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EARLY DIAGNOSTICS OF GEOMAGNETIC STORMS BASED ON OBSERVATIONS OF SPACE MONITORING SYSTEMS

V.G. Getmanov
Geophysical Center of RAS,
Moscow, Russia, vgetm2015@yandex.ru
Schmidt Institute of Physics of the Earth, RAS,
Moscow, Russia, vgetm2015@yandex.ru

A.D. Gvishiani
Geophysical Center of RAS,
Moscow, Russia, a.gvishiani@gcras.ru
Schmidt Institute of Physics of the Earth, RAS,
Moscow, Russia, a.gvishiani@gcras.ru

D.V. Peregoudov
Geophysical Center of RAS,
Moscow, Russia, d.peregoudov@gcras.ru

I.I. Yashin
National Research Nuclear University MEPhI,
Moscow, Russia, IIYashin@mephi.ru

A.A. Soloviev
Geophysical Center of RAS,
Moscow, Russia, a.soloviev@gcras.ru
Schmidt Institute of Physics of the Earth, RAS,
Moscow, Russia, a.soloviev@gcras.ru

M.N. Dobrovolsky
Geophysical Center of RAS,
Moscow, Russia, m.dobrovolsky@gcras.ru

R.V. Sidorov
Geophysical Center of RAS,
Moscow, Russia, r.sidorov@gcras.ru

Abstract. We address the problem of early diagnostics of geomagnetic storms based on the use of models of coordinates of movements of centers of solar coronal mass ejections (CME) and observations of their angular positions obtained from space monitoring systems. We propose a method for early diagnostics of geomagnetic storms, introduce a function to predict the distance between Earth and CME centers, and establish a decision-making procedure. We give an example of calculating the distance prediction function and implement the diagnostic decision-making procedure based on coordinate models and model observations of angular positions of CME centers. We determine the efficiency of the decision-making procedure for the algorithm for early diagnostics of geomagnetic storms.

Keywords: coronal mass ejections, geomagnetic storms, space monitoring, diagnostic solutions, triangulation functional.

INTRODUCTION

Coronal mass ejections (CMEs) have a significant impact on Earth's magnetosphere, cause magnetic storms and serious problems of functioning of technical and biological objects. Early diagnostics of geomagnetic storms is an urgent research problem [Handbook of Cosmic …, 2015; Solar Eruptions and …, 2006]. There are two categories of articles on models related to the diagnostics and prediction of CME arrival time. The first category includes articles describing models that use approaches based on equations of magnetohydrodynamics (MHD) of plasma formations; the second contains articles describing various versions of nonlinear CME models.

Odstrcil [2003] describes the ENLIL model, used by NASA for predictions in the heliosphere, which are made by solving MHD equations. The main feature of this model is the absence of the phenomenologically described mechanism for heating the solar corona. The accuracy of predictions of CME arrival at Earth by this model is about eight hours. Jin et al. [2017] describe the BATSRUS model, which is also based on MHD equations, but contains the mechanism for heating the solar corona by Alfvén turbulence. As a result, this model consistently describes not only the heliosphere, but also the solar corona. The authors also describe the EEGGL tool that enables us to specify initial conditions for CME from optical and magnetic observations. Further CME propagation through the corona and heliosphere can be calculated from equations of the model. The website [http://helio-weather.net/archive/2008/05] presents the WSA-ENLIL model, which is an advanced version of [Odstrcil,2003]. The approaches based on solutions of MHD equations and a detailed examination of physics of heliospheric processes can potentially provide an effective solution to the problem of early diagnostics.

Owens, Cargill [2004] have examined three phenomenological models of CME propagation, capable of calculating the arrival time. The first model considers that CME moves with a constant acceleration all the way from the Sun to Earth's orbit. The second assumes that up to a certain distance shorter than the radius of Earth's orbit, CME moves with constant acceleration and then uniformly. The third model supposes that the acceleration of CME is proportional to the difference between CME and ambient solar wind (SW) velocities; the proportionality factor depends on the distance to the Sun according to the power law. The first model has two parameters (initial velocity and acceleration); the second, three parameters (initial velocity, acceleration, and distance over which the acceleration ends). The third model includes four parameters (initial velocity, drag coefficient power and multiplier, and asymptotic SW velocity). Gopalswamy et al. [2000], using 28 interplanetary CME events, have developed an empirical formula of CME arrival, the work of which has been studied: its predictive characteristics are shown to be better for fast CMEs than for slow ones. Mittal, Narain [2015] have used the simplest model linear dependence between the velocity at which CME leaves the Sun and the time of its propagation to Earth for calculating the arrival time (by the example of slow (<500 km/s) and fast (>500 km/s) CMEs). Michalick et al. [2004] describes an approach to estimating CME velocity, which is based on the solution of a special optimization problem.

Finally, the material [Gopalswamy, 2016] is a survey of the history of CME studies, which is mainly focused on observational data and their systematization. Problems of diagnostics and respective models of CME propagation are not discussed in detail.

The space monitoring systems in use here include Solar and Heliospheric Observatory (SOHO) [Brueckner et al., 1995; Delaboudiniere et al., 1995] (NASA and ESA (European Space Agency) project); Solar TErrestrial RElations Observatory (STEREO) [Howard et al., 2008] (NASA project), and the muon hodoscope (MH) HURRICANE [Barbashina et al., 2008; Yashin et al., 2015] (MEPhI (RF) project).

