УДК 629.058:519.23
ББК 39.57
DOI 10.51955/2312-1327_2021_3_14

PECULIARITIES OF USING A MOBILE PSEUDOLITE FOR INCREASE OF POSITIONING ACCURACY ON AIRCRAFT LANDING

Oleg Nikolaevich Skrypnik,
orcid.org/0000-0002-2006-0428,
Doctor of Technical Sciences, Full professor
professor of traffic management and security in air transport department
Belarusian State Academy of Aviation,
77, Uborevich
Minsk, 220096, Republic of Belarus
skripnikon@yandex.ru

Roman Olegovich Arefyev,
orcid.org/0000-0001-8040-6470,
Candidate of Technical Sciences
associate professor of aviation electronic equipment department
Moscow State Technical University of Civil Aviation (Irkutsk branch),
3, Kommunarov
Irkutsk, 664047, Russia
aqua160905@mail.ru

Natalya Gennadyvna Arefyeva (Astrakhanceva),
orcid.org/ 0000-0002-9916-1239,
Candidate of Technical Sciences
associate professor of aviation electronic equipment department
Moscow State Technical University of Civil Aviation (Irkutsk branch),
3, Kommunarov
Irkutsk, 664047, Russia
n_astrahanceva_awesome@mail.ru

Tatyana Yuryevna Portnova,
orcid.org/0000-0001-6134-143X,
Candidate of Philological Sciences
associate professor, Department of social and political disciplines
Moscow State Technical University of Civil Aviation (Irkutsk branch),
3, Kommunarov
Irkutsk, 664047, Russia
taty-port@yandex.ru

Abstract. The authors study accuracy characteristics (dilution of precision) of an integrated navigation-and-time field in the terminal area created by GLONASS with its mobile pseudolite augmentation. A mobile pseudolite is placed onboard an unmanned aerial vehicle (UAV). The purpose of the article is optimization of UAV flight path which will provide the best aircraft positioning accuracy. The problem of finding an optimal track for the UAV was solved using Hooke-Jeeves method for an aircraft approaching along a flexible track. The article presents the results of the conducted experiments as the UAV optimal flight paths and their charts built according to DOP values for cases of using stationary and mobile pseudolites. Practical recommendations on the choice of optimization criteria are given, and the conditions for using a mobile pseudolite placed on board an unmanned aerial vehicle are determined.

Keywords: pseudolite, mobile pseudolite, unmanned aerial vehicle, Position Dilution of Precision, GLONASS, optimization of flight trajectory, integrated navigation and time field.

*This work was supported by the Russian Foundation for Basic Research (Grant No. 19-08-00010 A).

ОСОБЕННОСТИ ПРИМЕНЕНИЯ МОБИЛЬНОГО ПСЕВДОСПУТНИКА ДЛЯ ПОВЫШЕНИЯ ТОЧНОСТИ ПОЗИЦИОНИРОВАНИЯ ПРИ ПОСАДКЕ ВОЗДУШНОГО СУДНА

Олег Николаевич Скрыпник,
orcid.org/0000-0002-2006-0428,
доктор технических наук, профессор,
профессор кафедры «Организация движения и обеспечения безопасности на воздушном транспорте»
Белорусская государственная академия авиации,
ул. Уборевича, 77
Минск, 220096, Республика Беларусь
skripnikon@yandex.ru

Роман Олегович Арефьев,
orcid.org/0000-0001-8040-6470,
кандидат технических наук,
доцент кафедры авиационного радиоэлектронного оборудования
Московский государственный технический университет гражданской авиации (Иркутский филиал),
ул. Коммунаров, 3
Иркутск, 664047, Россия
aqua160905@mail.ru

Наталья Геннадьевна Арефьева (Астраханцева),
orcid.org/ 0000-0002-9916-1239,
кандидат технических наук,
доцент кафедры авиационного радиоэлектронного оборудования
Московский государственный технический университет гражданской авиации (Иркутский филиал),
ул. Коммунаров, 3
Иркутск, 664047, Россия
n_astrahanceva_awesome@mail.ru

Татьяна Юрьевна Портнова,
orcid.org/0000-0001-6134-143X,
кандидат филологических наук
доцент кафедры Гуманитарных и социально-политических дисциплин
Московский государственный технический университет гражданской авиации (Иркутский филиал)
ул. Коммунаров, 3
Иркутск, 664047, Россия
taty-port@yandex.ru

Аннотация. Исследуются характеристики точности (геометрические факторы) интегрированного навигационно-временного поля в зоне аэродрома, создаваемого спутниковой системой навигации ГЛОНАСС при ее функциональном дополнении мобильным псевдоспутником. Псевдоспутник размещен на борту беспилотного летательного аппарата (БПЛА). Целью данной статьи является оптимизация траектории полета БПЛА, что позволит достичь наилучшей точности определения координат воздушного судна. Задача нахождения оптимальной траектории БПЛА решена с использованием метода Хука-Дживса для случая захода на посадку воздушного судна по гибкой траектории. Приведены результаты проведенных экспериментов в качестве оптимальных траекторий полета БПЛА и их графиков, построенных по значениям геометрических факторов для случаев применения стационарного и мобильного псевдоспутников. Даны практические рекомендации по выбору критерия оптимизации, определены условия применения мобильного псевдоспутника, размещенного на БПЛА.

