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Predicting Future Solar Modulation and Implementation in MCNP6

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INTRODUCTION

The application of detecting low level radiation in the field requires quantification of the natural radiation background specific to that location. This background is made up two primary components: naturally decaying radionuclides in the soil and atmosphere known as terrestrial background, and the particle cascades caused by high energy cosmic radiation interacting within the earth's atmosphere known as cosmic background. The terrestrial component dominates the background spectrum below approximately 2 MeV, however, the cosmic component comprises the entirety of the high-energy spectrum [1]. Furthermore, the terrestrial component is relatively constant for a given location while the cosmic component is heavily dependent on solar activity, an effect known as solar modulation. Annual values of the solar modulation parameter, φ, have been determined since 1936, and their fluctuations are seen to be roughly sinusoidal over time [2].

If one wished to predict or simulate the outcome of an experiment in the future, a prediction for the solar modulation would be necessary to accurately determine the cosmic background contribution. The previous version 6.1.1 of MCNP [3] contained solar modulation data for 46 years between 1960 and 2005. This data was updated with newer solar modulation data, from I. G. Usoskin et al. [2], which reports solar modulation data for an additional 33 years between 1936 and 2014 (see figure 1).

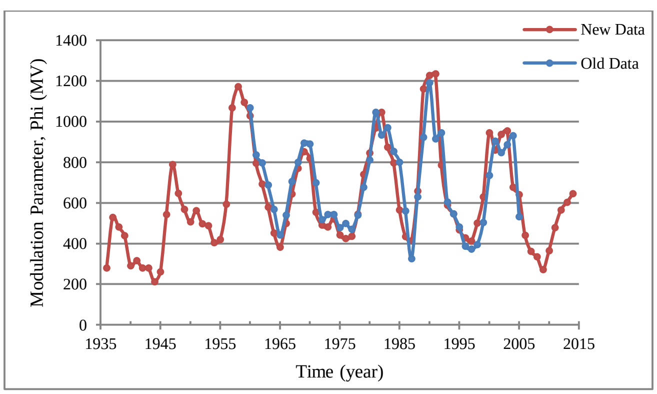

Fig. 1. Old solar modulation data (in blue) was already implemented in MCNP 6.1.1 [4]. This data was replaced new data (in red).

In order to use past solar modulation data to predict cosmic background radiation fluctuations for dates beyond 2014 an algorithm was developed to forecast future solar modulation data based on the sinusoidal behavior exhibited in recorded data. This algorithm was implemented into MCNP 6.1.2 to be used for cosmic background simulations and tested against benchmark data to assess its accuracy.

DESCRIPTION OF ACTUAL WORK

The general prediction algorithm consists of the following steps: To start, an input date for which the program will predict the solar modulation is selected. This input date is then processed in one of three ways. If the input year is before 1936, the modulation data from 1936 is used. If the input year is between 1936 and 2014, the program uses a linear interpolation[a] to calculate a value for solar modulation. If the input year is after 2014 (or is after the most recent year for which solar modulation data has already been collected), several of the most recent modulation data points available (further referred to as "predictor points") are used. A sinusoidal curve is fit to those predictor points, extrapolated out to the input date, and from that curve, the desired year's solar modulation is predicted. Note that the use of a "sinusoidal" fit refers to a fit of the following form:

$$\boldsymbol{y = A\sin(wt) + B\cos(wt) + C} \quad (1)$$

Where y is an estimate of the solar modulation, t is a time index related to the year[b], A, B, and C are unknown real-valued constants, and w is the angular frequency given by:

$$\boldsymbol{w = \frac{2\pi}{T}} \quad (2)$$

Where T is the solar modulation period.

