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VP-SEM Investigation of 3-D Surface Morphology in Cirrus-like Ice Crystals

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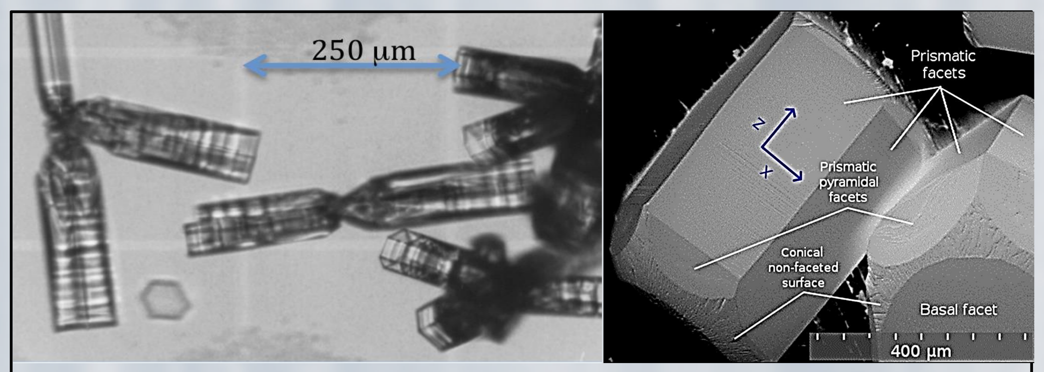
Nick Butterfield and Steven Neshyba

Introduction:

Left: Schematic diagram of incident sunlight scattered from cirrus clouds.

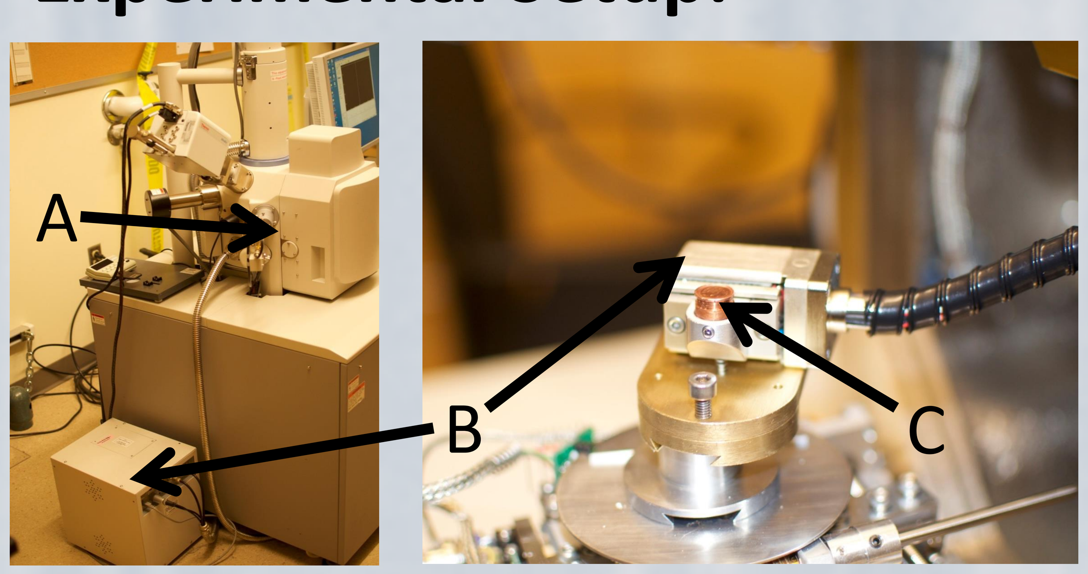
Cirrus clouds play an important role in the earth's radiative budget due to their scattering properties.[1] One important factor in scattering from cirrus clouds is the surface morphology (i.e. roughness) of cirrus ice crystals, as can be seen in the images below.

