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Exploring Ground Level Enhancement Precursor Signals in Neutron Monitor Data

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Abstract

Energetic solar neutrons cause electromagnetic showers in Earth’s atmosphere. The flux of secondary neutrons produced in these showers may appear as brief enhancements in ground-level count rate data collected and archived by the Neutron Monitor Database (NMDB). Thorough analysis of these enhancements could lead to a deeper understanding of the events involved in their production. Furthermore, it may be possible to characterize a predictive relationship between some attributes of these enhancements and various properties of subsequent proton-precipitated ground-level events. Unfortunately, there currently exist very few records of these enhancements. To remedy this, several analytical methods were applied in attempts to create an algorithm that can consistently locate the fingerprint of these solar neutrons. This paper describes the setup and implementation of these techniques; however, assuming the aforementioned enhancements exist in NMDB data, the techniques’ ability to confidently identify such enhancements is found to be less than promising.

Keywords: space weather – signal analysis – anomaly detection – solar energetic particle – impulsive solar events
1 Background

Space weather forecasting is becoming increasingly essential as humanity continues to expand into space. In the search for new and better tools to predict future states of the space environment, it is important to precisely study the Sun and the processes through which it affects its surroundings.

Solar energetic particle (SEP) events are major contributors to the population of particles in the solar system. Gradual SEP events, associated with coronal mass ejections (CMEs) and wide shockwaves, are responsible for a significant fraction of particles up to 500 MeV/nucleon. Impulsive SEP events, on the other hand, are produced by resonant acceleration of particles in the solar atmosphere [1]. Impulsive events accelerate particles of higher average energy than do gradual events.

1.1 Ground-level Enhancements (GLEs)

The interaction of protons produced by impulsive SEP events with atomic nuclei in the Earth’s atmosphere can result in extensive air showers which propagate to the surface of the planet if the primary proton possesses enough energy. This energy threshold, known as the atmospheric cutoff, requires the incident primary to have an energy of approximately 430 MeV per nucleon, depending on the thickness of the atmosphere in which its shower may take place [4]. Particles with much lower energies may still create air showers, but these showers will cease before reaching the ground.

Secondary neutrons produced from such a shower can be detected in neutron monitor (NM) stations, of which there exists a global network. Many NM stations continuously upload their data to the Neutron Monitor Database (NMDB). The NMDB has collected data from 53 detectors globally (a map of these detectors’ locations is shown in Figure [1]). When two or more widely separated stations in the NMDB network report a sudden, significant enhancement in the count rate of neutrons, a GLE has occurred—the energies of
solar protons incident on the Earth’s atmosphere have exceeded the atmospheric cutoff, and their population has greatly increased.

Figure 1: Map of some NM stations in the NMDB network. Taken from Mavromichalaki et al. 2011 [2].

Seventy-two GLEs have been recorded since 1942 [3]. This figure does not include the various recorded sub-GLE events, in which significant neutron flux enhancements are not detected near sea level [4]. The analyses described in this paper were not performed on sub-GLEs, but were performed on all GLEs of sufficiently fine time resolution. See Section 2: Methods and Results for more detail on time resolution.

1.2 GLE Precursor events

Neutrons and electrically neutral atoms produced in impulsive solar events can “free-fly” to Earth, unlike charged particles, which follow the Parker spiral of magnetic field lines connecting the Sun to the Earth. Since a path following the field lines is longer, a given uncharged particle produced by a SEP event will reach the Earth before a charged counterpart of the
same speed.

Free neutrons \(\beta\)-decay with a half-life of 10.61 minutes [5]. This short lifetime warrants examining the loss rate of solar impulsive neutrons before they reach 1 AU. The kinetic energy \(E_k\) of any particle can be expressed as follows:

\[
E_k = E - E_0 = \gamma m_0 c^2 - m_0 c^2 = (\gamma - 1) m_0 c^2
\]

where \(\gamma\) is the relativistic Lorentz factor and \(m_0\) is the rest mass of the particle. Using the definition of \(\gamma\) and the result of Equation 1 one can obtain the speed \(v\) of a particle as a function of its kinetic energy:

\[
\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}
\]

\[
\frac{v}{c} = \sqrt{\frac{E_k^2 + 2E_k m_0 c^2}{(E_k + m_0 c^2)^2}}
\]

