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A global atmosphere model in flight performance assessment and building the reach line when preparing flight missions for sea-based unmanned aerial vehicles

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When standard atmosphere is used in range and altitude flight profile assessment of the unmanned aerial vehicles (UAVs) flight performance, it does not take into account the huge variety of meteorological factors on different routes. Hence, it does not accurately assess the maximum flight range. It is a strategy of the "worst combinations in terms of the probability of meteorological factors" for the entire surface of the Earth at all seasons. The paper proposes a global atmosphere model to be used in flight range assessment, and compares the model with the meteorological data archive. To build the reach line when preparing flight missions for sea-based unmanned aerial vehicles, the study proposes to use the global atmosphere model, which takes into account the meteorological parameters of a given place and month, since the wind, for example, has a particularly strong effect on the flight range and has significant seasonal-latitudinal variability. The global atmosphere model and a simplified mathematical flight model can be also used in assessing the maximum permissible length of the operational section when preparing a flight route.

Keywords: *global atmosphere model, flight performance assessment, reach line, operational section assessment*

Introduction. The existing methodology for estimating FTC "according to the worst-case combination of meteorological factors" significantly underestimates the flight range, which is confirmed by the results of real experiments. Disadvantages of the standard atmosphere when used in mathematical flight models are the constancy of the atmospheric parameters from the start point to the end point of the route and the lack of statical data on wind, which is main factor. Therefore, the standard atmosphere cannot adequately account for changes in atmospheric parameters on routes with long distances. In reality, depending on the place of application, season and length of the route the atmospheric parameters can change very significantly.

This paper considers the possibility of applying the Global Atmosphere Model (GAM) [1] in flight modelling of Unmanned Aerial Vehicles (UAVs) for flight performance evaluation, comparing the standard atmosphere used in the mathematical flight model of the standard [2] with the Global Atmosphere, as well as applying GAM when calculating route parameters in the operational area. (Operational area is an area of the route when flying over the sea, the parameters of which are calculated just before the launch of the UAV.)

Thus, the work addressed three main issues:

1) estimation of the range gain when using GAM compared to the "according to the worst-case combination of meteorological factors" methodology, which gives an underestimate of the range;

2) rationale for moving from a range attainment probability of 0.993 (2.7σ) to 0.95, equal to the probability of no-failure operation;

3) estimation of the gain in route calculations at the operational site when using improved range estimates depending on the launch location and time of year. This concerns the increase in the length of the operational area and radius of reach of the stationary area of the route (stationary area is an area of the route when flying over land, the parameters of which are calculated in advance before the launch of the UAV).

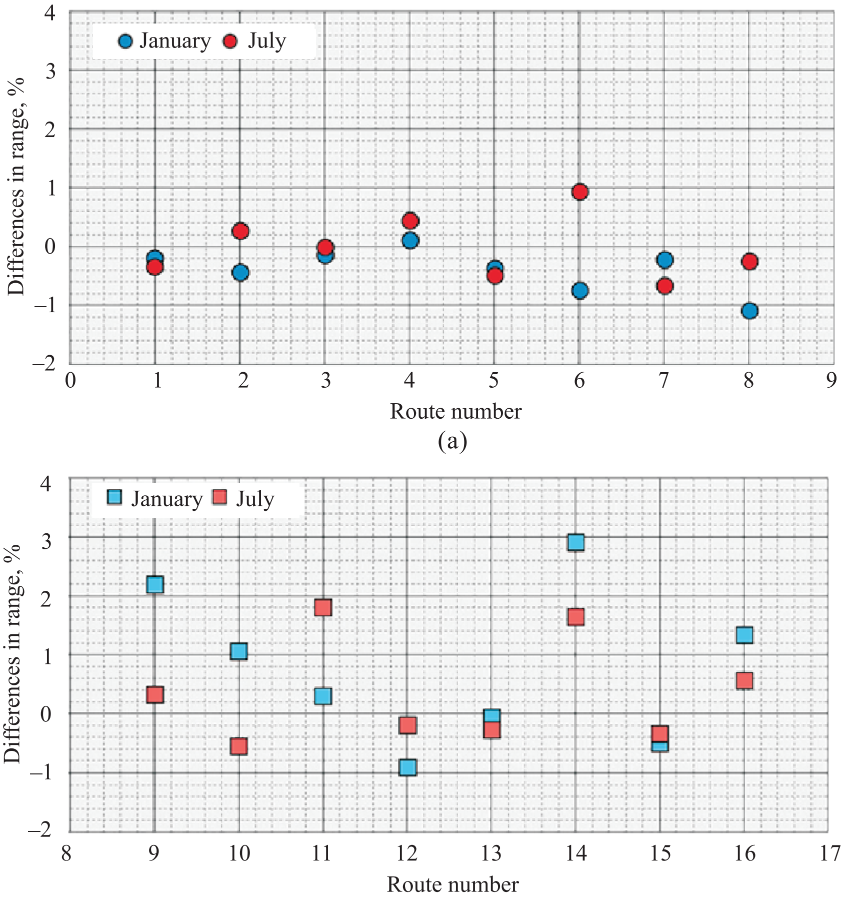
Comparison of the Global Atmosphere model with the weather archive. In order to compare GAM and the weather archive [3, 4], flight modelling based on the statistical simulation method for range estimation was considered. When modeling the flight using the weather archive, the atmospheric parameters were formed according to the following conditions:

1) since there is no sufficient amount of meteorological data over the sea (due to the lack of stationary meteorological stations) the operational section used GAM to calculate temperature, pressure, density at heights from 0 to 5000 m and wind components at heights from 250 to 5000 m. At heights from 0 to 250 m zonal and meridional wind was calculated from the wind archive [4, 5];

2) at the fixed section, the weather archive from stationary weather stations was used [6]. Based on the atmospheric parameters from the weather stations, the temperature, pressure, density at the heights from 0 to 5000 m and the wind components at the heights from 0 to 250 m were calculated. At the heights from 250 to 5000 m the zonal and meridional wind was calculated using GAM [7–10].

Statistical modelling was calculated on 16 typical routes: 8 standard routes (no. 1–8) and 8 routes with long operational section (no. 9–16) for two months (January, July). Figures 1 (a) and (b) show the results of statistical modeling and one can note the differences in flight range between GAM and the weather archive in percenttages.

As one can see from Figure 1, the long operational area affects the range estimation error when using GAM, depending on the route and season (the maximum error does not exceed 3%).



(b)

Figure 1. Differences in range calculated using GAM and weather archive, for standard routes (a) and for routes with long operational section (b).

Application of the Global Atmosphere model in range estimation. Several routes in different parts of the Earth were chosen to estimate the FTC (e.g., range to complete fuel burnout) using GAM. For each route and month (January, April, June, and October), 1000 realizations were calculated. As a range estimate for each route and month, the range that, with a probability of 0.993, would be reached by the UAV was chosen.

The table shows the increase in the range estimate by months and routes, calculated using GAM, relative to the range calculated using the according to the "worst-case combination of meteorological factors" methodology with a probability of 0.993.

Our calculations have shown that the use of the Global Atmosphere model allows increasing the range estimate by 4–13%, depending on location and time, compared with the existing methodology. Thus, range cannot be set by one number for all routes and months. The range estimation methodology for the preparation of flight routes will be outlined below.

Range increment, %.

Month	Route number											
	1	2	3	4	5	6	7	8	9	10	11	12
January	11.4	6.4	12	7.4	4.3	10.7	12.9	11.5	12.9	11.5	11.2	12.8
April	12.4	7.5	12.1	9.3	5	8.6	13	10.7	13	10.7	13	12.2
June	12.8	8	11.9	9.9	5.7	8.6	12.2	12.5	12.2	12.5	13.7	13
October	12.4	6.4	12.1	9.5	5.6	9.7	12.6	12.3	12.6	12.3	12	12.8

Justification of the transition from the probability of reaching the range of 0.993 (2.7σ) to the level of 0.95. The probability of succeeding in the task is described by a chain of events and is calculated by the formula

$$P_1 = P_{vbr} P_{top} P_{bdk}, \tag{1}$$

where: P_1 is probability of success for the one UAV;

P_{vbr} is failure-free probability;

P_{top} is probability of falling at the end of the fuel;

P_{bdk} is probability of safely reaching the final route point.

The required UAV outfit for the probability of a successful mission is equal to 0.9 is calculated according to the formula

$$N_{0.9} = \frac{\ln(1-0.9)}{\ln(1-P_1)}. \tag{2}$$

The following probability levels will be used for estimations:

$$P_{vbr} = 0.95; \quad P_{top} = 0.993/0.95; \; P_{bdk} = 0.686.$$

The result is

$$N_{0.9} = 2.2 \quad \text{for } P_{top} = 0.993; \quad N_{0.9} = 2.4 \quad \text{for } P_{top} = 0.95.$$

The difference is 0.2 UAVs and their number will be taken as three UAVs, for the probability of success is not less than the required normative level. That is, reducing the probability P_{top} to the level of P_{vbr} has almost no effect on the size of the required UAV outfit to reach the required level of success probability, especially given the large uncertainty in the probability level P_{bdk}. In this transition, as follows from the above graphs, the range increases by 3% for extremely long routes. For comparison, let us point out that it is assumed that the design of the UAV is more complicated in order to more fully exhaust the residual fuel, which increases the flight range by 2% c.u. Thus, it is recommended to use the 0.95

level when estimating the range and calculating the route. The required level of probability of reaching the endpoint of the route can be set is calculated by formula (7) below.

