Quality Assessment of Aircraft Glide Path Entrance

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Abstract. The article proposes a method for analyzing and assessment of aircraft glide path in three-dimensional coordinates. The issues of prediction of glide path boundaries by autocorrelation function at different flight complexity have been considered. This is particularly true in the event of abnormal situations in flight. Negative factors impact on pilots' psychophysiological state may lead to quality deterioration of flight technique. In most cases pilots don't notice it. Thus they need to be informed about this. In this regard a comparison method of autocorrelation functions is suggested. The landing quality depends on accuracy execution of all stages of land approach. Therefore the proposed methods introduction with further warning automation on deterioration of glide path supposes flying safety benefits. These methods were developed for the director regime of modern aircrafts management.

Keywords: flight trajectory, glide path, human factor, parameters amplitude

1 Introduction

Modern automatic control systems make it possible to unload the crew from routine operations and perform flights in conditions of poor visibility. However, in abnormal flight operations it is necessary to go to the director mode of aircraft control [1]. This can lead to increased psychophysiological pilot's tension that in most cases negatively affects the quality of aircraft piloting techniques. The article proposes a method for analyzing and assessing of aircraft glide path in three-dimensional coordinates and method introduction with further warning automation on deterioration of glide path supposes flying safety benefits. It should be noted that flights safety issues rank one of the main places in the air transport system. The final approach (landing) depends on timely glide path entrance and its further path following. Many authors devote their work to the problem of the human factor in aviation [2-12]. Some authors consider the final approach [13-15]. The glide path boundaries are regulated by restrictions on altitude and course, but in special flight cases pilots may not withstand the necessary flight paths. Probability boundaries of the glide path are modeled by the correlation functions of flight parameters. Human operator tension is determined even by one flight parameter. It is reasonably to demonstrate this on the information model of a pilot's sensorimotor field. In addition theoretical training of the crew in this direction is necessary.

2 Problem statement

Goal. The goal of this work is to improve ergatic control system quality of an aircraft at the glide path entrance.

Often amplitude increasing of an aircraft's flight parameters (AIAFP) occurs due to a pilot's increased psychophysiological tension. A human-operator's tension increasing can be determined by the autocorrelation functions of flight parameters. Until that time such a method was considered only on a glide path landing. In this article there is also a good reason to analyze a glide capture phase.

3 Determination method of glide path capture boundaries in the form of an ellipsoid

The operator uses information *I* (*t*), that is under distortion *I'(t)* due to a combination of certain reasons.

$$I^{'}(t) = I(t) \cdot (1 + m(t) \cos \Omega t), \tag{1}$$

where $\Omega = 2\pi f$ is angle speed, *f* is frequency, *m(t)* is amplitude.

Function *I'*(*t*) can take this form on the basis of the an experimental fact of the existence of the phenomenon of amplitude increasing of an aircraft's flight parameters (AIAFP) including due to a pilot's increased psychophysiological tension. This is about integro-differentiated motor dynamic stereotype. It is the end result of human operator's actions when piloting [16].

If the functions *m*(*t*), *I*(*t*) – stationary random functions, φ_i = *const* ($\varphi_i = \Omega_i \tau$), *i* – the test number (landing approach) according to the known tests category (landings). Then the function *I'*(*t*) depends only on time and is completely determined by the result of each test, landing.

The above data are obtained after considering a correlation function of flight path trajectory $\rho(\tau)$. According to $\rho(\tau)$ the aircraft should fly without information distortions in the reception of information and management.

$$\rho(\tau) = I(t) \cdot I(t - \tau) =$$
$$= \lim_{T \to \infty} \left(\frac{1}{T_L} \right) \int_0^{T_L} I(t) \cdot I(t - \tau) dt = \frac{1}{T_L} \int_0^{T_L} I(t) \cdot I(t - \tau) dt, \tag{2}$$

where τ is delay time, T_L is flight time at a certain specific area of length *L*, for example, $T_L = T_n$, where T_n is an airplane's landing time.

A correlation function AIAFP is presented in the following form:

$$\rho_{AIAFP}(\tau) = \rho(\tau) + \frac{1}{2} I(t) \cdot I(t-\tau) m_i(t) \cdot m_i(t-\tau) \cos\Omega_i \tau. \tag{3}$$

A correlation function of landing trajectory with AIAFP equals the sum of a correlation function of landing trajectory without AIAFP and a term depending on statistics of trajectory without AIAFP trajectory without AIAFP and statistics AIAFP.