Ключевые слова: псевдоспутник, мобильный псевдоспутник, беспилотный летательный аппарат, геометрический фактор, ГЛОНАСС, оптимизация траектории полета, интегрированное навигационно-временное поле.

*Статья написана в рамках исследования при финансовой поддержке гранта Российского фонда фундаментальных исследований (РФФИ). Проект № 19-08-00010 А «Интеллектуальная система планирования маршрутов и графиков воздушного движения гражданской авиации при изменении метеоусловий, спроса пассажиров и потере навигационной точности воздушных судов в полете», выполняемый в Московском государственном университете гражданской авиации. Руководитель проекта – Е. Е. Нечаев.

Introduction

Over the medium term, the satellite navigation systems including Russia's GLONASS system will be an essential means of navigational support of all aircraft flight phases in accordance with the ICAO categories [Скрыпник, 2020]. At the present stage of development, however, the satellite navigation systems (SNS) have insufficient integrity, interference resistance and sometimes accuracy of the navigation and time field (NTF), and this reduces the efficiency of their use specifically for solving problems of aircraft landing.

For supporting promising navigation applied processes [Performance-based Navigation (PBN) Manual, 2013], GNSSs need the aircraft-based augmentation system (ABAS), ground-based augmentation-system (GBAS), satellite-based augmentation system (SBAS). The augmentations allow some GNSS drawbacks to be compensated, in particular, the differential corrections for the coordinates measured by users to be determined [Скрыпник, 2020]. However, they are also subject to the influence of some destabilizing factors so SBAS/ GBAS application does not fully provide GNSS navigation accuracy. For instance, within its coverage area, SBAS provides en-route flight, flight in the terminal area as well as APV-I and APV-II approach. The APV-I and APV-II approach procedures can be accomplished only in specific assigned zones, not in the whole SBAS coverage area [Global Navigation Satellite System (GNSS) Manual, 2013]. GBAS problems are degradation of coordinate correction accuracy as the aircraft recedes from a local augmentation station as well as need for transmission of digital data (error corrections) over long distances. For this purpose datalinks with high capacity are needed which requires installation of additional onboard equipment for receiving differential corrections.

One of possible ways to improve the accuracy of SNS navigational sightings is an augmentation in the form of a pseudolite (PL). In the traditional conception, PLs are stationary transmitting ground-based or near-ground-based devices, (e.g., a high mast, hot air balloon) the signals of which are synchronized with the SNS signals and the signal parameters and their format are close or equal to the parameters and format of SNS signals [Бабуров и др., 2005; Балов, Геворкян, 2002]. An integrated NTF created within the PL coverage area possesses improved accuracy and reliability characteristics in comparison with the initial SNS NTF.

Analysis of works [Бабуров и др., 2016; Борсоев и др., 2011; Нигруца, и др., 2012] devoted to problems of using PL showed that augmentation of SNS navigation satellites with one or several PL would improve the geometry in the vertical channel, increase the information redundancy that would lead to enhancement of accuracy and reliability of navigational sightings. The integrated NTF generated with using PL can meet the requirements for aircraft navigation accuracy during approach.

When applied PLs should be located in the terminal area optimally to achieve the maximum accuracy of integrated SNS NTF. [Скрыпник, 2020] shows that as SNS geometry changes with time, the optimal location of a ground-based PL also changes. Therefore, work [Скрыпник и др, 2017], for instance, suggests using a mobile PL to achieve the maximum accuracy of the integrated GLONASS NTF for each time.

Application of a mobile ground-based PL involves a number of problems e.g. shading its signals by terrain roughness or aerodrome facilities, limitations on speed and movement area and others. Therefore, it is proposed to consider applying a PL located on an UAV which significantly extends PL dynamic behavior and possibilities of steady reception of its signals [Jones, 2017] as well as allows such a method to be applied when an aircraft approaches on flexible trajectories. It is necessary to solve the problem of finding an optimal UAV trajectory in the airspace of the terminal area.

The task of finding an optimal track is identical both for a UAV and for an aircraft and depends on boundary conditions and criteria. For example, work [Adler et al., 2012] reviewed the task of constructing an optimal flight track under engine-out conditions where the criterion is maximization of energy efficiency. Articles [Веремей, Сотникова, 2016; Gardi et al., 2016; Khardi, 2012] deal with the multi-criterion tasks of constructing an optimal flight track where the criteria are minimization of noise, fuel consumption and account for weather conditions. In this article, the optimality of the UAV trajectory with a PL onboard depends on the navigational conditions formed in the terminal area.

The research purpose is to find an optimal flight trajectory and to estimate the efficiency of using a mobile PL located on board a UAV for enhancement of accuracy of the integrated GLONASS NTF by reducing DOPs in the terminal area when approaching on a flexible trajectory.

Materials and research methods

The accuracy of the integrated NTF can be seen in the values of the Position DOP (Position Dilution of Precision) or its components - vertical VDOP (Vertical Dilution of Precision) and horizontal HDOP (Horizontal Dilution of Precision) DOP at the observation point. At that,

$$PDOP^2=HDOP^2+VDOP^2, \quad (1)$$

and accuracy of position-fixing (horizontal coordinates) and that of flight altitude determination are related to the values of the corresponding DOP by the expressions

$$\sigma_r=\sigma_R*HDOP,\ \sigma_H=\sigma_R*VDOP$$

where σ_r is a root mean square error (RMS) of position-fixing (radial RMS), σ_H is RMS of determining the height, σ_R is RMS of determining the pseudo-range to the NS.

