Monitoring the flux of cosmic muons for CRNS incoming correction

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1 Project description

Finapp is a Cosmic Ray Neutron Sensing (CRNS) device that is also able to detect cosmogenic muons. Evidence was collected that the muon flux detected by Finapp probes is generally correlated with the neutron flux published by the Neutron Monitor Database (NMDB) network. Since occasional differences may be due to site-specific conditions, a fair comparison demanded a Finapp sensor to be installed at the very site of a neutron monitor. On December 20, 2023, a Finapp probe was installed on the upper terrace of the Sphinx observatory at Jungfraujoch (Figure 1), where the JUNG neutron monitor is also located. After fixing a configuration issue related to connectivity on the site, the probe became fully functional in mid-January 2024 and has regularly collected and transmitted data since then.

After a whole year of data acquisition, we started the analysis to estimate the corrective factors to account for atmospheric effects, in particular the barometric factor β_μ and the temperature factor α. The ultimate goal is to quantify the correlation between the relative variations of the muon count rate by Finapp and the neutron count rate by JUNG, assess the need for scaling factors between the two, and investigate the possible reasons for the residual differences.



Figure 1: Photos of the Finapp probe mounted on the fence of the Sphinx observatory at Jungfraujoch, including a view of the inside of the box.

2 Project background

CRNS is a widely used approach to measure the water content in soil or in the snowpack at a scale much larger than the usual point-scale sensors and at sub-daily resolution through the detection of the cosmogenic neutron count rate in proximity to the ground (Bogena et al. 2015; Schattan et al. 2017).

The technique is based on the absorption of epithermal neutrons by hydrogen: the drop of the neutron count rate with respect to a baseline is correlated to the amount of water present within the sensor footprint, both in the form of soil water content or snow. The use of cosmogenic neutrons for this purpose overcame the need for an artificial radioactive source of neutrons, thus opening the way for widespread deployment of permanent sensors on-field for automatic long-term monitoring (Bogena et al. 2022; Evans et al. 2016). However, it introduces the need to monitor the natural variation of the incoming radiation to correct the signal accordingly: the so-called incoming correction.

The fluxes of epithermal and thermal neutrons at ground level ultimately depend on the fluxes of high-energy secondary neutrons, which in turn depend on the solar wind and its interactions with the magnetosphere. The incoming correction is therefore usually obtained by referring to the NMDB data, with the Jungfraujoch neutron monitor (NMDB-JUNG) being the preferred one due to its high-quality and reliability and its location. A crucial local parameter to take into account is in fact the magnetic cut-off rigidity (R_c), which ultimately determines the amount of cosmic radiation that can penetrate the Earth magnetic field and which is strongly dependent on latitude (Gerontidou et al. 2021). The issue therefore arises of how to correctly scale the relative variations of incoming flux seen by JUNG, or any other specific NMDB station, to far sites with significantly different R_c values. This is a crucial topic for the CRNS community, especially in countries with low availability of NMDB stations and high R_c variability,