In general, we describe the flight path of the aircraft using the function: $Z = f(x, y)$.

When landing, this trajectory is determined by the path of the glide path:

$$Z = f(x, y) = const.$$

The flight trajectory is determined by the ergatic system and is related to pitch angles (υ), roll angle (γ), slope of the trajectory (θ), heading (ψ), and the speed (v) of the aircraft. The coordinates of the flight trajectory are dependent on all the above parameters listed and are determined by the functional expressions:

$$Z=F_1(\upsilon, \gamma, \theta, \psi, v),\ Y=F_2(\upsilon, \gamma, \theta, \psi, v),\ X=F_3(\upsilon, \gamma, \theta, \psi, v).$$

Glide path coordinates ($y=const$):

$$Z=F_4(\upsilon, \gamma, \theta, \nu),\ \psi=const,\ Z=F_5(\upsilon, \gamma, \theta, \nu),\ y=const.$$

We define the glide path trajectory with a straight line connecting the position of the beacon ($x = L$, $Z = 0$) and the point at which the landing began ($x = 0$, $Z_0 = h$). In (Fig. 1), these points are characterized by a significant angle of change in the trajectory α. The real flight trajectory assumes smooth smoothing of the indicated angles, which in the future must be taken into account [17].

Glide path coordinates are determined by the relationship:

$$Z = Z_0 + x \cdot tg\alpha\ , \tag{4}$$

where Z_0 is the initial coordinate along the height, α is the angle between the trajectory line and the direction X; $Z_0 = h$, $tg\alpha = -h/L$, L is the length of the glide path. In these designations, the glide path trajectory will look like:

$$Z(x) = h - \frac{h}{L} \cdot x \cdot \tag{5}$$

To further analyze the movement of the aircraft during landing, we calculate the correlation function of the trajectory described by the equation $Z(x)$:

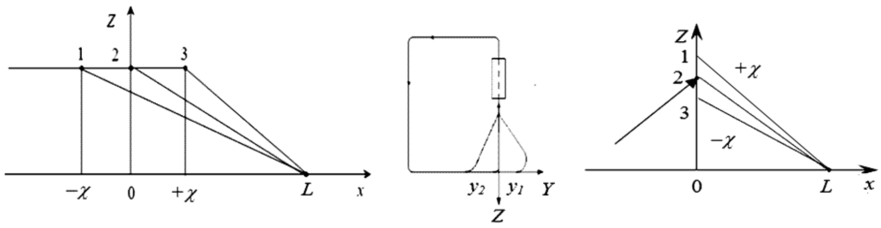
$$\rho(\chi) = \frac{1}{L} \int_0^l Z(x) \cdot Z(x-\chi) dx.$$

Consider one of the possible variants (fig. 1).

Normal glide path entry $Z = h - \frac{h}{L} \cdot x = h\frac{L-x}{L}; \quad 0 < x << L;$

Ahead $Z = h\frac{L-x}{L+x} - \chi; \quad -\chi << x << L;$

Delay $Z = h\dfrac{L-x}{L-x} + \chi; \quad \chi << x << L.$



a) b) c)

Fig. 1. The normal glide path trajectory is 2, the delay is 3(below the glide path is c) and, accordingly, the glide path ahead is 1(above the glide path is c), a is at the entrance to the glide path from a straight line, c is when flying in a circle

Let us split the range (0, L) into two parts (0, $L-\chi$) and (0, $L+\chi$). Outrunning function at part ($L-\chi, L$) equals zero: $Z(x+\chi)=0$. Consequently, the outrunning correlation function is determined by integrating only in the interval of (0, $L-\chi$)

$$\rho_{pout} = \rho(+\chi) = \frac{1}{L}\int_0^{L-\chi}\left(h - \frac{h}{L}\cdot x\right)\cdot[h - \frac{h}{L}(x+\chi)]dx = \frac{h^2}{3} - \frac{h^2}{2L}\cdot\chi. \tag{6}$$

Consider the expression:

$$\rho(-\chi) - \rho(+\chi) = \frac{h^2}{L}\cdot\chi.$$

It can be concluded that

$$\rho(-\chi) > \rho(+\chi). \tag{7}$$

Autocorrelation function of outrunning path is equal to

$$\rho_{ak}(+\chi) = \frac{1}{L}\int_0^L [h - \frac{h}{L}(x+\chi)]^2 dx = \frac{h^2}{L}\int_0^L [1 - \frac{x+\chi}{L}]^2 dx = \frac{h^2}{3} - \frac{h^2\cdot\chi}{L} + \frac{h^2}{L^2}\cdot\chi^2.$$

$\rho(-\chi) - \rho(+\chi) = 0$ as long as $\chi = 2L$ that is unreal condition when the aircraft has not landed.

