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ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН»
ЧФ «Халық»

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Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

ЧФ «ХАЛЫҚ»

В 2016 году для развития и улучшения качества жизни казахстанцев был создан частный Благотворительный фонд «Халык». За годы своей деятельности на реализацию благотворительных проектов в областях образования и науки, социальной защиты, культуры, здравоохранения и спорта, Фонд выделил более 45 миллиардов тенге.

Особое внимание Благотворительный фонд «Халык» уделяет образовательным программам, считая это направление одним из ключевых в своей деятельности. Оказывая поддержку отечественному образованию, Фонд вносит свой посильный вклад в развитие качественного образования в Казахстане. Тем самым способствуя росту числа людей, способных менять жизнь в стране к лучшему – профессионалов в различных сферах, потенциальных лидеров и «великих умов». Одной из значимых инициатив фонда «Халык» в образовательной сфере стал проект Ozgeris powered by Halyk Fund – первый в стране бизнес-инкубатор для учащихся 9-11 классов, который помогает развивать необходимые в современном мире предпринимательские навыки. Так, на содействие малому бизнесу школьников было выделено более 200 грантов. Для поддержки талантливых и мотивированных детей Фонд неоднократно выделял гранты на обучение в Международной школе «Мирас» и в Astana IT University, а также помог казахстанским школьникам принять участие в престижном конкурсе «USTEM Robotics» в США. Авторские работы в рамках проекта «Тәлімгер», которому Фонд оказал поддержку, легли в основу учебной программы, учебников и учебно-методических книг по предмету «Основы предпринимательства и бизнеса», преподаваемого в 10-11 классах казахстанских школ и колледжей.

Помимо помощи школьникам, учащимся колледжей и студентам Фонд считает важным внести свой вклад в повышение квалификации педагогов, совершенствование их знаний и навыков, поскольку именно они являются проводниками знаний будущих поколений казахстанцев. При поддержке Фонда «Халык» в южной столице был организован ежегодный городской конкурс педагогов «Almaty Digital Ustaz.

Важной инициативой стал реализуемый проект по обучению основам финансовой грамотности преподавателей из восьми областей Казахстана, что должно оказать существенное влияние на воспитание финансовой грамотности и предпринимательского мышления у нового поколения граждан страны.

Необходимую помощь Фонд «Халык» оказывает и тем, кто особенно остро в ней нуждается. В рамках социальной защиты населения активно проводится работа по поддержке детей, оставшихся без родителей, детей и взрослых из социально уязвимых слоев населения, людей с ограниченными возможностями, а также обеспечению нуждающихся социальным жильем, строительству социально важных объектов, таких как детские сады, детские площадки и физкультурно-оздоровительные комплексы.

В копилку добрых дел Фонда «Халык» можно добавить оказание помощи детскому спорту, куда относится поддержка в развитии детского футбола и карате в нашей стране. Жизненно важную помощь Благотворительный фонд «Халык» оказал нашим соотечественникам во время недавней пандемии COVID-19. Тогда, в разгар тяжелой борьбы с коронавирусной инфекцией Фонд выделил свыше 11 миллиардов тенге на приобретение необходимого медицинского оборудования и дорогостоящих медицинских препаратов, автомобилей скорой медицинской помощи и средств защиты, адресную материальную помощь социально уязвимым слоям населения и денежные выплаты медицинским работникам.

В 2023 году наряду с другими проектами, нацеленными на повышение благосостояния казахстанских граждан Фонд решил уделить особое внимание науке, поскольку она является частью общественной культуры, а уровень ее развития определяет уровень развития государства.

Поддержка Фондом выпуска журналов Национальной Академии наук Республики Казахстан, которые входят в международные фонды Scopus и Wos и в которых публикуются статьи отечественных ученых, докторантов и магистрантов, а также научных сотрудников высших учебных заведений и научно-исследовательских институтов нашей страны является не менее значимым вкладом Фонда в развитие казахстанского общества.

С уважением,
Благотворительный Фонд «Халык»!

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DEVELOPMENT OF A DIRECTION FINDER WITH DIRECTION DETERMINATION FOR SMALL-SIZED UNMANNED AERIAL VEHICLES

