Calculation of the barometric coefficients for the particle detectors belonging to the world-wide networks at the start of the 24^{th} solar activity cycle

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***Abstract*. After major modernization of the data acquisition electronics of the Aragats Space Environmental Center (ASEC) particle detectors the calculations of the barometric coefficients of all ASEC particle monitors were performed in the beginning of 24^{th} solar activity cycle. The time periods of minimal disturbances of the interplanetary magnetic field (IMF) were selected to avoid biases due to transient solar events. The barometric coefficients of different particle detectors measuring various secondary cosmic ray fluxes located at altitudes of 1000 m, 2000 and 3200 m. a.s.l. are calculated and compared. The barometric coefficients for the several Neutron Monitors of recently established Eurasian data base (NMDB) and SEVAN particle detector networks also were calculated. The latitude and altitude dependencies of the barometric coefficients were investigated, as well as the dependence of coefficients on the most probable energy of the primary protons generated definite species of the secondary fluxes.**

***Keywords*: Atmospheric pressure effects, Secondary cosmic rays, Instrumentation and techniques**

I. INTRODUCTION

Particle detectors of the Aragats Space Environmental Center [1], [2] are located at slopes of mountain Aragats and in CRD headquarters in Yerevan, Armenia; geographic coordinates: 40^o30'N, 44^o10'E, altitudes - 3200m, 2000m and 1000m a.s.l.. Various ASEC detectors, measuring fluxes of diverse secondary cosmic rays, are sensitive to different energetic populations of primary cosmic rays. Two neutron monitors (18NM-64) operating at Nor-Amberd and at Aragats research stations detect secondary neutrons. The Nor-Amberd muon multidirectional monitor (NAMMM) detects low energy charged particles and muons with energies above 350 MeV. The Aragats Multidirectional Muon Monitor (AMMM) registers high energy muon flux (threshold energy $-$ 5 GeV). The Aragats Solar Neutron Telescope (ASNT) is measuring neutrons and charged particles. ASNT is part of a world-wide network coordinated by the Solar-Terrestrial Laboratory of the Nagoya University. Another monitoring system, based on the scintillation detectors of the Extensive Air Shower (EAS) surface arrays, MAKET-ANI and GAMMA (3200 m a.s.l.), detects low energy charged particles. New world-wide particle detector networked, named SEVAN, is in operation now in Armenia, Bulgaria and Croatia [3], [4]. SEVAN detectors are measuring low energy charged particles, neutral particles (gammas and neutrons) and high energy muons. NAMMM and ASNT measuring channels are equipped with Amplitude-to-Digital (ADC) convertors and microcontroller based advanced electronics. Data Acquisition (DAQ) electronics and flexible software triggers allow to not only register the count rates of the detector channels, but also histograms of energy releases; correlations of the charged and neutral fluxes; and many other physical phenomena. Details of detector operation can be found in [4], [5].

Cosmic Ray flux incident on the terrestrial atmosphere and measured elementary particles on the Earth's surface comprise very different entities although genetically connected with each other. Primary particles interactions with atmospheric nuclei and different meteorological effects can hide genuine variations of the primary flux and prevent from understanding of dynamics of ongoing physical processes in solar-terrestrial chain.

For recovering the primary particles fluxes incident on the Earths atmosphere it is necessary to know the relationship between observed count rates of the detectors and the primary particles fluxes, as well as the influence of the meteorological effects on the flux of secondary particles reaching Earth surface. Dorman's theory of meteorological effects [6] gives detailed classification of the effects; mentioned the barometric one has a major influence on particle fluxes (at least for highest energies $10-100$ GeV). Therefore, it is of greatest importance to accurately measure the barometric coefficients to "unfold" the solar modulation effects. Besides this main goal there are several independent research problems connected with barometric coefficient dynamics:

- rigidity dependence;
- solar cycle phase dependence;
- height dependence;
- detected particle type dependence.

All these dependences can be investigated at ASEC and by SEVAN network due to different altitudes, various detected particle fluxes and planned long-term operation.

