Influence of environmental parameters on secondary cosmic ray neutrons at high-altitude research stations at Jungfraujoch, Switzerland, and Zugspitze, Germany

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Abstract

Neutrons of secondary cosmic radiation (CR) are produced when primary cosmic radiation interacts with the nuclei in the Earth's atmosphere. The secondary neutron spectra in the atmosphere do not include many thermal and epithermal neutrons at energies below several eV. In contrast, close to the Earth's surface many more of those neutrons are present, due to albedo neutrons backscattered from the ground. The number of albedo neutrons is mainly determined by the environment, i.e. the material in the environment (characteristics of the underground and the environment (building, topology of landscape)). If the environment (buildings, underground) is constant with time then the variation of the albedo neutron fluence is dependent on the soil moisture and snow cover.

To investigate snow cover effect in detail, in June 2016 and September 2018 two measurement campaigns were carried out at the High Altitude Research Station Jungfraujoch, Switzerland. During these campaigns the energy distributions of secondary CR neutrons were measured by means of a mobile extended range Bonner sphere spectrometer (ERBSS) at two different positions with different environmental conditions: under the cupola of the astronomical observatory in the Sphinx building at an altitude of 3,585 m a.s.l., and below the shelter roof of the research station at 3,466 m a.s.l.

In addition, since 2004 the energy spectra of neutrons from secondary CR have been continuously measured at the Environmental Research Station (UFS Schneefernerhaus; 2,650 m a.s.l.) close to the summit of the Zugspitze mountain, Germany. To measure the neutron spectra in the energy range from a few meV up to several GeV, a stationary ERBSS has been used.

The chosen measurement positions allow quantification of environmental conditions which affect the neutron spectral distribution in the whole neutron energy range up to several GeV. With this spectral information, it is also possible to derive detailed information about the neutron ambient dose equivalent ($H^*(10)$) at these altitudes and geomagnetic latitudes.

The ERBSS measurements at Jungfraujoch presented here show that snowpack in the surrounding area does not affect the fluence rate of secondary neutrons significantly. However, the influence of topography of the chosen measurement locations on secondary CR neutrons was observed.

1. Introduction

The Earth's upper atmosphere is constantly bombarded with high-energy particles from outer space known as galactic cosmic rays (GCR). The GCR interacts with the nuclei in the atmosphere producing a complex field of secondary cosmic radiation, predominantly made of neutrons, electrons, muons, pions, protons and photons. The secondary neutrons are of particular interest because they contribute up to 50% to the effective dose of air crew from CR [Chen and Mares, 2008, 2010].

Since the late 1950's, a number of ground-based neutron monitors (NMs) record continuously the intensity of the secondary neutrons from CR at ground level, forming a global NM network [http://www.nmdb.eu]. Two NMs also operate at Jungfraujoch [Flückiger and Bütikofer, 2009]. The first, IGY NM, operates on the roof of the Sphinx observatory (3,580 m a.s.l.) since 1958, while the second, an NM64, situated on the roof of the Research Station (RS) (3,475 m a.s.l.) was put in operation in 1985. A NM is a ground-based detector to measure CR variability at the surface of the Earth. NMs are very sensitive to high-energy neutrons (E > ~10 MeV) (Clem and Dorman, 2000), but a single NM cannot provide information on the spectral fluence rate distribution of secondary neutrons. However, the worldwide network of NMs together with the Earth's magnetic field acts as huge spectrometer. The CR spectrum and its variation with time can be determined in the energy range ~500 MeV to ~15 GeV near Earth outside of the geomagnetosphere.