The measuring satellite system SOHO is at the Lagrange point, about 1.5 million km from Earth. It has the following CME monitoring instruments: Extreme Ultraviolet Imaging Telescope (EIT) and Large Angle and Spectrometric Coronagraph (LASCO). EIT takes pictures at wavelengths of 17.1, 19.5, 28.4 nm (Fe lines), and 30.4 nm (He line). It can also obtain images of the entire solar disk; its field of view is $1.5R_{\odot}$ (here $R_{\odot}$ is the solar radius), pixel resolution is 1024×1024. LASCO consists of three coronagraphs with overlapping fields of view: from 1.1 to 3, from 1.5 to 6, and from 3.7 to $30R_{\odot}$. The coronagraphs operate in the visible band with a pixel resolution of 1024×1024.

STEREO consists of two satellites, put into near-Earth orbits, and moves round the Sun with periods of 346 and 388 days. Radii of the orbits differ from the radius of Earth's orbit by about ±4 %, so that the first satellite gradually moves away from Earth forward in the orbit; and the second, backward. Each STEREO satellite has CME observation instruments: part of the SECCHI (Sun Earth Connection Coronal and Heliospheric Investigation) instrument suite – the Extreme Ultraviolet Imager (EUVI) with a field of view up to $1.7R_{\odot}$, two coronagraphs with fields of view from 1.4 to 4 and from 2.5 to $15R_{\odot}$, and two wide-angle telescopes covering angles from 4° to 24° and from 19° to 89° from the Sun $(15–84)R_{\odot}$ and $(66–318)R_{\odot}$ in Earth's orbit plane. All the instruments have a pixel resolution of 2048×2048.

In Figure 1, dashed lines show the orbits; dots mark the position of Earth, the Sun, SOHO (L), and STEREO (A, B) corresponding to October 08, 2010 [https://stereo.gsfc.nasa.gov/where].

Figure 2, *a*, *b* presents CME images captured by LASCO (SOHO) [https://cdaw. gsfc.nasa.gov/CME]. The image in Figure 2, *a* can be used to approximately estimate the CME center position relative to the Sun's center: we can see that in the former case, the CME center is at $\approx 3.4R_{\odot}$; in the latter in Figure 2, *b*, the CME center shifts over a distance of $\approx 4.2R_{\odot}$.

Figure 3, *a*, *b* presents CME images from a STEREO coronagraph with a field of view of $(2.5\div15)R_{\odot}$ [https://stereo.gsfc.nasa.gov/cgi].

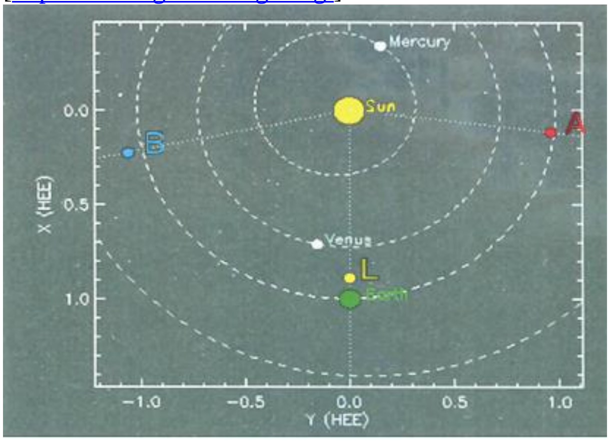

Figure 1. Planetary orbits, positions of Earth, the Sun, SOHO, and STEREO

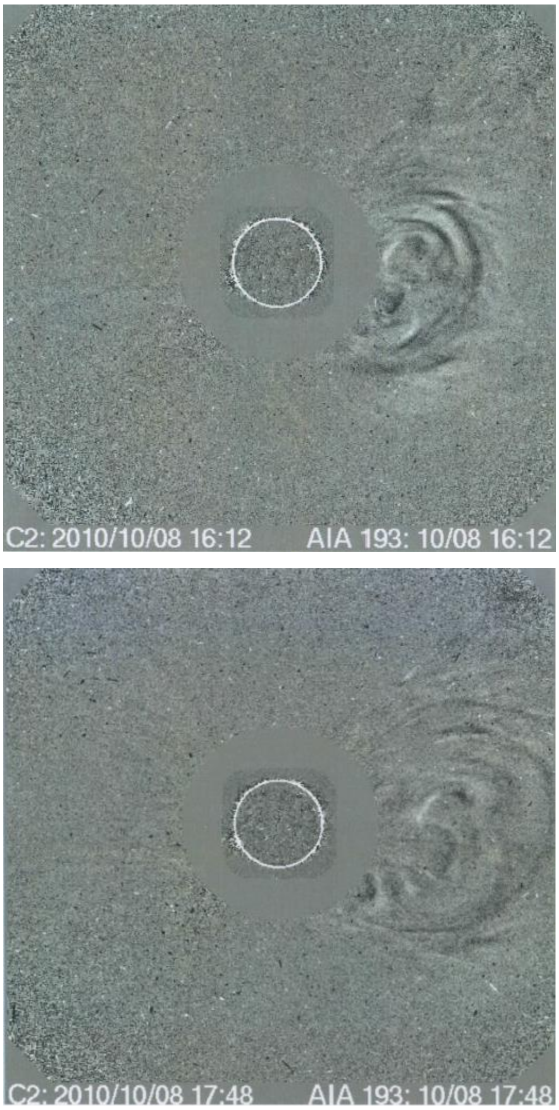

Figure 2. CME images from SOHO for October 08, 2010, at 16:12 (*a*), 17:48 (*b*)

From images shown in Figure 3, *a*, *b* we can find an approximate position of CME centers relative to the Sun's center: in the former case, the CME center is located at $\approx 5.1R_{\odot}$ from the Sun's center; in the latter, the

CME center shifts over a distance of $\approx 7.3R_\odot$.

