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Online application for the barometric coefficient calculation of the NMDB stations

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HIGHLIGHTS

- The main correction of the primary cosmic ray data is the pressure one due to the barometric effect.
- An online tool that calculates the barometric coefficient for the neutron monitors is described.
- This tool uses the High resolution real-time Neutron Monitor database-NMDB.
- Each station can check if the barometric coefficient used for the data processing is correct.
- The use of a reference station leads to satisfactory results even in the active cosmic ray periods.

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ABSTRACT

The primary processing of the neutron monitor data includes all the necessary actions and procedures that each cosmic ray station follows in order to provide the worldwide neutron monitor network with good quality data. One of the main corrections of the primary data is the pressure correction due to the barometric effect. The barometric effect induces variations to the measured data of the neutron monitors which are related to the variations of the local atmospheric pressure of the stations. This correction requires the definition of the barometric coefficient which is calculated experimentally. The accurate calculation of the coefficient is a prerequisite for the quality of the data. This paper presents the implementation of an online tool which calculates the barometric coefficient of a cosmic ray station, by taking advantage of the fact that most stations publish their data on the Neutron Monitor Data Base.

1. Introduction

Neutron monitors are ground based detectors used to measure cosmic rays that reach the Earth's surface. The cosmic rays consist of the galactic part referring to particles which originate from stellar sources and have been accelerated to extremely high energies. The galactic cosmic rays reach the Earth as highly isotropic flux. However, the solar activity via the solar wind affects the terrestrial magnetic field and modulates the galactic cosmic rays. Moreover, during periods of high solar activity, solar cosmic rays which consist of high energetic solar particles reach the Earth. When the cosmic rays enter the terrestrial atmosphere, they interact with nuclei of atmospheric gasses and produce showers of particles.

The neutron monitors that consist of a number of identical proportional counters, measure the variations of the cosmic ray intensity with time by measuring the neutrons produced by the interaction of the cosmic rays with the atmosphere. The worldwide network of neutron monitors measures the cosmic ray intensity in many locations on Earth, which allows the scientific community to gather important information about the solar activity. During the last years, most of the neutron monitor stations have begun to send their measurements to the global High Resolution Neutron Monitor database in real time, which makes the observation of the cosmic ray variations easier (http://www.nmdb.eu/).

In order for the neutron monitor measurements to be reliable and useful, they must go through procedures that insure their quality. The primary processing of the data includes all the necessary procedures that are used for the quality control of the neutron monitors data. The first control that is applied relates to the filtering of the possible instrument variations that may occur during the operation of the neutron monitors. These detectors include a number of electronic modules that are necessary for the data acquisition such as the power supplies, the pre-amplifiers and amplifiers modules, the ADCs and the discriminating modules. The problematic behavior that some of these modules may show, distorts the quality of the data. Algorithms such as Median Editor, Median Editor plus and Super Editor are responsible for the correction of them when the instrument variations occur by using the efficiency of the neutron monitor counters (Yanke et al., 2011).

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Another parameter that affects the measurements of the neutron monitors is the local atmospheric pressure of the station due to the barometric effect. The barometric effect reflects the change of the atmospheric thickness above the NM location and thus the flux of the secondary cosmic rays at the Earth. Therefore, it induces an important variation to the counting rate of a cosmic ray detector which is not related to the real variations of the cosmic ray intensity. For this reason, the correction of the counting rate, regarding the barometric pressure, is a main task for the primary data processing. More specifically, the measured data should be transformed to a common pressure in order for the time series of the measurements to only reflect the variations of the cosmic ray intensity.

The correction of the primary data for pressure has been studied both theoretically and experimentally in the past. This correction requires the use of the barometric coefficient, which is calculated by each station using the past measurements. In most cases, the study of the barometric effect is performed in a quiet cosmic rays period when the variations of the neutron monitor measurements are related mainly to the variations of the atmospheric pressure. However, since a quiet cosmic rays period is not always the case, another method may be used, which excludes the cosmic ray variations by using the measurements of a reference station.

The accurate calculation of the barometric coefficient is a prerequisite for the good quality of the neutron monitor data. In this work, an online tool for the calculation of the barometric coefficient of the various neutron monitor stations is presented. This tool takes advantage of the fact that most stations publish their measurements on the NMDB in real time and calculates the barometric coefficient either by using a reference station for the exclusion of the primary cosmic ray variations or by only using the main station measurements.

2. Barometric coefficient calculation

The affection of the atmospheric pressure to the measured cosmic ray intensity on the Earth's surface is a well known phenomenon (Carmichael et al., 1968; Dorman, 1972, 1974). In the case the cosmic ray incoming flux is constant, the measured intensity N depends only on the local atmospheric pressure and this dependence can be described via the expression:

$$dN = -\beta \cdot dP \tag{1}$$

where dN is the change of the measured intensity due to the dP change of the pressure and β is the barometric coefficient. By integrating this expression and supposing that for pressure P_o the measured intensity is N_o, the counting rate N of the detector when the atmospheric pressure is P, is:

$$N = N_o \cdot e^{-\beta \cdot (P - P_o)} \tag{2}$$

By applying the natural logarithm on both sides of the equation it becomes that:

$$\ln N - \ln N_0 = -\beta(P - P_0) \tag{3}$$

As it has already been mentioned, Eq. (3) is valid only when the incoming cosmic ray flux is stable, so any variation of the measured counting rate is related to the change of the pressure. In the case that there are variations in the cosmic ray flux, the measured intensity is:

$$N' = N \cdot (1 + v) \tag{4}$$

where N' is the measured intensity and the factor $(1 + v)$ contains the variations of the cosmic rays flux. By using Eq. (4), the Eqs. (2) and (3) become:

$$N' = N_o \cdot (1 + v) \cdot e^{-\beta \cdot (P - P_o)} \tag{5}$$

$$\ln N' - \ln N_0 - \ln(1 + v) = -\beta \cdot (P - P_0) \tag{6}$$

The variations v can be calculated by using the corrected for pressure data of a reference station (S) (Chiba, 1976). The station (S) should have similar rigidity to the main station in order to assume that they both have similar cosmic ray spectra. The primary variation of the cosmic rays for the reference station is:

$$v_S = \frac{N^S_{pcorr} - \overline{N^S_{pcorr}}}{\overline{N^S_{pcorr}}} \tag{7}$$

In order to transform the primary variations of the reference station to the variations of the main station, the coupling coefficients are used (Belov et al., 1993; Yasue et al., 1982). If the coupling coefficients of the zero harmonic are C_0 and C_0^S for the main and the reference station respectively, Eq. (6) becomes:

$$\ln N' - \ln N_0 - \ln\left(1 + \frac{C_0}{C_0^S} v_S\right) = -\beta(P - P_0) \tag{8}$$

The Eq. (3) and (8) can be used to experimentally calculate the barometric coefficient β by applying a linear regression on the measured values of the variables that are presented in the equations, for a specific time period. The parameters N_o and P_o can be considered as the average values of the N' and P respectively, over the defined time period. More details of this method are given in (Kobelev, 2011).

3. Limitations of the barometric coefficient calculation online tool

The Neutron Monitor Database (NMDB) is a mySQL database with the master server located in the Kiel station and a number of mirror servers located in different places such as the Athens station. The main task of the NMDB is to gather the high resolution data of the worldwide network of neutron monitors in a real time basis. This is a very important task since it makes possible for the scientific community to access these data instantly and in a common format. It also makes possible the implementation of online applications such as the one described in this work. Currently, more than forty stations send their 1-min resolution data to the NMDB every minute. The database consists of five tables for each station and of a common table for all stations. A description of the NMDB tables is given in Table 1.

The online tool described in this work, uses the NMDB data and calculates the barometric coefficient through a linear regression and according to the Eq. (3), (8). More specifically, the tool uses the data from the STATION_1 h or the STATION_ori tables which contain the 1 h and the 1 min measurements respectively. The primary key of these tables is the 'start_date_time' field which has a datetime format and represents the date and the time of the beginning of the measurement. The processing of the data is performed

Table 1
Tables of the Neutron Monitor database.

Table name	Description
STATION_ori	Stores the original 1 min data of the station. The data can be written only once. Any possible revision is stored in the STATION_rev table
STATION_rev	Stores any revision of the original 1 min data
STATION_1 h	Stores the data averaged to 1 h
STATION_env	Stores the environmental data of the station (optional use)
STATION_meta	Stores general information about the station
Station_information	Information about all the stations

Where STATION = the abbreviation of the station's name.

via SQL queries that are sent by PHP scripts. The challenging issue of the implementation is the development of an application that can effectively calculate the barometric coefficient in a reasonable time. It is important to notice that the NMDB is an active database that each minute gathers the data of several neutron monitor stations and also accepts queries from several applications such as the GLE Alert (Souvatzoglou et al., 2009), the NEST (http://www.nmdb.eu/nest/search.php) and the described tool. For this reason, it is necessary to limit the quantity of the data that are requested and processed in order to reduce the necessary bandwidth and hardware resources.

In order to limit the data quantity, a reduction of the resolution of the NMDB data is required. For example, it is not reasonable to calculate online the barometric coefficient for the time period of one year by using the 1 min data of a station. Such a calculation would require the retrieval of two datasets with more than 500.000 elements each and the linear regression between these two sets. The time for this calculation would exceed the maximum execution time for the PHP scripts (set to the optimal 30 s). The solution is to retrieve the data from the database in a reduced resolution, in order to reduce the number of the retrieved records.

The decrease of the resolution is possible by averaging the data. A good approach in mySQL for this task is the generation of an intermediate field that has the same value for all the records that will be grouped and averaged. When interfering with records distinguished by date time, this can be done by using a method that generates time slices in the database. The time slices are constructed by using the TIMESTAMPADD, TIMESTAMPDIFF and FLOOR functions of the SQL. The following example shows how this method works. If the starting date of the calculation is the 1st of September 2011 and the desired resolution of the retrieved data is 1-day, the TIMESTAMPDIFF function is used to find the difference in days between the 1st of September and the date time key of each record. The SQL expression is the following:

```
TIMESTAMPDIFF(DAY,'2011-09-01 00:00:00',start_date_time)
```

The output of this expression for a record that has a key that differs less than a day will be in the form 0.xxxx. The use of the FLOOR function on this output rejects the decimal part, so the number becomes zero. After that, the application of the TIMESTAMPADD function creates a new datetime field that is called timeslice:

```
TIMESTAMPADD(DAY,
  FLOOR(TIMESTAMPDIFF(DAY,'2019-09-01
00:00:00',start_date_time)),
    '2011-09-01 00:00:00') as time slice
```

The expression above outputs the same date time for all the keys that are within the same day, starting counting from the 1st of September 2011. After that, the records with the same timeslice value are grouped and averaged.