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Abstract. To date, small-sized unmanned aerial vehicles (UAVs) have taken an important place in the life of human activity and are used in solving a wide range of tasks: in the civil sphere (for example, for logistics, healthcare, agriculture, emergency rescue operations), for unauthorized surveillance of important objects, for relaying data between remote subscribers of networks communications, for carrying out terrorist attacks and sabotage (for example, access beyond the perimeter of protected objects, obstruction of air traffic at airports), for carrying prohibited goods (weapons, drugs), in military affairs (for example, for reconnaissance, tracking objects, adjusting fire, striking). In parallel with the development of UAVs, methods of combating them are gaining great popularity. So, to counter UAVs, means of fire damage, functional damage by ultrahigh-frequency and laser radiation, radio-electronic suppression, etc. are used. The main means of target designation for these systems are radar stations, optical-electronic, acoustic and electronic reconnaissance, the latter of which have the highest priorities due to the lack of their own radiation, sufficient detection range and all-weather conditions. The article considers a variant of determining the direction to small-sized unmanned vehicles in a phase two-channel radio direction finder with amplitude modulation of the signal. Proposals for the implementation of the bearing assessment method have been developed, shortcomings have been identified and ways to solve them have been worked out. A block diagram of a two-channel phase direction finder with amplitude modulation of the signal has been obtained and its layout has been developed. The structure of checking the quality indicators of the direction finder is considered and the results of the bearing assessment are presented.

Keywords: small-sized, unmanned aerial vehicle, two-channel phase direction finder, radio direction finder layout, quality indicators, antenna system, bearing assessment

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ШАҒЫН КӨЛЕМДІ ПИЛОТСЫЗ ҰШУ АППАРАТТАРЫНЫҢ БАҒЫТЫН АНЫҚТАЙ ОТЫРЫП, РАДИОПЕЛЕНГАТОРДЫ ӘЗІРЛЕУ

Аннотация. Бүгінгі таңда шағын пилотсыз ұшу аппараттары (ұшқышсыз ұшу аппараттары) адам өмірінде маңызды орынға ие болды және көптеген міндеттерді шешуде қолданылады: азаматтық салада (мысалы, логистика, денсаулық сақтау, ауыл шаруашылығы, авариялық-құтқару операциялары үшін), маңызды объектілерді рұқсатсыз бақылау үшін,байланыс желілерінің қашықтағы абоненттері арасында деректерді қайта тарату үшін, террористік шабуылдар мен диверсиялар жүргізу үшін (мысалы, күзетілетін объектілердің периметрінен шығу, әуежайларда әуе қозғалысына кедергі жасау), тыйым салынған тауарларды (қару-жарақ, есірткі) тасымалдау үшін, әскери істе (мысалы, барлау, объектілерді бақылау, өртті түзету, соққы беру үшін). Ұшқышсыз ұшу аппараттарының дамуымен қатар, олармен күресу әдістері үлкен танымалдылыққа ие болуда. Осылайша, ұшқышсыз ұшу аппараттарына қарсы тұру үшін отты зақымдау құралдары, ультра жоғары жиілікті және лазерлік сәулеленудің функционалдық зақымдануы, радиоэлектрондық басу және т. б. осы жүйелер үшін негізгі нысаналы құралдар оптикалық-электрондық, акустикалық және радиоэлектрондық барлаудың радиолокациялық станциялары болып табылады, олардың соңғылары өз сәулеленуінің болмауына, жеткілікті анықтау қашықтығына және барлық ауа райы жағдайларына байланысты ең жоғары басымдықтарға ие. Мақалада сигналдың амплитудалық модуляциясы бар фазалық екі арналы радиопеленгатордағы шағын ұшқышсыз ұшу аппараттарына бағытты анықтау нұсқасы қарастырылады. Бағыттауды бағалау әдісін енгізу бойынша ұсыныстар әзірленді, кемшіліктер анықталды және оларды жою жолдары әзірленді. Сигналдың амплитудалық модуляциясы бар екі арналы фазалық пеленгатордың құрылымдық схемасы алынды және оның орналасуы жасалды. Пеленгатордың сапа көрсеткіштерін тексеру құрылымы қаралды және пеленгті бағалау нәтижелері ұсынылды.

Түйін сөздер: шағын ұшқышсыз ұшу аппараты, екі арналы фазалық пеленгатор, радиопеленгатордың орналасуы, сапа көрсеткіштері, антенна жүйесі, пеленгті бағалау

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РАЗРАБОТКА РАДИОПЕЛЕНГАТОРА С ОПРЕДЕЛЕНИЕМ НАПРАВЛЕНИЯ ДЛЯ МАЛОРАЗМЕРНЫХ БЕСПИЛОТНЫХ ЛЕТАТЕЛЬНЫХ АППАРАТОВ