Using the Global Atmosphere Model in the Construction of the Reach Boundary. Improvements in FTC in terms of refining range estimates can be achieved for both the fixed section when solving the planning problem in advance and for the operational section before the launch of the UAV. This section discusses how a GAM and a fixed section can be used to construct a range. The UAV range is highly dependent on wind speed and direction. The Global Atmosphere model allows us to estimate the operational section range given the seasonal-latitude meteorological data of a given location and month. Also for the construction of the range boundary, it is necessary to calculate in advance the fuel residuals for a particular fixed section for all 12 months (the partitioning intervals may vary); the obtained residuals should be contained in the Initial Data (ID) for the construction of operational section.

First, the route to the first stationary turning point of the route (PPMS1) is laid according to the final route point coordinates. Using GAM at statistical modeling of flight determines fuel residuals at PPMS1 for a given stationary section and for all 12 months. Based on the simulation results, an array of fuel residuals (mathematical expectations and RMS for each month) is recorded in the ID together with the parameters of the route of the stationary section.

When you are in a given area for the current month, the range radius of the first stationary PPM for the given route is calculated. The range radius R_d is calculated using the specific range table using the formula

$$R_d = Lw(h, T, uve)\, m_r, \tag{3}$$

where $Lw(h, T, uve)$ is a table of specific range, km/kg;

uve is a projection of the average month wind on the direction of the range radius;

m_r is a remaining fuel at some set level.

Current temperature T is known at the time of the launch of the UAV and does not require the involvement of Global Atmosphere model data.

To calculate the boundary of the “optimistic” reach boundary, the directions of the radius of the boundary from the first stationary PPM are selected. The full contributions of wind components “U” (zonal) and “W” (meridional) are projected onto the selected directions. The lengths for these directions are calculated by formula (3). In this way the boundary of the “optimistic” boundary of the first stationary PPM reach for a given stationary section is calculated.

Estimation of maximum permissible length of operational area in preparation of a flight task. After constructing the range boundary, the closest starting point within the range is selected. From the selected point a route of the required configuration is laid to the first stationary BCP.

Using the Global Atmosphere model at the points along the route, the wind components “U” and “W” are calculated, containing not only monthly multiyear average values, but also their variations. Before each simulation of a flight at the operational section, it is necessary to calculate the wind speed components by means of GAM and to translate them into the orthodromic coordinate system. Having statistically modeled of the flight, we obtain a histogram of fuel consumption at operational section (Figure 2).

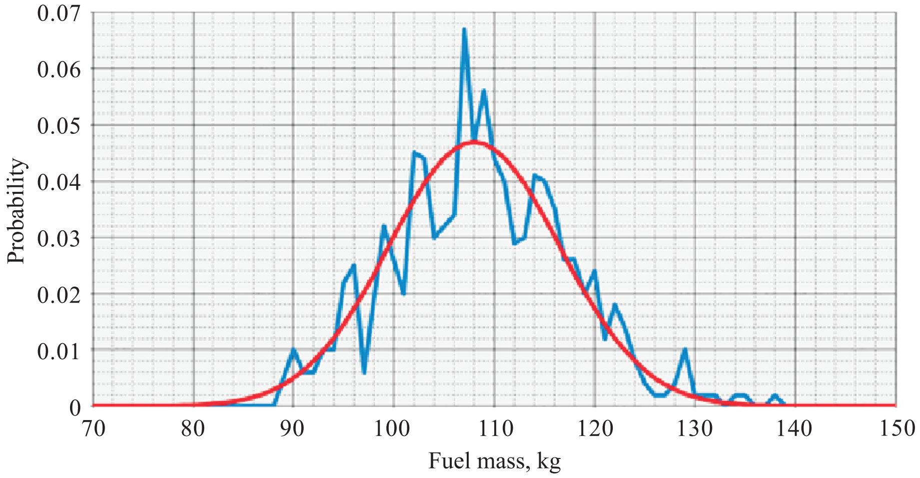


Figure 2. Fuel consumption in the operational area:
▬ — fuel consumption histogram; ▬ — Normal law