If $L >> \chi$ the delay value is much less than the length of the glide path, which is quite real, the autocorrelation function is equal to the outrunning path

$$\rho_{ak}(+\chi) = \frac{1}{3}h^2. \tag{8}$$

square of integral difference trajectory of an aircraft's flight Δ is

$$\Delta = L\rho_p - 2L\rho_{pr} + Lp_r, \tag{9}$$

where functions $L\rho_p$, $L\rho_{pr}$, $L\rho_r$ are respectively the autocorrelation functions of the planned flight ($L\rho_p$), the correlation function between the planned trajectory and the real trajectory $L\rho_{pr}$, and ρ_r is the autocorrelation function of the real flight trajectory.

Let us substitute values $\rho_p, \rho_{ak}(+\chi)$ and $\rho_{pout}(+\chi)$ into the equation (9) and get the ratio of square of integral difference trajectory of an aircraft's flight Δ to its length L (fig. 2)

$$\frac{\Delta}{L} = \frac{1}{3}h^2 - \frac{2h^2}{3} + \frac{h^2 \cdot \chi}{L} + \frac{h^2}{3} - \frac{h^2 \cdot \chi}{L} + \frac{h^2 \cdot \chi^2}{L^2} = \frac{h^2 \cdot \chi^2}{L^2}.$$

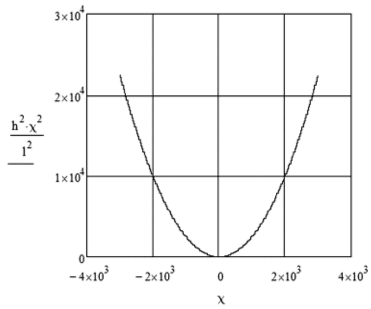


Fig. 2. Graph of relation between $\frac{\Delta}{L}$ and χ (χ is within the range from-3000mto3000m, for fig. 1a).

This figure shows that in the case of the glide path entrance delay, the probability of hitting the threshold level of runway increases. The probability of the preconditions for occurrence of aircraft accident increases.

It is seen from the formula that when the delay χ of the start of landing increases, the correlation function changes.

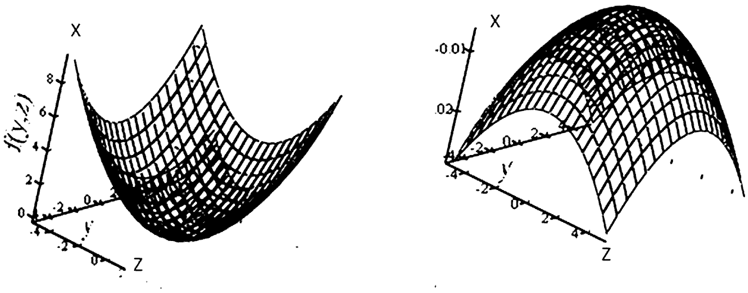
From the above it follows that it is possible to determine the trajectory of the aircraft at the entrance to the glide path according to the above formulas, namely, by the function of correlation of the inactivity of factorial overlays and on the glide path with a periodic factorial overlay. The correlation function of the glide path allows you to determine stationary random functions of the flight trajectory, and therefore to identify AIAFP.

