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CALCULATION METHOD OF PARAMETERS OF FOREST FIRES AS DYNAMIC PROCESSES ON THE EARTH'S SURFACE ON THE BASIS OF SPACE MONITORING DATA

A simple method for calculating the parameters of a forest fire is offered. The method is based on the representation of a fire as a mobile set on the surface of the Earth. The information base for the proposed methodology is the data of space monitoring of forest fires.

Keywords: forest fires, forecasting, space monitoring, dynamic processes.

One of the areas where it is required to use methods of mathematical modeling and control theory is the protection and rational use of natural resources. As a rule objects that belong to this area are characterized by their spatial distribution and dependence on a large number of hard-to-control factors.

A special group includes objects representing mobile sets or plane waves on the surface of the Earth. Forest and steppe fires, pollution zones of land and water surfaces, areas affected by plant pests, areas of soil erosion and desertification can serve as examples. The importance of studying such objects is increasing in connection with the increasing anthropogenic load on the biosphere and processes of climatic changes.

Enumerated objects have different physical nature, different spatial and temporal scales, but under certain assumptions their dynamics including the processes of their control can be described in a unified manner. A forest fire can serve as an example to illustrate a set of problems connected with the study of these processes and the urgency, goals and objectives of such researches most fully.

The problem of forest fires is very acute in the world today. In the Russian Federation, according to the data of an information system for remote monitoring of Federal Forestry Agency (ISDM-Forestry) 35,337 fires took place during the fire-hazardous seasons in 2008 and 2009, fire covered 15,565,510 hectares, including 9,772,782 hectares of forested areas [1]. Since forest is one of the most important strategic resources, the task of protecting forests from fires, including modeling and forecasting the spread of fires is an extremely important task. By now there has been developed a sufficient number of mathematical models of the forest fires spread and forecasting methods based on them. These models and methods contain different approaches to considering the process of burning in natural fires, however their common feature is the high demands for information support of modeling, that is, the exact knowledge of the set of terrain characteristics, where fire occurs, the state of plant combustible materials, weather conditions are the necessary condition for an adequate model building and, accordingly, forecasting. At the moment it is impossible to create an information base for provision of forecasting on the basis of such models in Russia.

The most complete information about forest fires is currently available in ISDM-Forestry. This information system has existed and is developed since 1995. The sources of the information provided for ISDM-Forestry is the data of space, aviation and ground monitoring of forest fires. Because of vast areas of observation, methods of space monitoring play a leading role. Satellites of such series as NOAA, TERRA, AQUA, SPOT, LANDSAT ETM +, МСУ-Э [1] take part in data collection.

The presence of a reliable forecast of the spread and development of a forest fire allows to evaluate the threat to environment, economic resources and population aggregates, to take necessary measures to prevent damage, to plan the work of fire fighting forces. One of the most important factors in predicting of forest fires is the construction of their contours. In the present paper the method of calculating of large (more than 200 hectares) forest fires contours on the basis of limited information available in ISDM-Forestry [2; 3] is presented.

The most complete information available in ISDM-Forestry and data bases of territorial airbases is connected with the dynamics of changesof the forest fires area. That's why it is reasonable to begin the modeling of the fire spreading process with this figure. When simulating the configuration of fire it is convenient to use Huygens' principle, which describes the propagation of waves in an anisotropic plane environment. This technique can be used for modeling of other dynamic processes mentioned above.

Original assumptions. The following assumptions were taken:

1. The dynamics of change of the forest fires area is determined by

$$S(t) = k_0(t - t_0)^{\alpha}, \quad (1)$$

where t is current time, day; t_0 is the time of fire appearance, day; α is the indicator of fire dynamics; k_0 is the constant coefficient having the dimension n/d^{α}. As it is clear from geometrical considerations and will be shown below, the change in rate of the fire front is also connected with the indicator α : when $\alpha = 2$ the fire front rate is constant, when $\alpha < 2$, this rate decreases with time, and if $\alpha > 2$ the rate increases.

2. The rate of the fire front in accordance with Huygens' principle is presented as

$$v(\varphi, t) = v_0(t)\xi(\varphi),$$

where $v_0(t)$ is the maximum rate of the fire front propagation to be determined (for example downwind); $\xi(\varphi)(|\xi| \le 1)$ is an indicatrix of the front full rate, which determines the configuration of the fire; φ is the propagation direction (0 ≤ φ ≤ 2π). Thus, in general

$$\nu_0 = \nu_0(w, t),$$
$$\xi = \xi(w, \varphi),$$

where *w* is wind speed rate, m / s. We omit the dependence on *w* where it is not required.

