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Joint Stock Company "Russian Space Systems",
ul. Aviamotornaya 53, Moscow, 111250 Russia
Tel. +7 (495) 673-96-29
www.russianspacesystems.ru
e-mail: journal@spacecorp.ru

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Dear colleagues!

In 2017, we celebrate the 35th anniversary of the first rescue operation carried out by the international search and rescue system COSPAS-SARSAT. For us, this date is also significant by the fact that the signals about the disaster that happened to the crew of a small plane in Canada, were sent by a Russian low-orbiting spacecraft of the system COSPAS-1.

Since then, the COSPAS-SARSAT system has changed significantly, the spacecraft with the search and rescue system function in both low and geostationary orbits. In total, during the operation of the system since its launch, more than 41 000 people have been rescued.

Currently, the State Corporation ROSKOSMOS together with industry enterprises, representatives of the Ministry of Transport and the Ministry of Foreign Affairs of the Russian Federation, as well as with foreign partners, conducts an active policy for the development of the international COSPAS-SARSAT program.

In the near future, the Russian low-orbit constellation will be reinforced with the Meteor-M No. 2-1 and No. 2-2 spacecraft will carry the COSPAS-SARSAT search and rescue equipment on board. Within the framework of the current Federal Space Program, work is planned to create an advanced search and rescue equipment for the Meteor-M, Electro-L, Arktika-M, and Louch-5M satellites. In addition, a new complex of ground facilities is being developed, designed to replace the technology of the previous generation with simultaneous improvement of its main performance characteristics. Within the scope of the Federal Target Program "GLONASS", a payload is developed for the Russian segment of the future medium-orbit search and rescue system.

It is necessary to remember another significant event: In 2012, the crew of a Canadian helicopter was rescued for the first time using the COSPAS-SARSAT relay equipment installed on a GLONASS spacecraft.

In the history of the Russian participation in the international COSPAS-SARSAT program, there are many glorious moments and major achievements. This international program serves an extremely noble purpose: saving lives. In addition, the development of the national segment of COSPAS-SARSAT is also a matter of our country's own security. We need to constantly move forward and stay strong in the pursuit of our goals.

Director General of ROSKOSMOS State Corporation
I.A. Komarov

Dear colleagues!

You have before you a special issue of the "Rocket-Space Device Engineering and Information Systems" journal devoted to the 35th anniversary of the international system of search and rescue COSPAS-SARSAT, that is the most humane space system working for the mankind benefit. The journal includes the most important and interesting articles, which reflect the status of the COSPAS-SARSAT system and the ways of its further development.

The issues of the present status of the COSPAS-SARSAT system are discussed and the basic principles of the offered concept of the development of the Russian segment are analyzed in the paper of Romanov A.A., Kuzenkov A.N., Tyulin A.E. et al.

The article of Studenov V.V. notes that since the beginning of the implementation in 1982, the COSPAS-SARSAT system has provided the help at the rescue of at least 41 750 people in 11 788 incidents. Only in 2016, the emergency data of COSPAS-SARSAT were used in 885 incidents at the rescue of 2250 people.

The paper of Antonov D.V. is devoted to the issues of the estimation and optimization of a service area of the Medium Earth Orbit Local User Terminal (MEOLUT). The results of the mathematical simulation of the size of the service area depending on the planning algorithm and number of the antennas installed on the MEOLUT are presented.

The possibility of adding two channels of the geostationary segment already in existence to the ground station with four antennas of the MEO segment is analyzed in the paper of Antonov D.V., Arkhangelsky V.A. et al. The results of the mathematical simulation of the service area of the received station with six channels are given.

The article of Antonov D.V. presenting the experimental results of the determination of the locations of a slowly moving emergency radio beacon by means of the MEOLUT equipped with 4, 6 or 12 antennas finishes the review of the MEO segment of the COSPAS-SARSAT system.

The paper of Boyko S.N., Isaev A.V. et al. opens the subject heading "Radio Engineering and Space Communication". It offers a promising design of the antenna, which is built into the emergency radio beacons of the second generation of the COSPAS-SARSAT search and rescue system, which provides the required efficiency of radiation.

The article of Romanov A.A., Kondrashov A.S. et al. presents the evolving scheme of the realization of the unified onboard complex of the search and rescue system, which can be used on spacecraft of all segments of the COSPAS-SARSAT system.

The results of the application of continuous engineering methods when organizing the operations on the adaptation of a search and rescue complex onboard the spacecraft of the Meteor-M type are given in the article of Romanov A.A. and Romanov A.A.

The paper of Arkhangelsky V.A. and Seleznev V.V. is devoted to the analysis of the ways to increase the accuracy of the determination of the emergency radio beacons locations independent of the GNSS on the COSPAS-SARSAT ground stations. The method allowing one to achieve a significant increase in the accuracy of the determination of the locations of narrow band emergency radio beacons is described in detail in the article.

The article of Arkhangelsky V.A. et al. crowns the journal. The results of the flight tests of the Russian geostationary segments of the COSPAS-SARSAT system created on the basis of the Louch-5A and Louch-5V spacecraft and also the results of the international tests of the geostationary search and rescue satellite system based on Louch-5A are given in the paper.

Editor-in-Chief
"Rocket-Space Device Engineering
and Information Systems"
Romanov A.A.

Basic Principles of the Development Concept of the Russian Segment of the International Search and Rescue System COSPAS-SARSAT

A.A. Romanov, *Dr. Sci. (Engineering), professor, romanov_alal@risde.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.N. Kuzenkov, *Cand. Sci. (Engineering), kuzenkov_an@risde.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.E. Tyulin, *Cand. Sci. (Engineering), tulin_ae@risde.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.D. Kuropyatnikov, *Cand. Sci. (Engineering), kuropyatnikov@marsat.ru*
Federal State Unitary Enterprise "Morsviazsputnik", Moscow Russian Federation
K.V. Borisov, *borisov.kv@roscosmos.ru*
State Corporation "Roscosmos", Moscow, Russian Federation
O.V. Kem, *kem.ov@roscosmos.ru*
State Corporation "Roscosmos", Moscow, Russian Federation

Abstract. The paper deals with basic principles of the suggested development concept of the Russian segment of the International Search and Rescue Satellite System COSPAS-SARSAT. The issues of the present status and principles of the future building of the system are discussed. An attempt to determine strategic development trends of the Russian segment in view of the documents of the strategic planning and the plans on the Programme development is made. The terms and main results of the realization of the suggested concept are given.

Keywords: COSPAS-SARSAT, search and rescue operations, Russian segment, development concept

Introduction

The paper presents the general provisions of the newly developed concept that defines the main directions of the organizational, technical and scientific policy for the fulfillment by the Russian Federation of the international obligations in accordance with the Agreement on the International COSPAS-SARSAT Program of 01.07.1988 (hereinafter the Agreement) [1].

The creation of the Russian segment of the COSPAS-SARSAT system is regulated by the Resolution of the Central Committee of the CPSU and the Council of Ministers of the USSR of 26.01.1977 No. 81-84 [2] and by the Resolution of the Council of Ministers of the USSR of 12.01.1978 No. 33-15 "On the creation of joint activities with the USA, Canada an experimental satellite system for determining the location of aircraft in distress"[3].

The conceptual development provisions were developed taking into account the efforts of the International Maritime Organization (IMO) to establish the Global Maritime Distress and Safety System based on the International Convention for the Safety of Life at Sea (SOLAS) signed in London November 1, 1974 [4], the International Convention on Search and Rescue, signed in Hamburg on April 27, 1979 [6], as well as the obligations of the International Civil Aviation Organization (ICAO) and the International Telecommunication Union (ITU) in the respective fields of activity.

Due to the systemic crisis that occurred in the Russian Federation at the end of the 20th century, many aspects of the creation and development of the COSPAS-SARSAT system were relegated to the background. The main system documents were not updated, while the system inevitably developed and moved forward. Therefore, there is a need to revise the basic system documents that regulate the creation of the elements of the system. The paper makes an attempt to examine the problem of creating and developing the system as widely as possible, taking into account the current state of the search and rescue system.

When considering the urgent issues of the development of the search and rescue system, it is necessary to take into account the provisions of the main system documents of strategic planning, the COSPAS-SARSAT Strategic Plan [7], and the 406 MHz Medium Earth Orbit Search and Rescue system (MEOSAR) [8].

Therefore, in this work, the concept of the Russian segment of the international search and rescue system COSPAS-SARSAT is defined, its current status is determined and the main problems and ways of development of the Russian segment and the COSPAS-SARSAT system as a whole are discussed.

The status of the COSPAS-SARSAT system

The COSPAS-SARSAT system is an international search and rescue system, the creation of which was defined by the Agreement [1] signed in Hamburg on April 27, 1979 between four countries: the USSR, the USA, France and Canada, taking into account the requirements of the International Convention on Search and Rescue.

The search and rescue system is designed to reduce, as much as possible, the delay in the delivery of emergency information to search and rescue services, as well as the time required to detect the emergency, since these parameters directly affect the probability of survival of the people in distress. Rapid detection and determination of the coordinates of the emergency also contributes to the reduction of the cost of search and rescue operations and risks for rescuers [7].

The international system is designed to ensure the transmission of emergency reports on a global, non-discriminatory and gratuitous basis. It operates in the frequency bands allocated by the International Telecommunication Union (ITU) solely for warning of emergencies, that is, situations that are a serious and imminent threat to the safety of human life.

The international COSPAS-SARSAT system in accordance with [1] consists of three segments: space, ground and radio beacons intended for the transmission of emergency radio signals at frequencies of 406 MHz, the characteristics of which comply with the requirements of the International Telecommunication Union and the COSPAS-SARSAT specifications.

The space segment, under normal operating conditions, should consist of at least four satellites. The ground segment includes local user terminals (LUTs) for receiving signals transmitted from the satellites and processing them for the purpose of locating the beacon, and mission control centers (MCCs) to obtain the output data from the reception stations and send the message about an emergency and its location to the appropriate rescue services (Figure 1).

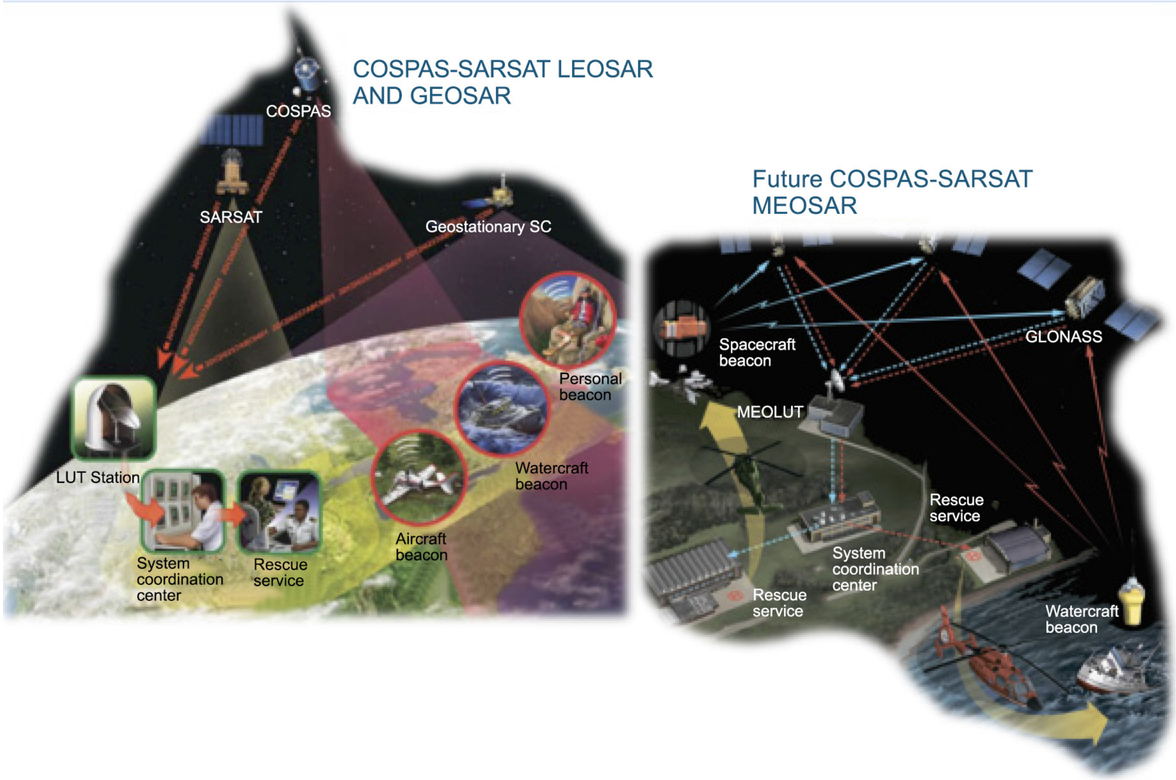

Fig. 1. Mode of operation of the international search and rescue system

In accordance with the Agreement, the USSR and later the Russian Federation are obliged to support two satellite platforms in the low Earth orbit, two receiver-processor units with memory units for working with beacon signals at a frequency of 406 MHz and two relays. In addition, the Russian Federation operates a MEOLUT for low-Earth orbit satellites, as well as the COSPAS mission center (CMC) of the system transmitting information to search and rescue services. In the future, we will apply the general term "Russian segment" of the international COSPAS-SARSAT system to the space and ground facilities of the international search and rescue system operated by the Russian Federation.

The overall operation of the COSPAS-SARSAT system is based on the fundamental requirement of the possibility of determining the coordinates of the ES independently from any other navigation system anywhere in the world [7, 9].

Due to ballistic restrictions, a significant disadvantage of the currently operational low-orbit segment of COSPAS-SARSAT (the constellation of the low-orbit spacecraft and their associated local user terminals are collectively called the LEOSAR) is the need to wait for a communication session with the satellite to transmit information about the emergency situation and, therefore, the impossibility of alerting the emergency services in close to real-time mode.

In 1998, the Council of the International COSPAS-SARSAT Program decided to expand the capabilities of the COSPAS-SARSAT system by placing repeaters on geostationary satellites [8] in order to detect beacon signals at a frequency of 406 MHz (hereinafter, GEOSAR system). The service areas of geostationary satellites are fixed relative to the Earth's surface, thus each satellite provides a continuous coverage of the geographic area defined by its service area. This makes it possible to reduce the detection delays that are characteristic of the LEOSAR system. Given the altitude of each satellite, the GSODS ensures coverage of a very large area (about one-third of the Earth's surface, excluding regions above ± 70° latitude).

