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Mini neutron monitor measurements at the Neumayer III station and on the German research vessel Polarstern

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Abstract. Neutron monitors (NMs) are ground-based devices to measure the variation of cosmic ray intensities, and although being reliable they have two disadvantages: their size as well as their weight. As consequence, [1] suggested the development of a portable, and thus much smaller and lighter, calibration neutron monitor that can be carried to any existing station around the world [see 2; 3]. But this mini neutron monitor, moreover, can also be installed as an autonomous station at any location that provides ”office” conditions such as a) temperatures within the range of around 0 to less than 40 degree C as well as b) internet and c) power supply. However, the best location is when the material above the NM is minimized. In 2011 a mini Neutron Monitor was installed at the Neumayer III station in Antarctica as well as the German research vessel Polarstern, providing scientific data since January 2014 and October 2012, respectively. The Polarstern, which is in the possession of the Federal Republic of Germany represented by the Ministry of Education and Research and operated by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research and managed by the shipping company Laeisz, was specially designed for working in the polar seas and is currently one of the most sophisticated polar research vessels worldwide. It spends almost 310 days a year at sea usually being located in the waters of Antarctica between November and March while spending the northern summer months in Arctic waters. Therefore, the vessel scans the rigidity range below the atmospheric threshold and above 10 GV twice a year. In contrast to spacecraft measurements NM data are influenced by variations of the geomagnetic field as well as the atmospheric conditions. Thus, in order to interpret the data a detailed knowledge of the instrument sensitivity with geomagnetic latitude (rigidity) and atmospheric pressure is essential. In order to determine the atmospheric response data from the Neumayer III station here we will perform comparisons to other polar stations, resulting in an atmospheric pressure coefficient of 7.5‰/hPa, while the rigidity dependence will be determined experimentally by utilizing several latitude scans. Thereby, the atmospheric pressure and temperature correction will be discussed in more detail and the results of the latitude scan performed between October 2012 and March 2013 will be presented. Moreover, we will show that this latitude scan can also be described by using the yield function of [4].

1. Introduction

Ground-based measurements of Galactic Cosmic Rays (GCRs) have been performed since their discovery by Viktor Hess in 1912. Since the 1950s neutron monitors (NMs) are utilized for these kind of measurements [5; 6]. Because NMs are integral counters with a threshold energy defined by the minimum of the magnetic cut-off energy and the shielding by the atmosphere, several NMs have been installed world-wide from which more than for forty are accessible through the NM data base(www.nmdb.eu). This should allow to determine the energy spectra from about 400 MeV to above 10 GeV of GCRs as well as solar energetic particles (SEPs) during Ground Level Enhancements, strong SEP events which can be detected on the ground. In order to calibrate the world-wide distributed NMs against each other Moraal et al. [7] proposed the development of a calibration NM, which has been realized at the North-West-University [1; 2; 8–10]. This NM relies on a ^{3}He counter in order to achieve count rates of 1 count/second at sea level allowing a statistical accuracy on the percent level by using hourly averages. This device is well calibrated for temperature as well as atmospheric pressure and has been used at several locations [10]. Based on this idea, Krüger and Moraal [3] suggested to use such a mini NM as a mobile station that can be placed at almost any location in the world that can provide an office, power supply and internet access. In order to make the data easily accessible, they are provided to the NM database (www.nmdb.eu). Due to the price of the ^{3}He counter, recently a new concept on the basis of a ^{10}BF$_3$-tube has been developed [3]. Such a device was successfully installed at the German research station Neumayer III located at the Ekström Shelf Ice, Atka Bay, north-eastern Weddell Sea (70°40'S, 008° 16'W) in January 2014. Here we will report on the first results.

