# Resist evaluation at 50 nm in the EUV using interferometric spatial frequency doubled imaging

Michael D. Shumway[a,b], Patrick Naulleau[b], Kenneth A. Goldberg[b],
Eric L. Snow[a,b], and Jeffrey Bokor[a,b]
[a]EECS Department, University of California, Berkeley, CA 94720
[b]Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

## ABSTRACT

By using a spatial frequency doubling method, our 10× Schwarzschild optic can print high-contrast features at 50 nm with low line-edge roughness (LER). In this paper, we also present new techniques for evaluating photoresists at EUV wavelengths using our system. One method is used to determine the ultimate resolution of a resist through linewidth vs. dose measurements. Another is to investigate line-edge roughness properties by varying the aerial image contrast of a pattern. A novel filtering method is proposed that would allow multiple contrasts to be printed in a single exposure. This is achieved by varying the duty cycle and line/space transmission levels of the object grating. Since this is a single exposure technique it would allow for more controlled contrast tests when evaluating resists.

**Keywords:** extreme ultraviolet lithography, EUV, Schwarzschild objective, spatial frequency doubling, imaging

## 1. INTRODUCTION

Using EUV wavelengths to print small features is crucial to the timely development of resists and processing techniques for the EUV lithography program. Currently, features at or below 50 nm are necessary for this investigation and there are only a few systems in the world that can achieve this result at EUV wavelengths. Our two-mirror, 10×-demagnification Schwarzschild optical system has been used for both EUV interferometry[1] and EUV imaging[2] experiments. These experiments were done in a circular sub-aperture with a numerical aperture (NA) ranging from ~0.07 to 0.09. The full pupil of the system is annular, with a NA of 0.29. The smaller sub-aperture is used in order to minimize wavefront aberrations over a larger field of view than would be allowed using the full annular pupil. The 0.08 NA system has a theoretical resolution limit for dense features of about 100 nm. Previously, we have shown that by using the spatial frequency doubling technique we could surpass this limit and print line and space features from 30 to 70 nm.[3]

## 2. SPATIAL FREQUENCY DOUBLING

The spatial frequency doubling technique requires the use of a special pupil-plane aperture stop and spatially coherent illumination. The coherent, monochromatic EUV radiation is provided by an undulator beamline (beamline 12.0.1 at the Advanced Light Source, Lawrence Berkeley National Laboratory). The undulator beamline provides continuously tunable illumination from 5-nm to 25-nm wavelength with spectral resolving power as high as $\lambda/\Delta\lambda$~1000. The technique is most easily envisioned for a system configured to produce an image of a simple grating object. An aperture stop is designed to block the 0th diffracted order generated by the grating while allowing the +1 and –1 diffracted orders to propagate through the system and reach the image plane. In this configuration, a high-contrast spatial frequency doubled image of the grating pitch is produced.

In our case, we combine the 10× demagnification provided by the optic with the frequency-doubling technique to achieve a 20× reduction of the object grating pitch. For example, 1-micron dense lines on an object grating will print as 50-nm dense lines onto a resist coated wafer. To get these small features, the line and space patterns are restricted to one orientation and a dense 1:1 spacing. By restricting the field of view, the effective NA of the optic can be extended, up to almost the NA of the full annular pupil. Currently, a 40 × 40 μm square transmission grating is used as the object. The object grating consists of a silicon nitride ($Si_3N_4$) membrane patterned with nickel (Ni) lines as an EUV absorber.

Line-edge roughness measurements were done on some of our 50-nm features at Sandia National Laboratory. Figure 1 shows a couple of samples and the resulting data. LER was measured to be around 4 nm rms (single-side 3σ measurement). The two samples were taken at slightly different dose levels. By current EUV imaging standards, this is extremely low LER and emphasizes the high contrast that is possible with this printing technique.

