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ПРИМЕНЕНИЕ МЕТОДОВ ТРАЕКТОРНОГО АНАЛИЗА ДЛЯ РАЗРАБОТКИ СИСТЕМЫ БЕЗОПАСНОГО ВЗЛЕТА И ПОСАДКИ ЛЕТАТЕЛЬНЫХ АППАРАТОВ / APPLICATION OF TRAJECTORY ANALYSIS TO DESIGN A SYSTEM OF SAFE TAKE-OFF AND LANDING OF AIRCRAFT

Аннотация. *Предметом статьи является применение некоторых методов высокоточного траекторного анализа для повышения безопасности взлета и посадки летательных аппаратов. Эта проблема особенно важна для аэропортов, где имеется высокая плотность потока воздушного движения, а за безопасность взлетов и посадок самолетов отвечают диспетчерские службы. В настоящее время для этих целей основной является курсо-глиссадная система посадки (КГС), однако все категории КГС чувствительны к помехам и влиянию метеорологических условий. Использование спутниковых навигационных систем (СНС) снижает недостатки КГС, однако без дополнительных компонентов они не дают необходимой точности, сравнимой хотя бы с КГС I категории. Цель исследования - найти подходы для получения точных, надежных и достоверных навигационных данных непосредственно на борту летательного аппарата, независимо от погодных условий. Предлагаемый подход основывается на математической модели системы траекторных измерений, определяющей параметры полета летательного аппарата в беззапросном режиме. Для решения поставленных задач были использованы методы линейной алгебры, математическое моделирование случайных процессов, а также компьютерные методы обработки измерительной информации. Математическая модель и результаты расчетов демонстрируют возможность высокоточного измерения на борту летательного аппарата в беззапросном режиме шести текущих навигационных параметров: дальности, радиальной скорости, азимута, угла места и скорости изменения азимута и угла места. Предлагаемый метод позволяет увеличить безопасность взлета и посадки летательных аппаратов в самых сложных метеорологических условиях.*

Ключевые слова: *Курсо-глиссадная система, Спутниковая навигационная система, Траектория посадки, Отражение сигнала, Взлет и посадка, Авиационная безопасность, Навигационные данные, Траекторный анализ, Математическая модель, ГЛОНАСС.*

Abstract. *The subject of this article is the application of some techniques of high-precision trajectory analysis for the improvement of safety of takeoff and landing of aircraft. This issue critically important for airports with the high density air traffic, where the air traffic service (ATS) is responsible for the safety of takeoffs and landings. Nowadays the Instrument Landing System (ILS) is the primary system for these purposes, but all categories of the ILS equipment are sensitive to interferences/obstructions and depend on meteorological conditions. The use of the Satellite Navigation System (SNS) smooths over the deficiencies of the ILS, but without additional components, it does not ensure accuracy comparable at least with the ILS CAT I. The study aims at finding the approaches for obtaining accurate, reliable and credible navigation data directly on board of the aircraft, regardless of weather conditions. The proposed approach is based on the mathematical model of the system of trajectory measurements, defining the flight parameters of an aircraft in a non-query mode. In order to achieve the research goals, the author uses the methods of linear algebra, mathematical modeling of stochastic processes, and computer methods of measurement data processing. The mathematical model and the results of the simulation demonstrate the possibility of high-precision measurement, on board of a plane in a non-query mode, of six current navigation parameters: distance; radial velocity; azimuth; elevation and the rate of change of azimuth and elevation. The proposed method allows increasing the safety of takeoff and landing of an aircraft in the most adverse weather conditions (Category IIIc ICAO).*

Keywords: *Navigation data, Aviation Safety, Takeoff and Landing, Signal reflection, Landing trajectory, Satellite Navigation System, Instrument Landing System, Trajectory analysis, Mathematical model, GLONASS.*

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Introduction

In recent years the problem of flight safety, as well as providing accurate and reliable navigational data, has become particularly acute. The high rate of the air accidents in the Russian Federation [1] is one of the critical factors influencing the flight safety and the readiness of aviation to carry out its tasks. The pendency of this issue may threaten national security.

In Russia, the index, characterizing the accident rate level for the past 30 years, is kept at the level of 4–5 accidents per 100,000 flight hours, whereas in the leading aviation countries this index is two or more times lower [2-4]. In the medium term, aviation accidents remain one of an essential challenge to the stable development and safe functioning of aviation.