2. Instrumentation

The design of the mini NM (as installed at the Neumayer III station) has been described in detail in Krüger and Moraal [3]. The mini NM has a length of ~80 cm and a radius of 20 cm. In September 2011 the International Panel on Dangerous Goods increased the maximum atmospheric pressure of ^{10}BF$_3$ counters from ~ 300 to ~ 900 hPa, thus by increasing the diameter of the tube from 0.5 to 0.89 cm the count rates of the modified mini NM are comparable to the ones using the ^{3}He-tube. The counter itself has a length of 63 cm (one third of the standard length of the LND25373 and NM64 counters). It is surrounded by a 2 cm thick moderator made of paraffin wax, which is surrounded by a 5 cm lead ring acting as a producer of neutrons. In addition, around the lead ring there is an outer paraffin wax reflector with a thickness of 9.5 cm. In this configuration the mass of the whole unit is estimated to be 220 kg of which 170 kg are contributed by the lead and 25 kg by the paraffin wax. With these dimensions and mass it could be conveniently placed at the Neumayer III station and the Polarstern.

3. Data reduction and validation

The temporal resolution of the data recorded by the mini NM at Neumayer III is in the millisecond range allowing to determine the registration of multiple hits by the corresponding time stamp. From left to right Fig. 1 displays the temperature and atmospheric pressure. While the temperature only varies between ~12 and ~28 degree C atmospheric pressure spans a range of ~950 to ~1020 hPa, with a mean value of about 980 hPa. According to [3] the temperature correction coefficients for ^{10}BF$_3$ counters vary between -0.05%/degree C and 0.05%/degree C. Thus, in a first approximation a smooth variation in the temperature can be neglected. Since the total atmospheric pressure correction is more than 20 times more important than the temperature one, a careful analysis for atmospheric pressure changes will be postponed.

3.1. Temperature and atmospheric pressure corrections

The standard method to determine the barometric coefficient is to find a time period where the GCR flux outside the magnetosphere is constant and the magnetosphere shows no strong disturbances [11; 12]. Paschalis et al [12] provide an application within the NM database project to calculate the barometric coefficient based on hourly data. For the Neumayer III station the statistical accuracy of the hourly count rate is less than the one for the one minute averages obtained by standard NMs. In order to make use of the whole data set, we calculate the daily averaged ratio of a atmospheric pressure corrected NM that has a cut-off rigidity below 0.4 GV and is located at altitudes below 100 m, i.e. Terre Adelie (TERA), Inuvik (INVK), McMurdo (MCMU), Nain (NAIN), Peawanuck (PWNK), and Thule (THUL).

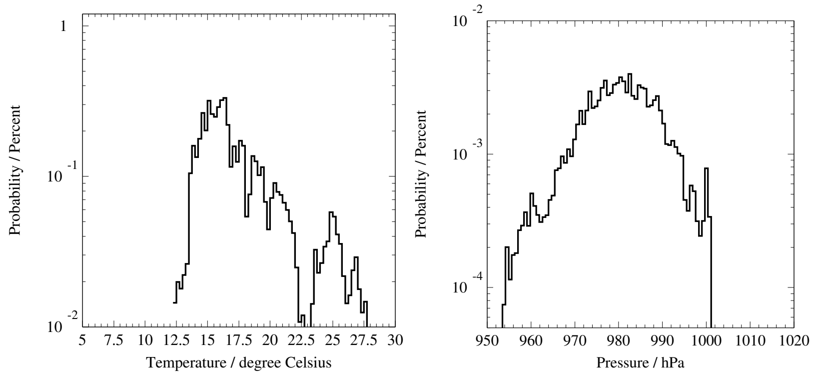

Figure 1. From left to right the temperature and atmospheric pressure from doy 40 to 260 of 2014 is shown. While the temperature only varies between ~12 and ~28 degree C the atmospheric pressure spans the range from ~950 to ~1020 hPa, with a mean value of about 980 hPa.