The author of work [Скрыпник и др., 2017] solved the problem of finding an optimal location of the ground-based PL which provides minimal mean value $VDOP_{mean}$ along the whole glideslope. It was shown that, because of changing the NS location relative to the aircraft due to their orbital motion, there is no single optimal PL location providing the minimal DOP, in the case under consideration – $VDOP_{mean}$

With sufficiently good (no more than 2-2.5) VDOP values, the application of a PL located at a typical point (not optimally) allows $VDOP_{mean}$ to be improved by 22-25%.The PL location at optimal points for considered moments of time allows $VDOP_{mean}$ to be decreased by 7-9% in comparison with its location at the typical point.

Proposed in [Скрыпник и др., 2017] technique of finding the only (quasioptimal) position of the ground-based PL allows $VDOP_{mean}$ to be decreased by 3-4%. Thus, to ensure the minimal DOP value along the whole landing trajectory it is necessary to use a mobile PL located on a UAV. At that, the UAV should move along an optimal trajectory formed by a set of points where the minimal DOP value is achieved for each time of solving the optimization problem.

To conduct the research by methods of mathematical simulation in the LabVIEW graphical programming environment the following initial data were chosen:

− runway middle coordinates of the landing airdrome are 71.927 N 114.08 E, the height above sea level is 30m, UTC + 9, the runway heading is 174.22 degrees;

− approach trajectory (*fig.1*): curvilinear (height is 600m) from the Initial Approach point (IA) to the Final Approach point (FA) located at a distance of 10 km from the runway threshold; rectilinear with the glideslope angle of 3 degrees – from the FA point to the runway touchdown; aircraft speed along the whole trajectory is 250 km/hour;

− the initial UAV (mobile PL) position in the horizontal plane coincides with the IA point, the UAV speed is equal to the aircraft speed on the landing trajectory;

− the optimization problem was solved by the Hook-Jeeves method at 22 selected discrete points of the aircraft flight trajectory which were separated by the 10 s time slots.

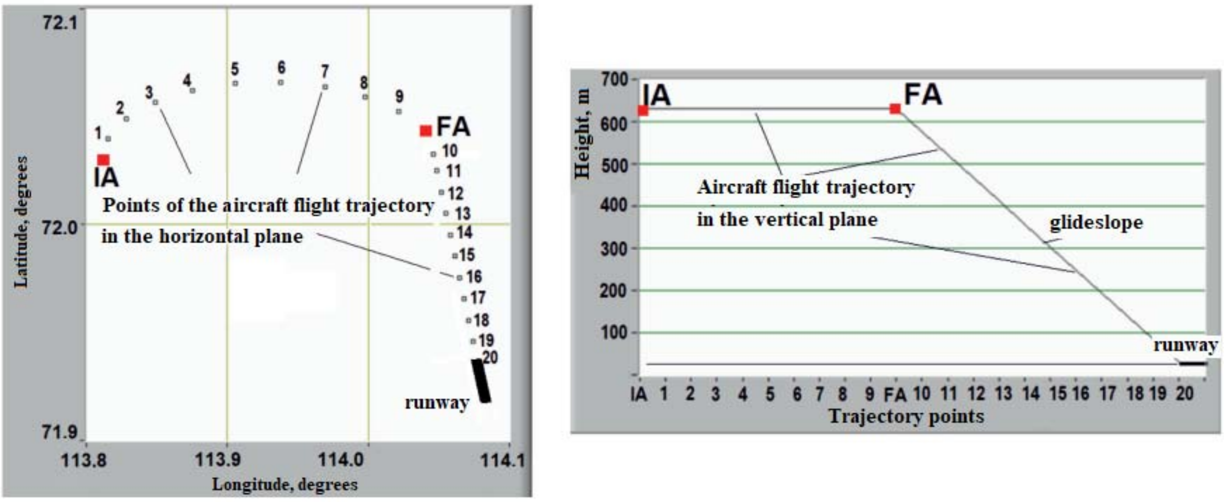
The problem of finding the optimal UAV flight trajectory was solved in the horizontal plane (its flight at a constant altitude was considered) and in space (with a change in the flight altitude). The optimization criterion was the DOP minimum (either Position PDOP or horizontal HDOP or vertical VDOP) for navigational sightings on the aircraft:

$$DOP_i(\bar{X}_{PLi} \mid \bar{X}_{Ai}, \bar{X}_{NS1i}, ..., \bar{X}_{NSki}) \rightarrow \min,$$

where $\bar{X}_{PLi}$ is the desired vector of UAV coordinates at the ith trajectory point and at the ith time moment, $\bar{X}_{Ai}$, are the known coordinates of the aircraft at the ith point of the trajectory at the ith moment of time, $\bar{X}_{NS1i}$ are known coordinates of the navigation satellites within the visual range, k is the number of visible NSs.

For DOP calculations, the UAV, aircraft and NS coordinates are shown in the earth-fixed geocentric system. As the optimal trajectory of the UAV flight is constructed in the geodetic reference system (latitude, longitude, altitude), the coordinates are converted from geodetic to the earth-fixed geocentric system [Скрыпник, 2020].

