3D Visualization of Snow Samples by Microtomography at Low Temperature

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Snow on the ground is a mixture of ice particles, air and occasionally liquid water and it can take different aspects. In most cases, recent snow is a very loose powder, which can transform into hard, crusted or pasty material. This means that each snowfall undergoes metamorphism [1, 2] according to weather conditions and exposure, leading to a layered snowpack.

The growth of ice particles is caused by vapor diffusion in dry snow and melt-freeze exchanges in wet snow. Normally, dry snow covers are warmer on the bottom than on the top. The value of the temperature gradient determines whether rounded (small gradient) or faceted crystals (large gradient) will grow [3].

Metamorphism has huge consequences: the physical and mechanical properties of the different snow layers can change dramatically, commonly over several orders of magnitude. In some cases the snow crystals are able to stick on vertical rocks, whereas in other cases just one skier can release a slab avalanche of several thousand tons. The shape and arrangement of the grains and the quality of the ice bonds will govern the snow properties.

The important parameters describing the state of a snow layer are the specific area, the grain connections and the local grain curvature. They cannot be directly derived from classical two-dimensional (2D) observations. For the first time, tomographic methods provide data on the three-dimensional (3D) microstructure of snow that is both statistically significant because it represents a large number of grains, and at a high resolution compared to the grain scale.

Experimental Technique

Microtomography is an established technique for the 3D visualization of quite diverse objects, with spatial resolution better than 20 µm. Many 2D images are recorded at angular positions of the object around an axis (vertical in our case) spanning 180°. "Tomographic" reconstruction provides, from the 2D images, and via appropriate algorithms and programs, the 3D information from which cuts, projections, or perspective renditions of the object can then be obtained at will. The number of 2D images necessary is approximately equal to the number of pixel columns used by the image on the detector. At the ID19 imaging and diffraction beamline at the ESRF this number is usually between 600 and 900. The time needed for recording the 2D images is of the order of an hour, and a few hours are needed for the computer reconstruction of the 3D image.

In the case of snow, a cryostat specially designed for image recording, i.e. displaying a homogeneous behavior over the whole angular range, was used. Its main features are a regulated nitrogen (- 60°C) gas flow to cool the sample, which sits in a cylindrical enclosure with double plexiglas walls, 0.5 mm thick and polished. Figure 1 shows the cryostat, the rotation stage, and the Frelon CCD camera [4] used to record the images.

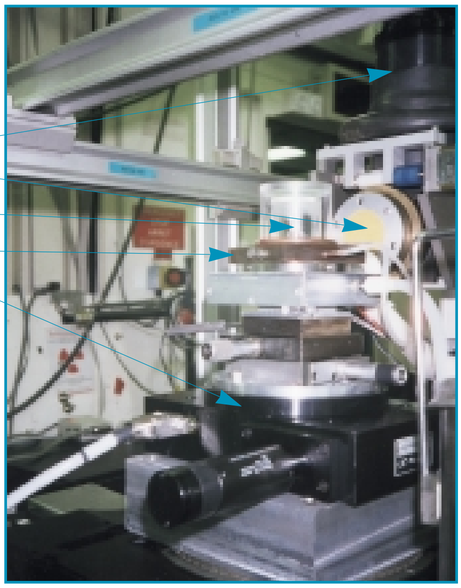

Fig. 1: View of the microtomographic set-up used for snow, where the high accuracy rotation stage, the cryostat and sample and the Frelon CCD camera are identified.

Sample Preparation and Results

3D views of three different snow samples are shown in Figure 2. For samples (a) and (b), fresh snow, collected on the field, was allowed to evolve in a cold laboratory. The sample (a) was obtained by immersion in water at 0°C : it consists of well-rounded grains; the mean convex radius of curvature computed from 2D images of grain outlines [5] was $< r > = 0.25$ mm. The sample (b) was transformed under the action of a large temperature gradient (of the order of 1°C/cm) applied during eight days; due to experimental problems, this temperature gradient was not maintained the following three days. It exhibits faceted crystals: $< r > = 0.17$ mm, estimated grain size: 0.4 mm. The third sample (c) is a melt-freeze crust, partially faceted under a natural temperature

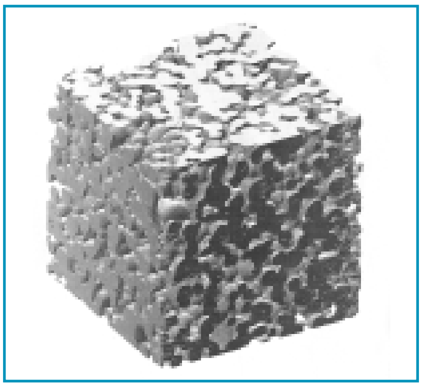

Fig. 2: 3D views of snow reconstructed from 1000 tomographic images. Image size is 600^3 voxels, voxel size is 10 µm, exposure time 1s/view.
(a): wet snow, energy 12 keV.