4. Implementation of the tool

The online tool is running on the localhost of the Athens station (http://cosray.phys.uoa.gr/Local_Data/barometricForm.html) and retrieves the data from the NMDB mirror server located in the station. It provides the online user with the possibility to create two different kinds of graphs. The first one demonstrates the linear regression between the parameters of the Eq. (3), (8) and calculates the barometric coefficient for a defined time period. The second one plots the variation of the monthly value of the barometric coefficient for a defined time period. The application is separated in three main parts each one of which is described thoroughly in the following paragraphs.

4.1. The input form

The input form is the interface where the online user enters the necessary for the application parameters. It is implemented in HTML with the support of javascript. A screenshot of the form is shown in Fig. 1. The selection between the two different kinds of graphs mentioned above is performed via radio button under the 'Plot type' section. The calculation of the barometric coefficient for a specified time period is performed when the 'Beta Calculation' is selected, while the plot of the monthly barometric coefficient variation is performed when the 'Monthly Variation' is selected.

In the case that the user selects the 'Beta Calculation', he has to set the time period for which the calculation will be performed. This is achieved by using the drop-down menu for 'Year', 'Month', 'Day', 'Hour' and 'Minute' located in 'From' and 'To' sections. The user is free to select any combination of the beginning and the ending dates. The only limitation is that the beginning date should be before the ending one. After that, the user has to set the resolution of the data that will be retrieved. The tool gives the choice of selecting between hourly and daily data, using two radio buttons. There are several reasons the application allows these two choices. On one hand, the hourly data provide a good resolution of data while they minimize the statistical fluctuations of the measurements. On the other hand, the daily data provide a fair resolution and reduce the influence of the anisotropy of the cosmic rays. In general, the '1 h' resolution is recommended when the defined time period is short while the '1 day' resolution is more appropriate for long periods of time. Since the application is online and in order to protect the NMDB mirror server from big loads, the '1 h' resolution has a limit of retrieving up to 3000 records from the database. When the rows that will be retrieved are more than 3000, the resolution is automatically changed to '1 day' even if the user has selected the '1 h' resolution. The 3000 records limit was selected because it allows a good statistical calculation of the barometric coefficient and gives a reasonable execution time for the application. In the final step, the user selects the station for which the barometric coefficient will be calculated. The selection is performed by using the 'Station' dropdown menu. The second dropdown menu, labeled 'Support', is used in the case the barometric coefficient will be calculated with the support of a reference station. In the case the 'No Correction' choice is selected, the calculation will be performed using the Eq. (3). In the case a support station is selected, the calculation will be performed using the Eq. (8). Although the user is free to select any station as reference, the correct evaluation of the barometric coefficient, according to the theoretical analysis, requires the support station to have similar rigidity with the main one.

In the case the user selects the 'Monthly Variation' plot type, only the year and the month of the starting and ending dates are used. The barometric coefficient is calculated for each month in the defined time period using the data in '1 h' or '1 day' resolution according to the user's selection. Due to performance reasons, the '1 h; resolution for the 'Monthly Variation' plot is limited to a 5 years period of time. For longer periods the resolutions is forced to '1 day' even if the user selects the '1 h' resolution.

Finally, the form contains a checkbox labeled 'Allow usage of 1 min data table'. The application normally uses the hourly data of the stations (tables STATION_1 h) for two reasons. The hourly data of the stations are characterized as of better quality compared to the minutely data. Also since the available resolutions are '1 h' and '1 day', the usage of the hourly data optimize the performance of the application. However, in some cases the hourly data of the stations are not available in the NMDB database. By checking the

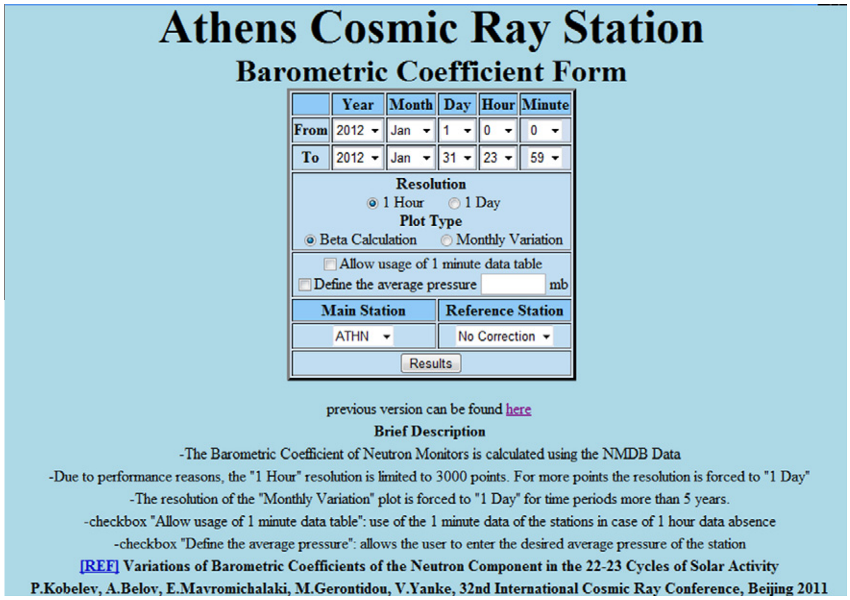


Fig. 1. Application Form.

discussed checkbox, the application is allowed to use the 1 min data of the station in the case of the 1 h data absence.