One can then use Equation 3, taking into account special relativistic time dilation experienced by a moving particle, to determine the Earth-frame distance \(r\) traveled by the particle in proper time \(t_0\):

\[
r = v\gamma t_0 = c\sqrt{\frac{E_k^2 + 2E_k m_0 c^2}{(E_k + m_0 c^2)^2}} \left(\frac{E_k}{m_0 c^2} + 1\right) t_0
\]

A large number of neutrons each with energy equal to the atmospheric cutoff of 430 MeV (comparable to the 500 MeV minimum detectable energy for most neutron monitors [6]) would thus have traveled a distance \(r = 1.35\) AU (in the frame of an observer on Earth) before half of their population was lost to \(\beta\)-decay. Neutrons with higher energies would travel even farther.

If indeed of the same range of energies as the protons produced by the SEP event, the solar neutrons under consideration will not only reach 1 AU, but they will also bypass the
atmospheric cutoff and shower to the surface of Earth. Therefore one would expect an amplification of the secondary neutron count rate as a result of the primary neutrons many minutes before the charged SEPs ever reach the Earth. The expected effect of this GLE precursor on a time series of NM data is shown in Figure 2.

![Figure 2: A mock plot displaying the expected behavior of an NMDB time series including and preceding the main GLE. The precursor signal is thought to appear as a low-amplitude, short-duration enhancement in the neutron count rate.](image)

Evidence of such precursory events do appear in reports over the past several decades [7][8]. However, any relationship between the properties of the precursor signal, those of the main GLE signal, and those of the eruption event that generated each have yet to be well characterized.

This paper explores various methods used to detect similar signals, and evaluates their efficacy in locating the neutron precursor signal in NM data.

## 2 Methods and Results

Locating a precursor signal presents an interesting problem because so little is known about its features. No standard shape of the signal has been accepted; no precise constraints have been imposed on its amplitude, duration, or arrival time. Therefore, techniques to locate the signal that do not require previous knowledge of exact values of its attributes must be
It is certainly possible that precursor signals’ durations are very short, on the order of minutes or less. To account for this possibility, analyzed data should have as high a temporal resolution as possible. The NMDB offers resolutions as fine as 1 minute in many cases. Other large archives of NM data have poorer resolution, such as the World Data Center for Cosmic Rays dataset (1 hour resolution at best) or the University of Oulu’s GLE database (5 minute resolution at best). The NMDB’s good resolution and mostly continuous monitoring lead to an incredible volume of information and make the data it provides a prime target for study.

2.1 Data Preparation

Measurements of neutron count rate were taken exclusively from the NMDB because of its large amount of highly-resolved data, as described above. As of the time of writing, NMDB lacks a mass-download interface, so data for each time period of consideration were iteratively scraped from NMDB webpages using a custom Python script.

The script followed a series of steps to ensure standard formatting of the NMDB data. First, the user would input a range of dates and NM stations for which he or she wished to access the corresponding data. Second, the script would submit a request to the NMDB archive. Third, it would scrape the resulting html content and parse it to create a string containing the data. Fourth and finally, if the data possessed the optimal 1-minute resolution, the script would convert the string into a pandas dataframe to ensure standard format and save locally for later use.

The data are represented as an array of time series, with each column of the dataframe corresponding to a single equal-interval time series of average neutron counts per second for a certain detector. Several examples of these time series are shown in Figure 3.

A GLE precursor was not immediately apparent to the human eye in any plot for the stations and time periods assembled. Several methods were implemented in attempts to amplify any precursor signals; to draw them from the noise and make their presence more
obvious.

Figure 3: Examples of raw NM data from the 24 August 2002 GLE. The GLE peaks are clear but there are no immediately visible precursor enhancements.

