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An Alternative Incoming Correction for Cosmic-Ray Neutron Sensing Observations Using Local Muon Measurement

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Key Points:

- Incoming correction in cosmic-ray neutron sensing observations based on local muon measurements at ground

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Abstract Measuring the variability of incoming neutrons locally would be usefull for the cosmic-ray neutron sensing (CRNS) method. As the measurement of high energy neutrons is not so easy, alternative particles can be considered for such purpose. Among them, muons are particles created from the same cascade of primary cosmic-ray fluxes that generate neutrons at the ground. In addition, they can be easily detected by small and relatively inexpensive detectors. For these reasons they could provide a suitable local alternative to incoming corrections based on remote neutron monitor data. The reported measurements demonstrated that muon detection system can detect incoming cosmic-ray variations locally. Furthermore the precision of this measurement technique is considered adequate for many CRNS applications.

Plain Language Summary The measurement of the variability of the incident neutron flux is of fundamental importance for the cosmic-ray neutron sensing technique. This type of measurement is not easy to use to have local and instantaneous values. For this reason in this work it is reported how this type of information can be obtained through the measurement of the flux of cosmic muons, which are correlated with the flux of cosmic neutrons. This type of measurement, being easier to perform, allows you to have a local and real time value in a very simple way.

1. Introduction

Cosmic-ray neutron sensing (CRNS) has been introduced as a valuable method for non-invasive soil moisture estimation (Desilets et al., 2010; Zreda et al., 2008). The approach relies on the correlation between natural neutron of background cosmic radiation and hydrogen content. Due to the specific capabilities of the neutrons to move in air and to penetrate into the ground (Desilets & Zreda, 2013; Köhli et al., 2015), the signal detected by the sensor installed above-ground is sensitive to an area of several hectares horizontally and of several decimeters below ground. Additionally, the detectors can record data with high temporal resolution, usually in the order of hours. For these reasons, CRNS has been recognized as a valuable method filling the gap of current approaches (Ochsner et al., 2013; Robinson et al., 2008). This soil moisture areal value is representative for many approaches, from catchment scale models (usually 100 m grid) used for managing the freshwater resource, to eddy covariance measurements used for actual evapotranspiration estimation, or again for irrigation systems in agriculture like the center-pivot system. Furthermore CRNS can be used for estimating other variables (Andreasen et al., 2017; Desilets et al., 2010; Rivera Villarreyes et al., 2011) such as biomass (Franz et al., 2013; Jakobi et al., 2018; Tian et al., 2016), canopy interception (Baroni & Oswald, 2015) or snow-water-equivalent (Schattan et al., 2017; Sigouin & Si, 2016).

The CRNS method is now used by several research groups at increasing number of sites around the world (Andreasen et al., 2017) and a national CRNS soil moisture networks under the acronym of COSMOS have been established first in the United States and then in other nations: the United Kingdom, Australia, India (Evans et al., 2016; Hawdon et al., 2014; Upadhyaya et al., 2021; Zreda et al., 2012) and recently also in Europe (Bogena & Hey, 2022).

The neutron intensity measured at the ground level is affected by the temporal variability of the incoming neutron flux and atmospheric conditions. At first, the variability of neutron flux is due to solar activities (Simpson, 2000). Neutrons are attenuated by the mass of the air (Desilets & Zreda, 2001; Paschalis et al., 2013). Specifically, air pressure variations modify the absorption, decay and generation effects on secondary cosmic rays, producing a variation of their intensity, anti-correlated to atmospheric pressure fluctuations (Dorman, 2004; Sagisaka, 1986). Finally, air humidity has shown to be relevant (Köhli et al., 2021; Rosolem et al., 2013).

Air pressure and humidity corrections rely on local measurements that could be easily collected. In contrast, the incoming correction to account for cosmic-ray fluctuations by solar activity is so far based on measurements from a neutron monitor network (Simpson, 2000). Data from the network (Neutron Monitor DataBase, hereinafter NMDB, http://www01.nmdb.eu/) is used to correct the CRN intensity for the variation in incoming cosmic radiation as the data are available online in real-time.