Producing an Initial Fit

To establish an initial fit the common method of minimizing the mean-square errors (MSE) is employed as seen in Tilden, 2001 [5]. This method fits a function to the solar modulation data by minimizing the difference between the given data points and the fit points. Mathematically, the following expression is minimized:

$$\sum_{i=1}^{n}(\varphi_i - A\sin(wt_i) + B\cos(wt_i) + C)^2 \quad (3)$$

Where φ_i, is the solar modulation data from the predictor points corresponding to the year, t_i, where i is the number of predictor points, n. To do this, the value of *w must be known or estimated*, and the correct coefficients A, B, and C must be determined. Using Equation 2, a matrix expression in which the calculated values for A, B, and C (A_0, B_0, and C_0 respectively) are collected into one vector of unknowns can be created. If x_0 is defined as a vector of unknowns such that

$$x_0 = \begin{bmatrix} A_0 \\ B_0 \\ C_0 \end{bmatrix} \quad (4)$$

and φ is defined as the vector whose i^{th} component is φ_i, and D_0 is defined such that

$$D_0 = \begin{bmatrix} \sin(wt_1) & \cos(wt_1) & 1 \\ \sin(wt_2) & \cos(wt_2) & 1 \\ \vdots & \vdots & \vdots \\ \sin(wt_n) & \cos(wt_n) & 1 \end{bmatrix} \quad (5)$$

Then a much simpler matrix expression to can be written replace Equation 3:

$$(\varphi - D_0 x_0)^T(\varphi - D_0 x_0) \quad (6)$$

Assuming an educated guess, w_0, can be made for w, Equation 6 can be minimized and x_0 can be determined using the following equation from Tilden et al., 2001 [5].

$$x_0 = (D_0^T D_0)^{-1}(D_0^T \varphi) \quad (6)$$

Once w_0 and x_0 are obtained, an initial guess can be made. Since it is known that the solar cycle's period, T, is approximately 11 years [6], from Equation 2 it can be seen that the angular frequency is ~ 0.57 /year. Therefore the value of w_0 = 0.57 /yr was chosen as an initial guess. However, a closer inspection revealed that if the estimate of the period is wrong by as little as ±0.5 yr (a reasonably probable occurrence) then a change of ±0.02 in w can occur, causing a poor fit. In fact, when examining fit, it was found that the actual modulation data can have a local "period" of up to 12.3 years (see figure 1 around 1984-1993) or down to 8.4 years (see figure 1 around 1995-2006), though the overall average may be about 11 years.

Ensuring Fit Quality

Since the modulation period of the sun is not exactly 11 years, more accurate estimate for w is needed. To find it, the matrices were modified to yield a Δw , the amount by which the estimate of w changes after each iteration. Said another way, initial values of w_0, A_0, B_0, and C_0 are used as a starting point to find new values, w_1, A_1, B_1, and C_1 using Δw. Once these new estimates are obtained, the process is iterated, each time using the newest, improved set of values to find an even better set. The assumption is made that through the process of this iteration, the coefficients' values would converge to a certain specific set of values which, if found, would give the best possible fit. Since that convergence could take a long time, however, it was decided to stop the iteration when the coefficients no longer change by a certain specified amount, which was chosen based on the desired level of precision. A limit was also added on the amount that the final estimate for w can deviate from the average of 0.57 /yr. This way, the unreasonable fits can be eliminated. Since the highest frequency found in the recent past was ~0.75 /yr and the lowest was ~0.51 /yr, the bounds are set for the frequency to be 0.45 /yr and 0.79 /yr. (Note that this corresponds to a change in the period of up to 3 years from the average of 11 years.) If, after the iterative process, the value of w was estimated to be outside the above bounds, the program would automatically reset the estimate for w back to 0.57 /yr since an estimate outside the bounds was deemed to be unreasonable. After all iterations or resets are complete, the final coefficients determine the final fit and thus the estimate for the solar modulation for the input year.

Accuracy of the Prediction

Once the basic algorithm was in place, several methods were used to quantitatively measure the accuracy of predictions and to increase accuracy where possible.

Measuring Accuracy

In order to test the predictions, predicted values were compared with actual data. To accomplish this, the algorithm was modified to perform a sinusoidal fit to "predict" years between 1936 and 2014. Then, by using the algorithm with a year from the past as the input, a solar modulation value was predicted and compared to the measured value for that year. Of interest was also how far into the future the fit generated for a particular input year would be valid. To determine the prediction accuracy for an input year, as well as the next three years after the input year, predictions were compared to measured data to determine how each prediction would match reality as it was carried further into the future. A comparison was made of absolute and relative differences for each of the four predicted years for a given input year, the results of which are discussed later.

