Cosmic Ray Intensity Measurements at Dourbes

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Release:	1.0	10.01.2013	Unclassified

DOCUMENT CHANGE RECORD

VERSION	DATE	CHANGE RECORD	AUTHOR
0.1	01.01.2013	First Draft	D. Sapundjiev
0.2	02.01.2013	Draft, revised and updated	S. Stankov
1.0	10.01.2013	First release	S. Stankov

SUMMARY

This report describes the principles of measurement and processing of the cosmic radiation intensity as currently performed at the RMI Geophysical Centre in Dourbes (4.6°E, 50.1°N). Cosmic ray measurements have been carried out at the Centre since the 1960s with a standard (9-NM64) neutron monitor and a large database has been accumulated over the years. In addition to the retrospective data correction that was necessary to be done for the period from 1999 to 2003, better data quality control and processing procedure was needed to be implemented in order to comply with the data quality standard of the International Neutron Monitor Database (NMDB). The data cleaning and processing algorithm (including error identification, filtering and correction) will be described together with the calculation of the geomagnetic cut-off rigidity, an important station-specific parameter. The newly developed Automatic Data Quality Correction (ADQC) system is applicable to all measurements since 2003.

ACKNOWLEDGEMENTS

The authors thank C. Steigies and D. Ruffolo for the helpful discussions. This work is funded by the Royal Meteorological Institute (RMI) via the Belgian Solar-Terrestrial Centre of Excellence (STCE).

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1. Introduction

The interplanetary space is continuously traversed by very energetic nuclear particles called cosmic rays consisting mostly of protons and helium nuclei with few nuclei of heavier elements. The particles have a broad energy range, from less than 1 GeV (10^9eV) to more than 10^{11} GeV (10^{20}eV). Cosmic rays are key components of space weather -- the complex interaction between the Sun and the interplanetary space on the one side and the Earth on the other. As such, cosmic ray measurements have been carried out at the RMI Geophysical Centre in Dourbes (4.6°E, 50.1°N) since the 1960s with the help of a standard (9-NM64) neutron monitor consisting of three sections with three counter tubes each (**Fig.**1-1) (*Jodogne*, 1970, 1982; *Jodogne* et al., 1979; *Jodogne and Stankov*, 2002; *Stankov*, 2002; *Stankov* et al., 2012).

Fig.1-1: The cosmic ray observatory in Dourbes (left) and a section of the neutron monitor (3 counter tubes) (right).

The purpose of this report is to describe the principles of measurement and processing of the cosmic radiation intensity as currently performed at the Dourbes observatory. This became necessary after some disruptions occurred in the control/processing of the neutron monitor measurements back in the period from 1999 through to 2003. In addition, a better quality control and processing of the data was needed in order to comply with the data quality standard of the international neutron monitor data base (NMDB), which is a real-time database for high resolution neutron monitor measurements. All steps in the data cleaning and processing algorithm will be given that include error identification, filtering and correction. The calculation of the geomagnetic cut-off rigidity, an important station-specific parameter, will also be described. The newly developed Automatic Data Quality Correction (ADQC) system is applicable to measurements since 2003.

The report is organized as follows. First, a brief overview of the cosmic rays is given followed by basic information on cosmic radiation measurements and on construction of neutron monitors. Next, the neutron monitor measurement data processing and correction procedures are detailed including the Automatic Data Quality Correction (ADQC) system. The following section presents the calculations of the cut-off rigidity, an important station-specific parameter. The report concludes with a summary of the results and an outlook to future work towards further improving the cosmic ray monitoring at Dourbes.

2. Cosmic rays – an overview

Cosmic rays were discovered by the currents observed in rarefied gases at the absence of apparent ionisation sources. In an attempt to eliminate background (terrestrial radiation) Victor Hess performed measurements during several balloon flights and found that the intensity increased with altitude (*Hess*, 1912; *Carlson*, 2012). The follow-on research determined that the surface radiation observed at the Earth's is not the original cosmic radiation but "secondary" (**Fig**.2-1). In addition, the intensity of the ground level measurement strongly depends on the geographical latitude (**Fig**.2-2) which has led to the conclusion that the original particles are charged and interact with the magnetic field of the Earth.

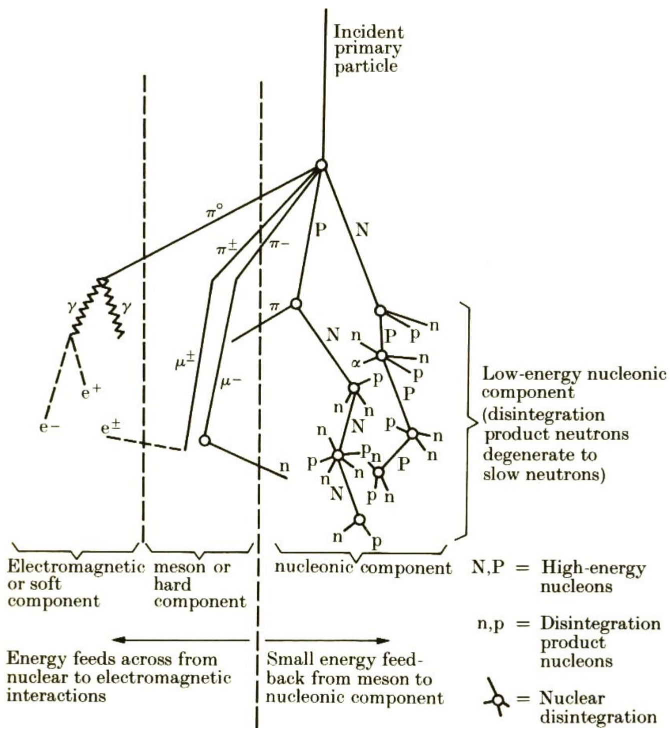

Fig.2-1: Interaction of a primary cosmic ray particle and the terrestrial atmosphere resulting in production of several secondary components of the cosmic rays.
Source: *Akasofu and Chapman* (1972)

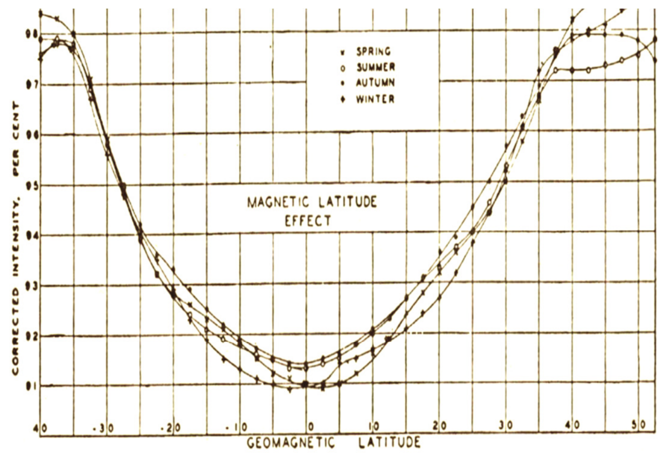

Fig.2-2: The intensity of cosmic radiation varies with latitude, indicating that it consists (at least partially) of charged particles which are affected by the Earth's magentic field. Source: *Compton and Turner* (1937)

Nowadays, it is well known that the primary cosmic radiation consists of mainly hydrogen nuclei (protons), about 89-94%, helium nuclei, 5-10%, and about 1% are nuclei of heavier elements (*Akasofu and Chapman*, 1972; *Dorman*, 1974). These particles originate from the Sun (solar cosmic rays) and the interstellar space (galactic cosmic rays). An open questions however is the mechanism responsible for the acceleration (or production) of the cosmic radiation with very high energies (in the order of TeV).

