced by lower-performance, cheaper substitutes because, their value is lost in the noise of the AFM.

Resolution and sensitivity of an AFM cannot be determined from the performance specifications of a component, or of a collection of components. While tabulated numerical specifications can make one AFM look better than another, the usefulness of a specification, a "spec", is only validated if it can be shown to directly correlate with better performance, the definition of which we limit here to higher resolution and better sensitivity. For example, one AFM may be specified to allocate two more bits than another AFM, for analog-to-digital (A/D) conversion of the voltage applied to the piezoelectric actuators, thus implying that tip fine positioning resolution is superior in the first AFM. But in fact, when it comes to AFM image resolution, those two extra bits may add nothing of value if the lowest achievable noise level, the noise floor, of the two AFMs are the same, and larger than the equivalent of three digital bits in both AFMs's A/D converters.

This question of usefulness, of relevance, extends to noise specifications just as well. Does a particular definition of noise, and the spec derived from that definition, directly relate to the AFM's performance when it comes to resolution and sensitivity? In the majority of AFM noise studies published so far, the AFM tip and the sample have been out of direct contact (Figure 1(a))[1]. Although the details may vary from one experiment to the next, we refer to the noise measurements in those experiments as "non-contact noise". While non-contact noise measurements may be useful, and they certainly are, for example in estimating a cantilever's spring constant, they may not have direct implications for resolution and sensitivity of an AFM. In fact, we have found that **lower non-contact noise does not necessarily imply better image resolution**.

So, on the one hand, a potential user/buyer of an AFM must be able to decipher from the list of noise-related specifications in product literature those that are meaningful to his or her work with the instrument. These lists can be read unduly complicated, in many cases with items that relate to components only, and useless as a true measure of the noise performance of the instrument as a whole. On the other hand, the published literature in scientific journals have so far been largely concerned with such noise as detector shot noise, electronic Johnson noise, and cantilever non-contact thermal noise, most of which are equally remote from being a useful figure of merit when it comes to characterizing the instrument's overall noise performance for recording atomic resolution images. (For a thought-provoking philosophical perspective on a related subject, see the article by Baird and Shew).[2]

In this application note, we introduce a figure of merit that quantifies the noise floor of an AFM as a whole system, in a manner that is immediately relevant to image resolution of the AFM. That figure of merit is **Intrinsic Contact Noise**, or ICN for short, and we show that it can be used as a reliable means to compare AFMs.

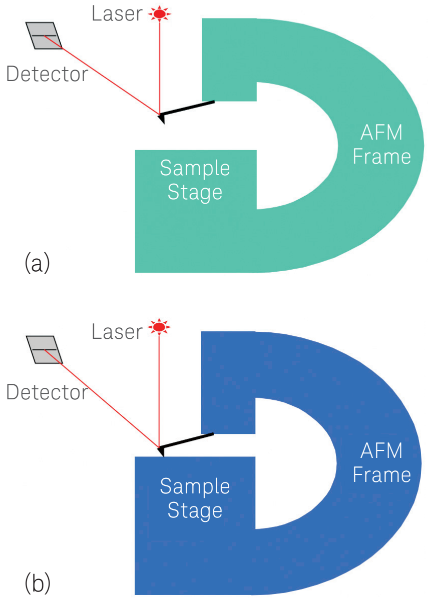

Figure 1. Generic diagrams showing the AFM in the configuration when (a) non-contact noise is measured with the tip and sample apart, and (b) when ICN is measured with the tip in direct contact with the sample (stage). Note the diagrams make no assumption about the tip-scanning or sample-scanning configuration of the AFM. (Also, see text).

## Intrinsic Contact Noise

ICN is simple to define. Novice or experienced, an AFM user will no doubt find it an intuitively meaningful quantity to measure in order to judge the AFM's noise performance as it relates to image resolution. In brief, after minimizing noise from sources external to the AFM, raster-scanning is disabled so that no voltage is applied to the X and Y actuators; the AFM tip is brought into contact with a sample on the AFM stage (Figure 1(b)); and the primary feedback loop is turned off, so that no voltage is applied to the Z-actuator, which is then idle at its neutral position. The AFM detector signal is then collected at a user-defined sampling rate and acquisition time. The collected data is then the ICN.

