Neutron monitor calibrations: progress report

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Abstract. In order to obtain rigidity spectra from the ~40 stationary neutron monitors around the world, two calibration neutron monitors were built in 2002. Various tests were performed on these neutron monitors, and some calibrations have been done. Due to electronic development during the past ten years, the electronics heads were completely redesigned and rebuilt in 2011. The progress and results of the calibration effort, as well as plans for a network of mini neutron monitors, are reported.

1. Introduction
In order to derive spectra from the approximately 40 worldwide neutron monitors (NM) in operation, as with spacecraft, one has to take into account that each monitor has its own detection efficiency. The reason is that the counting rate depends on design, environment, cutoff rigidity and altitude.

The counting rate, \( N \), of a NM at cutoff rigidity, \( P_c \), is

\[
N(P > P_c) = \int_{P_c}^{\infty} (-dN/dP) dP = \int_{P_c}^{\infty} S(P, x) j(P, t) dP,
\]

where \( dN/dP \) is the differential response function, \( j(P, t) \) is the primary cosmic-ray intensity above the atmosphere, and \( S \) is the NM yield function of the secondary cosmic rays at atmospheric depth \( x \).

In principle, a differential response function can be calculated from the counting rates of the world’s stationary NMs, by dividing the difference in counting rates by the difference in cutoff rigidities:

\[
\frac{dN}{dP} \approx \frac{N(P_{c2}) - N(P_{c1})}{|P_{c2} - P_{c1}|}.
\]

However, due to the difference in detection efficiency of each NM, the counting rates must be normalized. Therefore, two identical mobile calibrators were built in 2002 to obtain spectra from the worldwide NMs. Figure 1 (adapted from [4]) shows e.g. a typical differential response function as function of cutoff rigidity when 11 NMs are inter-calibrated. The vertical error bars show an assumed 0.2\% uncertainty in the counting rate of each individual NM.

Several properties of these mobile NMs were investigated in [1] and [3], to assure accuracy within 0.2\%. These experiments are summarized below.

1) For several years the Bartol group conducted latitudinal surveys from Seattle, USA, to McMurdo, Antarctica. One calibrator was on five of these surveys, together with a standard 3NM64, as described in [1]. The result was that the calibrator is \( \approx 4\% \) more sensitive in its energy response than the 3NM64 over a cutoff rigidity range between 0 and 16 GV.

2) Independent studies showed that NMs have fairly large instrumental temperature sensitivities, as described in [1]. The coefficient for the calibrator was largest, at 0.12\%/°C. It is important to
correct for these temperature sensitivities, or to keep the NMs as near as possible to a constant temperature.

3) Changes in neutron absorbing or producing materials around the NMs affect the stability of a monitor. To avoid environmental effects, calibrations have to be done by placing the calibrator outside, far away from any absorbing or producing structures.

4) Further, it was determined that the calibrator has a large sensitivity to the type of surface underneath it. A series of experiments were performed, by varying the height of water beneath the calibrator (in a portable swimming pool), to determine the amount of water needed to eliminate these effects, as described in detail in [3]. Similar experiments were performed in Kiel, Germany, and at Doi Inthanon, Thailand. The results show that the counting rate decreases with ~ 4.0% per 30 cm, but it levels off when the water layer below the NM exceeds ≈ 30 cm.

Taking these factors into account, the results of inter-calibrations done so far, are discussed. This paper also discusses a new, broader, concept of a mini NM.

![Figure 1. Typical differential response function for 11 inter-calibrated neutron monitors.](image1)

![Figure 2. The older (left) and new (right) electronics heads of the calibrator.](image2)

### 2. Calibration process

Table 1 shows four successful calibration results so far. The details of each are described in [2].

| Period     | Monitor     | Latitude | Longitude | Altitude a.s.l. (m) | Atmospheric pressure (mm Hg) | $P_c$ (GV) |
|------------|-------------|----------|-----------|---------------------|------------------------------|------------|
| SANAЕ, Antarctica | 2006/07     | 6NM64/   | 71.66° S  | 02.85° W            | 856                          | 660        | 0.73      |
|             |             | 4NMD     |           |                     |                              |            |           |
| Kiel, Germany | 2007/08     | 18NM64   | 54.34° N  | 10.12° E            | 54                           | 755        | 2.36      |
| Pochefstreet, South Africa | 2008 | 15 IGY   | 26.70° S  | 27.09° E            | 1351                         | 652.4      | 6.94      |
| Doi Inthanon, Thailand | 2009/10    | 18NM64   | 18.59°N   | 98.49°E             | 2560                         | 563        | 16.8      |