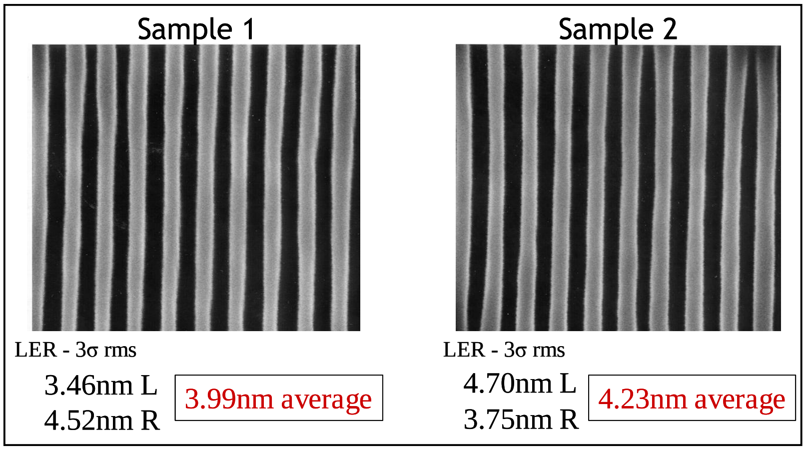

Figure 1 - LER for 50-nm lines/spaces with Shipley “EUV-2D”

## 3. RESIST RESOLUTION

The ultimate resolution of a resist can be calculated through linewidth vs. dose measurements at a series of pitches.[4] By assuming a Lorentzian shape for the resist line spread function (LSF) one can determine the resolution (the full width at half maximum of the LSF). This has previously been demonstrated in the deep-UV. Ideally, one would want to be able to print the multiple feature sizes on the same wafer. This would remove processing variations from the experiments. Even better would be to print the multiple pitches during the same exposure so both processing and dose variations are removed.

For our configuration this can be conceived by using a multiple pitch grating. Figure 2 shows object grating simulations that will print several fine pitches (70, 60, 50, and 40 nm) at once. These small features are achieved by combining the spatial frequency doubling technique, discussed above, with a multiple-pitch grating. By printing in this configuration we could calculate resolutions for EUV resists.

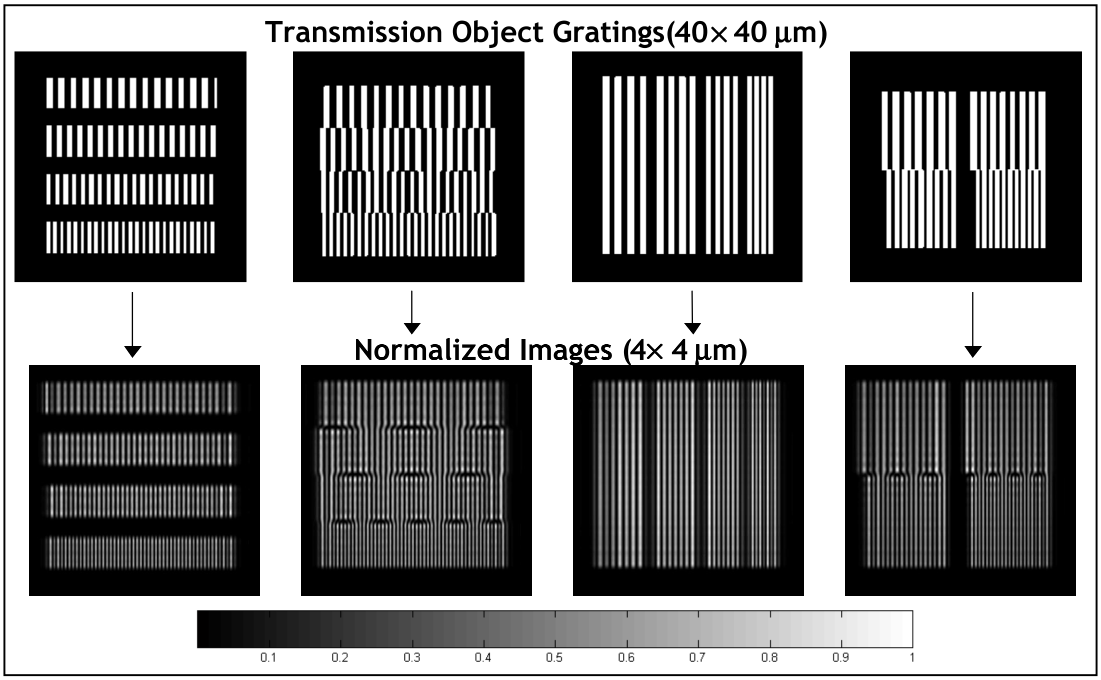

Figure 2 - Simulations combining multiple-pitch gratings with the spatial frequency doubling technique. Each layout prints 70, 60, 50, and 40 nm dense lines/spaces.