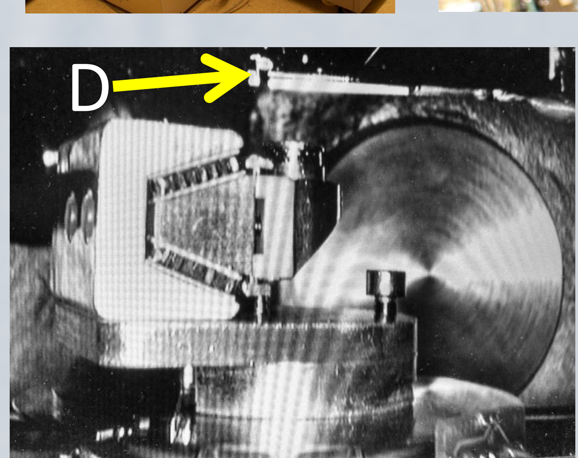


Above left: Photograph of naturally occurring cirrus crystals captured at the South Pole Station on July 21, 1992.[Walden et al. 2003] **Above right:** Image of cirrus-like ice crystals grown in the VP-SEM at UPS. Horizontal roughening bands can be seen on the prismatic facets of both images.

Little is known about the quantitative effects of roughness on reflectivity; the root of this problem is that little is known about the roughness itself. The goal of this project was to grow and image cirrus-like ice crystals at near-equilibrium conditions in a Variable Pressure Scanning Electron Microscope (VP-SEM) in order to generate 3D models of the prismatic facets.

Experimental Setup:

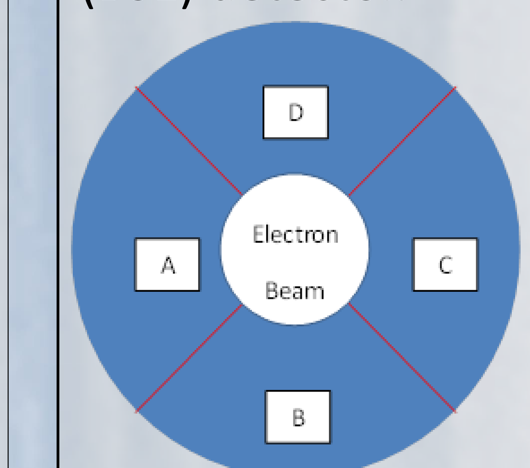


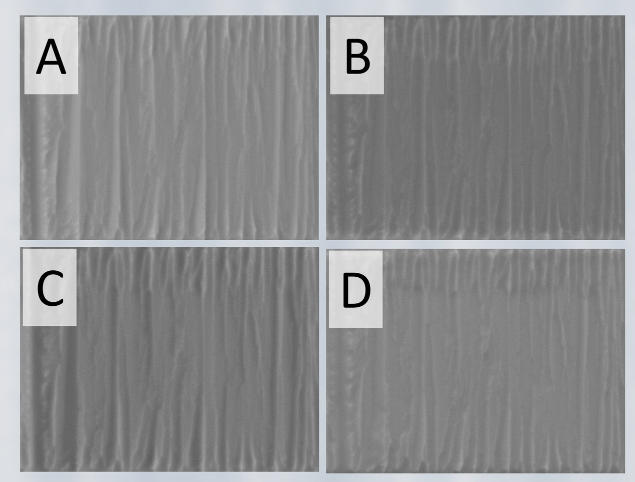


A) Hitachi S-3400N VP-SEM
B) Peltier cooling unit.
C) Roughened copper growth stage.
D) Backscatter Electron (BSE) detector

