Exploring the potential of Muon Scattering Radiography (MSR) to estimate the snow water equivalent

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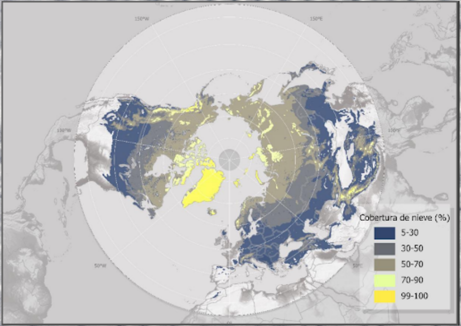
Intoduction

A new technique for SWE monitoring



Snow Cover area (2000-2021, ERA5Land)

1. The **seasonal snowpack** influences ecological and hydrological processes
2. But its **monitoring**, is still a scientific challenge
3. **Muon Scattering Radiography (MSR)** is a non-destructive technique able to extract information about the **internal properties of materials**
4. Complementary method to **improve the SWE monitoring networks**

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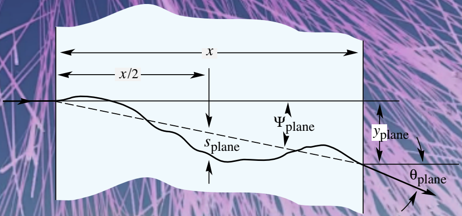
Intoduction

A new technique for SWE monitoring: Fundamentals

1. **Cosmic rays** interact with the atmosphere creating **muons**, among other particles
2. Muons arrive with an approximately **constant flux** to the earth surface ($10.000 \mu / m^2 min$)
3. We measure their **scattering angle** (θ) which is related to the properties of traversed material

Muon Scattering angle ($\theta_0 = RMS(\theta_{plane})$)

$$\theta_0 = \frac{13.6}{\beta cp} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0 \beta^2} \right) \right]$$



P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

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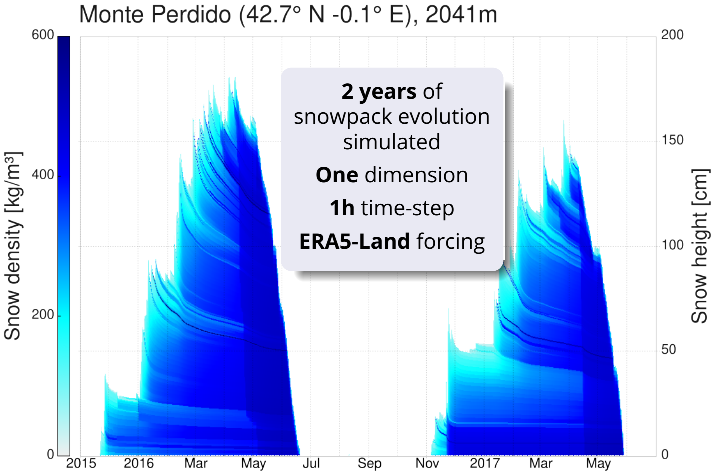
Simulation

Computing snowpack measurement simulations: SNOWPACK model



2 years of snowpack evolution simulated

One dimension

1h time-step

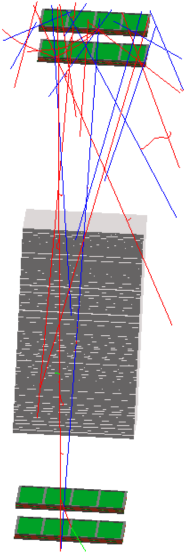
ERA5-Land forcing

Simulation

Computing snowpack measurement simulations: CRY and GEANT4

Simulation steps

- Cosmic muon flux using CRY
- GEANT4 snowpack as layers of variable height and content of water, ice and air determined by SNOWPACK
- Interaction of muons with the snowpack
- Detectors and their response