If the neutron fluence rate and ambient dose equivalent rate is required as a function of neutron energy in the range from thermal up to several GeV, an extended-range Bonner sphere spectrometer (ERBSS) has to be used. In 2005, the Helmholtz Center Munich (HMGU) installed an ERBSS system at the environmental research station "Schneefernerhaus" (UFS) close to the summit of the Zugspitze mountain, Germany (2,650 m a.s.l.), to perform continuous measurements of the spectral fluence rate distribution of secondary neutrons from CR [Leuthold et al., 2007]. During these measurements it has been observed that the snow accumulation in the environment of the detector has a significant effect on the measured neutron flux distributions. This effect was explained by seasonal changes of the number of ground albedo neutrons (from thermal energies to several MeV) depending on the amount of snow and water in the environment surrounding the detectors [Rühm et al., 2012]. The effect of a snow accumulation on the roof of the NM housing was reported by [Eroshenko et al, 2008]. To investigate these effects further, in June 2016 and September 2018 two measurement campaigns were carried out at the High Altitude Research Station Jungfraujoch, Switzerland, in cooperation with the University of Bern. During these campaigns the neutron energy distributions of secondary CR were measured at two different positions with different environmental conditions, i.e., during a period with permanent snow cover and during a nearly snowless period. In the present paper the results obtained at Jungfraujoch are presented and compared to those obtained at the Zugspitze mountain during the same time period.

2. Materials and methods

2.1 Extended range Bonner sphere spectrometer

To provide experimental data on the spectral fluence rate distribution in the whole neutron energy range from a few meV up to GeV, an Extended Range Bonner Sphere Spectrometer (ERBSS) was used. This mobile ERBSS system was composed of 3.3 cm diameter spherical ^{3}He (partial pressure of 172 kPa) proportional counters (type SP9, Centronic Ltd.) and 15 polyethylene (PE) spheres of different diameters (2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 7, 8, 9, 10, 11, 12, 15 inch) showing specific energy responses to neutrons. Furthermore, two additional 9 inch spheres were used that include lead shells of different thickness (0.5 and 1 inch), to increase the response for high-energy (E > 20 MeV) neutrons [Mares and Schraube, 1998]. A bare ^{3}He proportional counter without any surrounding material was used to get a high response to thermal neutrons. Proportional counters filled with ^{3}He gas are most suitable for the detection of thermal neutrons because of their high neutron capture cross-section ($\sigma_{n,th}$ = 5.330 b) for the (n,p) nuclear reaction. The signals from these SP9 proportional counters were amplified and shaped in charge sensitive preamplifiers and processed in a Multiport II MCA, both produced by Canberra Industries Inc. The electronic system used allowed simultaneous measurement with four spheres.

The fluence response functions of all Bonner spheres with a ^{3}He proportional counter in their center were calculated by means of Monte Carlo (MC) simulations [Mares et al., 1991, 1998] and experimentally validated at 13 neutron energies between thermal and 14.8 MeV [Alevra et al., 1992; Thomas et al., 1994] as well as with quasi-mono-energetic neutron fields with peak energies at 244 MeV and 387 MeV [Mares et al., 2013]. Neutron energy spectra can be derived by unfolding the ERBSS count rates recorded by the SP9 proportional counters using the corresponding fluence response functions [Mares et al., 1991] and an in-house version of the MSANDB unfolding code [Matzke et al. 1987].

A similar but stationary ERBSS system is installed at the Environmental Research Station (UFS Schneefernerhaus) at the Zugspitze mountain, to perform continuous measurements of the spectral flux distribution of neutrons of the secondary CR. Every hour this system provides the pulse height spectra of 15 SP9 proportional counters located within 13 PE spheres and two 9" PE spheres with lead shells, and one bare SP9 proportional counter. These spectra are stored and then downloaded to HMGU by remote control. The count rates are obtained by integrating over a region of interest (ROI) estimated for each counter by calibration using a 185 GBq ^{241}Am-Be neutron source. The count rates are corrected for any changes in air pressure to a reference pressure of 740 mbar.