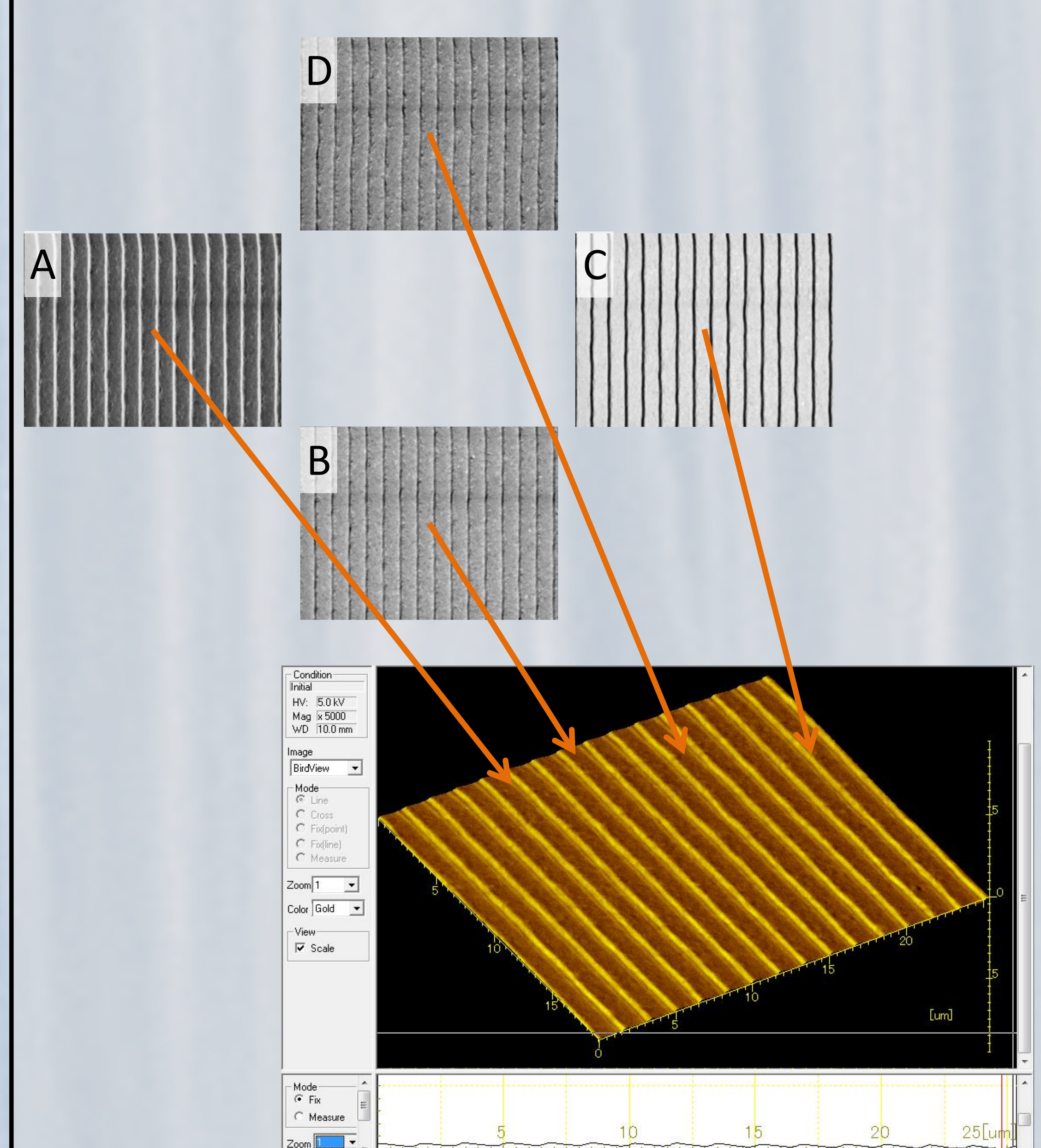
Experimental Methods:

A Deben Ultra-Cool Stage MK3 version Peltier cooling element is inserted into the SEM chamber along with a 4 mL ice reservoir. The chamber operates at low pressure conditions (<1 – 250 Pa), and the ice reservoir maintains that pressure as water vapor. By decreasing the temperature of the cold stage below the equilibrium water vapor pressure, the vapor nucleates onto the copper stub, where it is imaged using the SEM backscatter electron (BSE) detector.





Above left: Top-view diagram of BSE detector. Each quadrant detects electrons reflected from the object.
Above right: Ice surface shown in near-simultaneous images from each detector, acquired using the 3D capture function.



Above: 3D reconstruction of gold diffraction grating from four images using Hitachi's software. The blaze angle (angle between the long side and horizontal) for the grating is 17.5°, but the software reports this as only 5° as can be seen in the profile below the oblique image.

