ADOPTION OF THE DISCRETE-ADDRESS MODE IN THE SECONDARY RADAR

[1]Vyacheslav Vladimirovich Erokhin, [2]Boris Valentinovich Lezhankin, [3]Tatiana Yurievna Portnova, [4]Dilshod Elmuradovich Eshmuradov, [5]Vladislav Pavlovich Churbakov

[1]Doctor of Technical Sciences, Moscow State Technical University of Civil Aviation, Irkutsk Branch, Russia

[2]Candidate of Technical Sciences, Moscow State Technical University of Civil Aviation, Irkutsk Branch, Russia

[3]Candidate of Philological Sciences, Moscow State Technical University of Civil Aviation, Irkutsk Branch, Russia

[4]Candidate of Technical Sciences, Tashkent University of Information Technologies

[5]Student, Moscow State Technical University of Civil Aviation, Irkutsk Branch, Russia

https://doi.org/10.5281/zenodo.7927912

Abstract. *Air traffic management (ATM) requires high flight safety, regularity and efficiency. These targets can be achieved by using promising technologies and technical means. The remote control of aircraft can be provided by implementing surveillance systems ensuring operative information of spatial coordinates and motion parameters. The secondary radar based on discrete-address mode recommended by ICAO for implementation provides high-speed ground-to-air data exchange (between the traffic control and the aircraft crew). Assessment of the concept implementation efficiency by mathematical modelling is an urgent technical problem.*

Keywords: *air traffic management, aircraft, interrogation signal, reply signal, LabVIEW software.*

1. Introduction

Over the past decade, volume of passenger and cargo air transportation has been constantly growing which leads to increase in air traffic density, congestion of terminal areas and air routes. At the same time, the requirements for flight safety fulfilled due to ATM systems as automated service of air traffic control (ATC) are being tightened. The mission of ground services is to construct the desired tracks and control track keeping within the areas of their responsibility, prevent aircraft proximity in vertical and horizontal terms. Aircraft surveillance is performed by radar control. Radar control is the use of radar systems for detection and position-fixing of aircraft with the aim of providing pilots with information and messages concerning considerable deviations from the nominal flight trajectory including deviations from the conditions specified in the issued ATC instructions [1].

Aircraft of various purposes perform their missions within the assigned airspace. A modern aircraft is a complicated machine which has a high production and operation cost and requires effective control. ATC is continuous monitoring and regulation of flying in order to maintain established procedures of aircraft movements at airfields and in the airspace. Aircraft navigation and ATC from take-off to landing is a continuous consistent and interrelated process provided by a complicated complex of automated flight and navigation equipment, ground, satellite and other control systems [2; 3]. Deep interrelation of tasks performed by the objects of the air transport system (ATS) during the flight and ATC providing flight safety allows us to highlight a single ATC complex as an ATS part.

In this regard, the process of air traffic management should be considered in the terms of interaction of the ground and onboard equipment to provide safe, regular and efficient flying for achieving the objectives of regional, federal and international air navigation.

2. Concept of improving the surveillance in the interests of civil aviation

Concept of improving the surveillance in the interests of civil aviation is based on the use of rational combination of different technological solutions under specified geographical entity. Existing and promising surveillance facilities are considered as basic technologies in the Concept. The surveillance facilities for performing ATM tasks are Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), Automatic Dependent Surveillance-Broadcast (ADS-B), Automatic Dependent Surveillance-Contract (ADS-C) etc. The integrated use of these surveillance means should ensure realization and implementation of an ICAO concept – CNS/ATM whose name is an abbreviation of English words expressing the essence of the conception of civil avionics at the present stage. Its first half stands for Communications, Navigation, Surveillance, the other stands for Air Traffic Management. In other words, the avionics contributes to air traffic management by providing surveillance, establishing and maintaining communication, ensuring navigation.

The CNS/ATM Concept implies transition from rigid air traffic control to more flexible management by expanding the functions of communication, navigation and surveillance systems. Cooperative decision making and ATM-system-wide dissemination of information will allow the airspace users to participate in balancing ATM resource needs thus providing flexibility and predictability as well as benefits [4].

Specifically, the expected benefits are as follows: the entire airspace will be considered as a ready-to-use resource and hence its access will be improved; the possibility to use flight paths that users prefer will become higher; the capacity will be increased due to cooperation between community members. Thus, the CNS/ATM system contains: control objects (aircraft), navigation means (global satellite navigation system), ground surveillance means (radar stations) and communication means as well as automated ATC systems (fig. 1) [5].

