New energy estimates of inclined showers in terms of the EPOS LHC and QGSJETII-04 models

Dedenko L.G., Lukyashin A.V., Roganova T.M., Fedorova G.F.
M.V. Lomonosov Moscow State University Faculty of Physics
Skobeltsyn Institute of Nuclear Physics
NRC «KI» - ITEP
NRNU «MEPhI»

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Content

1. Introduction
2. Motivation
3. Modeling with GEANT 4.1
4. Comparison of modeling
5. Testing of hadronic interaction models
6. Simulating and calculations
7. Results
8. Conclusion
Introduction

- SSD are operated for almost ~ 100% of astronomical time, and detectors of Cherenkov radiatio and fluorescent light detector are only within 5-10%. Therefore, estimates of the $E_0$ (EAS energy) from the signals $s(r,\theta)$ in the SSD located at different distances $r$ from the shower axis (core) that fell on the plate at the zenith angle $\theta$ are very important!
## Detector technique at EAS-observatories

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSD</td>
<td>Surface Scintillation Detector</td>
</tr>
<tr>
<td>USD</td>
<td>Underground Scintillation Detector</td>
</tr>
<tr>
<td>ChD</td>
<td>Cherenkov radiation Detector</td>
</tr>
<tr>
<td>FluoT</td>
<td>Fluorescence Telescope</td>
</tr>
<tr>
<td>ChSD</td>
<td>Cherenkov Surface Detector</td>
</tr>
</tbody>
</table>

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Detector technique at EAS-observatories
Spatial distribution function of signal

A — distance from the shower core [m]
B — density of signal in detector [arb.particle/m²]
Yakutsk EAS Array

Web-link http://eas.ysn.ru/
Yakutsk EAS Array

Village Oktyomtsy, ~50 km at South from Yakutsk

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>~8 km²</td>
</tr>
<tr>
<td>Altitude</td>
<td>~100 m (a.s.l.)</td>
</tr>
<tr>
<td>SSD</td>
<td>58</td>
</tr>
<tr>
<td>USD</td>
<td>6</td>
</tr>
<tr>
<td>ChD</td>
<td>48</td>
</tr>
<tr>
<td>Detector pitch</td>
<td>250/500/1000 m</td>
</tr>
</tbody>
</table>

Web-link [http://eas.ysn.ru/](http://eas.ysn.ru/)
Scheme of detector at Yakutsk Array

Detectors arrangement in a station

Web-link http://eas.ysn.ru/
Method

• At first we have to determine approximation of spatial distribution function of signals \( s(r,\theta) \) in SSD for each inclined shower by least-squares method:

\[
y = b_0 + b_1 \cdot x + b_2 \cdot x^2
\]

• \( x = \log(r/[1\text{m}]) \), \( y = \log(s(r,\theta)) \).

• This approximation gives the signal \( s(600,\theta) \) at the distance \( d=600 \text{ m} \) from the shower core.

• For each angle - its own approximation.

<table>
<thead>
<tr>
<th>Toolkit</th>
<th>GEANT 4.1</th>
<th>CORSIKA 7.4</th>
<th>Original programs</th>
</tr>
</thead>
</table>

Approximation of signals $s(r, \theta_0)$ by quadratic polynomial
Detector model in frameworks of GEANT 4.1

Water as equivalent of snow (WINTER)

Sheathing (Iron, Aluminium, Wood)

Scintillator (Plastic)
Signals in detector induced by various particles

- All the tables of signals has been calculated via the GEANT4 package for both, winter and summer weather conditions.

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\gamma, e^{\pm}$</th>
<th>$\mu^{\pm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy interval</td>
<td>$10^{-1} \div 10^{5} \text{ MeV}$</td>
<td>$10^{2} \div 10^{7} \text{ MeV}$</td>
</tr>
<tr>
<td>Energy partition</td>
<td>20 points/order</td>
<td>20 points/order</td>
</tr>
<tr>
<td></td>
<td>121 points</td>
<td>101 points</td>
</tr>
<tr>
<td>Angular partition (Cos(\theta) values)</td>
<td>19 points</td>
<td>19 points</td>
</tr>
<tr>
<td>Statistics</td>
<td>$10^{4}$</td>
<td>$10^{4}$</td>
</tr>
</tbody>
</table>
Signals in SSD induced by muon

$E_{WC}$ and $E_{SC}$ the energies recording in winter and summer weather conditions.