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Аннотация. На сегодняшний день, малоразмерные беспилотные летательные аппараты (БЛА) заняли важное место в жизни деятельности человека и используются при решении широкого спектра задач: в гражданской сфере (например, для логистики, здравоохранения, сельского хозяйства, аварийно-спасательных операций), для несанкционированного наблюдения за важными объектами, для ретрансляции данных между удаленными абонентами сетей связи, для проведения терактов и диверсий (например, доступа за периметр охраняемых объектов, препятствование воздушному движению в аэропортах), для переноски запрещенных грузов (оружия, наркотиков), в военном деле (например, для разведки, слежения за объектами, корректировки огня, нанесения ударов). "Разведочные работы — это мероприятия, направленные на выявление и подготовку месторождений полезных ископаемых к разработке в промышленных масштабах." Целью геологических исследований является изучение местоположения месторождений полезных ископаемых и их состава. Кроме того, выявляется наличие сопутствующих компонентов включая газы и редкие металлы, исследуется возможность их последующего производства. Параллельно с развитием БЛА большую популярность набирают и способы борьбы с ними. Так для противодействия БЛА применяются средства огневого поражения, функционального поражения сверхвысокочастотным и лазерным излучением, радиоэлектронного подавления и др. Основными средствами целеуказания для данных систем являются радиолокационные станции, средства оптико-электронной, акустической и радиоэлектронной разведки, последние из которых обладают наибольшим приоритетам ввиду отсутствия собственного излучения, достаточной дальностью обнаружения и всепогодностью. В статье рассматривается вариант определения направления для малых беспилотных летательных аппаратов на фазовом двухканальном радиопеленгаторе с амплитудной модуляцией сигнала. Разработаны рекомендации по внедрению метода оценки направленности, выявлены недостатки и разработаны пути их устранения. Получена структурная схема двухканального фазного пеленгатора с амплитудной модуляцией сигнала и составлена его компоновка. Рассмотрена структура проверки показателей качества пеленгатора и представлены результаты оценки пеленгатора.

Ключевые слова: малоразмерный, беспилотный летательный аппарат, двухканальный фазовый радиопеленгатор, макет радиопеленгатора, показатели качества, антенная система, оценка пеленга

Introduction

The need for continuous intensive data exchange of UAVs with the control panel requires the presence of one or more broadband radio communication channels (for example, UAV radio control channels, transmission of useful information and video to the operator), for which it is very difficult to ensure the required secrecy of operation. In this regard, the high-frequency radiation of radio communications is the main unmasking feature of UAVs relative to electronic intelligence (Figure 1) (Makarenko et al., 2020: 1; Rembovsky et al., 2012: 3; Marple et al., 1990: 7).

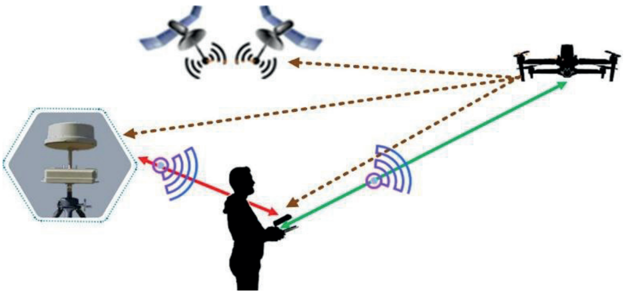

Figure 1. The scheme of interaction of the operator, UAV and radio direction finder

However, the continuous trend of improving small-sized UAVs requires retaliatory refinement (development) of radio intelligence tools, which should have the following advantages: small size, ease of implementation, low cost, minimal energy consumption and sufficient accuracy in determining the direction of the UAV. The realization of the totality of such advantages emphasizes the relevance of this topic.

The purpose of this article is devoted to the development of a radio direction finder with small weight and size characteristics, low power consumption, minimal costs, simple implementations and providing sufficient accuracy in determining the direction of small-sized UAVs necessary for guidance of countermeasures.

To solve this problem, a relatively cheap and simple from the point of view of implementation is a two-channel LimeSDR transceiver with integrated analog-to-digital and digital-to-analog converters operating in the frequency range of 100 kHz – 3.8 GHz (Figure 2) (LimeSDR-USB et al., 2023: 4; Solonar et al., 2023: 5; Kosachev et al., 2015: 5).

Figure 2. Appearance of the LimeSDR transceiver

The main advantages of the LimeSDR transceiver are: compactness, reliability and low energy consumption (5V).

These advantages determined the initial prerequisites for building a radio direction finder processing device based on a two-channel LimeSDR transceiver.

The analysis of the methods for estimating the direction of the UAV showed that the phase method of bearing has the best properties of the whole variety. Its main advantage is the simplicity of the implementation of the antenna system and the algorithm for obtaining the bearing reference, as well as resistance to parasitic amplitude modulation.

However, when developing a phase direction finder using a two-channel LimeSDR transceiver, a number of difficulties arose, which consisted of:

Firstly, in ensuring the directional properties of the antenna pattern (AP) and the minimum weight and size characteristics of the antenna system.

Secondly, in choosing the required switching frequency of antenna elements, which ensures the formation of a sufficient number of bearing estimates.

Thirdly, in choosing an algorithm for estimating the direction of the UAV.

Further, the article will consider ways to solve the above reasons with the subsequent development of the structure and layout of a two-channel phase direction finder.