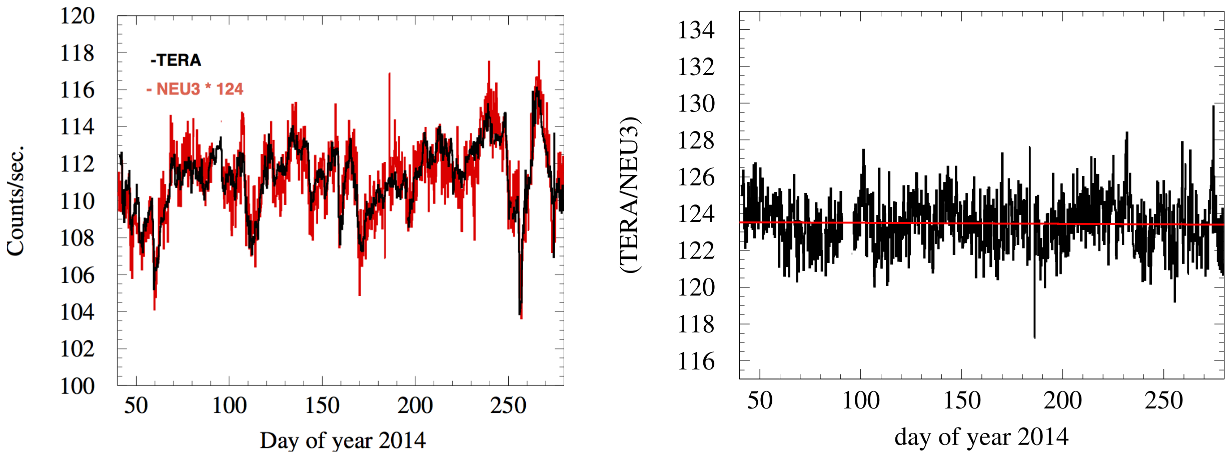

Figure 2. From left to right: Six hour averaged counting rates and ratio of the atmospheric pressure corrected count rates of Terre Adelie and Neumayer III. Here we used $f_p = 7.5‰/\mathrm{hPa}$ and $f_T = 0.6‰/\mathrm{degree\ C}$ for the mini NM. The red line in the right panel displays the fit of $r(t)|_{f_T} = r_0 + p_1 \cdot t$ with $r_0 = 123.5 \pm 0.2$ and $p_1 = -(0.1 \pm 0.1) \cdot 10^{-4}/\mathrm{day}$.

In what follows we compare the six-hour averaged count rates obtained by the mini NM with the ones obtained by the different stations as summarized in Table 2. The left panel of Fig. 2 displays the atmospheric pressure corrected counting rates of the NM at Terre Adelie (black curve) and Neumayer III (red curve) while the right panel gives the corresponding ratio. The Neumayer III corrections are based on the minute raw count rates $C_u(t)$ by applying:

$$C_c(t) = C_u(t) \cdot \exp(f_p \cdot (p(t) - p_0)) \cdot \exp(f_T \cdot (T(t) - T_0)) \tag{1}$$

This procedure results in corrected time profiles $C_c(t)$. Herein, f_p and f_T give the barometric and temperature correction factor and $p(t)$, p_0, $T(t)$ and T_0 the measured as well as the reference atmospheric pressure and temperatures. We choose $p_0 = 980$ hPa and $T_0 = 20$ degree C as reference values. The plot gives NM count rates from the Neumayer III station for $f_p = 7.5‰/\mathrm{hPa}$ and $f_T = 0.45‰/\mathrm{degree\ C}$. The red line in the right panel of Fig. 2 is a fit of the function