2.2 Neutron Rem Counter

An NM2B-495Pb rem counter (NE Technology Ltd.) was also used at Jungfraujoch to measure the neutron ambient dose equivalent, H*(10). This rem counter was based on a conventional Andersson-Braun rem-counter with a cylindrical BF_3 boron trifluoride proportional counter surrounded by an inner polyethylene moderator, a boron-doped synthetic rubber absorber, and an outer polyethylene moderator. To extend the detection range to higher energy neutrons, a 1 cm thick lead shell is added above the boron rubber. Pulse height spectra were registered to control the photon background and to properly setup the ROI. The ROI counts were then converted to corresponding H*(10) values through a calibration coefficient. Rem counter was calibrated using the 185 GBq ^{241}Am-Be neutron source mentioned above following ISO recommendations [ISO/DIS, 2001], and additionally at the CERN EU High Energy Reference Field (CERF) facility in Geneva, Switzerland [Höfert and Stevenson, 1994], which provides a radiation field of neutrons similar to that present at high altitudes (> 2,000 m a.s.l.). The fluence response function of the NM2B-495Pb rem counter from thermal to 10 GeV neutrons was calculated by means of different Monte Carlo codes [Mares et al., 2002].

2.3 Measurement locations

In June 2016 and September 2018, measurement campaigns were carried out at the High Altitude Research Station Jungfraujoch, Switzerland. During these campaigns the energy distributions of secondary CR neutrons were measured at two different locations: under the cupola of the astronomical observatory in the Sphinx building at 3,585 m a.s.l., and below the shelter roof of the research station at 3,466 m a.s.l. (see Fig. 1, left and middle picture). Close to these locations two neutron monitors (NM64 and IGY) are being operated by the University of Bern [Flückiger and Bütikofer, 2009].

At UFS Zugspitze a stationary ERBSS is located in a measurement shed (3 x 7 m^2) on the terrace at the 5th floor of the station. The wooden shed has a steep roof covered by aluminium roof panels to avoid snow accumulation over the detector. Moreover, it is heated inside (see Fig. 1, photo on the right).

Fig. 1: Measurement locations at Jungfraujoch and Zugspitze: 1) below the roof of the building of the Research Station close to the 3-NM64 location (left); 2) in the Sphinx astronomical cupola close to the 18-IGY NM installed in a detector housing at the terrace (middle); 3) in the instrumentation shed "Kugel Alm" at the UFS terrace (right). (Photos: V. Mares)

3. Results and discussion

3.1 Spectral fluence rate distributions of neutrons at Jungfraujoch and Zugspitze

Figure 2 shows the mean ERBSS count rates measured with the various Bonner spheres with ^{3}He detector (so-called "measurement vector") in September 2018 under the Sphinx astronomical cupola and those measured below the shelter roof of the Research Station (RS). Additionally, the mean count rates measured at UFS Zugspitze during the same time period are also included. The count rates measured at Sphinx are about a factor of 2 higher than those measured below the RS shelter, and the shapes of the measurement vectors are also different. At Sphinx the largest count rate was measured with the 6" PE sphere, while below the RS roof the largest count rate was measured with the 4" PE sphere and the bare detector. Due to their response functions, the bare detector and the Bonner spheres with small diameters are more sensitive to thermal and low-energy neutrons [Mares et al., 1991]. Interestingly, the count rate of the bare detector below the RS roof is about a factor of 3 greater than that measured at Sphinx. This was expected and can be explained by the different topology and environmental conditions of the two measurement positions. The high count rates at 9 inch represent the count rates from the 9 inch spheres with lead shells. Below the RS roof, the mean count rates of all spheres excluding the count rate of the bare detector and the spheres with led, are comparable to those obtained at UFS Zugspitze although a little bit higher due to the higher altitude at Jungfrauchjoch as compared to Zugspitze.