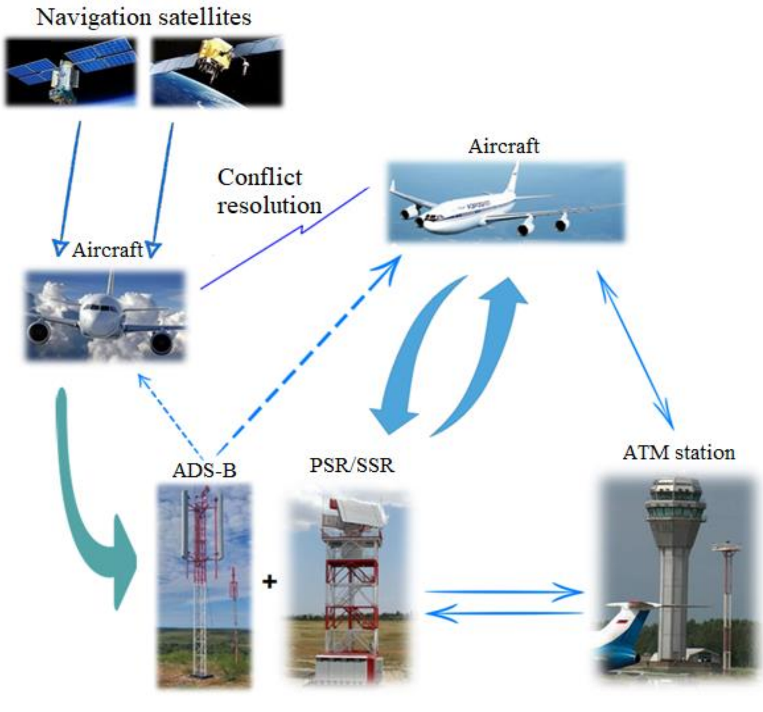


Figure 1. Structure of CNS/ATM system

Air surveillance systems are an important element of modern air navigation infrastructure and are necessary for safe management of growing volumes of even more complicated air traffic. Their use contributes to enhanced capacity and flight safety.

For implementing the concept, special attention is paid to the ground segment which is, according to preliminary estimates, the most expensive, however, the number of aircraft currently operated highlights the problem of collaboration and onboard equipment which is an object of property and operation of air traffic participants, i.e. airlines and legal owners of aircraft [6].

3. Analysis of existing surveillance systems performing the function of aircraft remote control

All currently used and promising systems surveying the air situation and termed by the FANS Committee “Surveillance Systems” are divided into two main types:

- dependent surveillance systems;
- independent surveillance systems.

In dependent surveillance systems, position of an aircraft or another vehicle is determined onboard and then the data are transmitted to an ATM station.

The dependent surveillance systems include equipment for transmitting crews’ voice position reports (VPR) [7]. Surveillance based on voice transmissions is mainly used in the areas where radar surveillance is impossible for some reason. This kind of surveillance is most often used in the air oceanic space or in the continental space with vast hard-to-reach land areas. The aircraft crews use radio communication means to inform the ATM stations of their position directly or via an aeronautical station with subsequent retranslation to ATC stations. For communication, high frequencies (HF) or very high frequencies (VHF) are used as carriers. The main disadvantages of this kind of surveillance are low operability, information capability and message transmission rate. Moreover, voice transmissions require a lot of time from the aircraft crews and especially from ground ATC controllers and distract them from their main functions [8]. The CNS/ATM Concept involves replacing this kind of surveillance with more advanced systems.

Nowadays, however, the promising channel of data transmission in ADS-B and multiposition navigation systems remains an onboard segment in the form of an aircraft transponder implementing discrete-address mode or S Mode at a frequency of 1090 MHz [9].

The independent surveillance systems require ground aids using secondary radar technique, and expansion of functional requires application of methods providing delivery of information containing more flight data which implies implementing the discrete-address mode of secondary radar (SSR).

4. Discrete-address mode of secondary radar

For improving the air traffic management, the discrete-address mode of the secondary radar is being introduced which allows the frequency band to be considerably relieved by reducing the number of interrogations and replies as each interrogation formed refers to a particular aircraft having its own personal number. The interrogation signal is generated at a frequency of 1030 MHz while the reply is formed at a frequency of 1090 MHz.

When developing the discrete-address technology the ICAO specified the condition of compatibility of the new mode with the currently used ones, without a sharp leap in costs for upgrading the onboard equipment.

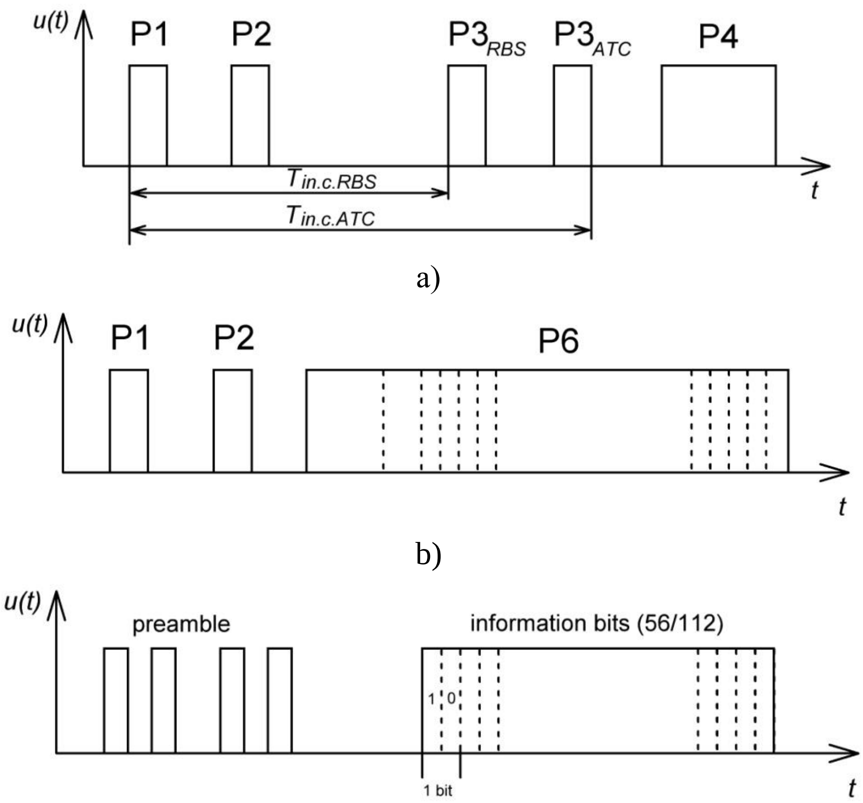
In this regard there are two types of interrogation signals [10]:

- all call interrogation (fig. 2.a) intended to interrogate all air traffic participants within the

SSR coverage for the transponder type (ATC, RBS or S);

- S mode interrogation (fig. 2.b) intended only for aircraft equipped with S transponders; it contains a personal 24-bit number assigned by ICAO.

