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Optimization of neutron monitor data correction algorithms

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ABSTRACT

Nowadays, several neutron monitor stations worldwide, broadcast their cosmic ray data in real time, in order for the scientific community to be able to use these measurements immediately. In parallel, the development of the Neutron Monitor Database (NMDB; http://www.nmdb.eu) which collects all the high resolution real time measurements, allows the implementation of various applications and services by using these data instantly. Therefore, it is obvious that the need for high quality real time data is imperative. The quality of the data is handled by different correction algorithms that filter the real time measurements for undesired instrumental variations. In this work, an optimization of the Median Editor that is currently mainly applied to the neutron monitor data and the recently proposed ANN algorithm based on neural networks is presented. This optimization leads to the implementation of the Median Editor Plus and the ANN Plus algorithms. A direct comparison of these algorithms with the newly appeared Edge Editor is performed and the results are presented.

1. Introduction

The neutron monitors are the ground based detectors that measure the secondary cosmic ray flux [19]. The first neutron monitor stations have been in operation for more than 60 years, while new stations are still being established. The measurements of the neutron monitors are of great importance for the scientific community and play a key role as a research tool in the field of space physics, solar–terrestrial relations, and space weather applications. For this reason, nowadays, a great number of neutron monitor stations broadcast the measured cosmic ray intensity in real time. Recently, a European project (http://www.nmdb.eu/) has developed a database to which the neutron monitor stations may send their one minute resolution data. This database also contains the data archives of the neutron monitor stations. The final aim is the gathering of all the neutron monitor measurements in real time, if it is technically possible, and in a common format, in order for them to be instantly used from the scientific community.

The fact that the neutron monitor stations are spread worldwide, in locations with different rigidities and that their measurements may be available in real time, gives the opportunity for widespread usage [20,11]. The measurements are used by web users, mostly scientists, by applications and by online services and for tasks such as the prediction of the space weather [8] or the Ground Level Enhancement (GLE) Alerts [21,10,5,18]. These kinds of uses, apart from the real time measurements, require data of good quality. In order to establish the data quality, a neutron monitor station should verify the validity of the measurements and apply the necessary corrections, in order to exclude the parameters that affect or distort the data. The challenging aspect of this task is that these corrections should be performed in real time, while the data are transferred from the neutron monitor registration system to the Neutron Monitor Database.

Referring to the neutron monitor data, the meteorological and physical parameters, such as the atmospheric pressure, the snow that may cover the station and the very low temperatures, have a great effect on the measurements. These effects should be excluded from the measurements, since they cause changes that are not related to the variation of the cosmic rays. The correction of the data for the pressure is a straightforward procedure that requires only an accurate calculation of the barometric coefficient [13]. Moreover, the correction for the snow effect or for the very low temperatures that are met at some stations is performed by using specific models. However, apart from these effects, the measurements of the neutron monitors are in some cases distorted by unpredictable instrument variations. These variations are related to sporadic problems of the electronics and can be categorized in abrupt spikes, slow drifts and abrupt changes of the mean counting rate with or without recovery [1,3,6]. The correction of these variations is not a straightforward procedure. The reason for this is that by principal, the measurements of a neutron monitor have statistical variations and a distinction between them and the instrument variations is not always obvious. The task for the correction of the instrument variations

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is handled by correction algorithms that filter the data in real time, while they are transferred to the Neutron Monitor Database.

In order for a filtering algorithm to be effective, it should have three characteristics. It should be fast, so that it can be applied in real time, it should filter effectively all the instrument variations and finally it should leave the rest of the data unaffected. A filtering algorithm takes advantage of the fact that a neutron monitor consists of a number of identical channels [2]. Using this fact, the detection of an instrument variation on a channel can be performed by comparing its measurement with the measurements of the other channels. Based on this principle, a number of filtering algorithms have been implemented in the past. The most known algorithm, used currently by many neutron monitor stations such as the Athens station [9], is the Median Editor [1,3,6,22]. The Median Editor is a very fast algorithm, which filters all the instrument variations and has shown a very stable behavior. However, it has the disadvantage of distorting noticeably the data, even in the cases where no instrument variations are observed, as it is shown in Fig. 1. In order to overcome this issue, the Median Editor Plus concept has been introduced, according to which, the algorithm is applied only to the cases where an instrument variation is detected [22]. Another filtering algorithm that has recently been presented is the ANN algorithm, which makes use of an artificial neural network [14]. The ANN algorithm has shown a better behavior compared to the Median Editor, however the distortion of the non-erroneous data is still present. Finally, the Edge editor is another filtering algorithm that has recently been presented as well [12]. This algorithm hosts the Median Editor Plus concept and uses a validation criterion in order to distinguish the erroneous channels and apply corrections only to them. The Edge editor has shown a great behavior since the distortion of the non-erroneous data is almost unnoticeable. However, a direct comparison with the Median Editor and the ANN algorithm cannot be performed, since the latter does not use a validation criterion and is applied to all the measurements.

In this work, an optimization of the Median Editor and the ANN algorithm is performed. This optimization refers to the combination of the Edge editor's validation criterion with these algorithms in order to implement the "plus" version of the algorithms. Then, a direct comparison among the Edge editor, the Median Editor Plus and the ANN Plus algorithm is performed using the Athens neutron monitor data [9]. The comparison framework and the results are presented in the last sections of the manuscript.

2. Validation criterion of measurements

Referring to the characteristics that a real time filtering algorithm should have, the practice has shown that it is rather simple to implement an algorithm that is fast and that filters effectively all the instrument variations. The challenging point is to combine these characteristics with a behavior that does not

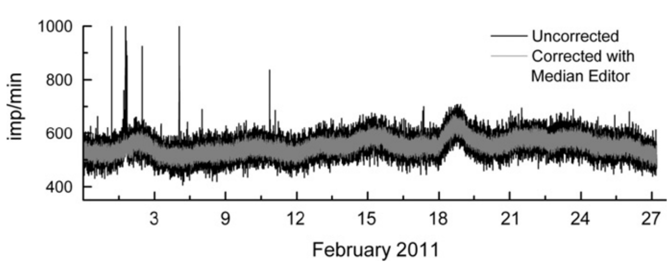

Fig. 1. Uncorrected (black line) and corrected with the Median Editor (gray line) data of the Athens NM's channel 6 for February 2011. The narrower variation of the corrected data implies a distortion of the original data.

affect the non-erroneous measurements. By principle, this is almost impossible since the processing of the measurements by an algorithm will cause little or great changes on them. The only way to protect the non-erroneous measurements from such effects is by not applying the algorithm on them. This issue leads to the conclusion that an optimized filtering algorithm should act in two steps, firstly towards the determination of the erroneous channels and secondly towards the application of a correction procedure only on them.