2 years of data taking simulated

1 m^2 snow surface

0.80 m^2 detectors with **3 m** of separation

```
if os.path.isfile(folder_2 + str(i)  + "_2_Density.txt"):
    v1 = np.loadtxt(folder_2 + str(i)  + "_1_Height.txt")
    v2 = np.loadtxt(folder_2 + str(i)  + "_2_Density.txt")
    v3 = np.loadtxt(folder_2 + str(i)  + "_3_Water.txt")
    v4 = np.loadtxt(folder_2 + str(i)  + "_4_Ice.txt")
    v5 = np.loadtxt(folder_2 + str(i)  + "_5_Air.txt")

    for j in range(0,len(v1)):

        print("Layer " + str(j+1))

        data['MultipleLayer']['xSize'].append("100")
        data['MultipleLayer']['ySize'].append("100")
        data['MultipleLayer']['zSize'].append(str(v1[j]))
        data['MultipleLayer']['material_snow_water'].append(str(v3[j]/100))
        data['MultipleLayer']['material_snow_ice'].append(str(v4[j]/100))
        data['MultipleLayer']['material_snow_air'].append(str(v5[j]/100))
        data['MultipleLayer']['xOffset'].append("0")
        data['MultipleLayer']['yOffset'].append("0")
        data['MultipleLayer']['zOffset'].append(str(sum(v1[0:j], -125)))
```

Experimental setup

Laboratory measurements

Detector and laboratory samples

- Multi-Wire proportional chambers (MWPC)
- 4 chambers (2D grids of 4 mm separated wires)
- Crushed ice samples emulating snow (0.08 m^2)

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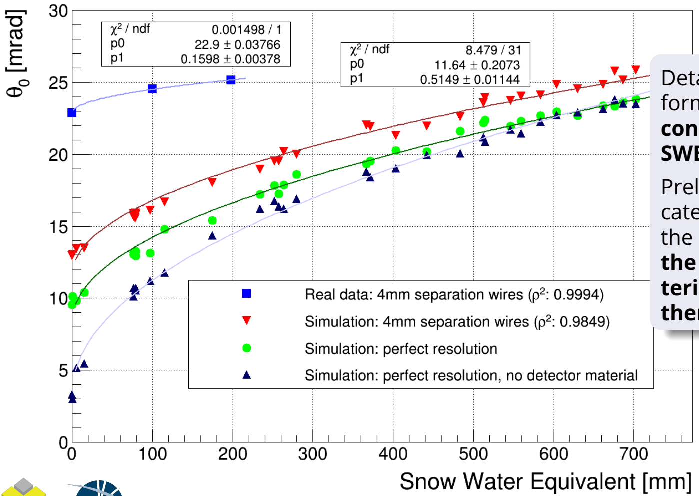
Results

Correlation and modelling (Simulation: 1st year, 5 hour weekly measurements)

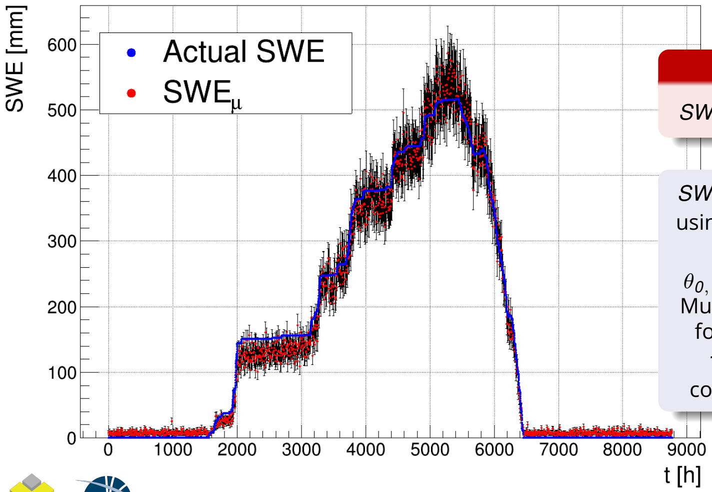


Detailed studies performed to understand the **constant bias at 0 mm SWE**.