Reply signals are generated by transponders according to the mode used and present a standard message, S Mode message form is shown in figure 2.c.



c)

Figure 2. SSR S Mode interrogation and reply signals:

a) all call; b) SSR S Mode; c) address reply

Figure 2.a) demonstrates an all call interrogation which consists of four pulses: the first three are intended for transponders operating in ATC and RBS Modes, time interval between them determines the meaningful information of the interrogation. The forth pulse is intended for transponders operating in SSR S Mode.

S Mode interrogation (fig. 2.b) includes a preamble consisting of two pulses designed to block ATC and RBS transponders since they consider this sequence as a signal emitted by a side lobe of the antenna pattern. The next portion of the interrogation signal is an informative part containing 56 or 112 bits of data transmitted due to differential phase-shift modulation. The phase modulation of a high-frequency carrier provides data transmission rate of 4 Mbit/s which allows a 112-bit message to be transmitted for the time corresponding to blocking of conventional transponders [11].

S Mode reply (fig. 2.c) consists of four pulses (preamble) typical for all replies followed by a sequence of pulses containing 56 or 112 bits of information, time position of the pulse inside a bit carries information of the value of the binary symbol (data unit).

5. Materials and procedures of solving the problem and assumptions made. SSR technique description

According to guidance documents, all aircraft flying in the upper airspace (instrument flights) have to be equipped with airborne RBS or M Mode transponders. Special attention is paid to the full implementation of the SSR air-to-ground channel of the discrete-address (S) Mode and namely to generation of an interrogation signal meeting the requirements of the prescribed standard.

The SSR system is currently the main surveillance means for air traffic management due to the following advantages:

- high accuracy of position-fixing;
- availability of additional information of an aircraft (tail number, altitude etc);
- lower emissive power compared to primary radars;
- long detection range.

In this regard, this surveillance facility is considered as the main means in operation of traffic control and provision of air traffic management.

Construction of the system operation functional is closely related to the structure of used signals carrying information for successful system operation. Therefore, the SSR block diagram containing the ground and airborne segments is shown in figure 3.

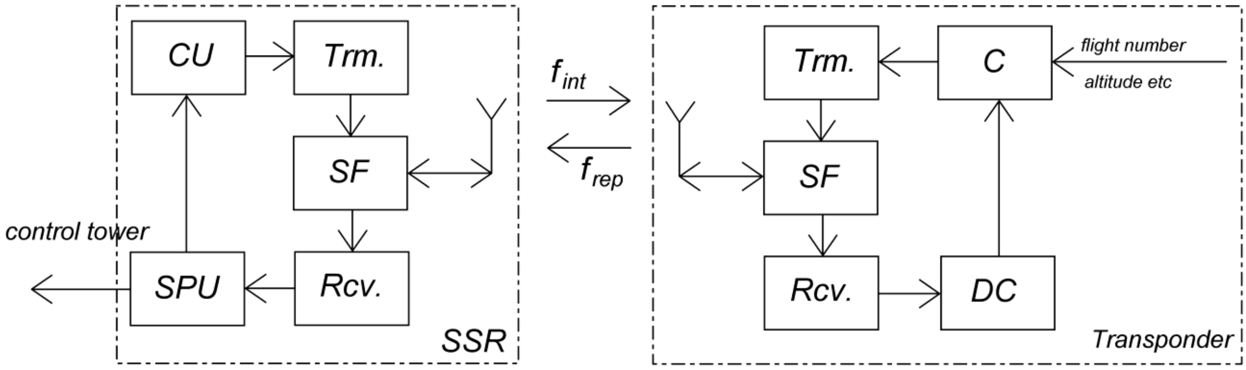


Figure 3. SSR block diagram: CU – control unit; Trm. – transmitters; SF – separation filters; Rcv. – receivers; SPU – signal processing unit; C – coder; DC – decoder

The SSR as the ground segment generates an interrogation signal at frequency f_{int} whose structure depends on the operation mode: the control unit (CU) determines the meaningful information embedded into the interrogation signal (interrogated parameter), the transmitter forms a signal as a sequence of radio pulses with specified parameters, and this signal, through the separation filter, enters the antenna system and is radiated in space.

Airborne transponders within the SSR coverage receive the interrogation signal at frequency f_{int} and the signal, through the separation filter, enters the receiver. The transponder receiver performs standard procedures of selection, frequency change, amplification and rectification of the interrogation signals as well as suppression of signals emitted by side lobes of the antenna pattern of the ground SSR. Then the decoder extracts the meaningful information of the interrogation (interrogated parameter: flight number, altitude etc) using the time interval between the signal pulses. Depending on the type of the interrogated parameter, the coder of the transponder generates a pulse sequence of the reply signal, the contents of the sequence being determined by the SSR mode (ATC, RBS or S). The transmitter of the transponder modulates the pulse sequence with a high-frequency component, amplifies it, sends it through the separation filter to the antenna and the sequence is emitted into space at frequency f_{rep}.