However, it should be noted that the GEOSAR system provides location information only if this information is provided from an external source (i.e., a receiver of the global navigation satellite system (GNSS) installed in a beacon) and transmitted in message from the beacon at a frequency of 406 MHz; the obstacles, if they block the radio beacon to SC communication line, cannot be

1978, January 12 – decree of the USSR Council of Ministers on the creation of a space search and rescue system "COSPAS"

1982, June 30 – first launch of the COSPAS-1 satellite

1987, September 10 – first rescue mission by a COSPASS signal

1987, December 8 – decree of the CPSU Central Committee on the system's operational commissioning

1988, July 1 – an international agreement on the International SAR system COSPAS-SARSAT
Article 3: General description of the system

"…space segment consisting of a minimum of four simultaneously operating satellite complexes…"
Article 5: Obligations of the parties:
Contributions of the parties into the space segment:
"…USSR: 2 satellite busses, 2 receiver-processor units, 2 relays…"
"…USA: 2 satellite busses…"
"…France: 2 receiver-processor units with memory units…"
"…Canada: 2 relays…"

Fig. 2. History of the COSPAS-SARSAT system

eliminated, since the satellite is stationary with respect to the radio beacon; moreover, the energy potential of the radio beacon-SC-LUT communication link of the GEOSAR is significantly lower than that of the LEOSAR, taking into account the longer radio transmission distance.

To overcome these limitations, in 2000, Russia, the United States and the European Commission (EC) began consulting with the COSPAS-SARSAT executive bodies on the possibility of installing a relay for beacon signals on the medium-orbit satellite systems (hereinafter referred to as MEOSAR) and the inclusion of the MEOSAR equipment in the COSPAS-SARSAT system [8]. The program of the Russian Federation was named SAR/GLONASS, in the US the MEOSAR program is called the Distress Alerting Satellite System SAR/GPS (DASS) and the European system is called Galileo Search and Rescue System (SAR/GALILEO).

During the initial studies, various possible benefits of the MEOSAR compared to the existing systems (LEOSAR and GEOSAR) were identified, including: an almost instantaneous global coverage with the possibility of accurate independent location determination; stable radio beacon to SC communication lines, high levels of redundancy and satellite availability; resistance to the presence of obstacles on the communication line to the radio beacon due to the movement of the spacecraft in orbit, as well as large number of spacecraft in the future; possibility of providing additional services.

Thus, the main shortcomings of the LEOSAR can be eliminated, and the operational characteristics of the COSPAS-SARSAT system can be substantially improved in the long term, provided that the additional capabilities offered by the geostationary and mid-orbit segments of the system are introduced.

Basic design concepts of the COSPAS-SARSAT system

The search and rescue system has a very rich history [10-15]. Since 1982, 41,750 lives have been saved in 11,750 rescue operations. COSPAS-SARSAT is a very unique phenomenon, since the solution of this problem (building one of the most humane systems in the history of mankind) today unites the efforts of several countries, often separated by political and ideological contradictions. That is why the development and change of the principles of the functioning of the system must be approached with due regard for the interests of all participants in the basic

Agreement. Here are some basic concepts for the future design of the system.

The COSPAS-SARSAT system should be a single set of spacecraft, land facilities and emergency beacons that are modified and improved in strict accordance with the COSPAS-SARSAT requirements under the mandatory and ongoing monitoring of the Search and Rescue Council [3, 11, 12].

The space segment of the COSPAS-SARSAT system, consisting of low-orbit, mid-orbit and geostationary elements, should be designed on a complementarity principles. In the medium term, taking into account the full deployment of COSPAS-SARSAT, the composition of the space segment of the system can be revised.

The ground segment should include ground stations capable of efficient operation and receiving information from spacecraft of a associated space segment. The system coordination center should ensure that emergency data received from the receiving station associated with any element of the COSPAS-SARSAT space segment reaches the search and rescue service or the point of contact for search and rescue [14].

Emergency radio beacons should be designed taking into account the growing needs of users of the search and rescue system, and in strict accordance with the future requirements of the COSPAS-SARSAT system.

The COSPAS-SARSAT system and the relevant national segments should develop and provide an adequate data capacity, taking into account the growth of the park of operating emergency beacons [7].

The creation of the COSPAS-SARSAT system, which effectively fulfills the assigned tasks, is possible only if all the countries-participants of the Agreement fulfill their obligations.

The Russian contribution to the international system should include both the space and ground segments, as well as the radio beacons of different purposes. The Russian segment of the COSPAS-SARSAT system, like the system as a whole, should be designed guided by the principles of integration of spacecraft, ground facilities, and emergency beacons, taking into account the most efficient use of the resources and capabilities of the system.

The Russian segment of the COSPAS-SARSAT system should be a single set of ground and space based facilities that are developed and created by the Russian Federation to ensure compliance with the international obligations of the COSPAS-SARSAT program in accordance with the Agreement and other normative documents of the international system.

The future development of the COSPAS-SARSAT system should provide all users and consumers with guaranteed, global, timely and free access to information about emergencies. The COSPAS-SARSAT system should dynamically improve its operational characteristics, enabling it to improve the effectiveness of search-and-rescue operations.

Although the COSPAS-SARSAT system does not intend to compete with commercial systems providing telecommunications services and positioning services, the system must continuously improve the quality of alerting and positioning services to ensure the long-term search and rescue requirements for ICAO, IMO, and other users and consumers.

In addition, the system should take into account the long-term development trends of the newly created telecommunications systems.

Strategic directions for the development of COSPAS-SARSAT

Taking into account the strategic plan for the development of the COSPAS-SARSAT system [7] and the projected needs of the main users of the system, it is necessary to determine the strategic directions of the prospective activity. Efforts must be made to address the issues in various areas of the system's development.

Technological modernization of space and ground elements of the Russian segment of the COSPAS-SARSAT system

Fulfillment of international obligations by the Russian Federation to maintain and replenish if necessary the LEOSAR (two spacecraft with search and rescue equipment on board) of the COSPAS-SARSAT system in the short and medium term is a critical task that should be solved in the nearest term. In 2017, two spacecraft "Meteor-M" No. 2-1 and No. 2-2 with search and rescue equipment on board are expected to be launched.

In view of the development of space elements, it is necessary to ensure the modernization, creation and deployment of the corresponding ground facilities.

For the successful operation of the Russian segment of the LEOSAR, it is necessary to modernize the LEOLUT stations to work with the on-board equipment of the new generation.

In addition, it is necessary to deploy the last generation of the GEOLUT stations, developed in the Russian Federation within the framework of the Federal Space Program for 2006-2015.

Currently, COSPAS-SARSAT is making great efforts to implement the LEOSAR system as soon as possible, the deployment of which involves significant expansion of capabilities compared to the existing segments due to the use of a large number of GLONASS/GPS/GALILEO navigation devices as relays of emergency beacon signals.

One of the priorities of the current development of the Russian segment and the search and rescue system as a whole is the development and deployment of payloads and ground stations of the medium-orbit segment COSPAS-SARSAT of a new generation that meets all the requirements of the COSPAS-SARSAT system, including the accuracy of determining the coordinates for any type of emergency beacons.

It should be noted that in the current programs (FTP "GLONASS") until 2025, it is planned to create a minimum of eight search and rescue payloads for placement on board of medium-orbit spacecraft.

In accordance with the plans for the development of the Russian space segment of COSPAS-SARSAT, in general, it is necessary to ensure the development and creation of the maximally unified onboard equipment for retransmission of emergency signals to be installed on board of a new generation of COSPAS-SARSAT low-orbit, mid-orbit and geostationary spacecraft.

One of the fundamentally new features of the medium-orbit system is the acknowledgment function, that is, providing a return channel with a radio beacon, which allows to confirm the receipt of a distress signal and the beginning of a rescue operation. To ensure the operation of this function, it is necessary to develop and deploy an appropriate ground infrastructure in the Russian Federation which allows sending "receipts" on board spacecraft and then transfer them to consumers.

The emergence of additional functions and subsystems within the Russian segment leads to the necessity of modernization of the Russian mission control center of the COSPAS-SARSAT system, which manages the acknowledgment subsystem and integrates the information from the receiving stations of the new generation of low-orbit, mid-range and geostationary segments.

Improvement of the regulatory and legal framework of COSPAS-SARSAT

The regulatory framework of COSPAS-SARSAT

At present, there is a serious need to revise the regulatory and legal framework of the COSPAS-SARSAT system, not only at the level of the Council of the system, but also at the state level in the Russian Federation.

In the Russian Federation, the relays of the COSPAS-SARSAT system are being prepared for launch in the medium term on the spacecraft of the Arktika-M system in the highly elliptical Earth orbit.

The international COSPAS-SARSAT system does not regulate the use of spacecraft in highly elliptical orbits, there are no corresponding regulations and standards for the use of information, there is no ground infrastructure.

To fully use the developed equipment, it is necessary to prepare and issue the relevant documentation of the COSPAS-SARSAT system at the level of the Search and Rescue Council.

To accelerate the introduction of this equipment into the COSPAS-SARSAT system, it is proposed to consider the possibility of commission of the spacecraft on highly elliptical orbits as an expansion of spacecraft capabilities on geostationary (and geosynchronous) orbits, complementing the geostationary segment of the system. This step will significantly shorten the timing of the implementation of the relevant procedures for commissioning relays and increase their quantity.

Normative documentation of the state level of the Russian Federation

The resolution of the Central Committee of the CPSU and the Council of Ministers of the USSR on the establishment of the Russian segment of COSPAS-SARSAT was adopted in 1978 (Decree of the Central Committee of the CPSU and the Council of Ministers of the USSR of 26.01.1977 No. 81-84 and USSR Council of Ministers Decree of 12.01.1978 No. 33-15, "On the creation of an experimental satellite-based system to determine the location of aircraft that have suffered an accident in cooperation with the United States and Canada"). It does not take into account the current realities of the development of the organizational structure of the space industry in the country and the COSPAS-SARSAT system.

It is necessary to draft and issue a resolution of the Government of the Russian Federation regulating the modernization and maintenance of existing (low-orbit and geostationary) and the creation of new elements (mid-orbit) of the Russian segment of COSPAS-SARSAT.

According to the requirements of the COSPAS-SARSAT system documents [8], it is necessary to determine the provider organization (supplier) of the elements of the space segment in the Russian Federation at the state level. The main tasks of the organization-provider (supplier) of the space segment is the organization of the uninterrupted operation of all elements of the COSPAS-SARSAT space segment under the responsibility of the Russian Federation; and ensuring the continuous provision of ephemeris information from spacecraft to the COSPAS-SARSAT ground segment.

Taking into account the changes in the organizational structure of the industry management, in order to increase the efficiency and ensure the unconditional fulfillment of the international obligations of the Russian Federation in the field of search and rescue, it is necessary to regulate and establish the institute of the General Designer of the Russian segment of the COSPAS-SARSAT system.

In 2000, the COSPAS-SARSAT Council decided to use personal radio beacons as part of the system. Currently, 12 countries have already adopted relevant laws allowing citizens to use the equipment in case of emergency.

In the Russian Federation in 2016, the first steps were taken to introduce COSPAS-SARSAT personal beacons. It was decided by the State Committee of Radio Frequencies that their application is possible taking into account the current frequency distributions.

Nevertheless, in the short term it is necessary to issue a complete package of regulations defining the use of personal radio beacons in the Russian Federation, as well as establishing contact points for the transfer of information and the procedure for carrying out search and rescue activities using signals from such devices.

The emergence of this regulatory framework will make it possible to ensure a significant development of the search and rescue system for personal use, including for possible use in road transport as a part of the emergency response system ERA-GLONASS.

Development of the critical technologies

In the interests of sustainable development of the Russian segment of the search and rescue system, as well as in the interests of ensuring the technological independence of the Russian Federation in the development of such systems, it is necessary to ensure the development of the following technologies in different segments.

In the interests of the space segment, it is necessary to ensure the development of a technology for creating COSPAS-SARSAT unified on-board equipment for all the segments, including a new generation of on-board receiver-processor units that provide reception and processing of the beacon signal with a higher accuracy. In addition, technologies for creating on-board relays of COSPAS-SARSAT beacon signals with a return channel are required.

For the ground segment, it is necessary to ensure the creation of technology for processing information and calculating the location of emergencies with an increased accuracy, the technology of the handshake system, the technology for creating antenna arrays for LUT stations, the technology of creating virtual antenna systems for receiving information (the technology of using distributed antenna systems within a single terrestrial information processing infrastructure), as well as radio-photonics technologies as elements of antenna systems of LUT stations.

For creating emergency beacons required are the technology of creating high-capacity batteries, technology for efficient encoding and transmission of information, short-range drive elements of prospective sea-based beacons.

Expected results of the implementation of the Concept

The implementation of the proposed concept for the development of the Russian segment of the COSPAS-SARSAT system will allow:

to fulfill the international obligations of the Russian Federation to maintain the space segment of the COSPAS-SARSAT system, eliminating the threat of significant deterioration of the system's capabilities due to a critical reduction in the number of the spacecraft in operation;

to modernize the COSPAS-SARSAT hardware and equipment, providing the possibility of creating new ground, sea and space based technologies;

to develop the procedure for the use of personal radio beacons in the territory of the Russian Federation, and, consequently, to increase the efficiency of the COSPAS-SARSAT system on the territory in the Russian Federation;

to increase the effectiveness of search and rescue operations, including by reducing the time required to determine the coordinates and improve the accuracy of locating the emergency;

to increase the degree of safety of sea navigation and air traffic in the territory of the Russian Federation, as well as the efficiency of public administration in emergency situations.

To assess the effectiveness of the implementation of the Concept, it is planned to create a system of indicators and benchmarks, which should include the requirements established by the state on the basis of requests from users (the corresponding rescue services) of the COSPAS-SARSAT system.

The main state indicators of the Russian space segment of the COSPAS-SARSAT system should be:

ensuring the national interests in the field of information support for conducting search and rescue operations;

the effectiveness of the COSPAS-SARSAT system;

the availability of the COSPAS-SARSAT system;

information support of measures to improve the safety of road, air and sea traffic;

general integration compatibility of equipment, elements and segments of the COSPAS-SARSAT system.

Indicators at the COSPAS-SARSAT system level should be developed taking into account the requirements of the internal standards and regulatory documents of the system, the standards and requirements of IMO, ICAO; they should reflect the quality of its segments, elements and / or subsystems, the degree of their consolidation, interoperability, technical infrastructure and compliance to the accepted standards.

Terms and stages of implementation of the concept

The main activities for the creation and development of the Russian segment of the COSPAS-SARSAT system are:

- In the short term (until 2018):

development, fabrication and launching of two spacecraft into low Earth orbit in order to ensure the unconditional fulfillment of the international obligations of the Russian Federation; in accordance with the Agreement; maintaining the operation of the geostationary segment; modernization of the Russian part of the COSPAS-SARSAT ground segment; testing and putting into operation a prospective MEOLUT station;

- in the medium term (until 2022):

the development of a new generation of maximally uniform payloads for the formation of the low-orbit, mid-orbit and geostationary elements of the COSPAS-SARSAT space segment; maintenance of the functioning of low-orbit and geostationary elements of the space segment; partial deployment of the mid-orbit space segment; development and deployment of a coordination center for a system supporting new elements of the COSPAS-SARSAT space segment, including the acknowledgment system;

- in the long term (until 2030):

the end of the life cycle of the low-orbit segment of the COSPAS-SARSAT system, the full deployment and commissioning of COSPAS-SARSAT MEOSAR. Creation and introduction into the system of LUT stations on the basis of a single or “virtual” antenna system. Full-scale introduction of the second-generation beacons, with a support for a return channel.

Conclusion

In conclusion, it should be noted that significant efforts are being made in the Russian Federation to develop the Russian segment of the international search and rescue system COSPAS-SARSAT.