The main drivers of these dependences are changing according to solar cycle phase primary flux, type of secondary flux, and location of the detector. At minimum of solar activity, the GCR flux is enriched by abundant low energy (below 10 GeV) particles, blown out from solar system by intense solar wind at maximum of solar activity. Particle detectors located at high latitudes also are sensitive to lower primary energies compared with detectors located at middle and low latitudes, because of lower rigidity cutoff. Detectors located at high altitudes are registering more cascade particles than sea level detectors due to attenuation of cascade in the atmosphere. Therefore, because pressure effects should be more pronounced for cascades initiated by particles of lower energies and at cascades containing more particles, following relation can be expected:

- Barometric coefficient absolute value for same secondary particle flux is greater for detectors located at high latitudes compared with low latitudes;
- Barometric coefficient absolute value for same secondary particle flux should be greater at minimum of solar activity compared with maximum;
- Barometric coefficient absolute value for same secondary particle flux should be greater for high altitudes compared with sea level location;
- Barometric coefficient absolute value should be greater for neutrons than for muons;
- Barometric coefficient absolute value should be inverse proportional to muon energy;
- Barometric coefficient absolute value should be inverse proportional to zenith angle of incident particle flux;
- Barometric coefficient absolute value should be lower for high multiplicities detected in Neutron Monitors and for greater dead times of DAQ electronics.

All mentioned dependences were investigated and discovered during last 50 years by the networks of neutron monitors and muon detectors [6]. Nonetheless, because of peculiarities of detection techniques, scarce statistics, highly different local meteorological conditions, cycle-to cycle variations of solar activities dependencies yet are more qualitative and additional investigations of dynamic and interrelations of barometric coefficients are needed. ASEC provides ideal platform for such research.
During more than $50-$years of operation of Neutron Monitors (NM) network prove to be extremely effective in observing solar modulation effects. Several attempts were made to enlarge NM information contain: put additional channels without lead coverage, measure so called multiplicity (number of multiple counts), etc... The monitors are equipped with new electronics providing time integration of counts by three dead times. The first dead time equals to 400nsec for collecting almost all secondary neutrons generated in the lead of NM. The second dead time is equal to the 0.25μsec and the third one equal 1.25μsec (as most of NM from world-wide network).
Physical analysis of the 3 time series from one and the same monitor and comparison of data from 2 monitors located at 2 altitudes will be presented in the report. Barometric coefficients of the all 6 time series will be calculated and compared.
The paper is organized in the following way: second chapter will explain the statistical techniques used for the barometric coefficient calculations; third section will present the main results obtained for ASEC monitors at beginning of 24^{th} solar cycle; in discussion section we'll compare our results with previously obtained data and will check consistency of obtained results with expectations.

II. Regression methods used for the barometric coefficient calculation

Experimentally, the intensity I of any secondary cosmic ray component varies with a small change in the atmospheric pressure P [7] as

$$dI = -\mu dP \tag{1}$$

where μ is the absorption coefficient for the secondary component under consideration. For μ = constant, the equation 1 gives

$$I = I_0 e^{-\mu(P-P_0)} \tag{2}$$

Where P is pressure and P_0 is reference pressure, usually the average pressure at station. I and I_0 are counting rates at these pressures.
After simple transformation we readily get equation of linear regression:

$$ln(I/I_0) = -\mu(P-P_0) \tag{3}$$

Empirically value of the barometric coefficient can be found by means of linear correlation between intensity of cosmic-rays I_i and data of atmospheric pressure P_i.
We have calculated barometric coefficients for all of the ASEC monitors. The Aragats Multichannel Muon Monitor (AMMM) after changing data acquisition electronics, demonstrates large deviations of measured and Poisson relative errors. Therefore, electronics of AMMM is moved and under repair now.
We also calculated barometric coefficients for the SEVAN monitors located at Aragats and in Yerevan. SEVAN detectors have 3 layers inter-layered with lead filters. Middle thick layer is sensitive to the neutral particles. Analyzing the outputs from each layer we can outline different species of the incident on detector particles. For instance combination (010 signal only in middle scintillator) selects neutral particles. Probability that neutral particle gives signal in upper 5 cm thick scintillator less than 5%; and the signal probability that neutron will give signal in middle 25 cm thick scintillator is $\sim$ 25%. The combination (111 signals in all scintillators) selects: muons with energies greater