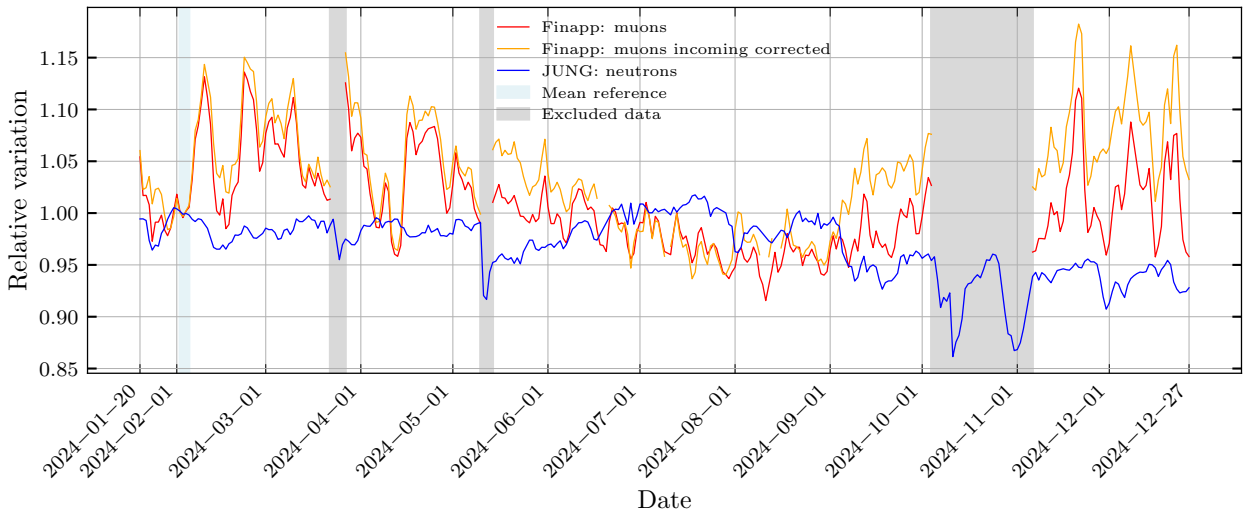


Figure 2: JUNG normalized neutron counts (blue), with gray bars highlighting the geomagnetic storm events that were excluded from the analysis; in red the Finapp (normalized) raw muon counts and in orange the incoming-corrected ones. The cyan square marks the interval chosen as a reference for normalization.

such as Australia, which triggered research on scaling factors (McJannet et al. 2023).

The detector developed and patented by Finapp is based on a plastic scintillator material (ZnS:Ag), which can detect charged particles, doped with lithium to gain the capability of detecting low-energy neutrons. By pulse shape discrimination, Finapp is therefore capable of contextually detecting neutrons and muons or electrons, which suggested a new approach to obtain a site-specific incoming correction. Muons are also generated by cosmic rays, but they are not back-scattered by the soil like neutrons are, which makes them suitable for monitoring the incoming flux itself. Preliminary work showed that the muon count rate is generally correlated with the incoming neutron flux (Stevanato et al. 2022) and that it can be successfully applied as incoming correction for CRNS applications (Gianessi et al. 2024).

3 Results and discussion

The muon flux that is measured at ground at any given time is known to be affected by atmospheric conditions, because the thickness and density of the atmosphere affect the processes of generation, decay, and absorption of muons (Mendonça et al. 2016). The dominant effect is an anti-correlation of the muon count rate to atmospheric pressure, while a second-order effect is the anti-correlation to atmospheric temperature. Following (Stevanato et al. 2022), we model the pressure effect with the factor:

$$f_p = e^{-\beta_\mu (p - p_{\text{ref}})} = e^{-\beta_\mu \cdot \Delta p} \tag{1}$$

representing the relative variation of the flux at pressure p with respect to a flux at reference pressure p_{ref}, and the temperature effect with the factor:

$$f_T = 1 - \alpha \cdot (T - T_{\text{ref}}) = 1 - \alpha \cdot \Delta T \tag{2}$$

which similarly scales the flux at temperature T to a reference temperature T_{ref}. The corrected muon count rate at any given time t is therefore obtained from the raw muon count rate $M_{\text{raw}}(t)$ as:

$$M_{\text{cor}}(t) = M_{\text{raw}}(t) \cdot f_p \cdot f_T \tag{3}$$

and it is expected to be correlated with the cosmogenic neutron count rate.

Here we present the analysis of the almost one-year-long time series of the muon count rate measured by our probe at Jungfraujoch, which allows us to accurately estimate both β_μ and α for this specific site.

The series consists of hourly muon count rate data ranging from 20/01/2024 to 27/12/2024, which has been aggregated to daily count rates for the purpose of this analysis. To study the correlation between rate variation and pressure and temperature fluctuations, different sources of variation must be removed. This implies that our raw signal needs to be corrected for the natural variation of the incoming cosmic ray flux. For this purpose, we used as a reference the JUNG neutron data and excluded from the analysis four time intervals in which the flux was strongly affected by major solar storms. Figure 2 shows the revised original JUNG time series obtained from (*NMDB* 2024), together with the Finapp raw and incoming-corrected daily-aggregated time series. All time series are expressed as relative variations, each normalized to its reference value defined by the average flux in the time interval marked in cyan (arbitrarily chosen for normalization). The intervals excluded from this analysis are marked in gray, characterized by deep sudden drops of the flux (Forbush decreases). Being M_{raw} the raw Finapp muon count rate and N the JUNG neutron count rate with reference value N_{ref}, the incoming corrected muon count rate is obtained as: $M_I = \frac{M}{N} \cdot N_{\text{ref}}$.