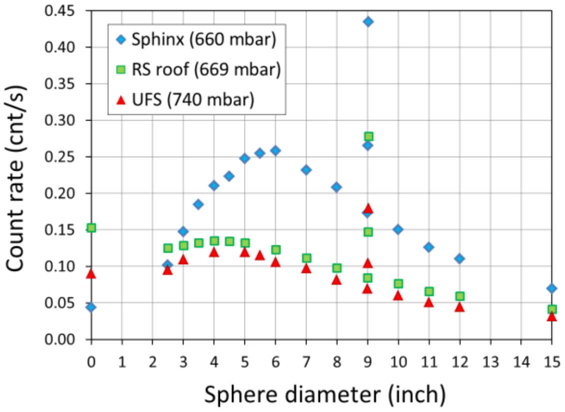

Fig. 2: Mean ERBSS count rates ("measurement vector") obtained in September 2018 under the Sphinx astronomical cupola (blue), below the roof of the Research Station (RS) at Jungfraujoch (green), and at Environmental Research Station (UFS) Zugspitze (red). ERBSS – extended range Bonner sphere spectrometer

Figure 3 shows the unfolded spectral fluence rate distributions using the mean count rates shown in Figure 2. These distributions show four regions with different fluence intensity: a) the Maxwell-Boltzmann (thermal) peak, b) a flat epithermal region, c) an evaporation peak due to neutrons from highly excited residual nuclei in the near environment, and d) a cascade peak that is due to a broad minimum in the relevant neutron cross sections in air. It can be seen that the three neutron spectra differ from each other both in their intensity and shape. These differences are due to the different environmental and topological conditions which are characterized by the steep rocky summit of Sphinx and the steep mountain slopes at the RS and UFS locations. In Fig. 3 RS distribution includes a high thermal peak, which is even higher than the evaporation peak. This is due to the fact that neutrons are moderated when passing through the thick roof of the RS building. In contrast, the evaporation peak is about a factor of 3 lower than the one measured at the Sphinx. This finding might be explained by the shielding of evaporation neutrons (which are isotropic) by the steep mountain slope where RS is situated, and partly also by the fact that these neutrons are efficiently moderated in the construction materials of the roof. In contrast, the small thermal peak in Sphinx hints towards an environment with little moderating materials.

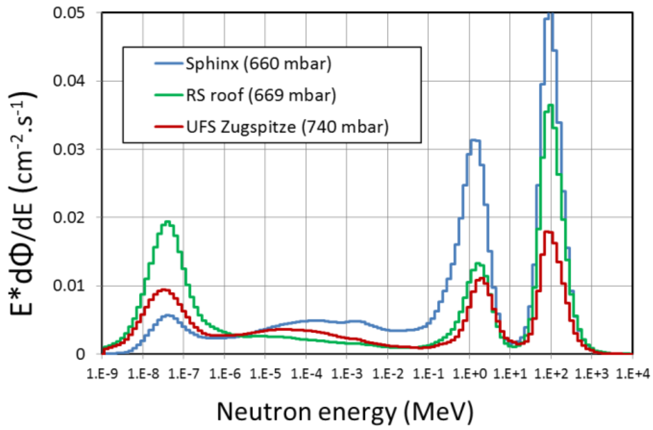

Fig. 3: Spectral neutron fluence rate distribution measured in September 2018 under the Sphinx astronomical cupola and below the roof of the research station (RS) at Jungfraujoch, compared to that measured at the Environmental Research Station (UFS) Schneefernerhaus at Zugspitze.

3.2 Snow effect at Jungfraujoch

To investigate the effect of the snow in the environment at Jungfraujoch in detail, two measurement campaigns were carried out, one during a period with permanent snow cover (June 2016) and the other during a period with much less snow (September 2018; see Fig. 4). Figure 5 shows the unfolded spectral neutron fluence rate distributions using the corresponding ERBSS mean count rates obtained under the Sphinx cupola and below the RS roof in June 2016 and September 2018 normalized to a reference pressure of 660 mbar and 669 mbar, respectively, and to the solar activity observed in September 2018 [Mares et al. 2019]. It is of interest to note that Sphinx neutron fluence rate distributions do not differ much in their intensity and shape. This observation could be explained by the similar snow cover that was present in the vicinity of the Sphinx cupola, at the steep rocky summit during both measurement campaigns (Fig. 4). It is interesting to note that the Maxwell-Boltzmann (thermal) peak is very low, probably due to the high measurement position above ground level and the very steep summit of the Sphinx rock.