Although the pace of deployment of elements of the Russian segment of the international COSPAS-SARSAT system has been somewhat reduced recently, new models of on-board and ground equipment were created within the framework of the Federal Space Program for 2006-2015, as well as in the framework of specialized programs of the Ministry of Transport of the Russian Federation . In addition, the formation of a promising scientific and technical base is stipulated by the current Federal target programs.

The development of information and production technologies in the Russian Federation provides an opportunity to substantially modernize and create the equipment of a new generation for terrestrial and space based COSPAS-SARSAT systems.

To ensure the sustainable development of the Russian segment of the COSPAS-SARSAT system and the search and rescue system as a whole, it is necessary to ensure the unconditional deployment and commissioning of the MEOSAR, since this direction is declared strategic in the

In turn, the deployment and maintenance of the MEOSAR will require the development and implementation of a number of critical technologies that will allow the production of ground-based and space-segment equipment, as well as components of emergency beacons meeting the international performance requirements.

In the long term, it is necessary to consider the possibility of joint development of COSPAS-SARSAT with the space segments of automatic identification systems (AIS) and dependent surveillance (ADS) of ships and aircraft, taking into account the rapid development of space systems extending the traditional capabilities of mobile object monitoring systems.

Systemic development of the Russian segment of COSPAS-SARSAT is possible only on condition that it provides continuous financing for the development and creation of its advanced elements and is currently envisaged in the framework of the Federal Space Program for 2016-2025, the GLONASS FTP, as well as in the specialized programs of the Ministry of Transport of the Russian Federation.

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Status of the COSPAS-SARSAT Programme and Its Future Development

V.V. Studenov, *Cand. Sci. (Engineering), vstudenov@cospas-sarsat.int*
Cospas-Sarsat Secretariat, Montreal, Canada

Abstract. The first COSPAS-1 satellite launch 35 years ago opened a new era of rescue of people in distress when timely and exact determination of coordinates of maritime, aviation or any other accident became possible by means of spacecraft.

The project of a satellite system for search and rescue COSPAS-SARSAT was started in 1979 by four countries: the USSR, Canada, France, and the USA. At the beginning of the twenty first century, this project continues to remain a unique model of the international cooperation of 43 states and organizations, which provide means of satellite communication free of charge for the end user in distress in every spot on the globe.

Today, the Medium Earth Orbit Search and Rescue (MEOSAR) satellite system for distress alerting and positioning is beginning to operate and will eventually serve as a replacement of the existing LEOSAR system. As a reminder, 1998 was marked (after several years of testing) to strengthen the LEOSAR system with the introduction of the GEOSAR geostationary satellite system. The realization of the MEOSAR system will guarantee that the COSPAS-SARSAT Programme will continue its successful activities in the near future, providing improvements to the operational parameters of the System, including the accuracy of determination of the coordinates of an emergency beacon.

The status and major avenues of the Programme development are considered in this paper.

Keywords: COSPAS-SARSAT System, LEOSAR, GEOSAR, MEOSAR, MCC, LUT, beacon

Introduction

The beginning of implementation of the International satellite system of search and rescue COSPAS-SARSAT was a necessary start of the first Soviet COSPAS-1 satellite in 1982. For the last 35 years, by means of the COSPAS-SARSAT System more than 44 000 people have been saved, more than 1600 people out of this number are from the countries of the former USSR and Russia. This outstanding achievement has gained a big recognition among the world community of users of the aviation and maritime transport and also individual users on the land [1].

As one of the leaders of the COSPAS-SARSAT system and one of the Parties of the Agreement on the COSPAS-SARSAT International Programme, Russia assumed responsibility and obligations of the former USSR for an involvement in the Programme, including obligations for launch and maintenance of the satellites, installation of the stations for reception and processing of information, and also creation and maintenance of the center of the COSPAS System providing processing and routing of abnormal data.

The participants of the COSPAS-SARSAT Programme express huge gratitude to Joint Stock Company "Russian Space Systems" (the former scientific research institute of space device engineering) for the creation of the COSPAS System, its maintenance in an operational state, and improvement within the last 35 years.

The main concept and other fundamental information on the COSPAS-SARSAT system can be found in three working languages of the Programme (English, French, and Russian) [2].

1. The COSPAS-SARSAT mission

The COSPAS-SARSAT Programme renders assistance to search and rescue services around the world by timely giving precise and reliable data on disaster and its location to the world community on a non-discriminatory basis.

The purpose of the COSPAS-SARSAT System consists in decrease, as far as it is possible, delays in providing emergency messages to search and rescue services and time for a fixing of the disaster, and assistance that directly influences the probability of survival of the person at the sea and on the land.

To achieve this purpose, the Participants of COSPAS-SARSAT put into operation, maintain, coordinate, and operate a satellite system, which is capable to find emergency signals from the beacons that meet the specifications and standards. Moreover, the System can define the location of the beacons in every place on the globe. Disaster data and its location are transferred by the Participants of COSPAS-SARSAT to the relevant search and rescue services.

COSPAS-SARSAT cooperates with International Civil Aviation Organization (ICAO), International Maritime Organization (IMO), International Telecommunication Union (ITU), and other international organizations for the purpose of ensuring compliance of the COSPAS-SARSAT services in providing data on disaster with requirements, standards, and the corresponding recommendations of the world community.

2. The latest decisions of the COSPAS-SARSAT Council

One representative from each of four Parties of the International COSPAS-SARSAT Programme Agreement (ICSPA), namely Russia, Canada, France, and the USA is included in the COSPAS-SARSAT Council. The Council is convoked at least once a year to carry out the corresponding tasks and to coordinate the actions of the Parties, but to perform its functions it can be convoked as required and more often. The decisions of the Council are made unanimously by the Representatives of the Parties.

At private meetings of the Council, there are only the Parties and, first of all, questions of the activity of the Secretariat and management of the Programme, including the relations with potential participants, users of the System, manufacturers, and the international organizations are considered.

The Council is also convoked at least once a year at an open meeting during which the associated countries and the organizations (COSPAS-SARSAT Participants) can discuss any problem concerning administration of the Programme and System management, which are of interest to the COSPAS-SARSAT Participants. The general expenses of the Programme, maintenance of the System and its development, the report and the recommendations of the Integrated committee (the organ of the Programme helping with preparation of decisions of the Council), and the relation with the international organizations belong to these questions.

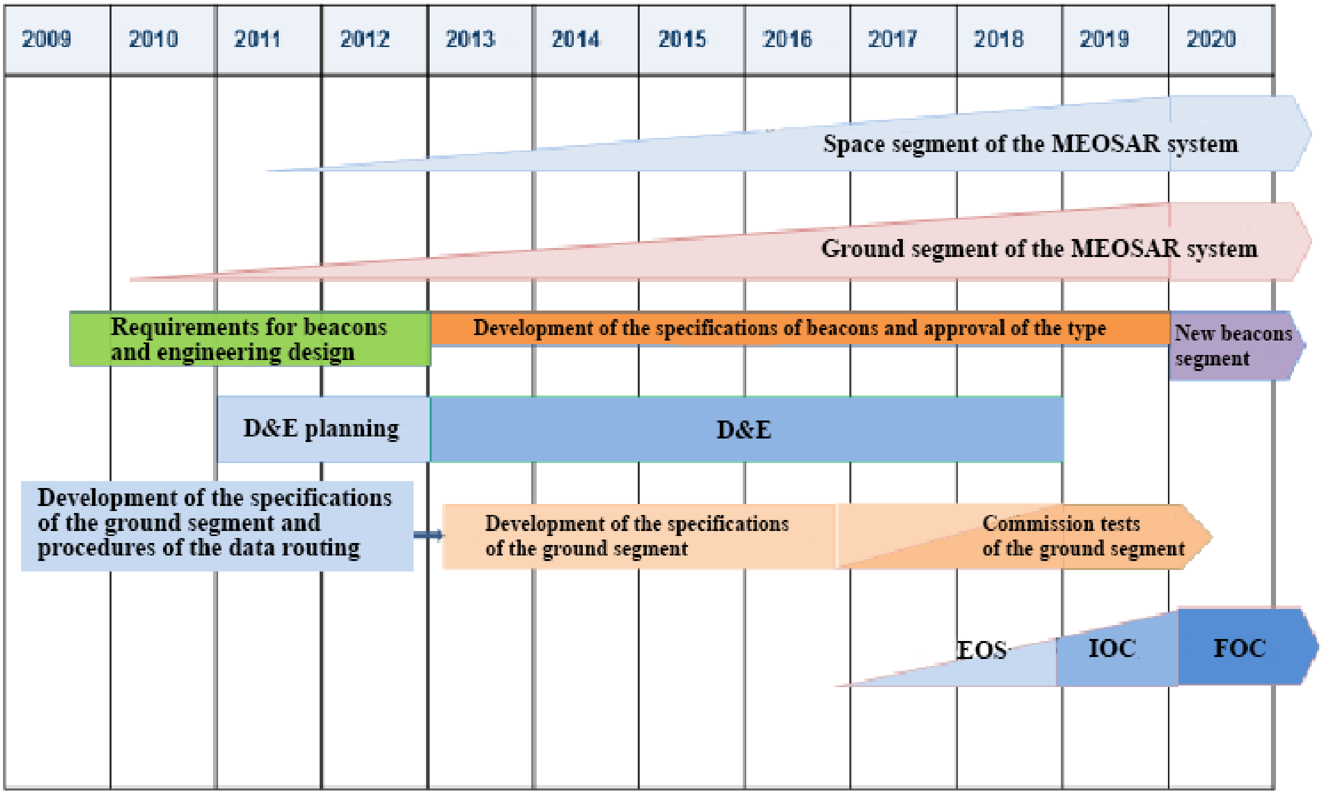

Fig. 1. Preliminary schedule of introduction of the MEOSAR system

At the closed and open meetings of the 57th session of the COSPAS-SARSAT Council (on December 1-8, 2016), key decisions concerned the beginning of routing of abnormal data of Medium Earth Orbit Search and Rescue satellite system (MEOSAR) at a stage of Early Operational Capability (EOC), and also advance on development of the specifications for second-generation beacons [3].

2.1. Medium Earth Orbit Search and Rescue satellite system (MEOSAR)

The MEOSAR system is created on the basis of the groups of the GLONASS navigation satellites (Russia), Galileo (European Union), and GPS (the USA).

The begun phase of the Early Operational Capability (EOR) already allows using operational data of the MEOSAR system. In the period of EOR, the MEOSAR system under development will allow one to improve the operational parameters of the System, including the accuracy of determination of coordinates of an emergency beacon in addition to the existing Low Earth Orbit Search and Rescue satellite system (LEOSAR) and the Geostationary Earth Orbit Search and Rescue satellite system (GEOSAR), and search and rescue services (SAR) should get acquainted with the MEOSAR system before the end of its Demonstration and Evaluation (D&E) Phase. By the present moment, commission tests within the MEOSAR system were passed through two Mission Control Centres (MCC) in France and the USA and also seven local user terminals (LUT) in Spain, Cyprus, Norway, the USA, Turkey, and France. Besides, now at the EOC phase, the MEOSAR system does not provide a global covering and not completely meet the expected requirements to its productivity, in particular concerning accuracy parameter.

The 57th session of the Council noted that all criteria, which allow one to begin the EOC phase of the MEOSAR system [4], were coordinated, and the beginning of this phase was announced. The letter notified all interested parties. The EOC phase began on December 13, 2016.

Each subsequent phase after EOC (that is Initial Operational Capability (IOC) and Full Operational Capability (FOC) provides improvement of operational parameters of the System.

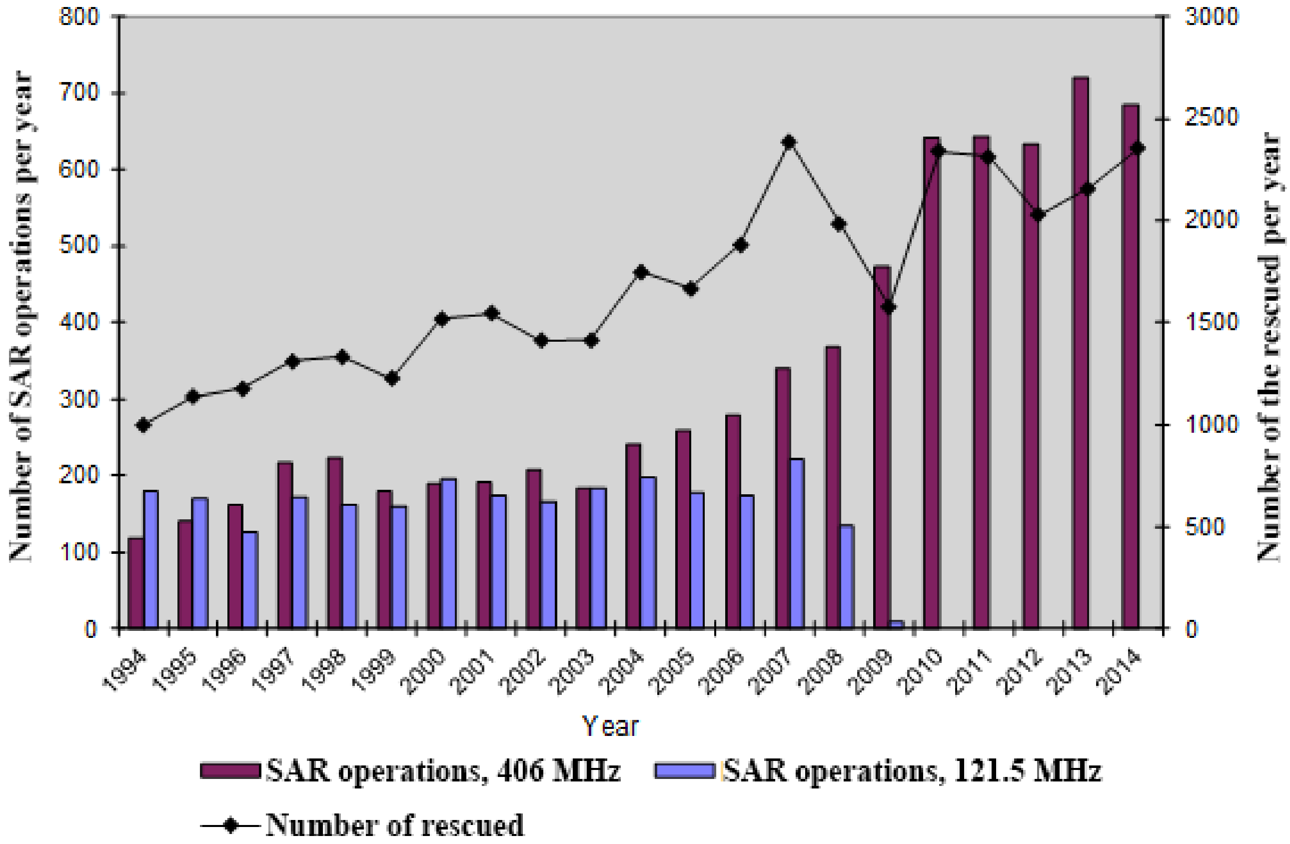

Fig. 2. Number of search and rescue operations and number of rescued people by means of the COSPAS-SARSAT emergency data (January 1994 – December 2015)

At the final stage of the IOC phase, all equipment of a ground segment of the MEOSAR system will conform to requirements for productivity without any restrictions.