4.2. The main program

The main program is implemented in PHP and gets the parameters from the form via the POST method. It connects to the NMDB mirror server by using a read-only user which was created for this application and retrieves the necessary data by sending SQL queries. In most cases the retrieval of the data requires the built of nested SQL queries. Especially in the cases where the selected resolution requires averaging of the stored data by creating timeslices, intermediate tables are constructed and joins among them are applied. The queries get even more complicated in the case the 'Monthly Variation' plot is selected by the user. However, this approach is the optimal one since it shifts the computational load of the tool to the mySQL database which provides internal and quick mechanisms for the processing of data.

In the case the user selects the 'Beta Calculation' plot, the main program sends a number of SQL queries to retrieve the data. Depending on the parameters that have been defined in the form, a decrease to the data resolution may be done. In the case only a main station has been selected and according to the Eq. (3), the queries that are sent aim to the calculation of the mean values (N_o, P_o) and to the generation of the ($\ln N - \ln N_o$) vs. ($P - P_o$) pairs. In the case a reference station has been selected, a join between the tables of the main and the reference station is firstly performed. After that and according to the Eqs. (7) and (8), the queries that are sent aim to the calculation of the mean values (N_o, P_o, $\overline{N^S_{pcorr}}$) and to the generation of the $\ln N' - \ln N_0 - \ln(1 + \frac{C_0}{C_0^S} v_S)$ vs. $(P - P_0)$ pairs. It is noticed that for the main station the raw data are used, while the pressure corrected data are used for the reference one. In order for these pairs to be calculated, the coupling coefficients are required. The coupling coefficients of the zero harmonic for most stations have been calculated in the past and are used directly from the main program (Yasue et al., 1982). For each station two coupling coefficients are available. The one corresponds to the minimum of the solar cycle and the other one to the maximum. For the time periods after the 1st of January 2007, the minimum value is used while for periods before that date, the maximum value of the coupling coefficient is used. For time periods that contain the 2007-01-01, the mean value of the minimum and maximum values is considered. The fact that only the coupling coefficient values of the minimum and the maximum phases of the solar cycle are used, does not affect the calculation of the barometric coefficient significantly. For the neutron monitor stations with medium and high values of rigidity, the coupling coefficient values for the solar minimum and maximum do not differ importantly. Moreover as it was mentioned above, since the main and the reference stations should have similar rigidities, even if the coupling coefficients C_o and the C_0^S slightly differ from the accurate values, the ratio $\frac{C_0}{C_0^S}$ is smoothed to the correct value. The operation of the main program for the 'Beta Calculation' case when only the main station is used is illustrated in Fig. 2, while the operation when a reference station is used is shown in Fig. 3.

In the case the user selects the 'Monthly Variation' plot, the main program performs the procedures described above for each month that is included in the time window determined from the starting and the ending date. However, in this case the main program does not aim only to the generation of the data pairs mentioned above but goes one step further. For each month, the barometric coefficient 'β' and the correlation coefficient 'r' are calculated directly via the linear regression of the generated data pairs by using a nested SQL query. The linear regression is performed by using the equations:

$$\beta = \frac{\overline{X \cdot Y} - \overline{X} \cdot \overline{Y}}{\overline{X^2} - \overline{X}^2}, r = \frac{n \cdot \sum X_i \cdot Y_i - \sum X_i \cdot \sum Y_i}{\sqrt{n \cdot \sum X_i^2 - \left(\sum X_i\right)^2} \cdot \sqrt{n \cdot \sum Y_i^2 - \left(\sum Y_i\right)^2}}, \tag{9}$$

where $X = P - P_o$ values, $Y = \ln N - \ln N_0$ or $Y = \ln N' - \ln N_0 - \ln(1 + \frac{C_0}{C_0^S} v_S)$ values depending on the usage of a reference station or not and 'n' the number of the retrieved records. The data used for the linear regression are the hourly or the daily values of the counting rate N and the pressure P that correspond to each month.

4.3. The graph

The last part of the tool is the graph where the output values from the previous step are plotted. The graphs are drawn by using