The fluctuations of M_I are then expected to be correlated with both the pressure and the temperature variations. An iterative approach is needed to separate the two effects, starting with the dominant one, which is the pressure. Following Stevanato et al. 2022, we start by fitting the linearized relation

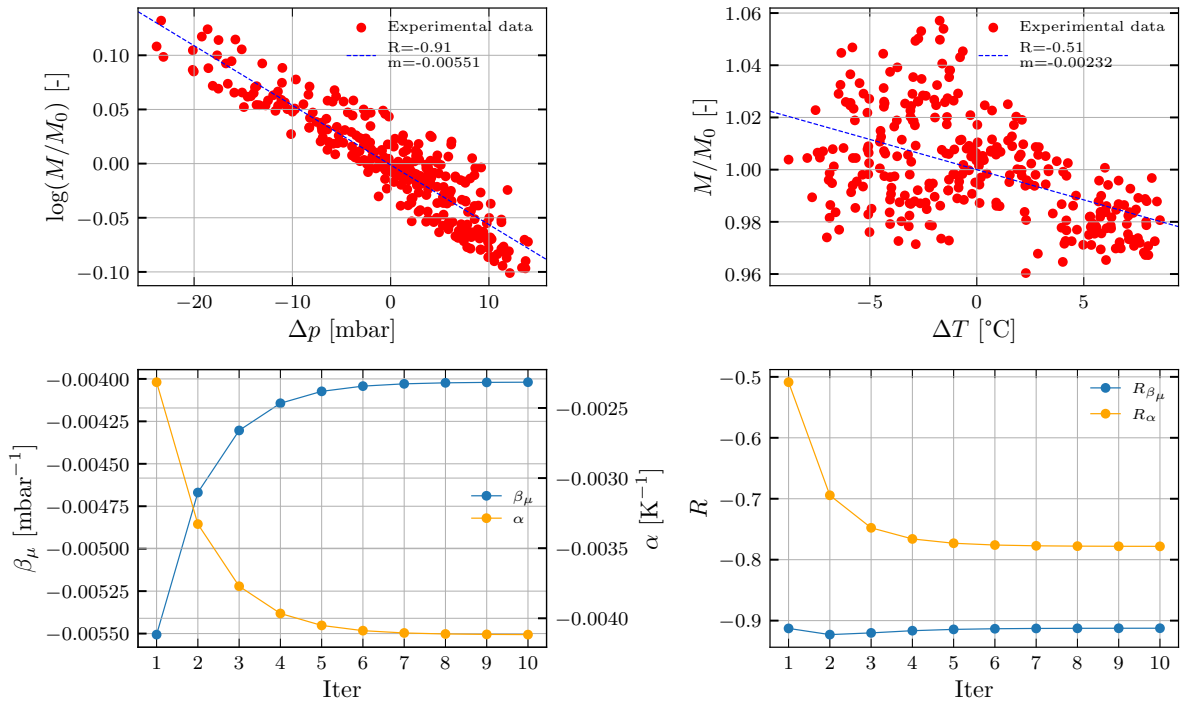


Figure 3: The top panels show the results of the first fit for β_μ (left) and α (right), respectively. The bottom panels show the convergence of the two fit parameters (left) and their correlation coefficients (right) after 10 iterations.

between normalized muon counts and pressure with a first-degree polynomial, where the slope represents an estimate of β_μ. Then we apply the pressure correction to the M_I series and fit the relation between muon counts and temperature, thus obtaining an estimate of α. Further iterations consist of applying the temperature correction to M_I first and obtaining a new fit for β_μ, then again applying the new pressure correction to M_I to obtain a new α, and so on.

The pressure data was acquired by a barometer integrated in the Finapp electronic board, while the temperature data was obtained from (*meteoblue* 2024) as the mean of an estimation of atmospheric temperature at two fixed geopotential height at JUNG location (respectively at 500 mbar and 250 mbar). The results of the iterative process are reported in Figure 3, showing convergence of the parameters. It can be seen that there is a steady decrease of Pearson correlation (R) coefficient for α reaching a value of -0.78, while $R_{\beta\mu}$ is consistently below -0.9. The final values for the two parameters are:

$$\beta_\mu = 0.004\,01(3)\,\mathrm{mbar}^{-1} \qquad \alpha = 0.004\,12(3)\,\mathrm{K}^{-1}$$

Using these parameters, we therefore obtain the corrected muon count rate series by Equation (3) and report it in Figure 4 for comparison with the JUNG neutron series. Finally, to show how the applied corrections improve the matching between them, we calculate the Pearson correlation coefficient (R) for N and M_{raw} and for N and M_{cor}, using the whole time series in this analysis, including geomagnetic storm events. The results are reported in Figure 5, showing a notable improvement and a significant correlation between the muon flux measured by Finapp and the neutron flux measured by JUNG.