However, the coverage of the network is primarily on the Northern hemisphere and most nations do not have stations at all. Thus, this procedure has some limitations where NMDB stations are too far from the CRNS site and NMDB data are not representative of the local conditions (Hawdon et al., 2014; Schrön et al., 2015), introducing errors that can be relevant for the estimation of soil moisture or other variables targeted (Baroni et al., 2018).

Measuring the variability of incoming neutrons locally would be a valuable improvement for the CRNS method. As the measurement of high energy neutrons requires large neutron detectors, alternative particles can be considered for such purpose. Among them, muons are particles created from the same cascade of primary cosmic-rays that generate neutrons at the ground. In addition, they can be easily detected by small and relatively inexpensive detectors. For these reasons they could provide a suitable local alternative to incoming corrections based on remote neutron monitor data.

In this work we want to show that the local measurement of muons at ground provide a good estimate of the incoming variations, suitable for correcting the CRNS observations at the same level of precision of the traditional corrections based on NMDB data.

2. Genesis of the Atmospheric Muons

Primary cosmic particles are mainly protons (~85%) and alphas (~13%) with typical energies above 300 MeV. By collisions with the atmospheric nuclei they produce secondary particles and, eventually, further cascades. Muons at ground come mainly from the decays of high energy charged pions (~100% BR to $\mu + \nu$) and kaons (~64% BR to $\mu + \nu$) produced in such interactions. Their energy spectrum at ground is related to the one of the decaying parent particles, with most of the yield concentrated in the low energy region below 20 GeV and a mean value around 4 GeV (Nakamura et al., 2010). Muons below 1 GeV come mainly from interactions of primary protons with energies below 20 GeV and therefore geomagnetic latitude and solar modulation has a strong impact in their production. Muons represent the most abundant fraction of cosmic particles that reach the sea level (see e.g., Cecchini & Spurio, 2012 for a short review on this topic). The total muon flux at sea level is about 170 muons/(s m^2) (Kouzes et al., 2008).

The muon flux that can be measured at ground depends significantly on the specific local conditions. In addition to the main effect of the atmospheric absorption (namely the air pressure at the measuring point) also the effect of cutoff rigidity has to be considered (Shea & Smart, 1990). Cutoff rigidity is a concept which describes the geomagnetic shielding provided by the earth's magnetic field against the arrival of charged cosmic ray particles from outside the magnetosphere. It is defined as the lowest rigidity a charged particle can possess and still arrive at a specific point on the earth's surface. The cutoff rigidity of any geographic location is a function of the zenith and azimuth angles of arrival, the altitude of the detection location, and the geomagnetic conditions at the time of the measurement. Primary nuclei having lower rigidity are deflected by the action of the geomagnetic field and do not produce muons at that latitude. "The cut-off values range from less than 1 GV near the geomagnetic poles to about 16 GV for vertical particles near the equator. […]The geomagnetic effects are important for sea level muons up to energies of about 5 GeV, and the effect is larger at higher altitudes" (Cecchini & Spurio, 2012). An updated world map of vertical cutoff rigidity can be found in (Gerontidou et al., 2021).

Being a subproduct of the primary cosmic ray flux as the incoming neutrons, the variations of the muon flux at ground, after correcting for the atmospheric absorption, reflect the ones on the incoming neutrons.

However, the pressure-corrected muon flux cannot be used as it is as normalization for the neutrons. Some studies show a further effect due to temperature (De Mendonça et al., 2016; DWD, https://www.dwd.de/). Temperature influences the creation and disintegration processes of muons in the atmosphere and are generally considered to have positive and negative components (Duperieb, 1951). The positive effect is related to the temperature influence on pion decay, which is the major source of muons in the cosmic ray cascade process. The higher the temperature, the lower the atmospheric pion absorption, which implies a higher generation rate of muons. On the other hand, the negative effect is associated with changes of the atmosphere thickness. It is expected that most muons are generated at higher altitude, therefore when the thickness is larger due to thermal expansion the path to the ground increases, allowing for more muons to decay before reaching the surface (Blackett, 1938). This effect is therefore predominant in summer.