$$r(t)|_{f_T} = r_0 + p_1 \cdot t \tag{2}$$

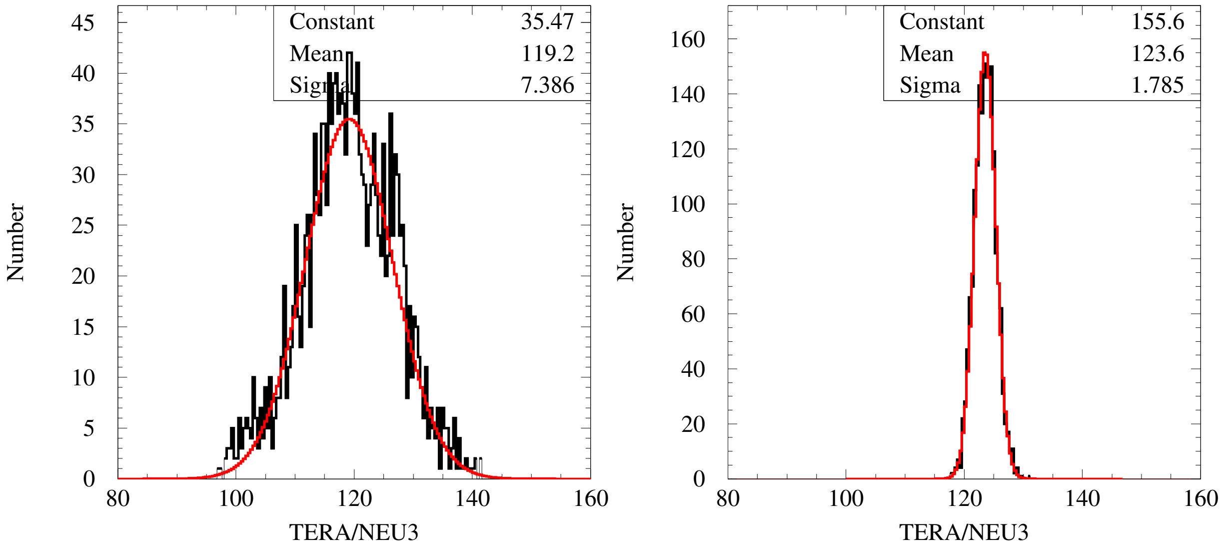

Figure 3. Ratio of six-hour averaged ratio of the counting rates of Terre Adelie and Neumayer III using a atmospheric pressure and temperature coefficient of 0‰/hPa and 0‰/degree C (left panel) and 7.5‰and 0.6‰/degree C (right panel), respectively. For details see text.

Table 1. Regions in the $f_p - f_T$-plane where a minimum of σ can be identified

Barometric coefficient f_p (‰/hPa)	Temperature coefficient f_T (‰/deg)
7.05 to 7.25	-0.65 to -0.5
7.05 to 7.25	0.45 to 0.75
7.25 to 7.55	0.2 to 0.45

to the data. If $p_1 = 0$, there will be no difference on the long term trend between Neumayer III and the reference NM (here Terre Adelie). Because the atmospheric pressure varies on short time scales, the spread of the ratio is mostly determined by the atmospheric pressure correction. Thus, in order to obtain the best agreement between the reference NM and the mini NM at Neumayer III, we vary the atmospheric pressure and temperature correction coefficient and determine the width σ of the ratio distribution. Fig. 3 displays the ratio of the six-hour averaged counting rates of Terre Adelie and Neumayer III using a atmospheric pressure and temperature coefficient of 0‰/hPa and 0‰/degree C (left panel) and 7.5‰/hPa and 0.41‰/degree C (right panel), respectively. The red line displays the result of a fit by a Gaussian to the distribution. While the width of the distribution in the left panel is about 7.4 it decreases to less than 1.8 for the parameter chosen in the right panel. In order to determine the best values for both corrections, we systematically vary the coefficient f_p between 0 and 10‰/hPa and f_T between -1 and 1‰/degree C using forty steps for both parameters. In our further analysis we only use these parameters for which the width σ becomes minimal. The left and right panels of Fig. 4 show the results of this analysis by using Terre Adelie as reference NM. The right panel corresponds to a detailed view of the left panel giving only the values between $f_p = 6.8$ ‰/hPa and $f_p = 7.8$ ‰/hPa. As expected, the width σ is sensitive to changes in f_p but not to the ones in f_T. In the right panel of Fig. 4 regions in the $f_p - f_T$-plane can be identified which result in a minimum of σ. The corresponding locations are summarized in Table 1. In order to distinguish between these results only the one is taken for which the long term trend of Neumayer III agrees best with the one of the reference NM. In our example the best values can be achieved for f_p between 7.0 and 7.6‰/hPa and f_T between -1.3 and 0.45 ‰/degree C, with an average