At the FOC phase, the MEOSAR system will have already sufficient resources of a space segment and a possibility of providing a global service.

Transition to phases IOC and FOC is expected within the next several years. In Fig. 1, the preliminary schedule of introduction of the MEOSAR system is given.

As a result of a full introduction of the MEOSAR system, removal from operation of the existing LEOSAR system is supposed in course of years.

2.2. Second-generation beacons

Second-generation beacons will promote improvement of operational parameters of the System, meeting new more rigid requirements for probability of detection of a beacon, accuracy of determination of its location, and capacity of the System.

Second-generation beacons assume also realization of return link service (RLS) offered by some Global navigation satellite systems (GNSS), at which the notification is sent to an emergency beacon after it has been detected by the COSPAS-SARSAT System.

2.3. The COSPAS-SARSAT Secretary

The COSPAS-SARSAT Secretary is an administrative body of the COSPAS-SARSAT International Programme, which mission consists in assistance to the Council in realization of all its functions for management of the Programme, including holding meetings, administrative support, maintaining documentation of the System, and implementation of international relations.

The Staff of the Secretariat provides technical and operational support and examination for the participating countries/organizations and also users on such questions as the status of the System, the specification and performance data of the System, approval like emergency beacons, registration of beacons, work of the Space and Ground segments, and routing of emergency data.

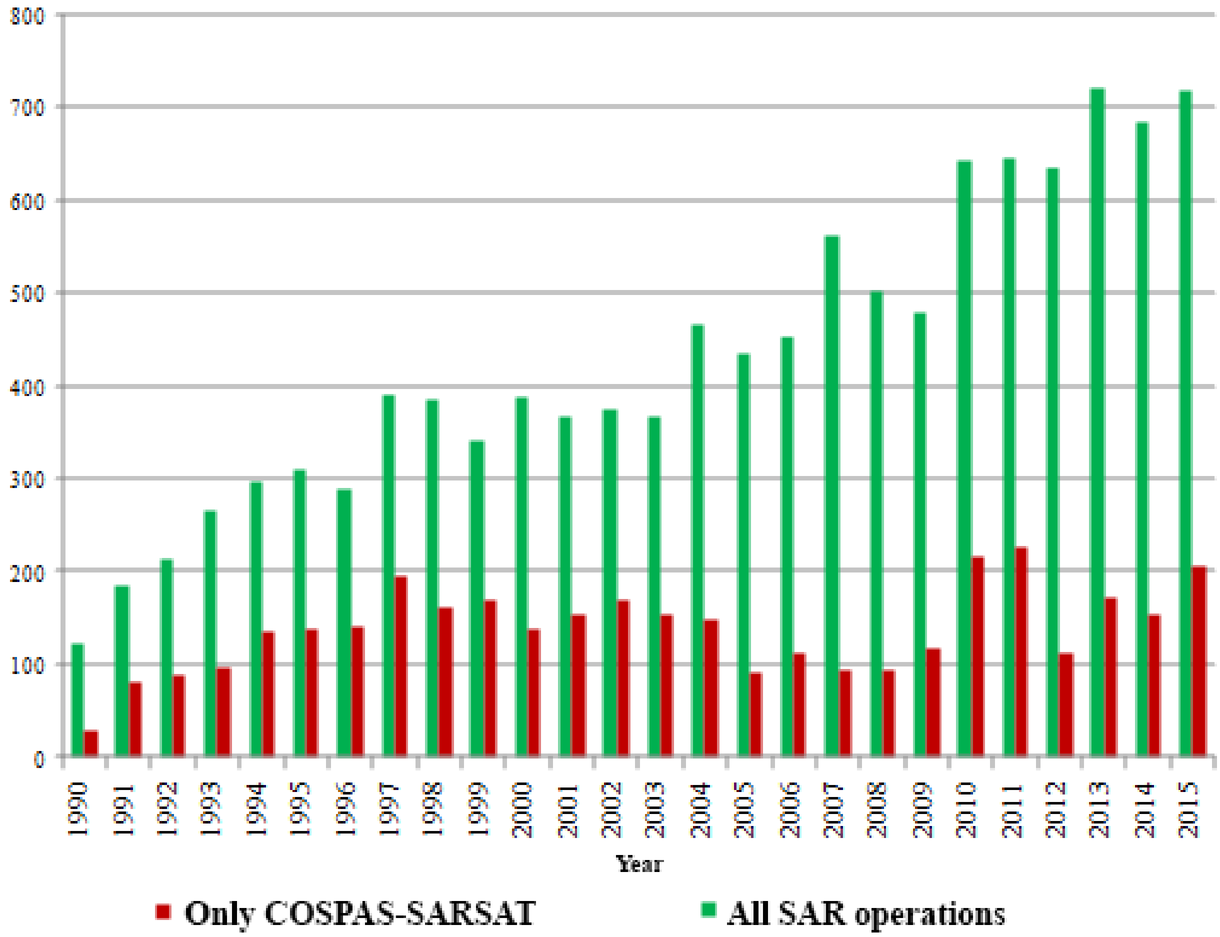

Fig. 3. Annual total number of SAR operations using the COSPAS-SARSAT emergency data and number of SAR operations when COSPAS-SARSAT was the only source of emergency information (1990-2015)

3. The COSPAS-SARSAT Participants

A total number of the Participants of the COSPAS-SARSAT Programme after accession of Malaysia in December 2016 has reached the number of 43 countries, among which 4 parties providing a space segment, 28 states providing a ground segment, 2 states-operators of a ground segment, and 9 states-users of the Programme [5].

4. The main operational statistics of the COSPAS-SARSAT System

In 2015 (processing of the statistics of 2016 has not been finished yet), the COSPAS-SARSAT emergency data were used in 718 incidents (in 2014 – 685), at the same time 2185 people were saved (in 2014 – 2354). Since September 1982 to December 2015, the COSPAS-SARSAT System provided help at rescue at least of 41 750 people in 11 788 incidents. Preliminary results show that in 2016, the COSPAS-SARSAT emergency data were used approximately in 885 incidents at rescue of 2 250 people.

Fig. 2 shows the number of search and rescue operations and number of saved people by means of the COSPAS-SARSAT emergency data from January 1994 until December 2015. [5].

As a component of the Quality Management System (QMS) [6] and for meeting the strategic plan of the COSPAS-SARSAT [7], a number of criteria of quality of work of the System has been developed. Fig. 3 depicts the annual total number of search and rescue operations (SAR) using the COSPAS-SARSAT emergency data, and a number of SAR operations when COSPAS-SARSAT was the only source of emergency information (1990-2015).

• The following classification is developed for COSPAS-SARSAT emergency data, which is defined by SAR services:

Table 1. Percent of the detected activated beacons that were registered (2011–2015)

Year	EPIRB		ELT		PLB	
	Number of registered beacons / Number of activated beacons	Percent (%)	Number of registered beacons/ Number of activated beacons	Percent (%)	Number of registered beacons / Number of activated beacons	Percent (%)
2011	4.879/6.264	77.9	6.631/10.102	65.6	699/909	76.9
2012	5.383/6.699	80.4	6.616/10.056	65.8	952/1.242	76.6
2013	5.362/7.126	75.2	6.997/10.867	63.4	1.135/1.611	70.4
2014	4.933/6.414	76.9	7.007/10.451	67.0	1.179/1.582	74.5
2015	5.672/7.412	76.5	7.606/11.276	67.4	1.363/1.907	71.5

- Only COSPAS-SARSAT (Only Alert – COSPAS-SARSAT was the only source of information on the disaster);
- COSPAS-SARSAT the first (First Alert – SAR services received and used the first signal from COSPAS-SARSAT about the disaster);
- Support of COSPAS-SARSAT (Supporting Data – COSPAS-SARSAT data were used along with other sources of information on the disaster);
- COSPAS-SARSAT is not used (Data Not Used in SAR – COSPAS-SARSAT provided emergency data, but for various reasons they were not used by SAR services).

5. 406 MHz beacons

The information obtained from 177 national administrations specifies that nearly 2 million beacons were in operation at the end of 2015.

According to the estimates of the COSPAS-SARSAT Secretariat, at the end of 2015, the number of beacons in the world with the protocol of location (LP) reached 54.2% of all available park of beacons.

Since 2009, COSPAS-SARSAT began to estimate annually the percent of the registered beacons from the number of the detected activated beacons. These data are provided in Table 1.

The general assessment of the level of registration of all available park of all types of beacons (not only the detected activated beacons) from 2011 to 2015 was as follows: 2011 – 77.8%, 2012 – 78.4%, 2013 – 78.4%, 2014 – 77.8%, 2015 – 75.9%.

It is well-known that in case of registration of a beacon in the National Beacon Database or in the Interantional Beacon Registration Database (IBRD), SAR services have an opportunity, in addition to the coordinates of the disaster, to obtain information on object of the disaster and its possible route of movement that significantly facilitates and accelerates acceptance of countermeasures on a distress signal.

The current provisions on beacons in various countries can be found in the document [7].

COSPAS-SARSAT supports IBRD [8], to which a free access for the users who do not have national databases is organized. Allowing users of beacons to register their beacons in IBRD, administrations help to simplify appropriate registration of beacons by their owners and prevent administrative expenses and inconveniences to their governments.

Administrations can also load the national registration data of beacons into IBRD for a guarantee of the round-the-clock availability to them for other SAR services in the presence of information on activation of beacons in a zone of their SAR responsibility.

In the beginning of 2017, 67 237 beacons from about 140 national administrations were registered in IBRD. On average per month, more than 325 times SAR services address in IBRD to obtain information on the registered beacons.

6. LEOSAR and GEOSAR systems

As of April 1, 2017, five spacecraft of the LEOSAR system had been in operation: SARSAT-7, SARSAT-10, SARSAT-11, SARSAT-12, and SARSAT-13. The planned launches of the LEOSAR spacecraft include: four Russian Meteor-M SAR COSPAS payloads onboard. The launches of Meteor-M No. 2-1, Meteor-M No. 2-2, Meteor-M No. 2-3, and Meteor-M No. 2-4 are planned in the 2nd quarter of 2017, the 4th quarter of 2017, and also in 2020 and 2021. The satellites of the Meteor-M No. 2 series are planed to operate in an orbit not less than for five years. According to the programme of the USA concerning the LEOSAR system, financing of the given LEOSAR satellite, which will be launched not earlier than 2021, is planned.

Moreover, as of April 1, 2017, there had been five devices of the GEOSAR system: GOES-13 and GOES-15 (the USA), INSAT-3D (India), MSG-2, and MSG-3 (EUMETSAT) in operation.

The Russian SAR payloads on the Electro-l No. 1, Electro-l No. 2, Louch-5A, and Louch-5B, have been undergoing the necessary tests.

The ground segment of the LEOSAR and GEOSAR systems includes 30 Mission Control Centres (MCC), 53 LEOLUTs in the LEOSAR system, and 21 Station of GEOLUT the GEOSAR.

7. Trends of perspective development of the COSPAS-SARSAT Programme

7.1. ICAO: GADSS (Global Aeronautical Distress and Safety System) and ELT(DT) emergency locator transmitter

In response to recent aviation incidents, ICAO has begun to realize Global Aeronautical Distress and Safety System (GADSS) to increase the efficiency of global search and rescue. It is supposed that routing of emergency data of the COSPAS-SARSAT from ELT(DT) (emergency locator transmitter), will be directly carried out in MRCC.

Additional requirements will be applied however: (“alarms” have to be delivered immediately in MRCCs, and “data on tracing of the disaster” have to be available to the parties concerned (air transport security units (ATSU), operators of airlines, investigating authorities, MRCC, etc.).

Appendices 11 and 12 to the Convention of ICAO, which describe delivery of “emergency messages” in the rescue coordination centers (RCC), have not been changed. However, the Appendix 6, which is agreed with GADSS, has undergone changes in that the operator of airline provided available data of autonomous disaster tracking (ADT) in, at least, ATSU, and MRCC.

The Appendix 6 also gives the chance to operators of airlines to allow the third parties, for example COSPAS-SARSAT or other suppliers, to perform this function according to the scheme.

For this reason, COSPAS-SARSAT considers the development of means for ATSU to get access to data on disaster tracking, at the same time continuing to send emergency data directly to MRCC.

The deadline of ICAO on readiness of ELT(DT) is January 1, 2021. From the point of view of COSPAS-SARSAT, the readiness of documentation on ELT(DT) is January 1, 2019.

It is considered preferable that COSPAS-SARSAT became the only storage of all data of ADT.

7.2. Global Maritime Distress and Safety System (GMDCC) (IMO)

The COSPAS-SARSAT system is a component of the GMDCC (IMO) system. Considering the inquiry of the 3rd session (2016) of a subcommittee of Navigation, Communications, and Search and Rescue Sub-Committee (ICAO-IMO) (NCSR) about a possibility of distribution of digital emergency data of the GMDCC system in addition to the routing in the existing COSPAS-SARSAT ground network from 406 MHz beacons, COSPAS-SARSAT carries out the analysis and assessment of this offer.

Conclusion

Development and introduction in practice of the essentially new method of search and in distress through the COSPAS-SARSAT Satellite System became the phenomenon of the end of the 20th century.

The former USSR, the USA, France, and Canada became initiators of creation of this international organization. Now the System unites 43 states, provides emergency information and location of disaster on a non-discriminatory basis and free of charge to any end user without any exception. There is only one condition: beacon (maritime, aviation, or personal) should be available for giving a distress signal. A beacon should be registered to know the owner. In total, in the world, there are already more than 2 million COSPAS-SARSAT beacons working at frequency of 406 MHz.

From the moment of the creation, more than 1 600 citizens (at first the USSR and then Russia) have been rescued when using the data of global system of search and rescue. By the present moment, the System has provided the emergency information and location of disaster for rescue of more than 44 000 people when carrying out more than 12 600 search and rescue operations.

Persistent improvement and advance of the COSPAS-SARSAT System begins with introduction of the MEOSAR system today. Parameters of compatibility of three constellations of System – LEOSAR, GEOSAR, and MEOSAR are coordinated. Upon completion of the FOC phase of the MEOSAR system, its space and ground segments will guarantee the implementation of the requirements of a global covering, productivity, and accuracy. In the same way, technical requirements for 406 MHz beacons of the second generation will allow one to provide further improvement of the COSPAS-SARSAT System.

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Estimation of the Medium Earth Orbit Local User Terminal Service Area

D.V. Antonov, *antonov_dv@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. This article for the first time presents an algorithm for satellite selection that iteratively optimizes the service area of the Medium Earth Orbit Local User Terminal (MEOLUT). The mathematical simulation performance results of the existing MEOLUTs with four and six antennas when they detect a fixed and slow moving beacon are presented. It is shown that the MEOLUT with four antennas cannot locate slow moving beacons with the required accuracy, while the MEOLUT with six antennas is capable of meeting requirements working with fixed and slow moving beacons. A mathematical simulation of the MEOLUT service area depending on the number of antennas at the MEOLUT and an algorithm for satellite selection are presented. These results are to determine the minimum number of antennas that allow one to reach the desirable service area. It is noticed that this number of antennas can be obtained either by installing antennas or by the process of the measurements exchange with the nearest MEOLUTs.