Preliminary results indicate the bias is due to the **finite resolution of the detector** and the **material of the detectors themselves**.

Projections

Simulation: SWE estimation and continuous monitoring (2nd year, 5 hour measurements)



Fitted function

$$SWE_{\mu,T} = \left(\frac{\theta_{0,T} - 11.64}{0.51}\right)^2$$

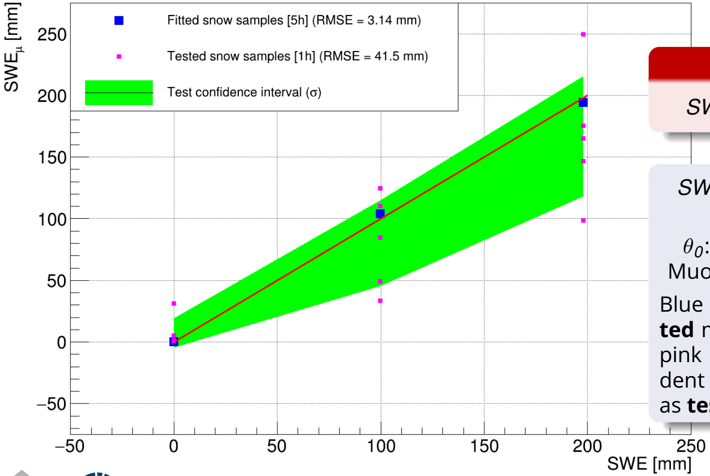
$SWE_{\mu,T}$: estimated SWE using MSR for the T^{th} 5h period

$\theta_{0,T}$: RMS of measured Muon Scattering Angles for the T^{th} 5h period

T: from 1 to 1754, covering the 2nd year

Projections

Real data: SWE estimation (preliminary results)



Fitted function

$$SWE_\mu = \left(\frac{\theta_0 - 22.90}{0.16}\right)^2$$

SWE_μ: estimated SWE using MSR

θ_0: RMS of measured Muon Scattering Angles

Blue dots represent **fitted** measurements, while pink dots are independent measurements used as **test** data

Conclusions

SWE detection, limitations and future work

We measured and modelled the **SWE evolution** of real (crushed ice) and simulated snow samples using **Muon Scattering Radiography (MSR)**

A very detailed understanding of **the detector material and resolution** influence in the measurements. Response is needed in order to estimate **systematic uncertainties** (work ongoing).

Real data preliminary study only covering SWE **between 0 and 200mm**. Is desirable to test the technique in field, increasing the analysed **snow surface** and the **data taking time**, in order to improve the **accuracy**, among other factors.

Muon Scattering Radiography (MSR) can be used to **monitor the SWE** and could potentially extract information about the **inner structure** of the snowpack

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Thank you

I look forward to receiving any questions or comments

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Backup

Fundamentals and simulation

Muon Scattering angle ($\theta_0 = RMS(\theta_{plane})$)

$$\theta_0 = \frac{13.6}{\beta cp} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln(\frac{x}{X_0 \beta^2}) \right]$$

βc: Muon velocity

p: Muon momentum

x: Path lenght of the muon in traversed material

Xo: Radiation length of traversed material. It is related to the energy loss of high-energy electrons in the material

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

CRY

Software which generates cosmic-ray particle showers for use as input to transport and detector simulation codes.

C. Hagmann, et al., “Cosmic-ray Shower Library (CRY),” 2012.

GEANT4

Toolkit for simulating the passage of particles through matter. Its functionalities include tracking, geometry, physics models and hits.

S. Agostinelli et al., “GEANT4 - A simulation toolkit,” Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 506, no. 3, pp. 250–303, Jul. 2003.

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High density artificial snow samples. Their density and SWE match with the SNOWPACK simulation final season (melting) snowpack.

SWE (mm)	m (Kg)	d (Kg/m³)	h (mm)
0	0	0	0
99.84	10.60	448.70	222.50
197.97	21.20	494.92	400

Table: Measured crushed ice laboratory samples