A large portion of the galactic (and solar) cosmic radiation has energy that is too low to penetrate the atmosphere; under the effect of the Earth's magnetic field they describe large helical trajectories and are channeled towards the poles. When they interact with the atoms in the atmospheres, a large number of so-called "secondary" cosmic ray particles are produced (**Fig**.2-1). Their number is so large, especially for the high energy component, that the phenomenon is often called "shower". These secondary particles form the radiation that can be observed at the Earth's surface.

The mechanism behind the “shower” is the deflection of the high-energy charged particles (e.g. electrons) by the electric fields in the atoms. Whenever a fast electron changes its direction of motion, light is emitted. The faster the electron, the shorter is the wavelength of the emitted light. For the case of high-energy cosmic ray electrons, the wavelength is even shorter than the wavelength of a γ-ray (*Born*, 1989). When these γ-rays pass through the matter they can be transformed into electron pairs ($electron + positron$), which have lower energy than the original γ’s but they can produce another γ-ray on deflection by the atomic electric field. This process is repeated until there is sufficient energy for pair creation. Pair production refers to the creation of an elementary particle and its anti-particle when a photon (or a neutral boson) interacts with a nucleus and there is enough energy (at least the total rest mass energy of the two particles) and the conditions allow that both the energy and the momentum are conserved (*Born*, 1989). The size of such shower may range from two to several thousand particles depending on the energy of the initialising electron.

Experiments with cosmic radiation have revealed the existence of particles with greater penetrating ability. The greater penetrating power has been explained with the smaller deflection of these particles by the atomic electric fields implying that the radiation consists of particles with greater mass. The mass of these particles has been determined to be about 200 times the mass of the electron. Therefore, they have been named “mesons” (middle, Greek). Mesons (muons, pions, and others), are unstable, they do not occur in the structure of the ordinary matter. Therefore, they cannot be the primary particles in the cosmic radiation, but has to be produced in the atmosphere by the interaction of protons with any of the atmospheric gas atoms.

On collision between the nucleus and the incident proton, meson waves are emitted in a similar way as “light” is emitted when electrons interact with the atoms. The meson wave then initiates the showers. Subsequently, mesons decay to muons and/or electrons - a large number of electrons are decay products of these mesons. These are the processes by which muons are being produced. Their detection is done by muon detectors at the ground and underground levels.

The neutrons observed at the ground level are also result of violent collisions of the high energetic primary protons and stable nuclei with the atoms of the atmosphere - called spallation (or spallation reactions). In these reactions secondary protons and neutrons are spalled from the atoms in the atmosphere which in turn, if the energy is sufficient, can produce more “tertiary” neutrons in subsequent processes called atmospheric cascades. A direct result of these processes is the abundance of neutrons, with a rather wide energy spectrum, at the surface of the Earth.

The neutron monitor has been invented and developed with the purpose of monitoring the intensity of the primary cosmic radiation by measuring the intensity of the secondary neutrons. A wider network of cosmic ray monitors allows the estimation of the energy of the primary cosmic radiation. This is done by using the Earth’s magnetic field as a spectrometer in order to measure the cosmic ray spectrum and place neutron monitors at a wide range of geomagnetic latitudes (*Simpson*, 1951, 2000).

3. Measurements of cosmic radiation intensity by neutron monitors

Standardised neutron monitors (NM) on the ground indirectly measure variations in cosmic radiation intensity from both the Sun and the galactic sources. For this purpose, high energy neutron detectors, developed first in 1948, are used (*Simpson*, 2000). They allow monitoring of the galactic cosmic rays modulation, e.g. by the 11-year solar activity cycle, the 22-year magnetic activity cycle, etc. Neutron monitors can also detect other solar events resulting in emission of particles with sufficient energy to raise the radiation levels at the Earth's surface. The NM measures by proxy the intensity of the primary particles and their time variations. The latter occurs on many different time scales some of which are still a subject of investigation.

The construction of a NM-64 Super Neutron Monitor consists of a large gas counter - a tube filled with a suitable gas (see below), to which a high voltage is applied so that the tube will work in a proportional mode. High energy neutrons interact rarely with nuclei but when they do, they produce a number of low energy neutrons - by a spallation reaction which results in the expulsion of large number of nucleons. For heavy target nuclei, a spallation event will result in the expulsion of 20-30 neutrons, a number that depends on the energy of the incident particles. The neutron monitors detect the spallation neutrons.

Here is a list and brief description (cf. *Simpson*, 2000) of the neutron monitor components:

- *Reflector*. This is the outermost shell made of hydrogen (proton) - rich material like paraffin ($C_{20}H_{42}$ to $C_{40}H_{82}$) or polyethylene, $(C_2H_4)_nH_2$. Low-energy neutrons are not affected by these types of material (i.e. they are elastically scattered / backscattered) and therefore, environmental neutrons (for example background radiation) cannot penetrate into the detector. Neutrons generated in the lead (the producer) are reflected and kept in the monitor. The reflector is largely transparent to the cosmic ray produced cascade neutrons due to their higher energy.
- *Producer*. The producer is a material of high atomic number - for example lead (Pb). Fast neutrons induce spallation reaction with the lead nuclei, as explained above, and produce about 10 (or more) lower energy neutrons. These neutrons are confined within the neutron monitor by the reflector.
- *Moderator*. This is, again, a proton-rich material which slows down the neutrons via a series of collisions in order to increase the efficiency of detection.
- *Proportional counter*. The slowed-down neutrons interact with the nuclei of the gas in the tube and cause nuclear reaction or disintegration of the target nuclei; the reaction products include energetic charged particles which ionise the gas in the counter and produce an electric signal; in the early years the active component in the gas was (^{10}B: $n+{}^{10}B \rightarrow \alpha+{}^{7}Li$); recent proportional counters use the reaction ($n+{}^{3}He \rightarrow {}^{3}H+p$) which yields 764 keV.

The actual detection is achieved by a nuclear reaction in the gas-filled tube. This, and the fact that the neutron is already "moderated", makes it impossible to determine the energy of the neutron causing the reaction. Therefore, NMs measure the intensity and not the energy of the particles. However, the energy of the primary rays can be determined by a set of neutron monitoring stations positioned at different geographic latitudes. Such a system of stations and the Earth's magnetic field operate as a giant mass spectrometer for primary cosmic ray particles (cf. *Simpson*, 2000).

4. Data processing and correction

The measured data from the neutron monitor is downloaded from the measurement equipment. In general, data strings from neutron monitor measurements consist of:

- time stamp
- counting rates registered at regular time intervals (for the NM Dourbes, every one minute by each detector unit)
- atmospheric pressure reading (in hPa)

Additional information, needed by some type of neutron monitors, includes the humidity and, for Helium (He) - filled tubes, the internal temperature. A sample of raw data is displayed in **Fig**.4-1.