1 – $\cos\theta=1$

2 – $\cos\theta=0,9$

3 – $\cos\theta=0,8$

4 – $\cos\theta=0,7$

5 – $\cos\theta=0,6$

6 – $\cos\theta=0,5$
Signals in SSD induced by positron

$E_{\text{wc}}$ and $E_{\text{sc}}$ the energies recording in winter and summer weather conditions.

1 – $\cos\theta = 1$
2 – $\cos\theta = 0,9$
3 – $\cos\theta = 0,8$
4 – $\cos\theta = 0,7$
5 – $\cos\theta = 0,6$
6 – $\cos\theta = 0,5$
Signals in SSD induced by electron

$E_{WC}$ and $E_{SC}$ the energies recording in winter and summer weather conditions.

1 – $\cos\theta=1$
2 – $\cos\theta=0.9$
3 – $\cos\theta=0.8$
4 – $\cos\theta=0.7$
5 – $\cos\theta=0.6$
6 – $\cos\theta=0.5$
Signals in SSD induced by gammas

$E_{WC}$ and $E_{SC}$ the energies recording in winter and summer weather conditions.

1 – $\cos\theta=1$
2 – $\cos\theta=0,9$
3 – $\cos\theta=0,8$
4 – $\cos\theta=0,7$
5 – $\cos\theta=0,6$
6 – $\cos\theta=0,5$
Signals in USD induced by muons

Ratio $R$ of the energy detected in the underground detector from the muon to the energy detected in the surface detector. This ratio is 10-40% higher due to the development of a cascade in the ground.

1 – $\cos \theta = 0.8$
2 – $\cos \theta = 0.9$
3 – $\cos \theta = 1$

$O$ – 0.5 m
$\triangle$ – 1 m
$\square$ – 2 m
$\diamond$ – 3 m
Signals (1) and muon energy losses (2) in the SSD. The ratio $R$ of the signal (1) to the losses (2) decreases due to the radiation losses. These losses cannot be registered in the detector.
Vertical Equivalent Muon

The problem is to determine the practical unit of measurement of the signal in VEM units in ground and underground detectors in standard eV units using a telescope located on the surface and at a depth of \( L = 0.5 \) m.

\[
VEM = \frac{\int_{E_{th}}^{\infty} E_S(E) \cdot S_\mu(E) \, dE}{\int_{E_{th}}^{\infty} S_\mu(E) \, dE}
\]

\( E_{th} \) – this value determined by the energy losses in a ground (depth value \( L = 0.5 \) m),  
\( E_s \) – signal,  
\( S_\mu \) – vertical muon spectra

<table>
<thead>
<tr>
<th>SSD</th>
<th>USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8 MeV</td>
<td>11.4 MeV</td>
</tr>
</tbody>
</table>
# Energy estimations at the Yakutsk Array

<table>
<thead>
<tr>
<th>Vertical showers</th>
<th>Inclined showers</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1 = 11.75$ MeV</td>
<td>$E_{inc} = E_1 \cdot \sec \theta$</td>
</tr>
</tbody>
</table>

\[
E_V = a \cdot (s_V(600))^{1.00 \pm 0.02}
\]

\[
a = (4.8 \pm 1.6) \times 10^{17} \quad \frac{eV}{VEM \cdot m^2}
\]

\[
s_V(600) = s_{INC}(600) \times \exp\left(\left(\sec \theta - 1\right)X_0 / \lambda_0\right)
\]

\[
\lambda_0 = (450 \pm 44) + (32 \pm 15) \cdot \lg(s_V(600)) \quad \frac{g}{cm^2}
\]
Signals in scintillation detector

