Study of the anisotropy of cosmic rays during the periods of the minima of the 24th solar cycle using the muonography method according to the data of the URAGAN muon hodoscope

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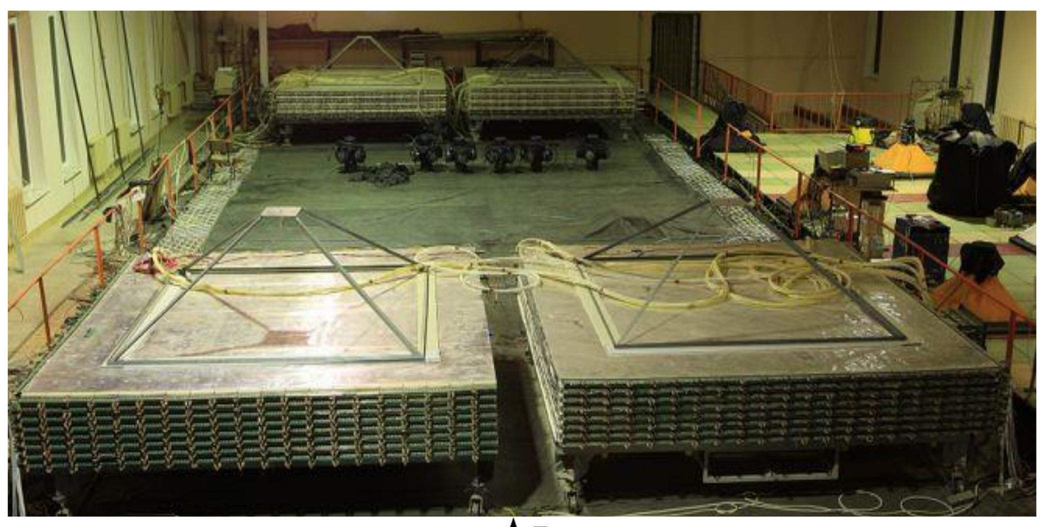
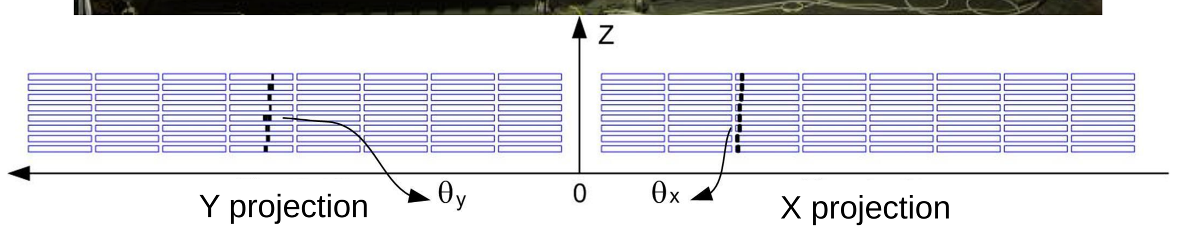
Muon hodoscope URAGAN (MEPhI, Moscow) with an area of 45 sq. m is capable of real time detection of all muons arriving from the upper celestial hemisphere with a high spatial and angular accuracy. The measured angular distribution of the muons flux over a certain period of exposure time and expressed in R.M.S. deviations from an averaged reference matrix and corrected for barometric and temperature effects represents matrix-muonograph (by analogy with X-ray radiography) of the Earth's atmosphere and near-terrestrial space. Such muonograph contains information on the current variation the flux of cosmic muons associated with modulation processes in the heliosphere, magnetosphere and atmosphere of the Earth. The sequence of muonographs converted to the GSE coordinate system allows one to study in real time the dynamics of cosmic ray anisotropy and to identify in advance geoeffective processes in the heliosphere associated with solar activity. Results of the analysis of the anisotropy of the CR muon flux at the minima of the 23rd (2009-2010) and 24th (2018-2019) solar cycles are discussed.

Muon hodoscope URAGAN

Muon hodoscope URAGAN (MH) is intended for detectIon of muons simultaneously from all directions of the upper hemisphere and to study of characteristics of muon flux variations.

