Correcting the Count Rate in Water Cerenkov Detectors for the Effects of Barometric Pressure and Local Temperature

EDUARDO DE LA FUENTE¹, ALEJANDRO LARA², ALBERTO SANTIAGO–HERNÁNDEZ¹,², MAGDALENA GONZÁLEZ³ AND ROGELIO CABALLERO–LÓPEZ² FOR THE MILAGRO AND HAWC COLLABORATION⁴

¹Departamento de Física, CUCEI, Universidad de Guadalajara, Jalisco, México
²Instituto de Geofísica, Universidad Nacional Autónoma de México, CU, México
³Instituto de Astronomía, Universidad Nacional Autónoma de México, CU, México
⁴See the special section of these proceedings

edfuente@gmail.com

Abstract: The cosmic ray intensity at the Earth’s surface is modulated by atmospheric variables such as barometric pressure and temperature. The cosmic ray flux also experiences other effects such as a diurnal variation due to the Earth’s rotation and the asymmetric geomagnetic field. These effects compromise studies of slow variations in the primary cosmic-ray intensity, such as Forbush decrease recoveries and time–extended ground level enhancements. To reduce and filter these fluctuations in a reliable way, we have developed a procedure to linearize the fluctuations, allowing more precise background corrections.

Keywords: Cosmic rays, Forbush decreases, Ground level enhancements, Atmospheric Corrections.

1 Introduction

Neutron monitors (NM) and ground based muon detectors are sensitive to cosmic rays produced both inside and outside the heliosphere. The count rate variation in such instruments is used to study a variety of solar and heliospheric phenomena. Abrupt increases, called Ground Level Enhancements (GLE), arise from particles accelerated to GeV energies within flares or shocks several solar radii above the Sun in front of Coronal Mass Ejections (CME). These CMEs also affect the local environment by sweeping away, as they pass by, lower energy galactic cosmic rays producing a Forbush Decrease (FD) typically characterized as a fast decrease and slow recovery.

Slow variations are studied as well. These include the slow decay of the GLE after the rapid onset, the slow recovery of the galactic cosmic-ray count rate after an FD and the 22-year solar-cycle modulation.

Superposed on the rate variations produced by these external phenomena, are variations from geophysical and geomagnetic effects. Foremost among these is barometric pressure and a diurnal variation produced by the asymmetric and non-uniform geomagnetic field and the Earth’s rotation. Although neutron monitors are relatively insensitive to atmospheric temperature, muon detectors are affected by both low altitude and high altitude temperature variations. Barometric pressure variations have time scales from minutes to months, and temperature varies similarly. Diurnal effects are, of course, predictable. These local effects are typically large and, if not removed, can compromise studies of the slower variations of solar and heliospheric origin.

Milagro was a Water Cerenkov Detector designed to enable gamma ray astronomy above 100 GeV (see [1] for details). However, it is a good instrument with which to conduct solar heliospheric physics and GLE studies (e.g., [2] [3] [4]). The successor of Milagro, HAWC (High Altitude Water Cerenkov; see Jordan Goodman et al. this proceedings for details), is a larger and more powerful gamma-ray telescope and it is in the process of being deployed at Sierra Negra, Puebla, México. It, also, can be used to study solar cosmic rays and heliospheric modulation phenomena from 5 to 100 GV.

Milagro and HAWC were, and are, intended as TeV gamma-ray telescopes, but they are also sensitive to hadronic and leptonic cosmic rays at the top of the atmosphere. As such, they can be, and have been, used to study GLEs and FDs. To use the data from these instruments to their maximum, local effects must be removed. Simple barometric corrections, as is used for NMs, are not sufficient, because Milagro and HAWC detect cosmic rays at the top of the atmosphere by way of the muons they create. Thus, the corrections for local effects are correspondingly more complicated.
We have studied this multidimensional background correction problem for Milagro and have constructed a procedure (in an algorithm) to produce a “CLEAN” count rate, relatively free of local-effect variations. The dependence of the rate on these local phenomena can only be studied during periods of low solar activity.

Here, we report our results in developing this algorithm to correct the Milagro scaler data for barometric pressure and ground-level temperature effects. Not included at this stage of development are corrections for diurnal variations and high-altitude temperature variations. We also neglect the very slow natural variation associated with the solar sunspot cycle. This algorithm includes a “Linear Fitting”, and we expect that it can be applied to the forthcoming HAWC data.

### 2 Atmospheric modulation

When a cosmic ray (CR) interacts with the atmospheric particles it produces a cascade of “secondary” particle which may reach the surface. In particular, muons are secondary particles produced by the galactic CR (GCR) flux, and registered in the instrument by its Cherenkov emission in the water.

Therefore, water cherenkov detectors, like Milagro, can detect (indirectly) the GCR flux as shown in Figure 1, much the same as NMs detect GCRs by way of the neutrons they create. In this Figure, the rate measured by the upper array of Milagro Photomultiplier Tubes or PMTs (i.e., the low energy array called “Air Shower”) is plotted. (These data were actually from the Milagro prototype, Milagrito).

![Figure 1: Scaler rate measured by the Milagro Air Shower array during the period of minimum solar activity; November 9 – 13, 2007.](image)

The secondary flux or detected rate depends not only on the primary flux but also on the physical conditions of the atmosphere above the detector and the conditions at the detector itself. The ambient pressure and temperature play a significant role in atmospheric modulation. For example, Figure 2 shows the measured rate (as in Figure 1) (as a percentage) (central panel), plotted along with the inverse of the ambient pressure (top panel) and temperature (bottom panel). We see that the measured rate depends directly on the temperature and inversely on the pressure.