Due to the need to use a two-channel LimeSDR transceiver, a sequential survey of space is implemented by continuous rotation of the AP (electronic scanning) in the form of a cardioid with angular velocity Ω_A (Figure 3), which leads to amplitude modulation of the direction-finding signal. In this case, the phase shift of the signal envelope relative to the origin (direction to the North) will correspond to the direction to the UAVθ.

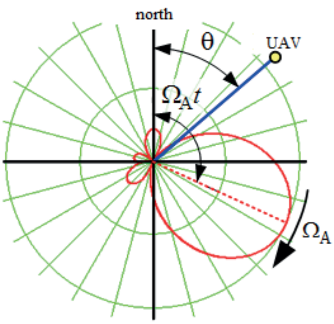

Figure 3. The method of rotation of the AP in the form of a cardioid

To reduce the weight and size characteristics of the radio direction finder, an antenna system consisting of two orthogonal direction-finding pairs (DFP) oriented in the directions "north – south" and "east – west" (cosine and sinusoidal directional patterns of the DFP, respectively $g_\Delta(\theta)$) is taken as a basis (Figure 4).

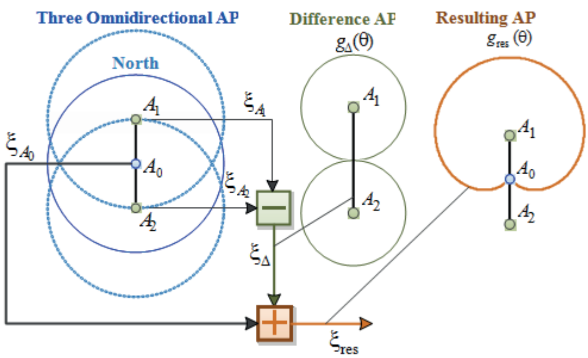

Figure 4. Explanation of the principle of forming a AP in the form of a cardioid
Three non – directional AP Finite difference AP Resulting AP

To form a cardioid $g_{\text{рез}}(\theta)$ (Figure 4), the difference signal of the DFP $\xi\Delta$ is summed up with the signal of a non-directional antenna element ξ_{A0} (AE) located in the middle of the antenna system. In addition, this AE A_0 is also used to solve the problem of detection.

The formation of a cardioid is provided when the conditions are met (Rembovsky et al., 2022: 2; Rembovsky et al., 2012: 3; Solonar et al., 2023: 5; Wentzel et al., 2001: 8)

the amplitudes of the signals of the central A_0 and DFP $A_{1(2)}$ AE are equal ($\xi_{A_0} = \xi_{A_1} = \xi_{A_2}$);

the initial phases of the signals of the central A_0 and first A_1 AE DFP are equal ($\varphi_{A_0} = \varphi_{A_1}$);

the initial phases of the signals of the central A_0 and second A_2 AE DFP differ by π ($\varphi_{A_0} - \varphi_{A_1} = \pi$).

The resulting AP of the three AE is a cardioid with a function of the form (Figure 4):

$$g_{\text{рез}}(\theta) = 1 + \cos(\alpha - \theta), \quad (1)$$

where α - angular position of the maximum AP.

To ensure signal reception in the 2.4–2.6 GHz frequency range, a biconic antenna is used as an AE (Figure 5). Modeling and verification of the main characteristics of AE (for example, bottom width, standing wave coefficient) was carried out using the CST Studio Suite software package. Practical tests of the biconic antenna showed a high degree of compliance with the simulation results (95 %). The value of the standing wave coefficient in the required band varied from 1.4 to 1.6.

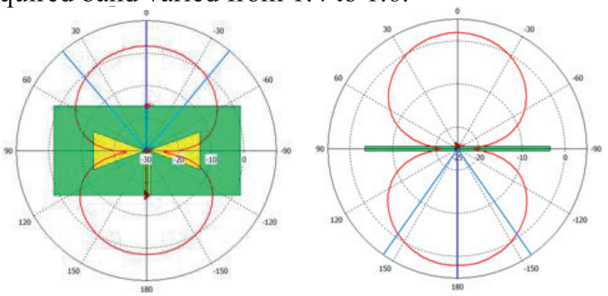

Figure 5. The appearance of one AE (biconic antenna) and its AP

It is proposed to use a pair of ring bridges operating in the frequency range of 2.4–2.6 GHz to subtract the signals of two DFP at a high frequency (Figure 6) (Buylov et al., 2023: 6)

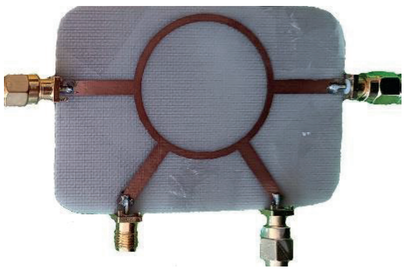

Figure 6. Appearance of the ring bridge

The use of a two-channel LimeSDR transceiver (LimeSDR-USB et al., 2023: 4) requires the use of a combined connection to the input of the receiver of the differential voltage DFP (Figure 7).