3. Experimental Setup

For this study, we used a FINAPP detection system (FINAPP, https://www.finapptech.com/en/why-finapp). The system is based on an improved Li-6 loaded scintillator for neutrons detection and a "2 × 2" cylinder of plastic scintillator for muons detection. Muons are discriminated from gamma rays thanks to their large energy release inside the active volume, which produces a well separated peak in the highest region of the energy spectrum.

A polyethylene shield is placed around the neutron detector to enhance the response to epithermal neutrons (0.5 eV–50 keV). The detectors are connected to a low noise photomultiplier, a custom electronics control board hosting the High Voltage power supplies, the digital signal read-out and the data processing. Ancillary weather sensors for measuring air pressure, air temperature and air humidity are also connected to the board and installed inside a radiation shield. An automatic calibration algorithm to stabilize the high voltage power supply and the gain of the photomultipliers with respect to environmental temperature variations is provided in real-time by the control board. This allows to operate the system in a wide temperature range (−25° /+ 55°; Stevanato et al., 2020). The possibility to measure locally muons to make a real-time estimation of the soil moisture with Cosmic Rays Technique is covered by a FINAPP patent (Stevanato et al., 2019).

The FINAPP system has been installed in the tower (30 m high) at Department of Physics of Astronomy of the Padova University (Italy).

4. Experimental Barometric Factor and Temperature Coefficient Estimation

We present in this section the analysis of the one-year muon data series taken in Padova, from November 2019 to October 2020, used to extract an estimation of the parameters needed to correct the muon flux for air pressure and temperature effects.

The relation between muon flux intensity and atmospheric pressure is well described by an exponential function (Dorman, 2004):

$$f_P = e^{-\beta_\mu \left(P - P_{\text{ref}}\right)} = e^{-\beta_\mu (\Delta P)}, \tag{1}$$

where f_P represents the relative variation of the flux with respect to a flux at reference pressure. β_μ is the barometric factor, P is the pressure when the measure is done and P_{ref} is the reference pressure determine in a long time period.

Equation 1 can be linearized to estimate the barometric factor (β_μ) for muon fluxes M as follows:

$$M = M_0 \cdot e^{-\beta_\mu (\Delta P)}$$

$$\ln\left(\frac{M}{M_0}\right) = -\beta_\mu \cdot \Delta P \tag{2}$$

where M represents the muon counts at pressure P compared to the corresponding counts at reference pressure (M_0).

In addition to pressure variations, atmospheric temperature changes can produce variations in the measured muons flux at ground. In De Mendonca et al. (2016), the temperature effect on four ground muon detectors of