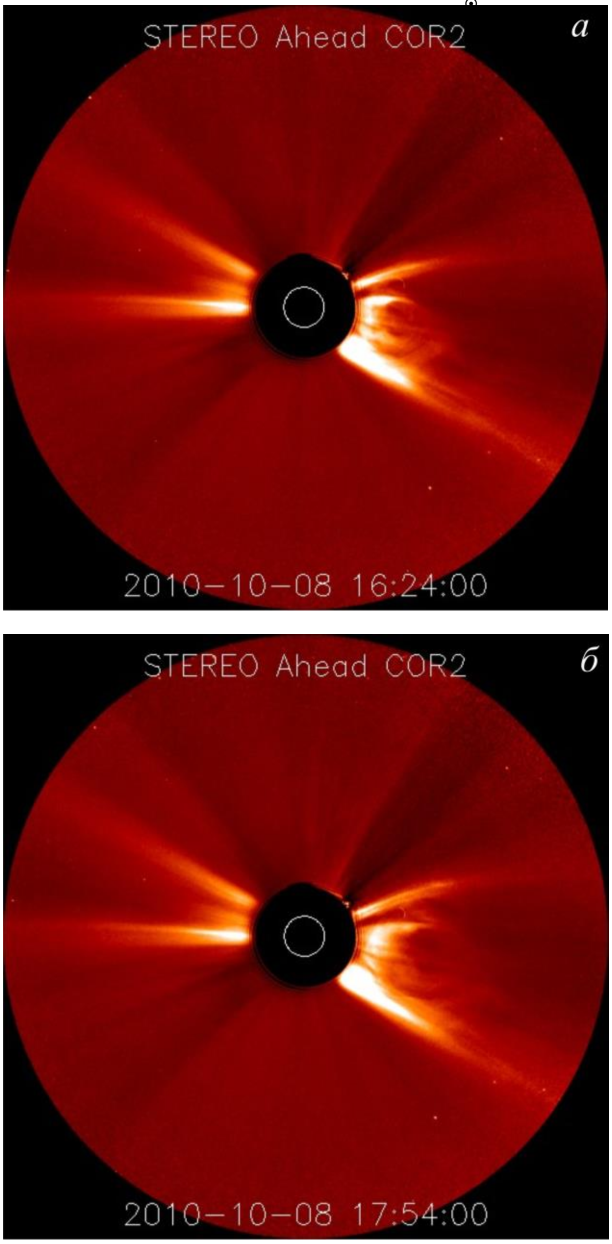

Figure 3. CME images from STEREO for October 08, 2010, 16:24 (*a*) and 17:54 (*b*)

SOHO and STEREO observations can be represented by sequences of discrete two-dimensional functions $S_1(i, j, T_1k)$, $S_2(i, j, T_2k)$, where to the indices $(i, j)\in S_{01}$, $(i, j)\in S_{02}$ correspond discrete measurements of azimuth and zenith angles; S_{01}, S_{02} are domains of indices; T_1, T_2 are intervals of observation discreteness. An algorithm for automatic determination of angular positions of CME – estimated azimuth $\varphi°(T_{1,2}k)$ and zenith $\theta°(T_{1,2}k)$ angles for these systems – can be formed in the first approximation by calculating the respective moment characteristics of $S_1(i, j, T_1k)$, $S_2(i, j, T_2k)$:

$$\varphi^\circ(T_{1,2}k) = \Big(\sum_{i,\, j\in S_{01,2}} iS_{1,2}(i, j, T_{1,2}k)\Big) \Big/ \sum_{i,\, j\in S_{01,2}} S_{1,2}(i, j, T_{1,2}k),$$

$$\vartheta^\circ(T_{1,2}k) = \sum_{i,\, j\in S_{01,2}} jS_{1,2}(i, j, T_{1,2}k) \Big/ \sum_{i,\, j\in S_{01,2}} S_{1,2}(i, j, T_{1,2}k). \qquad (1)$$

For the plane case, a CME center positioning error may be $\Delta R_{SC}=\alpha R_S$, where R_S is the solar radius, α is a given coefficient. An error in positioning the CME azimuth angle may be determined by $\Delta\varphi_{1,2}=\Delta R_{SC}/R_{SE}$, where R_{SE} is the Sun–Earth distance. Let α=3.0, $R_S=0.004652R_{SE}$, then $\Delta\varphi_{1,2}\approx 0.795°$.

The ground measuring system HURRICANE based on MH monitors observes functions of angular distributions of muon flux intensities. These observations of $S_3(i, j, T_3k)$, $i=1, \ldots, N_1$, $j=1, \ldots, N_2$ are in information MH matrices with a time increment T_3=1 min. The MH observations are realized within $0°\le\varphi\le 360°$ and $0°\le\theta\le 76°$ at azimuth and zenith angles relative to the Earth reference coordinate system with angular resolution in $\Delta\varphi=4°$, $\Delta\theta=1°$; each MH matrix has a dimension (N_1, N_2), $N_1=90$, $N_2=76$. The angular position of a possible CME center can be estimated by identifying abnormal angular regions in the MH matrices, which are associated with a decrease in the muon flux intensity during development of CME formations. The estimates are made using formulas similar to (1).