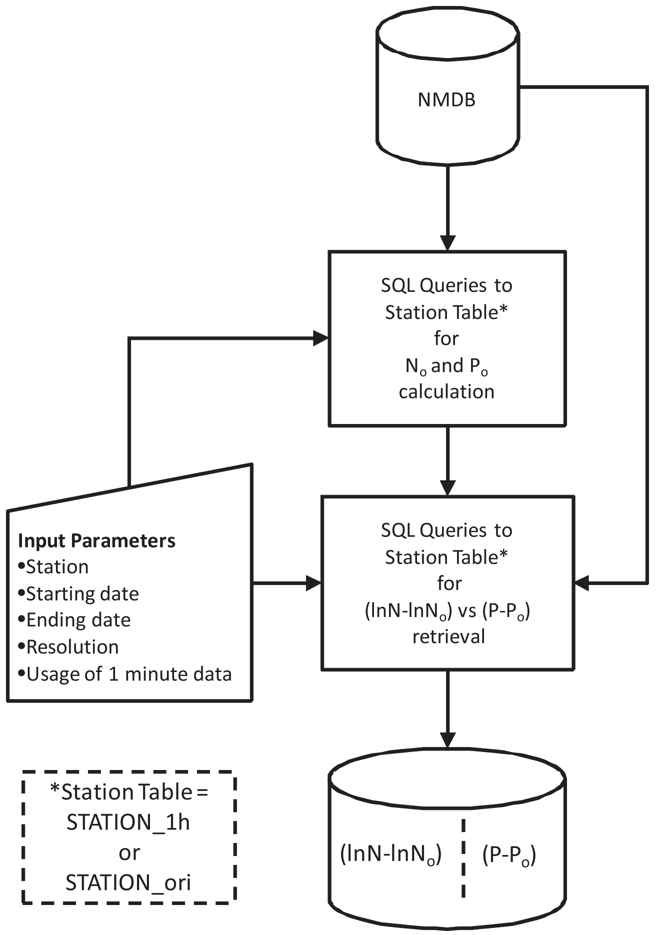


Fig. 2. Data retrieval for the calculation of the barometric coefficient without using any reference station.

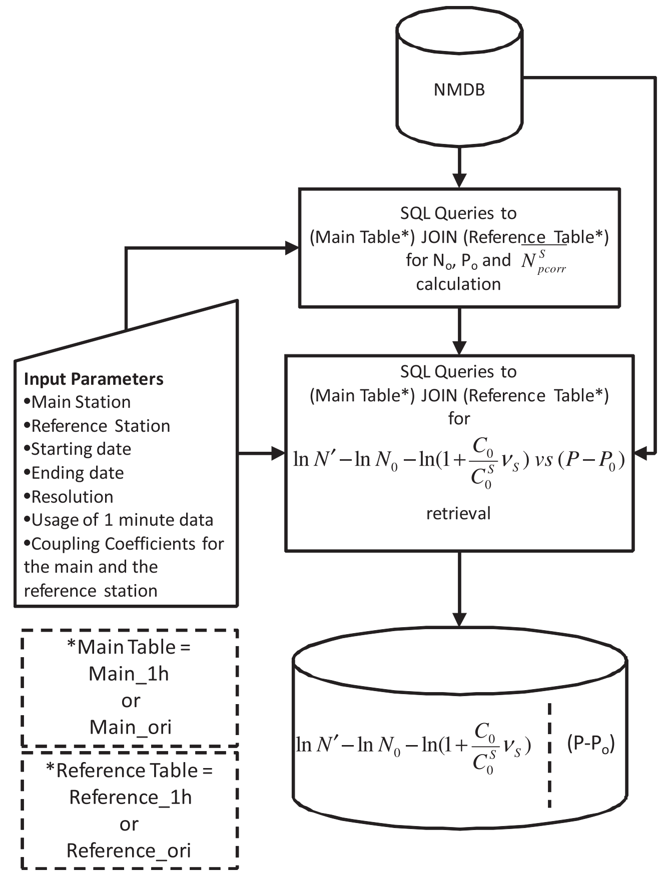


Fig. 3. Data retrieval for the calculation of the barometric coefficient by using a reference station.

the Jpgraph library (http://jpgraph.net) which is written in PHP and gives a variety of plot types and formatting choices through its classes.

In the case of the 'Beta Variation' plot, the graph is a scatter plot of the $(\ln N - \ln N_0)$ vs. $(P - P_0)$ or the $\ln N' - \ln N_0 - \ln(1 + \frac{C_0}{C_0^S} v_S)$ vs. $(P - P_0)$ values, depending on the usage or not of a reference station. The linear regression of the two datasets is performed by using the Linear Regression class of the Jpgraph library. The slope of the regression line that is drawn is equal to the barometric coefficient of the station. The output graph has a .png image format and contains a caption that displays all the necessary information about the processed data. The displayed information is given in Table 2. Apart from the graph, the output webpage contains links to additional graphs. More specifically, there are links to graphs for the uncorrected data and the pressure of the main station and also a link to a graph for the corrected for pressure data of the reference station. These additional plots are useful because the user can immediately check if the calculation of the barometric coefficient was done in a quiet or in a disturbed cosmic ray period and he can also check the variation of the atmospheric pressure.