Usually, air crash is the result of a combination of several dangerous factors.

As practice shows, in most cases, the direct causes of aviation accidents are the actions of the aviation personnel, or the aircraft condition, or the condition of means of flight safety ensuring.

In aviation, there are three main groups of specialists who are involved in the realization of flights. The first group is the aircraft crew, in which the captain is responsible for the successful fulfillment of the given task. Moreover, his decision, for example, to go to an alternate aerodrome because of bad weather conditions, will be the final one. Also, it is he who decides to activate the necessary radio devices (air navigation radio aids) to ensure a safe landing. The second group is the Air Traffic Service, whose main purpose is to prevent collisions and control proper usage of airspace. The third group is the Aerodrome Traffic Control which is in charge of monitoring the availability of various airfield facilities and functioning of the ground-based systems for maintaining of flights.

It should be noted that on-ground systems of flight safety are continually improving, but the pilots have little opportunity to obtain a high-precision, reliable and accurate navigation data onboard to ensure the safety of takeoff and landing in the difficult (near-zero visibility) weather conditions. This issue is the most critical for the airports, with the high density of air traffic flow, where air traffic service is responsible for the safety of takeoffs and landings of aircraft.

Nowadays, the Instrument Landing System (ILS) [5] of various categories provides the information basis for the solution of problems connected with flight organization in airport areas.

The standard ILS, classified as the ILS I category, allows to perform landing approaches in cloud conditions not lower than 60 m above the runway and with visibility 700 m (2400 feet), either with visibility of 550 m (1800 feet) in case the axial line and landing zone are lit up. More complex systems of II and III categories make possible to realize the landing in near-zero visibility, but they require additional certification of aircraft and pilot. Approaches according to the II category allow performing landing at the decision height of 30 m (100 feet) and with visibility 400 m (1200 feet). In case of the III category of landing, a plane lands using an automatic landing system, with no decision height and visibility not less than 250 m (750 feet) according to IIIa category, or 50 – 250 m according to the IIIb category. Each ILS certified under III categories has its own fixed decision height and minimums of visibility. Some ILS provides the landing in zero visibility conditions (Category IIIc). Category II and III systems must have lighting of the axial line, as well as the lighting in the landing zone, and other auxiliary aids.

Aircraft direction systems (i.e. systems that determine the position in relation to a runway and show it on the instruments) are sensitive to ILS signal reflections due to the presence of various objects such as houses, hangars in its scope. Near the beacon, planes and cars can create serious distortions of signals. Land slopes, hills, and mountains, as well as other terrain irregularities, can also reflect a signal and give rise to deviations of instrument readings. These factors may limit the safety of ILS operations.

Moreover, to ensure the normal ILS functioning in airports, it is necessary to introduce additional restrictions to aircraft terrestrial movement so that they would not shadow or reflect signals. This means to increase the minimal distance between an aircraft on the ground and runways, to close down some taxiway airport or to increase intervals between landings to give time to the landing airplane to leave the landing

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zone and to make sure that the next landing airplane will not experience radio – interference. That severely decreases airport capacity in Cat II & III weather conditions.

Solving navigation problems with the use of satellite navigation systems (SNS) like the American Global Positioning System (GPS) or the Russian Global Navigation Satellite System (GLONASS) reduces the above drawbacks. However, the SNS facilities with no auxiliary tools could not provide a needed accuracy even in comparison with ICAO Category I. In particular the Wide Area Augmentation System (WAAS) – the counterpart of the European Geostationary Navigation Overlay Service (EGNOS) can provide navigation (using the GPS) corresponding to Cat I. In addition to that, due to errors of the existing satellite navigation systems, most probably, ILS will remain in use as a reserve in a case of failure of ground equipment [6-8].

Thus, in order to remove restrictions on the use of the SNS, as is a unified radio navigation system in aviation, it is necessary to undertake further modernization of its components to improve precision and reliability of navigational measurements.

The article sets out the principles and methods for designing the all-weather System of safe Takeoff and Landing of Planes (STLP) based on the approach that allows obtaining the navigation data of high accuracy, reliability, and validity on a board of aircraft in any adverse weather conditions (category III ICAO).