In the previous works the methods for glide path capture boundaries determining by correlation functions were developed. Graphically they were paraboloids. It was shown that the ratio of square of integral difference trajectory of an aircraft's flight Δ to its length L at retardation value χ in considering in different spatial planes is determined by autocorrelation functions (fig. 3):

$$\frac{\Delta_1}{L_1} = \left(\frac{1}{3} - \frac{3\chi_1}{L_1} + \frac{2{\chi_1}^2}{{L_1}^2} - \frac{{\chi_1}^3}{3{L_1}^3}\right)x^2;$$

$$\frac{\Delta_2}{L_2} = \left(\frac{1}{3} - \frac{3\chi_2}{L_2} + \frac{2{\chi_2}^2}{{L_2}^2} - \frac{{\chi_2}^3}{3{L_2}^3}\right)y^2;$$

$$\frac{\Delta_3}{L_3} = \left(\frac{1}{3} - \frac{3\chi_3}{L_3} + \frac{2\chi_3{}^2}{L_3{}^2} - \frac{\chi_3{}^3}{3L_3{}^3}\right) z^2.$$



a) в)

Fig. 3. Calculation listing a) Δ/L = f (y, z), L = 1200, χ = 600, y = -300..300, z = -46-46 and b) Δ/L = f (y , z), where χ = 1450 m, y = -300..300, z = -50..50, for fig. 1 b).

Functional dependence $\rho = f\left(\frac{\chi}{L}\right)$ is a numerical parameter of the paraboloid function.

$$\frac{\Delta}{L} = \left(\frac{1}{3} - \frac{3\chi}{L} + \frac{2\chi^2}{L^2} - \frac{\chi^3}{3L^3}\right)\left(y^2 + z^2\right).$$

In a $\rho = f\left(\frac{\chi}{L}\right)$ paraboloid $\frac{\Delta}{L} = \left(\frac{1}{3} - \frac{3\chi}{L} + \frac{2\chi^2}{L^2} - \frac{\chi^3}{3L^3}\right)\left(y^2 + z^2\right)$, depending on the numerical value $\rho = f\left(\frac{\chi}{L}\right)$, geometric values and its position in three-dimensional space can vary.

At $\frac{\chi}{L} \in (-\infty;0.123) \cup (2.31;3.62)$ intervals the function has positive values. They determine the position of the paraboloid in such a way that it has a minimum point [18]. With an increase in the deviation χ with respect to the length *L*, the geometric dimensions of the paraboloid also decrease. It takes the form of a point with values

$$\frac{\chi}{L} \approx (0.123);\ \frac{\chi}{L} \approx (2.31);\ \frac{\chi}{L} \approx (3.62).$$

With negative numeric parameters of the function $\rho = f\left(\frac{\chi}{L}\right)$ at intervals $\frac{\chi}{L} \in (0.123;2.31) \cup (3.62;+\infty)$ the paraboloid flips 180° and has a maximum point. In real conditions, the ratio $\frac{\chi}{L}$ is a small value that tends to zero. Therefore, values in the vicinity of zero may be of practical interest. Function $\rho = f\left(\frac{\chi}{L}\right)$ of the relation χ from the entry point to the path *L* has the following form:

$$\rho = -\left(\frac{\chi}{L}\right)^3 + 2\left(\frac{\chi}{L}\right)^2 - 3\left(\frac{\chi}{L}\right) + \frac{1}{3}.$$

It has an extremum point: minimum point (1; -1); maximum point (3; 1/3). Points of intersection with the axes: ordinates (0; 1/3); abscissa (0.123; 0), (2.31; 0), (3.62; 0).

On the basis of the above formulas for three-dimensional space we get the function:

$$\frac{\Delta}{L} = \left(\frac{1}{3} - \frac{3\chi_1}{L_1} + \frac{2\chi_1^2}{L_1^2} - \frac{\chi_1^3}{3L_1^3}\right)x^2 + \left(\frac{1}{3} - \frac{3\chi_2}{L_2} + \frac{2\chi_2^2}{L_2^2} - \frac{\chi_2^3}{3L_2^3}\right)y^2 + \left(\frac{1}{3} - \frac{3\chi_3}{L_3} + \frac{2\chi_3^2}{L_3^2} - \frac{\chi_3^3}{3L_3^3}\right)z^2.$$

This function represents second-degree surface – three-axis ellipsoid. It is represented in a canonical form and the values of semi axes *a*, *b*, *c* of an ellipsoid are determined by the following expression:

$$\frac{x^2}{\frac{\Delta}{L}\cdot\frac{1}{\frac{1}{3} - \frac{3\chi_1}{L_1} + \frac{2\chi_1^2}{L_1^2} - \frac{\chi_1^3}{3L_1^3}}} + \frac{y^2}{\frac{\Delta}{L}\cdot\frac{1}{\frac{1}{3} - \frac{3\chi_2}{L_2} + \frac{2\chi_2^2}{L_2^2} - \frac{\chi_2^3}{3L_2^3}}} + \frac{z^2}{\frac{\Delta}{L}\cdot\frac{1}{\frac{1}{3} - \frac{3\chi_3}{L_3} + \frac{2\chi_3^2}{L_3^2} - \frac{\chi_3^3}{3L_3^3}}} = 1,$$