TABLE I
BAROMETRIC COEFFICIENTS, COUNT RATES AND RELATIVE ERRORS OF ARAGATS, IZMIRAN (MOSCOW) AND OULU (FINLAND) NEUTRON MONITORS, DATA FROM NMDB

Monitor	Barometric Coeff. [%/mb]	Correlation coefficient [GeV]	Count Rate [min]	Relative error	$1/\sqrt{N}$
NANM 0.4 μsec	-0.695 $\pm$ 0.013	0.997	28508	0.009	0.0059
ArNM 0.4 μsec	-0.730 $\pm$ 0.018	0.997	43954	0.007	0.0047
Moscow NM 0.4 μsec	-0.740 $\pm$ 5.11e-05	0.999	16054	0.012	0.0078
Oulu NM 0.4 μsec	-0.757 $\pm$ 3.37e-05	0.999	5990	0.019	0.0129

than 250 MeV the energy necessary to cross 10 cm. of lead.
In Table I we compare barometric coefficients of neutron monitors sending data to the Neutron Monitor Data Base (NMDB), a new European project to collect and present minute data from Eurasian detectors. The cutoff rigidities of selected monitors ranging from 0.81 to 7.1 GeV gave good representation of the network and, in addition, the Table provides some hints to compare monitor sensitivity to transient solar events and check of chamber failures. Different data reliability checks are of upmost importance when you are collected and compared data obtained from different detectors using various electronics and data acquisition software.

III. DISCUSION

Large diapason of the barometric coefficient values, covering approximately one order of magnitude, from 0.08% for the >5 GeV muon flux till 0.73% for the neutron flux demonstrates unique sensitivity of ASEC detectors to primary rigidities from 7 to 50 GV.
ASEC neutron monitors are simultaneously measuring count rates corresponding to the 3 preselected dead times: 0.4 μsec, 250 μsec and 1250 μsec. This additional information will provide possibilities to access different primary energies. Indeed, from Fig. 1 we can see that for both ANM and NANM larger dead times are correspondent to smaller barometric coefficients, i.e. to higher primary energies. As it was expected the absolute value of barometric coefficients increase with decreasing dead time, because of increasing sensitivity to lower energy primaries more influenced by pressure changes. In Fig. 1 in addition are depicted barometric coefficient obtained from data of 2 proportional counters located in Nor Amberd without lead filters. As it was expected, these chambers are most influenced by atmospheric pressure, due to their sensitivity to the lowest energy atmospheric neutrons.

In Table I and you can also see barometric coefficients for neutron monitors of Izmiran (Moscow) and Oulu(Finland) stations. Data were taken from Neutron Monitor Data Base (NMDB) in Kiel, Germany.

In Fig. 2 we compare barometric coefficients of Aragats (ARNM, 18 NM 64), Nor Amberd (NANM, 18 NM 64), Izmiran (Moscow 24 NM 64) and Oulu (Finland 9 NM 64) neutron monitors with barometric coefficients for neutron monitors calculated by [8] during minimum of solar activity in 1964-1965.

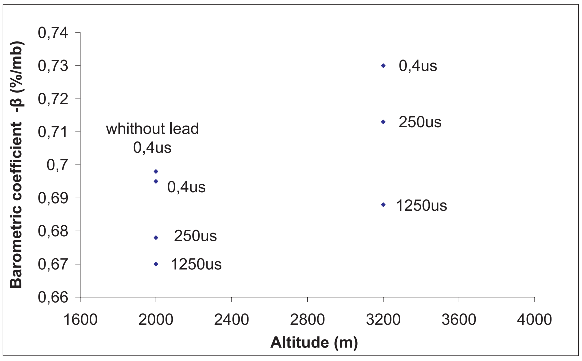

Fig. 1. Comparison of barometric coefficients of ASEC neutron monitors with different dead times

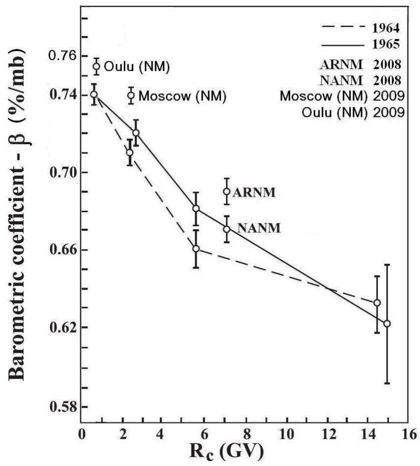

Fig. 2. Comparison of Aragats (ARNM), Nor Amberd (NANM), Izmiran (Moscow) and Oulu(Finland) neutron monitors with barometric coefficients for neutron component calculated by Dorman