## 4. AERIAL IMAGE CONTRAST AND LINE-EDGE ROUGHNESS

Line-edge roughness properties of a resist can be investigated by varying the aerial image contrast of a pattern. In a typical experiment, the aerial image contrast is varied in a known way, and then the resulting effects on LER are measured. This is commonly done by adding a background flood exposure on top of a patterned exposure.[5] But through aperture plane filtering it is possible to print multiple contrasts in a single exposure array and ultimately in the same exposure. This is achieved by varying the duty cycle and line/space transmission levels of the object grating. Since this is a single exposure technique and no flood is needed, it will allow for more controlled contrast tests to help in the evaluation of resists.

### 4.1 Description

This method is essentially a two-beam interference technique. By tuning the relative strength of one of the beams against the other it is possible to vary the contrast of the image. Since line/space patterns in resist are the features of interest it becomes advantageous to somehow manipulate a simple object grating. By changing the duty cycle of a grating, the strength of the diffracted orders will be altered. Unfortunately this could lead to the unwanted effect of producing different linewidths at different contrast levels. If, however, only the zero and one of the first orders is used to create the field mismatch at the wafer, this effect will not appear. By correct filtering in the aperture plane (removing all other orders), the resists will only see variations in contrast and will not print the encoded duty cycles. That information is lost in the filtering process.

It is important to note that this technique is different from the spatial-frequency doubling method that is primarily used with this imaging station. In that case, the +1 and –1 orders are used to expose the resist creating an effective 20× demagnification of the object grating. Since the +1 and –1 orders are of equal strength this gives a very high contrast image. This new method uses the intentionally unbalanced field strengths of the 0 and +1 orders and takes advantage of the 10x reduction from the Schwarzschild optic.

### 4.2 Modeling

A sketch of duty cycle modulation for a transmission grating is shown in Figure 3.

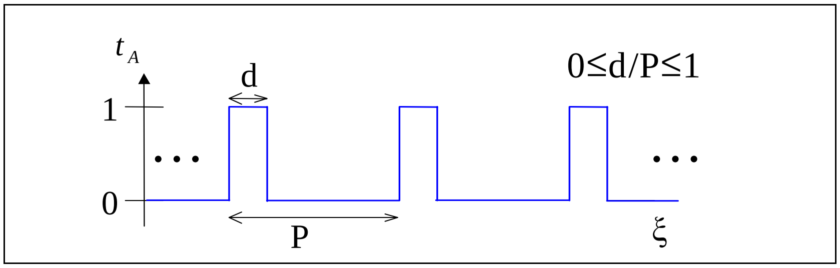

Figure 3 - A simple amplitude transmission grating

Using Goodman's[6] approach, the transmission function can be written as

$$t_A(\xi) = rect(\frac{\xi}{d}) \,, \tag{1}$$

and the diffraction coefficient for the K$^{th}$ order is given as

$$c_K = \frac{1}{P} \cdot FT\{t_A(\xi)\} \rightarrow f_x = \frac{K}{P} \,. \tag{2}$$

This leads to the result that

$$c_K = \frac{d}{P} \cdot sinc(\frac{d}{P}K) \,. \tag{3}$$

Where $sinc(x) = \frac{\sin(\pi x)}{\pi x}$. For a 50-50 duty cycle grating, $\frac{d}{P} = \frac{1}{2}$ which leads to the common intensity diffraction efficiencies ($\left|c_K\right|^2$): $\left|c_0\right|^2 = 25\%$ and $\left|c_1\right|^2 = \frac{1}{\pi^2} \approx 10\%$.

By varying the duty cycle, the strength in the zero and first orders will be modified to allow for a change in contrast. If we would like to also tune the dose required to print these contrasts another variable is needed. To do this we introduce a somewhat more generalized transmission grating as shown in Figure 4.