Making Improvements

When performing initial tests of the fit and making plots, a fixed number of eleven predictor points were used. It was found that using any fixed number of predictor points to make the sinusoidal fit did not give the best results when used over multiple years. See figure 2 where 11 predictors are used and the sinusoidal fit is thrown off by the small dip in φ between 2001 and 2004. It was also determined through many tests that to get the best fit, the most recent local maximum and minimum from the measured data included must be included in addition to a couple of points on the far side of the second extrema. Since, as was mentioned previously, the local frequency of the solar modulation can vary, simply using eleven points every time to make a prediction did not always ensure that both the most recent maximum and minimum (an approximate period) would be included in those eleven points. Furthermore, in some cases eleven points seemed to be too many, potentially including three of the most recent extrema, which also resulted in a bad prediction. So, to ensure that only the most recent local maximum and the most recent local minimum were used when finding the fit, logic was added to identify the two most recent extrema. The program then counted the number of predictor points that should be used to ensure that both extrema were included in the predictor points when calculating the fit. See figure 3 where 8 predictor points are used to calculate fit. Depending on the input year, more or fewer predictor points needed to be used.

Additionally, since the method of finding the coefficients assumed that the value of the coefficient was converging to a single value, it was noted that the algorithm might not work well for a certain input year if one or more of the coefficients were not converging to a single value fast enough, or at all. Thus a hard iteration limit was introduced, such that if after iterating many times the difference between subsequently calculated coefficients was not decreasing, the iterating process would stop at a fixed number of 25 iterations and issue a warning message to the user. Note that in some cases this could lead to a less accurate fit but would force the program to always produce a result in a reasonable amount of time.

Testing in MCNP

Once the algorithm was complete it was implemented into MCNP 6.1.2 and more testing was performed. The code was run with and without the solar modulation modification to ensure changes appeared as expected

First, the value of the solar modulation parameter, φ, was examined to see how much better MCNP, paired with the new solar modulation data, was able to predict φ than the version which had old solar modulation data implemented. To do this, MCNP was run for three cases, all with the input date January 1, 2014. First, with all of the new data in place (new version of the code), so the value for φ was simply the last of the new measured data points (see figure 1). Then, the previous version of the code was used, which utilized the old data and algorithms to predict the solar modulation for 2014 based on data from 2005 and earlier. In the final case, the new version of the code was run again, but this time measured data from 2014 was removed forcing the code to predict the value for φ in 2014 using data from 2013 and earlier. Similar runs were performed for the same date but at different latitudes. Results of the comparison of the values for the solar modulation parameter that were found are discussed in the results sections. Next, tests cases were developed in MCNP to compare the results obtained from the new version of the code to measured data. Input decks were created to simulate conditions under which experimental data was taken. Figure 4 compares results for a neutron flux measurement taken on the NASA ER-2 aircraft during a flight at latitude 18.5°N, longitude 127.2°W and at an altitude of 20.3 km [7].

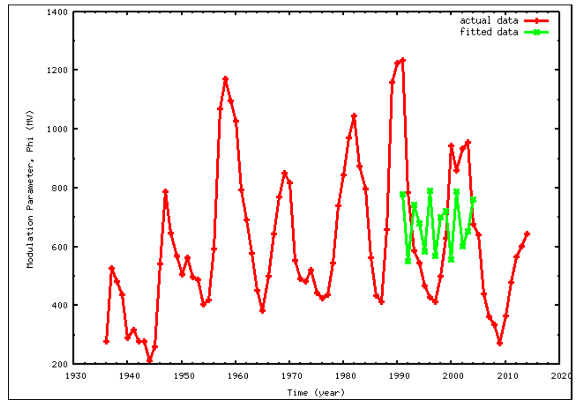

Fig. 2. Fit for years 2001-2004 using previous 11 points. The 11 predictor points and 4 predicted points are plotted in green.