## Intrinsic Contact Noise and AFM Performance

In a series of experiments performed on four different AFM configurations, we found a direct correlation between an AFM's ICN and its image resolution:

- AFMs that performed better in atomic-resolution imaging also had the lower ICN (Figure 2).

In retrospect this finding is logical. Intrinsic sources of noise in an AFM are numerous, but ICN is indiscriminate of the sources; it measures the noise in way that reflects the conditions of an AFM as it is used for imaging.

We also found that:

- The results were the same for imaging in water and in air.

With the same AFM cantilevers, on the same four AFM configurations, we also measured non-contact noise, and found that:

- Non-contact noise showed no clear correlation with imaging resolution.
- Non-contact noise also showed no clear correlation with ICN.
- Details of the experiments and results, can be found in the article by Han.[3]

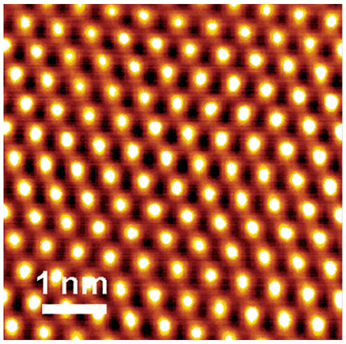

Figure 2. A typical atomic resolution image of freshly-cleaved mica using AFM configuration B. Similar images were routinely obtained with configuration A and B but not with configuration C and D. See text.

## Analysis and Discussion of Experimental Results

In this section, we first present and analyze some details of the experimental results. Then we discuss the difference between, and the relevance of ICN and non-contact noise to characterizing AFM image resolution and sensitivity.

Figure 3(a) shows the real-time noise data measured with cantilever I in air on the four different AFM configurations in our study: A, B, C, and D. The acquisition time was 1 second and the sampling rate 1 kHz. The RMS variation of the data appears next to each plot. These RMS values were measured after calibrating all four AFMs' Z-actuators with the same height reference sample, and then calibrating the motion of the cantilever in each AFM against that AFM's Z-actuator.

With this cantilever, we were able to routinely and repeatedly acquire atomic resolution images of a freshly-cleaved mica surface only with AFM configurations A and B, which have the lowest ICN (Figure 2). We were unable to do the same with AFM configurations C or D, despite the fact that C measured the lowest non-contact noise of all four configurations.

Figure 3(b) shows the noise spectrum density calculated from the real-time data in Figure 3(a). A comparison between the spectra of A and C in contact suggests that the presence of multiple peaks in C's spectrum (absent in A's) may be in part responsible for C's failure to routinely obtain atomic resolution images. Although peaks are also present in the contact spectrum of B, these are fewer, and all smaller than their counterparts in the contact spectrum of C. (Recall that B also performed well for atomic resolution imaging.) We note also that these isolated peaks are largely absent in the non-contact noise spectra.