2.2 Statistical Analysis of Timeseries

A simple statistical algorithm was implemented to try to detect precursor signals. An analysis script would sweep along the data in chronological order, keeping a first-in-first-out (FIFO) buffer record of the past $m$ measurements. The value of $m$ was first set to 5, then to 20, then to 50. The standard deviation and mean of the points in the buffer were computed. If a point in the timeseries entered the buffer was deemed anomalous, i.e. its counts per second value was more than $n$ standard deviations above the mean (trials were run at values of $n = 1.5, 2, 2.5, 3, 3.5$), the script would take note. If three successive points were found to be anomalous, the script would mark the first point in the series of three as the onset of the precursor signal. This method is similar to the NOAA SWPC criteria for characterizing an
x-ray event, which helps ensure that short-duration noise spikes are not accidentally classified as significant events [9].

However, the above detection method failed to reliably classify possible precursors. At low values of $n$, the algorithm often classified gradual increases in the baseline count rate as the precursor signal when they were of too long duration to actually represent the precursor. At high values of $n$, the algorithm only classified the GLE as the precursor since the GLE was the only feature of the data that rose sharply enough above the baseline to satisfy the high confidence requirement set by high $n$. Altering the value of $m$ did not substantially change these results.

To account for the possibility of precursor events being shorter than three minutes in duration, the number of anomalous points required for anomaly classification was reduced from three to one. At the same varying values of $m$ and $n$, this change consistently misidentified noise spikes as the precursor signal, or in the case of a smooth, low-noise baseline, misidentified the GLE as the precursor signal.

### 2.3 Principal Component Analysis

Principal component analysis (PCA) is a machine learning technique that transforms a set of data into a series of eigenvectors of the data. Specifically, the eigenvectors extracted are those that account for the most variation in the original data.

A precursor enhancement in the neutron count rate would account for some degree of variation. Thus it was expected that one or more principal components of a timeseries describing the period directly before a GLE would display a precursor more prominently than in raw data.

PCA was performed on 2-D arrays of data, each in the format described in Section 2.1: Data Preparation. Each array corresponded to a month containing one or more GLEs, and included only data from stations active during that month which had 1-minute resolved data.

Before PCA, any null elements in the arrays (signifying that the corresponding NM did
not report data for that minute) were filled by linear interpolation of the nearest non-null points. Null elements that were either the first or last element in their time series were filled with the nearest non-null element.

Also preceding PCA, the elements of each time series in the array were normalized using the “standard scaler” method:

\[ x_{scaled} = \frac{x_{initial} - \mu}{\sigma} \]  

where \( x_{initial} \) and \( x_{scaled} \) are respectively the initial and scaled values of a given element, and \( \mu \) and \( \sigma \) are respectively the mean and standard deviation of the time series of which \( x_{initial} \) is an element. This step must be undertaken in most PCA since the algorithm is highly influenced by the distribution of its input points.

PCA was then performed using the scikit-learn Python library. The maximum possible number of principal components were obtained for each input array. As expected, principal components beyond the first few showed only the effects of background noise, so only the first four principal components are displayed in the examples below. Figure 4 shows an example of the output when each principal component is plotted against time.

Again, as with the result of the procedure described in Section 2.2: Statistical Analysis of Timeseries, no GLE precursor is made clear using this method.

It is possible that the GLE accounts for so much variation in the data that its effects dominate the set of principal components. To ensure that this does not preclude a precursor from any principal components, PCA was performed a second time on intervals excluding all points after the GLE onset. As exemplified in Figure 5, no precursor became visible even with the effects of the GLE on the components taken into account.

The wider the window of a time series upon which PCA is performed, the greater chance there is that a non-precursor set of points in the window accounts for a large amount of variation. This implies that a precursor signal would be made most obvious in principal components taken over a smaller window. The precursor signal should precede its GLE,
which establishes an end boundary to the ideal PCA window. The beginning of the window, then, would be marked by the timing of the impulsive solar event that accelerated the SEPs.

Solar flare events are often identified by the GOES satellites, which make x-ray observations of the Sun. Using the GOES EPS database, the onset times of each GLE-associated solar flare were compiled. PCA was then performed on each NMDB time series for which the GOES database had recorded a solar flare. The output, examples of which are shown in Figure 6, again make no definitive suggestion about the presence of a precursor signal.