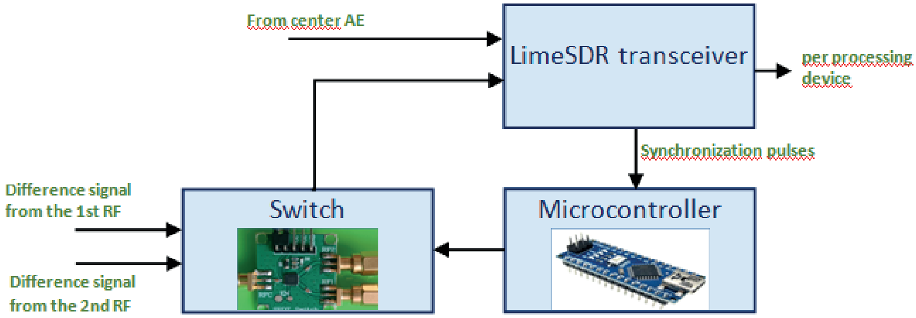

Figure 7. Wiring diagram of signals from the antenna system to the LimeSDR transceiver
from the central AE LimeSDR transceiver To the processing device
Finite difference signal from the 1st DFP Finite difference signal from the 2nd DFP
Switchboard Microcontroller Sync pulses

In this case, the signal of the central AE is fed to the input of the first channel of the LimeSDR transceiver, used to solve the problems of detecting UAVs and forming the resulting AP (cardioids) (Figure 7). The second channel is connected via a high-speed switch to the finite difference signals of the control unit controlled by a microcontroller using the sync signals coming from LimeSDR (Figure 7) (LimeSDR-USB et al., 2023: 4).

Thus, the proposed method of implementing the antenna system made it possible to eliminate the problem that arose during the development of the phase direction finder. For this purpose, the directional properties of the bottom and the minimum weight and size characteristics of the antenna system are provided due to the sum-difference processing of the received signal with sequential switching of the AE. The antenna system is represented by two orthogonal DFP oriented in the directions of the cardinal directions and one AE located in the center. The AE design in the form of a biconic antenna allows receiving signals in the frequency range of 2.4–2.6 GHz at the values of the standing wave coefficient of 1.4–1.6 (Rembovsky et al., 2012: 3; Yerzhan et al., 2023: 10; Plotkin et al., 2021: 11).

The choice of the switching speed of the DFP was determined by the characteristics of the signals of the control channels and video of small-sized UAVs. Despite their variety of types, models and manufacturers, the following signal parameters can be distinguished: the minimum duration of the signal of the UAV control channel $T_{0ку} = 500\,\mu s$; the width of the spectrum of a single signal of the UAV control channel $\Delta f_{0ку} = (0,3...2)$ MHz ;the grid band of pseudo-random frequency tuning of the signal of the UAV control channel $\Delta F_{ку} = 80$ MHz; the duration of the video signal transmitted from the UAV to the operator $T_{0в} = (2...3)$ ms; the width of the spectrum of the video signal transmitted from the UAV to the operator $\Delta f_{0в} = 20$ MHz.

In addition, in order to reduce the errors in determining the bearing, it is necessary to form at least 5–7 estimates for one contact with the UAV.

Having set the worst conditions for the formation of an estimate of the direction to the UAV (the minimum duration of the signal of the UAV control channel and the number of bearing estimates), the main requirements were worked out and the antenna system of the radio direction finder was developed (Figure 8) with the characteristics: AE switching frequency – 5 kHz; signal reception time by one AE – 50 microseconds; review cycle (full rotation of the bottom in the horizontal planes) – 200 microseconds.

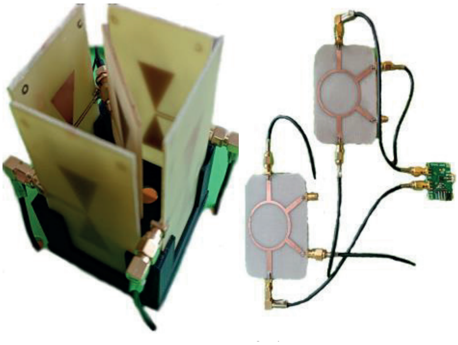

Figure 8. Appearance of the antenna system

Thus, the selected AE switching frequency Ω_A = 5 kHz provided by a high-speed switch allows you to generate at least 5 bearing estimates per contact with the UAV with the shortest duration of the control channel signal ($T_{0ку}$ = 500 µs).