Energies $s(r)$ and its fractions registered by scintillation detectors induced by EAS with energy $10^{18}$ eV

<table>
<thead>
<tr>
<th>Distance $r$, m</th>
<th>Signal $s(r)$, MeV/m²</th>
<th>$\gamma$</th>
<th>$e^+$</th>
<th>$e^-$</th>
<th>$\mu^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>$4,00 \times 10^2$</td>
<td>0,64</td>
<td>0,09</td>
<td>0,17</td>
<td>0,1</td>
</tr>
<tr>
<td>600</td>
<td>$3,85 \times 10^1$</td>
<td>0,58</td>
<td>0,08</td>
<td>0,15</td>
<td>0,19</td>
</tr>
<tr>
<td>1000</td>
<td>$5,63 \times 10^0$</td>
<td>0,47</td>
<td>0,08</td>
<td>0,12</td>
<td>0,33</td>
</tr>
</tbody>
</table>
• \( E_{\text{inc}} = a(\theta) \cdot s(600,\theta) \cdot 10^{17} \text{ eV} \)

• \( a(\theta) = a_0 + a_1 \cdot (\sec \theta - 1) + a_2 \cdot (\sec \theta - 1)^2 \)

• Formulas for signals at distances of 300 and 1000 m from the shower core are similar.

• Signals \( s(600,\theta) \) are expressed in units of \( E_{\text{VEM}} = 10.8 \text{ MeV} \).
Results of calculations $a(\theta)$ for models QGSJETII-04 and EPOS LHC as a function of $\sec(\theta)-1$
The result of approximation by a quadratic polynomial $a_0$, $a_1$ и $a_2$

The coefficients $a(\theta)$ has been calculated for vertical shower ($0^\circ$) and for inclined showers with zenith angles $15^\circ$, $30^\circ$ and $45^\circ$
Table of coefficients a(0)

<table>
<thead>
<tr>
<th>Model\Work</th>
<th>[1]</th>
<th>[2]</th>
<th>[2]/k</th>
<th>[3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGSJETII-04</td>
<td>3.52</td>
<td>3.19</td>
<td>2.93</td>
<td>2.88</td>
</tr>
<tr>
<td>EPOS LHC</td>
<td>3.74</td>
<td>2.87</td>
<td>2.64</td>
<td>2.59</td>
</tr>
<tr>
<td>Uncertainty of measurement</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±0.15</td>
</tr>
</tbody>
</table>


3) N. V. Anutin, L. G. Dedenko, T. M. Roganova, G. F. Fedorova, Physics of atomic nuclei 80, 260 (2017) [YadFiz 80, 1 (2017)].
Absorption range

<table>
<thead>
<tr>
<th>Model</th>
<th>$\lambda_0$, g/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGSJETII-04</td>
<td>690±80</td>
</tr>
<tr>
<td>EPOS LHC</td>
<td>740±80</td>
</tr>
</tbody>
</table>
Пробеги поглощения

• Модель $\lambda_0$, г/см$^2$
• QGSJETII-04 690+-80
• EPOS LHC 740+-80

$\lambda_0 = (450 \pm 44) + (32 \pm 15) \cdot \lg(s_B(600))$ г · см$^{-2}$

• Оценки пробегов на ЯКУ
Important note for testing

• Models QGSJETII-04 and EPOS LHC has been tested by using the LHC data in a region of pseudorapidity $\eta \sim 0$.

• In present work has been used the results of outer testing via atmospheric muon energy spectra (L3, LVD, MACRO collaborations) in a region of pseudorapidity $\eta \sim 8-12$. 
Primary cosmic ray spectrum

• The flux of primary protons and helium nuclei have been approximated.

• We have exploited the AMS-02 data for the energy range $E_n \in 10^2 - 1.8 \cdot 10^3$ GeV.