To compare the cosmic-ray intensity at any two sites, one has to take into account that the NMs are at different cutoff rigidities and atmospheric depths, with different efficiencies (due to difference in type of neutron monitor, number of counters, and different environment). To quantify the calibration process, suppose NM1 is calibrated against the calibrator at time $t_1$, and similarly NM2 at time $t_2$. Then we have the following five measurements: At $t_1$ the counting rate of NM1 is $N_{1,1}$ and that of the calibrator at NM1 is $C_{1,1}$. At $t_2$ the counting rate of NM1 is $N_{1,2}$, of NM2 is $N_{2,2}$, and that of the calibrator at NM2 is $C_{2,2}$. At time $t_2$ the counting rate of the calibrator at NM1 can be calculated as $C_{1,2} = (N_{1,2}/N_{1,1}) * C_{1,1}$. 

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The measured ratio of the counting rates of the two NMs at time $t_2$ is $R_m = N_{2,2}/N_{1,2}$. This ratio includes the differences in efficiency. The ratio of the calibrator’s counting rates at the two positions is $R_c = C_{2,2}/C_{1,2}$. (Note that $C_{1,2}$ is not actually measured, but can be calculated as mentioned above.) The calibrator at the two different positions should have the same efficiency. Thus, the ratio of efficiency of the two NMs is

$$R_{\text{eff}} = \frac{R_m}{R_c} = \frac{N_{2,2}/N_{1,2}}{C_{2,2}/C_{1,2}} = \frac{N_{2,2}C_{1,2}}{C_{2,2}N_{1,2}}.$$

This ratio reflects the difference in the counting rates of the two NMs due to their different design and environmental conditions. Therefore, to compare the counting rate of NM2 relative to NM1, the counting rate of NM2 must be divided by this number.

**Table 2.** Hourly counting rates during the calibrations.

|                      | $t_1$, Potchefstroom | $t_2$, SANAE NM64/NMD | $t_2$, Kiel | $t_2$, Doi Inthanon |
|----------------------|----------------------|------------------------|-------------|---------------------|
| SANAE/Kiel/Thailand NM | –                    | 586476 / 32415         | 61113       | 2190085             |
| Calibrator 1         | 10197                | –                      | 4520        | 12089               |
| Calibrator 2         | 10151                | 11703                  | –           | –                   |
| IGY in Potchefstroom  | 216767               | 216952                 | 217211      | 215230              |
| Efficiency ratio ($R_{\text{ef}}$) | 1.000                | 2.347/0.130            | 6.332       | 8.484               |

**3. Calibration results**

The Potchefstroom IGY is used as the standard (NM1), and time interval $t_1$ is for days 295–302 of year 2008. Time $t_2$ is for days 24–28 (2007) at SANAE, alternatively days 109–128 (2008) at Kiel, or days 98–110 (2010) at Doi Inthanon. Pressure-uncorrected counts were used, because the monitors have the same atmosphere above them during each set of measurements. Table 2 shows the average counting rate per hour and the ratio of efficiency of the monitors.

These efficiencies are reduced to the same atmospheric depth, using $N = N_0 \exp[-\beta(P - P_0)]$, where $P$ and $P_0$ are the station atmospheric pressure and reference level pressure and $\beta$ the barometric coefficient. The values of $P$ and $\beta$ for each station are shown in Table 3. However, one must take into account that $\beta$ varies with altitude, as was found by [5], when correcting the counting rates from a significant altitude to sea level. Therefore, Table 3 also shows our estimate for $\beta$ at sea level of the particular NM. Then the average of the two barometric coefficients was used to calculate the efficiency ratio of the five neutron monitors at sea level, as shown in the last column of Table 3.

The last two columns give the end result of the calibration procedure, which can be used to calculate differential response functions according to equation (2), after more calibrations are done. In future, refinements of the pressure corrections should be done by detailed studies of the variations of barometric coefficients with cutoff rigidities and altitudes.