3D Reconstruction Methods:

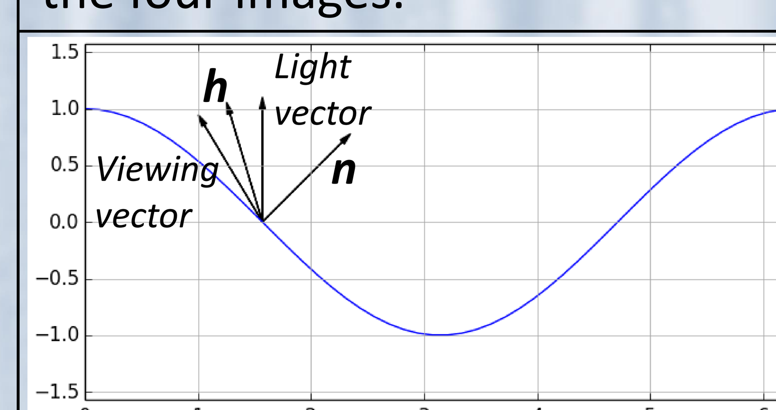
A 3D image can be constructed from the four bitmap images captured from the BSE detector using a generalization of parallax. A 3D reconstruction program (3D image Viewer v. 1.01 by Denshi Kougaku Kenkyusyo Company) was supplied along with the SEM, but when applied to a surface of known morphologies, it was unable to accurately reconstruct all the features. A new program was needed to analyze the images.

Various algorithms exist for graphic design that generate an image from an object; we needed to work backwards from the captured images to create the object. We selected the Blinn-Phong algorithm due to its simplicity and effectiveness.

The Blinn-Phong equation[2] is used to calculate the brightness of a point on the surface of an object:

$$c = v \cdot c_l(\boldsymbol{h} \cdot \boldsymbol{n})^p + c_o,$$

Where c is the observed light intensity, c_l is the incident light intensity, $\boldsymbol{n}$ is the surface normal vector, $\boldsymbol{h}$ is the half vector between the light source and the detector, and p is the Blinn-Phong exponent. The parameters c_o and v are the base brightness and contrast settings for the four images.



Left: Schematic of vectors used in Blinn-Phong algorithm.

The half vector is known from the geometry of the detectors, c_l is assumed constant for all images, and c is measured; p is a material property, so it can be determined from objects with known geometries; v and c_o can be found by an error minimization. The normal vector components are calculated by solving the matrix problem formed from combining the equations for each detector:

$$\boldsymbol{n} = \frac{1}{c_l^{1/p}} \begin{bmatrix} (x_C - x_A)/2h_x \\ (x_D - x_B)/2h_y \\ (x_A + x_B + x_C + x_D)/4h_z \end{bmatrix}$$

where $x_i = (v \cdot c_i - c_o)^{1/p}$.