1. Approximations of simulations by Berezhko E.G. have been used.
2. Normalization at 1.8 TeV to the AMS-02 data has been used.
The primary proton spectrum (approximation and data)
The primary helium nuclei spectrum (approximation and data)
Relative contribution of the primary protons with energies $E$ to the 1-st bin of muon energy spectrum

$\Phi_p E_p S_{p_p}(E_\mu, E) \approx 0.1 A_{\text{max}}$

SIBYLL 2.3

$E_\mu = 105.9$ GeV
Relative contribution of the primary protons with energies $E$ to the 21-st bin of muon energy spectrum.
Relative contribution of the primary protons with energies $E$ to the 41-st bin of muon energy spectrum.
Vertical muon energy spectrum data

\[ \Phi (E_\mu) E_\mu^3 \text{GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

\[ 10^{-1} \quad 10^{-2} \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \]

\[ E_\mu, \text{GeV} \]

- L3+Cosmic
- MACRO
- LVD
- Frejus
- MSU
- Baksan
- Smooth Approximation
Muon fluxes (data and simulations)

Vertical muons

\[ \Phi(\mu) \propto E^3 \]

- Data (Smooth Approximation)
- VENUS 4.12
- SIBYLL 2.3
- EPOS LHC
- QGSJETII-03
- QGSJETII-04

\[ \Phi(\mu) \propto E^3 \]

- Data (Smooth Approximation)
- VENUS 4.12
- SIBYLL 2.3
- EPOS LHC
- QGSJETII-03
- QGSJETII-04
Result of calculations (atmospheric muons)
Results

• To obtain the energy spectrum of the Yakutsk EAS Array, the number of 112 showers processed by the proposed approach from the database was divided into roughly equal parts: with an energy of less than $4.6 \cdot 10^{18}$ eV and more.

• For the QGSJETII-04 and EPOS LHC models, the mean values of the coefficients $R = E_{Yak}/E_n$ were determined, respectively, 1.67 and 1.85 for the first part and 1.51 and 1.68 for the second.
Energy spectra of primary cosmic rays

- new estimations based on SSD signals
- Yakutsk Array (Cherenkov radiation detector)

Δ – TA
■ – PAO
Results

• There is a good agreement for the first part of the spectra obtained at the Yakutsk Array by the signals of the SSD and the Cherenkov detector measurement data and the results of the TA.

• For the second part of the spectrum, one can speak of a satisfactory agreement, bearing in mind large errors.

• The spectra obtained in the framework of the EPOS LHC model are good and consistent with the PAO data in the first part of the spectrum and with TA - in the second.
Acknowledgements

• Authors thanks to M.I. Pravdin and S.P. Knurenko for the givens parts of the Yakutsk Array database for testing the new method.

• Thank to organizing committee of the ECRS+RCRC 2018 conference for administrative support!

Thank you for attention!
Backup slides

Backup slides
Cosmic Rays Data (Primary spectra)

Data of the muon spectra


<table>
<thead>
<tr>
<th>(\cos(\Theta))</th>
<th>(\Theta [\text{deg.}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,05</td>
<td>87,134</td>
</tr>
<tr>
<td>0,1</td>
<td>84,261</td>
</tr>
<tr>
<td>0,15</td>
<td>81,373</td>
</tr>
<tr>
<td>0,2</td>
<td>78,463</td>
</tr>
<tr>
<td>0,25</td>
<td>75,522</td>
</tr>
<tr>
<td>0,3</td>
<td>72,542</td>
</tr>
<tr>
<td>0,35</td>
<td>69,513</td>
</tr>
<tr>
<td>0,4</td>
<td>66,422</td>
</tr>
<tr>
<td>0,45</td>
<td>63,256</td>
</tr>
<tr>
<td>0,5</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\cos(\Theta))</th>
<th>(\Theta [\text{deg.}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,55</td>
<td>56,633</td>
</tr>
<tr>
<td>0,6</td>
<td>53,13</td>
</tr>
<tr>
<td>0,65</td>
<td>49,458</td>
</tr>
<tr>
<td>0,7</td>
<td>45,573</td>
</tr>
<tr>
<td>0,75</td>
<td>41,41</td>
</tr>
<tr>
<td>0,8</td>
<td>36,87</td>
</tr>
<tr>
<td>0,85</td>
<td>31,788</td>
</tr>
<tr>
<td>0,9</td>
<td>25,842</td>
</tr>
<tr>
<td>0,95</td>
<td>18,195</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Result of calculations (ratio)
Superposition conception (result for SIBYLL)