We use dead time equal to 1250 μsec, value commonly used in the world-wide network of neutron monitors in 60-ths. All coefficients relate to solar activity minimum years (1965 and 2008) and are in good agreement with each other. Also it is apparent increase of the absolute value of barometric coefficients with decreasing of cutoff rigidity.
From ASEC muon channels it's clear that absolute value of barometric coefficients is inversely proportional to the muon energy.
In addition, by SEVAN barometric coefficients we can illustrate that indeed measured fluxes selected by detector electronics are enriched by different species of cosmic rays. Of course we cannot measure pure flux

of neutrons, due to contamination of gamma-quanta and muons. However, we have obtained that, events selected as neutrons demonstrate barometric coefficients approximately twice as events selected as muons. Just same behavior we are expecting from the neutron and muon fluxes. SEVAN detector measure in addition different combinations of signals in detector layers; therefore we can pose problem of finding barometric coefficients of the pure fluxes, as it was described in [9].
The summary of ASEC barometric coefficients we present in Fig. 3 and 4. From simulations [10] we estimate the most probable energy for each detector.

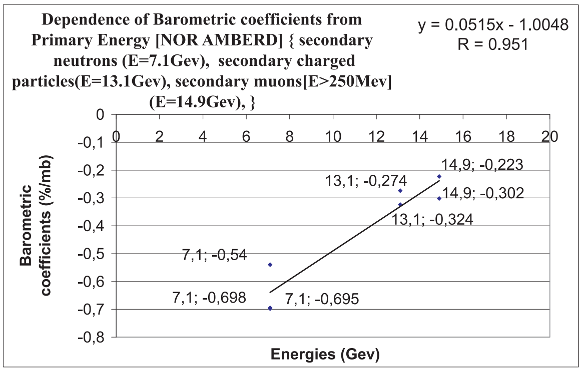

Fig. 3. The dependence of barometric coefficient on the primary energy for Nor Amberd station detectors

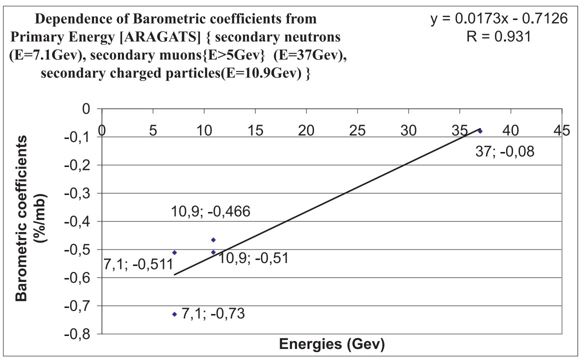

Fig. 4. The dependence of barometric coefficient on the primary energy for Aragats station detectors

As we can see in Fig. 3 4 and 4, energy of primary particle corresspondent to the secondaries measured by the detector and barometric coefficient correlate rather well.

IV. Conclusions

1) Large diapason of the barometric coefficient values, covering approximately one order of magnitude, from 0.08% for the $>$5 Gev muon flux till 0.73% for the neutron flux demonstrates unique sensitivity of ASEC detectors to primary particles with rigidities from 7 to 50 GV.
2) Barometric coefficients of monitors belonging to the new particle detector network SEVAN demonstrate that 3 layers of monitors are sensitive to different species of the secondary cosmic rays, namely: low energy charged, neutrons and high energy muons. It is independent check of the SEVAN monitors, proving results obtained by simulations.
3) Preliminary analysis of the barometric coefficients calculated for ASEC monitors proves expectations about its energy and altitude dependence. Obtained coefficients are used for correcting ANM and NANM data to appear in the Neutron Monitor Data Base (NMDB) in Kiel, Germany, a European project to collect on-line data of neutron monitors. Data also is transferred to mirror site in USA and will be transferred to new mirror sites of CRD site in Russia and Europe.

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