

Monte Carlo Simulations of South Pole Neutron Monitor Counting Rate since 1964

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Neutron monitors (NM) are ground-based cosmic ray detectors that measure the flux of primary cosmic rays at the GeV-energy range by counting (primarily) secondary neutrons in atmospheric cascades. The South Pole NM started in 1964 as an International Geophysical Year (IGY) monitor that operated until 1974. In 1977 three NM64 with boron-trifluoride proportional counters were installed. In January 2004, they were replaced with helium-3 detectors. Apart from a four-year gap (2005-2009), the NM has operated continuously since then. Over decades of its operation, a decline of the South Pole NM counting rate was observed, significantly larger than temporal changes observed by other NM stations. To investigate this decline, we simulated the counting rates of the NM64, for boron-trifluoride and helium-3 configurations, using the FLUKA Monte-Carlo package. We compare the observed count rates from 1964 to December 2021 with simulated count rates obtained using monthly values of the modulation parameter (ϕ , in MV) determined in two different ways. The extended data set and the simulations indicate that most of the observed decline can be associated with the transition from the IGY to the NM64. Further work with a specific IGY simulation is required.

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Figure 1: (a) Three NM64 type detectors housed in insulated wooden cases at the Amundsen Scott South Pole station. (b) Renderings of the 3-NM64 generated using Flair [1], an advanced user graphical interface for FLUKA [7, 8], along with the dimensions of the platform situated above the snow surface.

1. Introduction

Operation of a neutron monitor (NM) located outside the Amundsen-Scott station at the South Pole commenced in 1964 to detect secondary particles, particularly neutrons, produced by nuclear interactions between primary cosmic rays and atmospheric nuclei. This detector is mostly sensitive to cosmic rays in the few GeV energy range. By measuring fluctuations in the intensity of cosmic radiation over time-related to solar activity, the neutron monitor serves as a valuable tool in understanding the characteristics of cosmic rays and their impact on Earth's atmosphere.

Initially, an IGY-type neutron monitor [2] operated from March 1964 to October 1974 in a hut outside the "Old Pole" station. In January 1977, three separate units based on the NM64 were installed on a platform outside the "New Station Dome". The 3x1NM64 used BP-28 proportional counters (filled with Boron-trifluoride gas), a lead producer, a polyethylene reflector, and an outer wooden case filled with ISO foam, as shown in Figure 1. In 2004 the BP-28 was replaced with He-3 detectors and operated until November 22, 2005, when the detectors were removed and stored [3]. In February 2010, the 3x1NM64 detectors were moved to a new platform some distance from the current station and reactivated [4].

The IGY data collected from March 1964 until October 1974 exhibit significant deviations from the regression line of IMP-7 and IMP-8 HZHE rate against the South Pole NM64 rate [3]. To bring the IGY data in line with the NM64 data, [3] recommend multiplying the IGY data by a factor of 0.95. We have done this consistently.

The neutron counting rate at the South Pole follows an 11-year cycle with peaks during periods of low solar activity. However, from 1964 to 1997, a long-term decline compared to other neutron monitor stations was noticed [3, 5]. Figure 2 shows the count rates of South Pole (SOPO) and Thule (THUL multiplied by a factor of 2) along with their ratios. Both THUL and SOPO have negligible geomagnetic cutoffs but greatly different altitudes and asymptotic directions. There is no reason for the ratio to remain absolutely constant, but a systematic decline in the ratio through 2005 is arguably present. Further data provides a decrease of one order of magnitude for the continuation of the decline. Viewed as a whole, the only statement that can be made is that the ratio in the very early data is clearly higher than that in the latest data, but no systematic trend on decadal scales is visible in between. In this work, we examine the time dependence using simulated data compared



Figure 2: (a) Count rates of the South Pole NM (SOPO) and Thule NM (THUL). (b) The ratio of count rates of SOPO and THUL.

with the actual count rate.

2. Methodology

Figure 3 is a flow chart describing the methodology employed in this study to simulate the counting rate of the South Pole NM. The first two steps utilized FLUKA (FLUktuierende KAskade) [7, 8] downloaded from the website https://fluka.cern. The simulations employed FLUKA version 4-3.1 with the DPMJET [6] hadron interaction model (HEAVYNUC card). We used Flair to construct the 3xNM64 South Pole NM model.

The first step with FLUKA was done using an atmospheric profile generated from two databases: Global Data Assimilation System (GDAS) for pressure surfaces ranging from 20 to 1000 hPa and the Naval Research Laboratory Mass Spectrometer, Incoherent Scatter Radar Extended model (NRLMSISE-00) for higher altitudes [9]. We extracted data specifically for the South Pole location, situated at an altitude of 2.82 km, latitude of -90°, and zero longitude. In recent years data with a 3-6 hour cadence are available, but in the earlier years, no data exist. There are strong seasonal trends in the data, but multiple simulations were impractical with the resources available. Therefore we used a profile constructed as the average over the month of July in the data from 2010 to 2017.

Proton and alpha particles are specified in the input file with the *BEAM* card. The *SOURCE* card sets the minimum and maximum rigidities to 0.5 GV and 200 GV, respectively with a spectral index of 1.00. We concatenate the output files for several runs at the final boundary of the atmosphere to form libraries of secondary particles for subsequent runs. These libraries include proton (p), neutron (n), positron (e^+) , electron (e^-) , positive pion (π^+) , negative pion (π^-) , positive muon (μ^+) , negative muon (π^-) , and gamma rays (γ) . Statistics of the simulation runs are presented in Table 1.

In the second step, we employ the libraries of secondary particles in combination with the 3x1NM64 geometry created by Flair displayed in Figure 1(b) to carry out the detector simulation.