Keywords: COSPAS-SARSAT, MEOSAR, MEOLUT, service area, algorithm for satellite selection

Introduction

The most important characteristic of the Medium Earth Orbit Local User Terminal (MEOLUT) of COSPAS-SARSAT is a service area – an area of the Earth's surface in which a MEOLUT is capable to meet the requirements described in [1].

At the fixed precise measurements of times of a signal arrival of the emergency beacon (EPIRB) to relay satellites (TOA – Time Of Arrival) and its frequencies (FOA – Frequency Of Arrival), the size of a service area depends on the algorithm of the choice of relay satellites for pointing the MEOLUT antennas on them, a number of antennas on a MEOLUT, and an algorithm of determination of EPIRB coordinates.

In case of a normal distribution of TOA and FOA measurements, the algorithm of determination of coordinates described in [5] is optimum. Thus, the size of a service area can be increased due to increase in quantity of information and measuring complexes and optimization of a planning algorithm of the choice of relay satellites.

Since a considerable part of the MEOLUT cost makes a cost of information and measurement systems, thus, one of the questions of priority is a question on a minimum quantity of antennas necessary to achieve a desirable MEOLUT coverage area. Today in literature, there are no studies directed to the solution of the specified task. Moreover, there are no assessments of a service area for already in existence MEOLUTs with four and six antennas considering slow moving EPIRBs.

Thus, in terms of the present paper, the analysis of the size of the service area of already existing MEOLUTs will be carried out and also the size of the service area of a MEOLUT depending on the number of antennas and planning algorithm of pointing of MEOLUT antennas on relay satellites will be investigated.

Review of planning algorithms

In [2], the reference to two algorithms of the choice of satellites for pointing MEOLUT antennas on them is given.

The first of these algorithms is heuristic and suggests selecting relay satellites with the greatest elevation relative to the MEOLUT. The advantage of this method is its simplicity and less time for calculation. The lack of optimization when choosing relay satellites is a disadvantage.

The second algorithm offers a complete selection of all possible sets of relay satellites. For each set in the circle with the center in the place of the MEOLUT location and a radius of 2000 km, a geometric mean is calculated in the assumption that an EPIRB is motionless (a geometric mean calculation is given in [1]). For pointing of MEOLUT antennas, a set of relay satellites, which has the best geometric mean, is chosen. The advantages of this algorithm are the optimization when choosing a set of relay satellites. A potentially big labor input of a complete selection, the lack of a record of slowly mobile EPIRBs, and also the fact that in the course of the choice a combination of satellites the part of a responsibility area of a MEOLUT fulfills the set requirements is not checked. Fig. 1 gives an example when the best mean accuracy is not a correct criterion of the selection of relay satellites. In this example, the mean accuracy in the service area in the first case is 2.1 km, however not the whole area of responsibility meets the requirement for the accuracy of the independent solution. In the second case, the mean accuracy is 3 km, but at the same time the requirements for the accuracy of the independent solution are fulfilled in the whole area of responsibility. In addition, fixing of a radius of a circle for optimization (2000 km) is not considered rational, especially at a large number of antennas on a MEOLUT.

Taking into account the listed disadvantages, the author has developed a special algorithm allowing one to optimize a MEOLUT service area.

Planning algorithm allowing one to estimate a MEOLUT service area

A service area of the MEOLUT with an M-antenna is approximated by a circle with *R* radius. It is required to make the schedule of tracking of relay satellites with the MEOLUT antennas, providing the radius of the R_{max} service area as big as possible.

Such a circle of the largest radius can be found iteratively. On the *i*-th iteration, a circle with the R_i radius is considered. In this circle, a work of the equispaced EPIRBs is simulated.

Then a complete selection of all possible combinations of *M* out of N_j of the relay satellites being visible at the moment is made to each *j*-th analyzed time point. For each EPIRB under analysis in the circle with the R_i radius at each combination of *M* satellites being considered, a possibility

Fig. 1. Example of a wrong selection of satellite combinations according to the criterion of the best mean accuracy

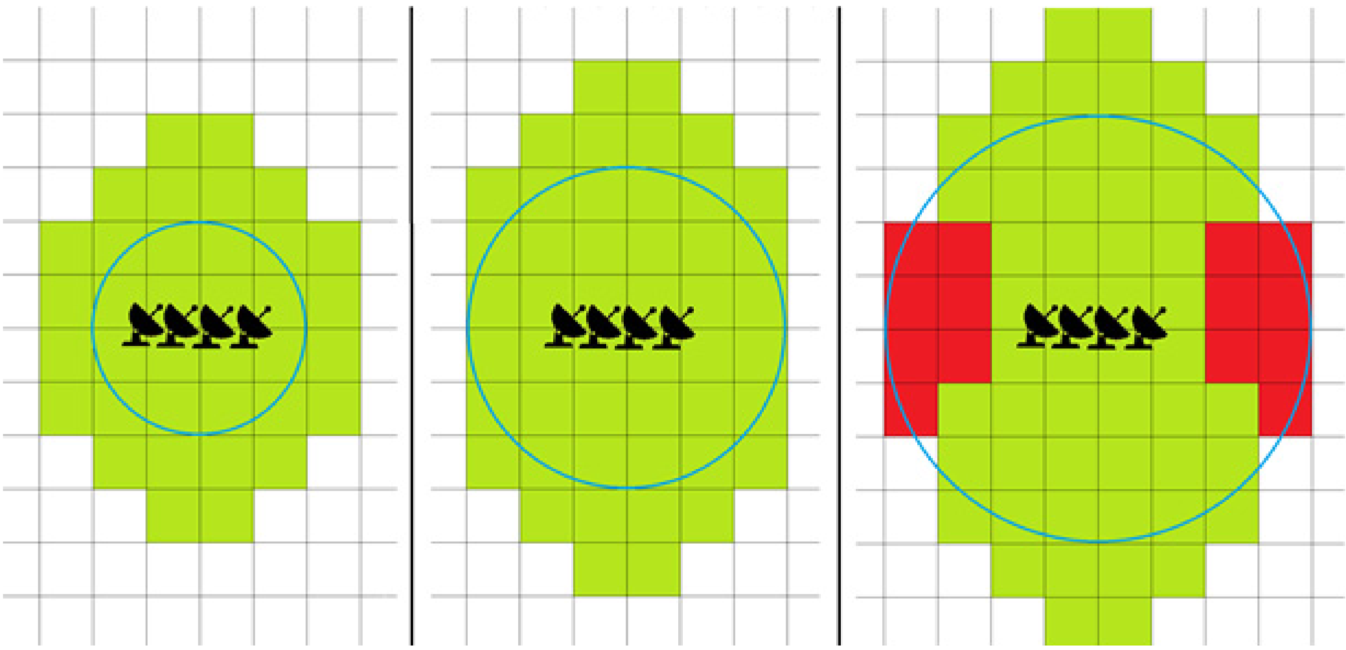

Fig. 2. Illustrations of the algorithm's operation on different iterations for the MEOLUT with four antennas

of determination of the coordinates of each EPIRB with an error not less than 5 km (formulae for calculation are given in [1]) is calculated and a constellation providing the largest number of conceptional EPIRBs in the circle with the radius R_i, which probability is not less than 0.95, is calculated.

If there are several constellations, for which all analyzed EPIRBs in the circle with the radius R_i meet this requirement, so any of these constellations is chosen. For example, it can be done by the criterion of the best mean accuracy (formulae of calculation of a theoretical accuracy are given in [4]) or the smallest number of

Table 1. Simulation parameters of the MEOLUT service area

Parameter	Criterion/value
Minimum MEOLUT angle of tracking of a satellite,°	5
Number of the radiated EPIRB messages	13
Time after receiving the first message, after which a solution is taken, min	10
Simulation duration, days	10
Time increment, min	15
Number of satellites to solve a navigation task	Not less than 3
σTOA	25 ms (the value taken from [1])
σFOA	0.2 Hz (the value taken from [1])
Dependence of the percent of the received messages on the elevation on the EPIRB – spacecraft line	70% for elevations 5-75° for S-band 70% for elevations 5-83° for L-band Only 9 first messages out of 13 (1-9) are considered received
Space segment	Suggested composition of the constellation for 2020 – 56 satellites

transfer of antennas from the satellite on the satellite. In such a way constellations are chosen for the whole time interval being analyzed.

Then for each imitated EPIRB and for each set of satellites on the *j*-th time point, probability of determination of the coordinates and the probability of determination of the coordinates with an accuracy not less than 5 km is calculated. Mean values of these probabilities for the whole considered interval of time will be P_1 and P_2 respectively. If for these probabilities the following conditions are satisfied

$$\begin{cases} P_1 \geq 0.98 \\ P_2 \geq 0.95 \times P_1, \end{cases} \quad (1)$$

so this point is included in the MEOLUT service area.

If the conditions (1) are met for all imitated beacons in the R_i circle, then the following iteration of the algorithm with the radius of a service area of $R_{i+1} = R_i + \Delta R$ is made. If for any EPIRB from a circle with the R_i radius the conditions (1) are not met, then R_{i-1} will be the circle with the largest R_{max} radius.

In the offered algorithm, the combination of satellites for each time point is chosen according to the criterion of the greatest one-time coverage area in the circle with R_i radius. However, other criteria can be considered. Further in article, the results of the operation of this algorithm, where the combination of satellites according to the criterion of the best geometric mean taking into account the presence of slowly moving beacons will be selected, will be considered.

Thus, as a result of fulfillment of this algorithm, the schedule of spacecraft for pointing on them the antennas and the evaluation of the service area will be obtained. Fig. 2 gives the example of the operation of an algorithm on different iterations of the selection of a service area to optimize the MEOLUT operation in this service area. A blue circle on each iteration is an area for optimization. A green color is the MEOLUT service area on each iteration, a red color is an area, which should join a service area, however the MEOSAR requirements are not fulfilled here. In this example on the left drawing, the area for optimization is too small, and on the right, this area is too big. Thus, the area shown in the middle drawing will be a service area.

Estimation of the service area of the present MEOLUTs

To check a possibility of a MEOLUT to implement the MEOSAR, to evaluate the accuracy of independent solution and size of a service area as well as to evaluate the influence of slowly moving EPIRBs (the velocity does not exceed 5 m/s; the peculiarities of the solution of a

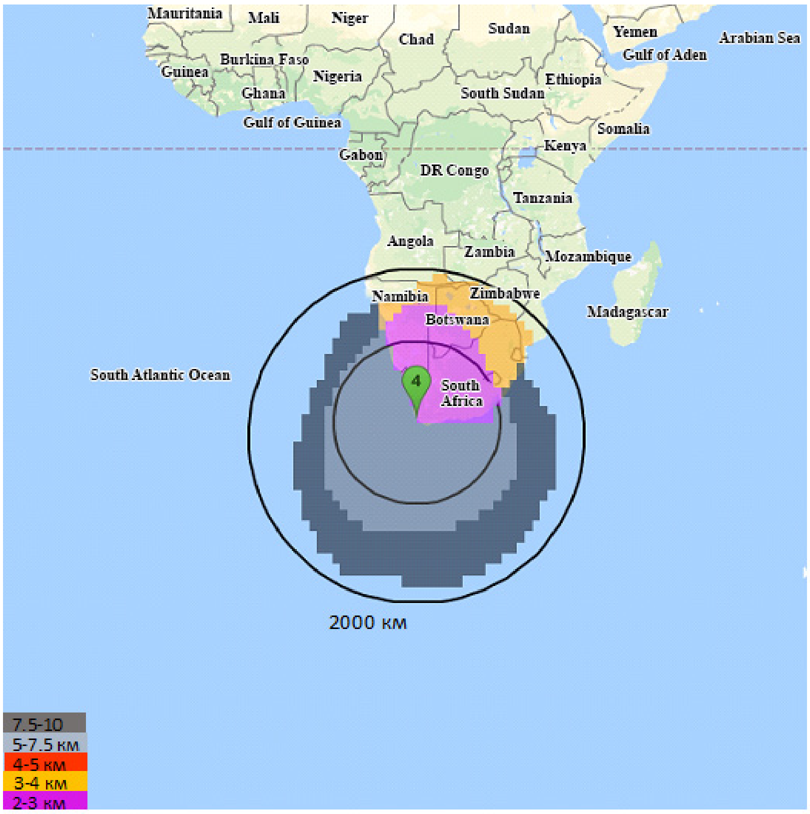

Fig. 3. Service area of the MEOLUT with four antennas in Cape Town (yellow and purple areas)

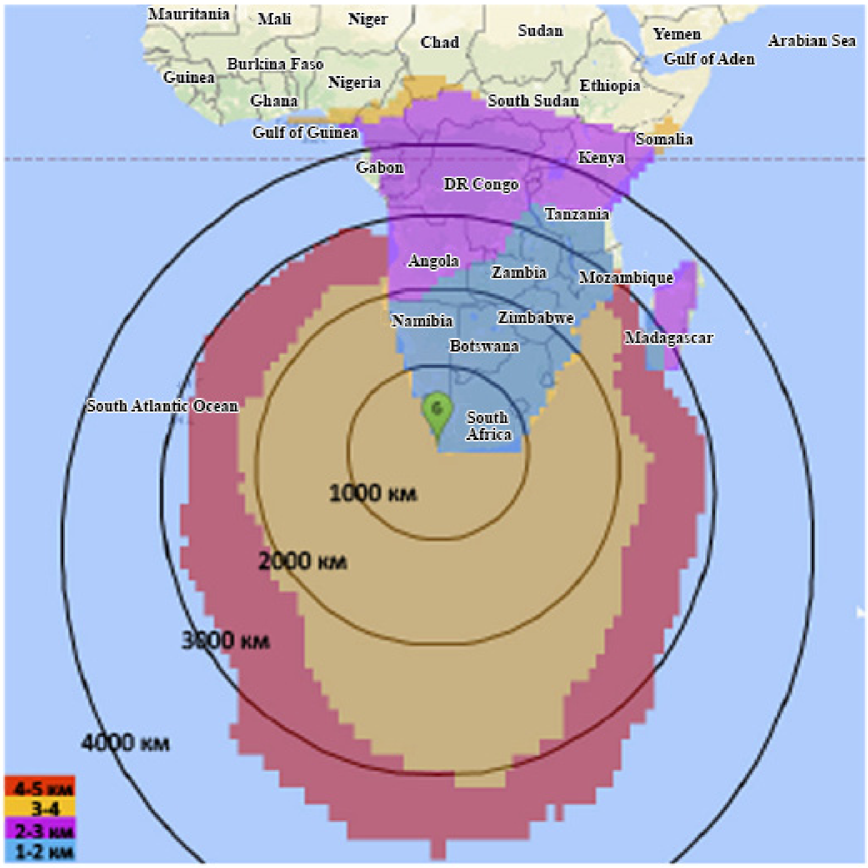

Fig. 4. Service area of the MEOLUT with six antennas in Cape Town

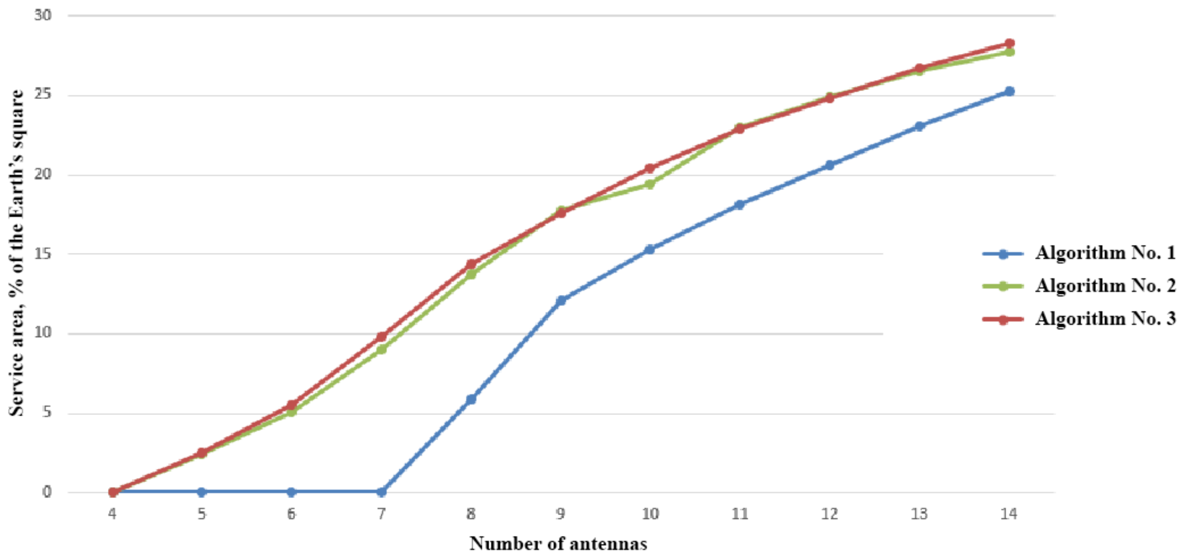

Fig. 5. Dependence of the size of the service area of the MEOLUT on the number of antennas with the assumption that all EPIRBs are movable