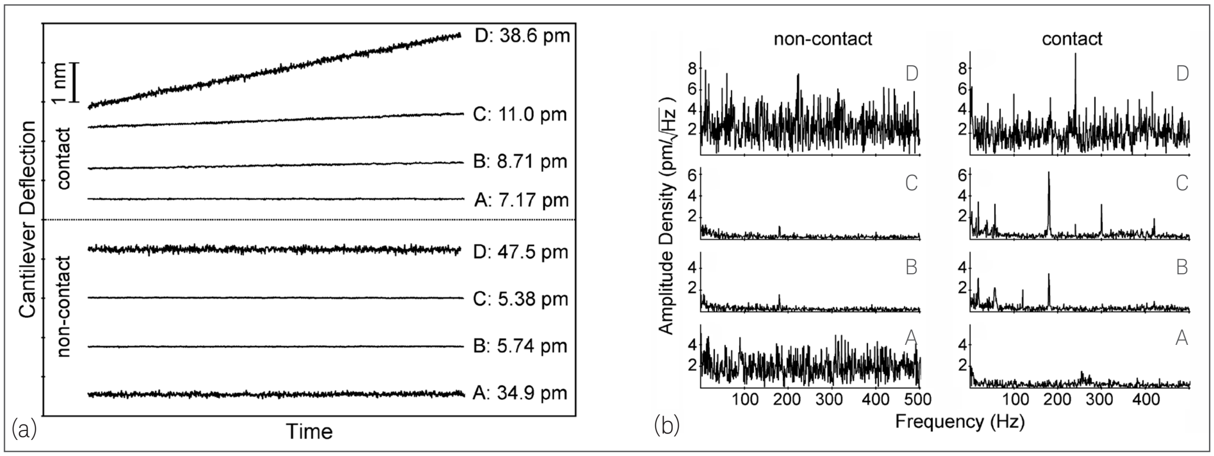

Figure 3. Non-contact noise and intrinsic contact noise (ICN) data recorded with cantilever I in air. (a) Real-time data recorded for 1 second at 1 kHz sampling rate. (b) Frequency spectrum of data in (a). The numbers are the measured RMS variations of the recorded real-time data.

Figure 4 shows the real-time noise data recorded similarly to those in Figure 3(a), but for cantilever II, in air (a) and in water (b). The configurations A and B show the lowest ICN, in air and in water.

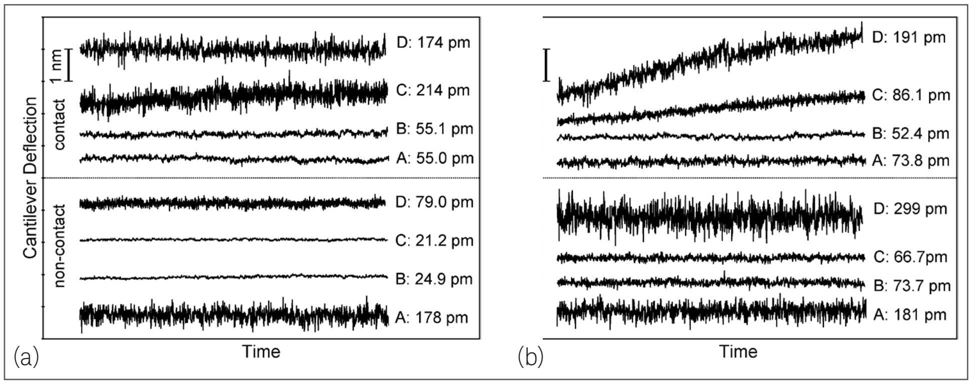

Figure 4. Real-time non-contact noise and intrinsic contact noise (ICN) data recorded with cantilever II at 1 second acquisition time and 1 kHz sampling rate (a) in air, (b) in water. The numbers are the measured RMS variations of the recorded real-time data.

Figure 5 summarizes a large collection of real-time measurements across the four AFM configurations and two cantilevers, in air and in water. A clear trend is deciphered for ICN, but not for non-contact noise.