After analog-to-digital conversion in the LimeSDR transceiver (LimeSDR-USB et al., 2023: 4) the resulting signal is sent to the spectroanalyzer. Estimation of the instantaneous signal spectrum can be implemented using discrete or fast Fourier transform (FFT) using statistical averaging (periodogram method) (Rembovsky et al., 2012: 3).

To reduce the level of the side lobes, a weight treatment (w - weight function) is used. The algorithm for estimating the instantaneous signal spectrum for n-th AE has the form:

$$S(\theta)_{i,s} = \frac{1}{N_{бпф}} \sum_{k=0}^{N_{бпф}-1} \left[w_k \xi_{рез\, k+\left(s - floar\{\frac{s}{N_{бпф}}\} N_{бпф}\right)\frac{N_{бпф}}{2}} \exp\left(-j2\pi k i / N_{бпф}\right) \right], \qquad (2)$$

where *floor(·)* - rounding function to a smaller integer value; $N_{бпф}$ - FFT window size; *s* - frequency reference number; *i* - FFT window number.

Averaging of the instantaneous spectrum during signal reception by one AE $T_{ФЭ}$ allows to reduce its dispersion:

$$S_{\Sigma}(\theta)_i = \frac{1}{L} \sum_{s=0}^{L-1} S(\theta)_{i,s}, \qquad (3)$$

where $L = floor\{T_{АЭ} / (N_{БПФ}\, t_{д})\}$ - the number of samples of the instantaneous spectrum size $N_{БПФ}$: $t_{Д}$ - time sampling step.

One of the main tasks solved during the development of the direction finder was to determine the algorithm for estimating the bearing on the UAV, due to three reasons:

By time-consistent estimation of the instantaneous power of the received radiation.

High requirements for the quality of UAV signal detection.

A large step (90^0) of spatial switching of the AP when scanning.

The first reason is caused by the need to form at least 5–7 bearing estimates for UAVs received from signals from four AE.

The solution to this problem was to use a sliding buffer for storing the results of the n-th AE signals $S_{\Sigma}(\theta)_n$ power estimation (Figure 9). After each AE switching, the signal power values are shifted by one cell "to the left" and a new value is recorded. So, for example, during the time of making a full turn of the AP (review cycle), the sliding buffer is filled with estimates of the signal power (buffer value "1, 2, 3, 4"), received by four AE (state 1, Figure 9). As a result, the first bearing estimate for the UAV is calculated. When the signal is received by the second AE (state 2), the buffer data is shifted "to the left" and a new signal power value is recorded (buffer value "2, 3, 4, 1"). The result of the shift is the formation of the second bearing estimate on the UAV. It should be noted that the use of a sliding buffer requires a bearing adjustment. So, for example, it is necessary to subtract 90^0 from the second bearing estimate, 180^0 from the third, etc.

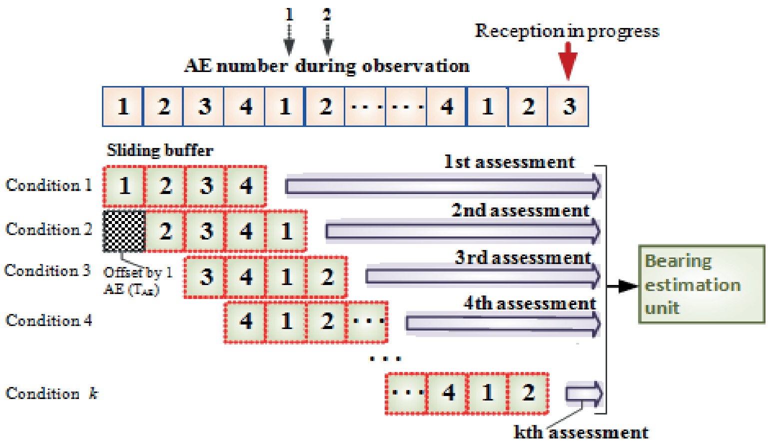

Figure 9. Explanation of the principle of using a sliding buffer

State 1 State 2 State 3 State 4 State k
AE number during observation reception is underway
Sliding buffer 1-st assessment 2-nd assessment 3-rd assessment 4-th assessment k-th assessment
Bearing assessment unit Offset by 1 AE (T_{AE})

Thus, the considered approach (Figure 9) makes it possible to form at least 5–7 bearing estimates when receiving the signal of the UAV control channel during $T_{0ку}$=500 μs.

The second reason is caused by the need to make the right decision about detection due to the fact that the survey of space is carried out sequentially in time.

The solution to this problem lies in the fact that the decision on detection is made only when the detection threshold is exceeded when receiving a signal from at least four AE. In this case, the calculated bearing estimate for the UAV is sent to the display device. Otherwise, the assessment is not formed.