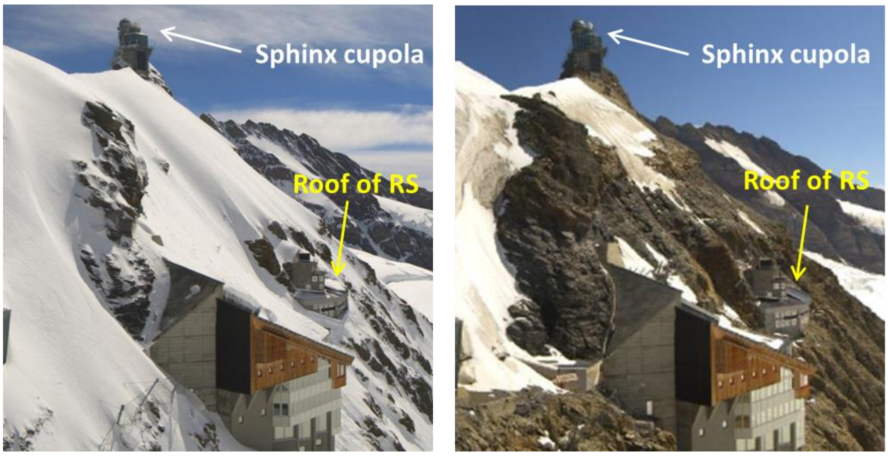

Fig. 4: View of the Jungfraujoch during two different environmental conditions; with snow cover in June 2016 (left) and without snow cover in the close vicinity of the measuring locations in August/September 2018 (right). (Source: https://panocam.skiline.cc/jungfraujoch#). Note that the snow conditions in the vicinity of the Sphinx cupola were similar, due to the high position of the cupola and the steep summit of the Sphinx mountain on which the cupola is mounted.

In contrast, the spectral neutron fluence rate distributions measured below the RS roof in June 2016 and September 2018 show a large thermal peak. This is probably due to the fact that neutrons were moderated passing through the thick roof of the RS building. The evaporation peak is rather low for both cases, which may be explained by the shielding effect of the steep mountain slope where RS is situated, and the moderation of neutrons in the construction materials of the roof. Again, the different snow cover does not seem to have any significant influence on the shape of the neutron fluence distributions.

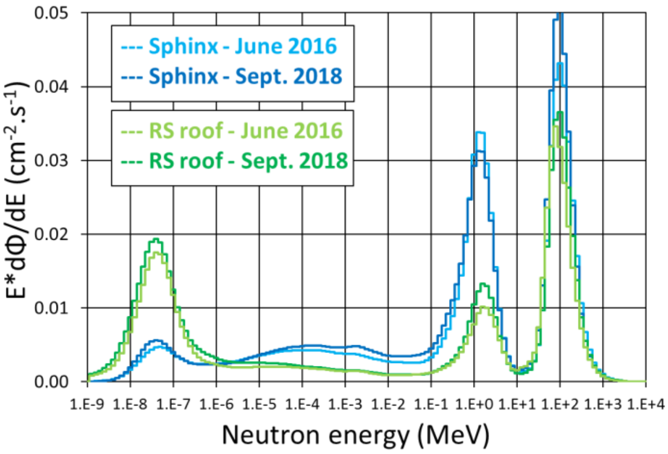

Fig. 5: Spectral neutron fluence rate distribution measured in June 2016 and September 2018 under the Sphinx astronomical cupola (blue lines) and below the roof of the research station (RS) (green lines) at Jungfraujoch (corrected for a reference pressure of 660 mbar and 669 mbar, respectively, and solar activity in September 2018).