The separation of the erroneous and the non-erroneous channels in the real time procedure is performed by using validation criteria. This kind of criteria can be constructed by performing a thorough data analysis on the past neutron monitor data that aims to the definition of the non-erroneous measurements pattern. Having defined this pattern, the real time measurements that follow it are considered as non-erroneous, while the ones that deviate from it are considered as erroneous. The pattern refers to the calculation of the physical statistical variations that each channel of the neutron monitor presents [7,15,12]. In this work, the Edge Editor's validation criterion is used for the determination of the erroneous measurements. The validation criterion of the Edge Editor [12], for the case of a neutron monitor with six channels as the Athens NM, is presented in Fig. 2. The validation criterion is separated into an offline analysis in order to calculate the necessary parameters and into an online application on the real time measurements.

Referring to the offline analysis, it is well known that each channel of the neutron monitor may measure a slightly different counting rate compared to the others, due to normalization factors. These factors correspond to the position and the characteristics of each tube (e.g. BF_3 density) and to the electronic modules. In order to perform an accurate analysis, it is required to normalize the measurements to the level of a selected reference channel 'j'. The reference channel can be any channel of the neutron monitor, independent of whether it is a channel that presents many or few instrument variations. The only use of the reference channel is the transformation of each channel's measurement into a common level by excluding the possible normalization factors. Therefore, the first step is the calculation of the normalization factors $R_{i,j}=(N_i/N_j)$ which refer to the ratio of the channels counting rates over the respective counting rate of the reference channel 'j', based on the historical data. The next step is the normalization of the historical data to the level that the reference channel 'j' measures by computing the variable $N_i^j=(N_i/R_{i,j})$. A statistical analysis is performed on the normalized measurements that results to the determination of the statistical variation σ_i^j for each channel. It has been shown in the past [12] that the statistical variations of the neutron monitor channels increase as the mean counting rate of the neutron monitor increases. In order to calculate the statistical variations σ_i^j, the mean counting rate of the neutron monitor (n_j) is calculated as the average of N_i^j for each minute. Then the N_i^j measurements are grouped by the n_j and the sigma of N_i^j is calculated in respect to n_j. Finally, a linear regression of σ^j with n_j gives the $\sigma_i^j=f(n_j)$ function. This procedure is performed for each channel. The offline analysis is taking place once and there is not any need for recalculation as long as the operational conditions of the neutron monitor are the same.

On the real time part, the measurements are normalized to the reference channel 'j' level and an estimation of the mean value is performed. On the contrary with the offline analysis, the estimation of the n_j cannot be done by simply averaging the normalized measurements, since one or more of them may contain an instrument variation. The weighted mean algorithm, that makes use of weight factors, is used for this task. Having estimated the n_j, the validation criterion calculates the estimated σ_i^j. Finally, a

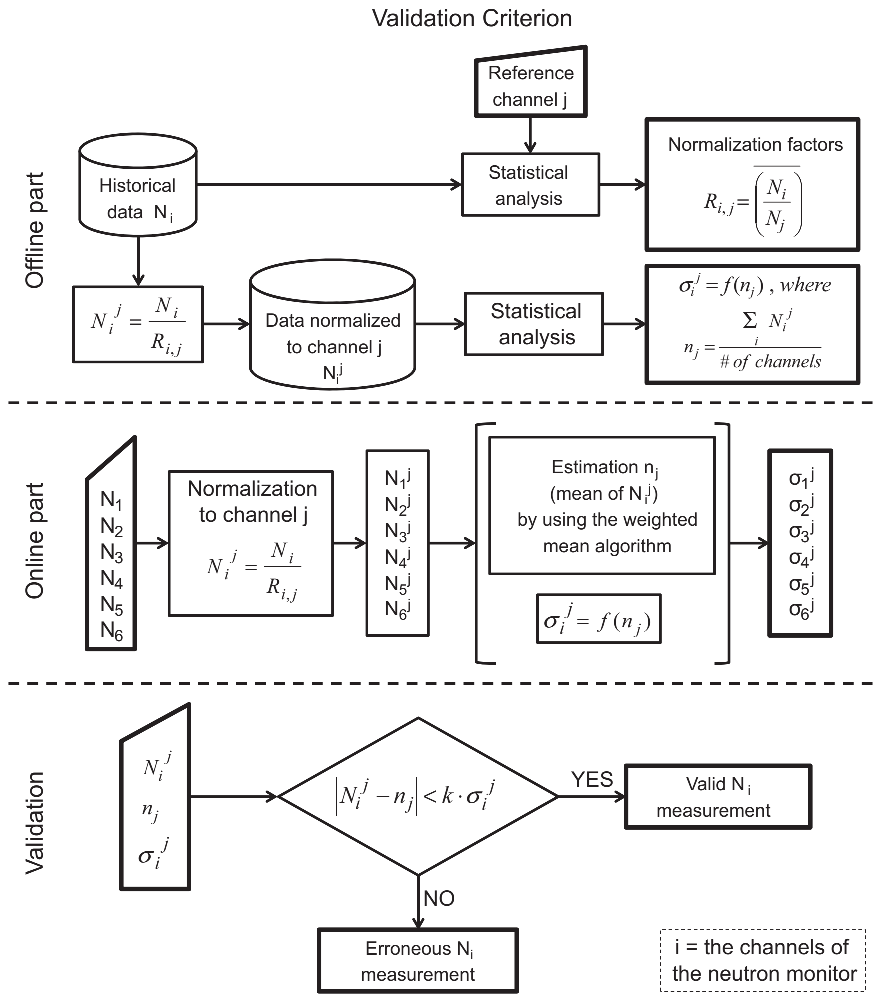

Fig. 2. Construction and application of the Edge Editor's validation criterion.