Figure 4 exemplifies the calculation of the modulus $|\Delta S_3(i, j)|$ of a decrease in muon flux intensities, obtained from the digital processing of sequences of MH matrices. The observation was made on June 06, 2015 at 15:30.

It can be seen that the abnormal region for an MH matrix with the maximum intensity decrease modulus can be defined in this case by the discrete coordinates $51\le i\le 52$, $30\le j\le 31$, which corresponds to the azimuth and zenith angles $204\le\varphi°_i\le 208°$, $30\le\theta_j\le 31°$. An error in angular positioning of CME observed by HURRICANE can be approximately $\Delta\varphi_{03}\approx(4^2+1^2)^{1/2}=4.12°$. The primary digital processing of a sequence $N_0=10\div 15$ of the information MH matrices enables us to reduce the angular errors to $\Delta\varphi_3\approx\Delta\varphi_{30}/\sqrt{N_0}=(1.06°\div 1.31°)$.

It should be noted that with the assumptions made, the error in angular positioning of CME formations from the measuring systems considered is $\Delta\varphi_{1,2,3}\approx(0.5°–1.5°)$. Notice that today there are no real observations from these systems; for calculations we use model observations.

This paper poses the problem of early diagnostics of geomagnetic storms based on the development of a method and algorithm for digital processing of angular observations from space monitoring systems, taking into account the model of Cartesian coordinates of CME movements. For this purpose, we propose a decision-making procedure for potentially hazardous proximity

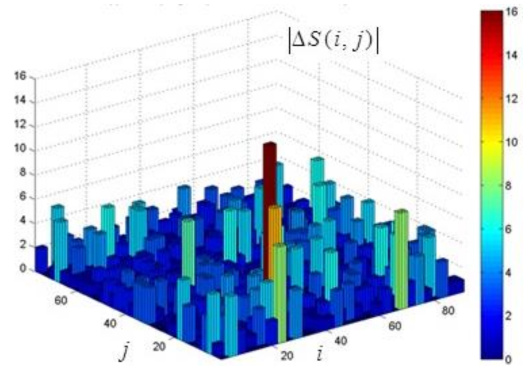

Figure 4. Function of the modulus of muon flux intensity decrease

of CME to Earth, which is based on the introduced function of prediction for the Earth–CME center distance. We develop an algorithm for estimating parameters of equations of Earth – CME center movement, which relies on the minimization of the generalized triangulation functional. We calculate the distance prediction function and realize the decision-making procedure for early diagnostics by comparing the minimum value of the prediction function with the specified safe distance between Earth and CME center.

To assess the effectiveness of the early diagnostics, we perform the statistical modeling based on models of CME movements and model observations. We estimate probabilities of errors in the decision-making procedure for early diagnostics of geomagnetic storms.

In this work, we assume that digital processing of data from space-based and ground-based space monitoring systems can be used to estimate angular positions of CME centers. This estimate can be performed when CME formations are at ≈0.05–0.2 AU from the solar surface (near-field zone). In this case, the CME formations have small angular sizes for Earth's orbit observations and can be taken with certain assumptions as near-point regions traveling in the near-field zone [Xue et al., 2005].

Our article addressing the problem of early diagnostics differs in essence from [Owens, Cargill, 2004; Gopalswamy et al., 2000; Mittal, Narain, 2015; Michalick et al, 2004]. It explores the possibility of applying a realistic model of CME movement and current angular observations of CMEs for decision making. The approach [Odstrcil, 2003; Jin et al., 2017], associated with the use of three-dimensional model MHD equations, takes into account a greater number of SW and CME characteristics than phenomenological models, but requires enormous computational resources.

1. METHODS FOR EARLY DIAGNOSTICS OF GEOMAGNETIC STORMS

Geometry of movements of the system the Sun – CME center – Earth – space monitoring systems for the problem considered in the 2D case is shown in Figure 5.

Center the Sun (S) in fixed rectangular Cartesian coordinates X_sSY_s. Denote the CME center by C. Assume that E_0 and $X_0E_0Y_0$ are Earth and its related coordinate axes parallel to X_sSY_s; E_r and $X_rE_rY_r$ are space monitoring systems with respective coordinate axes, r=1, $\overline{r}$.

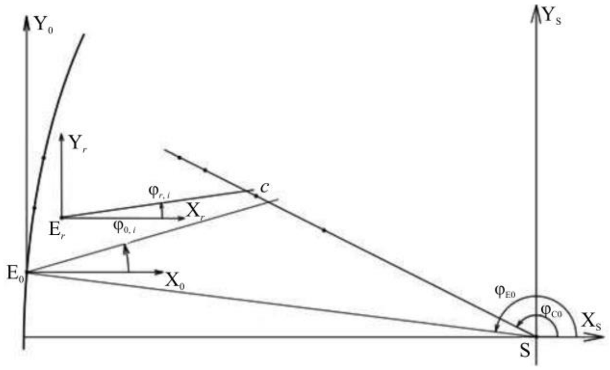

Figure 5. Geometry of movements of the system the Sun – CME center – Earth – satellite monitoring systems