During the research it is necessary to define how the result of optimization problem solution depends on the used criterion (PDOP, HDOP or VDOP minima), the aircraft and UAV flight altitude, the method of problem solution (in plane or in space).



a) *b)*

Fig.1 Aircraft flight trajectory in the horizontal (a) and the vertical (b) planes

Research results and their discussion

To achieve research goals using the method of mathematical simulation, the authors conducted computational experiments that differed in the options for using mobile PL and using various optimization criteria.

Assessment of the optimization criterion influence on the DOP values with the UAV flying along the optimal trajectory

The following situations were considered:

– PL is not available and navigation sightings are carried out only using the visible NSs;

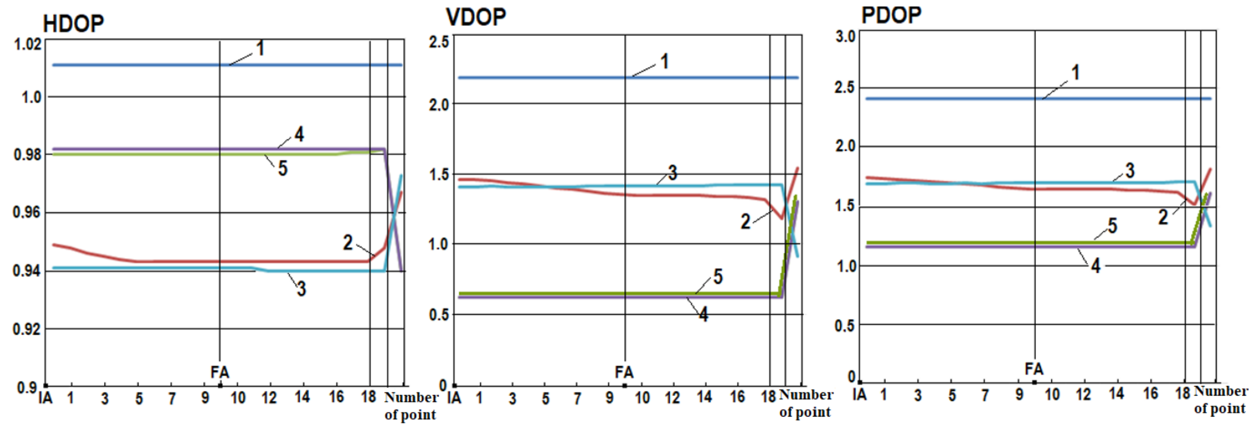
– PL is located at a typical point on the ground (point of location of the middle marker), at a distance of 1 km from the beginning of the runway and on the extension of its axis;

– the mobile PL is located on a UAV flying at an altitude of 50 m.

Fig. 2 shows the graphs for HDOP (*fig.2,a*), VDOP (*fig.2,b*) and PDOP (*fig.2,c*) changing on approach and landing aircraft trajectory. The figures show the following graphs: 1 – no PL and the navigation problem is solved only using the visible NSs; 2 – PL is located at a typical point; 3,4,5 –a mobile PL, HDOP, VDOP and PDOP optimization.

The analysis of the obtained results shows that using a ground-based PL located at a typical point improves HDOP from 1.01 to 0.94, and VDOP from 2.2 to 1.5 at the IA point and to 1.2 for aircraft flying over PL. After the aircraft flies over the PL, HDOP and VDOP degrade to $HDOP = 0.97$ and $VDOP = 1.55$.

The use of a mobile PL with HDOP minimum optimization gives an insignificant gain in the HDOP value (by 0.002–0.004) and a slight deterioration in the VDOP value (by 0.3–0.5) compared to the PL located at a typical point. When the aircraft descends below the PL ($H_{PL}>H_{Ai}$), we can observe HDOP degradation (by 0.04-0.05) and VDOP improvement (by 0.5). Thus, we can conclude that the effectiveness of mobile PL use is critical to the ratio of the aircraft and the UAV flight altitudes.



a) *b)* *c)*

Fig.2. Variation of DOP values at the points of approach and landing aircraft trajectory

UAV trajectory optimization by VDOP minimum and PDOP minimum gives almost the same results. This is caused by the fact that in the SNS the VDOP value is always larger than HDOP, so its contribution to PDOP (ref. expression (1)) will be decisive.

When the UAV flight trajectory is optimized by the minimal VDOP, the HDOP value is slightly worse (approximately by 0.04) while the VDOP value will be significantly improved (by 0.7-0.8) compared to using PL located at a typical point.

When the aircraft descends and condition $H_{Ai}<H_{PL}$ is met, the HDOP improvement (approximately by 0.04) and the VDOP degradation (approximately by 0.8) is observed.