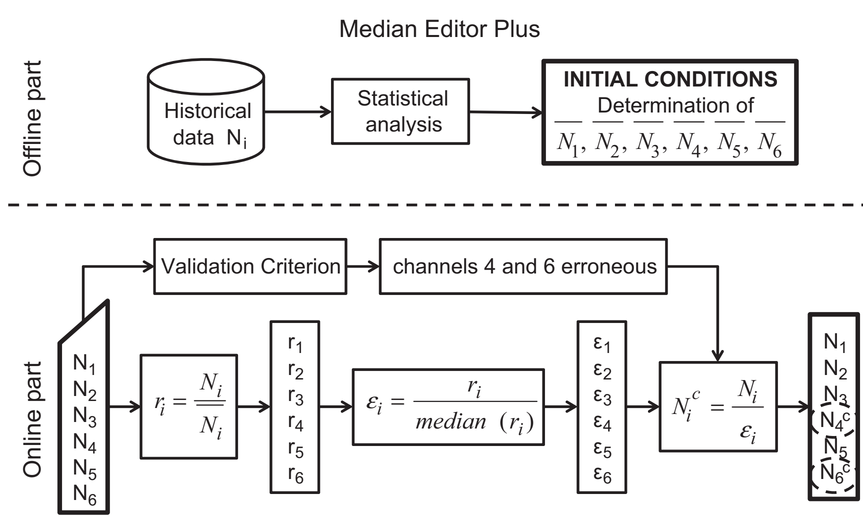

Fig. 3. Median Editor Plus algorithm for a neutron monitor with six channels and for the case that channels 4 and 6 are erroneous.

check is performed for each channel in order to determine if the normalized measurement N_i^j is in the $\pm k\sigma_i^j$ trust interval or not. If the measurement is within the trust interval the measurement is marked as valid, otherwise it is marked as erroneous.

The application of the validation criterion does not guarantee that the filtering algorithm will not affect non-erroneous measurements. The reason is that there is not a definite margin between the physical statistical variations and the undesired instrument variations [4,16,17]. Referring to the $\pm k\sigma$ trust interval used by the validation criterion, in the case $k=3$ is chosen, then the 99.7% of the measurements are expected to be inside the interval. Therefore, there is a 0.3% probability to mark as erroneous a measurement that is a normal statistical variation. Actually, the probability of marking a correct measurement as an undesired variation is a little greater, since the center n_j of the trust interval is also statistically estimated. A way to increase the insurance that the non-erroneous measurements will remain unaffected is to use a wider trust interval by selecting $k=4$. In that case, more than 99.9% of the non-erroneous measurements are expected to be in the trust interval. However, the tradeoff is an increase of the probability of losing the instrument variations.

The optimal selection for the trust interval depends on the station. In the zone between the 3σ and the 4σ there is a probability of about 0.2% for a correct measurement to appear. For stations or for specific channels with stable electronics for which the instrument variations are rare, the use of a 4σ trust interval is the optimal choice. However, for stations or for channels where the instrument variations are often, it is optimal to use a narrower trust interval since in the zone from 3σ to 4σ is more probable to observe an instrument variation than a statistical variation.

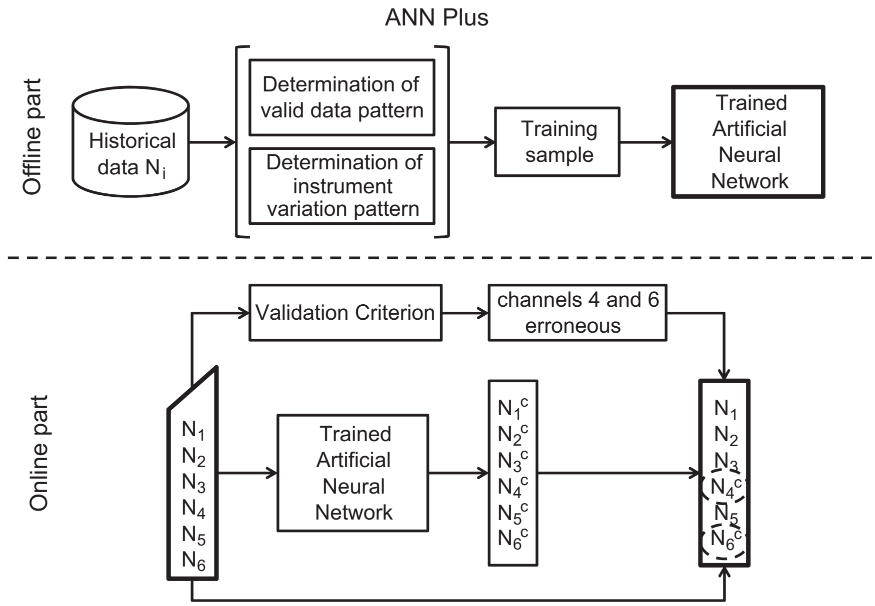

Fig. 4. ANN Plus algorithm for a neutron monitor with six channels and for the case that channels 4 and 6 are erroneous.

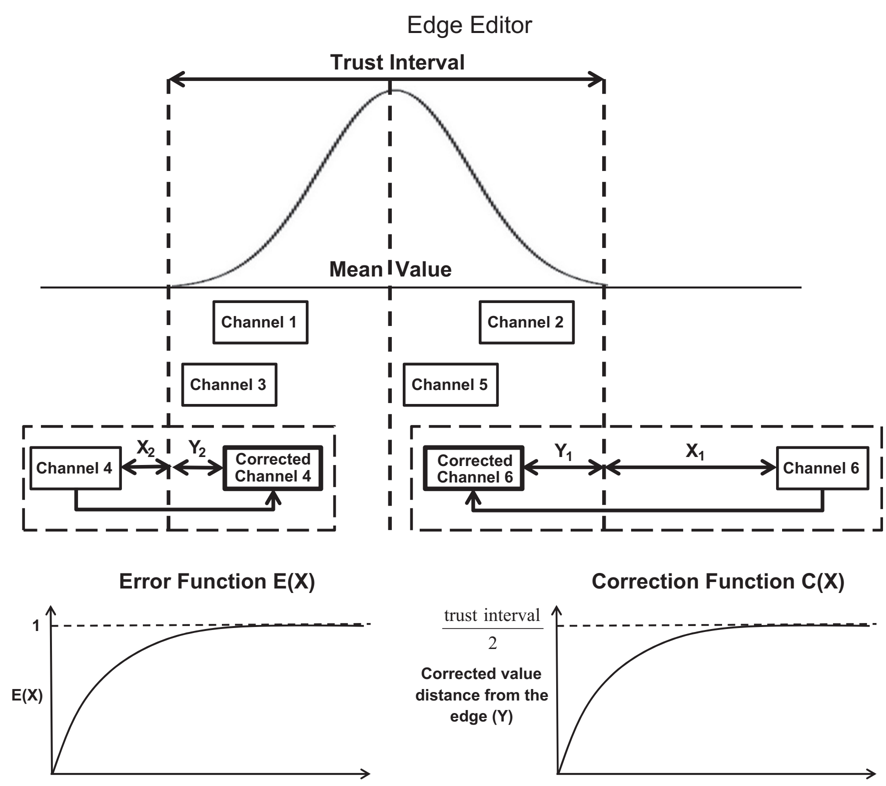

Fig. 5. (Upper) Edge Editor algorithm for a neutron monitor with six channels and for the case that channels 4 and 6 are erroneous and (bottom) shape of the Error and Correction Functions. The distance of the erroneous measurements from the trust interval edge is noted as X, while the respective distance of the corrected value is noted as Y.