Let $x_E(t)$, $y_E(t)$ be Cartesian coordinates of Earth, considered precisely known. Prescribe nonlinear functions of a general form $x_{CM}(c, t)$, $y_{CM}(c, t)$, which we take as models of Cartesian coordinates of traveling CME center, which depend on the vector of parameters $c^T=(c_1, \ldots, c_{n0})$. In particular, these functions can be polynomial – linear, parabolic, etc.; the choice of functions of models allows us to form sufficiently arbitrary paths of CME movements in the heliosphere. Suppose that at a certain time interval (t_0, t_f) from observations of CME angular coordinates of measuring systems and considering models of CME Cartesian coordinates we can estimate $c°$ and hence functions of coordinates for the CME center $x_{CM}(c°, t)$, $y_{CM}(c°, t)$. Predict the position of the CME center, introduce a function of the distance between Earth and CME center

$$R_{EC}(c^\circ, t) = \\ = \sqrt{\left(x_E(t) - x_{CM}(c^\circ, t)\right)^2 + \left(y_E(t) - y_{CM}(c^\circ, t)\right)^2}, \\ t_0 \le t \le t_f. \quad (2)$$

For the known numerical estimate of the vector of parameters $c°$ the function $R_{EC}(c°, t)$ is completely defined. Estimate the minimum predictable distance between Earth and CME center. Take time boundaries as t_0, t_f such that the function $R_{EC}(c°, t)$ from (2) in the interval (t_0, t_f) a fortiori reaches its minimum. Find the minimum of $R_{EC}(c°, t)$ in the interval of interest, calculate the corresponding time $t°(c°)$, and $R_{EC}(c°, t(c°))$ – the minimum predictable distance:

$$t^\circ(c^\circ) = \arg\left\{\min_{t_0 \le t \le t_f} R_{EC}(c^\circ, t)\right\}, \\ R^\circ_{EC\min} = R_{EC}(c^\circ, t^\circ(c^\circ)). \quad (3)$$

Realize the method for early diagnostics of geomagnetic storms through the decision-making procedure to verify the inequality $R^\circ_{EC\min} \le \overline{R}_{EC}$, where $\overline{R}_{EC}$ is the minimum safe distance between Earth and CME. If the inequality holds, we make a decision that the center of a probable CME is close enough to Earth and this CME is a potential danger in terms of the occurrence of a geomagnetic storm. If the inequality does not hold, we make the opposite decision.

2. ALGORITHM FOR ESTIMATING PARAMETERS OF MODEL FUNCTIONS OF

CME CENTER MOVEMENTS

2.1. Let us generally consider the algorithm for estimating parameters of model functions of CME center movement. Turn to Figure 5. Suppose that the observations are made at time instants $t_{r,i}$ and to them correspond $\varphi_{r,i}$ – angular observations of the CME center, given in the coordinate systems $X_rE_rY_r$ and measured from the E_rX_r axis counterclockwise, r=0, 1, …, r–1; i=0, 1, …, N_r–1, where N_r is the number of observations made by the measuring system with an index r; the axes of the coordinate system $X_rE_rY_r$ move parallel to the axes of the coordinate system X_sSY_s.

Find dependences of the Earth coordinates $x_E(t_{r,i})$, $y_E(t_{r,i})$ on $t_{r,i}$, using the following functions of time

$$\varphi_E(t_{r,i})=\omega_E t_{r,i}+\varphi_{E0},\ x_E(t_{r,i})=R_{ES}\cos\varphi_E(t_{r,i}),$$
$$y_E(t_{r,i})=R_{ES}\sin\varphi_E(t_{r,i}), \quad (4)$$

where φ_{E0}, ω_{E0}, R_{ES} – the initial angle, the angular velocity of Earth orbiting around the Sun, and the Sun– Earth distance – are considered as specified for (4). Calculate the CME center coordinates for $t_{r,i}$, using models of the given type $x_{CM}(c, t_{r,i})$, $y_{CM}(c, t_{r,i})$ (Section 2). Write the expression for the generalized triangulation functional $S_{\bar{r}}(c,\varphi)$ as the double sum whose physical meaning is clear:

$$S_{\bar{r}}(c,\varphi)=\sum_{r=1}^{\bar{r}}\alpha_r\times$$
$$\times\sum_{i=0}^{N_r-1}\left(\varphi_{r,i}-\operatorname{arctg}\frac{y_{CM}(c,t_{r,i})-y_E(t_{r,i})}{x_{CM}(c,t_{r,i})-x_E(t_{r,i})}\right)^2, \quad (5)$$

where φ is the block vector of angular observations, α_r are the weight factor accounting for various accuracies of angular observations from the measuring systems of interest. Estimate the vector of parameters c° by minimizing the functional in width (5) from the vector of parameters $c\in\bar{C}$, where $\bar{C}$ is the restrictive set $c^\circ=\arg\left\{\min_{c\in C} S_{\bar{r}}(c,\varphi)\right\}$.