The neutron fluence rates measured in June 2016 and September 2018 at the Zugspitze and Jungfraujoch are given in Fig. 6 for the four neutron energy regions mentioned above, together with the corresponding total neutron fluence rates. It should be noted that the total neutron fluence values deduced from the ERBSS measurements are uncertain by about 10%. Larger uncertainties of up to 18% have been reported for neutron fluences of epithermal and high-energy neutrons [Pioch et al. 2010]. It is clearly seen that the total neutron fluence rate is increasing with increasing altitude. The same is true for high-energy neutrons, while evaporation and thermal neutrons are strongly affected by environmental conditions, like topography, and shielding and moderating materials in the environment including snow accumulation and soil moisture.

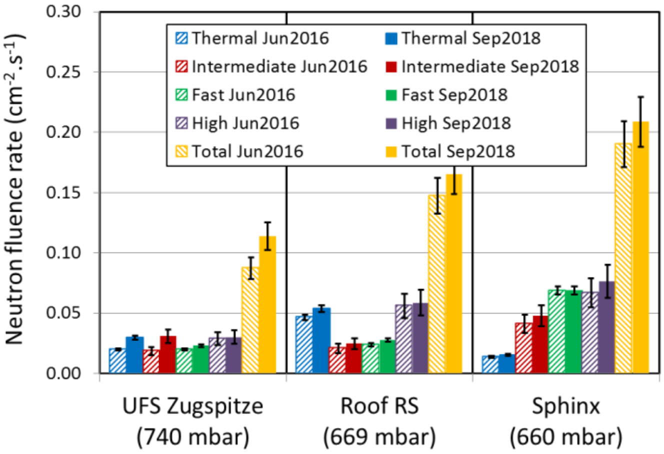

Fig. 6: Energy-dependent ERBSS neutron fluence rate contributions to total neutron fluence rates measured in June 2016 and September 2018 at Zugspitze and Jungfraujoch, for four neutron energy regions: thermal (1 meV ≤ E < 0.4 eV), intermediate (0.4 eV ≤ E < 100 keV), fast (100 keV ≤ E < 20 MeV) and high (E ≥ 20 MeV). Data are corrected to a reference pressure of measurement position and solar activity in September 2018. ERBSS – extended range Bonner sphere spectrometer.

3.3 Ambient dose equivalent

All measured neutron spectra were folded with fluence-to-dose conversion coefficients from [ICRP, 1997; Pelliccioni, 2000] to estimate the corresponding neutron ambient dose equivalent, *H**(10). The resulting mean value of *H**(10) dose rates measured in the Sphinx astronomical cupola and the RS roof in September 2018 were 182 nSv/h and 110 nSv/h, respectively. These values are very close to those measured in June 2016, i.e. 170 nSv/h in the Sphinx cupola and 104 nSv/h below the RS roof. The 6-7% higher values in September 2018 may be due to less snowpack in the environmental area. This assumption may be verified by particle transport simulations using Monte Carlo techniques. In contrast, the mean value of *H**(10) measured at UFS Zugspitze in September 2018 was 70 nSv/h and in June 2016 61 nSv/h. These values are consistent with a mean value of 67.1 nSv/h averaged over the period January 2006 – May 2009 obtained at the UFS Zugspitze [Rühm et al. 2012]. The ambient dose equivalents at all three mentioned locations measured in time period from 31st August to 6th September 2018 using the ERBSS and an extended Rem counter are shown in Fig. 7. Note that *H**(10) dose values from secondary neutrons from cosmic radiation as deduced from ERBSS measurements are uncertain by about 10% [Pioch et al., 2010]. These results are also consistent with a mean value of 75.0 ± 2.9 nSv obtained with an ERBSS for the same location, for October 2008, and of 73.0 ± 8.6 nSv/h obtained with an extended Rem counter [Rühm et al. 2009].