After statistical modeling of the flight we can calculate the mathematical expectation $E(m_{c1})$ and RMS of fuel consumption at the operational section, as the normal law approximates the fuel consumption histogram well (see Figure 3). It is also necessary to calculate the mathematical expectation $E(m_2)$ of fuel consumption for the first orthodromy shortened by distance ΔL_{ort1}. Using these parameters we can calculate the specific range using the following formula:

$$Lw = \frac{\Delta L_{ort1}}{E(m_{c1}) - E(m_2)}. \tag{4}$$

Figure 3 shows the probability distributions of the residuals at fixed section (blue line) and expenditures at operational section (red line). At some given level of probability P_s we determine the fuel consumption m_c

at the operational section, as well as the remaining fuel m_r at the fixed section. Next, we calculate the remaining fuel for the flight along the entire route:

$$\Delta m = m_r - m_c. \tag{5}$$

Mathematical expectation $E(m_c)$ of fuel consumption in the operational section is corrected by the value Δm (the red line in Figure 3 is shifted to the left or right depending on the sign):

$$E(m_c) = E(m_c) + \Delta m. \tag{6}$$

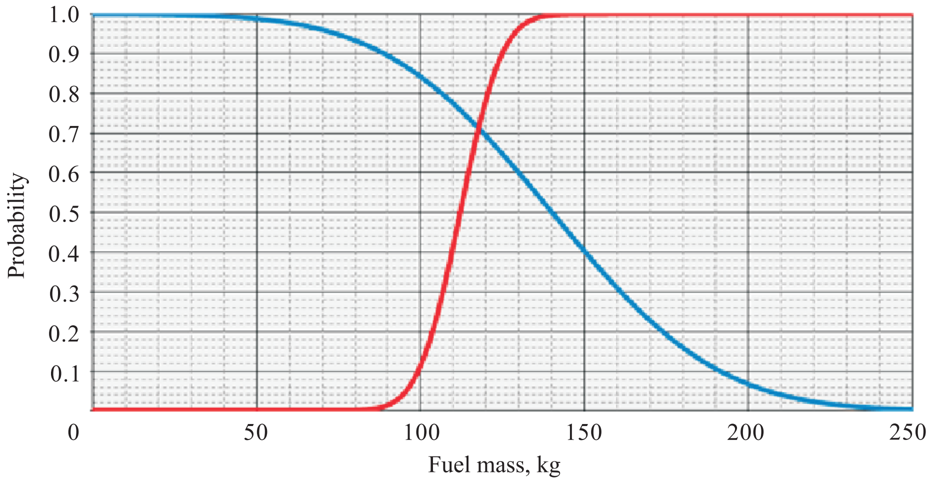


Figure 3. Distribution of probabilities of fuel residuals at the fixed section (▬) and fuel consumption in the operational section (▬).

The probability of reaching the endpoint of the route by fuel is calculated by the formula

$$P_{top} = \int_{M_n}^{M_k} f_{oct} P_{rtp} dm, \tag{7}$$

where f_{oct} is the probability density of residual fuel in the fixed section,

P_{rtp} is a distribution of the probability of fuel consumption at the operational section (red line in Figure 4).

If the probability P_{top} differs from the required value (e.g., 0.95), after correcting the mathematical expectation of fuel consumption at operational section, then Δm cyclically increases or decreases by 1 kg (which corresponds to an increase or decrease in the length of the first orthodromy). Recalculation of the probability of reaching the endpoint of the route by fuel P_{top} occurs in each cycle and is calculated by formula (7). As soon as the difference ($P_{top} - 0.5$) changes sign the cycle stops and it is necessary to recalculate the length of the operative section by the following formula:

$$\sum L_{ort} = \sum L_{ort} + \Delta m L w, \tag{8}$$

where Lw is defined by equation (4),

L_{ort} is the orthodromy length.

If the residual fuel Δm is positive, then the length of the operational section increases, if the residual fuel is negative then it decreases. As a result, we obtain the maximum permissible length of the operational section, which for practical reasons can be reduced.

Conclusion. Calculations show that application of the GAM in determining FTC increases the range estimate by 4–13%, depending on the route location and month, compared to the existing methodology "worst-case combination of meteorological factors". A new methodology has been developed to estimate the reachability of the endpoint of the route and to estimate the maximum allowable length of the operational section along the chosen route, using the GAM and the "fast" mathematical model of the flight.

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