- 4 independent supermodules (SM)
- SM - 8 planes of streamer tube chambers with external strip read-out (8×[320-X & 288-Y] chan.). SM area ~11 m^2.
- SM trigger: coincidence of signals from ≥ 4 X-planes within time gate 250 ns.
- Resolution: angular – 0.8°; spatial – 1 cm





Real time data format

- Data of each SM – sequence of 2D muon matrices (**90×90 angular cells**) of number of muon tracks detected in real time mode from any direction of upper hemisphere during one minute intervals.
- One minute matrix: ~ **80,000 muons.** For long-time heliospheric disturbances, the sequence of **one hour matrices.**
- The statistic of every such matrix is **~ 15 million events.**
- Graphical representation of the matrix changes of the angular intensity distribution of events during the last hour normalized to data during the preceding 24 hours (in terms of the R.M.S.errors)

Muonography

To visualize the spatial-angular variations of the muon flux intensity in time, the **muonography technique** is used. Muonographs allow to study the dynamics of two-dimensional muon flux variations.

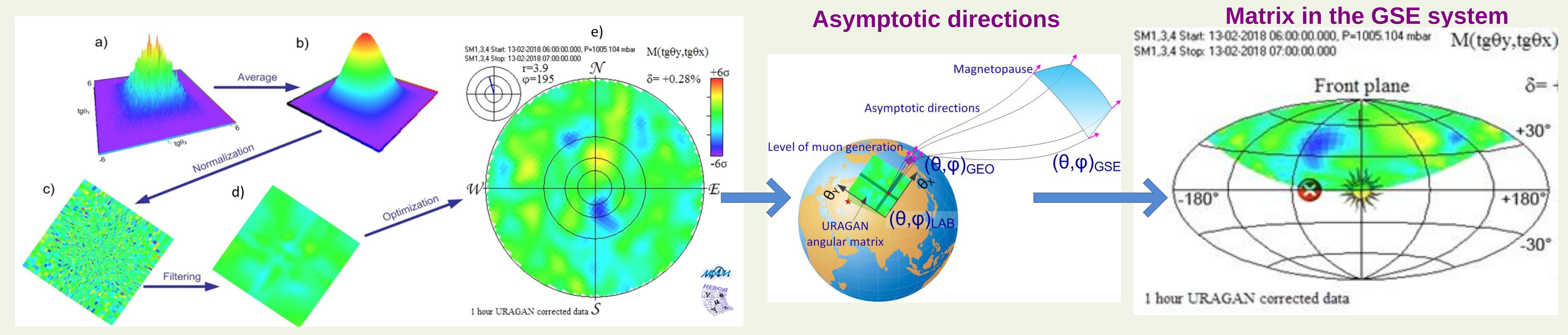
Meteorological effect correction:

$$M^{cor}[tg\theta_Y, tg\theta_X] = M[tg\theta_Y, tg\theta_X] + \Delta M^P[tg\theta_Y, tg\theta_X] + \Delta M^T[tg\theta_Y, tg\theta_X]$$

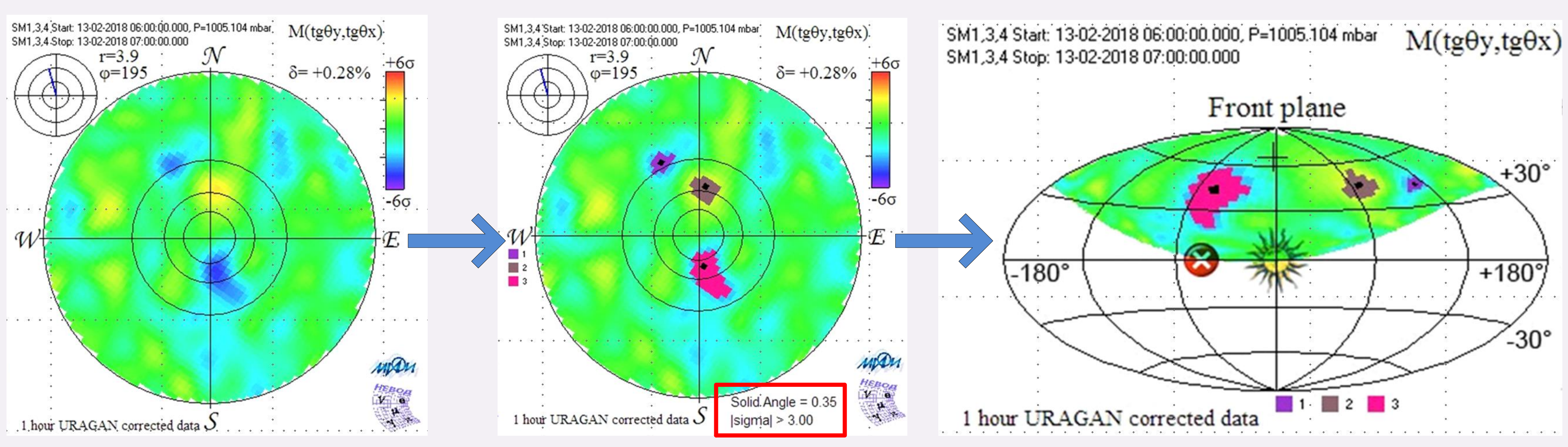
Variations in the counting rate in units of R.M.S.:

$$\delta_\sigma(tg\theta_Y, tg\theta_X) = \frac{M(tg\theta_Y, tg\theta_X) - M_{24h}(tg\theta_Y, tg\theta_X)\cdot T_{live}/T_{24h}}{\sqrt{M_{24h}(tg\theta_Y, tg\theta_X)\cdot T_{live}/T_{24h}}}$$

Muonograph – "snapshot" of upper hemisphere in **"muon light"**



GSE-mapping



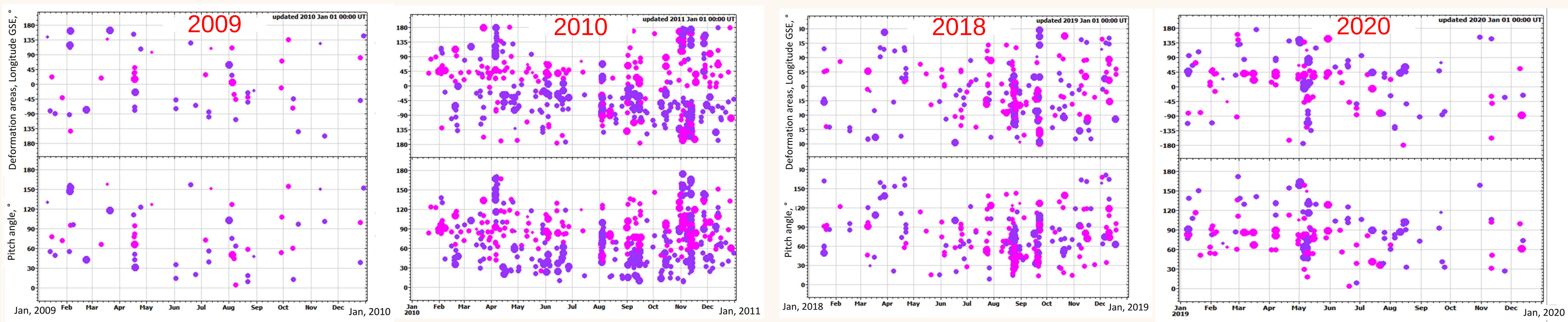
- ***Muonograph*** is an hourly matrix of track parameters normalized to the number of events, smoothed with respect to slow trends and daily fluctuations in the intensity, and corrected for the shape of the angular distribution of the muon flux.
- To obtain muonographs, the relative deviations of the intensities of the muon flux are calculated in units of R.M.S.
- Using asymptotic directions, muonographs from the laboratory coordinate system are transformed into the angular distribution of parent protons at the magnetopause in the GSE system.

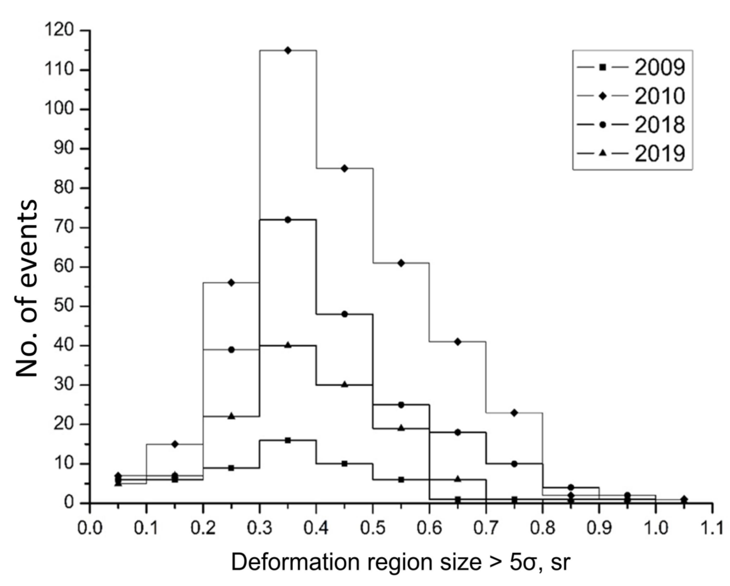
On the ***GSE muonographs***, regions (≤10) are selected with deviation ***δ >3σ***. These areas are referred to as ***deformation areas***. For each deformation area following values are calculated:

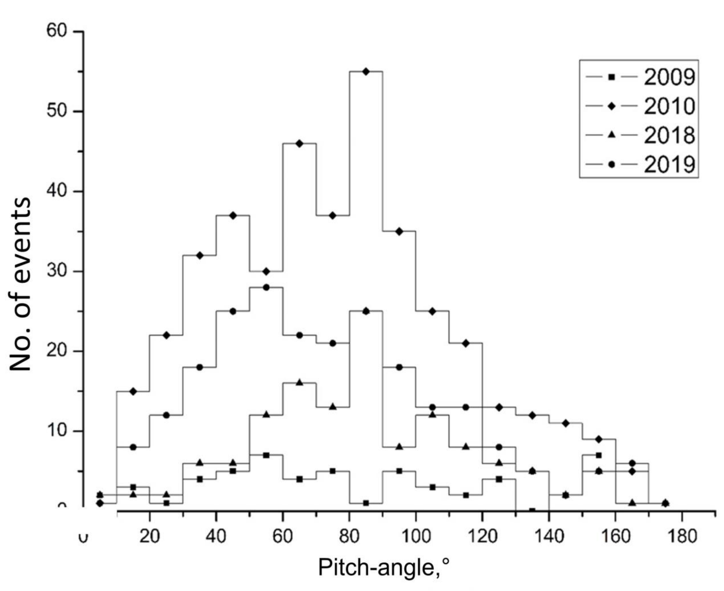
- ***Solid angle*** of deformation and ***pitch angle*** of peak deviation in the GSE system;
- ***Peak value in percentages*** *and its angular coordinates (ϑ, φ) in the Lab. Coordinate System.*

Muonography the periods of the minima of 23rd and 24th Solar cycles

- During periods of low solar activity, the high-speed solar wind is one of the main causes of disturbances in the heliosphere and magnetosphere of the Earth. Also it leads to modulations of cosmic ray fluxes penetrating the Earth's magnetosphere and can be detected by ground level horoscopic facilities. We analyzed muonographs of deformations of the angular distribution of CR in the GSE system, obtained by the URAGAN during the periods of minima solar activity in 2009-2010 and 2018-2019.
- We analyzed the magnetic storms that occurred as a result of the impact of the high-speed solar wind generated by coronal holes on the Earth's magnetosphere. A total of 81 events were considered that occurred over period 2009 (15 storms) - 2010 (25 storms) and the period 2018 (30 storms) - 2019 (14 storms).







Distributions of deformation areas with deviations ≥ 5σ (both increase (pink) and decrease (violet)) and pitch angles in the CR flux. During these periods, deformation regions with sizes ranging from **0.1 to 0.8 sr** were observed. The most frequently recorded areas were **0.4 sr**, regardless of the year.

Analysis of the pitch angles showed that in **2009**, the particles detected by the URAGAN most often flew into the Earth's magnetosphere with a pitch angle of **50°**, in **2010** with an angle of **90°**, in **2018 - 50°**, and in **2019 - 80°**. Particles with pitch angles of **180°** and **0 °** (directed along and against the geomagnetic field line) **did not enter the magnetosphere.**

Conclusion

The muon hodoscope URAGAN allow us to provide study of variations not only integral characteristics of muon flux and its anisotropy, but also to analyze in time the changes in the angular distribution of the muon flux caused by the effects of inhomogeneities of the interplanetary magnetic field on the flux of charged primary cosmic rays. The proposed approach of mapping the anisotropy area in the angular distribution in matrix form allows us to estimate the degree of deformation, the zenith and azimuthal angle of the anisotropy area center in the local coordinate system, and its GSE longitude and latitude. The use of the muonography method made it possible to estimate some of the features of the dynamics of the anisotropy of cosmic rays during periods of minimum solar activity with different polarities of the interplanetary magnetic field.

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