Reflection-based C-axis Measurement of Ice Crystals

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We report initial results in the development of a reflection-based method to determine the c-axis orientation in ice crystals. The current state-of-the-art for measuring crystal orientation in ice is the Wilen stage method [1-2] based on older Rigsby stage techniques [3]. In Wilen's method, a thin section of ice is sliced from a core and placed between crossed polarizers in four sequential orientations. In each orientation the polarizers are rotated while light is transmitted through the slice, and the light intensity is measured. This method produces an accurate and complete measurement of fabric, but at the expense of destroying the local region of the core and requiring a dedicated laboratory for measurement. A technique that could utilize optical reflection instead of transmission would be non-destructive and could be built into field instrumentation used in boreholes. This abstract describes a first step towards direct measurement of c-axis orientations in ice cores and boreholes using backscattered light from trapped bubbles.

Similar to the Wilen stage, we solve for two angles, ϕ and θ, and their corresponding degeneracies in a sequence of four measurements. We tested our proposed method on crystals from a vertical thin section from WAIS Divide at a depth of 420 meters (courtesy of Dr. Joan Fitzpatrick and Dr. Don Voigt). With a bare silicon wafer placed behind glass-mounted thin section to serve as test reflector, a sequence of four measurements was performed with a 1.7 mW 675 nm fiber-coupled laser and a pair of crossed polarizers at different orientations as illustrated in Fig.1. In stage 1, the two possible values for ϕ are determined by looking for light extinction while rotating the thin section with respect to the optics. Stage 2 resolves the degeneracy for ϕ by observing the polarizers orientation for extinctions. Stage 3 and 4 determine θ in a similar fashion. From the measurements as shown in Fig.2 and Table.1, ϕ was found to be -46° and θ was found to be -80°, which deviates slightly from Dr. Voigt's data at -46.60° and -75.62° respectively. Ten other crystals have been measured at stage 1 showing similarly good matching with traditional c-axis techniques.

Currently the technique requires measurement of each point individually, but work is in progress to use bubbles within the ice as the "back reflector" to eliminate the need for ice slices and eventually to automate the measurement so that data can be taken from many points simultaneously.

[1] Wilen, L. A. "A new technique for ice-fabric analysis." *Journal of Glaciology* 46.152 (2000): 129-139.
[2] Hansen, Dirk P., and Larry A. Wilen. "Performance and applications of an automated c-axis ice-fabric analyzer." *Journal of Glaciology* 48.160 (2002): 159-170.
[3] Langway, Chester C. "Ice fabrics and the universal stage." *Department of Defense, Department of the Army, Corps of Engineers, Snow Ice and Permafrost Research Establishment,* 1959.

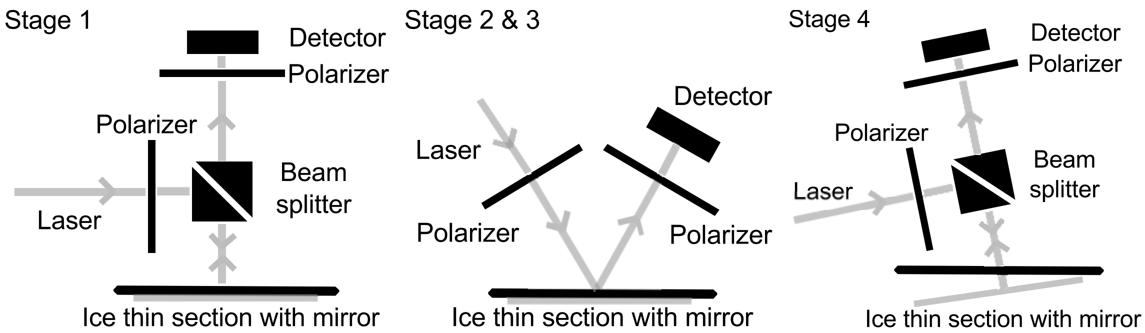

Fig.1 Optical setups, viewed from the side, for single point c-axis measurement. In all stages the polarizers rotate in unison, remaining crossed at all times. The ice thin section was backed by a bare silicon wafer which acted as a mirror.

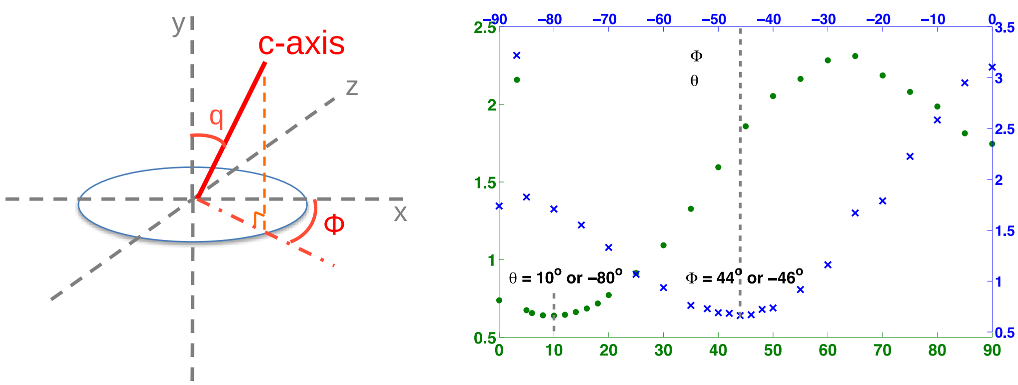

Fig.2 (a) For an ice crystal in the x-z plane, the c-axis can be determined by the angles ϕ and θ. (b) Determining angles ϕ and θ by rotating a pair of crossed polarizers through 0° to 90°. For clarity, the rotations for resolving degeneracies (stages 2 and 4) are not shown.

	Step 1	Step 2	Margin of error	Angle from Dr. Don Voigt
ϕ	44° or -46°	-46°	+/- 1°	-46.5982
	Step 3	Step 4	Margin of error	Angle from Dr. Don Voigt
θ	10° or -80°	-80°	+/- 2°	-75.6162

Table.1 Summary of c-axis determination experiment using back reflections. The error margins stem from the angular resolution of the equipment available in our laboratory.