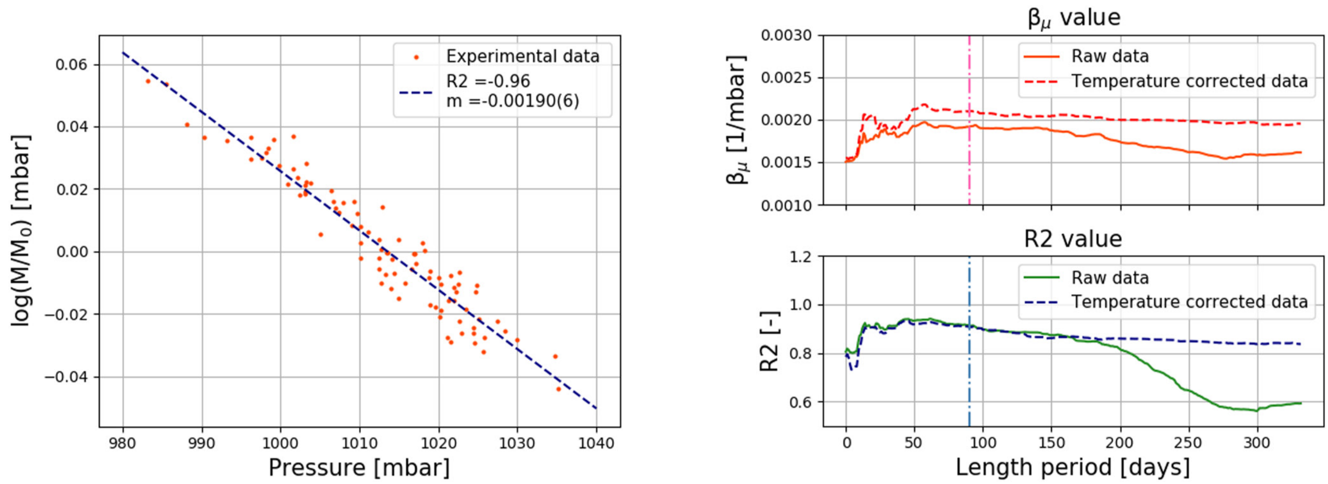

Figure 1. Logarithm of normalized muon counts at Padova in a winter period as a function of pressure (left). β_μ and R^2 calculated with increasing length of time period (right) up to the full measurement period; without temperature correction (solid lines) and with temperature correction (dashed lines). See text for details.

the Global Muon Detector Network (GMDN) was studied. For the determination of the atmospheric temperature, they used daily atmospheric temperature profiles obtained with radiosondes installed on meteorological balloons and by the Sounding of the Atmosphere using Broadband Emission Radiometry instrument installed over a spacecraft. The determination of temperature with that kind of instrument is quite complex. Nevertheless, a simpler approach using temperature values registered at ground was also considered and shown to provide useful results as well.

We will use therefore local ground temperature to account for this effect. At first order the relation between temperature and muon counts is expressed by a linear relation as in the following:

$$\frac{M}{M_0} = 1 - \alpha \cdot \Delta T, \tag{3}$$

where M represents the muon counts at temperature T compared to the corresponding counts at reference temperature (T_0). As reference temperature, the average local temperature over the considered period of observation was used.

The logarithm of the relative muon count as a function of the average daily atmospheric pressure for the Padova series is presented in Figure 1 together with the fit of data using Equation 2 (left panel).

As discussed in De Mendonca et al. (2016), for the experimental determination of β_μ it is important to choose a period when the muon intensity variation is predominantly influenced by a significant pressure variation to better estimate the barometric factor for muons. The analysis was initially performed using the first 90 days of measurements. During this winter period we had a quite significant span in pressure vales (over more than 40 mbar) and we expect a minimal variation associated to temperature effects.

The result of our fit gives $\beta_\mu = 0.190$ (6)% mb^{-1}. The linear correlation factor R^2 is equal to 0.96, showing the strong correlation between the two variables.

As expected by Hansen et al. (2003), the barometric factor β_μ for muons is significantly lower than the value generally used for neutrons $\beta_n = 0.76\%$ mb^{-1} (Zreda et al., 2012). However, the value quantified based on our data is slightly higher than the ones measured at the GMDN by De Mendonca et al. (2016), between 0.12% and 0.17% mb^{-1}. This systematic difference can be explained considering that the values reported usually in scientific literature are obtained using powerful muon telescopes to measure muon flux as a function of muon energy and incident angle. As a consequence, muons with a given incident angle and a given energy or energy threshold are used to determine the beta barometric factor. As an example, the GMDN data used by De Mendonca et al. (2016)