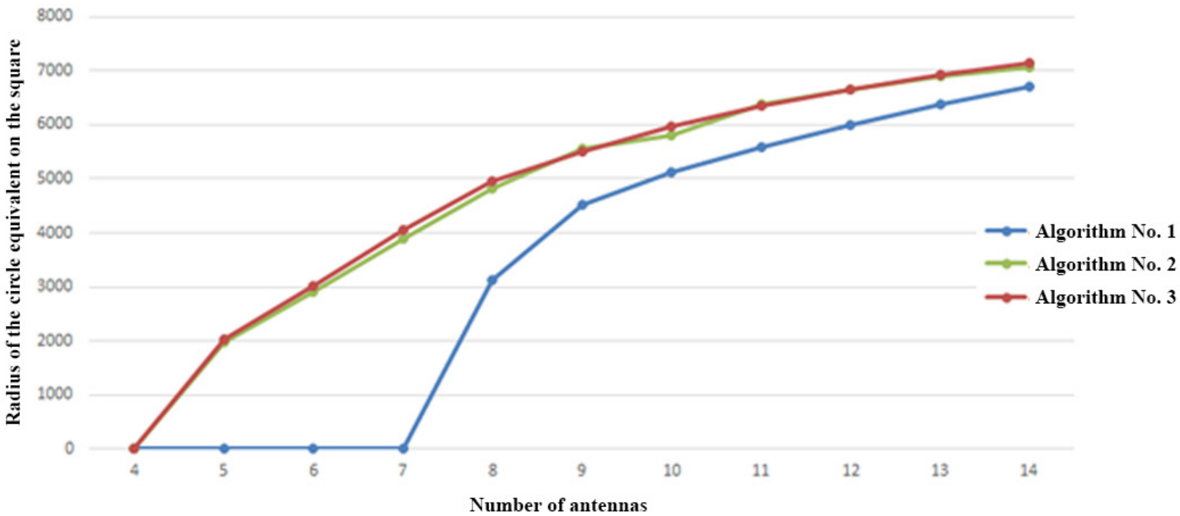

Fig. 6. Dependence of the radius of the circle equivalent as to the square of the service area of the MEOLUT on the number of antennas with the assumption that all EPIRBs are movable

navigation task in case of a slowly moving EPIRB can be found in [5]), a number of simulations was carried out. The general parameters for all simulations are presented in Table 1.

Since today all MEOLUT stations have four or six antennas, so the analysis of a service area of the MEOLUT of such configurations deserves attention first of all. Cape Town, the Republic of South Africa was chosen as the location for the MEOLUT under simulation. Such choice is caused by existence in close proximity both extensive water areas and land that makes it possible to compare the characteristics of the MEOLUT performance during the work on motionless and slowly moving EPIRBs. All EPIRBs being on the land were considered motionless; all EPIRBs being on water were considered slowly moving under the influence of rolling, wind, and currents.

During the work on moving EPIRBs (at the sea), it is required to determine five parameters by the measurements of the FOA differences – the longitude, latitude, and three components of velocity (an EPIRB can have both horizontal velocity due to current and wind and vertical component because of rolling). Therefore, MEOLUTs with four antennas during the work on slowly moving EPIRBs cannot use the FOA measurements.

For such EPIRBs, the location is calculated only according to the TOA measurements. While operating a motionless EPIRB (on the land) in the presence of the measurements from three and more spacecraft, the TOA and FOA measurements were used. Fig. 3 presents the results of simulating of the MEOLUT with four antennas.

The schedule was formed on the algorithm described in the previous section. The carried-out simulation has shown that the required accuracy of 5 km in 95% of cases was not reached at the sea in any area; the accuracy of 5.5–10 km has been reached in the area of 1500–2000 km. On the land, the accuracy was 2–4 km in the area about 2000 km.

Moreover, the simulation was carried out for the MEOLUT with six antennas. When determining the coordinates of EPIRBs, the TOA and FOA measurements of on both motionless and slowly moving beacons were used. The results of the simulation of the service area for the MEOLUT with six are given in Fig. 4. At the sea, the accuracy of 3–5 km was reached in the radius of 3000 km. On the land, the accuracy was 2–4 km, and the radius of the service area exceeded 4000 km.

Thus, the MEOLUT with six antennas unlike the MEOLUT with four antennas is capable to fulfill the MEOSAR requirements both during the work on a motionless EPIRB and during the work on a slowly moving EPIRB. When operating motionless EPIRBs, the radius of the service area of the MEOLUT with six antennas exceeds by more than 2 times the radius of the service area of the MEOLUT with four antennas (more than four times as to the square of the service area). It leads to an important conclusion about a low efficiency of the MEOLUT with four antennas and impossibility of their work with the required quality on maritime EPIRBs.

Simulation of the service area depending on the planning algorithm and the number of antennas on the MEOLUT

As it was mentioned above, the size of the MEOLUT service area can be increased due to optimization of the algorithm of the choice of satellites for pointing of the MEOLUT antennas on them and due to increase in number of antennas on the MEOLUT. To make an assessment of the size of the MEOLUT service area depending on these parameters, a mathematical simulation was carried out. At the same time the following algorithms of the choice of spacecraft for pointing of the MEOLUT antennas on them was used:

- An algorithm No. 1 is the algorithm with the choice of relay satellites with the biggest elevation relative to the MEOLUT.
- An algorithm No. 2 is the algorithm with a complete selection of sets of satellites and the choice of the set, which provides the best one-time mean accuracy in the service area. The service area is approximated by a circle of the largest radius of service; its radius is found iteratively.
- An algorithm No. 3 is the algorithm with a complete selection of sets of satellites and the choice of the set, which provides the largest one-time square in the service area. The service area is approximated by a circle with the largest radius of service; its radius is found iteratively.

Figs. 5–8 show the results of the carried-out simulation. Depending on the number of antennas for each algorithm, Fig. 5 depicts the service area (in % of the Earth's surface), and Fig. 6 illustrates the size of the radius of a circle equivalent on the square to the MEOLUT service area.

As it can be seen form Figs. 5 and 6, at the number of antennas less or equal seven, using the algorithm No. 1 leads to a zero service area. At eight antennas, the service area by more than 2 times is at disadvantage in relation to the service area obtained according to the algorithms No. 2 and 3. At further increase in the number of antennas, the difference in the results of operation of these algorithms decreases, but, nevertheless, the algorithms No. 2 and No. 3 always provide a big service area than the algorithm No. 1.The algorithm No. 3 gives advantage in the service area (up to 10% of the service area) relative to the algorithm No. 2 at the number of antennas less or equal ten, however at further increase in the number of antennas both algorithms provide a service area identical in the size.

Fig. 7 gives a diagram of the dependence of the mean accuracy in the service area depending on the number of antennas for each planning algorithm. It is seen that the algorithm No. 2 has a kind of better mean accuracy (up to 15% of the required accuracy) comparing to the algorithm No. 3.

Fig. 8 illustrates the dependence diagram of the effectiveness (the square per one antenna) of using the MEOLUT antennas for each algorithm depending on the number of antennas.

As it is seen from these drawings, existing MEOLUTs with six antennas are capable to fulfill the MEOSAR requirements both for mobile and for slowly moving

Table 2. Increase in the service area when adding antennas to the MEOLUT with six antennas

Number of antennas added to the MEOLUT with six antennas	Resulting number of antennas on the MEOLUT	Increase in service areas in % relative to the service square of the MEOLUT with six antennas
+1	7	+78%
+2	8	+162%
+3	9	+220%
+4	10	+271%
+5	11	+316%
+6	12	+351%
+7	13	+385%
+8	14	+415%

beacons (in the circle with the radius about 3000 km), however installation of six antennas on the MEOLUT is not effective. If the size of the service area of the MEOLUT with six antennas is taken as a unit of measure, then addition of only one antenna increases a service area by 78%, two antennas – by 162%, three antennas – by 220%. Other values are given in Table 2. At further increase in antennas, the efficiency of their use will decrease.

The number of antennas installed on a MEOLUT directly depends on a desirable service area. The diagrams given above are designed to estimate the necessary number of antennas and to give an assessment of the received service area. At the same time, the required number of antennas can be reached both due to installation of antennas on MEOLUTs and due to exchange of measurements with next MEOLUTs on condition of their coordinated work.

However, the desirable service area can differ from a circle, the accuracy of measurement of times and frequencies can also not coincide with the brought values in [1], geographical coordinates of a MEOLUT and a space segment will also differ. In practice, for each specific MEOLUT, knowing its parameters and a desirable service area, it is necessary to carry out separate simulations.

Conclusions

This paper presents the analysis of the size of the service area of the MEOLUT with various number of antennas when using different algorithms of the choice of satellites for pointing of MEOLUT antennas on them taking into account the presence of slowly moving beacons.

The analysis of two available algorithms of the choice of relay satellites for pointing MEOLUT antennas on them is carried out, their advantages and disadvantages are given. It is necessary to point out a lack of the record of the presence of slowly moving beacons and a lack of optimization of the MEOLUT service area among the disadvantages.

The new planning algorithm providing iterative optimization of the MEOLUT service area considering the presence of slowly moving EPIRB is offered.

A mathematical simulation of the service area for the configurations of the MEOLUTs that are present today (four or six antennas) is performed. This simulation has shown a low efficiency of the MEOLUT with four antennas and impossibility of operation of a slowly moving EPIRBs, while the MEOLUT with six antennas has shown a possibility of implementation of requirements as on motionless (in the radius about 4500 km) and on mobile EPIRBs (in the radius about 3000 km).

The analysis of the MEOLUT service area depending on the number of antennas and three algorithms of planning is carried out:

- An algorithm No. 1 is the algorithm with the choice of spacecraft with the greatest elevation relative to the MEOLUT.
- An algorithm No. 2 is the algorithm with the choice of the set of satellites providing a one-time best geometrical factor in a circle with the maximum radius. The circle with the maximum radius is found iteratively.
- An algorithm No. 3 is the algorithm with the choice of set of satellites providing a one-time biggest service area in a circle with the maximum radius. The circle with the maximum radius is found iteratively.

By the results of the simulation, the algorithm No. 1 provides a less service area than the algorithms No. 2 and No. 3 that is most expressed at the small number of antennas. At twelve and more antennas, disadvantage of the algorithm No. 1 makes less than 20% of the service area.

The algorithms No. 2 and No. 3 lead in many respects to similar results. At the number of antennas less than 10, the algorithm No. 3 gives advantage in a service area (up to 10% of the size of the service area), while the algorithm No. 2 has advantage on mean accuracy in the service area (up to 15% of the required accuracy).

It is shown that in the autonomous mode a MEOLUT reaches the biggest specific efficiency (per one antenna) with 9–11 antennas installed on it. If the value of the service area of the MEOLUT with six antennas is taken as a unit of measurement, so addition of only one antenna increases a service area by 78%, two antennas – by 162%, three antennas – by 220%.

The given simulations should give an assessment of the minimum number of antennas required for providing the service with the set characteristics in the desirable service area. It is noted that the necessary number of antennas can be reached due to their installation on a MEOLUT or due to the exchange of measurements with the nearest MEOLUTs on condition of the coordination of their work.

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Possibility and Effectiveness of Including the Geostationary Segment into the Medium Earth Orbit Segment of the COSPAS-SARSAT System

D.V. Antonov, *antonov_dv@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
V.A. Arkhangel'skiy, *Cand. Sci. (Engineering), varhangelskij@gmail.com*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
V.I. Semin, *semin.50@list.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.V. Fedoseev, *andrewxf@gmail.com*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. This article describes necessity of having frequency measurements obtained through at least six satellites to locate slow moving beacons (velocity < 5 m/s) with the required accuracy in the Medium Earth Orbit segment of COSPAS-SARSAT. The possibility of adding two geostationary channels to the Medium Earth Orbit Location User Terminal (MEOLUT) with four antennas to achieve the required accuracy for slow moving beacons is shown. The necessary revision of hardware and software is described; the results of the mathematical simulation of the service area of the resulting LUT with six antennas are provided.

Keywords: MEOSAR, MEOLUT, DBDRS, service area, slow moving beacons, navigation task

Introduction

The coordinates of the emergency beacons (EPIRBs) in the Medium Earth Orbit (MEO) segment of COSPAS-SARSAT are determined by the measurements of times of arrival of an EPIRB signal to relay satellites (the time has the designation TOA) and their frequencies (FOA). EPIRB signals are relayed to MEOLUTs, where there is a measurement of the TOA and FOA values, and then the coordinates of the EPIRB that radiated a signal are determined.

Theoretical and experimental studies [1, 2] have shown that a high precision of determination of the EPIRB coordinates can be reached solving a navigation task of the FOA measurements of high precision (standard deviation is 0.04–0.08 Hz). At the same time the errors of such definition will be less than 1–2 km with probability ≥ 95% that it is better than the required accuracy (5 km with probability of 95% [3]) by 2.5–5 times.

To obtain such an accuracy of the solution of navigation tasks, it is necessary to use not less than three relay satellites when determining the coordinates of a motionless EPIRB, and, generally, not less than six relay satellites located not less than in three different orbital planes for determination of the coordinates of the EPIRBs moving under the influence of currents, winds, and sea rolling [1].