![Figure 2: Ambient pressure (inverted in top panel); uncorrected scaler rates in percentage (middle panel); and ambient temperature (bottom panel).](image)

As our goal, we are interested in detecting and studying heliospheric transient events such as GLEs and FDs over their full duration. It is important to note that the Milagro threshold is close to the geomagnetic cutoff, i.e., a few GV. It is only above this rigidity that we can study these phenomena. Therefore, to study heliospheric phenomena, it is necessary to “CLEAR” the scaler rate as much as possible of the atmospheric modulation. In the standard Milagro Scaler software, there is an atmospheric correction (included [5] method) but this was intended for short duration corrections as for cosmic gamma ray bursts, lasting a few minutes at most. This correction is not satisfactory for long duration solar events such as Forbush decreases. One such occurrence is shown in Figure 3 where the raw scaler (black) and the standard corrected (gray) data are plotted. A better correction method is necessary to conduct our desired studies.

### 3 The Correction Algorithm

The scaler rate as a function of both pressure (top panel) and temperature (bottom panel) is presented in Figure 4. Here, we assume that the scaler rate can be resolved into a function of barometric pressure and a function of external ground-level temperature. This relationship is modeled by two linear equations:
Figure 3: Uncorrected (lower black curve) and Milagro-Software corrected (upper gray curve) scaler rates in percentage. An additional 1% is applied to corrected data rate to separate the curves.

\[
\begin{align*}
rate_p &= (m_p \text{ Pressure}) + b_p \\
rate_T &= (m_T \text{ Temperature}) + b_T,
\end{align*}
\]

where \(m_{\text{PAR}}\) and \(b_{\text{PAR}}\) are the slope and constant terms, respectively, and “\(\text{PAR}\)” can be either \(P\) (pressure) or \(T\) (temperature).

Assuming that the effects are separable, we correct \((\text{corr})\) first for one parameter (e.g. pressure):

\[
\text{rate}_{\text{corrP}} = \text{rate}_{\text{uncorr}} - \text{rate}_P + <\text{rate}_{\text{uncorr}}>
\]  

and then apply the appropriate correction of the other parameter (in this case temperature), as:

\[
\text{rate}_{\text{corrected}} = \text{rate}_{\text{corrP}} - \text{rate}_T + <\text{rate}_{\text{corrP}}>
\]

where \(\text{rate}_{\text{uncorr}}\) is the uncorrected scale rate data, and \(<\text{rate}_{\text{term}}>\) is the appropriate numerical average.

This method of correction was applied to twenty-five quiet days to see if the rate curve flattens as expected for this time period:

- \(m_p = 1.68513 \times 10^5\)
- \(b_p = 5.1 \times 10^6\)
- \(m_T = 87.1\)
- \(b_T = 1.3 \times 10^6\)

4 Results

We have applied the linear fit algorithm to the Milagro scalar rates for our trial period (Figure 1). For completeness the correction method proposed by [6] was also performed and is plotted for comparison [6]:

\[
\begin{align*}
\text{rate}_{\text{corrD}} &= \text{rate} - \text{rate}_0 \exp \beta (p - p_0) + <\text{rate}>
\end{align*}
\]

where \(\text{rate}_{\text{corrD}}\) is the corrected rate (by this method); \(p_0\) is the pressure measured at \(\text{rate}_0\) value; and \(\beta\) is a constant related to the attenuation length of the atmospheric muons.

Our results are presented in Figure 5, where plots of uncorrected data (in dark gray, Fig. 1), data corrected according to Dorman’s method (in light gray), and our results (in black) are superposed. The corrected rate is reasonably free of the modulation from pressure and temperature, compared to that of Dorman, who did not include the temperature effect. The corrections are confirmed by the correlation coefficients between the scaler rates and the atmospheric parameters as shown in Table 1. Here:

\[
\begin{align*}
r_p &= \frac{\sigma_x \sigma_{\text{rate}_p}}{\sigma_{\text{rate}_p} \sigma_p} \\
r_T &= \frac{\sigma_x \sigma_{\text{rate}_T}}{\sigma_{\text{rate}_T} \sigma_T}
\end{align*}
\]

For quiet solar period considered, the method works well. However, we expect this procedure to exhibit problems for other periods when the stratospheric temperature is more...
Table 1: Correlation Coefficient between Corrected data atmospheric parameters.

<table>
<thead>
<tr>
<th></th>
<th>$r_P$</th>
<th>$r_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milagro Software</td>
<td>-0.96</td>
<td>0.23</td>
</tr>
<tr>
<td>Dorman Algorithm</td>
<td>0.71</td>
<td>$1.76 \times 10^{-9}$</td>
</tr>
<tr>
<td>Linear Algorithm</td>
<td>0.05</td>
<td>$8.79 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

Figure 5: The linear fit corrected (black curve) compared with the original uncorrected scaler data (dark-gray) and the Dorman [6] method.

variable and the temperature of the instrument itself is variable. A more detailed analysis will follow.

For future work, we will apply this method to an active solar period to identify and study heliospheric phenomena, such as GLEs and FDs detected by Milagro or Milagrito. Furthermore, we will apply this procedure to the forthcoming HAWC data.

We acknowledge James Ryan and Anthony Shoup for read the manuscript and useful contributions. E de la F and AS–H also thank grant PROMEP /103.5/10/1493, México.

References