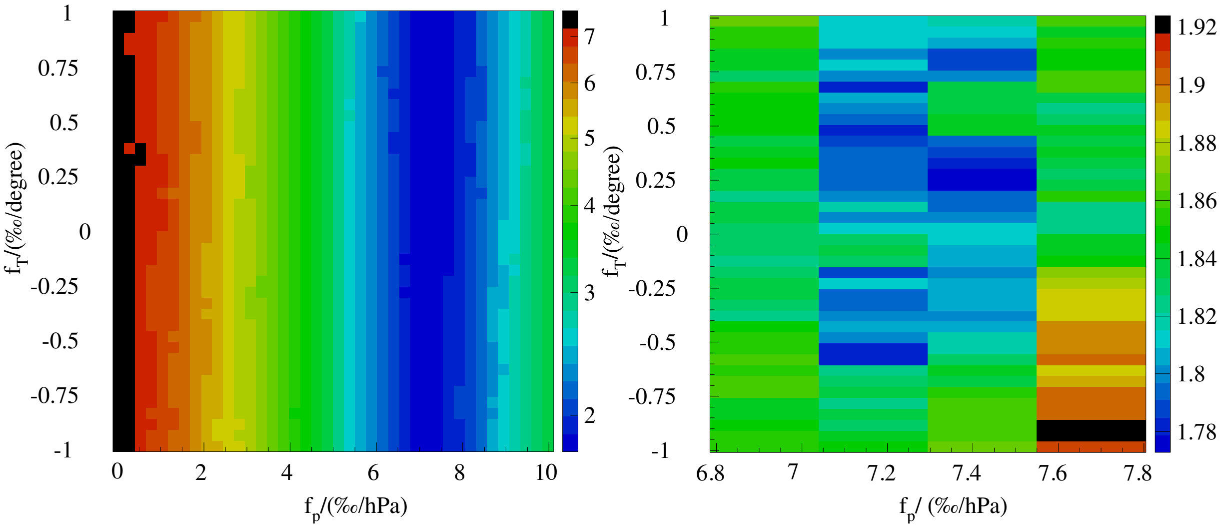

Figure 4. Color coded sigma values (see Fig. 3) as function of the atmospheric pressure p_c and the temperature t_c coefficients. The right panel shows the range between 6.8‰/hPa and 7.8‰/hpa in more detail.

Table 2. Atmospheric pressure and temperature correction coefficients for different NMs located at cut-off-rigidities less than 0.4 GV and altitudes less than 100 m. Temperature corrections are only applied for the mini NM. Note, the in contrast to the Neumayer mini NM the Polarstern mini NM utilizes a ^{3}He-counter tube [13].

Station	Temperature coefficient f_T (‰/deg)	Barometric coefficient f_p (‰/hPa)
TERA	0.6	7.4
INVK	0.8	7.5
MCMU	0.25	7.2
NAIN	-1.3	7.4
PWNK	-1.	7.5
THUL	1.6	7.6
Average		7.5
Polarstern	1.18	7.8

value of f_p = 7.5 ‰/hPa and $f_T \sim -0.4$ ‰/degree C. In addition, the same analysis has been applied to the other NMs, the results are summarized in Table 2. While the barometric coefficients determined by the comparison with the other NMs agree within less than 10%, the temperature coefficients differ by more than a factor of two. The calculation of the later relies on the long term stability of these NMs and thus we expect that an analysis on a longer data interval will improve the accuracy of f_T. The average values of $f_p = 7.5$‰/hPa and $f_T = -0.4$‰/degree C are in reasonable agreement with the ones given in the literature [9] and are used to correct the minutely and hourly averages as provided to the NM data base (www.nmdb.eu). For comparison reasons, the last row of Table 2 gives the correction coefficients of the ^{3}He-counter tube as used by the mini NM aboard the Polarstern [9].