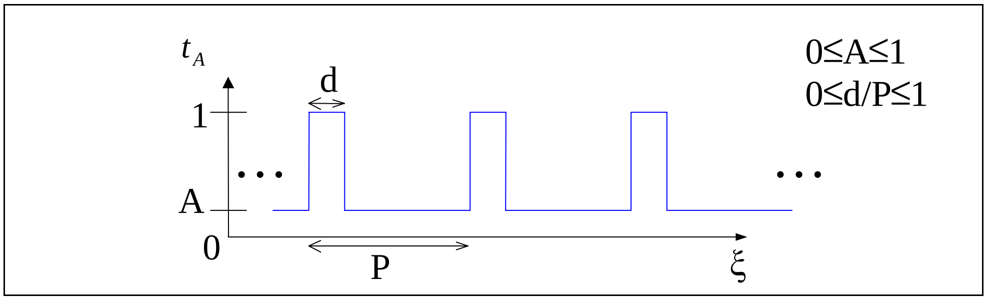

Figure 4 – A more arbitrary amplitude transmission grating

The transmission function follows as

$$t_A(\xi) = A \cdot rect(\frac{\xi}{P}) + (1-A) \cdot rect(\frac{\xi}{d}). \tag{4}$$

Which yield diffraction coefficients of the form

$$c_K = A \cdot sinc(K) + (1-A) \cdot \frac{d}{P} \cdot sinc(K\frac{d}{P}). \tag{5}$$

So the field strengths for the zero and first orders are

$$c_0 = A + (1-A) \cdot \frac{d}{P} \tag{6}$$

and

$$c_1 = (1-A) \cdot \frac{d}{P} \cdot sinc(\frac{d}{P}). \tag{7}$$

One can then define the intensity maximum and minimum based on the field strengths:

$$I_{\max} = \left|c_0 + c_1\right|^2 \tag{8}$$

$$I_{\min} = \left|c_0 - c_1\right|^2. \tag{9}$$

The contrast, *C*, can then be calculated using the equation

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}. \tag{10}$$

The relative dose, *D*, defines the midpoint of the intensity variation:

$$D = \frac{1}{2}\left(I_{\max} + I_{\min}\right). \tag{11}$$

In summary, this gives contrast, *C*, and dose, *D*, as functions of *A* and the ratio d/P. So with these equations one can calculate the contrast and dose values achieved from a specific duty cycle and dark area transmission percentage. Or inversely, after choosing desired dose and contrast levels, suitable grating parameters can be determined.

The graphs in Figures 5–8 show some of the results from these duty cycle calculations. The x-axis represents the amount of 100% transmission (open area) that is contained in a single pitch of the grating (ratio d/P from Figure 4). The three separate curves represent values for the amount of light that is transmitted in the "dark" region of the grating (variable *A*). It is evident from Figures 5 and 6 that as more light is allowed through "dark" region the zeroth order field strength increases and the first order field is weakened. The grating becomes less efficient for diffracting light.

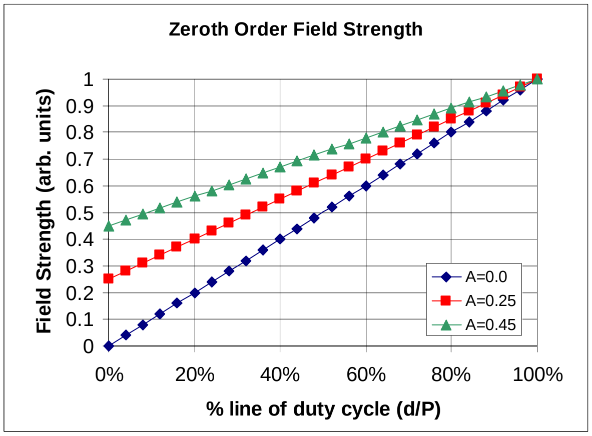

Figure 5 – Zeroth order field strength as a function of d/P

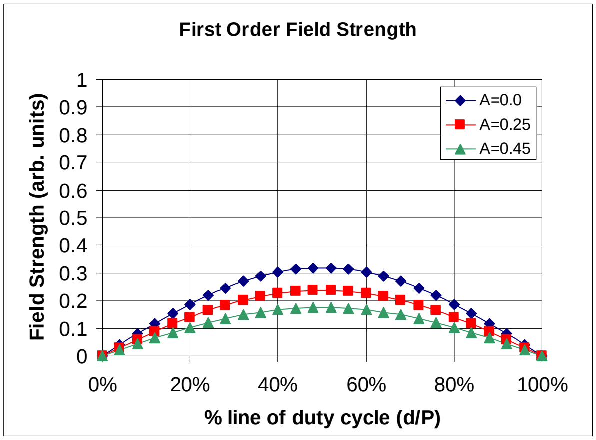

Figure 6 – First order field strength as a function of d/P

Contrast and dose plots are shown in Figures 7 and 8 respectively. These two plots also show data as d/P is varied. For most choices of A, it is possible to achieve a certain contrast level at two values of d/P. Dose is always increasing with d/P since less light is getting attenuated by the grating. It is a simple extension in Figure 9 to then plot contrast and dose against each other for every value of d/P.