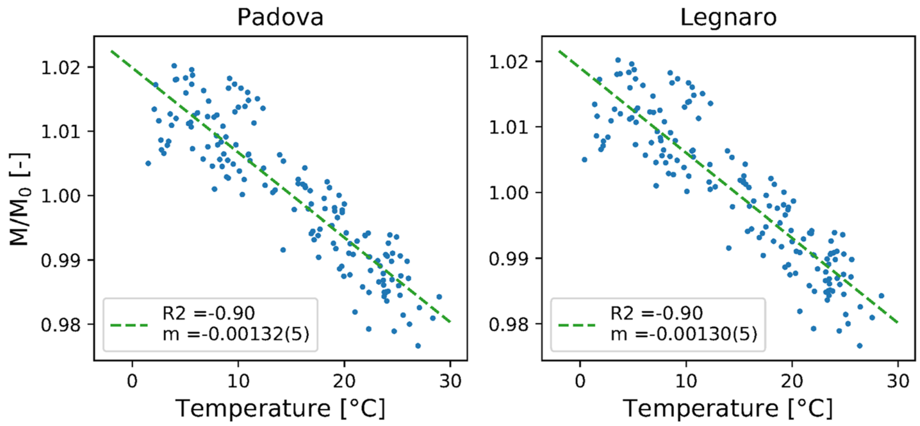

Figure 2. Correlation between the muon counts and the temperature measured at Padova and Legnaro ARPAV weather station. The data are fitted with a first-degree polynomial.

refer to vertical muons with energies higher than 50 GeV, in order to minimize the effect due to the different cut-off rigidity R_C of the detector sites.

In the simpler muon detector inside the FINAPP detection system, neither direction nor energy selection can be applied to muon signals, which are therefore representative of an incident angle- and energy-integrated muon flux.

For a given altitude, inclined muons are associated with larger mean paths in atmosphere, making them more sensitive to pressure. The incident angle-integrated muon flux is therefore expected to be more affected by pressure variation than the vertical muon flux, thus being reflected in a larger beta value.

The parameter β_μ was then further estimated using increased measurement period lengths (Figure 1, right panel), though then containing larger temperature variations. It can be noted that β_μ decreases to about 0.16% mb^{-1}, while also R^2 is decreasing below 0.6, showing a progressive loss of correlation. This is not surprising since we already know that also a temperature correction needs to be considered, and this correction is not independent from the air pressure correction.

We estimated the air temperature effect from our data by fitting the relative muon count variations as a function of temperature (Figure 2, left panel) with a linear fit, obtaining the α coefficient of Equation 3 equals to 0.132 (5)% K^{-1}, about a factor 2 smaller than what was found by De Mendoca et al. (2016) in the Northern hemisphere.

In order to avoid possible bias of our temperature sensor located within an urban environment, we use also temperature from Legnaro ARPAV weather station to study temperature dependencies of muons. This weather station is placed in countryside, 7.5 km away from our muon detector. Again, the correlation between temperature and muon counts is good within statistical fluctuations and the result of the fit confirms no significant dependencies of the temperature for urban environment (Figure 2, right panel). This result clearly supports the hypothesis that to study and quantify the temperature effects of the muons at the ground is sufficient to use the temperature information from a weather station located nearby (De Mendonca et al., 2016). It is therefore not a requirement, at least at this level of the description, to know the temperature at high atmosphere for the temperature corrections.

Since we expect the pressure and temperature effects to be correlated, we repeated the β_μ evaluation analysis after correcting the raw data for temperature. The results are shown in the right panel of Figure 1 (dashed lines). The new estimation of the barometric factor is slightly higher (around 0.21% mb^{-1}), but the main difference is that it is now much more stable over the full range of time period lengths considered, as confirmed also by the R^2 correlation coefficient, then always well above 0.8.

This result supports our expectation of significant correlation between air pressure and temperature effects. If we iterate the analysis by re-evaluating the α and β_μ coefficients and by varying the fitting conditions, we find values fluctuating between 0.20%–0.22% mb^{-1} for the β_μ barometric coefficient and between 0.15% and 0.17% K^{-1} for the α temperature coefficient. We finally quote $\beta_\mu = 0.21$ (1)% mb^{-1} and $\alpha = 0.16$ (1)% K^{-1} as our final