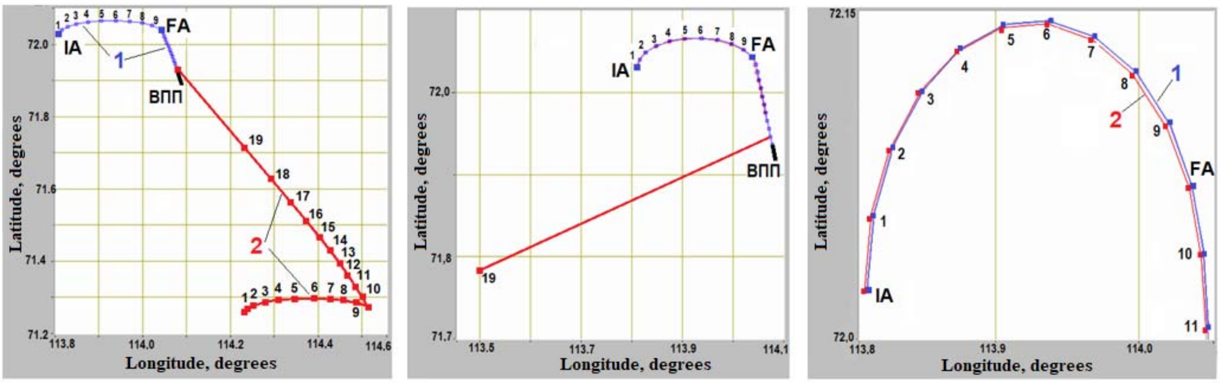
Thus, we can conclude that for optimizing UAV flight trajectory it is appropriate to use the PDOP minimum or VDOP minimum criterion that provides the best accuracy of the flight altitude determination and high accuracy of the aircraft horizontal coordinate determination in the greater part of the approach and landing trajectory. For this purpose, it is necessary to use a low-altitude UAV as, when the aircraft descends below UAV flight altitude, the efficiency of the mobile PL use will be decreased.

Estimate of optimization criterion influence on constructing an optimal UAV flight trajectory

Let us consider a situation when the UAV flies at an altitude of 50 m, the task of optimizing its trajectory is performed in a plane with no restrictions on the region of acceptable optimal UAV positions.

Fig. 3, a, Fig. 3, b, present the results of performing the optimization task with minimal HDOP and PDOP used as an optimization criterion, correspondingly. *Fig. 3*, c shows the curved part of the flight trajectory of the aircraft (curve 1) and UAV (curve 2) on an enlarged scale.

For optimization by minimal HDOP, offset of the UAV and the aircraft trajectory points at a constant altitude to the FA point is about 88 km and the form of the UAV flight trajectory repeats the aircraft trajectory (*fig. 3 ,a*, trajectory sections from point 1 to point 9). When the aircraft descends from the FA point, the optimal UAV flight trajectory is close to the aircraft trajectory coinciding with it at the point located at the altitude of 50 m (when $H_{Ai}=H_{PL}$).



a) *b)* *c)*

Fig.3 UAV and aircraft flight trajectory in horizontal plane

For optimization by minimal PDOP, the optimal UAV flight trajectory is close to the aircraft trajectory (offset in the horizontal plane is 80 m on the section of the constant aircraft flight altitude up to the FA point). The offset of the UAV flight trajectory reduces from 80 m to 7 m in the aircraft descent segment. For $H_{Ai}<H_{PL}$ (in the vicinity of the runway) the optimal point of the UAV flight trajectory gets offset at a distance of more than 20 km.

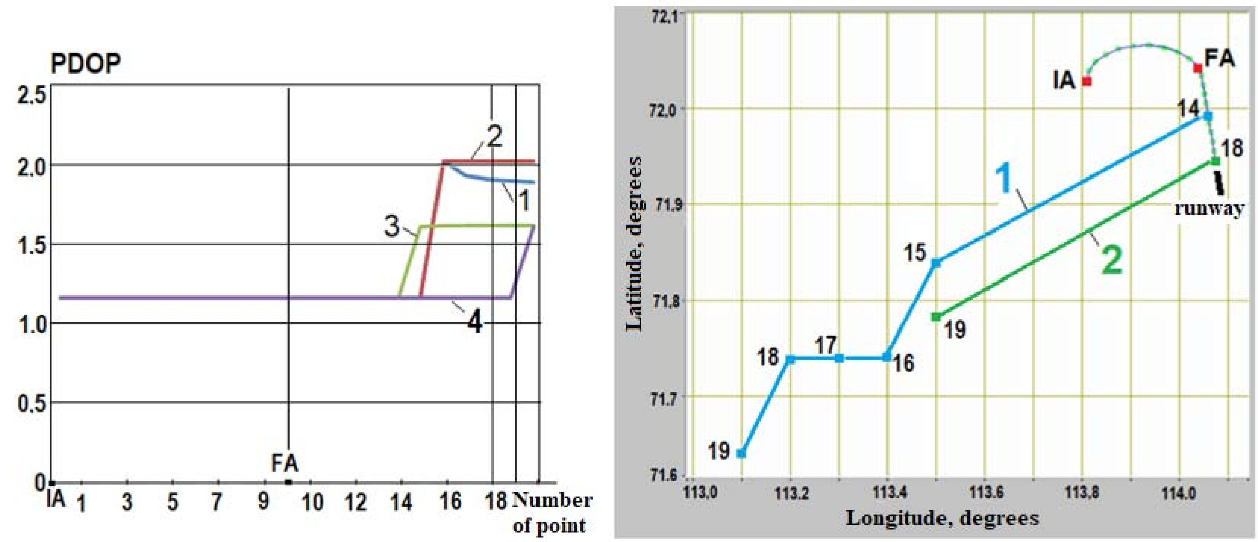
Similar experiments carried out for other time intervals showed that, due to the change in the grouping of navigation satellites within the visibility range, offset of the optimal UAV flight trajectory in horizontal plane changes , for example, it decreased and was 35 m on the flight section to the FA point and 3 m near the runway. The reduction in the offset value at the stage of aircraft descent retains the character described above.