where each of the semi-axes is determined by the expression:

$$a = \sqrt{\frac{\Delta}{L}\cdot\frac{1}{\frac{1}{3} - \frac{3\chi_1}{L_1} + \frac{2\chi_1^2}{L_1^2} - \frac{\chi_1^3}{3L_1^3}}};$$

$$b = \sqrt{\frac{\Delta}{L}\cdot\frac{1}{\frac{1}{3} - \frac{3\chi_2}{L_2} + \frac{2\chi_2^2}{L_2^2} - \frac{\chi_2^3}{3L_2^3}}};$$

$$c = \sqrt{\frac{\Delta}{L}\cdot\frac{1}{\frac{1}{3} - \frac{3\chi_3}{L_3} + \frac{2\chi_3^2}{L_3^2} - \frac{\chi_3^3}{3L_3^3}}}.$$

Thus, the obtained function of a three-axis ellipsoid can be written,

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1.$$

A characteristic feature of a three-axis ellipsoid is the formation of ellipses when crossing its surface by planes that are parallel to each of the three coordinate planes (see Fig. 4).

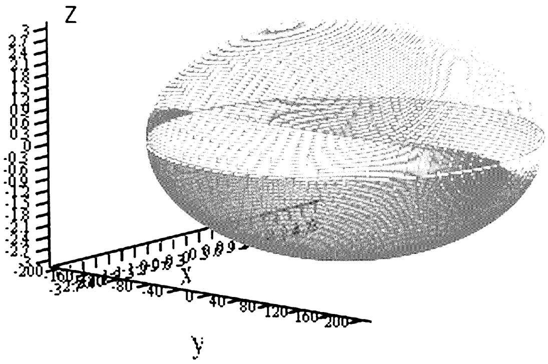


Fig. 4. Dependence graph $f(x, y, z)$, for. fig. 1 c).

If any semi axes are equal to each other, for example, $b=c$, when $\chi_2=\chi_3$, then a three-axis ellipsoid turns into an ellipsoid of revolution.

$$\frac{x^2}{a^2}+\frac{y^2+z^2}{b^2}=1.$$

It is formed by rotating an ellipse around one of the axes of the coordinate system. For example, if ellipse rotate around the abscissa.

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1.$$

If $\chi_1=\chi_2=\chi_3$, then the semi axes of the three-axis ellipse will be equal to: $a=b=c$. And this means that it is transformed into a sphere, $R^2=a^2=b^2=c^2$, where R – sphere radius

The obtained results of our studies coincide with the data given in the work [15]. It examines the issues of runway hit accuracy.

Thus, an aircraft deviation from a given point of glidepath capture in three-dimensional space in the general case is described by a three-axis ellipsoid, and in particular cases by a rotation ellipsoid and a sphere (Fig. 5).

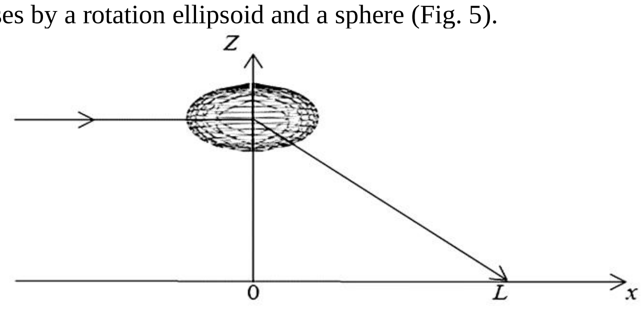


Fig. 5. Dependency graph $f(x, y, z)$, where parameters vary within χ = 92-1450 m (trajectory shift amount in the coordinates), $x = y$ = -300+300 m, z = -46+46 m.

