

LOG-LOG SCALE ROUGHNESS SPECTROSCOPY OF SURFACES

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Optical interferometry, confocal light microscopy, stereopair scanning electron microscopy, scanning tunneling microscopy, and scanning force microscopy, can produce topographic images of surfaces on size scales reaching from centimeters to Angstroms. Second moment (height variance) statistics of surface topography can be very helpful in quantifying "visually suggested" differences from one surface to the next. The two most common methods for displaying this information are the Fourier power spectrum and its direct space transform, the autocorrelation function or interferogram. Unfortunately, for a surface exhibiting lateral structure over several orders of magnitude in size, both the power spectrum and the autocorrelation function will find most of the information they contain pressed into the plot's origin. This suggests that we plot power in units of $\text{LOG}(\text{frequency}) \equiv -\text{LOG}(\text{period})$, but rather than add this logarithmic constraint as another element of abstraction to the analysis of power spectra, we further recommend a shift in paradigm.

Any given topographic image will boast some average level of vertical fluctuations, measureable by the rms variation in heights across the image. The question we pose is simple: Over what lateral size scales is this rms variation distributed? More specifically, how many Angstroms of rms variation, per decade in the range of lateral sizes, does the image contain for spatial periods throughout the range represented in the image? A plot of this quantity on a LOG-LOG scale *by inspection* lets us estimate both the rms variation as a function of image size, and the impact of any given range of frequencies on the total rms variation observed.

Figure 1 shows calculated surfaces consisting of Poisson distributed 5nm-high hemispheres and Gaussian bumps whose volume is set equal to a hemisphere of equal height, along with their two-dimensional (2D) roughness spectra on size scales ranging between 1 nm (origin) and 100 nm (perimeter). Figure 2 shows analytical 1D (azimuthally averaged) spectra for Gaussian bumps of several sizes, and Figure 3 shows a similar 1D spectrum for a 2048x2048 image of 55nm-high hemispheres Poisson distributed on a surface. In this latter image, dotted curves showing the envelope of rms variations in this quantity as a function of azimuth are plotted as well. This envelope is very helpful in showing up deviations from isotropy in experimental images. The dashed "line of hemispheres" basically flags the transition between "smooth surfaces" populated by oblate (pancake-like) protrusions below the line, and "forested surfaces" populated by prolate (rod-like) protrusions above the line. The lower "dot-dash" line illustrates schematically where we expect very smooth surfaces (like polished VLSI wafer silicon) to plot.

As you can see, these plots provide a context in which to examine quantitative roughness variations measured over a wide range of sizes, with a wide range of techniques. Application of these plots to the scanning probe study of surface nucleation and growth, as well as to time-domain and feedback loop artifacts in such images, are discussed in two separate papers submitted to this conference. Semper 6 macros have been used for doing the 2D and 1D calculations described here.