The antenna system of the ground SSR receives the reply signal from the aircraft, sends it through the separation filter to the receiver where, along with the standard procedures of selection, frequency change, amplification and rectification of the reply signals, suppression of signals emitted by side lobes of the antenna pattern is performed. The signal processing unit (SPU) carries out the tasks of aircraft position-fixing by measuring time delay between the interrogation and reply signals (the range is calculated) and fixation of the current angle of rotation of the antenna system at the moment of receiving the reply signal (azimuth). Besides, the SPU extracts the information of the value of the interrogated and, correspondingly, transmitted-by-aircraft parameter (flight number, altitude etc). The measured coordinates and the parameter value are transmitted to the control tower for creating an aircraft mark on the indicator of the ATM controller. The SPU also controls the ground SSR transmitter and determines the priority of generating different types of interrogation signals.

The ground segment is currently the most understandable and implemented in the existing facilities of radiotechnical communications and navigational equipment, however, the onboard part of the SSR system introducing the S Mode experiences some troubles related to the development of domestic analogues ensuring safe operation of the entire ATM system.

6. Results. Construction of the model of interrogation and reply signal formation

Estimating the efficiency of the data exchange channel implementing SSR S Mode by conducting real measurements on the operating surveillance equipment requires high expenditures. However, the capabilities of the promising S Mode can be assessed by using the modern software which allows creating adaptive models of SSR operation using the structure of the data exchange signals.

As a result of research the interrogation and reply signals of the SSR discrete-address mode were modelled in the LabVIEW software environment.

The LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) software is a development environment and a platform for performing the programs created on "G" graphical programming language by National Instruments (the USA). The environment allows different signals to be modeled for estimating their main features and parameters: amplitude, frequency, phase, pulse duration, spectrum width and signal base [12].

The model of an all-call interrogation signal is presented in figure 4. The time interval between pulses P1 and P2 ($T_{in.c.}$ – time of interrogation code) carries information about the type of the parameter interrogated by an aircraft, the value of 8 us corresponds to the interrogation of the aircraft number (Squawk). Pulse P2 serves for protection of the transponder from receiving antenna side-lobe interrogations, pulse P4 is intended especially for S-Mode transponders [13].

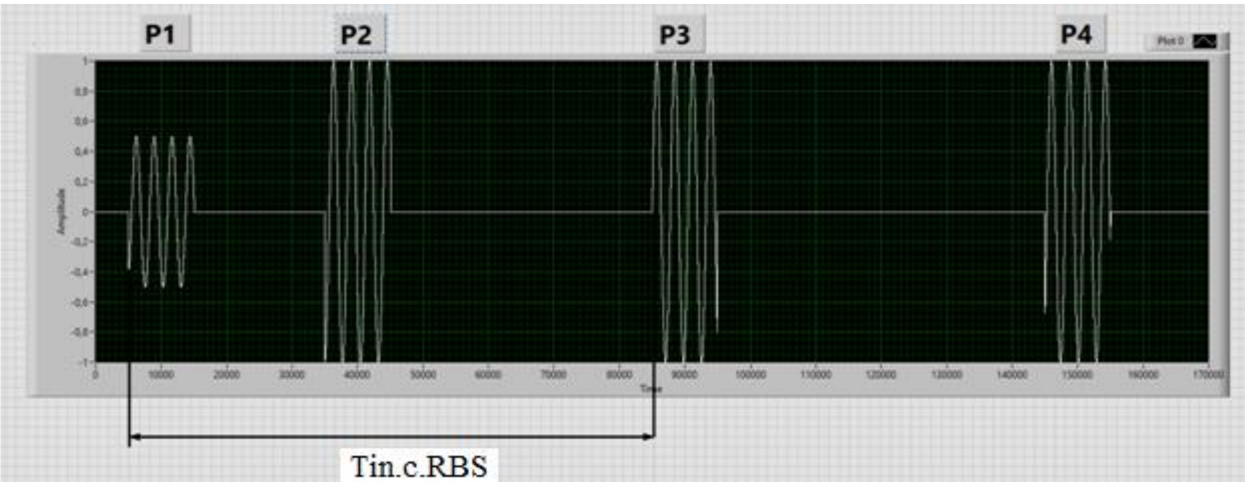


Figure 4. Form of an all-call interrogation signal

The model of an S Mode interrogation signal is presented in figure 5 without suppression (a) and with suppression (b). Pulses P1 and P2 emitted by the main lobe of the antenna pattern have identical amplitudes and, for ATC and RBS transponders, are marked as pulses emitted by a side lobe of the antenna pattern so that these transponders cannot receive them as desired interrogations. To prevent the address transponder from receiving antenna side-lobe interrogations, pulse P5 is used which is radiated by a suppression channel and aligned with the time interval of the first phase reversal corresponding to zero on the time scale of the code sequence. If the amplitude is sufficient, P5 pulse shades the synchro phase reversal in the address transponder resulting in the information not being coded (fig. 5.b).