During the design of the Russian MEOLUTs, on the grounds of economy of expenses, it was decided to create a four-channel station capable to receive signals only from four relay satellites. To ensure the reception of EPIRB signals at least from six spacecraft, it was supposed to use the exchange of measurements with others (Russian and foreign) MEOLUTs.

Today the first Russian MEOLUT located in Moscow showed high precise characteristics when determining the coordinates of the motionless EPIRBs according to the results of international Demonstration and Evaluation tests of MEOSAR at the II stage [2]. This MEOLUT showed its results after the production in 2013 at the development test. The reached precision characteristics were better than the requirements by 2.5–5 times, and considerably (more than by 5 times) better than the accuracy received by all other foreign MEOLUTs.

When determining the coordinates of maritime movable EPIRBs, in view of the lack of a necessary number of measurements from different spacecraft, only the measurements of TOA were used that led to a considerable deterioration in accuracy. The errors of the determination reached 10–15 km and even more.

A low accuracy of determination of the coordinates of maritime EPIRBs, as it follows from the above, is explained by the insufficient number of relay satellites, signals from which this MEOLUT can accept (only four instead of necessary six) simultaneously.

The exchange of measurements with foreign MEOLUTs to obtain the necessary number of measurements and precise measurement of the coordinates of movable EPIRBs is much less effective in view of a low accuracy of the FOA measurement on them. In addition, the exchange of the measurements with foreign MEOLUTs is not a reliable source of data, as, according to the COSPAS-SARSAT specifications, it is an optional function and is not obligatory to be fulfilled [3].

Solving a navigation task by means of the measurements received from MEO and GEO segments

In this article a new way of the solution of a problem of determination of the coordinates of movable EPIRBs with the required accuracy is offered. The essence of this way is that when solving a navigation task, the measurements of the EPIRB relayed by the geostationary artificial satellites equipped with COSPAS-SARSAT retransmitters and received by distress beacon data receiving stations (DBDRS) are used in addition to the measurements received from four channels of this MEOLUT. Though the measurements of FOA from geostationary spacecraft cannot directly help to determine the EPIRB coordinates (since a geostationary spacecraft is almost not movable relative to the Earth and the movement of the spacecraft does not cause a considerable Doppler shift of frequency), they help to determine the EPIRB velocity, since the EPIRB speed in this case causes a Doppler shift of frequency. Thus, when solving a navigation task of the FOA measurements, to determine six unknown parameters (longitude, latitude, three components of velocity, and an unknown frequency of radiation), at least three measurements from MEO spacecraft and at least three more measurements from MEO or GEO spacecraft are required.

In a hardware, such a solution demands costs only for retrofitting of DBDRS with the equipment of measurement of frequency and time of arrival of signals from geostationary spacecraft.

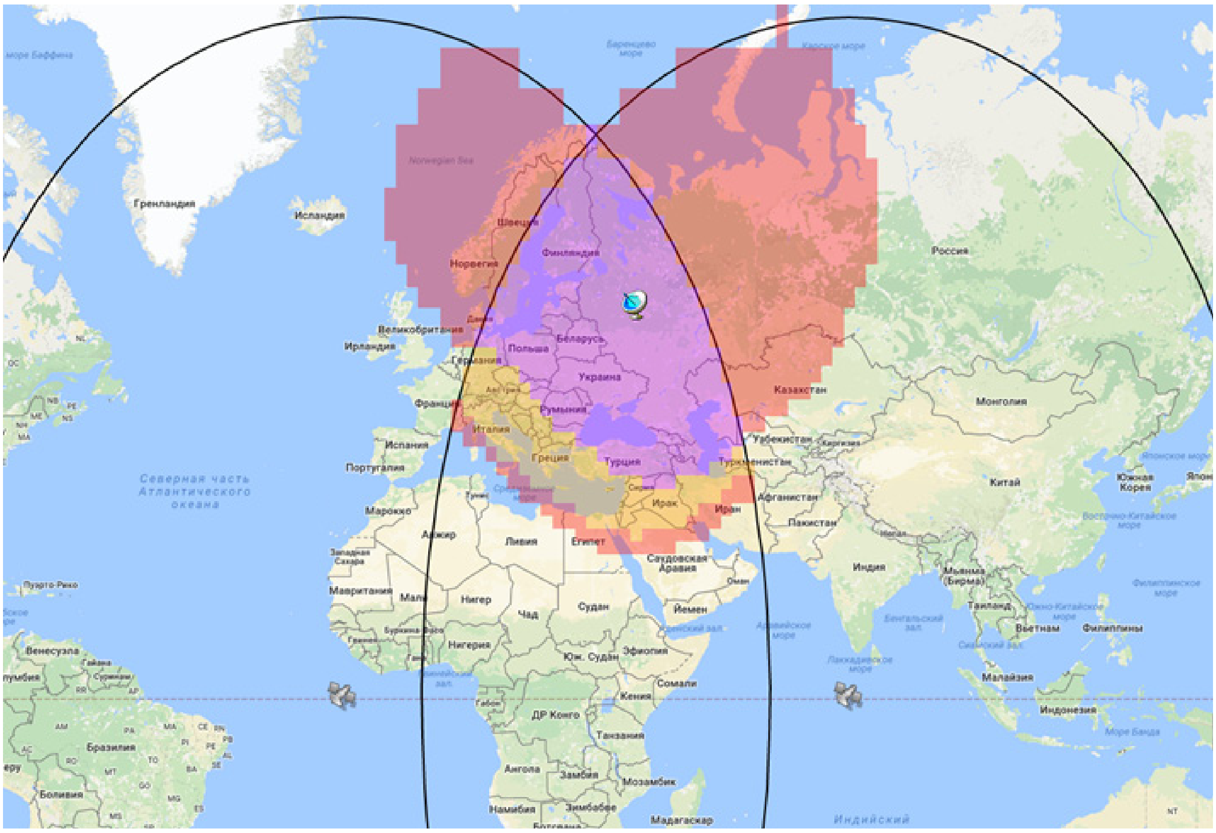

Fig. 1. Service area of the MEOLUT with four antennas with two geostationary channels when working with slow moving EPIRBs

To check the expediency of using the measurements from geostationary relay satellites, a computer simulation in which the Moscow MEOLUT with four antennas used the measurements from two DBDRS stations, which received data from the geostationary spacecraft Electro-L No. 1 (14.5 west longitude) and Electro-L No. 2 (76.0 east longitude) was carried out. The results of this simulation are shown in Fig. 1.

The color areas in Fig. 1 depict the service area, different colors correspond to different accuracy of determination of the coordinates, the presented satellites are Electro-L No. 1 and Electro-L No. 2, black lines mark an area of radio visibility of these spacecraft, and the antenna marks the MEOLUT and two DBDRS stations located in Moscow.

Improvement of DBDRS and MEOLUT necessary to realize and master the offered method

The efficiency of adding the measurements of EPIRB signals relayed by at least two geostationary spacecraft to the measurements received by the Moscow MEOLUT with four antennas is shown in the previous section. For implementation of this decision, at the moment there are almost all sophisticated and expensive means:

– The Electro-L geostationary spacecraft:

• No. 1 – will be transferred to the position of 14.5° west longitude;

• No. 2 – being in the position of 76° east longitude;

• No. 3 – will be put to orbit to the position of 165° east longitude;

– The Louch-5 geostationary spacecraft:

• Louch-5A – being in an orbit in the position of 167° east longitude;

• Louch-5V – being in an orbit in the position of 95° east longitude.

All these spacecraft have EPIRB signal repeaters of COSPAS-SARSAT;

– The Moscow DBDRS was put into operation as a part of the Russian geostationary segment of the COSPAS-SARSAT System in 2013 and now is successfully performing the functions together with Electro-L No. 1;

– Four more DBDRSs are placed in the cities: Moscow,

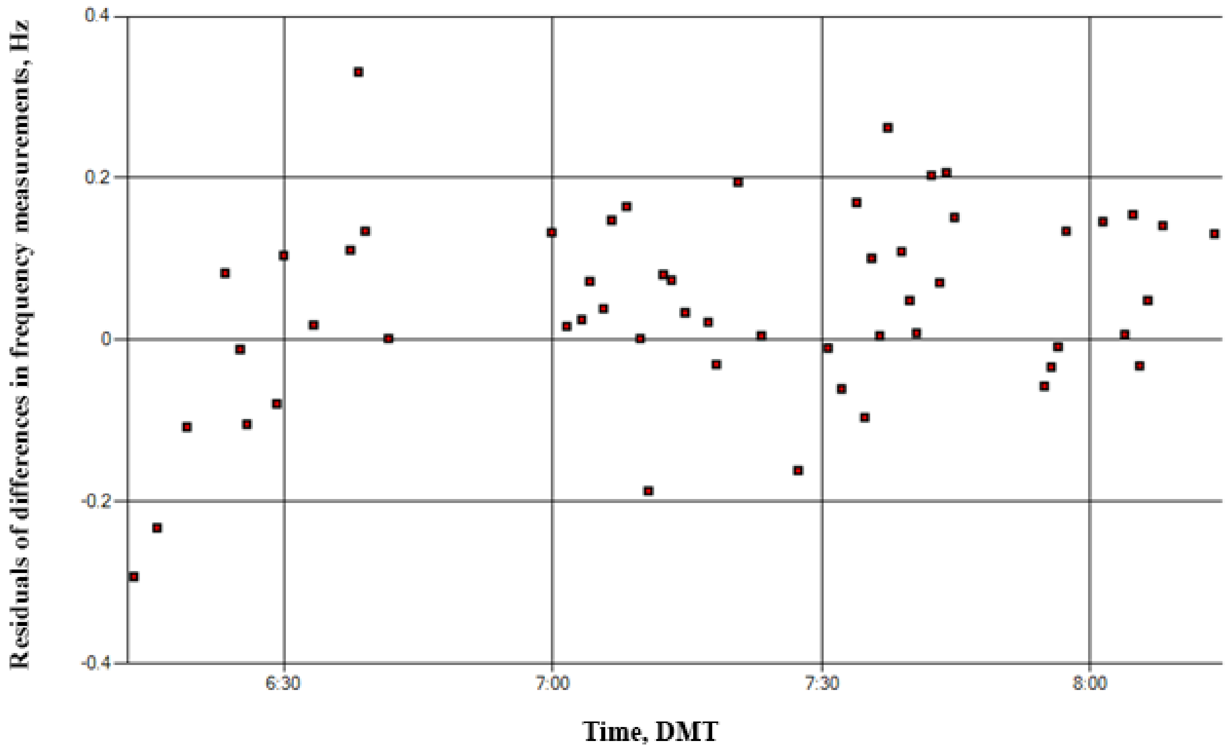

Fig. 2. Residuals of differences in the FOA measurements from Electro-L No. 1 and GPS No. 12, 22.10.2015.

Zheleznogorsk, and Khabarovsk (two complexes) to work with Electro-L No. 2, Electro-L No. 3, Louch-5A, and Louch-5V.

To realize the offered method, these DBDRSs have to be mastered in order to perform the measurements of FOA and TOA. It is possible to realize such improvement without difficult mastering the equipment and the DBDRS programs, however retrofitting will be required by the receivers used in a MEOLUT (analogue-to-digital receivers of a signal from MEO spacecraft) and low-directed antennas for reception of signals from navigation satellites by the special navigation (second) channel of these receivers and also carrying out necessary improvement of the software.

Apart from the listed improvements for realization of the offered method to increase the accuracy of determination of the coordinates of moving EPIRBs, it is necessary to solve two more technical problems:

- Operative measurement and record when processing the instant values of the frequencies of heterodynes (reference generators) of EPIRB signal retransmitters on geostationary spacecraft;
- A rather precise understanding the parameters of the orbits of geostationary spacecraft in real time.

To check a possibility of these tasks solving, the experiment was carried out. The EPIRB messages received from the Moscow DBDRS tracking the geostationary Electro-L No. 1 spacecraft were calibrated according to the French orbitografical beacon (No. 9C634E2AB509240) that possess a high frequency stability of the radiated signal and time of radiation. After calibration, the FOA measurements of a beacon No. BBBF0DEE6437320 located in Hong Kong were analyzed. As it is described in [1], it is expedient to make an analysis on the differences of the measurements from two spacecraft. Fig. 2 shows an example of the errors of differences of the frequency measurements (with the considered Doppler shift of frequency caused by the spacecraft movement) from the relay satellites Electro-L No. 1 and GPS No. 12 (the average value was 0.043 Hz; standard deviation is 0.118 Hz).

Thus, the conducted experiment shows a basic possibility of using the measurements from geostationary relay satellites to solve a navigation task for slowly moving EPIRBs in the MEO segment of COSPAS-SARSAT.

Conclusions

One of the methods to increase the accuracy of determination of the coordinates of mobile EPIRBs in the MEO segment of COSPAS-SARSAT is to use additional measurements of the frequency (FOA) of an emergency beacon received by DBDRS stations from the Electro-L No. 2, Electro-L No. 3, Louch-5A, and Louch-5V geostationary satellites. Such a method allows one to use, without large expenses, financially technical ground of the Russian geostationary stations to increase the accuracy of determination of the coordinates and expansion of a service area of emergency beacons of the Russian MEO segment of the COSPAS-SARSAT System.

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Experimental Evaluation of the Slow Moving Beacon Location Accuracy in the Medium Earth Orbit Segment of the COSPAS-SARSAT System

D.V. Antonov, *antonov_dv@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. The COSPAS-SARSAT Demonstration and Evaluation phase is being performed. Its purpose is to determine the maintenance characteristics of the Medium Earth Orbit Search and Rescue System (MEOSAR) being developed at present. This article shows the experimental results of a slow moving EPIRB obtained at the Medium Earth Orbit Local User Terminal (MEOLUT) equipped with 4, 6, and 12 antennas. These results match the theoretical conclusions and mathematical simulations made earlier: the MEOLUT with four antennas cannot locate slow moving beacons with the specified quality (5 km in 95%). Meanwhile, the measurements from six satellites (a MEOLUT should have at least six antennas) are sufficient to meet the accuracy requirements for slow moving beacons.

Keywords: COSPAS-SARSAT, MEOSAR, MEOLUT, Demonstration and Evaluation, locating, experimental results, moving EPIRBs

Introduction

As it is shown in [1], when using the measurements of frequency for independent determination of the coordinates in the Medium Earth Orbit (MEO) segment of COSPAS-SARSAT, unlike the Low Earth Orbit (LEO) segment, the presence even of a small speed at a beacon (EPIRB) can lead to big and unpredictable mistakes if this speed is not considered. As a rule, an EPIRB has its own speed being on the surface of water under the influence of currents and wind, at the same time its speed does not exceed 5 m/s. Later, an EPIRB, which move with the speed no more than 5 m/s (18 km/h), will be considered as mobile.

As maritime EPIRBs make the most part of the park of all beacons [2], and, besides, introduction of a new type of the aviation beacons activated in a flight (ELT-DT) is expected, therefore, the problem of mobile EPIRBs gains a huge value for the Medium Earth Orbit Search and Rescue (MEOSAR) satellite system.

