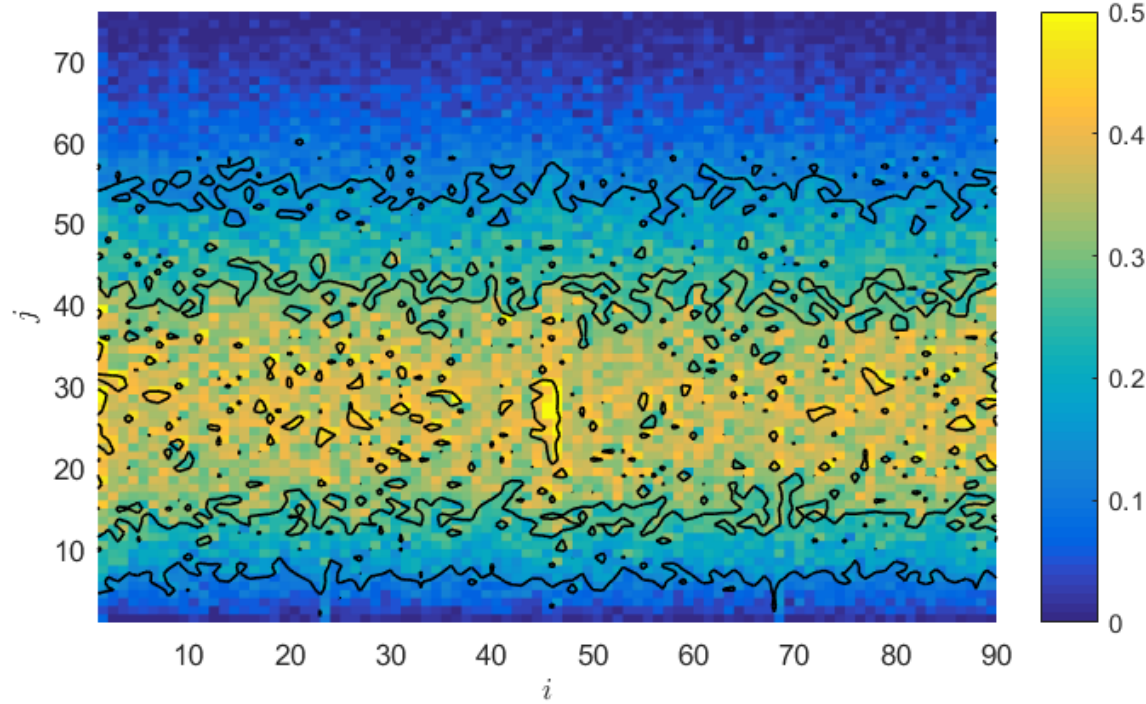


A method for muon flux intensity modulations recognition using the indicator matrices for the URAGAN hodoscope matrix data

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The time series of muon hodoscope (MH) matrix data, consisting of a set of Poisson processes corresponding to azimuthal and zenithal elements of MH matrices, are considered.



1-minute sampled normalized Poisson-distributed matrix data from the muon hodoscope with muon flux intensity modulations (MFIM):

$$Y(i, j, Tk), k = 1, 2, \dots, i = 1, \dots, N_1, j = 1, \dots, N_2, \xi_k(i, j) = Y(i, j, Tk)$$

$$\text{Local anisotropy areas} \Rightarrow \Psi_{a,k}(i, j) \in \Psi_{a,k} \subset \Psi_0, k = 1, 2, \dots \Psi_0 = \{(i, j): i = 1, \dots, N_1, j = 1, \dots, N_2\}$$

$$\text{Math. expectations } \bar{\lambda} = \bar{\lambda}(i, j) = \frac{1}{k_f} \sum_{k=1}^{k_f} \xi_k(i, j), \text{ conf. level } \gamma, \Phi(\delta_\gamma) = \gamma/2,$$

$$\text{confidence intervals} - h_{mn} \leq \bar{\lambda} \leq h_{mx},$$

$$h_{mn} = \{-\delta_\gamma / (2\sqrt{k_f}) + \sqrt{\bar{\lambda} - \delta_\gamma^2 / 4k_f}\}^2, h_{mx} = \{\delta_\gamma / (2\sqrt{k_f}) + \sqrt{\bar{\lambda} + \delta_\gamma^2 / 4k_f}\}^2,$$

Matrices of estimates of mathematical expectations are calculated and, taking into account the Poisson property, the matrices of reference confidence intervals are calculated. Next, the current time sections are formed, on which the matrices of the current confidence intervals are calculated.