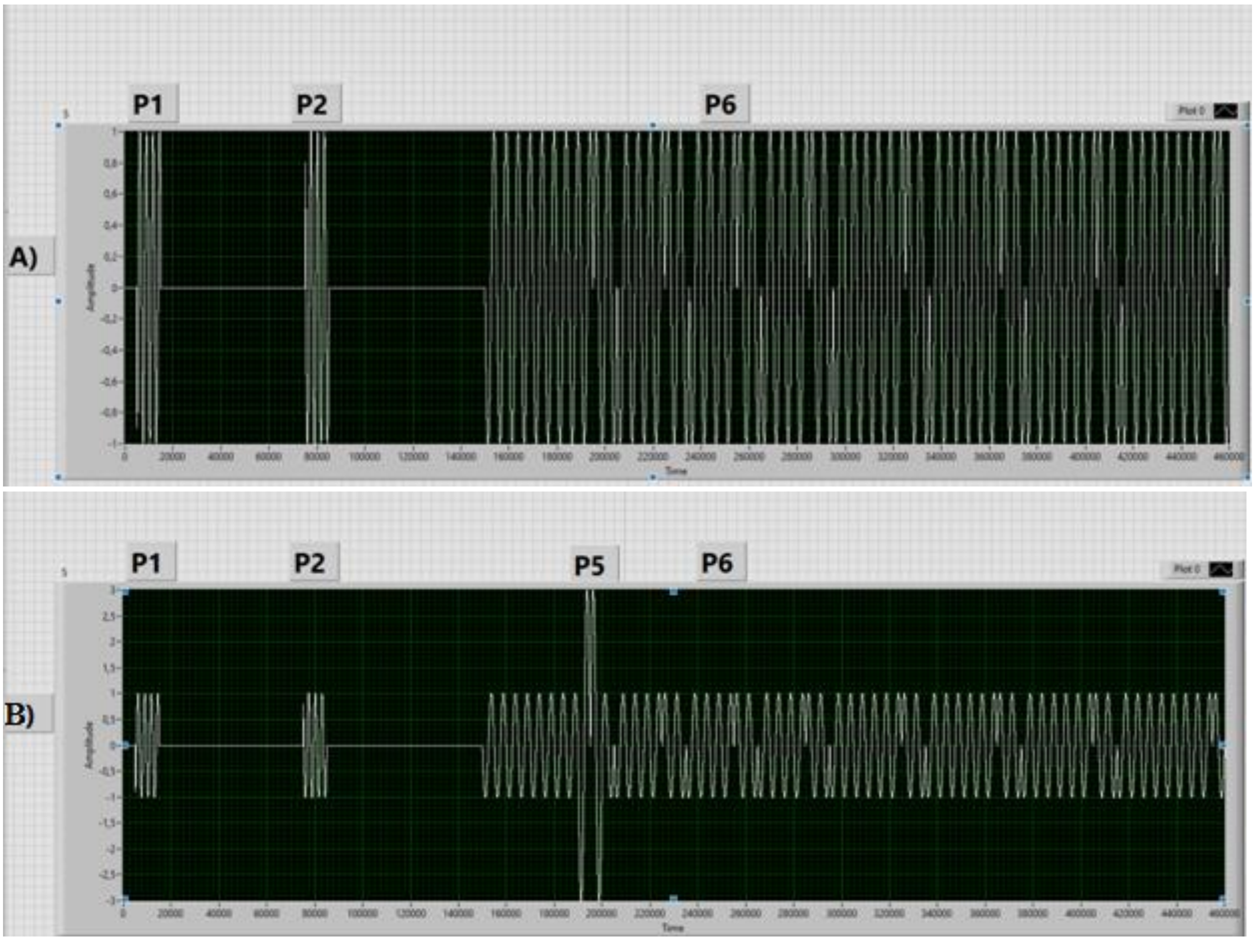


Figure 5. S Mode interrogation signal: a) without suppression; b) with suppression

P6 pulse carrying personal information for an aircraft equipped with the S Mode transponder is coded with the Differential Phase Shift Keying (DPSK), and only the signal phase is changed depending on the information element while the amplitude and frequency remain the same. Each information bit is associated with the phase variation relative to the previous value, not with the absolute phase value. The information part of the interrogation signal carried by P6 pulse is shown in figure 6 and includes:

- two long sendings (1.25 и 0.5 us) designed for phase adjustment of the local oscillator of the onboard transponder;
- 32 or 88 pulses for transmitting the interrogation code;
- 24 pulses of the interrogation address.

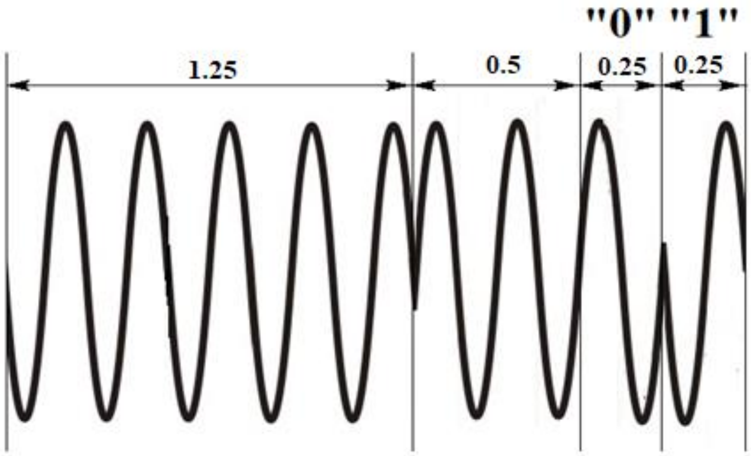


Figure 6. Structure of P6 pulse of S Mode interrogation signal

Formation of the noise constituent in the data transmission channel allows us to conduct the noise immunity research and to assess the quality of the transmitted information on the receiving end. The noise constituent is white Gaussian noise with a spectrum shown in figure 7.