3. Median Editor Plus, ANN Plus and Edge Editor correction method

In order to implement the Median Editor Plus and the ANN Plus algorithms, the validation criterion of the Edge Editor is used for the determination of the channels for which a correction should be applied. Afterwards, for the erroneous channels, the ordinary procedure of the Median Editor and the ANN algorithm is used. Each algorithm uses a completely different approach of the correction procedure. The common points are that the correction is performed by comparing the counting rate of the channels and that each algorithm makes use of initial conditions that are defined by the analysis of the historical data. As it was described in the previous paragraph, the comparison of the channels counting rates cannot be performed directly due to normalization reasons. In order to make a comparison among the channels, a new variable, for which the normalization factor of each channel has been taken into account, should be defined and compared.

The procedure of the Median Editor is shown in Fig. 3 [22]. The initial conditions of this algorithm are the mean values of the channels counting rates $\overline{N_i}$. These mean values are calculated for a long period of time by using the valid historical data of the neutron monitor. On the real time part of the algorithm, the ratios $r_i = (N_i/\overline{N_i})$ are calculated. The ratios are the variables where the normalization factor of each channel is excluded since they represent the percentage change of the counting rate. Therefore, a direct comparison among the ratios is possible. The algorithm then, makes use of the median value of the ratios, which is called theta, and calculates the efficiency of each channel through the expression $\varepsilon_i = (r_i/theta)$. Finally, the corrected counting rate of the channels is generated by using the $N_i^c = (N_i/\varepsilon_i)$.

The ANN algorithm uses a completely different approach [14]. The statistical parameters of the past measurements are used for the generation of the training sample and the ANN algorithm is the product of an Artificial Neural Network that has been trained with this sample. Therefore, any initial conditions and normalization factors are stored in the weights of the Artificial Neural Network's synapses. The ANN Plus algorithm is shown in Fig. 4. According to this, the set of the uncorrected measurements is being input to the Neural Network and the set of the corrected measurements is being received. At the same time, the validation criterion is applied. For the erroneous channels the respective corrected value is used, while for the valid channels the initial measurement is considered.

Finally, the Edge Editor operations are shown in Fig. 5 [12]. Contrary to the other algorithms, the Edge Editor's correction

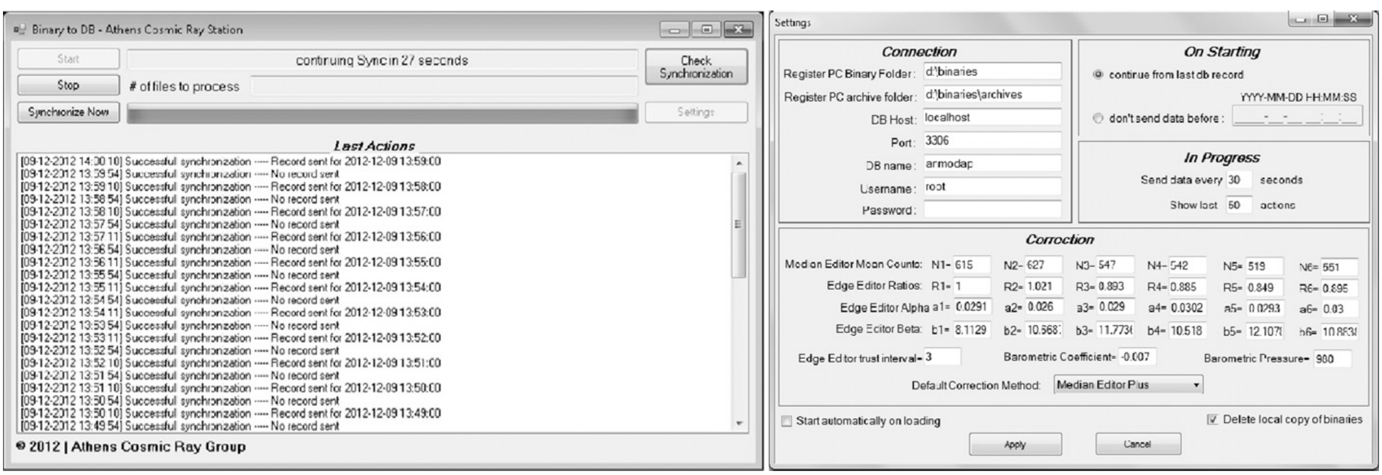

Fig. 6. Application for the real time correction of the data (left screenshot) and the settings form (right screenshot).