4 Conclusions and perspectives

These results demonstrate that the muon flux is locally correlated with the incoming neutron flux after proper, site-specific atmospheric correction factors are applied and that the correlation remained significant also in 2024, a year in which the cosmic rays flux was significantly disrupted by intense solar activity. For the purpose of expanding the project and investigating how the correlation would scale with the R_c parameter, another Finapp probe was deployed to the Oulu observatory in October 2024, where it was installed in the temperature-controlled room where the NMDB-OULU neutron monitor is located. This project at Jungfraujoch will also be maintained to collect multiple seasonal cycles. The need for additional scaling factors to deal with the anomalous decreases associated with Forbush decreases will also be investigated.

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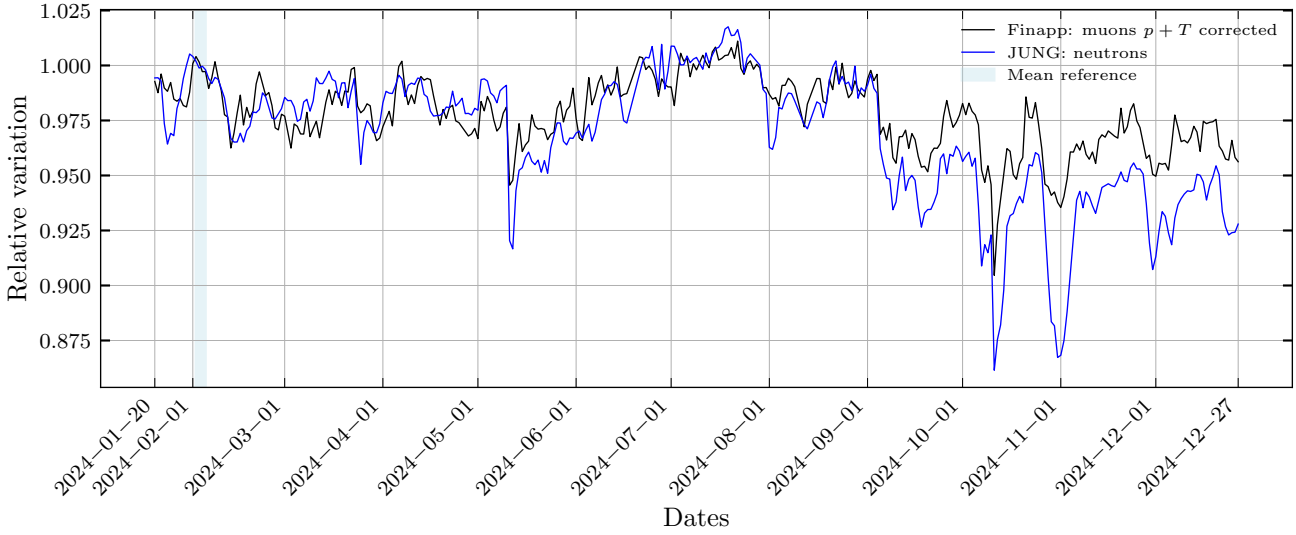


Figure 4: Comparison between JUNG neutron counts and the Finapp pressure and temperature corrected muon counts.

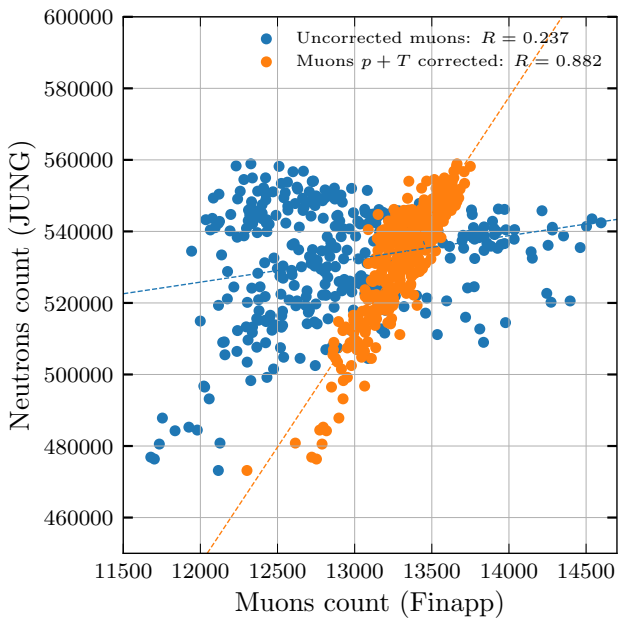


Figure 5: Relationship between the JUNG neutron counts and the Finapp muon counts, either raw (blue) or corrected (orange).

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