In total, PCA was implemented three times on the NMDB data, each time with different windowing criteria. For all three implementations, principal components began to describe the noise in the signal before representing any GLE precursors. This suggests that if precursors exist in the NMDB data, they account for no more variation in the time series than
Figure 5: The first four principal components of the 2-hour period leading up to the Aug 2002 GLE, this time with the GLE not included. No precursor is visible preceding the GLE onset at minute 33200. Note that the vertical scale for principal components 3 and 4 is different than for components 1 and 2.

noise does.

2.4 Autocorrelation Analysis

A common technique in finding a signal shrouded by noise is to multiply a time series with a shifted copy of itself. Examples of such shifted functions are given in Figure 7. Given a discrete function $f(t)$, and a shift $\tau$ in units of $f(t)$’s discretization, it is useful to define the correlation function $C(t, \tau)$ as such:

$$C(t, \tau) = \sum_{a=\tau_{\text{max}}}^{a} f(t) \cdot f(t + \tau)$$  \hspace{1cm} (6)

where $a$ is an index of $f(t)$ that denotes the extent of the shift and $\tau_{\text{max}}$ is the maximum value that $\tau$ will take in any of the autocorrelations. $a$ must be greater than or equal to $\tau$, ...
Figure 6: The first four principal components of the period following the 14 July X5 flare, with the GLE not included in the window. Once again, no precursor is immediately visible in the hour after the flare. Note that the vertical scale for principal components 3 and 4 is different than for components 1 and 2.

otherwise the point at index $t + \tau$ will be outside the domain of $f(t)$. However, $\tau$ may be any valid index of $f(t)$ less than $a$.

The reason $\tau_{\text{max}}$ is used rather than simply $\tau$ is as follows: over the course of many calculations of $C(t, \tau)$, one should keep constant the size of the interval over which the time series is autocorrelated. If this interval were to grow with $\tau$, for example, then $C(t, \tau)$ might also grow with $\tau$ — not because $f(t)$ was autocorrelating better, but because $C(t, \tau)$ would be adding together more values. Therefore in every calculation (no matter the value of $\tau$) the summation is defined by the widest summation interval among the set of calculations.

The implication of the autocorrelation process is that $C(t, \tau)$ will take large values when, for a given $\tau$, large values of $f(t)$ are multiplied by large values of $f(t + \tau)$. For one example, one should always expect $C(t, \tau = 0)$ to be relatively large since all the large values of one function will be enhanced by the large values of the other. When small values of $f(t)$ are
Figure 7: Examples of various $\tau$ shifts on the SOPO detector for the 24 August 2002 GLE. Multiplied by small values of $f(t + \tau)$, the result will be analogously diminished.

These behaviors are displayed in Figure 8 in which a noiseless model time series is autocorrelated at various $\tau$. When the primary series' precursor peak overlaps with the shifted series' GLE peak, the autocorrelation function displays a local maximum in the region of overlap. One might expect to see a similar increase in the correlation factor in similar plots for NM data in which precursor signals are hidden.

Autocorrelation functions $C(t, \tau)$ for time series with a visually prominent GLE peak do not follow the expected pattern, but do display some similarities to it. An example of a time series and its autocorrelation function is shown in Figure 9. As the window $[a - \tau_{\max}, a]$ must include both the expected location of the precursor and the majority of the GLE, the parameters $a = 2550$ minutes and $\tau_{\max} = 160$ minutes were chosen for the event displayed. These allow for a precursor peak to interact with the GLE if the precursor occurs at any time approximately two hours before the GLE onset. A precursor event is expected to
Figure 8: A model precursor-GLE time series at various shifts, and its associated autocorrelation curve. As the original function correlates very well with itself, the correlation factor is large at low $\tau$ and falls off quickly. When the precursor of the original function and the GLE of the shifted function overlap in time, there is a momentary increase in the correlation factor.

occur minutes before the GLE onset, meaning any present precursor signal should be clear in the autocorrelation plot at just a few units of $\tau$. However, no such enhancements in the correlation factor were observed in any autocorrelation plot for all GLE events in the NMDB dataset.