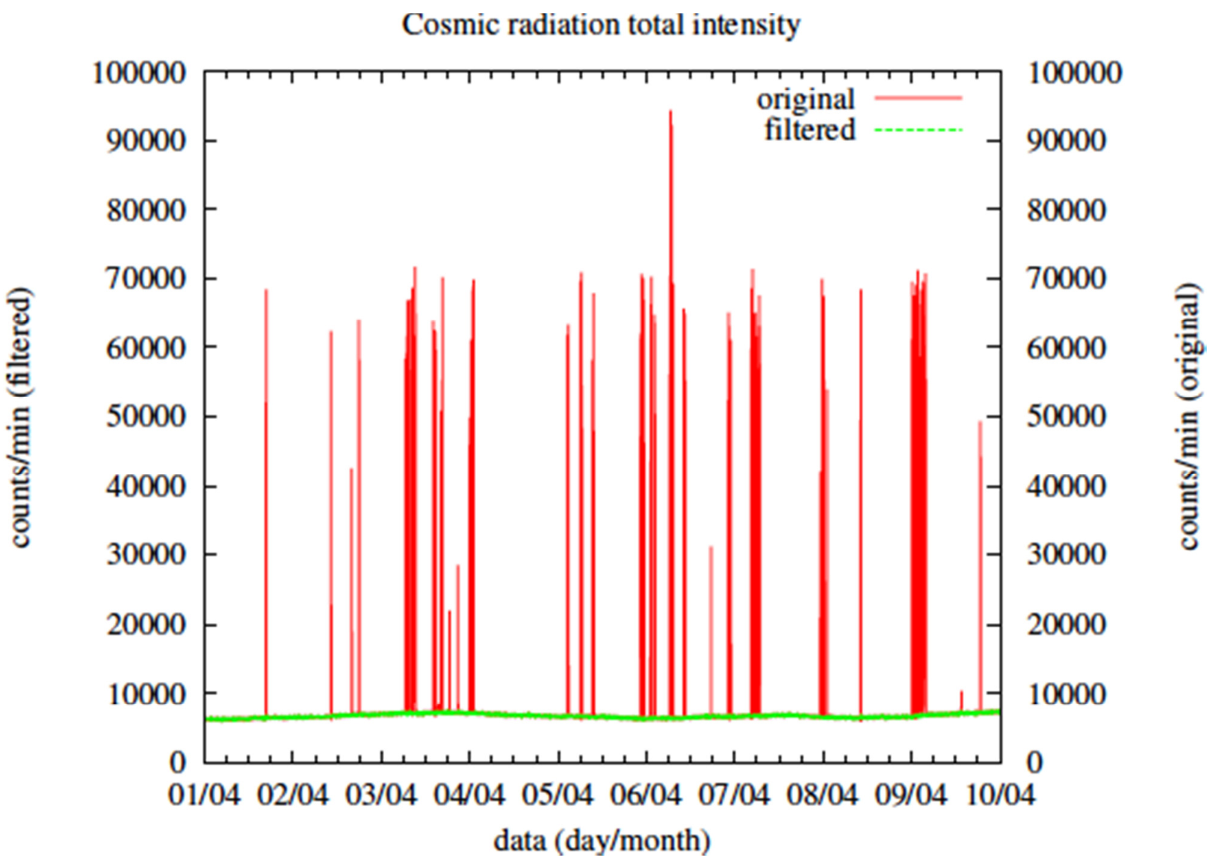

Fig.4-1: Original uncorrected and unfiltered cosmic radiation intensity measurements: counts from individual noisy tubes (in this case, tube 4 and, occasionally, tube 2 and 3 simultaneously) produce very large peaks in the total intensity. The data has been filtered and plotted (dashed line) in the same figure for comparison.

Such data is difficult to interpret, due to the presence of large peaks (with intensity greater than 10000 counts per minute). The original data may be missing some values from the pressure measurement, due to malfunction of the sensor, or values from one or more detector tubes. Therefore, to extract useful information from the cosmic radiation intensity measurements, the original data has to be processed.

In general, the processing of the original data consists of an automatic quality control, standard pressure correction, and application of standard normalisation factors.

4.1 **Automatic data quality control**

The Automatic Data Quality Control (ADQC) has the objective to detect a noisy, erroneous, or missing detector signal or pressure measurements. The quality control of the readings of each tube or section (a group of three tubes) is made by comparing the count rates between identical detection tubes or sections. For this purpose, a reference count rate ratios has to be calculated for a period with a stable operation of the station.

A deviation from the count rate ratio indicates possible malfunction of one or more sections. The automatic data quality control detects which section(s) gives the erroneous measurement by looking at the values of the ratios between all sections (counter tubes) of the station. Ideally, the ratios are calculated for every tube of the station, e.g. if we have a station with three tubes A, B, and C, the control is made by comparing the ratios A/B, B/C and C/A with ratios from a normal operation of the station. With this method however, it is still not possible to detect a simultaneous malfunction of all three sections.

Presently, this is the algorithm used for the control of the individual detector sections of the neutron monitor in Dourbes. However, if the deviation of more tubes is comparable (to the same extent of magnitude) then the “ratios” method will result in incorrect fault detection (see later in this section how this type of data is processed). After the problematic section is identified, the wrong value is removed from the total intensity (i.e. the sum of the counts of all sections) and the result is multiplied by a factor that accounts for the contribution of the noisy section (or the sum of contributions if more than one section is producing a noisy signal).

The contribution of each detector section is plotted in **Fig**.4-2.