Principles and methods

The idea of STLP is to complement the SNS navigation measurements by an onboard distance- and angle-measuring system that will determine the landing point with the accuracy of 1 m in overcast conditions. In this case, the landing system locates aircraft deviation from the runway axis with the accuracy of 3.6 arc minute from the distance of 100 km [9-12].

Practical implementation of STLP will not require much effort on the development or modernization of existing navigation equipment since the bulk of the work will be related to development and upgrading of the software.

Tasks to be solved by STLP

The proposed system addresses the following issues:

- provides takeoffs and flight according to the route; allows to bring the aircraft out to the given region and to the aerodrome for landing,
- provides pre-landing aircraft maneuvering and landing in normal and complicated weather conditions at day and night;
- it provides the crew with continuous and precise data as to the aircraft position;
- provides group management flights with data on the situation in the air in the airport region as well as additional information concerning the flight received from the aircraft;
- makes possible individual identification of aircraft and reception of signals from airplanes in distress location of their position and informs group management flights;
- provides the control of movements of aircraft and special vehicles along the airfield.

The functionality of STLP

1. Determination of flight parameters of the of flight parameters in the Local Topocentric Coordinate System on board a flight vehicle from the distance of 200 km.
2. Prediction of a flying vehicle (FV) movement for given period of time.
3. Determination of the direction towards the point of landing in horizontal and vertical planes.
4. Calculation of the landing trajectory (glissade) from the point of approach to landing.
5. Calculation of flying parameters deviation from the landing trajectory (glissade).
6. Monitoring flying parameters according to 3D maps of the locality.

Characteristics of Accuracy

The STLP makes possible to determine the coordinates and the vector of a flight velocity (*x, y, z,* V_x, V_y, V_z) aboard an airplane by measuring six parameters:

- slant range, *R*, within the limits of 0.5 ÷ 200 км;
- radial velocity (f_D = ± 210 kHz) within the limits of – 2 ÷ + 2 км/s;
- distance differences of wave arrival $q_{13} = R_1 - R_3$, $q_{24} = R_2 - R_4$ (within the limits of – 1000 ÷ + 1000 m) from two pairs of antennas (1,3 and 2,4), situated along the *X* and *Z* axis of the local system of coordinates proportional to direction cosines $\cos\theta_x$ and $\cos\theta_z$;
- the speed of distance differences of wave arrival $\dot{q}_{13} = \dot{R}_1 - \dot{R}_3$, $\dot{q}_{24} = \dot{R}_2 - \dot{R}_4$ (within the limits of – 140 + 140 m/s (± 3.5 kHz) from two pairs of antennas (1,3 and 2,4), situated along the *X* and *Z* axis of the local system of coordinates proportional to the speed of change direction cosines $\cos\dot{\theta}_x$ and $\cos\dot{\theta}_z$.

Measurement errors	(δ = Δ + 2.7σ)
δR	= 5 m
$\delta \cos\theta_x, \cos\theta_z$	= 5×10^{-6}
$\delta \dot{R}$	= 0,01 m/s
$\delta \cos\dot{\theta}_x, \cos\dot{\theta}_z$	= 5×10^{-6}

STLP Design

The system consists of two components - ground-based and onboard-based ones (Fig. 1).

1. Ground-based Equipment (STLP-G) includes:
- navigation equipment of the consumer (NEC);
- high-stability frequency generator of $10^{-11} \div 10^{-12}$;
- reference frequency generator;
- precision phasing system;
- transmitter;
- data output unit.

The high-stability reference generator is a source for the formation of coherent frequency network necessary for on-board measuring channels functioning.

A reference frequency generator is the large-scale generator frequency for the measurement of range, radial velocity, angles and angular velocities.

The transmitter includes a modulator of carrier frequency and an exit cascade to transmit modulated carrier frequency to the antennas.

The precision phasing system along with the adjustment antenna serves to calibrate all measuring channels.

The navigation equipment (NEC) is intended to monitor the navigation field integrity and to work out differential correction against the current constellation of navigation satellites in the airport region.