Form the set $\bar{C}$, using the system of inequalities $c_{n,\min}\le c_n\le c_{n,\max}$, n=1, …, n_0. Adopt the search method for minimizing the zero order by direct search to find the optimal estimates of the vector of parameters [Singiresu, 2009]. Organize the search – selection of discretized parameters $c_n(k_n)$ – using the following relations:

$$c_n(k_n)=c_{n,\min}+\Delta c_n(k_n-1),$$
$$\Delta c_n=(c_{n,\max}-c_{n,\min})/(K_{fn}-1),\ K_{fn}>1, \quad (6)$$

where Δc_n is the step of search by parameters, k_n=1, ..., K_{fn}, n=1, ..., n_0. Due to the introduced discretization, represent functional (5) as dependent on k_1, k_2, ..., k_m, and find optimal parameters c_n° through the minimizing search by integer variables

$$(k_1^\circ,...,k_{n_0}^\circ)=\arg\left\{\min_{k_n,\ n=1,...,n_0} S_1(k_1,...,k_{n_0},\varphi)\right\},$$
$$c_n^\circ=c_n(k_1^\circ,...,k_{n_0}^\circ),\ n=1,…,n_0. \quad (7)$$

2.2. Analyze the case of one measuring system, when $\bar{r}=1$, and find $t_{0,i}=t_i$, i=0, 1, …, N–1. For the time functions of Earth's coordinates $x_E(t_i)$, $y_E(t_i)$ use formulas (4). Consider the simplest example of the model of Cartesian coordinates of the CME center in the form of linear functions

$$x_{CM}(c,t_i)=R_{C0}+V_{C0}t_i)\cos\varphi_{C0},\ y_{CM}(c,t_i)=$$
$$=(R_{C0}+V_{C0}t_i)\sin\varphi_{C0}. \quad (8)$$

For (8), the CME center moves uniformly and linearly with a velocity V_{C0} at an angle φ_{C0}, which is measured from the SX_s axis counterclockwise and at the initial instant of time is at a distance R_{C0} from the Sun. In this case, represent the three-dimensional vector of model parameters as $c^T=(c_1, c_2, c_3)$, $c_1=V_{C0}$, $c_2=\varphi_{C0}$, $c_3=R_{C0}$.

For specified t_i and observations of angular positions φ_i of the CME center, i=0, 1, …, N–1, write the triangulation functional as a single sum

$$S_1(c,\varphi)=\sum_{i=0}^{N-1}\left(\varphi_i-\operatorname{arctg}\frac{y_{CM}(c,t_i-y_E(t_i)}{x_{CM}(c,t_i-x_E(t_i)}\right)^2.$$

Represent the optimal parameters c_n°, n=1, 2, 3 for the model functions of CME center coordinates as in (7)

$$(k_1^\circ,k_2^\circ,k_3^\circ)=\arg\left\{\min_{k_1,k_2,k_3} S_1(k_1,k_2,k_3,\varphi)\right\},$$
$$c_n^\circ=c(k_n^\circ),\ n=1,2,3. \quad (9)$$

We examine this example due to short time spans required to calculate parameters of model (8). Of course, more realistic models of CME movement in the form of parabolic and other functions can also be calculated at long time spans.

3. MAKING DECISIONS ON EARLY DIAGNOSTICS OF GEOMAGNETIC STORMS

Let us make decisions on early diagnostics of geomagnetic storms from estimates of parameters of model functions of CME center movements $c_1^\circ=V_{C0}^\circ$, $c_2^\circ=\varphi_{C0}^\circ$, $c_3^\circ=R_{C0}^\circ$, , obtained using (9).

For discrete instants of time t_l, $t_l=t_{f0}+\Delta t(l-1)$ with an increment $\Delta t=(t_f-t_{f0})/(L_f-1)$, calculate, using (2), a sequence of prediction functions for the Earth – CME center distance $R_{EC}(c^\circ, t_l)$, l=1, …, L_f:

$$R_{EC}(c^\circ,t_l)=$$
$$=\sqrt{(x_E(t_l)-(R_{C0}^\circ+V_{C0}^\circ t_l)\cos\varphi_{C0}^\circ)^2+}$$
$$\sqrt{+(y_E(t_l)-(R_{C0}^\circ+V_{C0}^\circ t_l)\sin\varphi_{C0}^\circ)^2}. \quad (10)$$

For sequence (10) find the minimum predictable distance between Earth and CME $R_{EC\min}^\circ$

$$l^\circ=\arg\left\{\min_{l=1,...,L_f} R_{EC}(c^\circ,t_l)\right\},$$
$$R_{EC\min}^\circ=R(c^\circ,t_{l^\circ}).$$

The decision-making procedure consists in checking the inequality $R^{\circ}_{\text{EC}\min} \le \bar{R}_{\text{EC}}$. When this inequality holds, we make a decision that the CME center is close enough to Earth and this CME is a potential danger in terms of the occurrence of a geomagnetic storm. If the inequality does not hold, we make the opposite decision.

If the estimated vector of parameters c° considerably differs from the original vector of parameters c, there may be type I and II errors in performing the decision-making procedure.

1. When the condition $R_{\text{EC}\min}(c) \ge \bar{R}_{\text{EC}}$ holds, the inequality $R_{\text{EC}\min}(c^{\circ}) \le \bar{R}_{\text{EC}}$ takes place which corresponds to the false CME alarm, characterized by the conditional probability α

$$\alpha = P\left\{R_{\text{EC}\min}(c^{\circ}) \le \bar{R}_{\text{EC}}\right\}$$

for

$$R_{\text{EC}\min}(c) \ge \bar{R}_{\text{EC}}. \qquad (11)$$

2. When the condition $R_{\text{EC}\min}(c) < \bar{R}_{\text{EC}}$ holds, we have the inequality $R_{\text{EC}\min}(c^{\circ}) > \bar{R}_{\text{EC}}$ corresponding to the case of CME omission, which is characterized by the conditional probability

$$\beta = P\left\{R_{\text{EC}\min}(c^{\circ}) > \bar{R}_{\text{EC}}\right\}$$

for

$$R_{\text{EC}\min}(c) < \bar{R}_{\text{EC}}. \qquad (12)$$

It is evident that the value 1–β is a probability of correct decision on the early diagnostics.