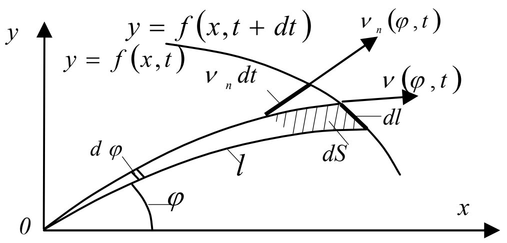
3. The indicatrix is determined by speed and wind direction, it has been adopted unchanged in the settlement period of time. The angle φ in the formula below is measured from the wind direction clockwise.

Formulas for calculating of the fire front rate. To simplify the formulas in this section let $t_0 = 0$. Let's consider an elementary area increment *dS*. Figure shows the edge of the fire in two close points of time *t* and (*t* + *dt*). From the figure it follows that $dS = \nu_n dtdl$, where ν_n is normal front rate; *dl* is the increment of the contour length, which is calculated by the formula [4]:

$$dl = ld\varphi = d\varphi\sqrt{\xi^2(\varphi) + \xi^2(\varphi)}\int_0^t v_0(\tau)d\tau . \qquad (2)$$

In its turn, the normal rate is associated with the full rate by the ratio:

$$v_n(\varphi, t) = \frac{v(\varphi, t)}{\sqrt{1 + \left(\frac{v'(\varphi, t)}{v(\varphi, t)}\right)^2}} = \frac{v_0(t)\xi^2(\varphi)}{\sqrt{\xi^2(\varphi) + \xi'^2(\varphi)}} .$$



Derivation of the formula of the fire front rate

Hence

$$dS = d\varphi dt v_0(t)\xi^2(\varphi)\int_0^t v_0(\tau)d\tau .$$

The area increment in all directions of propagation:

$$dS_{2\pi} = \int_0^{2\pi} dSd\varphi = 2dtv_0(t)\int_0^{\pi} d\phi\xi^2(\varphi)\int_0^t v_0(\tau)d\tau .$$

The rate of growth throughout the area of fire:

$$\frac{dS}{dt} = 2v_0(t)\int_0^{\pi}\xi^2(\varphi)d\varphi\int_0^t v_0(\tau)d\tau , \qquad (3)$$

and the dynamics of the total area becomes

$$S(t) = 2\int_0^{\pi}\xi^2(\varphi)d\varphi\int_0^t v_0(\tau)\int_0^{\tau} v_0(\xi)d\xi d\tau .$$

Now let us consider the law of variation of the fire front rate. We search for the function $\nu_0(t)$ in the form $\nu_{0S}(t^{\beta})$, where the quantities β and ν_{0S} are to be determined. Then the time integral over in equation (3) will be:

$$\int_0^t v_0(\tau)d\tau = \frac{1}{\beta}v_{0S}t^{\beta+1} ,$$

And the rate of area growth:

$$\frac{dS}{dt} = 2\frac{v_{0S}^2}{\beta+1}t^{2\beta+1}\int_0^{\pi}\xi^2(\varphi)d\varphi .$$

On the other hand, from the initial assumption $S(t) = k_0 t^{\alpha}$ follows:

$$\frac{dS}{dt} = k_0\alpha t^{\alpha-1} ,$$

whence we get the equation

$$2\frac{v_{0S}^2}{\beta+1}t^{2\beta+1}\int_0^{\pi}\xi^2(\varphi)d\varphi = k_0\alpha t^{\alpha-1} . \qquad (4)$$

Accepting in equation (4) exponents of *t*, we obtain $2\beta + 1 = \alpha - 1$, whence

$$\beta = \frac{\alpha}{2} - 1 .$$

Next, equating the factors of *t*, we define the value of ν_{0S}:

$$v_{0S} = \left(\frac{\alpha k_0(\beta+1)}{2\int_0^{\pi}\xi^2(\varphi)d\varphi}\right)^{1/2} = \frac{\alpha\sqrt{k_0}}{2\int_0^{\pi}\xi^2(\varphi)d\varphi} = \frac{\alpha\sqrt{k_0}}{2P(w)}, \qquad (5)$$

where

$$P(w) = \int_0^{\pi}\xi^2(w, \varphi)d\varphi .$$

Equation (5) is the desired formula for calculating of the fire rate.