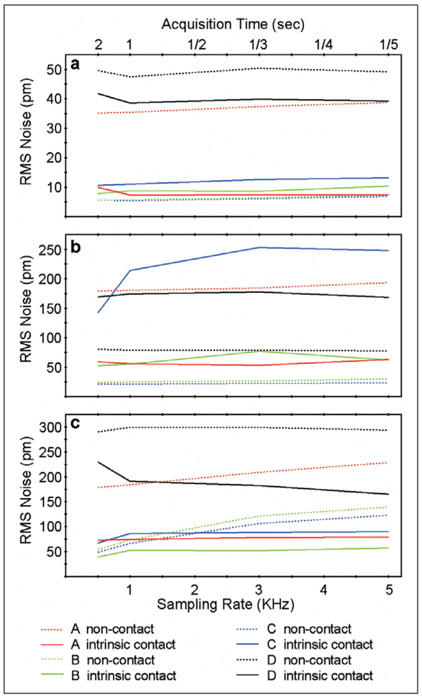

Figure 5. Intrinsic contact noise (ICN) and non-contact noise measured at different measurement bandwidths, always with 1000 points in the real-time data. Top only: cantilever I in air. Middle: cantilever II in air. Bottom: cantilever II in water. ICN levels for AFM configurations A and B consistently measured smaller than for configurations C and D. Non-contact noise variations across the configurations, however, fails to show a readily decipherable trend commensurate with ICN.

## Contact Noise versus Non-contact Noise

In this section, we consider some changes that take place upon tip-sample contact in regards to the way that intrinsic vibrations from the AFM couple to the cantilever and change the measured noise.

When the tip and that sample are **not** in direct contact (Figure 1(a)), the cantilever may, for now, be regarded as a true “cantilever beam” as defined in continuum mechanics of solid bodies: fixed at one end and free at the other, the tip end. It is in this state that non-contact noise is measured in most experiments, including ours.

When the tip comes into contact with the sample, the boundary conditions on the cantilever change; it is no longer free at the tip end. The cantilever now resembles a beam that is fixed at both ends, and its thermally-induced vibrations, those that are inherent to the cantilever itself, those that do originate in the frame of the AFM, are damped out because of the contact with the sample. Theoretically, this change alone, absent from any other consideration, should reduce the measured noise from the level of non-contact noise. In Figure 3, we see this expected reduction for AFM configurations A and D, but not for B and C! In Figure 4(a), we see this expected reduction for A only, but if we also consider Figure 4(b), we see it for all configurations, except for C. There appears to be no clear pattern relating the measured noise before and after the tip-sample contact.

To understand these seemingly disparate results, we must look at the other changes brought about by tip-sample contact. But even before we do that, we recall that earlier we referred to the cantilever as having one fixed end and two, respectively, before and after tip-sample contact. In fact, however, neither end of the cantilever is ever really fixed. Before contact, the cantilever is driven by the thermal energy associated with the non-zero temperature of the lab, not only directly, but also indirectly. More to the point, the cantilever is driven at its so-called fixed end, by the mechanical vibrations originating in the frame of the microscope (Figure 1(a)). In the absence of external noise sources, those mechanical vibrations in the AFM are the ones we consider thermal noise inherent to and intrinsic in the AFM itself, and which contribute to ICN, less at lower temperatures.

Once the tip comes into contact with the sample, the boundary conditions on the cantilever change, but again, not to that of a fixed-fixed beam; rather, to that of a beam that is subject to the intrinsic mechanical vibrations (intrinsic thermal noise) of the AFM at both ends. One important consequence of this change is that the average mechanical path between the intrinsic sources of thermal noise in the AFM and the cantilever is now reduced (Figure 1(b)). And this means more intrinsic thermal noise enters the cantilever from the AFM.

To make this more tangible, we can say, for example, that the thermal noise in the sample stage used to have to travel up through the frame of the AFM before entering the cantilever at its so-called fixed end, and in doing so, much of this noise dissipated in the frame of the AFM. But with the tip and sample in direct contact, the thermal noise from the sample stage is readily coupled to the cantilever, and contributes more significantly to the measured noise.

These considerations in part explain why the intrinsic contact noise, or indeed any measure of contact noise, is less readily amenable to fundamental (including theoretical) comparative studies than non-contact noise, and why the latter has been the subject of far more publications. But we have shown here that contact noise and, by extension, inherent contact noise is a better metric for assessing an AFM's performance for imaging resolution.

## Summary

Intrinsic contact noise, or ICN, is a reliable measure of an AFM's performance as it relates to the instrument's imaging resolution (Figure 2); and, by extension, to its sensitivity to changes in cantilever deflections in contact with the sample surface during force spectroscopy measurements. Figure 5 further validates this finding by providing a panoramic view of ICN versus non-contact noise measurements across the parameter variations that we built into our experiments: four AFMs, two cantilever types, and two environments — air and water.