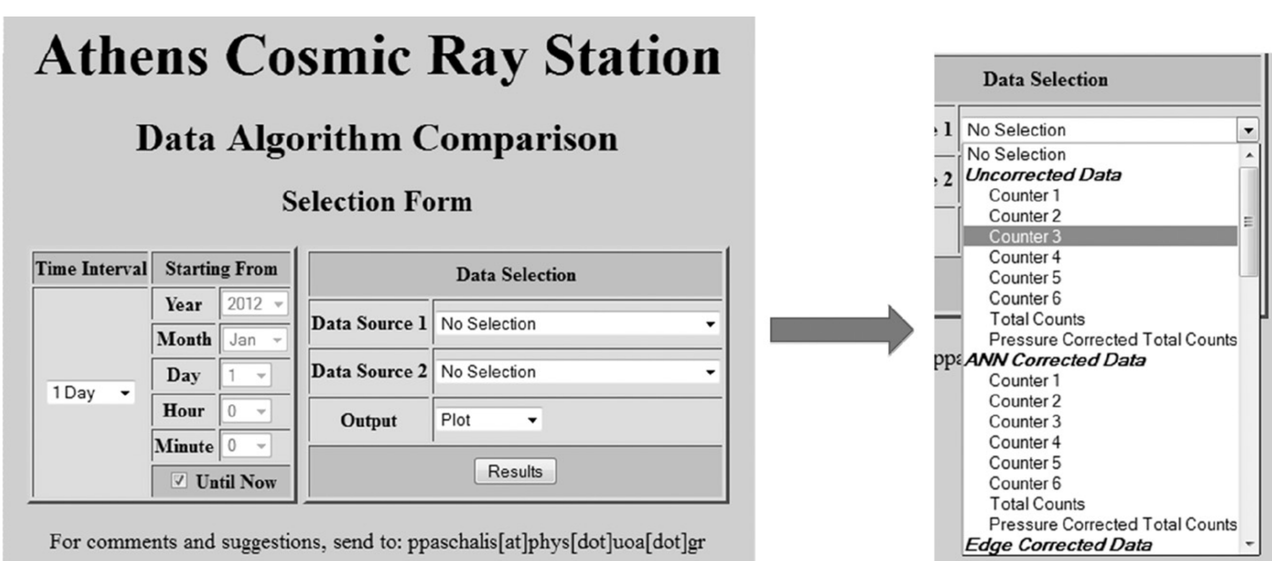

Fig. 7. Web interface for algorithms comparison.

procedure is being bind with the validation criterion. The algorithm does not only use the validation criterion for the determination of the erroneous channels but it also uses the edges of the trust interval for the correction procedure. According to this procedure, an error function $E(x)$ is used, in order to determine how "wrong" is a measurement that is outside the trust interval. For measurements that are near the edges of the trust interval the error function tends to zero. For the measurements that are too far from the edges, the error function tends to 1. Finally, a correction is performed according to a correction function $C(x)$. For the channels that the erroneous value is near the edges, the corrected values are positioned also near the edges but inside the trust interval. For the channels that the erroneous measurements are far from the edges, the corrected values are positioned near the center of the trust interval. The logic behind this procedure is the following. By using a trust interval, the determination of the erroneous channels is performed with a specific confidence (e.g. 99.7% for a 3σ rule or 99.9% for a 4σ rule). The measurements that are near the edge of the trust interval are more possible to be a physical statistical variation; therefore the corrected value should not be changed a lot. On the other hand, the measurements that are far from it should be considered as instrument variations and should actually be rejected.

4. Algorithms comparison framework

In order to compare the described algorithms, a.NET application that reads the data generated from the neutron monitor registration system, applies the corrections according to all the algorithms and stores the data in a mySQL database, was implemented. The database contains separate tables for the uncorrected data and for the data corrected with the Median Editor, the Median Editor Plus, the ANN, the ANN plus and the Edge Editor. Apart from the corrected data, in each table the application stores the variables related with the operation of the algorithms which is the efficiency in the case of the Median Editor and the error index in the case of the Edge Editor. The application provides a settings form where the necessary parameters for the Median Editor and the Edge Editor are set.

The data stored in the database can be retrieved by a web interface that provides graphical or text output. With this interface, the user can easily compare channel by channel, for a defined period of time and check the performance of each algorithm for many cases through the years, in order to decide if there would be any improvement by changing the parameters of the algorithms. The interface allows simple access to the tables of the database.

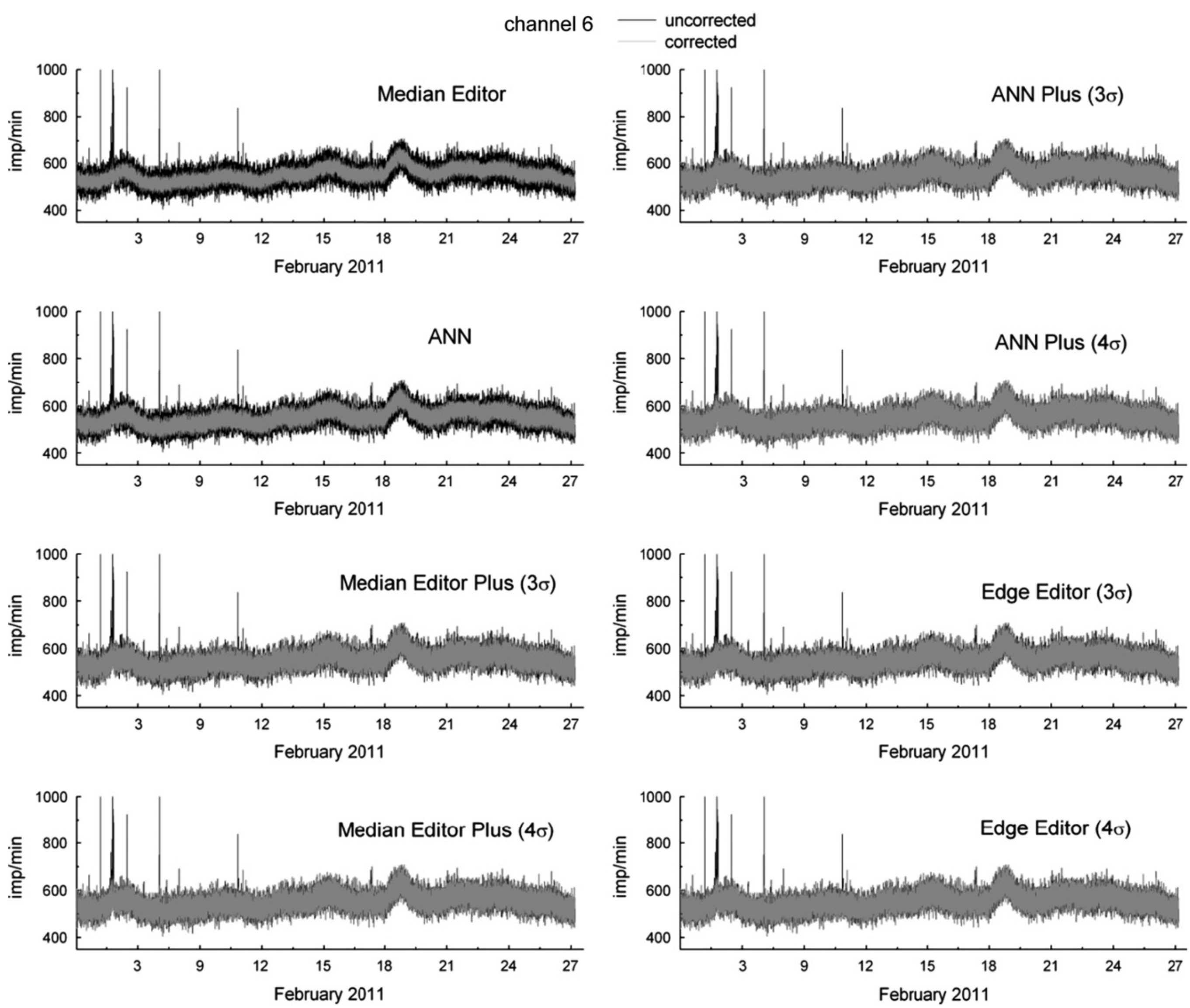

Fig. 8. Uncorrected and corrected data of channel 6 for February 2011.