In the third step, we use the output files from the detector simulation to perform post-analysis and obtain the simulated count rate. Here, we applied the following deadtime values for each tube: 20, 28, and 28 μs when facing the monitors from left to right, respectively. Specifically, we use monthly values of the solar modulation parameter (ϕ , in MV) from March 1964 to February 2023 in a force field model to generate the count rate time series. We use two different ϕ parameter models: Ghelfi et al., 2017 [12] (GH17) for the South Pole (available at https://lpsc.in2p3.fr/crdb/) and Usoskin et al., 2017 (US17) [10, 11] (available at https://cosmicrays.oulu.fi/phi/Phi_Table_2017.txt).

Type of particles	Number of cycles	Number of particles
Atmospheric Simulation (PP)		
Proton	200	10,000
Alpha	200	10,000
Detector Simulation (SP)		
Neutron	100	1,000,000
Proton	100	1,000,000
Muon	100	1,000,000

Table 1: Number of cycles and particles used in FLUKA simulation.

3. Results

Figure 4 shows the ratio of helium-3 to boron-trifluoride simulated (He3/BF3) data. The horizontal line represents the average value of the ratio. With an average value of 1.0551, it can be interpreted that the NM64 model, which includes helium-3, exhibits a slightly higher simulated count rate compared to boron-trifluoride, by approximately 5.5%. This is a significant finding, particularly when comparing it to Figure 7 of [3]. The normalization factors at the South Pole exhibited variations ranging from 0.965 to 1.015 during the tube replacement period from 1985 to 2005. In essence, our NM64 simulation at the South Pole has been validated. Considering that the experimental normalization factor for boron-trifluoride is within a similar order of magnitude, we can conclude that both simulations are in agreement.

Figure 5 shows the relationship between the ϕ parameter from the two different models (GH17 and US17). The IGY monitor rate from March 1964 to October 1974 is included after applying a



Figure 3: Flow chart of the simulation used in this study.



Figure 4: The ratio of helium-3 to boron-trifluoride (He3/BF3) simulated data (shown as the blue color plot on the left y-scale) and the ϕ parameter (shown as the gray color plot on the right y-scale) as a function of time. The horizontal line indicates the average value of the ratio.





Figure 5: Scatter plot showing the correlation between ϕ parameters derived from GH17 (left panel) and US17 (right panel) and the count rate of the South Pole NM. Gray points indicate time-matched data obtained



Figure 6: Comparison between the simulated South Pole count rate using the GH17 and US17 models and the actual count rate. The first period, from 1964 to 1974, used the IGY monitor but is modeled as an NM64. The second period, from 1977 to 2006, employs the 3xNM64 monitor filled with ${}^{10}BF_3$ gas. The third period, from 2010 to December 2021, uses the 3xNM64 monitor filled with ${}^{3}He$ gas.

scaling factor of 0.95, as discussed above. As might be expected, the relation between the count rate and the GH17 version of ϕ is rather smooth – after all, that parameter was constructed from the South Pole count rate. The relation of the US17 parameter to the count rate is much more complex. Some scatter is to be expected, but there is a major, systematic difference in the correspondence of modulation level and count rate for the IGY monitor between the two modulation models.

The implications of the different models are explored using the simulations. Figure 6 shows the simulation results divided into three distinct periods characterized by different detector types. The graph employs four different colors to represent four distinct cases. After being corrected for pressure, the actual SOPO data are represented in green. Simulations for the US17 model are carried through the gaps in the data even though the GH17 model is not available. Figures 4,6, and 7 show the solar magnetic polarity. Positive polarity (A>0) indicates that the solar magnetic field in the northern hemisphere is directed away from the Sun. Conversely, negative polarity (A<0) has the northern magnetic field pointing toward the Sun. It is interesting that near the times of the magnetic reversals, the various simulations and actual data agree better than they do at other times. All the simulations predict a higher count rate than is observed, but there is little difference (apart from a scale factor) between the BF3 and He-3 simulations at all times. The US17 and GH17



Figure 7: Comparing simulations to data as ratios using the US17 model. The black line represents the ratio's linear fit from January 1977 (when three separate units based on NM64 were installed) until December 2021, while the yellow line shows the linear fit of the ratio from December 2010 to December 2021. The slope of the black line is 0.001426, and the slope of the yellow line is 0.000169. These slopes can be used to interpret the decline of South Pole data. More detail explains in the text.

simulations generally followed each other during the NM64 era but differed greatly when the IGY was in operation.

In Figure 7, the relations between the simulations and the data are shown as ratios. At present, we do not understand the details of the over-prediction in the model. Possibly much of the excess count rate comes from high-energy particles – leading to a relatively constant error in the prediction that would show up when viewed as a ratio. The force field approximation disregards the influence of solar magnetic polarity, which becomes apparent when examining the ratios shown in the figure. The slopes in the figure investigating the decline are notably small, particularly during the Helium-3 operation epoch, where the slope value approaches zero.

4. Discussion and Conclusions

Our main observation is that a relatively consistent simulation of the South Pole count rate is obtained by ignoring the difference between an IGY monitor and an NM64, provided that the modulation parameter is derived from the count rate of each in the same way. However, if the modulation parameter is derived independently, there is a significant inconsistency with the observed count rate when the IGY is modeled as an NM64. This calls into question the normalization of the IGY and NM64 by matching the count rates.

An extended dataset from the NM64 era shows no conclusive evidence of a continuing longterm decline in the South Pole count rate. To obtain a definitive conclusion on the decline in the 3x1NM64 counting rate at the South Pole, we require continuous data collection for at least one more solar cycle. Our simulations call into question the interpretation of the count rate from the IGY era. The next step in our program is a simulation of the IGY monitor and its environment at the South Pole.

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