4. EVALUATION OF THE EFFICIENCY OF THE DECISION-MAKING PROCEDURE FOR EARLY DIAGNOSTICS OF GEOMAGNETIC STORMS

The efficiency of the decision-making procedure for early diagnostics of geomagnetic storms has been assessed using a statistical modeling technique.

We specified the sequence of the time instants t_i, t_i=0, 1, …, N–1, numerical values of the initial condition and constants $\varphi_{\text{E}0}$, ω_{E}, R_{ES} and the initial parameters of model functions of CME-center Cartesian coordinates $c_1=V_{\text{C}0}$, $c_2=\varphi_{\text{C}0}$, $c_3=R_{\text{C}0}$ to calculate the sequence of Cartesian coordinates of Earth $x_{\text{E}}(t_i)$, $y_{\text{E}}(t_i)$ from (4) and model Cartesian coordinates of CME $x_{\text{CM}}(\text{c}, t)$, $y_{\text{CM}}(\text{c}, t)$ from (8).

We computed the sequence of angular positions $\varphi_{0,\,i}$ of the CME center in the coordinate system $x_0E_0y_0$ for t_i, t_i=0, 1, …, N–1.

$$\varphi_{0,\,i} = \operatorname{arctg}\frac{y_{\text{CM}}(c, t_i) - y_{\text{E}}(t_i)}{x_{\text{CM}}(c, t_i) - y_{\text{E}}(t_i)}.$$

For the statistical modeling, we formed realizations for sequences of model random errors $\delta\varphi_{s,\,i}$, distributed according to the normal law with zero mathematical expectation and given standard deviation (SD) σ,i=0, 1, …, N–1, s=1, …, M_0, where M_0 is the number of realizations. We formed realizations of angular observations $\varphi_{s,i}=\varphi_{0,\,i}+\delta\varphi_{s,\,i}$, i=0, 1, …, N–1, which comprised vectors of observations $\varphi^T_s=(\varphi_{s,\,0}, \varphi_{s,\,1}, \ldots, \varphi_{s,\,N-1})$, s=1, …, M_0.

We solved M_0 problems of optimization of (9) with observations of φ_s. To organize the direct search, we specified the number of selections K_{fn}, n=1, 2, 3, lower search limits $c_{1,\,\min}$, $c_{2,\,\min}$, $c_{3,\,\min}$, steps of search $\Delta c_1=\Delta V_{\text{C}0}$, $\Delta c_2=\Delta\varphi_{\text{C}0}$, and $\Delta c_3=\Delta R_{C0}$, calculated $c_{n,\max}$, using (6). We found the optimal parameters $c^{\circ}_{n,\,s}$, n=1, 2, 3, s=1, …, M_0 from (9). For the statistical modeling, we specified the number of realizations M_0=100. We took K_{fn}=100, n=1, 2, 3, $c_{1,\,\min}=250\cdot10^3$ m/s, $c_{21,\,\min}$=145°, $c_{22,\,\min}$=120°, $c_{3,\,\min}=75\cdot10^9$ m/s. For reliable operation of the algorithm – to achieve the acceptable accuracy in estimating the optimal parameters – it appeared to be necessary to make the minimizing search with sufficiently small increment: we used steps of search $\Delta V_{\text{C}0}$=5000 m/s by velocity, $\Delta\varphi_{\text{C}0}$=0.5° by angle, and $\Delta R_{\text{C}0}=1.5\cdot10^6\cdot10^3$ m by initial range.

The time instants of observations for the calculations were determined by the relation $t_i=t_{\text{H}}+T(i-1)$, $t_{\text{H}}=0_{\text{H}}$ $T=0.25\cdot3600$ s, i=0, 1, …, N–1. We specified values of the initial angle $\varphi_{\text{E}0}$=180° and constants $\omega_{\text{E}}=2\pi/(365\cdot24\cdot3600)c^{-1}$, $R_{\text{ES}}=150\cdot10^9$ m. We predetermined numerical values of the initial parameters $c_1=V_{\text{C}0}=500\cdot10^3$ m/s, $c_3=R_{\text{C}0}=0.1R_{\text{ES}}$.

The number of observations N, the angle $c_2=\varphi_{\text{C}0}$, and the specified safe distances $\bar{R}_{\text{EC}}$ varied in the course of the statistical modeling.

The order of the calculation of the error probabilities α°β° was as follows:

1. Calculating the predicted minimum distance $R_{\text{EC}\min}(c)$ for the prescribed initial vector of parameters c.

2. Calculating realizations of estimated vectors of parameters c°_s and estimated minimum distances $\bar{R}_{\text{EC}\min}(c^{\circ}_s)$, s=1, .., M.