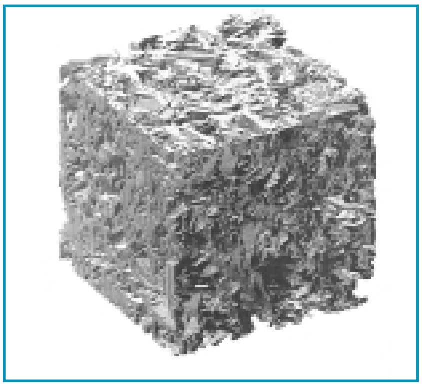

Fig. 2(b): faceted crystals, energy 10 keV.

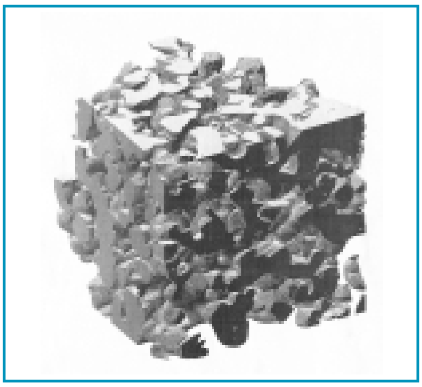

Fig. 2(c): melt-freeze crust, energy 10 keV.

gradient: < r > = 0.25 mm. It was collected on the field at Col de Porte (1340 m, Chartreuse mountain, France).

Those three samples were then prepared in the cold laboratory. To prevent sublimation and grain damage during sample machining and handling, the snow structure was strengthened by using diethyl-orthophthalate [6] (phthalate for short, m.p. -5°C). Before any handling, liquid phthalate was poured at -5°C on snow, and allowed to freeze at -20°C. Frozen lumps of ≈ 100 cm^3 were then extracted and machined at -20°C, in the cold laboratory, into cylinders 10 mm high, with diameter 10 mm. Phthalate was then removed by rinsing in isooctane at -2°C. Isooctane was then drained from the sample (10 s on blotting paper), finally quickly evaporated under vacuum (30 s). The sample was put in a gas-tight cylindrical sample holder and stored in a cool box with CO_2 dry ice until the start of the experiments, in order to prevent sublimation.

The quality of the reconstructed images shows that the samples neither moved nor evolved during tomography.

DISCUSSION

Curvature has long been recognized as a central parameter in snow microphysics. Its importance derives from the fact that the pore size distribution of snow clusters is in the capillary range (0.1 - 1 mm). The structure of snow evolves with temperature and humidity fields, with a specially strong effect of the presence of liquid water when the temperature reaches 0°C. Except at the high sublimation rates leading to faceted shapes, these structure modifications are governed by local curvature.

Until recently, only the 2D local curvature of grains could be used. This gave valuable information on grain types for modeling snow metamorphism but could not, for instance, account correctly for water percolation. The availability of 3D information directly from tomography makes it possible to use the full curvature. We have developed a code for curvature computation from the 3D images, and we checked it on a set of microtome serial cuts of refrozen wet snow [7]. Applying this code to the data files obtained for the above three samples (a, b, c) produced the curvature histograms shown in Figure 3. Samples a, b, c, obtained through three different physical processes as described above, lead to three quite different curvature «signatures». For instance, the histogram of refrozen snow (sample a) shows two modes. One of them, being positive, is characteristic of grain size. The other mode points out negative curvatures and should correspond to interconnected liquid water menisci (concave).

Tomography high resolution images will allow further investigation of other features of snow microstructure such as specific area, relevant for metamorphism dynamics, or ice bond geometry, relevant for mechanical and thermal properties. ■

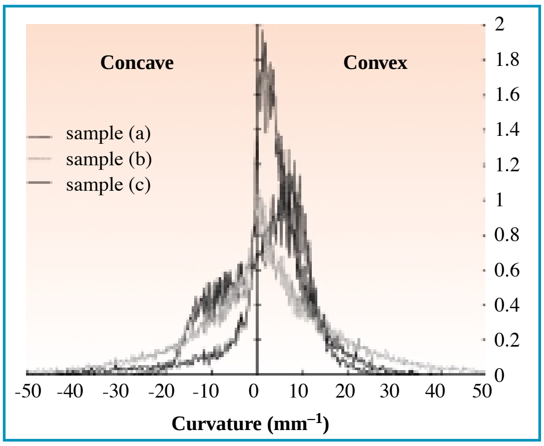

Fig. 3: Histogram of 3D local curvature of grain surface computed from a 128^3 voxels subsample of each image. This curvature is defined at any point as $1/R_1 + 1/R_2$ where R_1 and R_2 are radii of curvature in any pair of orthogonal planes containing the normal vector.

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