On the basis of the formula (2) we can also calculate the perimeter of the fire burning edge. In a particular case, when a fire develops from a seat of small radius (point seat):

$$L(t) = 2\int_0^{\pi} ld\varphi = 2\int_0^t v_0(\tau)d\tau\int_0^{\pi}\sqrt{\xi^2(w, \varphi) + \xi'^2(w, \varphi)}d\varphi .$$

The formula for the rate of growth of the fire perimeter the becomes

$$\frac{dL(t)}{dt} = 2v_0(t)Q(w), \qquad (6)$$

where

$$Q(w) = \int_0^{\pi}\sqrt{\xi^2(w, \varphi) + \xi'^2(w, \varphi)}d\varphi .$$

Indicatrices of front velocity. Let's consider the specific expressions for the indicatrices.

1. The exponential indicatrix [4]

$$\xi(\varphi) = \exp(\alpha(w)(\cos(\varphi) - 1)),$$

where $\alpha(w)$ is the coefficient dependent on wind speed:

$$\alpha(w) = 0{,}785w - 0{,}06w^2.$$

The formula is valid under the conditions $0 \le w \le 3$ m/s. Then the integrals appearing in expressions (5) and (6) take the form

$$P(w) = \int_0^\pi \xi^2(w,\varphi)d\varphi =$$

$$= \exp(-2a(w))\int_0^\pi \exp(2a(w)\cos(\varphi))d\varphi,$$

$$Q(w) = \int_0^\pi \sqrt{\xi^2(w,\varphi) + \xi'^2(w,\varphi)}d\varphi =$$

$$= \int_0^\pi \xi(w,\varphi)\sqrt{1 + \frac{a^4(w)}{4}\sin^2(2\varphi)}d\varphi.$$

The calculated values of these integrals for certain values of wind speed are shown in tab. 1.

2. The elliptical indicatrix

$$\xi(\varphi) = \frac{1 - e(w)}{1 - e(w)\cos(\varphi)},$$

where $e(w)$ is the eccentricity of the ellipse, which depends on wind speed.

To assess the dependence of the elliptic indicatrix eccentricity on the wind velocity the diagrams of indicatrices shown in the work of F. Albini [5] were approximated by ellipses; the corresponding eccentricities were calculated for a larger range of wind speeds. The following approximation of the dependence of eccentricity on the wind speed was obtained:

$$e(w) = 1 - \exp(-0{,}4w).$$

Then the values of the integral $P(w)$ and $Q(w)$ were calculated. The results are given in tab. 2.

Comparing tab. 1 and 2, we can see that the values of the functions $P(w)$ and $Q(w)$ for both indicatrices can differ markedly at the same wind speeds. It should be born in mind that in the first case the wind speed was calculated at a height of two meters from the ground and in the second – at a height of ten meters, and this also explains a more elongated form of an elliptical indicatrix.

The error of the proposed technique. It is clear that the errors of all inputs result in an error in the final result. In this paper we confine ourselves to the simplest calculation of errors associated with the estimation of the fire area and its daily increment. A more accurate calculation would require involvement of the laws of distribution of variables.

Let the error in determining the fire area is δS ha. We'll consider the model parameters errors caused by this fact (1). The error in the estimate of the coefficient k

$$\delta S = \frac{\partial S}{\partial t}\delta k = t^\alpha \delta k,$$

whence

$$\delta k = \frac{\delta S}{t^\alpha}. \quad (7)$$

The error in the estimation of the fire propagation time:

$$\delta S = \frac{\partial S}{\partial t}\delta t = k\alpha t^{\alpha-1}\delta t,$$

whence

$$\delta t = \frac{\delta S}{k\alpha t^{\alpha-1}}. \quad (8)$$

The error in estimating α:

$$\delta S = \frac{\partial S}{\partial \alpha}\delta\alpha = kt^\alpha \ln t\delta\alpha,$$

whence

$$\delta\alpha = \frac{\delta S}{kt^\alpha \ln t}. \quad (9)$$

Formulas (7)–(9) show that the error of all variables that affect the model (1) are time-dependent and decrease with increasing *t.*

A numerical example of calculating the rate of fire propagation. The fire K-1002 registered in the system ISDM-Forestry was burning in Idrinskoye forestry from 10.05.2008 to 16.05.2008. The fire was registered on the area of 393 ha, the area of fire suppression was 1.163 hectares. The air temperature was 22.7 degrees, the wind speed – 1 m/sec, wind direction – 180 degrees.