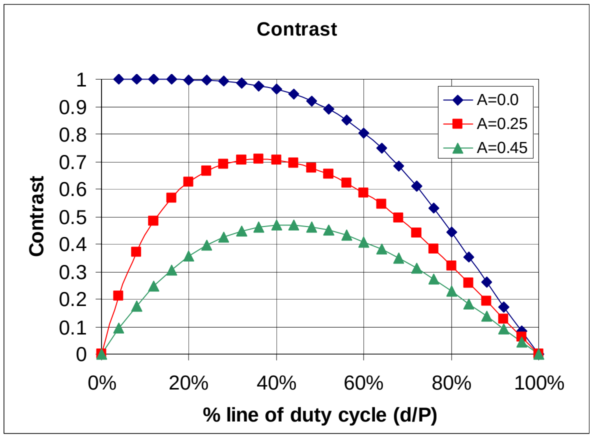

Figure 7 – Contrast as a function of d/P

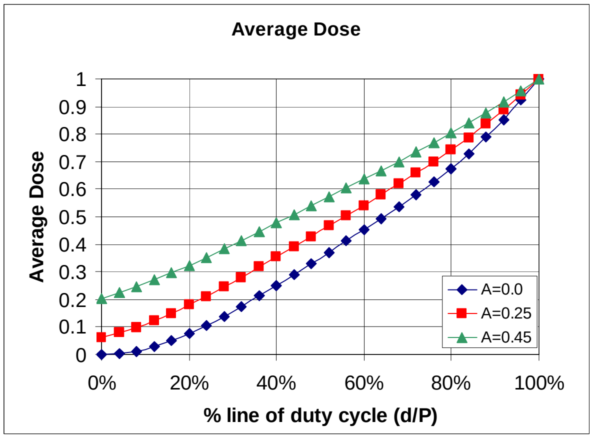

Figure 8 – Dose as a function of d/P

When creating an object grating, things can be kept simple by keeping A fixed. Then through Figure 7 one can pick contrast levels by careful choice of the duty cycle. Then by simply having different duty cycles on an object you can print the various contrasts. But it will take separate exposures. What we have shown here is that if you take this process a step further you can print multiple contrasts during a single exposure. In brief, after choosing a dose level, one can vary the duty cycle and transmission of the grating to reach desired contrast levels. See Figure 10 for a sample grating that would produce contrast levels of 20, 30, 40 and 50% in a single exposure.

## 5. CONCLUSIONS

Here we have demonstrated an EUV imaging technique capable of producing 50-nm lines with very low LER. Measurements showed LER to be around 4 nm rms. Such exposures will help in the evaluation of resists for EUV lithography. Other techniques are also being prepared. Resist resolution will be investigated using spatial frequency doubling with a multiple pitch mask. Line-edge roughness properties of a resist can be investigated by varying the aerial image contrast of a pattern.