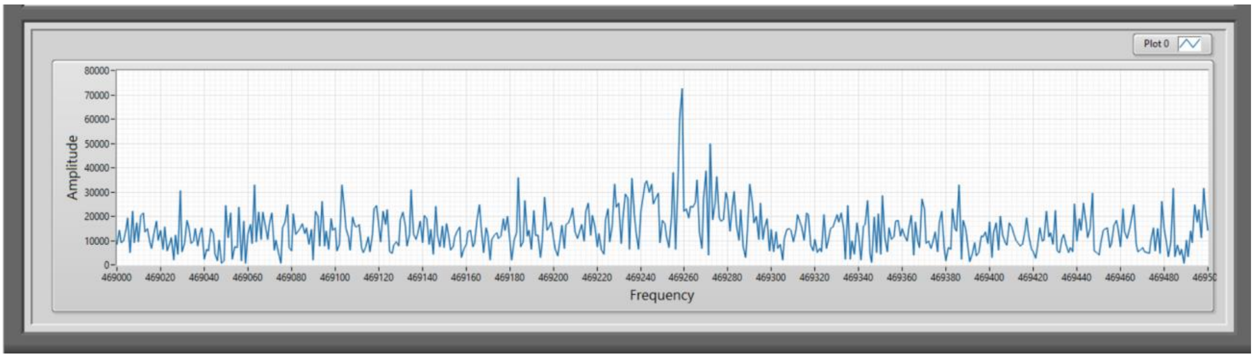


Figure 7. Spectrum of a WGN signal

The time diagram of the interrogation signal and the noise acting in the data transmission channel is shown in figure 8.

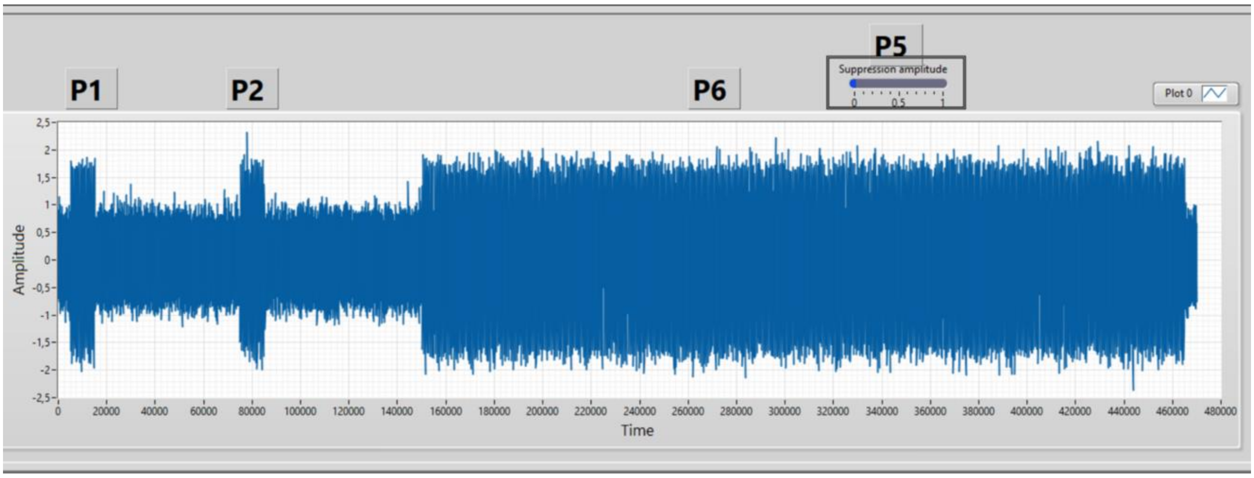


Figure 8. Mixture of an interrogation signal and WGN

The S Mode reply signal was formed according to the structure shown in figure 9 with the information pulse using the modulation where a two-time interval is allocated to each bit of the transmitted information; if the pulse is in the beginning of the interval, the binary unit (“1”) is transmitted and if it is at the end of the interval, the logic zero (“0”) is transmitted. This coding technique provides high noise immunity and significantly saves the energy potential of the transmitter as the number of pulses in a sending is constant regardless of the transmitted code combination. There are two types of the reply signals: a short message containing the aircraft number and a long message which additionally carries the value of the transmitted parameter.

Figure 9. Structure of a typical reply expanded message

Operation of the reply shaper presented in figure 10 is based on the principle of a consistent construction of the information word having independent parts.

The reply signal starts with an information preamble intended to identify the discrete-address mode and all the replies have an identical 8-bit preamble generated by the preamble shaper (PS). Then, on the basis of the reply structure, the format identifier shaper (FIS) creates a format identifier which carries the information of the message type (either a short 56-bit message or a long 112-bit one). The following 27 bits are created by the check symbol shaper (CSS) and contain the tracking and control information. Then the unit of the information part shaper (IPS) generates the information part consisting of 56 or 112 bits depending on FIS. The message ends with 24 bits created in the personal number shaper (PNS) containing information of the aircraft number (fig. 11).