The underlying methodology of ICN measurement can also be extended to the intermittent contact domain, where the AFM tip is to be brought into intermittent contact with the sample surface, as if to record an intermittent-contact image. In the simplest implementation, the collected data will then be of the cantilever's amplitude of vibrations, rather than quasi-static deflection.

# Experiment and Measurement Details

In our experiments, two different AFM cantilevers were used to measure ICN and also non-contact noise. Cantilever I triangular, 85 micrometers long, spring constant 0.5 nN/nm, fundamental resonance frequency around 107 kHz. Cantilever II rectangular, 200 micrometers long, spring constant 0.02 nN/nm, fundamental resonance frequency around 14.5 kHz. For ICN measurements, a freshly-cleaved mica surface was used.

The measured signal was that from the AFM's Position Sensitive Photodiode Detector (PSPD), and it was recorded unfiltered (Figure 1). Each record contained the same number of data points: 1000. The signal sampling frequency, f, varied between 500 Hz and 5 kHz. By comparison, a typical AFM image with 512 data points per line, recorded at a raster-scanning rate of 5 round-trips per second (5 image lines per second), includes data approximately up to 2.5 kHz, with signals at higher frequencies averaged out. Similarly, force spectroscopy curves with 1024 data points recorded at 2.5 Hz capture signals up to approximately 2.5 kHz. In both imaging and spectroscopy applications of AFM, usually signals at higher frequencies are filtered out, and in our experiments, a built-in low-pass filter with roll-off around 5 kHz helped limit aliasing from higher frequency signals.

In some cases, the recorded signal had contributions from thermal drift or from spurious sources, such as acoustic noise in the lab or building vibrations (Figure 6). Vibration isolation techniques were used in all experiments to mitigate the effect of building and other mechanical vibrations. When thermal drift was present, it was allowed to stabilize, and then was subtracted out of the data as a first-order correction. When spurious acoustic noise was present, attempts were made to minimize noise in the lab environment, and then several short-duration measurements were recorded, and the data with the minimum amplitude were considered to represent the Intrinsic Contact Noise and were analyzed. After measuring ICN, the sample and cantilever were retracted, terminating contact, and then non-contact noise was measured.

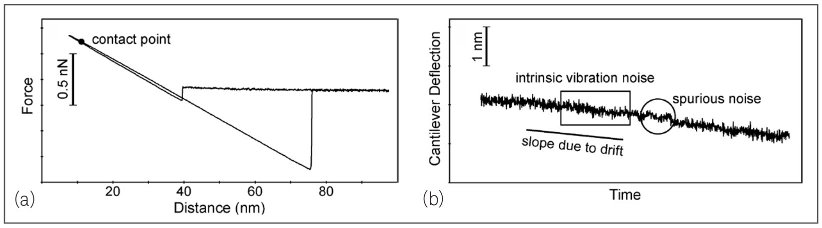

Figure 6. (a) A typical force spectroscopy (force-distance) curve recorded with cantilever I and a freshly-cleaved mica sample. (b) Real-time cantilever deflection data (noise) measured over a 1 second acquisition time at 1 kHz sampling rate, with the tip and the sample in contact, as indicated in figure (a) "contact point". The real-time data in (b) includes the contributions from a stable thermal drift (the slope), spurious acoustic noise from the environment, and vibrations intrinsic to the AFM.

# References

1. Han, Wenhai "Intrinsic contact noise and non-contact noise in atomic force microscopy", 8–10 and 16–18
2. Davis Baird, Ashley Shew, "Probing the History of Scanning Tunneling Microscopy", in Discovering the NanoScale, D. Barid, A. Nordmann, and J. Schummer (editors), Amsterdam, IOS Press, 2004
3. Han, Wenhai "Intrinsic contact noise and non-contact noise in atomic force microscopy"

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(BP-09-23-14)

Published in USA, July 31, 2014
5989-7203EN
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