- He $1.26 \times 10^6$ GeV vs. Super($p^+$) $3.162 \times 10^5$ GeV SIBYLL 2.1

Ratio $He/(4p^+)$ vs. Energy $E_\mu$ [GeV]
Superposition conception (result for SIBYLL)

- N $1.4 \cdot 10^7$ GeV vs. Super(p$^+$) $1 \cdot 10^6$ GeV SIBYLL 2.1

Ratio $N/(14p^+)$ vs. Energy $E_\mu$ [GeV]
Superposition conception

- Helium nuclei ($A=4$) and nitrogen nuclei ($A=14$) is a system of $A$ nucleons.

\[
S_{He} \left( E_\mu, E_{He} \right) \approx 4 \cdot S_p \left( E_\mu, E_p = \frac{E_{He}}{4} \right)
\]

\[
S_N \left( E_\mu, E_N \right) \approx 14 \cdot S_p \left( E_\mu, E_p = \frac{E_N}{14} \right)
\]
Superposition

SIBYLL 2.1

$S_{He}(E_{He})$ vs. $4 \cdot S_p(E_p = E_{He}/4)$

- He 948 GeV
- He $1.26 \times 10^4$ GeV
- He $1.26 \times 10^5$ GeV
- He $1.26 \times 10^7$ GeV
- He $1.26 \times 10^8$ GeV

- 4p 237 GeV
- 4p $3.162 \times 10^3$ GeV
- 4p $3.162 \times 10^4$ GeV
- 4p $3.162 \times 10^6$ GeV
- 4p $3.162 \times 10^7$ GeV

Energy of muons $E_{\mu}$ [GeV]
Superposition

SIBYLL 2.1

$S_N(E_N) \text{ vs. } 14 \cdot S_p(E_p = E_N/14)$

- $N \times 1.86 \times 10^3 \text{ GeV} \quad 14p \ 133 \text{ GeV}
- $N \times 1.05 \times 10^4 \text{ GeV} \quad 14p \ 750 \text{ GeV}
- $N \times 1.4 \times 10^5 \text{ GeV} \quad 14p \ 10^4 \text{ GeV}
- $N \times 1.4 \times 10^6 \text{ GeV} \quad 14p \ 10^5 \text{ GeV}
- $N \times 1.4 \times 10^7 \text{ GeV} \quad 14p \ 10^6 \text{ GeV}
- $N \times 7.872 \times 10^7 \text{ GeV} \quad 14p \ 5.623 \times 10^6 \text{ GeV}$

$E_\mu \cdot S_{\mu}(E_\mu, E_N)$

Energy of muons $E_\mu \ [\text{GeV}]$
Contribution to the muons generation with fixed energies

1 - $E_\mu = 105.9$ GeV
2 - $E_\mu = 1059$ GeV
3 - $E_\mu = 10590$ GeV

$E \cdot S_p(E_\mu, E)$

$E$, GeV

$E_\mu$, GeV
Ps. rapidity and rapidity distributions of secondary particles

SIBYLL 2.1
$\sqrt{s}=7\text{TeV}$

pp
Ps. rapidity and rapidity distributions of secondary particles

- Secondary particles with rapidities $\sim 8 \div 12$ carried almost of energy of primary protons.
- Fraction of such particles is below 5%.
Ps. rapidity and rapidity distributions of secondary particles
Links

• **GEANT 4.1** The GEANT 4 Collab.,

• **CORSIKA 7.4** D. Heck, J. Knapp, J-N Capdevielle et al.,

• **TA Collaboration:** R. U. Abbasi, M. Abe, T. Abu-Zayyad, M.