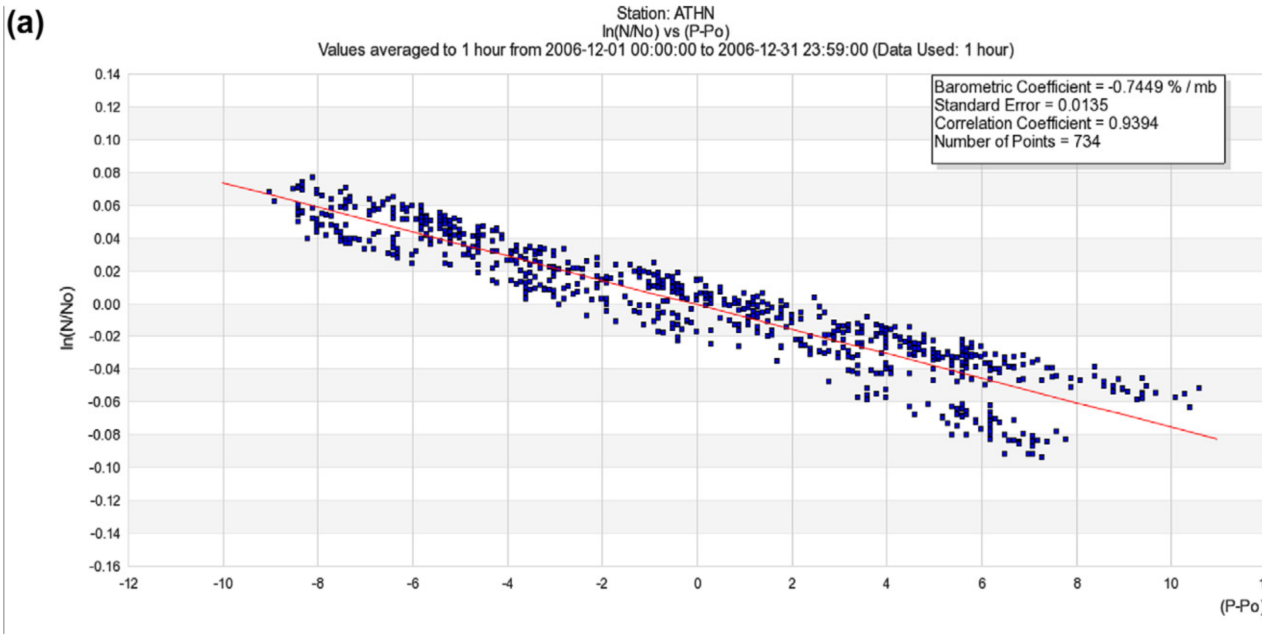
In the case of the 'Monthly Variation' plot, the monthly values of the barometric coefficient and the corresponding correlation coefficient have already been calculated from the previous step. In that case a line plot from the Jpgraph library is used where the values are plotted with the time. The correlation coefficient, which varies from 0 to 1, uses an inverted axis which provides a better visual result.

Table 2
Information displayed on the output graph.

Station and reference station (in case it exists)
Resolution of data (1 h or 1 day)
NMDB tables that were used (1 h or 1 min)
Barometric coefficient (the slope of the regression line)
Standard error of the linear regression
Correlation coefficient of the linear regression
Number of points plotted

5. Results and conclusions

The calculation of the barometric coefficient for the Athens station without the use of a reference station, for the active cosmic ray period of December 2006, is shown in the upper plot of Fig. 4. It is obvious that the calculation in this case is not very accurate since the variations of the measured counting rate are not related only to the variation of the atmospheric pressure but mainly to the variations of the cosmic ray incoming flux. As a result the plotted points are far from the regression line and this is reflected on the correlation coefficient which is 0.9394. In order to exclude the variations of the cosmic rays, the Rome station can be used as a reference one, since it has a close value of the Athens station's rigidity. The result in that case is given in the bottom plot of the Fig. 4, where the improvement in the calculations is obvious. The correlation coefficient is very close to the unique, as it takes the value of 0.9927 and all the measured points are close to the regression line which means that the method is working well. The additional plots provided by the tool, the uncorrected and the pressure data of



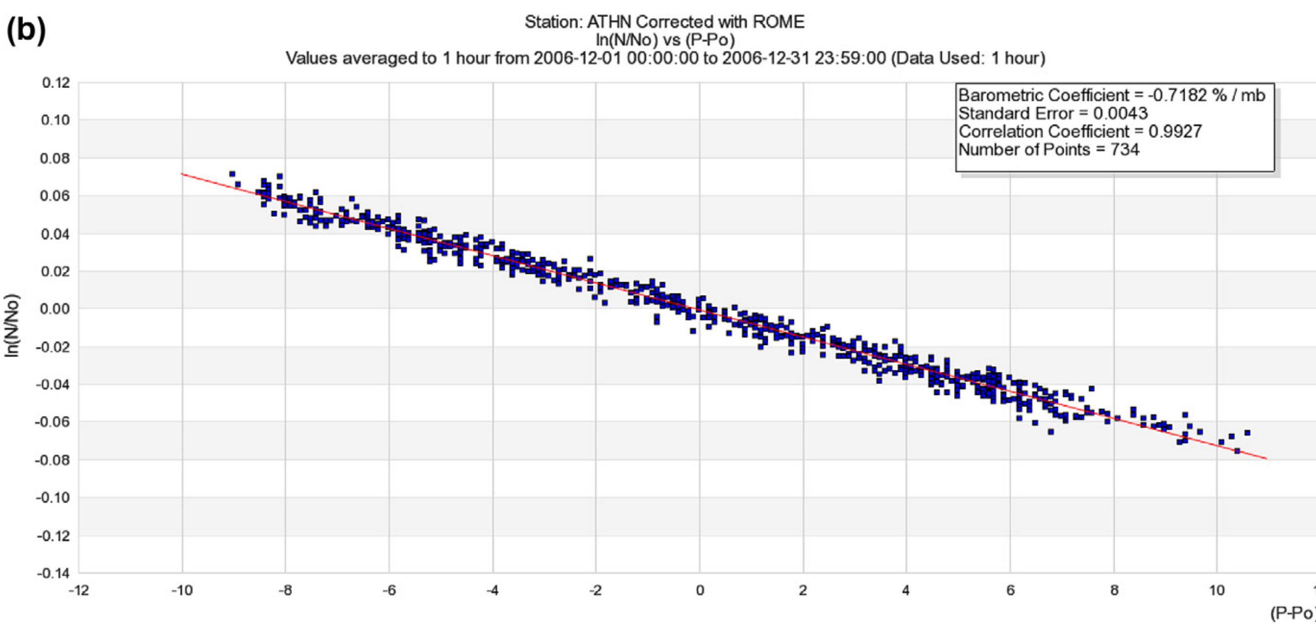


Fig. 4. The barometric coefficient calculation during December 2006 for the Athens NM station, (a) without using a reference station (upper plot) and (b) by using Rome station as a reference one (bottom plot).

the Athens station and the corrected for pressure data of the Rome station as well are given in Fig. 5.