For retrieving the data in more complicated form, as in the case of the diagrams presented in this work, the user should send specific queries to the database. A screenshot of the application is shown in Fig. 6, while the interface is shown in Fig. 7.

5. Results

In order to compare the algorithms, the raw data from January 2007 to March 2012 were used. Two runs of the application were performed, the first time a 3σ trust interval was selected while during the second run the trust interval was 4σ. Each run consumed about 260 min for reading, correcting by using all the algorithms and storing in the database, about 2,750,000 records. This means, that the correction of 1 record with all the algorithms requires less than 5.7 ms of computational time in average.

The uncorrected and the corrected, by using all the described algorithms, data of channel 6 for February 2011, are shown in Fig. 8. It is obvious that all the algorithms filter the undesired spikes effectively. Moreover, as it has already been mentioned, the simple Median Editor affects the non-erroneous measurements significantly. The simple ANN algorithm presents an improved behavior, as far as this fact is concerned, but the effect of the non-erroneous measurements is still noticeable. The behaviors of the Median Editor Plus, the ANN plus and the Edge Editor seem very similar to each other. Actually, it is impossible to visually find any difference since the validation criterion is common and the correction of the measurements is performed only to some of the data. It is also verified, that when using a 4σ trust interval more spikes remain unfiltered.

The satisfactory results by all the algorithms and the identical visual results, lead to the necessity of a more thorough analysis, in order to examine the possible differences. Since the instrument variations are effectively filtered by all the algorithms, the aim is to find which algorithm distorts less than the non-erroneous data. As a measure of how different the corrected data are from the initial measurements, the correlation coefficient of these datasets is used. The desired behavior is to have a correlation coefficient near 1, when comparing the datasets in cases where no instrument variations exist. The correlation coefficient for the monthly measurements of channel 3, when using a 3σ and a 4σ trust interval, are shown in Fig. 9. In these plots, the very low values of the correlation coefficient correspond to the months when instrument variations exist, therefore the corrected data show differences compared to the uncorrected ones. This is a desired effect and these low values are not to be used in the comparison of the algorithms. By taking into account the rest of the values, that fluctuate near 1 and correspond to the months for which no instrument variations are present, it is proven numerically that the Median Editor distorts the non-erroneous data more than the ANN. The Median Editor Plus shows an improved behavior, however the ANN Plus and the Edge Editor show the best performance. The behavior of these algorithms is almost identical and their lines are indistinguishable when using a great scale in the correlation coefficient axis. In order to better compare them, the diagrams are presented in a low scale containing the correlation coefficient of two algorithms. It is noticed that the Edge Editor presents a slightly better performance. The same conclusions are reached, regardless of whether using a 3σ or a 4σ trust interval.

A final test of the algorithms' performance is the checking of the algebraic difference (corrected – uncorrected) of the measurements. The algebraic differences of the channel 4 in an histogram form are shown in Fig. 10. In the case of the Median Editor the differences fluctuate around zero. Similar behavior appears for the ANN but the histogram is narrower which means that the corrected values are closer to the initial ones. A completely different behavior is met when testing the rest of the algorithms. In their histograms there is an extremely high peak at the zero value which corresponds to the cases

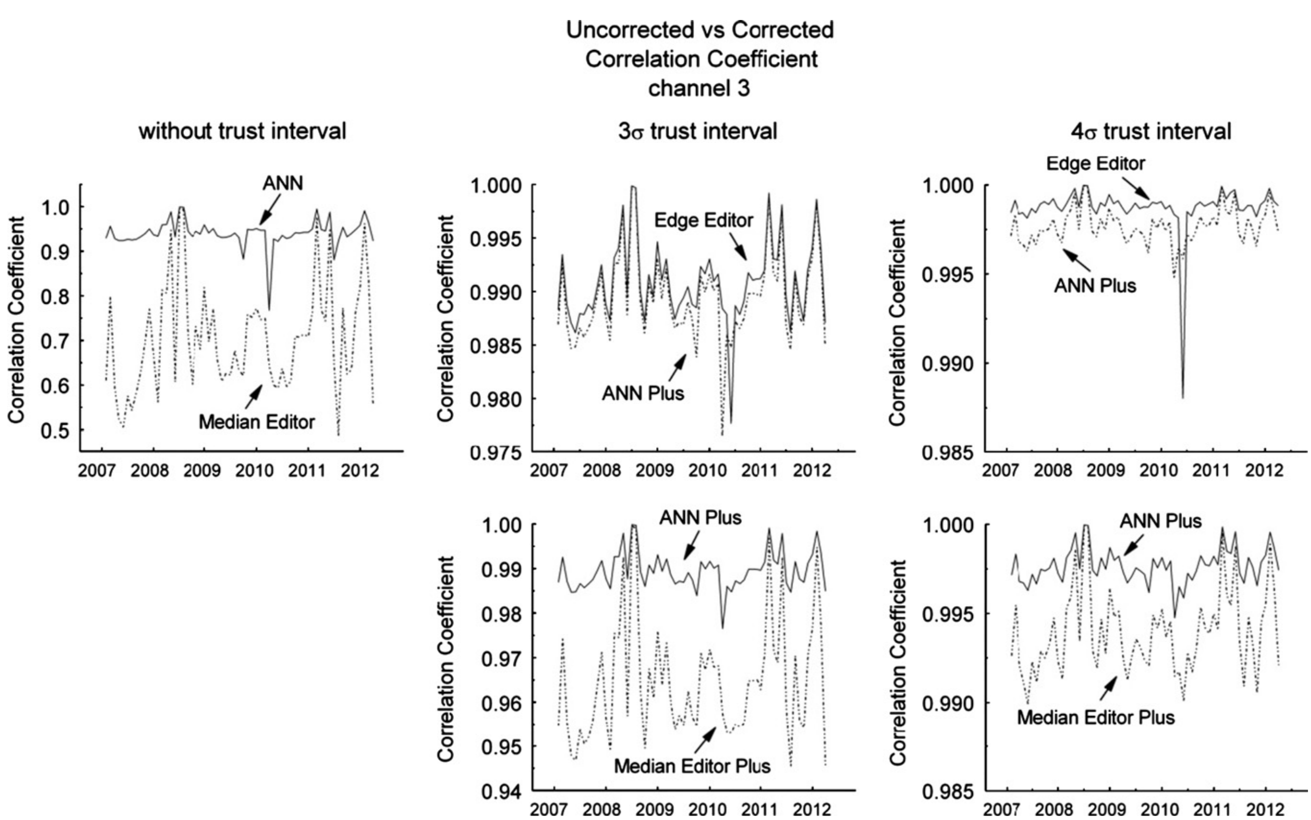

Fig. 9. Correlation coefficient of the monthly uncorrected vs the monthly corrected datasets of channel 3, from January 2007 to March 2012.