• **PAO Collaboration:** A. Aab, P. Abreu, M. Aglietta, E.J. Ahn et
  [arXiv:1509.03732].
Cosmic Rays DataBase

Database of Charged Cosmic Rays

D. Maurin (LPSC), F. Melot (LPSC), R. Taillet (LAPTh)

If you use this database, please cite Maurin, Melot, Taillet, A&A 569, A32 (2014) [arxiv.org/abs/1302.5525].

Description

This database is a compilation of experimental cosmic-ray data. The database includes electrons, positrons, antiprotons, and nuclides up to Z=30 for energies below the knee. If you spot any errors or omissions, want to contribute, or simply comment on the content of the database, please contact us. We are eager to extend the database to Z>30 and to higher energy ground measurements and any help is welcome.

Warning: several sets of Solar modulation values are provided per sub-experiment. We refer the user to Sect.2.3 of Maurin et al. (2013) for a complete discussion, and only give below a brief description of the different sets of modulation parameters available in the CRDB: [read more]

Current version / Latest data added / Acknowledgements

Structure of the database

This is a MySQL database containing lists of experiments (name, dates of flight, experimental technique in brief, website), the corresponding publications (ref. and link to the ADS database), and all available data points (fluxes and ratios of leptons, nuclides, and anti-protons including their statistical and systematic error whenever available).

Accessing the database

- Experiments/Data: list of experiments, publications, data
- Data extraction: selection by flux/ratio/energy range... (on this web site or via a REST interface)
- Export database content in USINE or GALPROP compliant format (ASCII files)
- Get all bibtex entries and Latex cite (by sub-experiment)

Acknowledgements: this project has been financially supported by the PNHE


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Approximation of primary cosmic rays

Equations for flux of the primary protons.

\[
\frac{d\Phi_p}{dE} = \begin{cases} 
0.4544 \cdot \left(\frac{E}{45}\right)^{-2.849} \cdot \left[1 + \left(\frac{E}{336}\right)^{5.5417}\right]^{0.024} & E \in \left[10^2 \div 1.8 \cdot 10^4\right] \text{GeV} \\
8728 \cdot E^{-2.7} \cdot \left(\frac{E}{10^4}\right)^{0.06} & E \in \left[1.8 \cdot 10^4 \div 10^6\right] \text{GeV} \\
8728 \cdot E^{-2.7} \cdot \left(\frac{E}{10^4}\right)^{0.06} \cdot \text{Exp}\left[-\frac{E-10^6}{6 \cdot 10^6}\right] & E \in \left[10^6 \div 10^7\right] \text{GeV}
\end{cases}
\]
Approximation of primary cosmic rays

Equations for flux of nucleons of the primary helium nuclei. $E$ — energy per nucleon.

$$
\frac{d\Phi_{He}}{dE} = \begin{cases} 
0.1896 \left( \frac{2 \cdot E}{45} \right)^{-2.78} \cdot \left[ 1 + \left( \frac{2 \cdot E}{245} \right)^{4.4074} \right]^{0.027} & E \in [10^2 \div 1.8 \cdot 10^4] \text{ GeV} \\
921 \cdot E^{-2.7} \cdot \left( \frac{E}{10^4} \right)^{0.068} & E \in [1.8 \cdot 10^4 \div 10^6] \text{ GeV} \\
921 \cdot E^{-2.7} \cdot \left( \frac{E}{10^4} \right)^{0.068} \cdot \exp \left[ -\frac{E - 10^6}{6 \cdot 10^6} \right] & E \in [10^6 \div 10^7] \text{ GeV}
\end{cases}
$$

As primary protons and helium nuclei contribute to the energy spectrum $\sim 98\%$ we relegate the more heavier nuclei.
Literature

At the first recalculation mentioned above, because of the unit of signal measurement chosen at the Yakutsk unit, the electron-photon part of the signal is forcibly underestimated and, consequently, the zenith angular dependence of this part is distorted.

Currently, major installations are upgrading to register cosmic rays in the energy range $<10^{18}$ eV.

Therefore, the testing of the new methodology on the part of the data bank of the Yakutsk installation allows applying it to the entire bank and obtaining new scientific results earlier than in other installations.