**Table 3.** Barometric coefficient and efficiency ratio of each NM relative to the Potchefstroom NM.

| $P_c$ (GV) | Atmospheric pressure (mm Hg) | $\beta$ at NM (%/mm Hg) | $\beta$ at sea level (%/mm Hg) | Efficiency ratio, $R_{\text{ef}}$ | $R_{\text{ef}}$ at sea level |
|------------|-------------------------------|--------------------------|-------------------------------|----------------------------------|------------------------------|
| SANAE NM64 | 0.73                          | 660                      | 0.97                          | 0.96                             | 2.347                        | 2.800                        |
| SANAE NMD  | 0.73                          | 660                      | 1.01                          | 1.00                             | 0.130                        | 0.155                        |
| Kiel       | 2.36                          | 755                      | 0.96                          | 0.96                             | 6.332                        | 6.332                        |
| Potchefstroom | 6.94                       | 652                      | 0.99                          | 0.972                            | 1.000                        | 1.000                        |
| Doi Inthanon | 16.8                        | 563                      | 0.83                          | 0.815                            | 8.484                        | 10.649                       |

**4. New mini neutron monitors**

Due to electronic development during the past 10 years, the electronics heads of the calibrators were completely redesigned and rebuilt, as shown in Figure 2. Two more calibrators with new electronics heads were built in 2011. One of these new calibrators is presently on the research vessel Polarstern of the German Polar Programme, to conduct continuous latitudinal surveys between cutoff rigidities 1 to
15 GV, for at least the next solar cycle. The second new calibrator was installed in December 2011 at
the Neumayer station, Antarctica for continuous monitoring of the cosmic-ray intensity.

These two new detectors have broadened the concept of a calibration NM to that of a mini NM, i.e.
a permanent detector in its own right. The motivation is as follows:

1) Due to the current unaffordable price of a $^3$He counter, we have to revert back to $^{10}$BF$_3$
counters. In September 2011, the International Panel on Dangerous Goods lifted the maximum
pressure of $^{10}$BF$_3$ counters from 0.3 to 0.9 atmospheres. In this pressure range, the detection efficiency
is nearly proportional to pressure. Hence this should increase the counting rate with a factor of
three.

2) We decided to aim for another factor of three in counting rate by tripling the volume of the
cylindrical proportional counter, increasing its diameter from 50 to 89 mm.

3) The combined two steps will increase the counting rate of the $^{10}$BF$_3$ mini NM nine times, to
$\approx 3.6$ counts per second, which is 1/3 of that of a single counter of the super NM64.

4) With a barometric coefficient of $\approx 0.7$ %/mm Hg, the counting rate of a NM increases as
$\exp(0.00095 \, h)$, with altitude $h$ expressed in m. At 3000 m this gives a factor of $\approx 15$ in
counting rate relative to sea level. Hence, a mini NM at 3000 m altitude will give the same
counting rate as a 5-counter NM64 at sea level.

Whereas it is (was) difficult and expensive to deploy full-size NMs at remote mountain stations,
this is easy for a portable instrument with semi-autonomous electronics, that needs no further
infrastructure than exists at many meteorological and geophysical stations. This makes it possible and
affordable to deploy mini NMs at many sites as the equivalent of 5-NM64, especially in places where
the funding of the standard NM is threatened.

The concept of calibration is retained in this strategy, because the mini NMs are dispatched from
their point of manufacture as already-calibrated units that are not dismantled in transport which may
affect their efficiencies.

In the immediate future, the two existing calibrators, with redesigned and modernized electronics
heads, will be used to recalibrate the Potchefstroom and SANAE NMs, and then to calibrate the
Hermanus and Tsumeb NMs.

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References
[1] Krüger H, Moraal H, Bieber JW, Clem JM, Evenson PA, Pyle KR, Duldig ML and Humble JE
2008 A calibration neutron monitor: energy response and instrumental temperature
sensitivity Journal of Geophysical Research 113 A08101 doi: 10.1029/2008JA013229
[2] Krüger H, Moraal H, Ruffolo D, Saiz A, Nutaro T, Kamyan N, Nuntiyakul W, Heber B and
Steigies C 2011 Progress report on the intercalibration of the world’s neutron monitors
Proceedings of the 32th ICRC Beijing 11 446-449
[3] Krüger H and Moraal H 2010 A calibration neutron monitor: statistical accuracy and
environmental sensitivity Advances in Space Research doi:10.1016/j.asr.2010.07.008
[4] Moraal H, Belov A and Clem JM 2000 Design and co-ordination of multi-station international
neutron monitor networks Space Science Reviews 93 283-303
[5] Potgieter MS, Raubenheimer BC, Stoker PH and Van der Walt AJ 1980 Modulation of cosmic
rays during solar minimum Part 2 Cosmic ray latitude distribution at sea-level during 1976
South African Journal of Physics 3 77-8