The monthly variation of the barometric coefficient for the Athens station, without using any reference station from January 2001 to January 2012, is shown in the upper plot of Fig. 6. As it can be seen, the barometric coefficient is almost stable from 2006 onwards, while from the year 2001 to the year 2005 there are important fluctuations. The same plot in the case when the Rome station is used as a reference one, is shown in the bottom of the same figure. The fluctuations from 2001 to 2005 are disappeared, that means that they were previously observed due to the fact that this period was not a quiet one, so the calculation of the barometric coefficient was not accurate without the use of a reference station. It is important to notice that when there are important fluctuations of the barometric coefficient, the corresponding value of the correlation coefficient is far from the value 1, which means that the data of that period do not lead to a successful calculation. For example, the noticeable reduction of the barometric coefficient at the beginning of 2005 which is noticed on both plots of Fig. 6, is due to the poor data of the Athens station. The same noticeable reduction during 2011 which is noticed only on the bottom diagram is due to the poor data of the Rome station. Finally, the absence of the barometric coefficient values in the bottom plot during 2007 is due to the absence of the corresponding Rome station data.

In conclusion, the online tool described in this work can effectively calculate the barometric coefficients for the neutron monitor stations that send data in real-time to the High Resolution Neutron Monitor database-NMDB. The use of a reference station leads to satisfactory results even in the active cosmic ray intensity periods. Each station is able to easily check if the barometric coefficient used for the primary data processing is correct and improve the quality of the data. Moreover, each station can check the stability