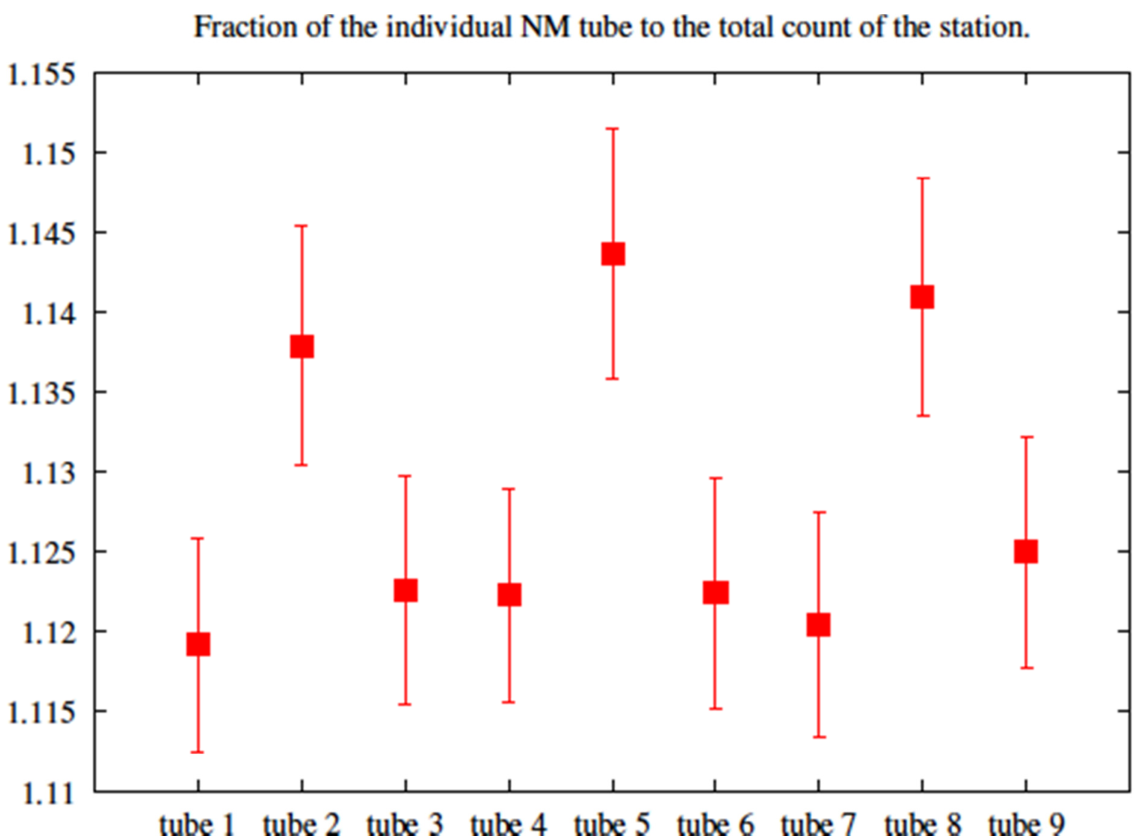

Fig.4-2: Tube factors for correcting the total count rate for a faulty reading. The larger factors (tubes #2, #5, and #8) are (probably) due to the fact that these tubes are newer or with different characteristics (see text).

The data filtered by the ratios algorithm is plotted in the following **Fig**.4-3.

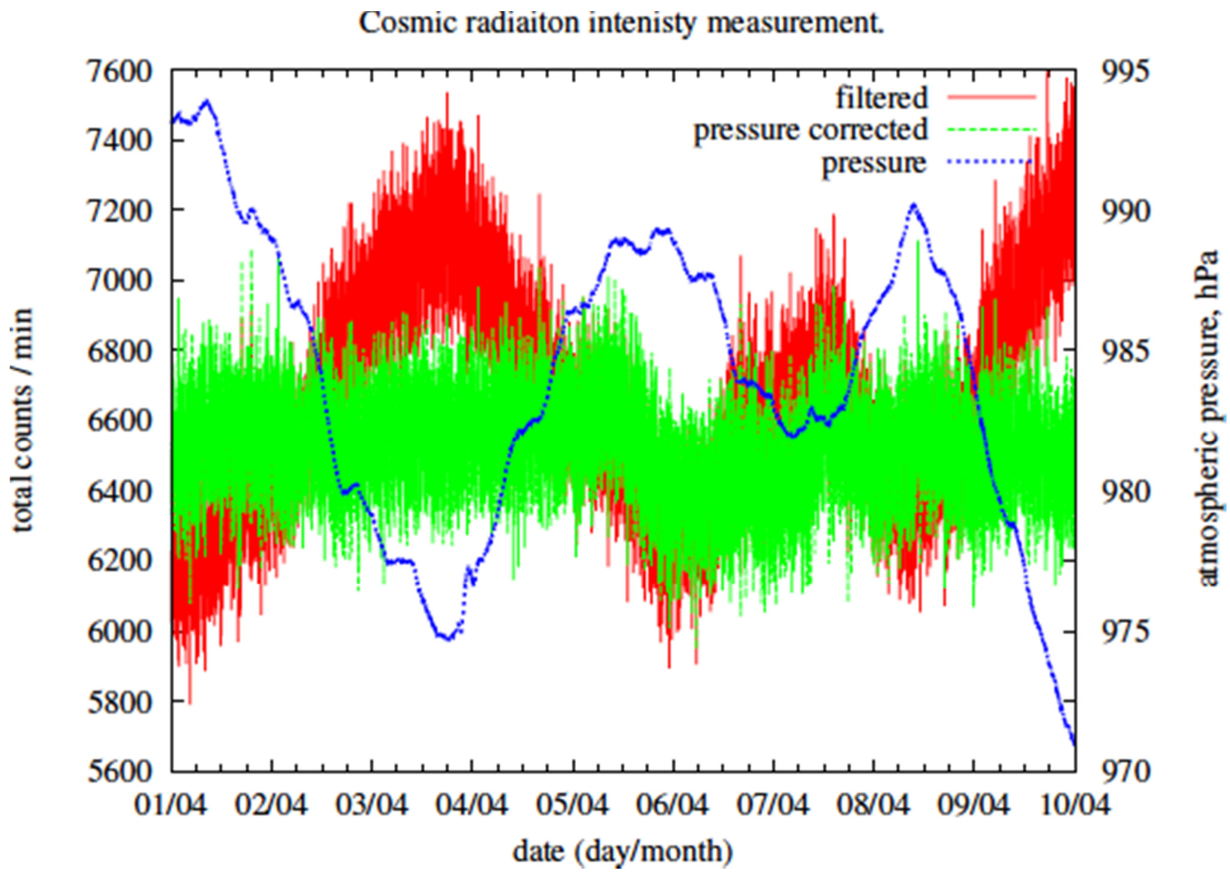

Fig.4-3: Filtered cosmic radiation intensity, plotted together with the atmospheric pressure and the same data corrected for pressure.

The corresponding correction factor for each tube section is determined from a large manually-verified dataset and calculated for each section using the following expression:

$$k_j = \frac{\sum_i I_i}{\sum_i I_i - I_j}$$

Mathematically, the correction can be presented as follows: the individual section intensity ratios form a matrix, R_{ij}. The reference section ratios form a reference matrix $R_{ij\,ref}$, where the R_{ij} element equals the ratio between the intensity measurements I_i / I_j of sections i and j . Then the condition for a faulty section signal, say section i , can be written as the logical multiplication:

$$\bigwedge_{j=1}^{n} |R_{ij} - R_{ij_{ref}}| > 3\sigma_{ij}$$

where the logical multiplication is over all sections (detector tubes) (for the Dourbes station, n=9).

The automatic correction based on this condition is carried out only if

$$\bigvee_{j=1}^{n} |\mathrm{R_{ij}} - \mathrm{R_{ij_{ref}}}| > 4$$

which means that at least four ratios that the i-th detector forms with the remaining detector sections has to be abnormal. This does not exclude the problematic case when half of the sections give simultaneous, comparable deviation (noisy) signal. In such case, if 4 or 5 sections produce noisy results, then the condition would also be satisfied.

This algorithm can be applied for stations with more than two detector sections. A larger number of tubes will improve the reliability of the intensity measurements as the probability for mutual faulty measurements would be smaller.

An additional quality test of a raw intensity measurement is to compare the readings of each tube with a minimum and maximum value produced by the tube throughout its entire service. The test checks if the current measurement exceeds its extreme values; if true, then (most probably) the value is incorrect. The extreme values are obtained from the entire available data and verified by an operator.

The "extrema" test is complimentary to the "ratios" algorithm and provides a way for automatic correction even when just one single tube produces correct measurements.

However, the "ratios" algorithm is not applicable if all sections are simultaneously producing noisy signals. It does work when the majority of the sections are functioning properly. This means that, for a station of three tubes, the automatic data control based on this algorithm will correct one tube (at most), for a station of five tubes – two, etc.

