

## SCANNED-PROBE MICROSCOPE ROUGHNESS SPECTROSCOPY

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Air based scanning tunneling and scanning force microscopes are capable of producing images very easily, but oft-times that is all that they produce. Since microscopic regions of specimens of course differ in detail from one to another, often judgements about how two regions differ fundamentally are left to qualitative intuition. Given a quarter of a million numbers, in the case of a typical large SPM image, we should be able to quantitatively compare the statistical properties evidenced therein from one specimen to another. Such quantitative insight may also yield information on artifacts (like time-domain noise and feedback-loop effects) in an image. To accomplish this most intuitively, we recommend simply decomposing the rms height variations in the specimen into two and one dimensional (azimuthally averaged) logarithmic (per decade frequency) roughness spectra. The basic properties of such a decomposition of topographic images are discussed in a paper submitted separately to this conference. We here discuss scanned probe microscope results.

Figs. 1a and 1b show log-log roughness spectra obtained for 512x512 scanning tunneling microscope (STM) images of the same region on a metal-coated diamond-like carbon specimen, taken at two different scan speeds. The upper and lower curves define the azimuthal standard deviation (i.e. the directional anisotropy) of the image roughness as a function of  $\text{LOG}(\text{period}) = -\text{LOG}(\text{frequency})$ . As you can see, the fast scan image contains a bit more high frequency (low period) structure, and this high frequency structure is drastically more anisotropic. We find this effect in the roughness spectra to be characteristic of feedback loop artifacts (i.e. of deviations away from the slow scan limit<sup>1</sup>). In fact, if the tip is moving slow enough to allow images at two different speeds without such an enhancement in anisotropy at high frequencies, such spectra would provide evidence that feedback loop artifacts are not a problem (i.e. that slow-scan limit assumptions are plausible). Roughness spectra are similarly useful in investigating likely effects of time-domain (stationary-tip) noise on images (cf. another submission by this group to the conference).

Fig. 2b shows the two-dimensional roughness spectrum of an STM image (Fig. 2a) from a Cu surface exposed for 5 seconds to an Ag plating bath, while Fig. 2d shows the analogous spectrum for an STM image (Fig. 2c) from a specimen with 60 seconds of Ag plating. Note that the second spectrum shows extra large size-scale anisotropy orthogonal to a deep crack running just to the left of center in Fig. 2c. Such large scale anisotropy should raise a flag of caution in considering Fig. 2d representative, since single sharp features like cracks can introduce significant roughness at all spatial frequencies. This anisotropy also shows up in the one-dimensional (azimuthally averaged) roughness spectra of these same specimens (Fig. 3a and 3b). Finally, note the peak near 50nm in the spectrum of Fig. 2b, associated with the mounds in the image. Bump nucleation/growth simulations predict well defined behavior for peaks in the roughness spectra, as a function of time. Thus roughness spectroscopy might aid in the quantitative detection and monitoring of such processes.

<sup>1</sup> P. Fraundorf and J. Tentschert, Ultramicroscopy 37 (1991) 125-129.