It is obvious that performing a flight of a real UAV with a PL onboard along an optimal trajectory at the final stage is almost impossible when there is its sharp offset. Therefore, the UAV flight along the optimal trajectory should end at a point that coincides in height with the aircraft flight altitude at the stage of descent.

To determine the most appropriate (in terms of ensuring the minimal or close to the minimal PDOP value) UAV flight trajectory when the condition $H_{Ai}<H_{PL}$ (final segment of landing trajectory) is met, the studies were carried out the results of which are presented in *fig. 4*, a for the following situations:

- The UAV is flying along an optimal trajectory at an altitude of 300 m up to the FA starting point of aircraft descent, then it is hovering at the FA point (curve 1);
- The UAV is flying along an optimal trajectory at an altitude of 300 m up to the FA starting point of aircraft descent, then it is going on flying along a straight path at an altitude of 300 m above the aircraft landing trajectory (curve 2);
- The UAV is flying along an optimal trajectory at an altitude of 300 m (curve 3), the optimization task is performed in the horizontal plane;
- The UAV is flying along an optimal trajectory at an altitude of 300 m (curve 4), the optimization task is performed in space, the UAV flight altitude is limited to 50 m, the UAV can descend by 10 m for each optimization cycle.

As follows from fig. 4, a, the minimal value of PDOP=1.2 is achieved practically along the whole trajectory of the aircraft approach and landing when performing the task of optimization in space (curve 4). Given the impossibility of performing the UAV flight along the optimal trajectory after the aircraft descends up to altitude $H_{Ai}=H_{PL}$, we can recommend the UAV hovering in the area of coincidence of the UAV and aircraft trajectory altitudes (with consideration of safety of their mutual position). In this case the PDOP value increases up to 1.8 but remains lower at the final approach of the aircraft than for other UAV flight trajectories.



a) b)

Fig 4. PDOP change (a) and optimal UAV flight trajectory (b)

Fig. 4,b presents the UAV flight trajectories for performing the optimization task by criterion of PDOP minimum in the horizontal plane (curve 1, Hpl=300 m) and in space (curve 2, the UAV can descend up to the altitude of 50 m). As follows from the obtained results, when $H_{Ai}<H_{PL}$, the optimal trajectory (curve 1) gets offset relative to the aircraft trajectory and the lower the altitude of the aircraft flight is, the stronger this offset is. For implementing the task of optimization in space with the aircraft descending, the optimal UAV flight trajectory (curve 2) also descends whereas being located under the aircraft trajectory. After reaching the altitude of 50 m (UAV altitude limit), the optimal trajectory gets offset essentially in the horizontal plane relative to the aircraft trajectory.

Influence of NS terrain blockage on the construction of an optimal PL flight trajectory

Under real conditions, reception of signals from all NSs in the aircraft visibility zone can be impossible due to, e.g. shading of signals from NS by terrain inequalities or high-altitude objects. This situation is very likely when aerodromes are located in mountainous areas as well as in the zone of megacities.

Let us consider the influence of NS signals shading for the following conditions:

− the UAV trajectory is optimized in the horizontal plane at the UAV flight altitude of 300 m and 50 m, the optimization criterion is PDOP minimum;

− the presence of shading will be taken into account by introducing a mask angle of 15 degrees and 30 degrees into the program for simulating the orbital GLONASS grouping and choosing a working NS constellation [Скрыпник, Ерохин, 2012]. Under normal SNS receiver operation, the mask angle is 5 degrees.

The research results are shown in fig. 5, a (H_{PL} = 50 m) and in fig. 5, b (H_{PL} = 300 m) where curves 1, 2, 3 correspond to the mask angles of 5, 15 and 30 degrees.