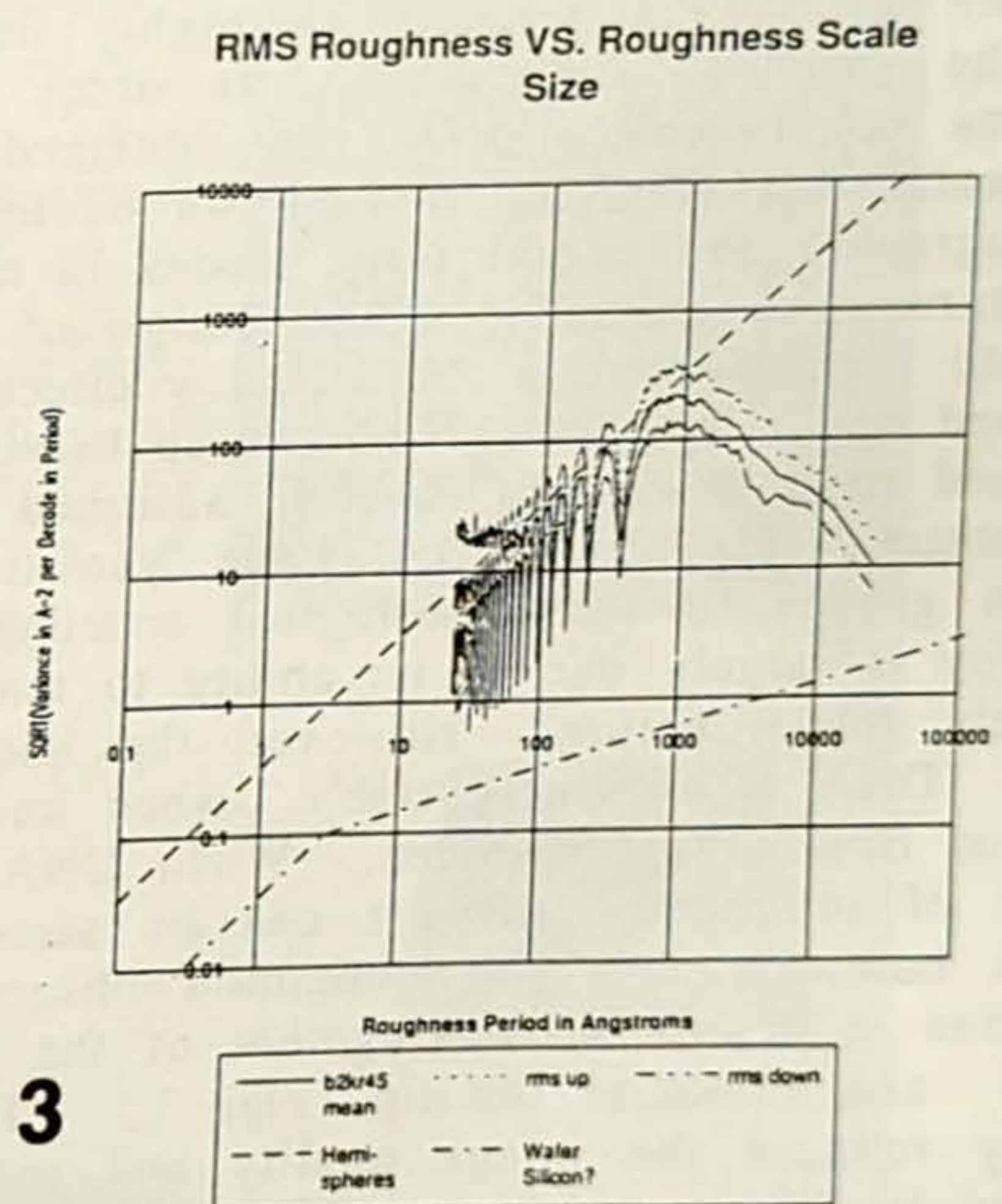
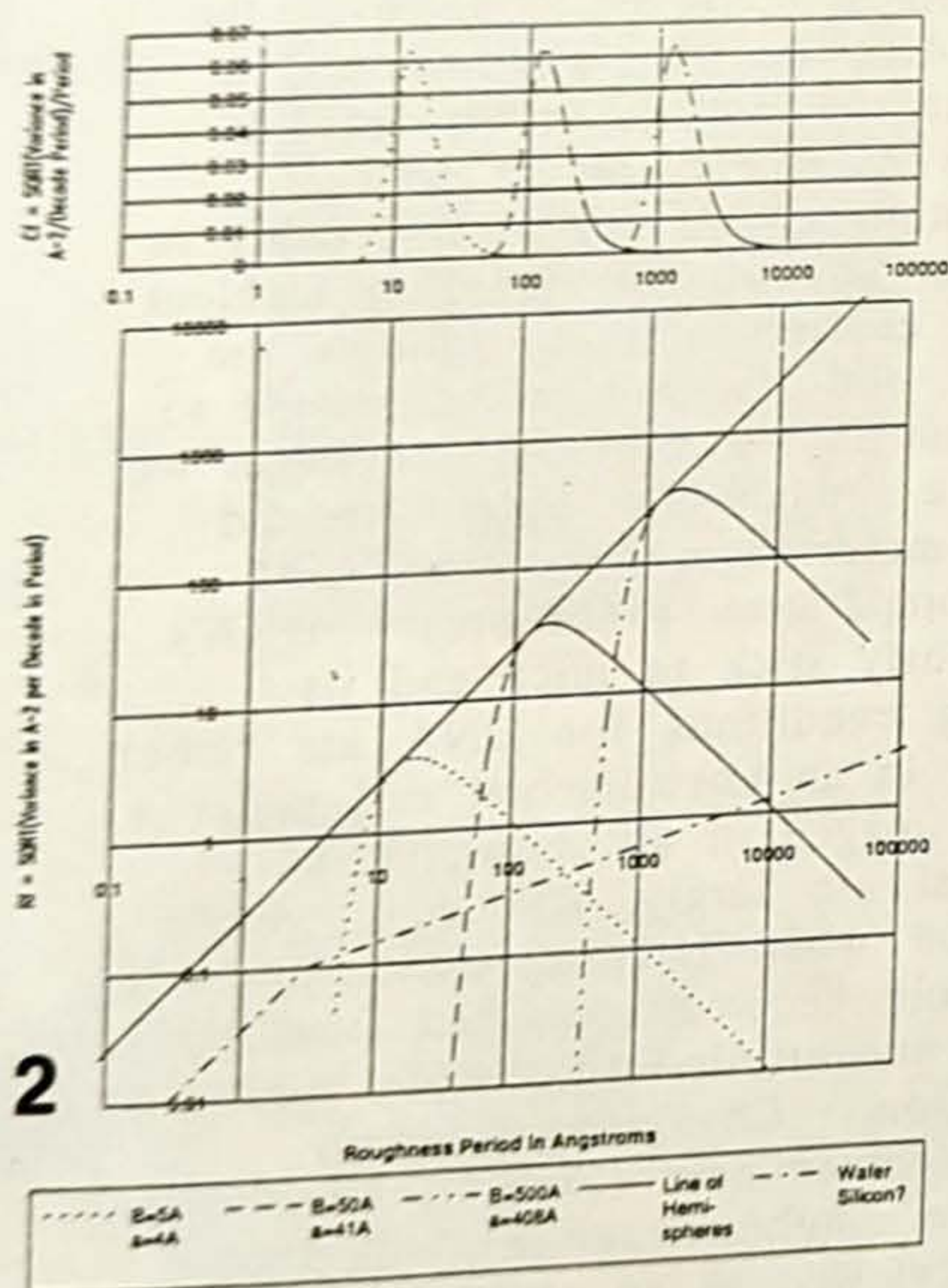
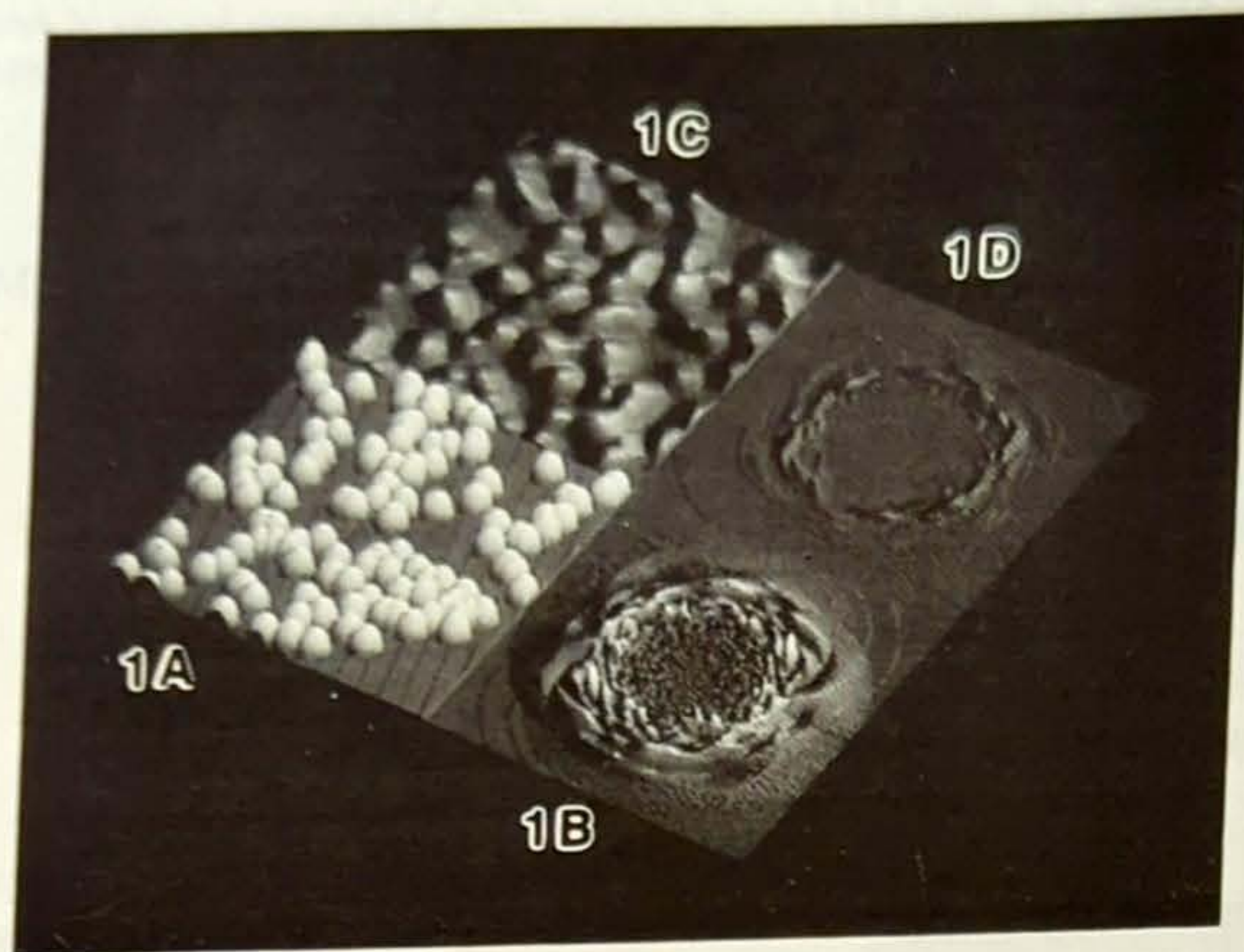


Fig. 1A: Poisson distributed hemispheres on a surface; **Fig. 1B:** Two-dimensional roughness spectrum of the hemispheres in 1A. The plot is radially logarithmic, with rms variation per decade displayed near the center of the plot for small size scales, and near the perimeter for large size scales; **Fig. 1C:** Poisson distributed Gaussian bumps, shown with the same vertical scale as 1A; **Fig. 1D:** Two-dimensional roughness spectrum of the bumps in 1C. Same vertical scale as 1B.

Fig. 2: One-dimensional (azimuthally averaged) roughness spectrum for Gaussian bumps whose volume is equal to that of a hemisphere of the same height, for heights of 5, 50 and 500 Angstroms. This analytical plot illustrates the kind of "line-widths" you might expect in such spectra for non-periodic surfaces.

Fig. 3: One-dimensional (azimuthally averaged) roughness spectrum computed from a 2048x2048 floating point image of 550 Angstrom radius hemispheres Poisson distributed on a surface. The beats (which are periodic in frequency) will be damped if experimental images as the spread in hemispheres becomes finite.