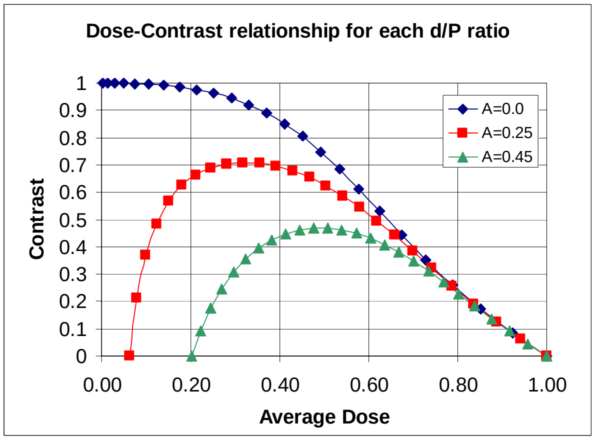

Figure 9 – Dose vs. contrast for each d/P value

In regards to contrast modulation, it is relatively easy to make a mask that prints different contrast levels at different dose levels. That would require only varying the duty cycle and filtering everything but the 0 and +1 orders. One way to balance the dose levels would be to add a second step into the mask development process where some light is allowed through the “dark” regions of the grating. This essentially creates a background that evens out the various patterns. So after fixing the dose level, one can vary the duty cycle and dark area transmission of the grating to reach a desired contrast level. The fabrication of such a mask, however, would be difficult. Rather than changing absorber thicknesses in the “dark” regions it would be simpler to pattern sub-resolution features with an e-beam writer. These sub-resolution features would act as absorbers depending on their surface densities. A four-contrast mask would require four separate duty cycles and 4 different absorber levels.

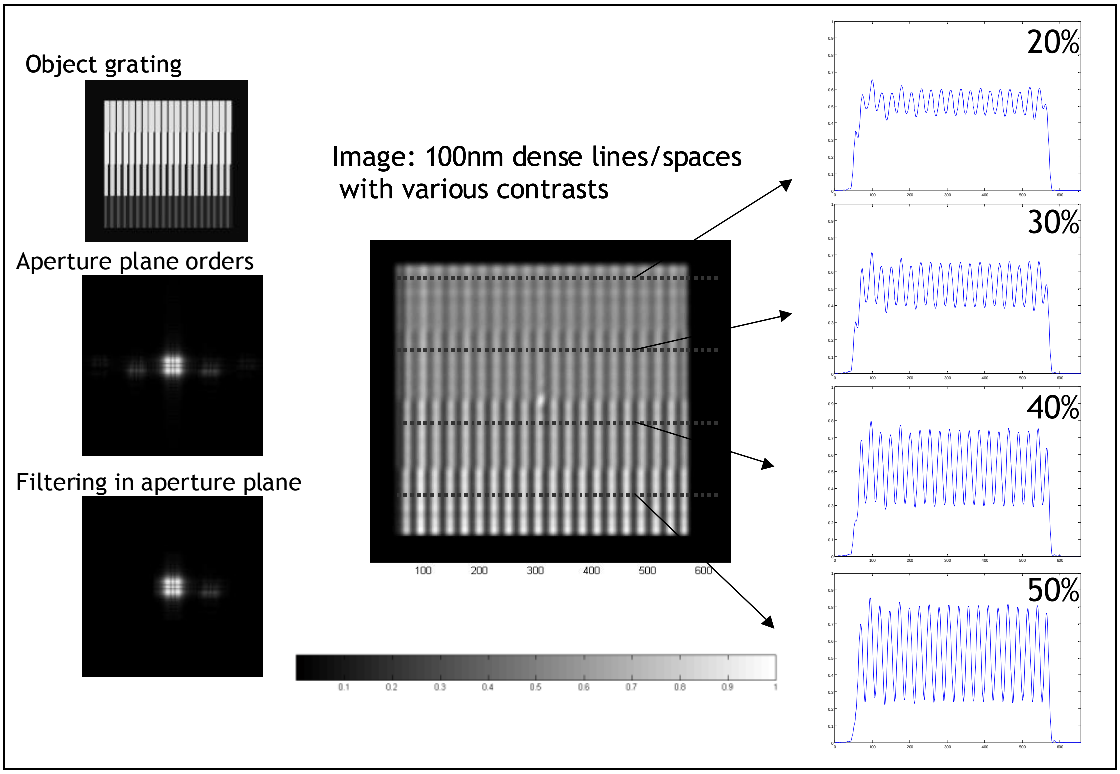

Figure 10 – Example of using duty cycle tuning to print four contrast levels in a single exposure

## ACKNOWLEDGEMENTS

The authors wish to thank Sang Hun Lee and Chang Cho for their efforts during the inception of this work. Paul Denham, Seno Rekawa, and Phil Batson for vital engineering assistance. Robert Brainard (Shipley Company) and Donna O'Connell (Sandia) are acknowledged here for contributing resist support. Wafer processing was done in the UC Berkeley Microfabrication Laboratory.

This research has been supported by the Semiconductor Research Corporation and the DARPA Advanced Lithography Programs. It was jointly sponsored under SRC contract 96-LC-460 and DARPA grant MDA972-97-1-0010.

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Further information
M. D. S.: Email: shumway@eecs.berkeley.edu