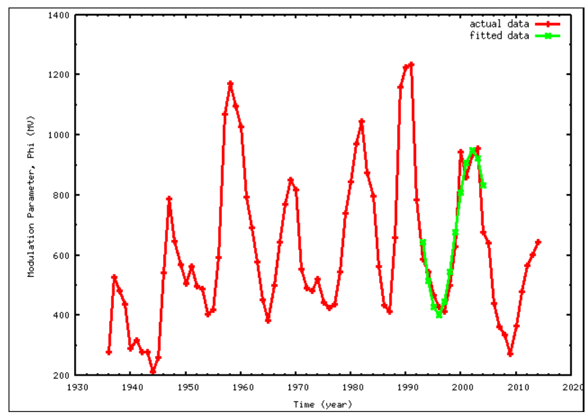

Fig. 3. Fit for years 2001-2004 using the number of points determined by a program that includes only the two most recent extrema. The 8 predictor points and 4 predicted points are plotted in green. The number of points will vary with input year.

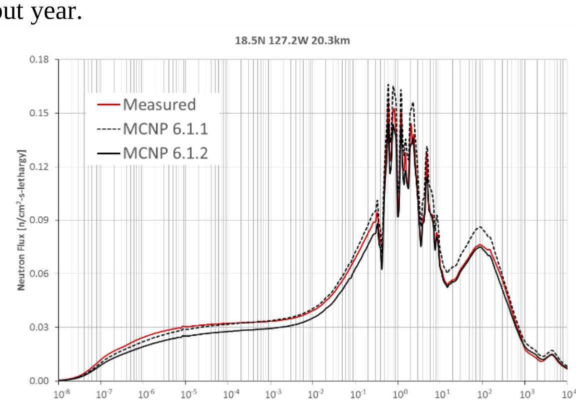

Fig. 4. Example of a comparison of the new code and old versions of the code to NASA ER-2 airplane data measured in the U.S.

RESULTS

Before discussing results, it is important to keep in mind that the sun's cycles are not exactly sinusoidal and thus the aim to predict the modulation using a sinusoidal fit will always have shortcomings. One should certainly not expect to accurately predict what the solar modulation will be a decade in the future using this method. According to the tests performed, however, after making a fit, one could expect an average difference from the actual modulation of around 8% for the first year in the future, a fairly good prediction. For the second, third, and fourth years in the future, however, one would expect an average difference of approximately 16%, 23%, and 29%, respectively. As is made evident by these values, the further in the future you try to predict, the worse the fit becomes (see figure 5). These overall percent differences were found by using the method described earlier for each of the years between 1999 and 2008 (inclusive) and taking an average for each year step into the future.

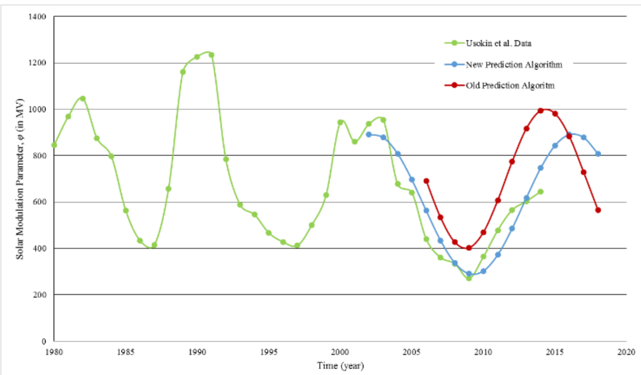

Fig. 5. Example of how well the new code predicts the solar modulation parameter, compared to what a prediction by the old code would look like for year 2018.

The relative difference between the updated measured value and the new predicted value for the modulation parameter at the latitude chosen for comparison is somewhat large (26%), but it is still an improvement from the previous predicted value, which had a relative difference of 54% from the measured value. Furthermore, when considering the relative difference that is subsequently imposed on the neutron flux, it is seen that the previous prediction algorithm under predicts by about 13%, while the new prediction algorithm over predicts by roughly 8% (see figure 5).

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ENDNOTES

[a] This part of the program takes in not only the year of the date, but also the month and day. It uses the month and day to convert the year to a fractional year so that the interpolated value will be more accurate.

[b] Since data from 1936 to 2014 has been recorded, the time index, t, sets the year 1936 as index 1 and the year 2014 as index 79.

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