Acknowledgements:
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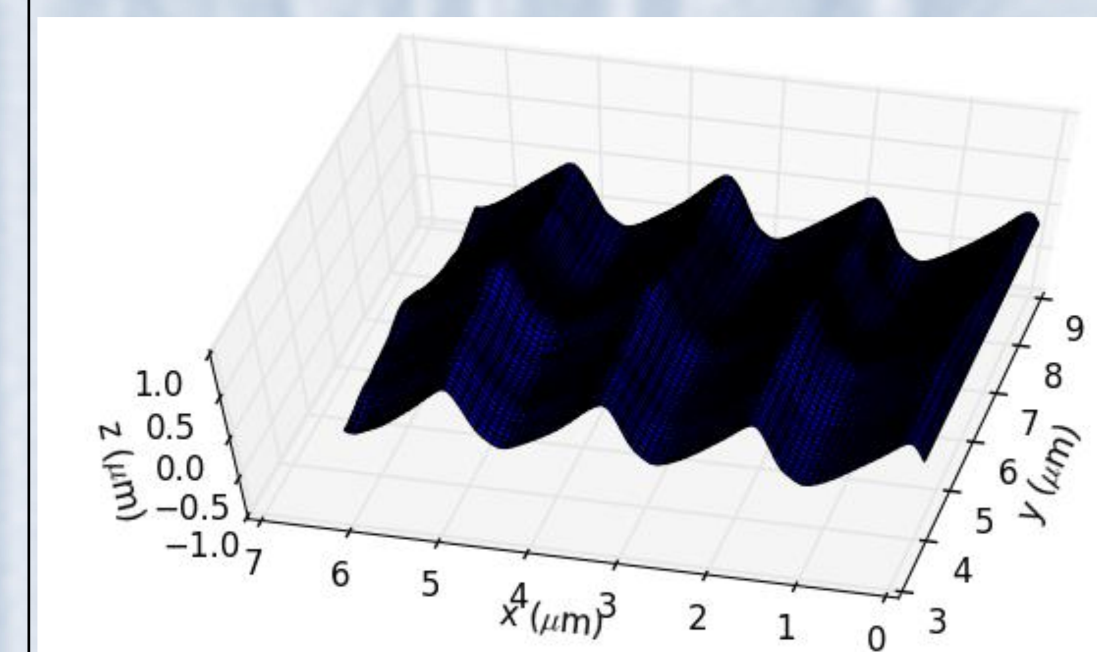
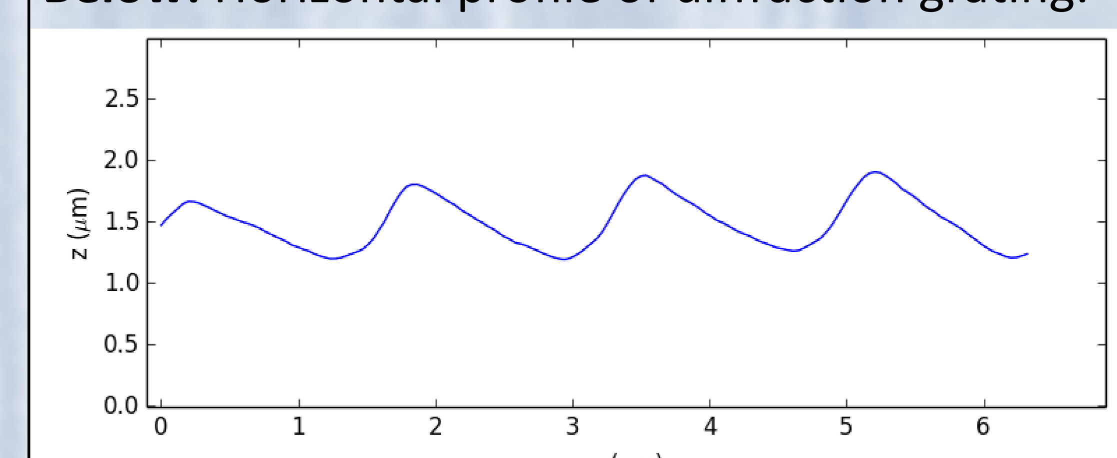
Once the components are found, a basic surface can be constructed by calculating the surface height at each point from the normal vector at the previous point:

$$z_{i,j} = z_{i-1,j} + \frac{n_{x(i-1,j)}}{n_{z(i-1,j)}} * d$$

Where z is the surface height function, d is the pixel size in micrometers, and i and j are the pixel row and column indices, respectively.



Above: Subsection from 3D reconstruction of gold diffraction grating generated in Python.
Below: Horizontal profile of diffraction grating.



Conclusions:

- One success of this summer work is the large body of ice crystal data collected; this data shows qualitative roughness trends at various pressures and temperatures.
- In order to improve the quantitative value of this data, I will continue to develop the Python reconstruction code as the subject of a thesis.

Further Work:

The major problems yet to be addressed are:
- Solutions of p, v, c_o, and c_l that generate an accurate surface are not unique.
- The reconstruction technique is not optimized to reduce error using all the available data.

References:
1) Neshyba et al., *Journal of Geophysical Research*, **2013**, *118*, 1-10.
2) Blinn, James F., *ACM SIGGRAPH Computer Graphics*, **Summer 1997**, *11.2*, 192-198