In low-noise series in the dataset, the correlation factor initially falls off with increasing $\tau$ just as predicted by the noiseless model. The curve levels off for a wide interval and then becomes steep again. This second period of rapid decrease in the correlation factor may
Figure 9: An example series displaying a GLE (and possibly a precursor signal) and a plot of its autocorrelation factor as a function of $\tau$.

indicate the point where the exponential tail of the GLE stops significantly correlating with the rising edge of the GLE (the slope of the rising edge is much higher in the model). In some higher-noise series, not shown here, the same effect is present but at lower values of $\tau$. In those series it may be due to an interaction between a post-GLE enhancement in the shifted series with the GLE in the original series. Both these features occur at too large values of $\tau$, and are not the right shape, to likely be due to precursor signals.
3 Enhancements Outside the Context of GLEs

Energetic events in the Sun produce free neutrons even if the events in question do not produce GLEs. Though a neutron signal was not identified with the above methods, it is possible that the same type of signal may appear in NM data outside the context of GLEs.

It is important to note that this neutron signal is likely not inherently different than the precursor signal discussed at length previously in this paper. The GLE precursors are produced by eruptive solar events, but these events can occur independently of the massive release of charged particles leading to a GLE. The signal has been termed “precursor” thus far only because its arrival at Earth precedes any GLE produced by the same impulsive event. Though analyzing the signal’s properties may yield useful information about subsequent GLEs, nothing about temporary enhancements in the neutron flux at Earth causes GLEs—such enhancements have been observed to exist at times when no GLE occurred [11]. This may be because the associated charged SEPs expelled from the Sun went wide of the Earth, because the charged SEPs that were produced were of too low energies to be detectable by ground-based NMs, or because of other reasons. Regardless of the relationship between neutron signals and GLEs, it is still useful to characterize the efficacy of the methods discussed previously in this paper in identifying all impulsive event neutron signals, not just those associated with GLEs.

Ions spiraling along magnetic field lines down into the solar atmosphere undergo nuclear interactions. The products of these interactions may be released in a specific direction depending on the details of the interaction in question. Downward-beamed ions experience magnetic mirroring as shown in Figure 10. Near the mirror point, almost all of an ion’s velocity will point in a direction perpendicular to the field line being orbited. Products of interactions with the ion then will preferentially be emitted in the direction of its near-90° pitch angle. In flare sites on the solar limb, products of interactions with mirroring ions escape from the Sun and fly towards Earth [12][13]. These products may be neutrons or photons, among others [14][15]. There is often a delay between emission of x-rays and
gamma rays from flare sites, but such delays do not exceed 1 minute \[16\][17]. As this is the resolution of the NMDB dataset used in this paper, the effects of such a delay are likely insignificant and will be ignored.

Because the neutrons produced at the mirror point are so strongly associated with high-energy photon emission, further investigation of small neutron enhancements was performed using the observation time of the photons as a reference. Even though solar neutrons are not uniquely produced from the interactions of mirroring ions, such continued investigations expand the parameters in the search for small, ground-level increases in the neutron flux.

![Diagram of magnetic mirroring](image)

Figure 10: Diagram of how the magnetic mirroring of ions in the solar limb can beam neutrons and photons towards Earth.

### 3.1 Superposed Epoch Analysis

In an attempt to identify neutron enhancements associated with impulsive solar events (but possibly not with GLEs), Superposed epoch analysis (SEA) was performed on a new subset of NM data.

This new subset was taken again from the NMDB. However, rather than selecting periods during which there was a GLE, the script accessed months during which there were one or more solar flares near the East or West solar limbs (\(|\text{longitude}| \geq 60^\circ\)) whose X-ray class was at least M5.0. These criteria, chosen somewhat arbitrarily, respectively restrict the dataset
to events whose mirroring ions directed most of their products towards Earth, and to events energetic enough to overcome the atmospheric cutoff and produce a change in neutron flux at ground level.

In SEA, a period of time is chosen around an event in each of a set of time series. These epochs are aligned, and then the resulting time series are summed element-wise. With a high enough population in the set of time series, noise from each series interferes destructively and is eliminated, while common events interfere constructively. This method’s possible usefulness in locating small signals in NM data is clear.