3. Calculating estimated probabilities α° and β° by comparing $\bar{R}_{\text{EC}\min}(c^{\circ}_s)$ and $\bar{R}_{\text{EC}}$. In this case, we can face the following:

Type I errors – a case when in fact there was a ratio $R_{\text{EC}\min}(c) > \bar{R}_{\text{EC}}$; the number of events, when $R_{\text{EC}\min}(c^{\circ}_s) \le \bar{R}_{\text{EC}}$, was calculated, and the probability of false alarm α° was estimated from (11), using sign(x)=1 for x>0 and sign (x)=0 for x≤0:

$$\alpha^{\circ} = \frac{1}{M}\sum_{s=1}^{M}\operatorname{sign}\left(\bar{R}_{\text{EC}} - R_{EC\min}(c_s)\right).$$

Type II errors – the case when in fact there was a ratio of $R_{\text{EC}\min}(c) < \bar{R}_{\text{EC}}$; the number of events, when $R_{\text{EC}\min}(c^{\circ}_s) \ge \ge \bar{R}_{\text{EC}}$, was computed and the omission probability β° was estimated using (12):

$$\beta^{\circ} = \frac{1}{M}\sum_{s=1}^{M}\operatorname{sign}\left(\bar{R}_{\text{ECmin}}(c_s) - R_{\text{EC}}\right).$$

From 1–β° we estimated the probability of correct decision on early CME diagnostics of geomagnetic storms.

Figures 6 and 7 present results of estimates of probabilities α°, 1–β ° of false alarms and correct decisions on early CME diagnostics of geomagnetic storms versus SD of angular observation errors σ. The number of observations N=160.

Curves 1 and 2 correspond to two values of safe distance $\bar{R}_{EC1} = 20 \cdot 10^9$ m, $\bar{R}_{EC2} = 60 \cdot 10^9$ m. To calculate α°, 1–β° for curves 1, we took CME angles c_{21}=145°, c_{22}=170°; for curves 2, c_{21}=156°, c_{22}=151°.

It can be seen that for angular errors with σ ≈ (0.5°–1.5°) and safe distance $\bar{R}_{EC1}$ the probabilities of spurious and correct solutions are practically acceptable values α°≈0.08, 1–β°≈0.85; for $\bar{R}_{EC2}$ characteristics of the diagnostics by probabilities of spurious solutions become worse and take values α°≈0.15; by probabilities of correct solutions, remain virtually the same – 1–β°≈0.83.

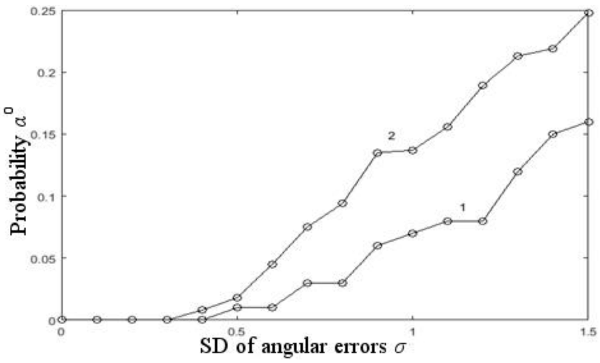

Figure 6. Estimated probability α° of spurious solution for early diagnostics of geomagnetic storms versus SD of angular errors σ

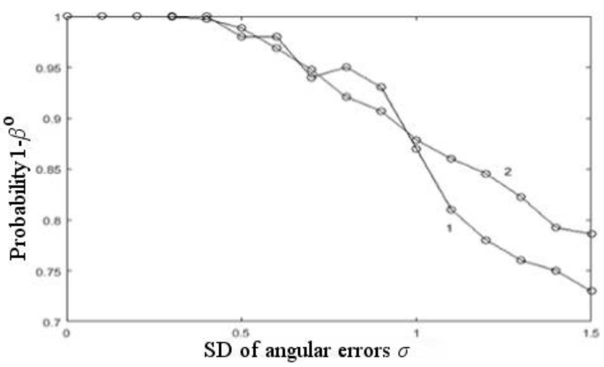

Figure 7. Estimated probability 1–β° of spurious solution for early diagnostics of geomagnetic storms versus SD of angular errors σ

From the analysis of the results of the statistical modeling for the number of observations $N_{1,2}$= 20, 40, $\bar{R}_{EC2} = 60 \cdot 10^9$ m, and c_{21}=156° we obtained estimates of the probabilities of spurious solutions, which increased up to $\alpha_1^\circ \approx 0.25, \alpha_2^\circ \approx 0.38$ for the angular errors σ≈(0.5°–0.7°). For small N, acceptable characteristics of early diagnostics can be obtained by reducing angular errors of observations, which can be achieved by improving the generalized triangulation approach.

The results of the statistical modeling of the probability estimates show that the proposed method and algorithm for early diagnostics of geomagnetic storms proved to be quite efficient.

CONCLUSION

1. The developed method and algorithm for early diagnostics of geomagnetic storms based on the digital processing of angular observations from space monitoring systems with the use of models of CME center movements have proved to be quite efficient.

2. The approach to early diagnostics, which is based on the generalized triangulation, is adequate for the problem addressed and can be elaborated.

3. The statistical modeling relying on the linear model of CME movement and model observations has confirmed the possibility of achieving acceptable accuracy in estimating parameters of model equations of CME movements.

4. Estimates of the probability of errors in making decisions, obtained from the statistical modeling, confirmed that the proposed method and algorithm for early diagnostics of geomagnetic storms are sufficiently effective. Thus, for SD σ≈(0.5°–1.5°) and at a safe distance $\bar{R}_{EC1} = 20 \cdot 10^9$ m probabilities of false alarms and correct decisions are practically acceptable values α°≈0.08, 1–β°≈0.85.

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