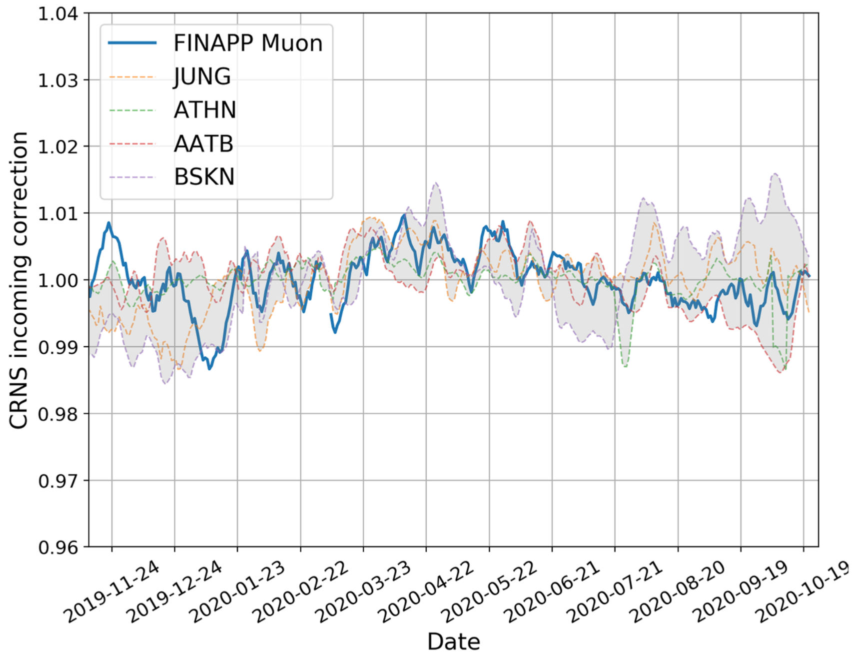

Figure 3. Comparison between incoming correction derived via muon fluxes from FINAPP and incoming correction based on data from Neutron Monitor DataBase (NMDB) with similar cut-off rigidity. The gray area shows the maximum variability between the considered NMDB stations.

estimate of the correction coefficients extracted from this data set. More data acquired simultaneously at different locations in different conditions will be needed to improve the overall description and to refine the procedure to be applied for the extraction of the coefficient.

5. Incoming Correction Based on Muon Fluxes

Finally, we evaluated the quality of our determination of the local incoming neutron component for CRNS based on our local muon signal. We compared the muons in the long PADOV time serie with the data available from the real-time neutron monitor database (Mavromichalaki et al., 2011; NMDB).

We extracted neutrons counts from four stations in Europe with cut-off rigidity R_{ch} relatively similar to Padova (R_C = 4.86 GV): AATB (Almaty, KZ) R_C = 5.90 GeV, altitude = 897 m, ATHN (Athens, GR) R_C = 8.53 GeV, altitude = 260 m, BSKN (Baksan, RUS) R_C = 5.70 GeV, altitude = 1700 m and JUNG (Jungfraujoch, SWI) R_C = 4.49 GeV, altitude = 3570 m a.m.s.l.

During the 1 year time series in Padova (Figure 3) the incoming muon flux shows only small fluctuations, mostly within the gray area representing the fluctuations between the considered NMDB stations.

The spread of the NMDB data is lower in certain periods than in others. In particular, we noticed that NMDB data are similar during more stable periods when the weather condition was similar in the regions. Muon measurement is also compatible with NMDB data in these periods.

On the contrary, during more unstable weather periods, a correlation between storms and variations in incoming cosmic-ray particles seems to be present for the different locations. As an example, we can focus on the correction based on locale muon measurements and on measurements from the JUNG neutron monitor station in three periods: mid-November 2019, end of December 2019 and beginning of January 2020 (Figure 4). In these periods (identified with colored area in Figure 4) the incoming correction was considerable different. Looking at the weather conditions in these periods we noticed that the polar vortex left the arctic region to cross the northern part of Europe. This had generated a low-pressure area that reached Jungfraujoch with snowfall and strong Föhn wind with stable weather conditions in northern Italy (Period 1 and 2). In January (Period 3), the weather conditions reversed with a high-pressure area in France and Switzerland and low-pressure area in Northeast Italy and