Reference and current time sections: $n = 1, \dots, n_0 + n_1$

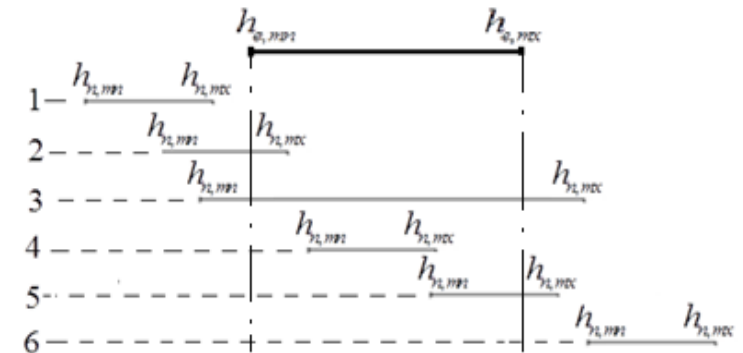
$k_{0,1} \leq k \leq k_{0,2}, k_{0,1} = 1, k_{0,2} \leq k_f$ reference time section,

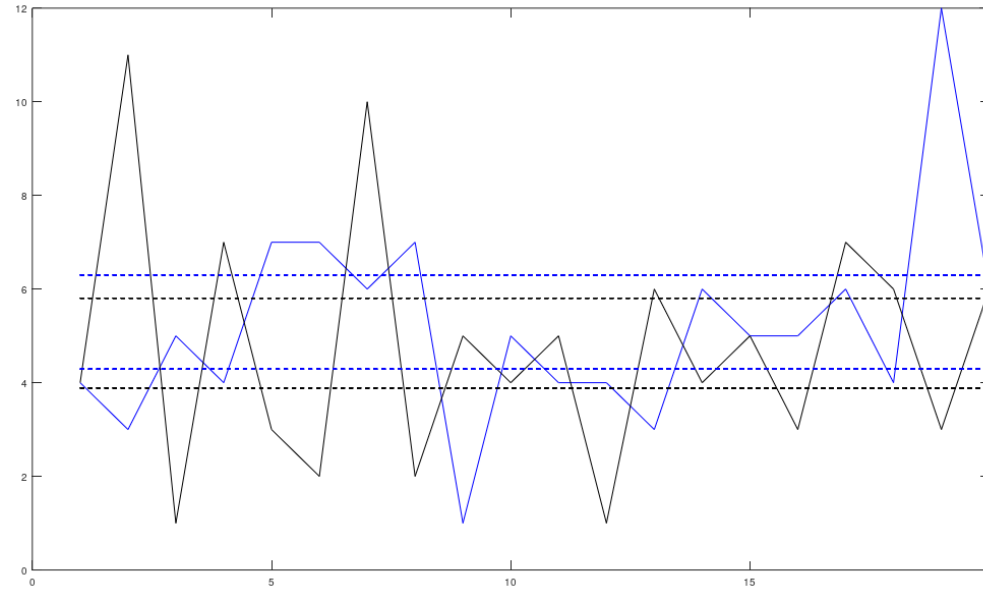
$k_{n,1} \leq k \leq k_{n,2}$, где $k_{n,1} = k_f + 1 + (n - 1)k_f, k_{n,2} = k_f + 1 + nk_f, n = 1, \dots, n_0 + n_1,$

Reference and current confidence intervals: $(h_{e,mn}, h_{e,mx}) \Leftrightarrow (h_{n,mn}, h_{n,mx})$

Local anomalousness: $a_n = a(h_{e,mn}, h_{e,mx}, h_{n,mn}, h_{n,mx}), a_n(i, j), dh_n = h_{n,mx} - h_{n,mn}$