The data output unit performs such functions as:
- monitoring the navigation field jointly with NEC and displaying the results of the monitoring;
- representation of the results of measuring channel calibration;

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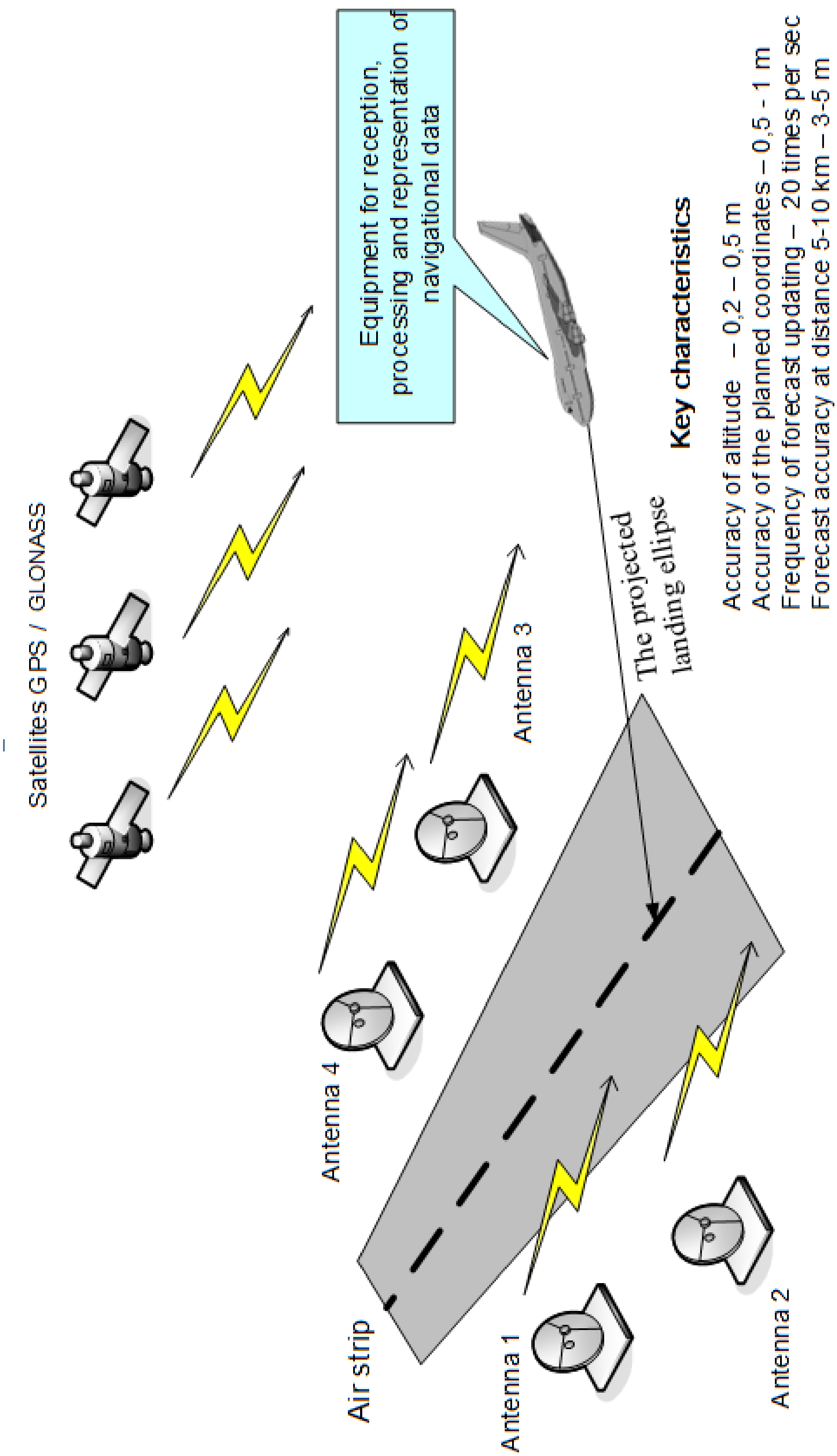

Figure 1. The layout of the placement of STLP component parts.

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- control over the emitted signals;
- display of data from the surveillance radar.

The surveillance radar is not part of STLP-G system, because it is an integral part of the airfield equipment.

2. Aircraft onboard equipment (STLP-A) includes:
- navigation equipment (NEC);
- high-stability frequency generator of $10^{-10} \div 10^{-11}$;
- multi-channel receiver;
- signal enhancement and processing device;
- measuring channels are:
  a) distance measurement onboard;
  b) radial velocity measurement channel;
  c) azimuth and position angle measurement channel;
  d) angular velocity measurement channel;
  e) channel for the angular deviation measurement from the runway-axis.
- output unit.