Table 1

The values of integrals of the square exponential indicatrix, depending on the wind speed

w, m /s	0	0,1	0,2	0,5	1,0	2,0	3,0
$\alpha(w)$	0	0,078	0,155	0,378	0,725	1,33	1,815
$P(w)$	3,142	2,705	2,361	1,1695	1,178	0,818	0,686
$Q(w)$	3,142	2,911	2,708	2,234	1,758	1,455	1,535

Table 2

The values of the integrals of the elliptic indicatrix square depending on the wind speed

w, m /s	0	1,25	2,5	5	10	15
$e(w)$	0	0,393	0,632	0,865	0,982	0,998
$P(w)$	3,142	1,469	0,782	0,588	0,539	0,193
$Q(w)$	3,142	2,151	1,60	1,424	1,379	1,194

Let's assume that the error in determining the area $\delta S = 100$ ha, $\Delta t = 16–10 = 6$ days. We accept the indicator of the fire area growth rate $\alpha = 2$, i. e. assume that the speed of the fire front is constant.

We calculate the coefficient k and its error in the model:

$$K = \Delta S/\Delta t^2 = 770/36 = 21.4 \text{ ha/per 24 hours},$$

$$\delta k = 100/36 = 2.7 \text{ ha/per 24 hours}.$$

An error estimate of the indicator α according to formula (9) yields:

$$\delta\alpha = \frac{100}{21.4 \cdot 6^2 \cdot \ln 6} = 0.07 .$$

As the wind speed is not great, we use the exponential indicatrix. For the wind speed $w = 1$ m/sec, from tab. 1 we determine the factor $P(w) = 1{,}178$ and $Q(w) = 1{,}758$.

In accordance with the formula (5), converting acres into square meters, we get:

$$v_{0S} = \frac{\sqrt{k}}{P(\omega)} = \sqrt{\frac{21.4 \cdot 10^4}{1.178}} = 426 \text{ m/day}.$$

In view of a possible error δk the value of the front velocity will be in the following ranges: $275 \le v_{0S} \le 577$ m/day.

With the help of formula (6) we can estimate the rate of the fire perimeter growth:

$$\frac{dL(t)}{dt} = 2v_0(t)Q(w) =$$
$$= 2 \cdot 426 \cdot 1.758 = 1498 \pm 531 \text{ m/day}.$$

The resulting estimate of the fire front rate together with the selected indicatrix of propagation allows us to form the predictive estimates of the fire contour over time.

A simple method of estimating the parameters of the distribution process presented in the article is based on the use of geometric models and allows to predict the forest fires propagation on the basis of information stored in ISDM-Forestry. The methodology uses the indicatrices of two kinds, depending on the wind speed in the area of fire: the exponential one and the elliptic one. The received formulas were used for the numerical calculation of a real fire parameters, their errors were estimated. The described method of calculation was used to construct the contours of fires on the basis of neural network forecasting in a software package "Taiga-2" and in the development of an information system of forest fires forecasting for ISDM-Forestry.

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A THERMAL VACUUM SPACECRAFT TEST: THE EXPERIENCE OF CREATING SOLAR SIMULATORS USING HIGH PRESSURE GAS-DISCHARGE LAMPS

In this article we have considered a possibility to use the commercial XBO xenon lamps to create a source of radiation, integrated in solar simulators. We have conducted experimental studies of photonic lamp performance.

Keywords: thermal vacuum test, solar simulator, radiation source, light flux, XBO-lamp.

One of the main stages of ground spacecraft testing is considered to be the thermal vacuum test. The tested object is a thermophysical spacecraft model of its elements. Instead of flight devices and blocks, the platform of the thermophysical model has its own thermal simulators – heater sections, simulating thermal dissipation during flight operations. The resistance sensors are installed in the model's elements to read the temperature information during the thermal vacuum test (TVT).

The purpose of the TVT is an experimental test of the thermal mode and thermal schemes of newly developed