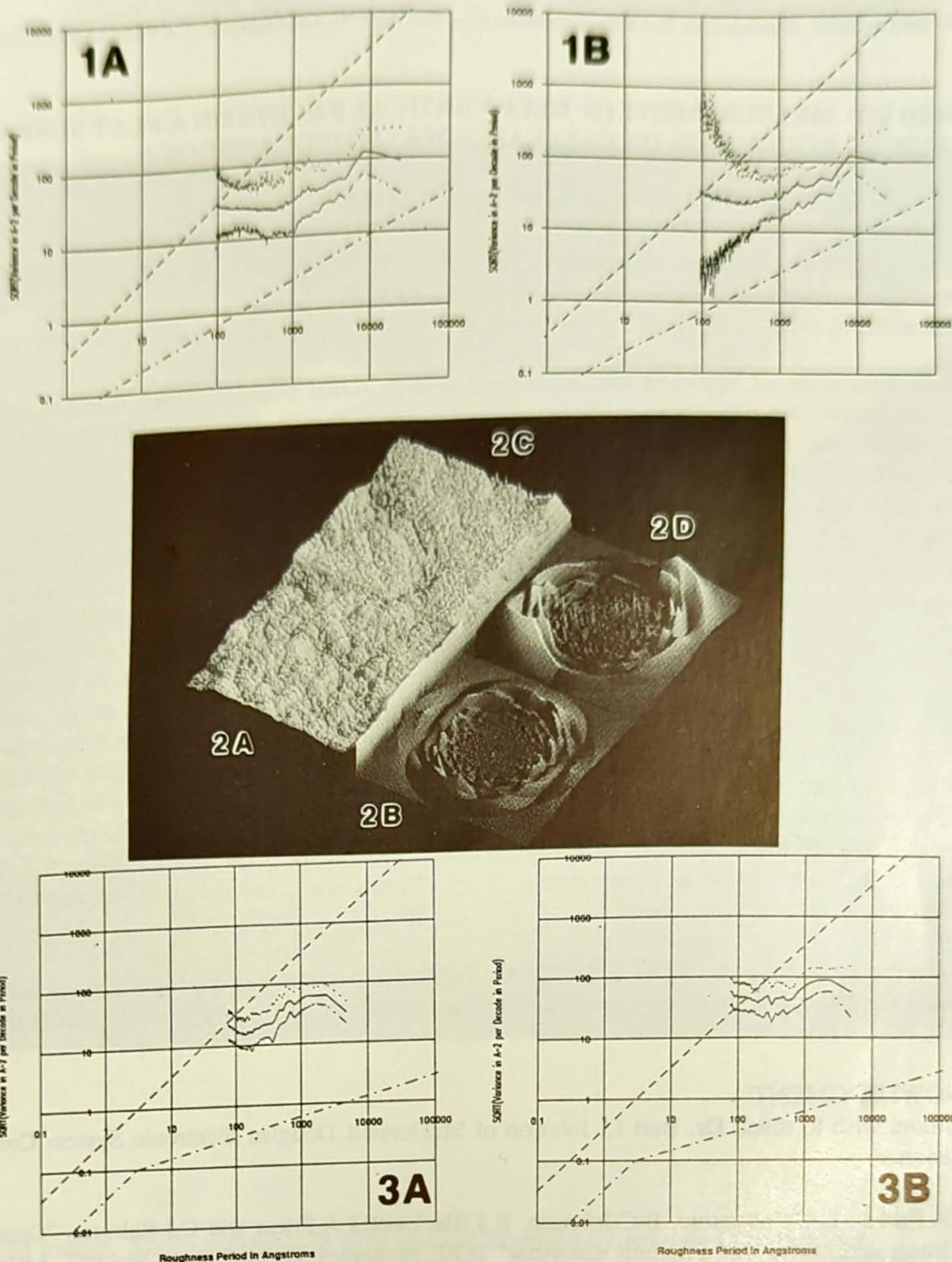


**Fig. 1A:** Azimuthally-averaged log-log roughness spectrum of a 512x512 STM slow-scan (e.g. 30 second) image of a metal-coated diamond-like carbon specimen.; **Fig. 1B:** Spectrum similar to 1A except of a fast-scan (e.g. 10 second) image.

**Fig. 2A:** STM image of a Cu surface exposed to a 5 second Ag plating bath; **Fig. 2B:** Two-dimensional roughness spectrum of the surface in 2A. The plot is radially logarithmic, with rms variation per decade displayed near the center of the plot for small size scales, and near the perimeter for large size scales; **Fig. 2C:** As in 2A, except exposure to bath is 60 seconds.; **Fig. 2D:** Two-dimensional roughness spectrum of the bumps in 2C. Same vertical scale as 2B.

**Fig. 3A:** One-dimensional (azimuthally averaged) roughness spectrum computed from the STM image shown in 2A. **Fig. 3B:** Same for image in 2C.