

## Radiographic monitoring of Alpine glaciers with cosmic-ray muons

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We report on recent developments of a new geo-exploration method referred to as cosmic-muon radiography. We present its performance on mapping the bedrock geometry under Alpine glaciers and discuss the feasibility of monitoring sub-glacial processes (e.g. mass balance; generation and annihilation of crevasses; melt-water channels).

Muon radiography is a technique that relies on the high penetration power of the muon components in the natural cosmic-ray flux. Specifically, one can resolve the internal density profile of a gigantic object by measuring the attenuation rate of the intensity of muons after passing through it, in a similar way to medical X-rays. This technique has been applied to many fields such where the scopes were to monitor volcanic eruptions [e.g. Tanaka et al., 2007], the detection of hidden chambers in pyramids, and the inspection of the inside of nuclear reactors [e.g. Morishima et al., 2017].

The Eiger-mu project proposes to apply this technology to map the bedrock geometry beneath active glaciers. The first feasibility test of the project has been performed at the Jungfrau region, Central Swiss Alps, Switzerland. We installed cosmic-muon detectors consisting of emulsion films along the Jungfrau railway tunnel that runs through the bedrock under the Eiger and the Aletsch glaciers (Jungfraufirn). Different detectors were exposed from 40 to 100 days in the tunnel and recorded tracks of muons, which passed through the glacial ice and the underlying bedrock. After the films were extracted, they were developed and scanned with fast and automated microscopes in our laboratory at the University of Bern.

The analysis of the muon absorption rate enabled us to image a three-dimensional shape of the boundary between the dense bedrock ( $\sim 2.7 \text{ g/cm}^3$ ) and the light ice component ( $\sim 0.8 \text{ g/cm}^3$ ) in the very uppermost part the glaciers with a resolution ranging from a few meters to 10 m. This is the first application of cosmic-muon radiography in the field of glaciology [Nishiyama et al., 2017]. Further technological developments will enable to monitor the seasonal variation of the bulk density of glaciers, which in turn will provide quantitative constraints on the mass balance, the generation and annihilation of crevasses and possibly on sub-glacial drainage systems.

### References:

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