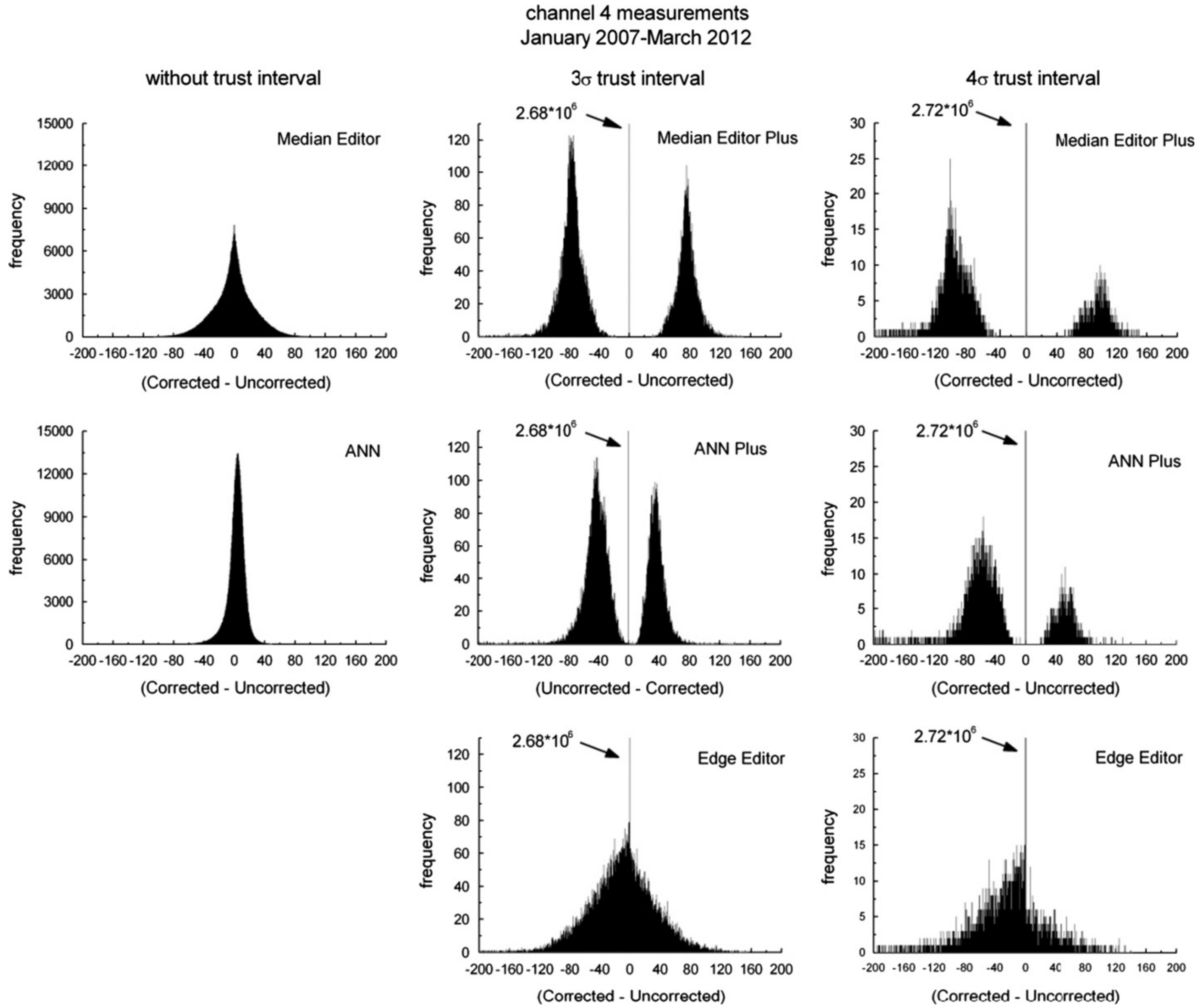

Fig. 10. Histogram of the algebraic difference (corrected – uncorrected data) of channel 4, from January 2007 to March 2012. The counting rate of the channel is measured in impulses/minute.

where the measurements are within the trust interval and therefore the corrected values are equal to the uncorrected ones. Apart from this, there are two stacks of measurements, located on each side of the center that correspond to the measurements that violate the validation criterion. These two stacks are located at almost the same distance from the center and have a noticeable difference in shape. This happens because the instrument variations are more probable to cause an increase of the counting rate, therefore the corrected – uncorrected value is more probable to be a negative number. Comparing the histograms of the Median Editor Plus, the ANN plus and the Edge Editor, it is concluded, that the corrected values when using the Median Editor are farther from the center (the initial uncorrected values), than the corrected values when using the ANN Plus algorithm. In the case of the Edge Editor, the two stacks of measurements are so near to each other that they form one single stack. The same conclusions come out regardless of whether a 3σ or a 4σ trust interval is used. The only difference when using a 4σ trust interval is that the peak on the zero value is higher, as expected, since less corrections are performed. The histogram stacks are at the same position but have a lower height. Finally, in Fig. 11 the same histograms are provided but for the total counting rate of the neutron monitor. While the counting rate of the channels is measured in impulses per minute, the total counting rate of the neutron monitor is expressed in impulses per second, since this is the unit that is used for the data that are sent to the NMDB from the neutron monitor stations. The conclusions are the same as the ones of Fig. 10.

As it has been mentioned in the previous description, the correction algorithms use initial conditions statistically calculated from the past neutron monitor data. An accurate determination of these conditions is obviously necessary; however an error in the determination may occur. A last check for the algorithms was the testing of the error tolerance. A 10% increase in the initial condition related with counter 3 ($\overline{N_3}$ and $R_{3,1}$) was induced for the Median Editor Plus and the Edge Editor in order to check the change of their performance. The effect of the correlation coefficient for the case of channel 3 in August 2011 is shown in Table 1. When using a 3σ trust interval, the change of the correlation coefficient is great for the Median Editor Plus while the Edge Editor is affected less. The same behavior is noticed when using a 4σ trust interval, which means that the Edge Editor presents a greater error tolerance on the estimation of the initial conditions. The results are representative for all channels.