1. if $(h_{n,mx} \leq h_{e,mn})$, then $a_n = (h_{e,mn} - h_{n,mn})/dh_n$,
2. if $(h_{n,mn} \leq h_{e,mn})$ and $(h_{n,mx} > h_{e,mn})$ and $(h_{n,mx} < h_{e,mx})$, then $a_n = (h_{e,mn} - h_{n,mn})/dh_n$,
3. if $(h_{n,mn} \leq h_{e,mn})$ and $(h_{n,mx} > h_{e,mx})$, then $a_n = ((h_{e,mn} - h_{n,mn}) + (h_{n,mx} - h_{e,mx}))/dh_n$,
4. if $(h_{n,mn} > h_{e,mn})$ and $(h_{n,mx} < h_{e,mx})$, then $a_n = 0$,
5. if $(h_{n,mn} > h_{e,mn})$ and $(h_{n,mn} < h_{e,mx})$ and $(h_{n,mx} > h_{e,mx})$, then $a_n = (h_{n,mx} - h_{e,mx})/dh_n$,
6. if $(h_{n,mn} > h_{e,mx})$, then $a_n = (h_{n,mx} - h_{e,mx})/dh_n$.





Current (blue solid line) and reference (black solid line) Poisson processes,
current (blue dotted line) and reference (black dotted line) confidence intervals.

Based on the comparison of the matrices of the reference and current confidence intervals, the current matrices of anomalies are formed, which are compared with the specified threshold matrix. Thresholds exceedings correspond to anomalous events.

Matrices of anomalousness: $a_n(i, j) \Leftrightarrow A_n$,

Threshold matrix: $a_0(i, j) \Leftrightarrow A_0, n = 1, \dots, n_0$ $a_0(i, j) = \frac{1}{n_0} \sum_{n=1}^{n_0} a_n(i, j)$

Indicator matrices (IM) $G_n, n = n_0 + 1, \dots, n_0 + n_1. g_n(i, j), i = 1, \dots, N_1, j = 1, \dots, N_2, g_n(i, j) = 1$, if $a_n(i, j) \geq a_0(i, j), g_n(i, j) = 0$, if $a_n(i, j) < a_0(i, j)$.

Recognition is to analyze IM sequence and identify areas of non-zero elements condensation that lead to the conclusion that there are significant MFIM. To reduce the recognition errors, the space-time IM filtering has been developed.

Experimental 1-minute sampled MH data: $Y(i, j, Tk)$, $k_f = 20$, $n = n_1 + 1, \dots, n_1 + n_2$, 15.08.2014;

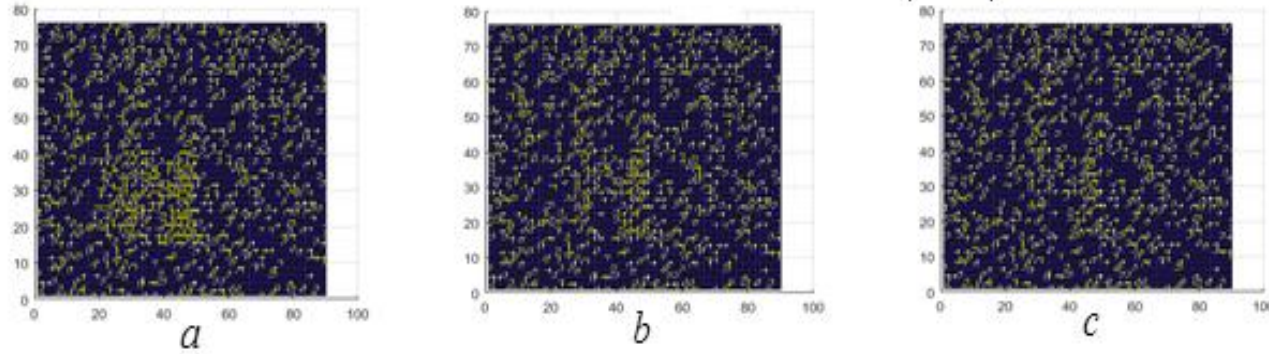
Model Forbush decreases $\mu(i, j)$, $i = 1, \dots, N_1$, $j = 1, \dots, N_2$, $\mu(i, j) = 1 - \delta\mu$ для $i_1 \leq i \leq i_2$, $j_1 \leq j \leq j_2$, else - $\mu(i, j) = 1$