In cases when all sections produce noisy signals, e.g. the noisy peak in the following sample of raw data:

```
2009/03/17,02:30:00, 618, 679, 632, 595, 700, 591, 604, 701, 698,1005.53
2009/03/17,02:32:00,1301,1442,1187,1255,1515,1363,1262,1369,1342,1005.53
2009/03/17,02:33:00, 687, 781, 744, 625, 728, 638, 614, 719, 725,1005.54
```

then the "ratios" algorithm would fail to identify the spike and the latter would pass the automatic data quality control:

```
2009/03/17,02:30:00, 618, 679, 632, 595, 700, 591, 604, 701, 698,1005.53, 5818, 6696.95
2009/03/17,02:32:00,1301,1442,1187,1255,1515,1363,1262,1369,1342,1005.53,12036,13854.30
2009/03/17,02:33:00, 687, 781, 744, 625, 728, 638, 614, 719, 725,1005.54, 6261, 7207.41
```

Median filters can do an excellent job for rejecting this type of a solitary "shot" or "impulse" noise in which some individual measurements have extreme values, as in the above example. The median filter should be applied after the data has already been filtered by the ratios algorithm. **Fig**.4-4 illustrates noisy data from simultaneous (for all sections) "shot" peaks before and after applying the median filter.

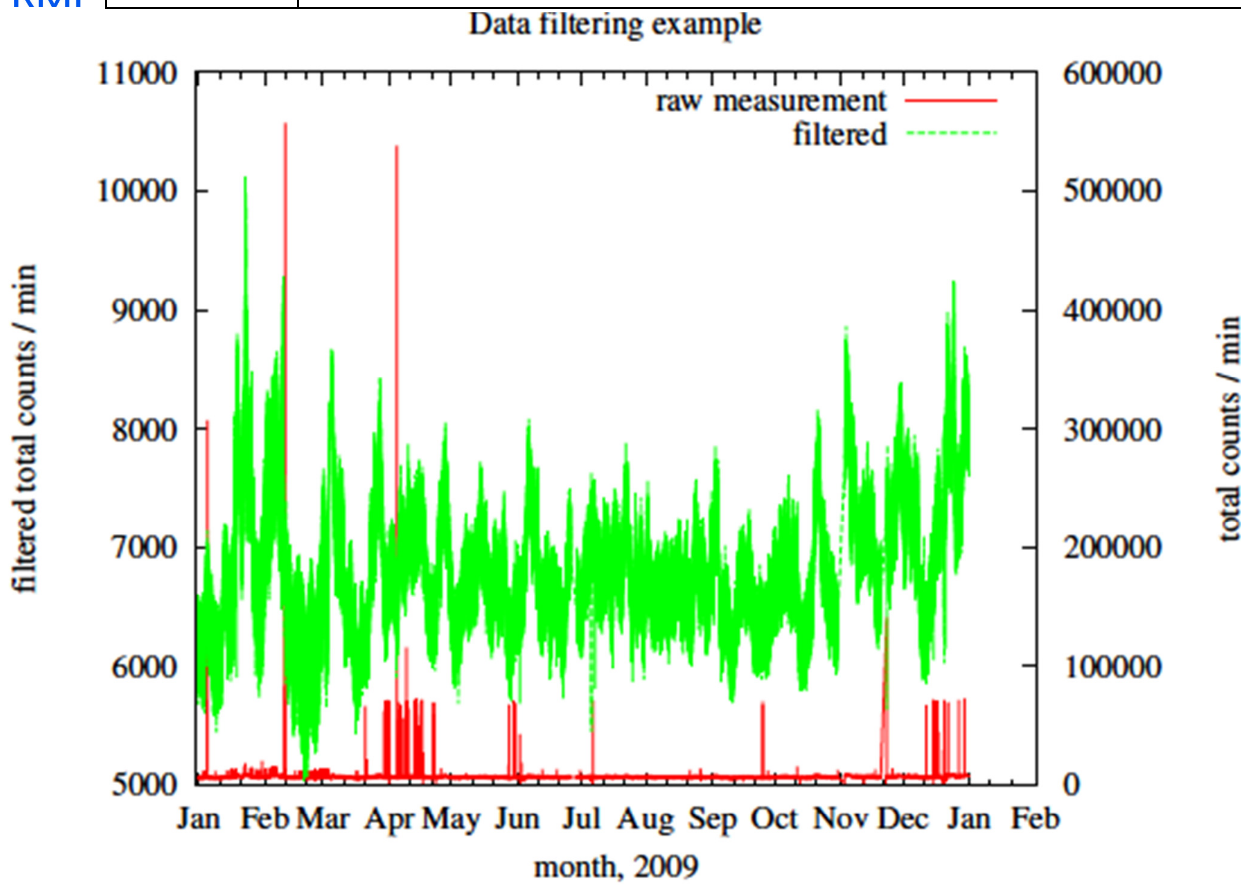

Fig.4-4: An example of single high-intensity peaks at different time intervals being removed by the median filter. Note that these peaks differ from the noisy data displayed in Fig.4-1 in that they come from simultaneous noisy values from all sections of the station while the peaks in Fig.4-1 occur as a result of a limited number (not more than) four erroneous sections (data from 2009).

The median filter is activated only if the intensity exceeds a certain threshold value. This threshold is determined on the basis of simulations of erroneous signals and from real data containing such peaks. The threshold can also be determined via the extrema test. Additionally, the median filter is designed to filter only a single shot peak - that is a peak for which the preceding and the following peaks are normal, as in the following example:

```
2009/03/17,02:30:00, 618, 679, 632, 595, 700, 591, 604, 701, 698,1005.53,5818,6696.95,-0.032193
2009/03/17,02:32:00,1301,1442,1187,1255,1515,1363,1262,1369,1342,1005.53,6261,7206.87, 0.041499
2009/03/17,02:33:00, 687, 781, 744, 625, 728, 638, 614, 719, 725,1005.54,6261,7207.41, 0.041576
```

The median filter will produce spurious peaks if the number of “shot” peaks exceeds one. It has also a problem if the correction is carried out on a finite number of input measurements - for example, minute measurements for a day. In such cases, if the peak is at the end or the beginning of the data group (input file), the median filter will meet a problem and produce a spurious peak. The extrema test would work reliably in these cases.

Verification of filtering algorithms has been carried out by processing a large amount of data and observing the input and the corrected data for missing or wrong input values or for possible “distortion” of good cosmic radiation measurements by the filtering program. This, however, might not have covered all possible combinations that can result in wrong correction or might not trigger any action.

4.2 **Pressure correction**

Measuring neutron intensity based on their local generation in the neutron producer has the advantage that there is no effect of air density, just a (relatively easily) computed barometric effect (*Dorman*, 1974). This effect modulates the intensity of the cosmic radiation measurement (cf. **Fig**.4-3). Therefore, a standard pressure correction needs to be applied in order to reduce (as much as possible) this modulation - the total filtered count rate of the station is transformed using the following relation:

$$\mathrm{I_c} = \mathrm{I_0} \exp(\beta(\mathrm{p} - \mathrm{p_0}))$$

where $\mathrm{I_c}$ is the corrected total intensity, β is the barometric coefficient (the reciprocal of the absorption coefficient for the radiation of interest), and $\mathrm{p_0}$=740 (mmHg) is the standard pressure for the station.

This effect appears due to the neutrons that are produced by unstable particles which amount to only a small fraction from the total neutron component.

The correlation coefficient, estimated before the pressure correction was applied (cf. **Fig**.4-3), is $corr(p, I)^* = -0.88$, showing a strong negative counter correlation between the pressure and the total count. The same coefficient was calculated after the intensity was corrected for pressure effects using β = 0.0099 (*Malcorps*, 1999), yielding $r(p, I) = -0.01$.