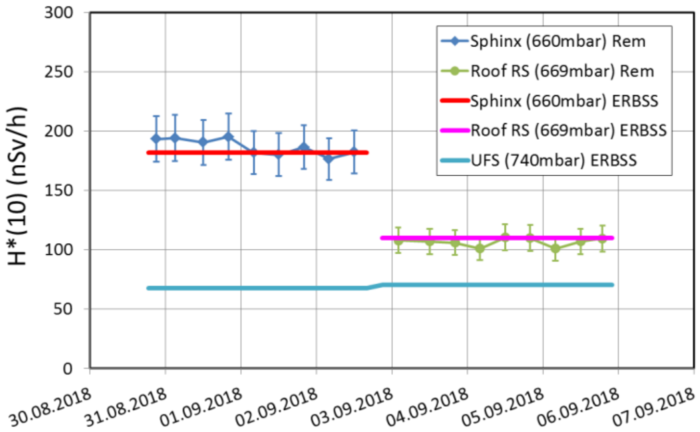

Fig. 7: Ambient dose equivalent rate measured in September 2018 at Sphinx astronomical cupola, below the roof of the research station at Jungfraujoch, and at UFS Schneefernerhaus at Zugspitze. ERBSS – extended range Bonner sphere spectrometer; Rem – Rem counter.

4. Conclusions

In the present study, an ERBSS was used to measure the spectral fluence rate distribution of neutrons from secondary CR at Jungfraujoch, Switzerland; during different environmental conditions with large (June) and with low or no snow accumulation (August/Setmbere) in the environment, for the first time. It was found that the neutron spectra (corrected for air pressure and solar activity) measured in June 2016 and September 2018 are very close to each other for both measurement positions. Only a small increase of about 10% of total neutron fluence rate was observed in September 2018 during so-called summer condition with much less snowpack. Accordingly, the $H^*(10)$ rates were about 6-7% higher in September 2018 compared to June 2016. It was observed that surrounding topography of measurement positions is extremely important. More specifically, it turned out that at the Jungfraujoch with its steep summit, snowpack has much less influence on the neutron distributions than at the environmental research station “Schneefernerhaus” on the Zugspitze mountain, Germany, which is located on a slope. This result confirms that the secondary cosmic neutrons measured at ground level are strongly affected by various environmental conditions.

As a next step, the measured results should be validated with Monte Carlo particle transport simulations, i.e. transport in the Earth’s atmosphere and through the material shielding the detector location (coupola, roof). In these computations the topography of the Alpine environment as well as the characteristics of the building construction above and near the detector locations should be considered.

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References

Alevra, A.V., Cosack, M., Hunt, J.B., Thomas, D.J., Schraube, H., Experimental determination of the response of four Bonner sphere sets to monoenergetic neutrons (II) Radiat. Prot. Dosim. 40, 91-10 (1992)

Chen, J., Mares, V., Estimate of doses to the fetus during commercial flights, Health Phys. 95, 407-412 (2008)

Chen, J., Mares, V., Significant impact on effective doses received during commercial flights calculated using the new ICRP radiation weighting factors, Health Phys. 98, 74-76 (2010)

Clem, J. M., Dorman, L. I., Neutron monitor response function, Space Science Reviews, **93**, 335-359, 2000.

Eroshenko, E., P. Velinov, A. Belov, V. Yanke, E. Pletnikov, Y. Tassev, A. Mishev (2008) Relationships between cosmic ray neutron flux and rain flows. Proceedings of the 21st European Cosmic Ray Symposium, 127-131

Flückiger, E. O., Bütikofer, R.: Swiss neutron monitors and cosmic ray research at Jungfraujoch, Advances in Space Research 44, 1155-1159, 2009.