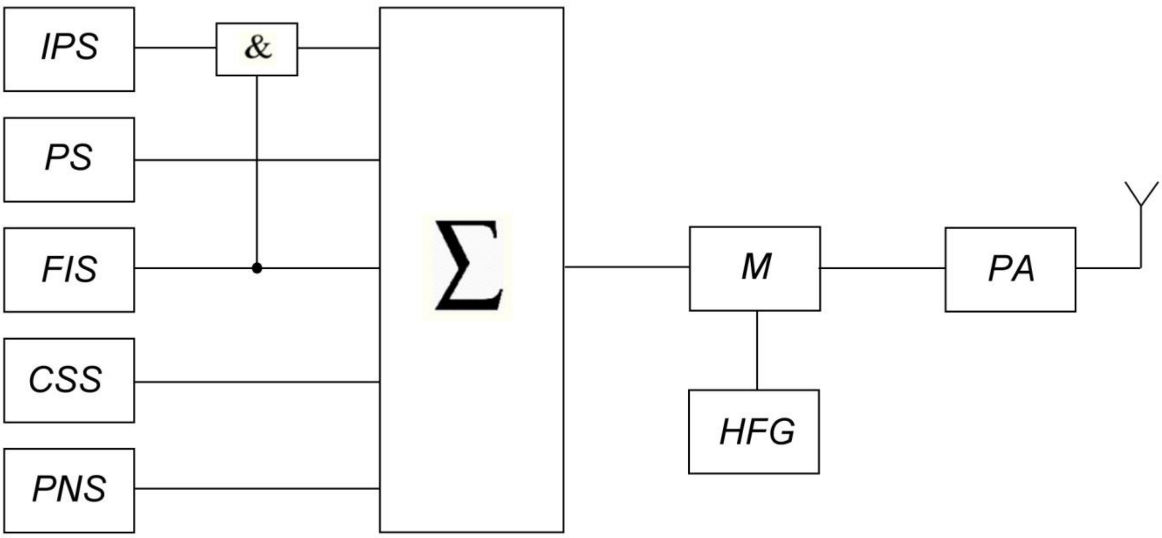


Figure 10. Reply shaper: IPS – information part shaper; PS – preamble shaper; FIS – format identifier shaper; CSS – check symbol shaper; PNS - personal number shaper; M – modulator; HFG – high frequency generator; PA – power amplifier

After adding all the components in the adder, the standard procedures of high-frequency modulation and amplification in the PA are performed for transmission to the antenna system and further translation to the ground segment of the surveillance means for performing the ATM tasks.

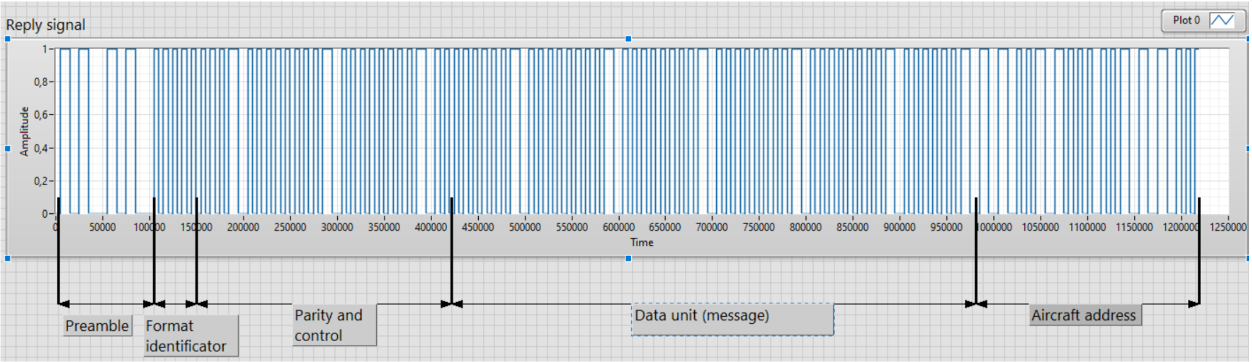


Figure 11. Generated S Mode reply message

7. Discussion

To study the efficiency of modern air traffic management concepts is possible through the use of the software meeting modern requirements of constructing the air systems. Modelling of the physical processes in the radio channel of data transmission using advanced technologies makes it easier to understand the construction and operation of surveillance systems and allows these processes to be visualized. Differential phase-shift modulation used in the interrogation signal provides high noise immunity and rate of ground-to-air transmission of information. Presence of the ICAO-assigned personal 24-bit aircraft identification number in the message significantly relieves the frequency range as each interrogation is addressed to only one aircraft. Formation of the pulse-modulated reply signal significantly increases the efficient use of the onboard equipment. Development of adequate models of constructing the data transmission channels between the ATM service and the aircraft crews allows estimating the efficient use of surveillance systems by creating different interference conditions. The proposed models can be implemented in the promising onboard and ground equipment introducing the CNS/ATM concept.

8. Conclusion

The air traffic management concept introducing the discrete-address mode (S |Mode) of the surveillance system based on the secondary radar and recommended by ICAO for implementation provides a significant improvement of flight safety, regularity and efficiency of air transportation. Adoption of the discrete-address mode in the secondary radar will provide implementation of common navigation methods in the world airspace.