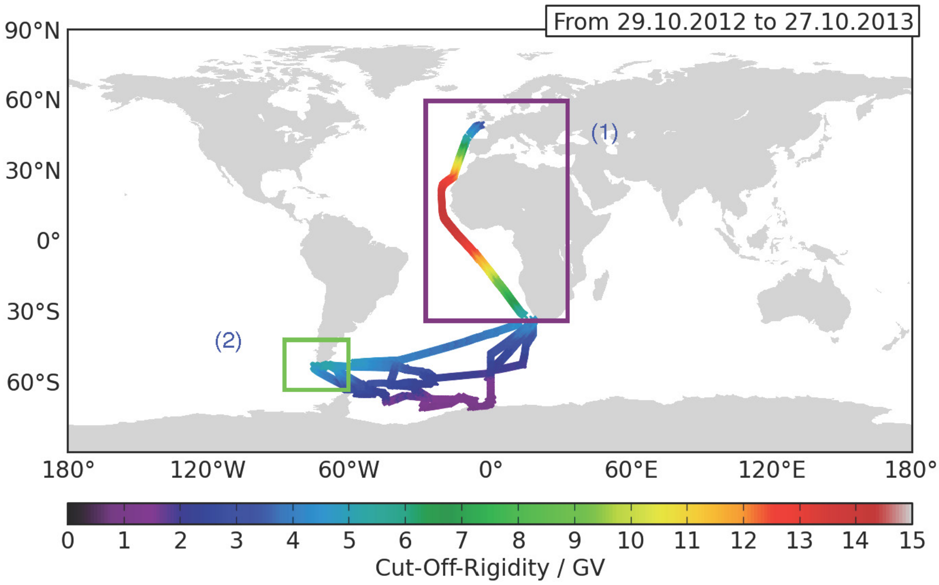

Figure 5. Cut-off-rigidity calculated along the route of the Polarstern from October 29, 2012 to October 27, 2013. The calculation is based on the IGRF dipole model. The cut-off-rigidity ranges from less than 1 GV at Neumayer to more than 14 GV in equatorial regions [14].

3.2. Variation with the effective vertical cut-off-rigidity

Latitude surveys have been used in the past to determine the differential response function of a NM [see e.g. 4]. As stated above, the intensity of GCRs entering the atmosphere strongly depends on the cut-off-rigidity, and with it on the geomagnetic location of the NM. A charged particle, with momentum p and charge q, interacting with the Earths magnetic field $\vec{B}$ has a rigidity R defined as $R = p/q = r_L B$, with r_L representing the Larmor radius. The effective vertical cut-off rigidity is the minimum rigidity that permits a charged particle to arrive from the vertical direction at a given latitude and longitude. In order to compute R_C in an arbitrary magnetic field, numerical computations are mandatory [15; 16]. For our studies we use the simulation code PLANETOCOSMICS [17]. The simulations were carried out for the IGRF model as well as for a magnetic field perturbed by the solar wind according to the Tsyganenko89 model [18]. Figure 5 displays the result of these calculations using an intermediate k_p index along the route of the Polarstern from October 29, 2012 to October 27, 2013. The values range from less than 1 GV at Neumayer to more than 14 GV in equatorial regions [see 14]. Marked by box (1) and (2) are two important regions that are discussed in the following. Figure 6 in its top left panel displays the calculated cut-off-rigidities for the time period between October 29, 2012 and end of March 2013. During the first period the Polarstern was going from Bremerhaven via the equator to Cape Town and continued its journey towards Antarctica (marked by (1) in Fig. 5). In 2013 the Polarstern went to Punta Arenas in Chile which is located at significant higher cut-off-rigidities (marked by (2) in Fig. 5) leading to the two plateau-like structures in the cut-off-time profile. The black and red curve in the left panel of Fig. 6 display the corresponding atmospheric pressure corrected mini NM counting rates and the one measured by the reference NM [red curve, see also 14]. While for most of the time the NMs