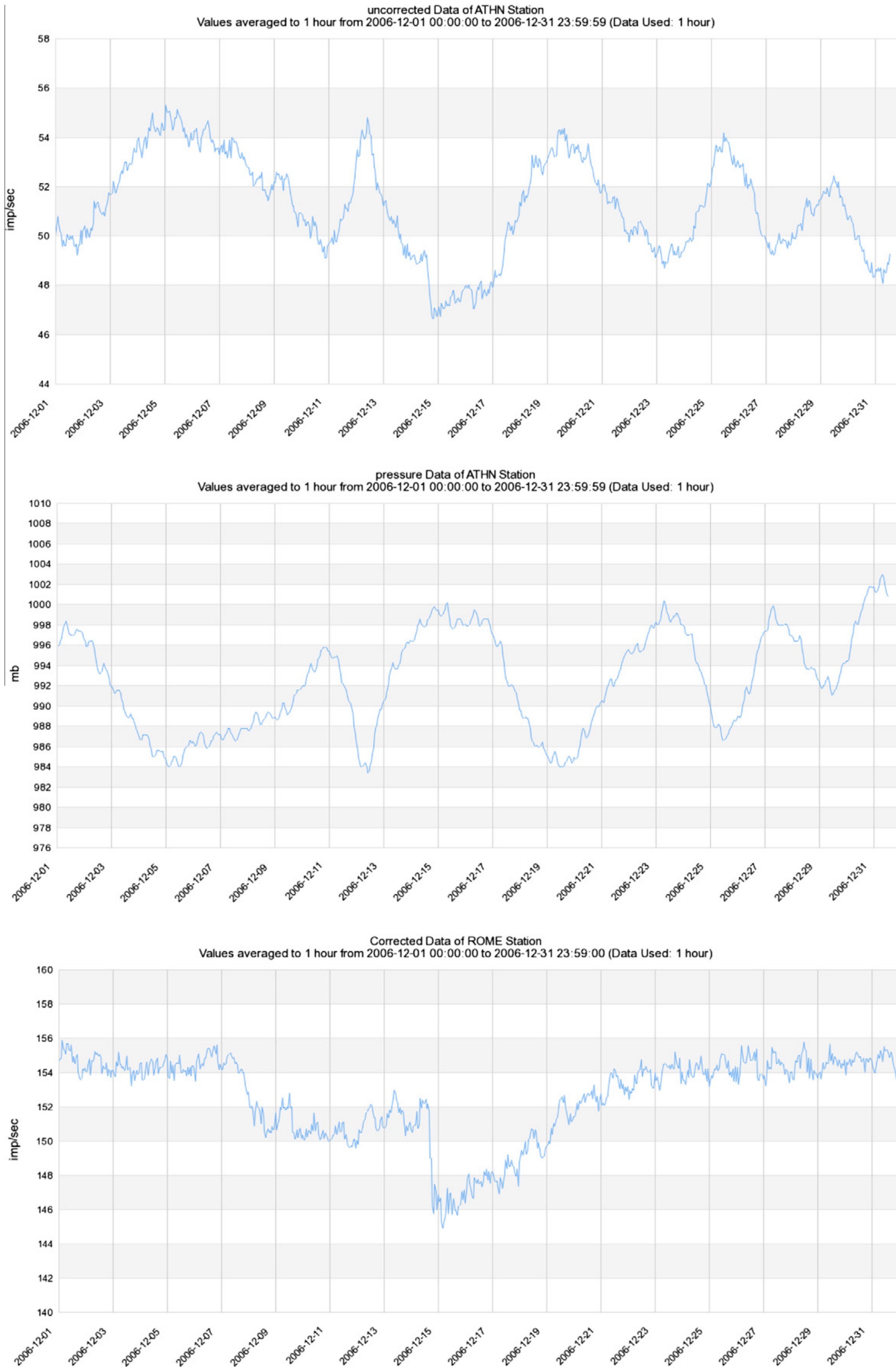


Fig. 5. Uncorrected data of the Athens station (upper plot), atmospheric pressure of the Athens station (middle plot) and corrected with pressure data of the Rome station, during December 2006 where a series of Forbush decreases were occurred.

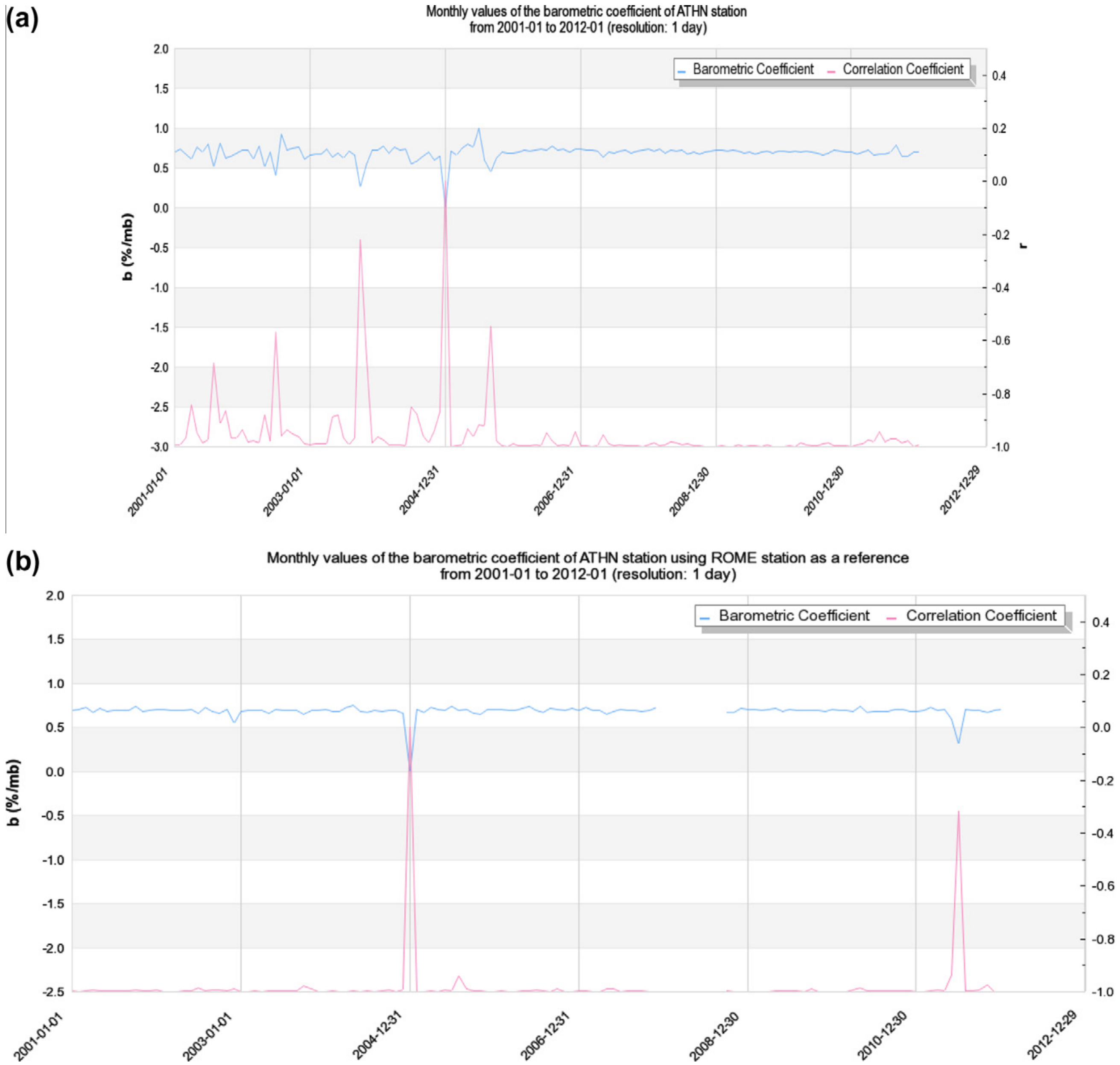


Fig. 6. Monthly variation of the barometric coefficient of the Athens station, from January 2011 to January 2012, (a) without using a reference station (upper plot) and (b) by using the Rome station as a reference (bottom plot).

of the barometric coefficient over time by using the 'Monthly Variation' plot. It is important to highlight that the correct calculation of the barometric coefficient highly depends on the correct setting of the application's parameters. For example the calculation of the coefficient in an active period without using a reference station can lead to doubtful results. Not trustful results may also produce the selection of a reference station with a completely different rigidity to the main station.

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