The third reason is due to the large step of switching the AP when scanning (90^0) due to the use of two DFP. In this case, the bearing on the UAV is estimated in the width sector (90^0), which contradicts the requirements for a radio direction finder.

The solution to this problem is to use a bank of reference envelopes (Figure 10), differing in the initial phase and then comparing them with the current estimates of signal power (error calculation block, Figure 10) obtained in each AE.

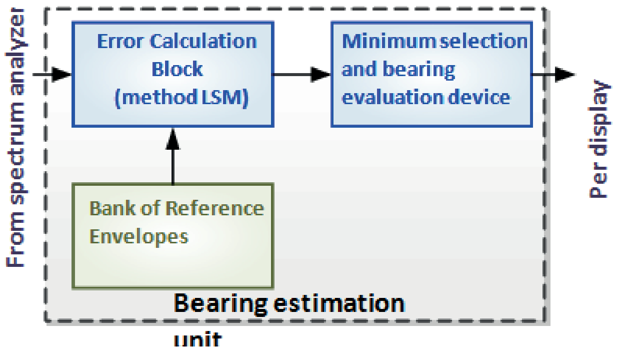

Figure 10. The structure of the bearing evaluation unit
From the spectroanalyzer Error calculation block (the LSM method)
Bank of reference envelopes Bearing Assessment Unit
Minimum selection and bearing estimation device
To the display device

Thus, an algorithm for estimating the bearing on the UAV has been developed, which includes three stages:

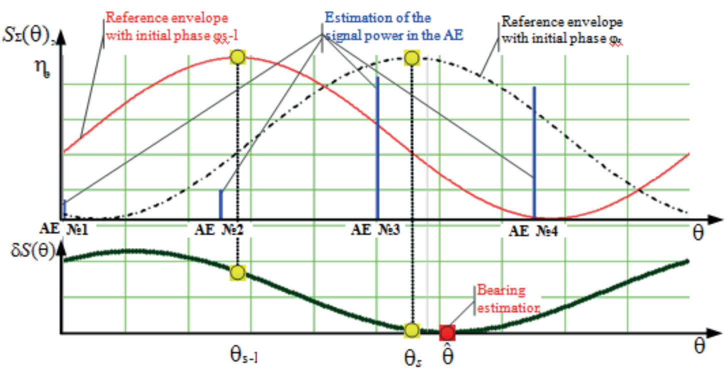

Figure 11. Explanation of the stages of bearing assessment

Reference envelope with initial phase Estimation of signal power in AE Reference envelope with initial phase Bearing estimation AE

At the 1st stage, the average square error is calculated $\delta S_k(\theta)$ (Figure 11) of the sum of the differences between the obtained estimates of signal power and the reference envelope $\eta_{э\,n,\,k}$ (Solonar et al., 2023: 5):

$$\delta S_k(\theta) = \sum_{n=0}^{N_{АЭ}-1} \left| S_\Sigma(\theta)_n - \eta_{э(n \cdot 90),\,k} \right|^2, \quad (4)$$

where $N_{АЭ}$ = 4 number of AE DFP; k - reference envelope number.

At the 2nd stage, a one-time bearing estimate for the UAV is estimated (according to the criterion of the minimum of the average square error) (Fig. 11, lower part of the figure):

$$\hat{\theta} = \arg[\min_k(\delta S_k(\theta))]. \quad (5)$$

At the 3rd stage, one-time bearing estimates $\hat{\theta}$ are averaged over the observation time $T_Н$:

$$\hat{\theta}_{ИРИ} = \frac{1}{M_{Тн}} \sum_{q=0}^{M_{Тн}-1} \hat{\theta}_q, \quad (6)$$

where $M_{ТН}$ - the number of UAV bearing estimates obtained during observation $T_Н$.

Thus, the use of the obtained algorithm makes it possible to calculate the bearing estimate on the UAV with an accuracy (units of degrees) sufficient to guide the means of counteraction.

Based on the results of the conducted research, the structure of a two-channel phase direction finder with amplitude modulation of the signal has been developed (Figure 12), which meets the requirements for modern electronic intelligence systems (Buylov et al., 2023: 6; Abdimuratov et al., 2021: 14; Neshina et al., 2023: 15).