REFERENCES

1. Глобальный аэронавигационный план на 2013-2028 гг. Международная организация гражданской авиации. Doc 9750-AN/963. 4-е изд., – 2013г. – 147 с.
2. Лежанкин Б.В. Системный анализ задачи определения местоположения воздушного судна в многопозиционной системе наблюдения / Б. В. Лежанкин, В. В. Ерохин, В. С. Марюхненко // Информационные технологии и математическое моделирование в управлении сложными системами. – 2019. – № 1(2). – С. 46-61. – EDN ZDOOGT.
3. Оценка наблюдения с использованием систем ADS-B и мультилатерации в целях обеспечения обслуживания воздушного движения и рекомендации по их внедрению. Международная организация гражданской авиации. Циркуляр ИКАО 326-AN/188, – 2013г. – 29 с.
4. Прохоров А.В. Анализ состояния и оценка возможности реализации средств многопозиционных систем наблюдения для аэродромных АС УВД / А. В. Прохоров, Г. В. Столяров, Д. С. Бондарь // Научный вестник Московского государственного

технического университета гражданской авиации. – 2013. – № 193. – С. 63-69. – EDN RAULGZ.

5. Бондарай А.А. Системный анализ процесса измерения угла места воздушной цели трассовым многочастотным радиолокационным комплексом / А. А. Бондарай, Б. В. Лежанкин // Актуальные проблемы и перспективы развития гражданской авиации : Сборник трудов VIII Всероссийской с международным участием научно-практической конференции, Иркутск, 14–16 октября 2019 года. – Иркутск: Иркутский филиал федерального государственного бюджетного образовательного учреждения высшего образования "Московский государственный технический университет гражданской авиации", 2019. – С. 104-114. – EDN ESJMYF.
6. Арефьев Р.О. Применение помехоустойчивого кодирования при обработке сообщений локальной корректирующей станции / Р. О. Арефьев, С. В. Туринцев, М. С. Туринцева // Актуальные проблемы и перспективы развития гражданской авиации: сборник трудов X Международной научно-практической конференции, Иркутск, 14–15 октября 2021 года. Том 2. – Иркутск: Иркутский филиал федерального государственного бюджетного образовательного учреждения высшего образования «Московский государственный технический университет гражданской авиации», 2021. – С. 22-32. – EDN YMDPPC.
7. Межетов М.А. Перспективы использования системы передачи данных LDACS для задач управления воздушным движением / М. А. Межетов, Е. С. Григорьева, П. Т. Никитич // Актуальные проблемы и перспективы развития гражданской авиации : Сборник трудов IX Международной научно-практической конференции, Иркутск, 15–22 октября 2020 года. – Иркутск: Иркутский филиал федерального государственного бюджетного образовательного учреждения высшего образования "Московский государственный технический университет гражданской авиации", 2020. – С. 176-182. – EDN GFCDDC.
8. Межетов М.А. Выделение сигналов тактовой синхронизации в системах передачи информации режима VDL-2 / М. А. Межетов, С. В. Туринцев // Crede Experto: транспорт, общество, образование, язык. – 2017. – № 2. – С. 191-200. – EDN YOXNJL.
9. Лежанкин Б.В. Демодуляция сигналов канала вторичной радиолокации в системе ADS-B / Б. В. Лежанкин, М. А. Межетов, С. В. Туринцев // Crede Experto: транспорт, общество, образование, язык. – 2018. – № 1. – С. 32-44. – EDN FWZOZC.
10. Лежанкин Б.В. Модель устройства формирования запросного сигнала вторичной радиолокации дискретно-адресного режима / Б. В. Лежанкин, В. П. Чурбаков // Актуальные проблемы и перспективы развития гражданской авиации : Сборник трудов XI Международной научно-практической конференции. посвященной празднованию 100-летия конструкторского бюро "Туполев", 55-летия Иркутского филиала МГТУ ГА, 75-летия Иркутского авиационного технического колледжа, Иркутск, 13–14 октября 2022 года. Том 2. – Иркутск: Иркутский филиал федерального государственного бюджетного образовательного учреждения высшего образования "Московский государственный технический университет гражданской авиации", 2022. – С. 56-64. – EDN MJFBLE.
11. Сосулин Ю. Г. Теоретические основы радиолокации и радионавигации: учеб. пособие для радиотехн. спец. вузов. М.: Радио и связь, 1992. 303 с.

12. Ерохин В.В. Автоматизированный программно-аппаратный комплекс в среде LabVIEW для исследования эффективности подавления ПЭМИН / В. В. Ерохин, Е. В. Зайнулин // Вестник научных конференций. 2021. No 5-2(69). С. 23-24. EDN SPKRAV.
13. Туринцев С.В. Программная реализация алгоритма кодирования и декодирования местоположения ВС в дискретно-адресном режиме вторичной радиолокации / С. В. Туринцев, М. С. Туринцева // Актуальные проблемы и перспективы развития гражданской авиации: Сборник трудов XI Международной научно-практической конференции посвященной празднованию 100-летия конструкторского бюро «Туполев», 55-летия Иркутского филиала МГТУ ГА, 75-летия Иркутского авиационного технического колледжа, Иркутск, 13–14 октября 2022 года. Том 2. Иркутск: Иркутский филиал федерального государственного бюджетного образовательного учреждения высшего образования «Московский государственный технический университет гражданской авиации», 2022. С. 115-121. EDN YGUUUY.