Subsequently, it was possible to further decrease the correlation coefficient down to 0.0003 by an optimisation of the barometric coefficient: β = 0.00985 (mmHg^{-1}). In this way, the barometric coefficient can be verified or, if not available, can be estimated by minimising the correlation coefficient between the pressure and the total intensity.

4.3 **Calculation of the relative increase**

In order to compare observations from different time periods and/or different stations, the readings of all measurement stations should be normalised in the same way. Attempts have been made to calibrate neutron monitor stations using “calibration” detectors but the results were not satisfactory (*Krüger* et al., 2008). The absolute values of a neutron monitor are difficult to standardise and experience has shown that relative intensity remains more accurate than the inter-calibration (*Ruffolo*, 2012).

For a long term study of cosmic ray variations it is quite common to use the monthly counting rate of a station from May 1965 as the 100% reference level. May 1965 is considered to be the month with a minimum solar modulation. If these data is not available, e.g. when a station became operational after 1965, an intensity measurement of the same station during the period with low geomagnetic and solar activity is selected. This is the case for the cosmic ray station in Dourbes (the earliest available data is from October 1965). Therefore, we have selected as a baseline the intensity during the year 2009 for which a minimum in the sunspot number has been reported (**Fig**.4-5). The filtered, pressure-uncorrected data is plotted in **Fig**.4-4. The final data, used for the calculation of the reference baseline intensity, is shown in **Fig**.4-6.

$$\mathrm{I_{\%}} = \frac{\mathrm{I} - \mathrm{I_R}}{\mathrm{I_R}} 100\%$$

where $\mathrm{I_R}$ = 6900±100 counts/min.

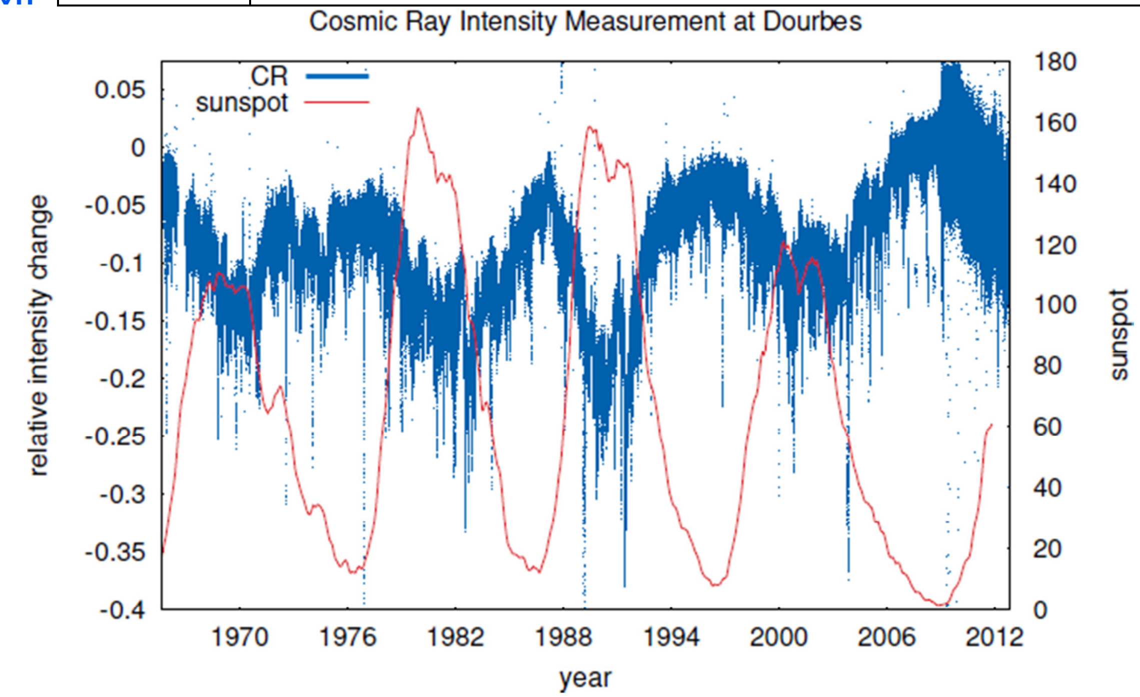

Fig.4-5: Sunspot number for the period January 1965 until May 2012 - the years (months) with minimum sunspots can be selected as a reference period with minimal solar modulation of the intensity of the cosmic radiation.

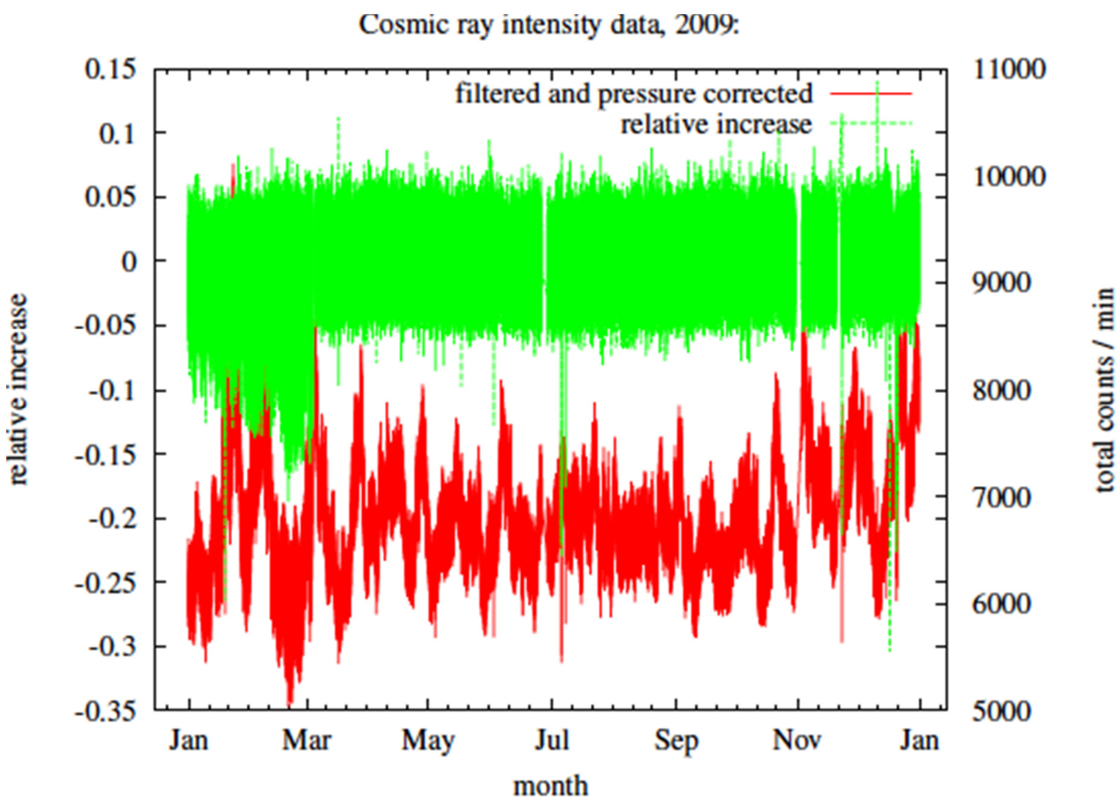

Fig.4-6: Filtered and pressure corrected cosmic ray intensity measurements at Dourbes from year 2009. This data is used to obtain the baseline reference intensity for the station which in turn is used to calculate the relative intensity increase. The latter is the reported data which is also used for detection of solar effects on the intensity of the galactic cosmic rays.