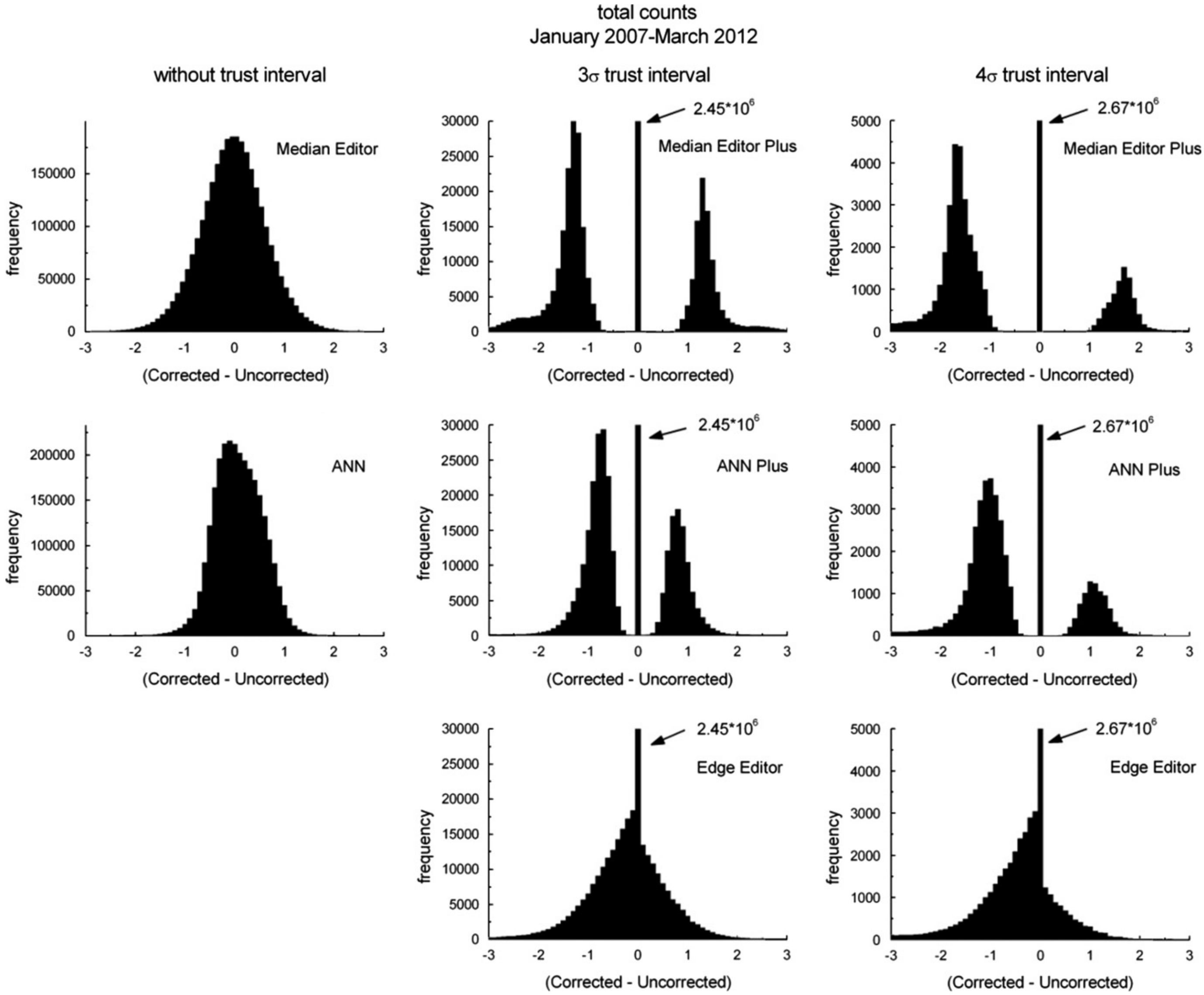

Fig. 11. Histogram of the algebraic difference (corrected – uncorrected data) of the total neutron monitor counting rate, from January 2007 to March 2012. The total counting rate of the neutron monitor is measured in impulses/second.

Table 1
Correlation coefficient of the uncorrected vs the corrected measurements of channel 3 for August 2011, when inducing a 10% increase in the initial condition ($\overline{N_3}$ for the Median Editor Plus and $R_{3,1}$ for the Edge Editor). The results are representative for all channels.

	Correct initial condition for channel 3		10% error in the initial condition for channel 3	
	3σ trust interval	4σ trust interval	3σ trust interval	4σ trust interval
Median Editor Plus	0.9455	0.9909	0.3864	0.7961
Edge Editor	0.9862	0.9986	0.7590	0.9600

6. Conclusion

In this work an optimization and comparison of the existing algorithms for the real time filtering of the neutron monitor data has been presented. From the analysis above it is concluded, that the Median Editor algorithm used at this moment by many stations has the disadvantage of distorting noticeably the data even in the cases where no instrument variations are observed. On the other hand, the optimized correction algorithms, such as the Median Editor Plus, the ANN Plus and the newly presented Edge Editor seem to overcome this issue. Moreover, the ANN Plus and the Edge Editor have a noticeably better performance compared to the Median Editor Plus. A more thorough analysis shows that the Edge Editor presents a slightly better behavior compared to the ANN Plus. The ANN Plus has also the disadvantage, that if the initial parameters of the algorithm should be changed, a new training of the network is necessary, while the Edge Editor is much more flexible. Also taking into account the great error tolerance on the initial conditions that the Edge Editor presents, it is concluded that it is the appropriate algorithm for the real time correction of the measurements.

Cosmic ray applications, such as space weather warnings (geomagnetic storms, solar energetic particle events) need access to the neutron monitor measurements in real time and with high time resolution. Reliable forecasts of geomagnetic storms are important in many technical areas (radio communication, electric power lines, etc.). Confident alert prediction of solar energetic particle events is highly important for manned space missions and for airline crew and passengers. We believe that this study unifies the cosmic ray community of the European neutron monitor network (http://www.nmdb.eu) in a coordinated effort to advance the quality of the real time measurements, so they can be efficiently used in Space Weather applications.

Acknowledgments

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