Multi-channel receiver and the device for signal enhancement are responsible for the reception of signals from STLP-G transmitting antennas as well as for measurement of temporary phase delays of carrier and modulation frequencies.

High-stability reference generator creates onboard frequencies grid necessary for measuring channels functioning. The measuring channels perform the processing of the received signals and put out flight parameters of the flying vehicle on the display unit in the required format.

Onboard navigation equipment of the consumer (NEC) performs the following functions:
- selection and registration of differential corrections;
- determination of the parameters of movement of the airplane outside the operational range of the STLP-G on-ground equipment;
- disclosure of ambiguity in a long-distance and angular measuring channels.

The data output device is a final stage in the work of the whole airborne navigation complex. The results its work form basis for obtaining the data on the airborne current navigation condition as well as for commands and signals, even for the "alarm" signal, which allow the aircraft crew to take up the necessary measures and includes the following subsystem:
- Input signals control complex which records the quantity and the numbers of navigation space satellites (NSS), the quality of the received signals as well as the results of monitoring of the navigation field integrity;
- Complex for representation of current navigation condition which shows the coordinates of the aircraft, estimate the accuracy of each parameter in the chosen coordinate system;
- Complex for representation of the system in a given region which shows the aircraft position and the most characteristic features of the terrain on the basis on digital 3D-maps of the area;
- Complex for the aircraft travel prediction which gives a prediction of the aircraft travel for the given period of time and evaluates the precision of the prognosis and the availability of dangerous objects on the way as well as accuracy of visualization of prediction at 3D-maps of the area with evaluation of deviation from the glissade and point of landing on a runway;
- Complex for data recording, updating and storing. The complex designed for storing and updating operational data as well as for collecting archives about a current navigational situation within a given period.

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The key benefits of STLP

1. The principle of STLP operation provides the availability of three parallel redundant channels:

- onboard navigation equipment of the consumer which directs the aircraft to the point of approach to landing with the precision of 20-30 m;
- onboard measuring channel of angular displacement from the runway axis which, in conditions of complete cloud cover, can determine the aircraft deviation from the local topocentric axis to within 3.6 arc minute from the distance of 10 km;
- built-in measurement channel angular displacement from the axis of the runway, which, in conditions of complete cloud cover, can determine the deviation of the aircraft from the local axis or a custom location within the 3.6 arc minutes from a distance of 10 km;
- onboard distance-measuring and goniometric system which determines the aircraft's flight parameters from the distance of 10 km and up to a point of landing with high reliability and accuracy to within

$$\sigma_{x,y,z} = 0.2 \div 0.5 \text{ m and } \sigma_{Vx,Vy,Vz} = 0{,}01 \div 0{,}3 \text{ m/s}$$

2. Due to the high accuracy of determination of flight parameters in real time in predicting the trajectory of the descent, it is possible to estimate not only distance, but also the presence of those or other objects that affect flight safety, including houses, towers, power lines, forests, high hills, and to estimate the speed of approaching them.

3. One set of the system provides take-off and landing of aircraft at all runway of the airfield, regardless of their number and location.

4. The system provides a safe approach to landing not only along a direct line in relation to the runway but also along an optimal trajectory ensuring safety in conditions of a limited maneuver, for instance, near mountains as well as not far from industrial and residential districts and adjacent forests.

5. The number of aircraft that can work with STLP simultaneously is not limited.

6. Takeoffs and landings safety guaranteed in the most unfavorable weather conditions even in zero visibility (category IIIc ICAO).

The simulation results for evaluation of the accuracy of determination of the flight parameters in the local topocentric system of coordinates $\sigma_{x,y,z,}$ $\sigma_{Vx,Vy,Vz}$ at the flight of 0.5 km, 1 km, and 10 km are shown in Table 1.