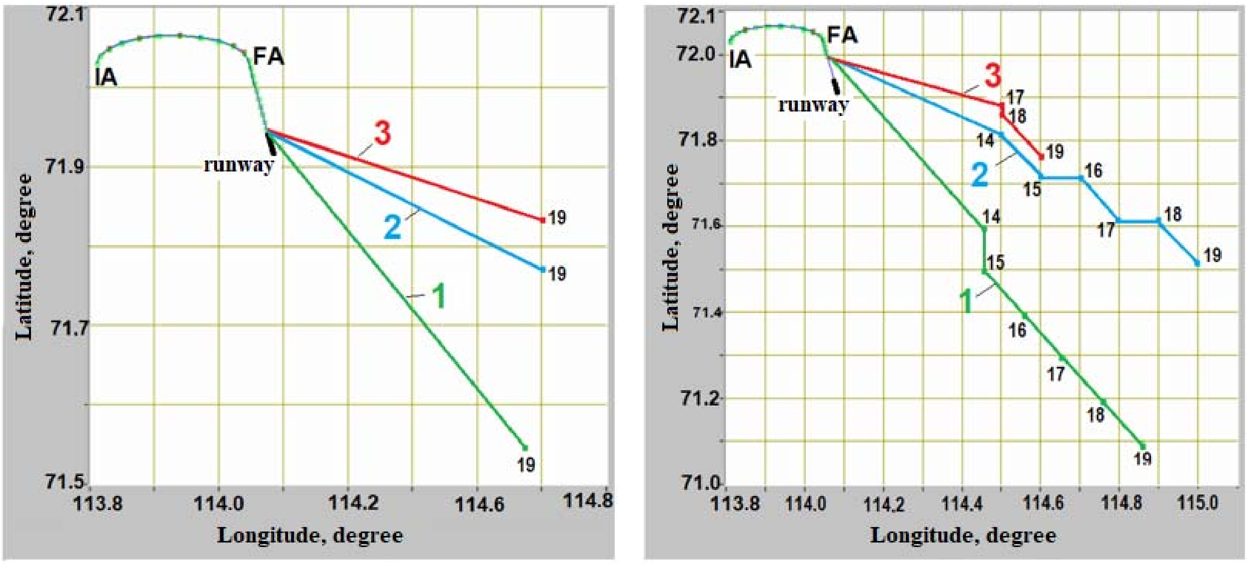


Fig. 5. Optimal UAV flight trajectories with GLONASS NSs shaded

As can be seen from the presented results, the PL optimal trajectory depends on its flight altitude relative to the aircraft and the shading presence. When $H_{PL} < H_{Ai}$, the optimal UAV trajectory is below the aircraft trajectory, and when $H_{PL} > H_{Ai}$, it gets offset in the horizontal plane, and the larger the height difference, the larger the offset is. The stronger the influence of shading is (this corresponds to an increase in the mask angle), the smaller the offset of the optimal UAV trajectory relative to the aircraft trajectory is.

PDOP estimate analysis of the data showed that, under experimental conditions, increase in the mask angle from 5 to 30 degrees led to an increase in PDOP from 2.2 to 2.9 with no PL. Application of a mobile PL moving along an optimal trajectory allowed us to reduce the PDOP to 1.2 (the mask angle equal to 5 degrees) and 1.7 (the mask angle equal to 30 degrees), i.e. 1.83 and 1.7 times, respectively. However, at the final approach, when $H_{PL} > H_{Ai}$, the gain from the use of a mobile PL decreases.

It should also be noted that in the investigated range of heights (from 50 to 300 m) almost the same PDOP value is provided regardless of the UAV flight altitude with the PL installed on it when the condition $H_{PL} < H_{Ai}$ is met.

Conclusion

The conducted research shows that the use of a mobile PL located on board a UAV moving along an optimal trajectory makes it possible to increase the accuracy of the integrated NTF by 5-7% in comparison with other ways of using PL.

It is recommended that:

- the Hooke – Jeeves method which has acceptable computation effort be used as tooling for constructing a UAV optimal trajectory;
- the PDOP minimum be used as an optimization criterion;
- an UAV flight be performed at altitudes as low as possible;
- UAV hovering be used for providing high accuracy of the integrated navigation-and-time field at the final approach (when Haircraft<Hpl).

It should also be noted that the use of a mobile PL will significantly mitigate such a PL use disadvantage, as the «far-near» effect [Скрыпник, Ерохин, 2012], since the change of the distance between the PL and the aircraft will be much less than when a stationary PL is used.

Библиографический список

Бабуров, В. И. Использование навигационных полей точности спутниковых радионавигационных систем и сетей / В. И. Бабуров, Н. В. Васильева, Н. В. Иванцевич, З. А. Панов. СПб.: Издательство «Агентство РДК-Принт»», 2005. 264 с.

Бабуров, В. И. Исследование точности навигационных определений летательных аппаратов по системе ГЛОНАСС и псевдоспутникам в арктическом регионе России / В. И. Бабуров, Н. В. Васильева, Н. В. Иванцевич // Региональная информатика и информационная безопасность. СПб.: Издательство «Санкт-Петербургское Общество информатики, вычислительной техники, систем связи и управления», 2016. № 2. С. 340-344.

Балов, А. В. Псевдоспутники в локальных системах расширения функциональных возможностей СРНС/ А. В. Балов, А. Г. Геворкян //Аналитический обзор. СПб.: РИРВ, 2002. № 27. 26 с.

Борсоев, В. А. Использование псевдоспутников группировки ГЛОНАСС/GPS в системах посадки воздушных судов / В. А. Борсоев, Р. Г. Галеев, А. В. Гребенников, А. С. Кондратьев