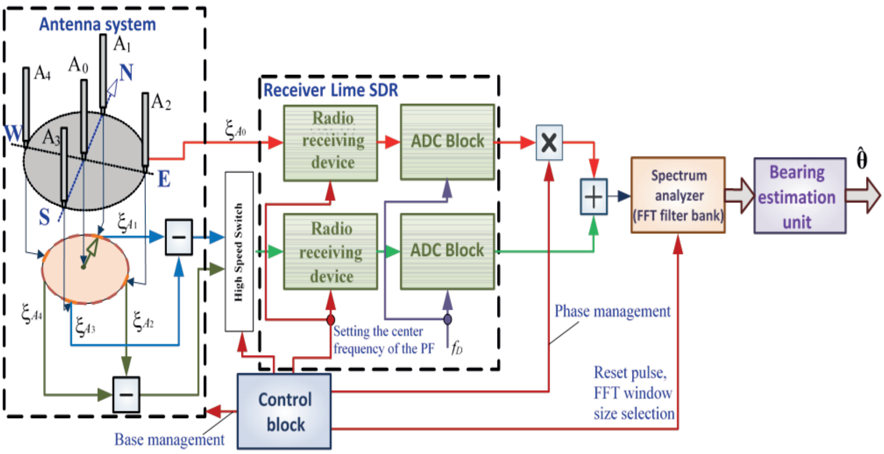

Figure 12. Block diagram of a two-channel phase direction finder

Antenna system High-speed switchboard Control unit Database management Lime SDR receiver Radio receiving device ADC Unit Setting the central frequency BPF Phase control Reset pulse, FFT window size selection Spectrum Analyzer (FFT filter bank) Bearing Assessment Unit

The appearance of the developed phase direction finder is shown in Figure 13

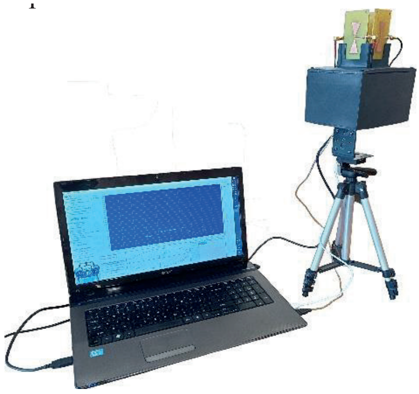

Figure 13 Appearance of the layout of a two-channel phase direction finder

To assess the quality indicators of the developed two-channel radio direction finder, mathematical modeling, a semi-natural experiment and full-scale tests were carried out in accordance with the structure shown in Figure 14.

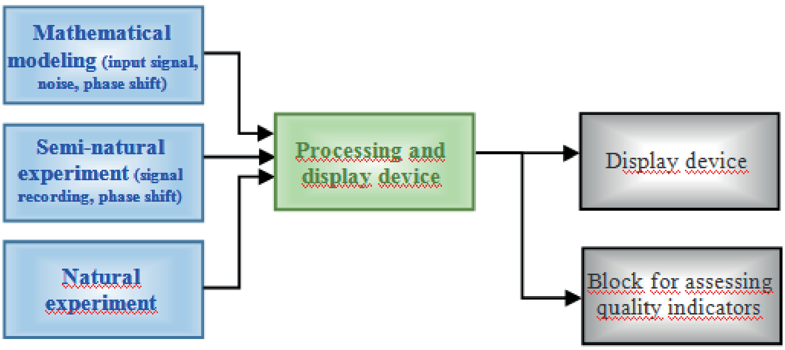

Figure 14. Structure of quality indicators verification

Mathematical modeling (input signal, noise, phase shift) Semi-natural experiment (recording of a real signal, phase shift) Full-scale experiment (real UAV) Processing and display device Display device Quality Indicators Evaluation unit

The tests were carried out under the following conditions:

the range to the small-sized UAV varied from 500 to 1000 m;

the effect of re-reflection of the received signal from the UAV was minimized;

the arithmetic mean deviation from the bearing norm was calculated based on the results of a study of 600 results, which corresponded to a reliable error of 0.9 and a measurement error of no more than 10% (Yerzhan et al., 2023: 16; Naizagarayeva et al., 2023: 12; Manbetova et al., 2021: 13).

The following results are obtained:

small-sized UAVs were detected at a distance of up to 1000 m;

the bearing estimate was consistent (no anomalies were observed);

the mean square deviation of the bearing did not exceed $(3\text{-}5)^0$ (depending on the test conditions).

Conclusions

Thus, in the course of the study, the structure of a small-sized phase two-channel radio direction finder was developed. It implements an algorithm for sum-difference processing of the received signal with sequential switching of AE, analog-to-digital conversion, estimation of the signal spectrum by the periodogram method, determination of the bearing on the UAV by the criterion of the minimum standard error, followed by its averaging during observation. Based on the results obtained, a layout of a two-channel phase direction finder has been developed, which has: small weight and size characteristics; simplicity of signal processing implementation; low cost in relation to existing radio direction finders of a similar type; minimum power consumption (5V). The test results confirmed the effectiveness of the developed direction finder. At the same time, the accuracy of the bearing estimation did not exceed 5 degrees at a distance of up to 1000 m.

This area of application of aerial drones is currently considered basic for the use of drones in mining. The data obtained will be necessary when creating field work plans, building access roads and infrastructure, further development of the facility and not only.

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