For the flare-defined NMDB dataset, the “event” around which epochs were defined were the solar flare peak times given in the aforementioned GOES EPS database [10]. As flare neutrons with sufficient energy to produce detectable secondaries at ground level reach the Earth just a few minutes after their associated photons do, a broad window of 60 minutes was chosen for the width of each epoch. The shape of the superposed curve is not affected by the window size; 60 minutes was chosen simply to view a large range of potential neutron arrival times.

Figure 11 shows an example set of aligned epochs before they were summed together. Distinct sets of baseline count rate levels appear because some neutron monitors are more sensitive to incoming radiation. Though the baseline level of an input series affects only the baseline level of the superposition, the fact that series with higher base count rates are more sensitive means their features will be exaggerated compared to series of lower base count rates. This bias should give the more sensitive detectors a greater weight and assist in magnifying impulsive event neutron signals.

The resulting superposition of each qualifying time series (of which there were 456) is displayed in Figure 12. While a short period minutes after the flare is slightly higher in summed count rate than its surroundings, it is not enough to confidently assert that it represents the presence of the sought-after neutron signal.

A couple of factors could improve the quality of SEA’s performance on NM data. For
Figure 11: An example set of 20 random time series from the NMDB, with their epochs aligned. The series are not yet superposed.

Figure 12: The superposition of all qualifying NM timeseries, each aligned by their associated X-ray flare time.

instance, a simple upgrade to the time resolution of the detectors could refine the 7-to-29 minute period mentioned above into a smooth distribution instead of an erratic, pseudo-oscillatory curve. Additionally, an examination of epochs anchored on gamma-ray flare times instead of only X-ray flare times may yield different results. In a set of NM data associated with gamma-ray flares, which are more strongly associated with the production of neutrons at the mirror point, new events may be introduced which more strongly display a neutron enhancement. Including enough of these series in the sum would show the enhancement in
the superposition.

4 Conclusion

A simple statistical method, principal component analysis, autocorrelation analysis, and superposed epoch analysis were all implemented on ground-based neutron monitor data from the NMDB network. These methods are generally recognized as techniques that work well at identifying important signals in the presence of noise. However, none of the methods implemented as described in this paper were able to confidently identify the presence of neutrons produced by an impulsive solar event.

It remains uncertain whether the methods lack the capability to do so, or whether the characteristic signals of these neutrons are simply not present in the data. The second option is less likely, given that the current physics describing the production and transport of these neutrons suggests that they should have detectable effects at neutron monitor stations. However, few such detections have been reported as of the time of writing, and papers describing them offer little investigation into their methods.

There is another possibility behind why no impulsive-event neutron signal was found in the data analyzed here: the assumptions made about the shape, amplitude, duration, or flare-relative timing of the precursor signal could be incorrect. In this case, more investigation into the underlying physics would be required so the desired signal can be better modeled. Whether or not the assumptions made in this paper are correct, an exact modelling of the signal would provide a good basis for future research, as then the model signal might be able to be fit to the NM data and very precisely identify its position.

Additional future methods of investigation of neutron flux enhancements should include wavelet analysis and singular spectrum analysis, techniques used in time series anomaly detection but not discussed in this paper. Wavelet analysis involves slowly sweeping a “window” from left to right in a time series and taking the Fourier transform of each window.
If the noise characteristic to NMDB data is of a different range of frequencies than a small neutron enhancement, that enhancement may be rendered visible by this technique.

Singular spectrum analysis, on the other hand, is commonly used to remove noise from a time series without altering the trends therein. This may work far better on NMDB data than would standard smoothing functions, which might destroy a neutron enhancement signal if it were smoothed too strongly. Once some degree of noise is eliminated, it is possible that other analysis methods, perhaps some of those included in this paper, would be powerful enough to locate the desired signal.
5 Appendix

The sections of Python 3.7 code used to perform the computer-aided processes described in this paper can be viewed and downloaded at github.com/ramanm262/neutron-analysis. The sections were written and tested primarily in Jupyter Notebook. As such, commands and conventions within them may not fit within standards or even compile in other Python environments.

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7 References

References