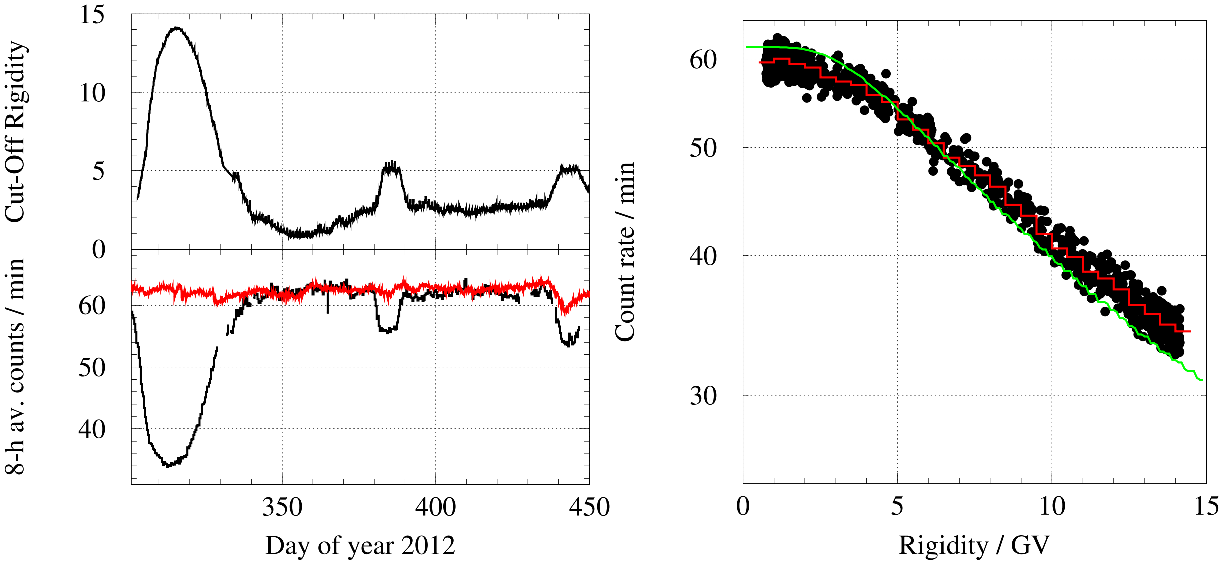

Figure 6. Left panel: Shown from top to bottom are the calculated cut-off-rigidities and the atmospheric pressure corrected count rates (black curve) of the mini NM from end 2012 to March 2013. The red line displays the measurements at Terre Adelie. Right panel: Atmospheric pressure corrected counting rates as function of the cut-off-rigidity (filled dots). The red histogram gives the average in intervals of 0.5 GV width. While above 3 GV the counting rate is well correlated with the cut-off-rigidity, the variation below 2 GV is mostly controlled by the atmospheric shielding.

agree well with each other there are three periods for which we find systematic disagreements. The first one from DOY 300 to 345 in 2012 which is attributed to the systematic change in the cut-off-rigidity. The other two coincide with the excursion towards Chile. In order to investigate this effect in more detail the six-hour averaged atmospheric pressure-corrected counting rates as function of the cut-off-rigidity during the corresponding time is displayed in the right panel of Fig. 6. Here the red and green line gives the mean value in intervals of 0.5 GV and the expectation using the yield function from [4]. While an obvious correlation is seen at rigidities above 3 GV, the atmospheric shielding leads to a flattening below 2 GV.

4. Summary

Galactic cosmic rays are high-energy charged particles, mainly protons, doubly ionized helium, and other fully ionized nuclei originating in the galaxy and bombarding the Earth from all directions. Measurements by various particle detectors have shown that the intensity varies on different timescales, caused by the Suns activity but also geomagnetic and atmospheric (mainly atmospheric pressure) variations. Most of the long term research on GCR intensity variations is based on the analysis of ground-based NMs. In order to enlarge the number of such stations a mini NM was developed [1]. In 2011 two mini NMs were installed, one aboard the research vessel Polarstern and one at the Neumayer III station in Antarctica acting as reference NM. Due to data acquisition problems an upgraded and improved version of the mini NM replaced the one at Neumayer III in 2014, thus the counting statistic now has improved by a factor of three. With a counting rate of ~60 counts/minute a statistical accuracy of <1% is reached for counts integrated over 90 minutes. This is sufficient enought to study most cosmic ray variations. Although the counting rate is more than 100 times smaller compared to the ones measured by e.g. the NM at Terre Adelie or other station at similar locations the time profiles agree well with each other if the reference NMs are used to determine the atmospheric pressure and temperature coefficients, thus the mini NM provides reliable measurements. However, for the latitude survey of the Polarstern between

October 2012 and March 2013 the reference NM at Neumayer III could not be used due to technical problems. For our analysis we, therefore, compared the Polarstern NM with the NM at Terre Adelie. We could show that the count rates of both NMs agree well with each other during times when the vessel is situated in regions with (computed) cut-off-rigidities below 2 GV while differing during times when the vessel is in regions with cut-off-rigidities above 2 GV (e.g. in fall 2012). The latitude survey has been used to determine the count rate variations with cut-off-rigidities in the range from 0 GV to below 15 GV.

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