$$Y(i, j, Tk, \mu) = Y(i, j, Tk)\mu(i, j)$$

Temporal filtering: $n_2 = 10$, $G_n(\delta\mu)$ – initial IM

$$g_\phi(n_2, i, j) = \frac{1}{n_2} \sum_{n=n_1+1}^{n_1+n_2} g_n(i, j), g_\phi(n_2, i, j) \leq \bar{g}, g_{\phi 1} = 1, \text{ else } g_{\phi 1} = 0$$

$$a - G_{\phi 1}(n_2, \delta\mu_1), \delta\mu_1 = 0.05; b - G_{\phi 1}(n_2, \delta\mu_2), \delta\mu_2 = 0.04; c - G_{\phi 1}(n_2, \delta\mu_3), \delta\mu_3 = 0.03.$$



Initial IM data

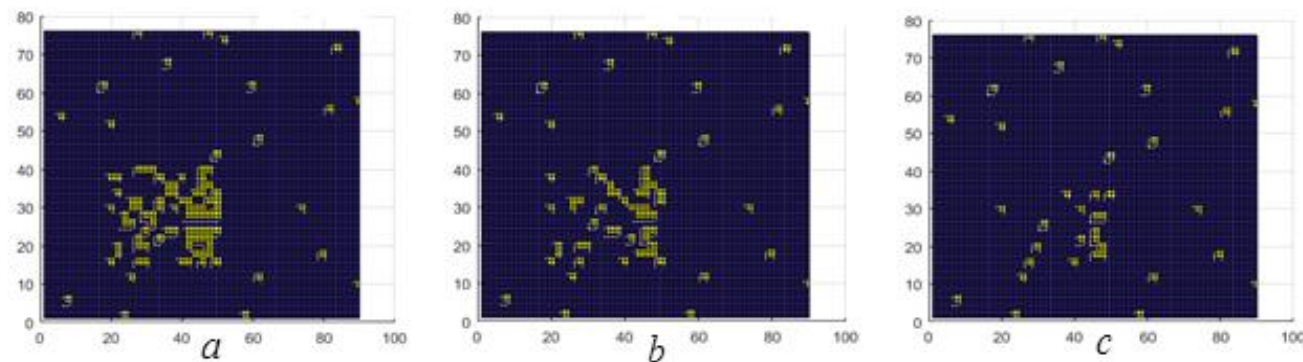
Spatial filtering:

$$\Delta N_1, \Delta N_2, \bar{p}\Delta N_1 = \bar{N}_1 \leq N_1, \bar{q}\Delta N_2 = \bar{N}_2 \leq N_2, \bar{p}, \bar{q}, p, q \Leftrightarrow i, j, 1 + (p - 1)\Delta N_1 \leq i \leq p\Delta N_1, p = 1, \dots, \bar{p}, 1 + (q - 1)\Delta N_2 \leq j \leq q\Delta N_2, q = 1, \dots, \bar{q}.$$

$$G_{\phi 2}(p, q) = \frac{1}{\bar{p}\bar{q}} \sum_{i=1+(p-1)\Delta N_1}^{p\Delta N_1} \sum_{j=1+(q-1)\Delta N_2}^{q\Delta N_2} G_{\phi 1}(i, j),$$

$$p = 1, \dots, \bar{p}, q = 1, \dots, \bar{q},$$

$$G_{\phi 2}(n_1, \delta\mu_1), \delta\mu_1 = 0.05; G_{\phi 2}(n_1, \delta\mu_2), \delta\mu_2 = 0.04; G_{\phi 2}(n_1, \delta\mu_3), \delta\mu_3 = 0.03$$



Filtering results

Testing on the generated time series of model Poisson MH matrix data with model MFIM confirmed the conclusion about the possibility of MFIM recognition by the proposed method with a decrease level of 3-4%. Application of spatial-temporal filtering made it possible to recognize MFIM for decreases with a level half as much.

Testing on the formed experimental matrix MH data time series with model MFIM led to a conclusion that it is possible to recognize MFIM with the magnitudes of decreases almost commensurate with the decreases for the case of model MH data.

The proposed MFIM recognition method based on indicator matrices for MH observation data allows optimization of parameters and can be successfully applied to solve problems of MFIM recognition and early diagnostics of geomagnetic storms.