4 The result of the experimental studies of dependence between the flight quality and the entry into the glide path accuracy

An analysis of 48 flights on a B-737-500 aircraft revealed that the maximum amplitudes of the autocorrelation functions spectra of the roll angle on the glide path significantly differ depending on the length of the glide path (Fig. 6). It can be described using the formulas for calculating normalized autocorrelation function $K(t)$ and unregulated autocorrelation function $\Psi(t)$:

$$K(t) = \frac{1}{\sigma \cdot \mathrm{N}} \cdot \sum_{i=0}^{N-t-1} \left[(\gamma_i - m) \cdot (\gamma_{t+i} - m) \right]; \qquad \Psi(t) = \frac{1}{\mathrm{N - t + 1}} \cdot \sum_{i=0}^{N-t-1} \left[(\gamma_i - m) \cdot (\gamma_{t+i} - m) \right],$$

where N is the number of observations in the time series t, γi is the amplitude of the roll angle, i = 1, 2, 3, N, m – mathematical expectation, σ – standard deviation.

The range of values of normalized autocorrelation functions during landing at the airport A presented in the Table 1.

Table 1. The value modulo the first negative amplitude of autocorrelation function of the roll angle during the Base Leg and after it before landing

№ п/п	Pilot	Flight during the Base Leg	Pilot	Flight after the Base Leg before landing
1	**3**	**0.17819**	**2**	**0.091785**
2	**3**	0.21424	**3**	0.12093
3	**3**	0.23082	**2**	0.24683
4	**3**	0.23975	**1**	0.30708
5	**3**	0.27361	**4**	0.30907
6	**1**	0.31251	**3**	0.33677
7	**4**	0.33913	**3**	0.37931
8	**1**	0.40327	**2**	0.46557
9	**2**	0.41642	**3**	0.60857
10	**2**	0.46975	**3**	0.63843
11	**2**	0.76226	**1**	0.66751

The amplitude of the spectrum in the first case is y_1 = 185.96, in the second case y_1 = 23.356. Thus, there is an excess of *y*1 landing with a shortened glide path from normal by 7.96 times.

Studies that were previously conducted on a complex simulator of the aircraft showed that the simultaneous introduction of more than two failures leads to an increase in the amplitude of flight parameters, which is associated with the psychophysiological tension of the human operator (pilot).

They were carried out after entering the glide path and before landing. Failures were selected in such a way that there was no effect on the aerodynamics of the airplane.

There were duplicate devices, with the help of which the flight parameters were measured. Good trainability was shown [19-26].

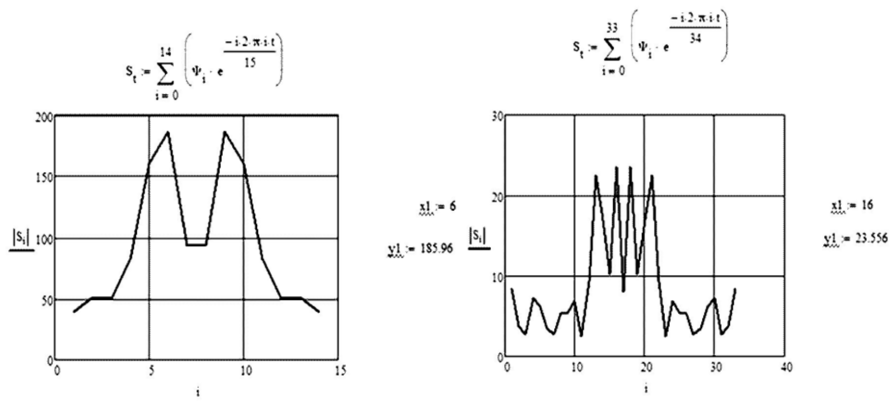


Fig. 6. Spectra of autocorrelation functions of the roll angle on the glide path: a) landing with a shortened glide path (t=60 s), c) landing with a normal glide path (t=260 s)

Thus, during the pilots' training it is advisable to change the section of the given path line in the aerodrome zone to the segment of the path before entering the glide path with the obligatory condition for observing the accuracy of entering it. Firstly, it will increase the discipline of entering the point of the glide path. Secondly, the exact entrance to the glide path will help to reduce the psychophysiological tension of pilots during the approach.

5 Conclusions

The probabilistic boundaries of the entrance to the glide path in the form of an ellipsoid are determined. They can be useful for assessing the piloting technique quality by the values of its coordinates. It is possible to determine the probability of inaccurate entry into the glide path.

The autocorrelation functions of the flight parameters determine the pilot's psychophysiological tension on integrated simulator. It is applicable both when flying on a glide path and entering it. The danger of late entry by plane into the glide path is proved.

It is advisable to use these methods for automated assessment of the piloting techniques quality.

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