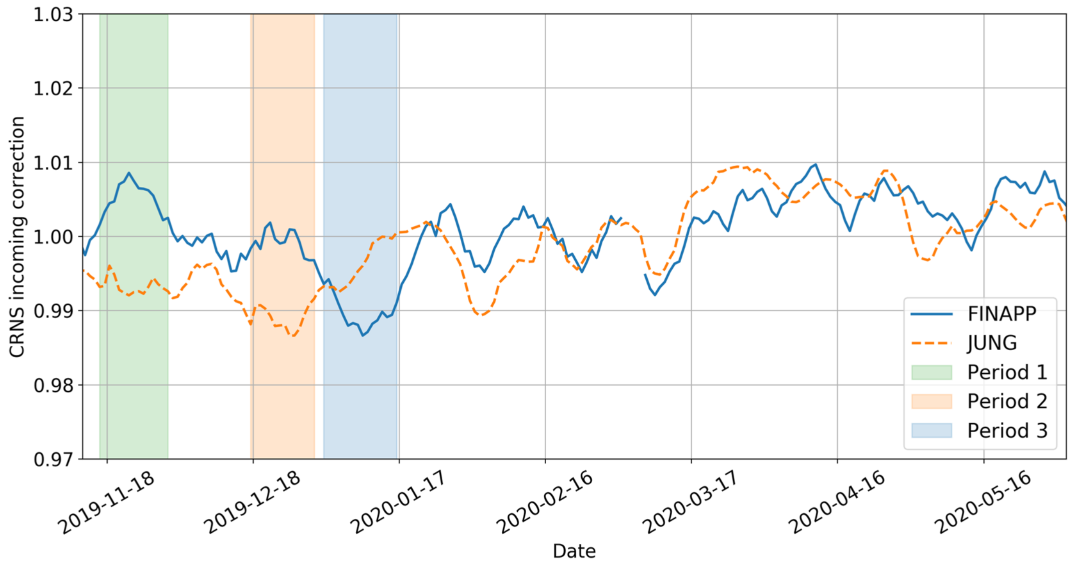

Figure 4. Comparison of the variations in incoming cosmic-ray particles between Jungfraujoch and Padova. Colored areas highlight the period in which the weather conditions are significantly different between the two sites.

Balkans (DWD). It seems that the water content vapor of the atmospheric profile can interfere with the process that generates the high energy particles cascade from cosmic rays.

This possible weather effect reinforces the advantage of using local incoming determination instead of external information taken far from the observation site, with possibly considerably different weather conditions in the atmosphere.

6. Conclusions

The reported measurements demonstrated that muon detection system can detect incoming cosmic-ray variations locally. The precision of this measurement technique is considered adequate for many CRNS applications. Raw muon counts have to be corrected for air pressure and temperature effects and we could calculate the correction coefficients directly from the ground data collected, for example, in Padova. We showed also how the value of the beta barometric factor is dependent on the muon detector geometry.

In general, we found that a first approximation of local beta for a given location can be easily extracted from data after a short period of use during which pressure spans over a sufficient range of values. Nevertheless, a significant correlation between the barometric factor and the temperature coefficient values was found in the Padova data, showing that a general procedure to obtain a better estimation of the local correction coefficients needs more studies to be assessed. Thus, a wider measurement campaign with FINAPP probes simultaneously installed at different locations and for longer periods could provide some additional insights.

Finally, we can state that the local monitoring of the cosmic muon flux is the missing piece that combined with the standard CRNS observations makes it possible to now determine the soil moisture and snow water equivalent in real time in a stand-alone system without the requirement of external information and offline data reanalysis.

Data Availability Statement

The time series from Padova used for all the calculation present in the study are available via Zenodo: https://doi.org/10.5281/zenodo.5541259 with Creative Common Attribution 4.0 International.

Conflict of Interest

Luca Stevanato, Marcello Lunardon and Sandra Moretto are of FINAPP S.r.l., 37029 San Pietro in Cariano, Italy. Otherwise the authors declare no competing interests.

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