// Научный вестник Московского государственного технического университета гражданской авиации. 2011. № 164. С. 17-24.
Веремей, Е. И. Алгоритмы оптимизации маршрутов движения с учетом погодных условий / Е. И. Веремей, М. В. Сотникова// International Journal of Open Information Technologies. 2016. Т. 4. №. 3. С. 55-61
Нигруца, И. В. Система посадки по сигналам псевдоспутников / И. В. Нигруца, А. В. Гребенников, М. Ю. Казанцев // Вестник СибГАУ им. академика МФ Решетнева. 2012. №. 1. С. 96-99.
Руководство по навигации, основанной на характеристиках (PBN). Doc. 9613. AN/937. 4-е изд. Международная организация гражданской авиации. 2013. 444 с.
Скрыпник, О. Н. Совершенствование аэронавигационного обеспечения этапа посадки путем оптимизации размещения псевдоспутников ГЛОНАСС / О. Н. Скрыпник, Р. О. Арефьев, Н. Г. Арефьева // Труды МАИ. 2017. № 92. С. 28.
Скрыпник, О. Н. Исследование параметров рабочего созвездия ГЛОНАСС на основе моделирования орбитальной группировки / О. Н. Скрыпник, В. В. Ерохин // Научный вестник Московского государственного технического университета гражданской авиации. 2012. №. 180. С. 70-77.
Скрыпник, О. Н. Радионавигационные системы аэропортов и воздушных трасс: учебник. М.: Инфра-М, 2020.325 с.
Adler A., Bar-Gill A., Shimkin N. Optimal flight paths for engine-out emergency landing //2012 24th Chinese Control and Decision Conference (CCDC). IEEE, 2012, Pp. 2908-2915.
Global Navigation Satellite System (GNSS) Manual. Doc. 9849. AN/457. 2-nd edition. ICAO. 2013. P. 90.
Gardi A., Marino, M., Ramasamy, S., Sabatini, R., Kistan, T. 4-Dimensional trajectory optimisation algorithm for air traffic management systems //2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC). IEEE, 2016. Pp. 1-7.
Michael Jones. Army pseudolites: What, why and how? GPS World. August 9, 2017. [Electronic resource]. URl: https:// www.gpsworld.com/army-pseudolites-what-why-and-how (date of access: 11.09.2021).
Khardi S. Aircraft flight path optimization. The hamilton-jacobi-bellman considerations //Applied Mathematical Sciences. 2012. T. 6. №25. Pp. 1221-1249.

References

Adler A., Bar-Gill A., Shimkin N. (2021). Optimal flight paths for engine-out emergency landing //2012 24th Chinese Control and Decision Conference (CCDC). IEEE, Pp. 2908-2915.
Baburov V. I., Vasilyeva N. V., Ivantsevich N. V. (2016). Investigation of accuracy of navigational sightings of aircraft using GLONASS system and pseudolites in the Russian Arctic. *Regional computer science and IT security.* Saint Petersburg: Izdatel'stvo «Sankt-Peterburgskoe Obshchestvo informatiki, vychislitel'noj tekhniki, sistem svyazi i upravleniya*»,* № 2: 340-344. (In Russian).
Baburov V. I., Vasilyeva N. V., Ivantsevich N. V., Panov Z. A. (2005). Use of navigational accuracy fields of satellite radio-navigation systems and networks. Sankt-Peterburg: Izdatel'stvo «Agentstvo RDK-Print»», 264 p. (In Russian).
Balov A.V., Gevorkyan A. G. (2002). Pseudolites in local SRNS augmentation systems. Analytical review. Saint Petersburg.: RIRT, № 27. 26 p. (In Russian).
Borsoev V. A., Galeev R. G., Grebennikov A.V., Kondratyev A. S. (2011). Usage of GLONASS/GPS pseudosatellites in aircraft landing systems. *Nauchnyj vestnik Moskovskogo gosudarstvennogo tehnicheskogo universiteta grazhdanskoj aviacii*. Moscow: MSTU CA, №164: 17-24. (In Russian).
Gardi A., Marino M., Ramasamy S., Sabatini, R., Kistan, T. (2016). 4-Dimensional trajectory optimisation algorithm for air traffic management systems // 2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC). IEEE, Pp. 1-7.

Global Navigation Satellite System (GNSS) Manual. Doc. 9849. AN/457. 2-nd edition. ICAO. 2013. P. 90.
Khardi S. (2012). Aircraft flight path optimization. The hamilton-jacobi-bellman considerations. *Applied Mathematical Sciences*. T. 6. №. 25: 1221-1249.
Michael Jones. (2017). Army pseudolites: What, why and how? GPS World. August 9, 2017. [Electronic resource]. URl: https:// www.gpsworld.com/army-pseudolites-what-why-and-how (date of access: 11.09.2021).
Nigruca I. V., Grebennikov A. V., Kazantsev M. Yu. (2012). Aircraft landing system bases on pseudo satellites signals. *Vestnik SibGAU im. akademika M.F. Reshetneva*. Krasnoyarsk: SibGAU imeni akademika M.F. Reshetneva, №1: 96-99. (In Russian).
Performance-based Navigation (PBN) Manual. Doc. 9613. AN/937. 4-th edition. International Civil Aviation Organization, 2013. 444 p. (In Russian).
Skrypnik O. N., Arefev R. O., Arefeva N. G. (2017). Improvement of air navigation support of the landing phase by optimizing the allocation of pseudolites GLONASS. *Trudy MAI*, №92, 28 p. (In Russian).
Skrypnik O. N., Erokhin V. V. (2012). Research of parameters of working constellation GLONASS on the basis of modeling of orbital grouping. *Nauchnyj vestnik Moskovskogo gosudarstvennogo tehnicheskogo universiteta grazhdanskoj aviacii*. Moscow: MSTU CA. №180: 70-77. (In Russian).
Skrypnik O. N. (2020) Radio navigation systems of airports and air routes: textbook. Moscow infra Publ. 325 p. (In Russian).
Veremei E. I., Sotnikova M. V. (2016). Optimal routing based on weather forecast. *International Journal Of Open Information Technologies*. T. 4. №. 3: 55-61. (In Russian).