Höfert, M.; Stevenson, G. R.; The CERN-CEC High—Energy Reference Field Facility, European Laboratory for Particle Physics, Report CERN / TIS-RP / 94-02 / CF; 1994

ICRP, International Commission on Radiological Protection (ICRP), Conversion coefficients for use in radiological protection against external radiation, ICRP Publication 74. Pergmon, 1997.

ISO/DIS 8529-1 2001, International Organization for Standardization, Geneva, Switzerland (2001)

Leuthold, G., Mares, V., Rühm, W., Weitzenegger, E., Paretzke, H.G., Long-term measurements of cosmic ray neutrons by means of a Bonner spectrometer at mountain altitudes – first results. Radiation Protection Dosimetry, Vol. 126, No. 1-4, pp. 506-511 (2007).

Mares, V., Schraube, G., and Schraube, H.: Calculated neutron response of a Bonner sphere spectrometer with ^{3}He counter, Nucl. Instr. Meth. **A 307**, 398–412, 1991.

Mares, M., Sannikov, A., and Schraube, H.: The response functions of a ^{3}He-Bonner spectrometer and their experimental verification in high energy neutron fields, SATIF-3 Proceedings, Sendai, Japan, 237-248, 1998.

Mares, V, Schraube, H.: High energy neutron spectrometry with Bonner spheres, Proceedings, The IRPA Regional Symposium on Radiation Protection in Neighbouring Countries of Central Europe, Prague, Czech Republic, September 1997, 543-547, 1998. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/031/30031466.pdf

Mares, V., Sannikov, A. V., Schraube, H., Response function of the Anderson-Braun and extended range rem counters for neutron energies from thermal to 10 GeV, Nucl. Instrum. Methods Phys. Res., Sect. A 476, 341–346 (2002)

Mares, V., Pioch, C., Rühm, W., Iwase, H., Iwamoto, Y., Hagiwara, M., Satoh, D., Yashima, H., Itoga, T., Sato, T., Nakane, Y., Nakashima, H., Sakamoto, Y., Matsumoto, T., Masuda, A., Harano, H., Nishiyama, J., Theis, C., Feldbaumer, E., Jaegerhofer, L., Tamii, A., Hatanaka, K., Nakamura, T., Neutron dosimetry in quasi-monoenergetic fields of 244 and 387 MeV, IEEE Trans. Nucl. Sc. 60, 299-304 (2013)

Mares, V.; Brall, T.; Bütikofer, R.; Rühm, W. Influence of environmental parameters on secondary neutrons from cosmic rays at high altitudes in Alpine region, International Foundation HFSJG - Activity Report 2018, 2019, pp53-55

Matzke M 1987 Private communication later integrated into the neutron metrology file IAEA1279 ZZ-NMF-90 available from NEA Databank (www.oecd-nea.org/tools/abstract /detail /iaea1279)

Pelliccioni M.: Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code, Radiat. Prot. Dosim. **88**, 279–297, 2000.

Pioch, C., Mares, V., Rühm, W., Influence of Bonner sphere response functions above 20 MeV on unfolded neutron spectra and doses, Radiation Measurements 45 (2019) 1263-1267.

Rühm, W., Mares, V., Pioch, C., Simmer, G., Weitzenegger, E. Continuous measurements of secondary neutrons from cosmic radiation at mountain altitudes and close to the north pole – a discussion in terms of H*(10). Radiat. Prot. Dosim. 136 (2009) 256-261.

Rühm, W., Ackermann, U. Pioch, C., and Mares, V.: Spectral neutron flux oscillations of cosmic radiation on the Earth's surface, Journal of Geophysical Research, VOL. 117, A08309 ,2012.

D.J. Thomas, A.V. Alevra, J.B. Hunt, H. Schraube: Experimental determination of the response of four Bonner sphere sets to thermal neutrons Radiat. Prot. Dosim. 54, 25-31 (1994)