4.4 **Normalisation and re-normalisation**

The long term operation of the station requires periodic normalisation and re-normalisation of the output data in order to account for hardware changes (e.g. detector tubes, electronics), infrastructure (e.g. buildings in the vicinity of the station), etc. For example, **Fig**.4-2 shows how the relative contribution of some tubes (2, 5, and 8) differs from that of the remaining tubes, thus providing more to the total count rate of the station. Therefore, older stations have to be subjected to periodic re-normalisation. This can be done in two ways: the count rate of the old tubes can be corrected to the new ones (for example to account for ageing) or, alternatively, the count rate of the new tubes to be adjusted (to the old ones).

A CR modulation study should also be accompanied by a set of correction factors accumulated for the NM over its entire operational time. This implies that the usual normalisation indirectly varies with time (*Usoskin* et al., 1999). The re-normalisation has also to take into account when the reference base level intensity for the station has been calculated: if the reference level was calculated before a change in the equipment, then a re-normalisation has to be carried out. This is done in order to achieve certain continuity in data over the time.

These operations belong to the maintenance of the station and the data. In addition, the parameters used for data correction (tube count ratios, extrema, etc.) are also falling into this category and need to be verified on a periodic basis.

A possible recalculation of the parameters used in the automatic data correction can be carried out annually (e.g. for Dourbes, it is in the month of June). Needless to say, any substantial variation of the parameters that exceeds the nominal statistical fluctuation has to be thoroughly investigated.

4.5 **Examples of Ground Level Enhancements and Forbush Decrease events**

The corrected data can be used to identify various events such as the Ground Level Enhancement (GLE) (cf. **Fig**.4-7) and Forbush Decrease (FD) (cf. **Fig**.4-8). For verification of the Automatic Data Quality Correction (ADQC) algorithm, developed and implemented at Dourbes, selected events have been compared to verified data from other stations of the international Neutron Monitor Data Base (NMDB). For the particular GLE and FD events presented in **Fig**.4-7 and **Fig**.4-8, the observed intensity change at Dourbes was found to be almost identical with the results from the (verified) neutron monitor in Kiel which has similar geomagnetic cut-off rigidity.

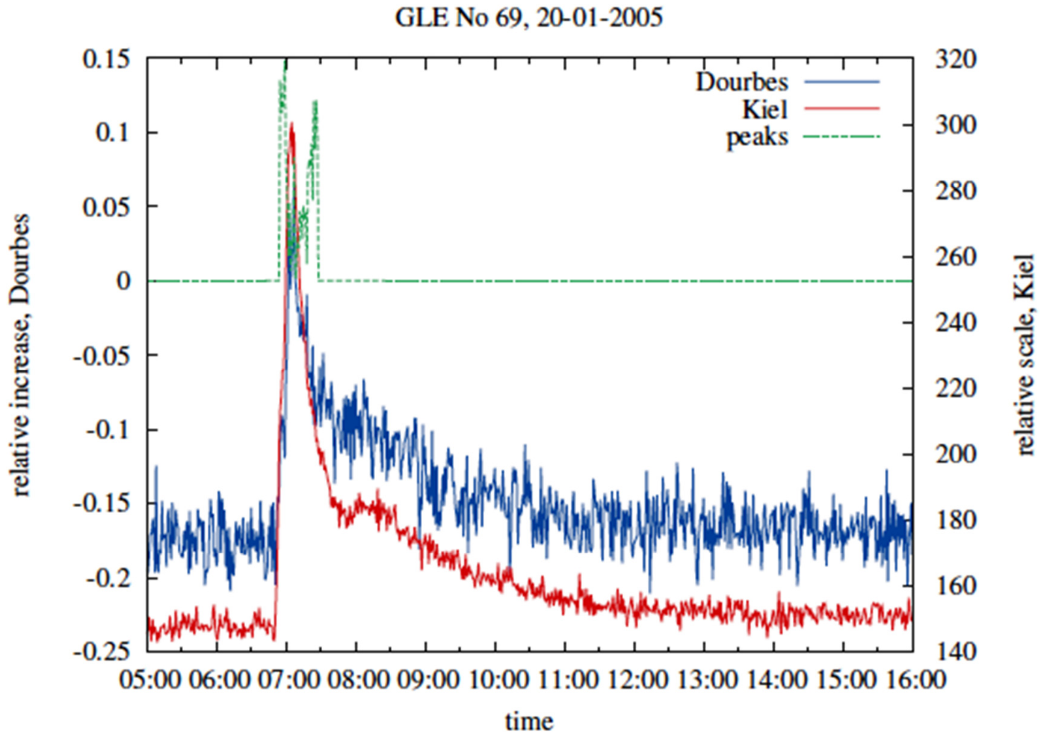

Fig.4-7: GLE event number 69 (20 January 2005) - data from Dourbes and from the neutron monitor in Kiel, Germany. The peaks plot is the signal from a peak identification algorithm used on the intensity data from Dourbes.

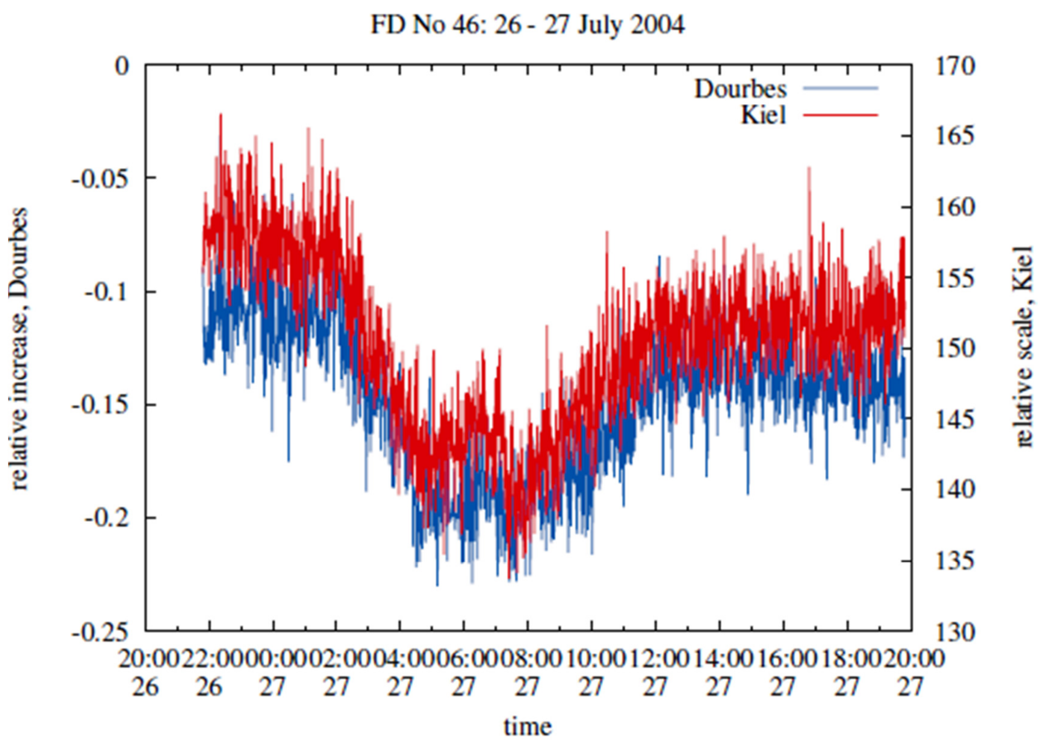

Fig.4-8: FD event number 46 (26-27 July 2004) as observed in Dourbes and verified with neutron monitor intensity measurements from Kiel, Germany.