Table 1

The simulation results for evaluation of the accuracy of determination of the flight parameters in the local topocentric system of coordinates

X, m	Y, m	Z, m	Vx, m/s	Vy, m/s	Vz, m/s	R, км
Root mean square error of determination of motion parameters when aircraft is flying at altitude of 0.5 km						
0.32	0.11	0.01	0.01	0.04	0.02	0.5
0.36	0.11	0.01	0.01	0.05	0.03	1
0.41	0.10	0.01	0.02	0.09	0.03	2
0.44	0.10	0.01	0.02	0.13	0.04	3
0.46	0.12	0.03	0.02	0.18	0.04	4

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X, m	Y, m	Z, m	Vx, m/s	Vy, m/s	Vz, m/s	R, км
0.46	0.16	0.03	0.02	0.23	0.04	5
0.47	0.20	0.04	0.02	0.29	0.04	6
0.47	0.26	0.03	0.02	0.36	0.04	7
0.48	0.32	0.03	0.02	0.43	0.05	8
Root mean square error of determination of motion parameters when aircraft is flying at altitude of 1.0 km						
0.32	0.03	0.01	0.01	0.03	0.02	2
0.36	0.05	0.02	0.01	0.04	0.03	3
0.41	0.07	0.03	0.02	0.07	0.03	4
0.43	0.09	0.04	0.02	0.09	0.04	5
0.46	0.10	0.04	0.02	0.11	0.04	6
0.47	0.11	0.03	0.02	0.13	0.04	7
0.48	0.12	0.03	0.02	0.16	0.04	8
0.49	0.14	0.03	0.02	0.19	0.04	9
0.49	0.17	0.03	0.02	0.22	0.05	10
Root mean square error of determination of motion parameters when aircraft is flying at altitude of 10 km						
0.11	0.48	0.03	0.01	0.02	0.01	3
0.12	0.47	0.03	0.02	0.03	0.02	4
0.17	0.46	0.03	0.02	0.04	0.02	5
0.21	0.44	0.03	0.02	0.05	0.03	6
0.24	0.42	0.03	0.02	0.05	0.04	7
0.27	0.40	0.03	0.02	0.05	0.04	8
0.30	0.38	0.03	0.03	0.06	0.04	9
0.32	0.36	0.03	0.03	0.06	0.04	10
0.34	0.24	0.04	0.03	0.09	0.05	20

Conclusion

Proposed principles of complex using of ground-based equipment, aircraft onboard equipment, and satellite radio devices combined with some applications of trajectory analysis allow providing the high-accuracy determination of key flight parameters aboard a flying vehicle. These principles give the methodological basement for designing an onboard aid system for safe takeoffs and landings of aircraft in any weather conditions.

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1. As an instrumental basis of STLP (the system of Safe Take-off and Landing of Planes) it is proposed to create a measuring complex which includes an on-ground segment consisting of four items for the formation and emission of radio signals of centimeter-wave range which will allow to measure in the onboard segment of a flying vehicle six key parameters:

- distance
- radial velocity
- azimuth
- elevation
- azimuth rate
- elevation rate

2. The simulation taking into account the proposed topology of measuring stations, chosen set of parameters, and required accuracy of measurement (root mean square error of distance measurement - 1 m; radial velocity – 0.01 m/s; azimuth and elevation - $\cos\Theta x$ and $\cos\Theta z$ 5×10^{-6}; azimuth rate and elevation rate - 5×10^{-6}) yielded following results.

In the case requiring prior synchronization and phasing the signals from terrestrial antennas, the accuracy of less than 0.5 m and 0.6 m/s for altitude, as well as the accuracy of less than 1.0 m and 0.12 m/s for aircraft coordinates, was obtained for the airplane that is on the final approach at a distance of up to 7 km.

These results meet all the requirements for safe aircraft landing in adverse weather conditions (Category IIIc ICAO).

3. The system that uses four sources of navigation signals with known coordinates which allow measuring the distance and radial velocity of flying vehicles makes possible, in principle, to determine with high accuracy the aircraft coordinates as well as the velocity components.

This solution significantly differs from the model that uses four navigational pseudo-satellites ("pseudolites") located in aerodrome environs, since it allows providing measuring onboard aircraft four additional parameters: azimuth and elevation with the accuracy of 5×10^{-6}; azimuth rate and elevation rate with the accuracy of 5×10^{-6}.

4. Preliminary calculations show that in repetitive manufacturing, the STLP cost will not exceed the cost of onboard navigation equipment of the consumer and the cost of ground meteorological radar because the main costs will be associated with the development of software.

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