5. Geomagnetic cut-off rigidity calculation for Dourbes

Magnetic rigidity is introduced to determine the effect of a particular magnetic field on the motion of a charge particle. It is a measure of the momentum of the particle and shows that particles with a greater momentum will have greater resistance to deflection by magnetic fields. Magnetic rigidity is defined as $B = B\rho = p/q$ where B is the magnetic field, ρ is the gyroradius of the particle due to this field, p is the particle momentum, and q is its charge. It follows from this definition that the intensity of the cosmic radiation will depend on the magnetic latitude of the measuring station. The geomagnetic rigidity then translates to the energy that a particle must have in order to penetrate the geomagnetic field and arrive at a specified position.

The geomagnetic cut-off rigidity for the Dourbes monitor has been calculated by a computer program developed by *Smart and Shea* (2001) utilising the trajectory-tracing technique: the motion of charged cosmic ray particles are calculated in a hard-order simulations of the geomagnetic field (GMF). The initial energies of the charged particles are taken within a certain interval and the destiny of the particle is determined for a given geographical position. The cut-off energy is then the lowest particle energy that reaches the specific position. As the GMF varies quite fast on a geological scale, the cosmic ray intensity measurements will also vary with time. The program used for the calculation of the cut-off rigidity uses the International Geomagnetic Reference Field (IGRF) 1995. The IGRF model is based on various magnetic field models and magnetic field measurements from satellites and observatories worldwide, and is updated every five years.

Using the coordinates of the neutron monitors in Dourbes, the value of the cut-off rigidity calculated by the TJI95 program is 3.18 GV. For comparison, the rigidity of other station have been also calculated and compared with the reported values from NMDB (cf. **Table** 5-1).

station	N	E	reported	calculated, GV		
				R_u	R_l	R_c
Moscow	55.47	37.32	2.43	2.4	2.22	2.31
Kiel	54.38	10.12	2.36	2.54	2.07	2.305
Dourbes	50.11	4.61	-	3.57	2.79	3.18
Novosibirsk	54.48	83	2.91	3.09	3.09	3.09
Rome	41.86	12.47	6.27	6.46	5.73	6.095

Table 5-1: Geomagnetic cutoff rigidity calculations for five stations, where: R_u - the upper cutoff, i.e. the rigidity of the last allowed before the first forbidden trajectory; R_l - the lower cutoff, i.e. the rigidity of the last allowed trajectory in a decreasing rigidity scan; and R_c - the effective cutoff, i.e. the average between R_u and R_l that accounts for the transparency of the penumbra (*Smart and Shea*, 2001).

6. Summary and Outlook

An automatic data quality control (ADQC) system has been recently implemented at the Dourbes station and the cosmic ray intensity measurements were corrected according to the requirements of the Neutron Monitor Database. The ADQC is capable to filter noisy shot peak signals from individual sections as well as from the entire station.

An important advantage of the here-presented ADQC is that it can recover missing values of all but one of the detector sections, based on the extrema test and the ratios algorithm. For the Dourbes station, which has nine sections, this means that the intensity data can be recovered even if only a single tube has operated correctly. In addition, missing pressure values can be interpolated or extrapolated; missing values replaced with the reference pressure for the station. The noise-filtered measurements data is further corrected for pressure and stored for detection of solar and geomagnetic events.

There are still some issues that need to be addressed. For example, it is necessary to determine the re-normalisation factors that would compensate slow temporal variations in the station output, e.g. ageing. Missing information about the time of replacement of the acquisition electronics and other detector hardware make the use of old data difficult in finding drifts in the intensity output. The different configuration of the neutron monitor station before 2003 requires a different approach in the implementation of the ADQC program.

Annex: Computer programming for Automatic Data Quality Control

One record of measurement of the intensities of the cosmic rays and pressure is saved every one minute on the file system in the following comma separated values (CSV) format:

<date>,<time>,
<count 1>,<count 2>,<count 3>,
<count 4>,<count 5>,<count 6>,
<count7>,<count 8>,<count 9>,
<pressure>

The patterns used for the different columns are given in **Table** 5-1.

Field	Pattern[1]
<date>	[:digit:]{4}/[:digit:]{2}/[:digit:]{2} (or YYYY/MM/DD in common notation)
<time>	[:digit:]{2}:[:digit:]{2}:[:digit:]{2} (or HH/mm/ss in common notation)
<count i> (i=1..9)	[:digit:]+
<pressure>	[:digit:]+\. [:digit:]+

Table A-1: Patterns ([1] POSIX Basic Regular Expressions) used for each field/column

One file is produced per day whose name indicates the date.That file is parsed by the program `CosmicRaysDataCorr` to produce a new one extended with three columns for the total intensity, the pressure corrected total intensity and the relative intensity increase calculated on the basis of the cosmic ray intensity in the year 2009. It also can feed a relational database accessed by the local Web application of Dourbes. Extraction from that local database can be done to send the same data to the NMDB database.

The current version of the source code of that program, written in C++, includes the following set of files:

```
CRMeasurement.hpp
CRDataCorrection.hpp
CRDataCorrection.cpp
main.cpp
```

The different options of running the program are listed below; the list is invoked by using the well-known “help” argument (-h).

```
cosmisRaysCorr [options]

OPTIONS:

-i <input filename>
     given with absolute path otherwise default path is chosen as current
     directory. (default is test/test.dat in current directory)
```

```
-O <output pathname>
     (default is current directory)

-o <output filename>
     relative to output pathname
     default is constructed as basename(inputFile.string()) + '.corr"

-C <config pathname>
     directory containing parameters files file tubeFractions.par and
     tubeRatios.par and reference data file refData.dat
     (default is subdir "config" in current directory)

-v
     verbose mode

-r
     with report

-f
     generates new parameters files <configPath>/tubeRatios,
     <configPath>/tubeFractions
     (needed in case of changes in the station hardware)

-h
  help
```

The program uses two parameter files and/or a reference data file:

`tubeRatios.par`	the tube fractions 9×9 matrix
`tubeFractions.par`	intensity contribution of each detector tube
`refData.dat`	file containing manually verified data

In case of changes in the order or the position of any of the sections, acquisition of new tubes, changes in the detection electronics or in the construction of the housing building, parameters files have to be regenerated by running the program with option (`-f`). That means that a new matrix with the tube ratios and the new tube fractions with the corresponding standard deviations have to be recalculated. That operation uses the file `refData.dat` containing a large number of original, not corrected for atmospheric effects, measurements over several days (at least a week) of the individual tubes:

```
683 698 634 637 737 668 594 762 663
712 722 672 675 729 643 648 753 676
687 746 677 668 738 602 ...
```

Detailed information about the operation of the program is given in the `manual.txt` file.

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NMDB (http://www.nmdb.eu/)
RMI Geophysical Centre in Dourbes (http://dourbes.meteo.be/)
ROB Sunspot Index and Long-term Solar Observations, SILSO (http://www.sidc.be/silso/)

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