In [1], it is shown that independent determination of the coordinates of mobile EPIRBs according to the measurements of the frequencies of the received signals (FOA – frequency of arrival) is possible in the presence of the measurements not less than from six relay satellites received from the same message of an EPIRB. When solving a navigation task of the measurements of the time of signals' arrival (TOA – time of arrival), the measurements from the same message of the EPIRB received not less than via three relay satellites are required.

At the achievable accuracy of the measurements of TOA (standard deviation = 25 microsec) and FOA (standard deviation = 0.08–0.20 Hz) on a MEOLUT, the accuracy of determination of the coordinates on the measurements of TOA is much lower than when using the measurements of FOA [1]. As a mathematical simulation, which results are given in [3], has shown, the MEOLUT equipped with four antennas is not capable to determine the coordinates of mobile EPIRBs by the measurements of TOA with the required accuracy of 5 km in 95% of cases in any zone, while the MEOLUT equipped with 6 antennas is capable to determine the coordinates both motionless and mobile EPIRBs.

At the present moment, within the international Demonstration and Evaluation tests of MEOSAR, an experimental inspection of the ability of a MEOLUT to determine the coordinates of an EPIRB with the required accuracy has been carried out only for a motionless EPIRB on the ground. This article gives the results of an experiment on determination of the coordinates of a mobile EPIRB, which has to show an experimental confirmation or a denial of the results of theoretical researches.

Experiment description

A maritime EPIRB (number 2065E84560FFBFF) was placed onboard the vessel moving between four ports near Bodø, Norway. This EPIRB was activated from May 3 to May 6, 2016. The route of this EPIRB built according to AIS data is presented in Fig. 1. The measurements of TOA/FOA were received by several MEOLUTs including the Moscow MEOLUT and the MEOLUT of the European Union (the EU).

After completing sending EPIRB messages, the EU presented the MEOLUT measurements along with high-precision AIS data on the location of the vessel to carry out an analysis of the opportunity to determine the coordinates of the mobile EPIRBs with the required accuracy.Fig. 2 taken from [2], depicts the results on the accuracy of the independent solutions depending on the own velocity of an EPIRB received in on the MEOLUT of the EU as well as by means of the LEO segment of COSPAS-SARSAT. The green line indicates the required accuracy of 5 km, the number under the dots is the quantity of solutions of the set velocity. When determining the EPIRB coordinates, it was considered that it was motionless. As it is shown, with the increase of the EPIRB velocity, the error of determination of the coordinates grows rapidly reaching hundreds and thousands of kilometers. Under such conditions, own value of an EPIRB influences greatly less on the accuracy of the solutions received with the help of a LEO segment.

To estimate a possibility of a MEOLUT with various numbers of antennas and to determine the coordinates of mobile EPIRBs on the basis of the measurements received on the MEOLUT with four antennas in Moscow and on the MEOLUT with twelve antennas of the EU, the following scenarios were reproduced:

• **Scenario 1.** A MEOLUT consisted of four antennas; to determine the coordinates, only the measurements of TOA were used. Input data of the Moscow MEOLUT were taken. Only the decisions received on the measurements from four spacecraft were included into the statistics.

• **Scenario 2.** The operation of the virtual MEOLUT consisting of six antennas was considered. Input data were

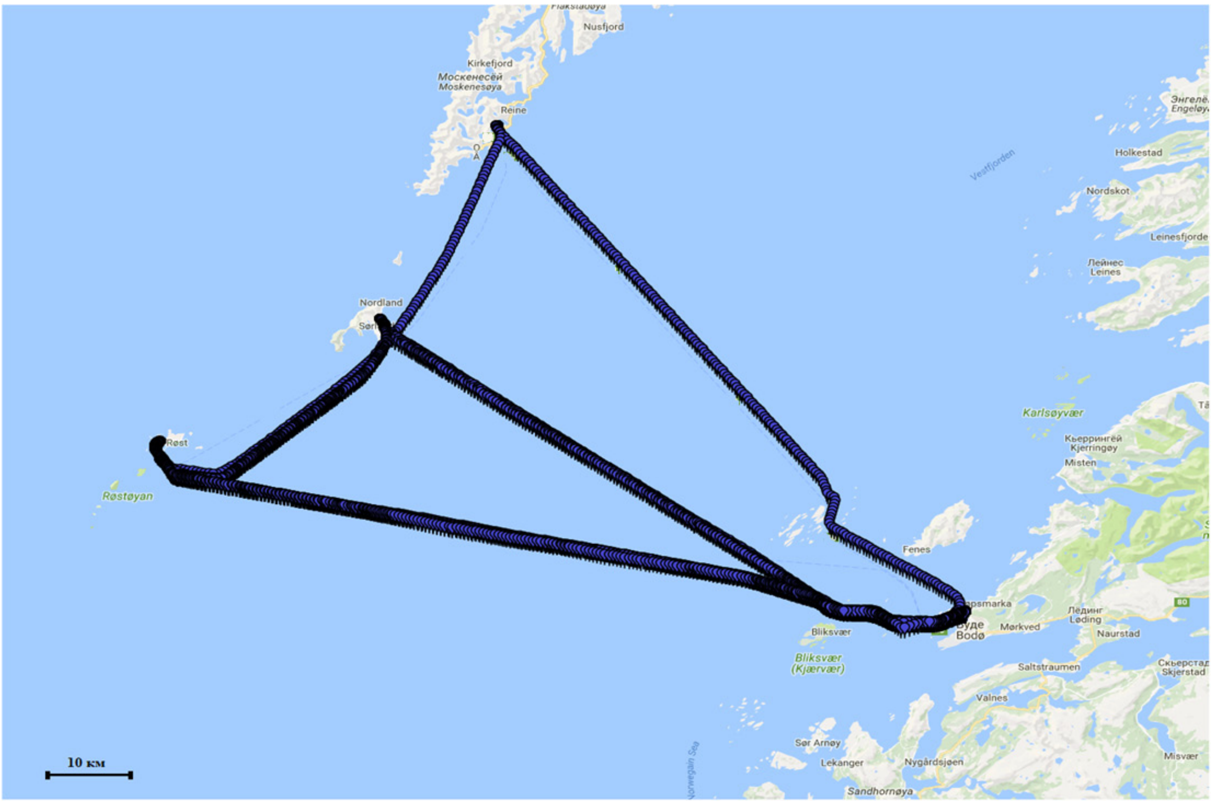

Fig. 1. Route of the EPIRB placed on the vessel

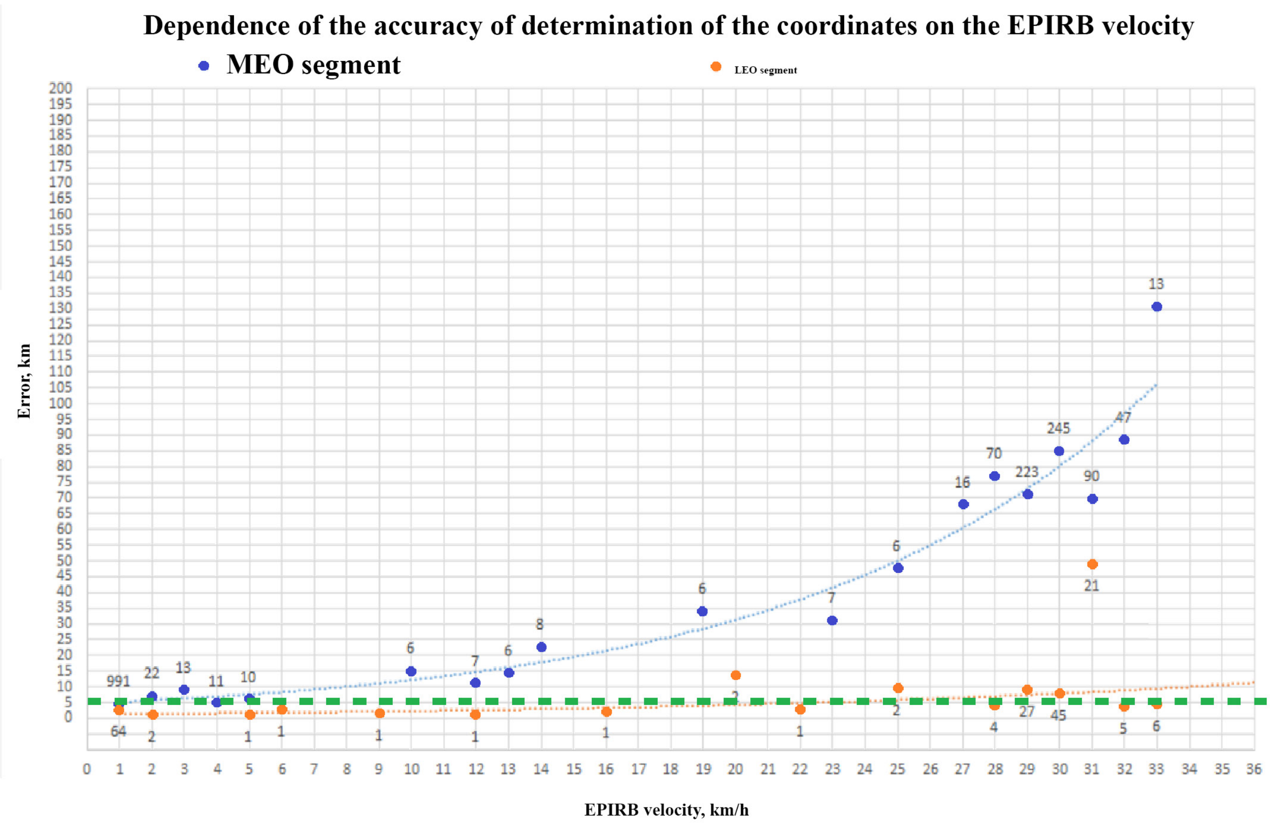

Fig. 2. Results of determination of the coordinates of a movable EPIRB by means of the MEOLUT of the EU (blue dots) and by means of a LEO segment of COSPAS-SARSAT (red dots)

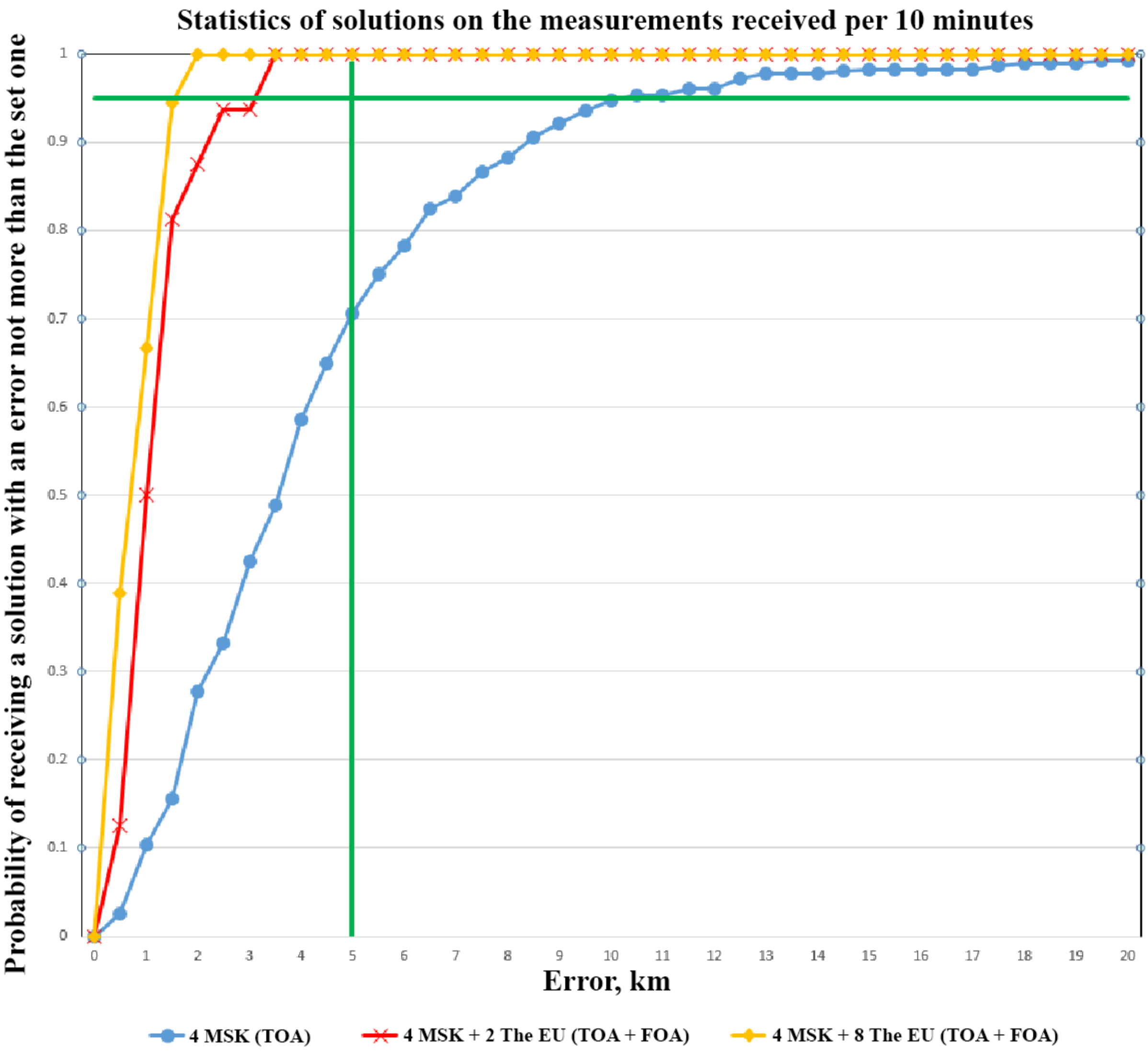

Fig. 3. Diagram of the probability of receiving a solution with an error not more than the set one

taken as the measurements of the Moscow MEOLUT (four antennas) and the data of the MEOLUT of the EU (two antennas). The coordinates of an EPIRB were determined by the measurements of TOA/FOA. Only the decisions received on the measurements from six spacecraft were included into the statistics.

• **Scenario 3.** The operation of the virtual MEOLUT consisting of twelve antennas was considered. The data of TOA/FOA from four antennas of the Moscow MEOLUT and eight antennas of the MEOLUT of the EU were taken as the input data. As a result, 6 – 11 measurements were received on one radiated message of EPIRB.

σTOA = 25 microsec, σFOA = 0.08 Hz (Moscow), 0.20 Hz (the EU) were taken as the accuracy of the measurements.

When solving a navigation task according to the TOA data, the entire period of radiation of messages was considered (from 2016.05.03 11:00 to 2016.05.06 12:50 UTC). When solving according to the TOA/FOA measurements, a shorter interval was used (from 2016.05.06 03:00 to 2016.05.06 06:00 UTC). The choice of such intervals is connected with the existence of a large number of the abnormal FOA measurements in the EU data. On the chosen three-hour interval, there were no abnormal values.

The EPIRB coordinates were determined by the measurements received for a 10-minute interval, at the same time, the decisions were taken to the middle of a 10-minute interval (it was made to minimize an error because of the change of the EPIRB position).

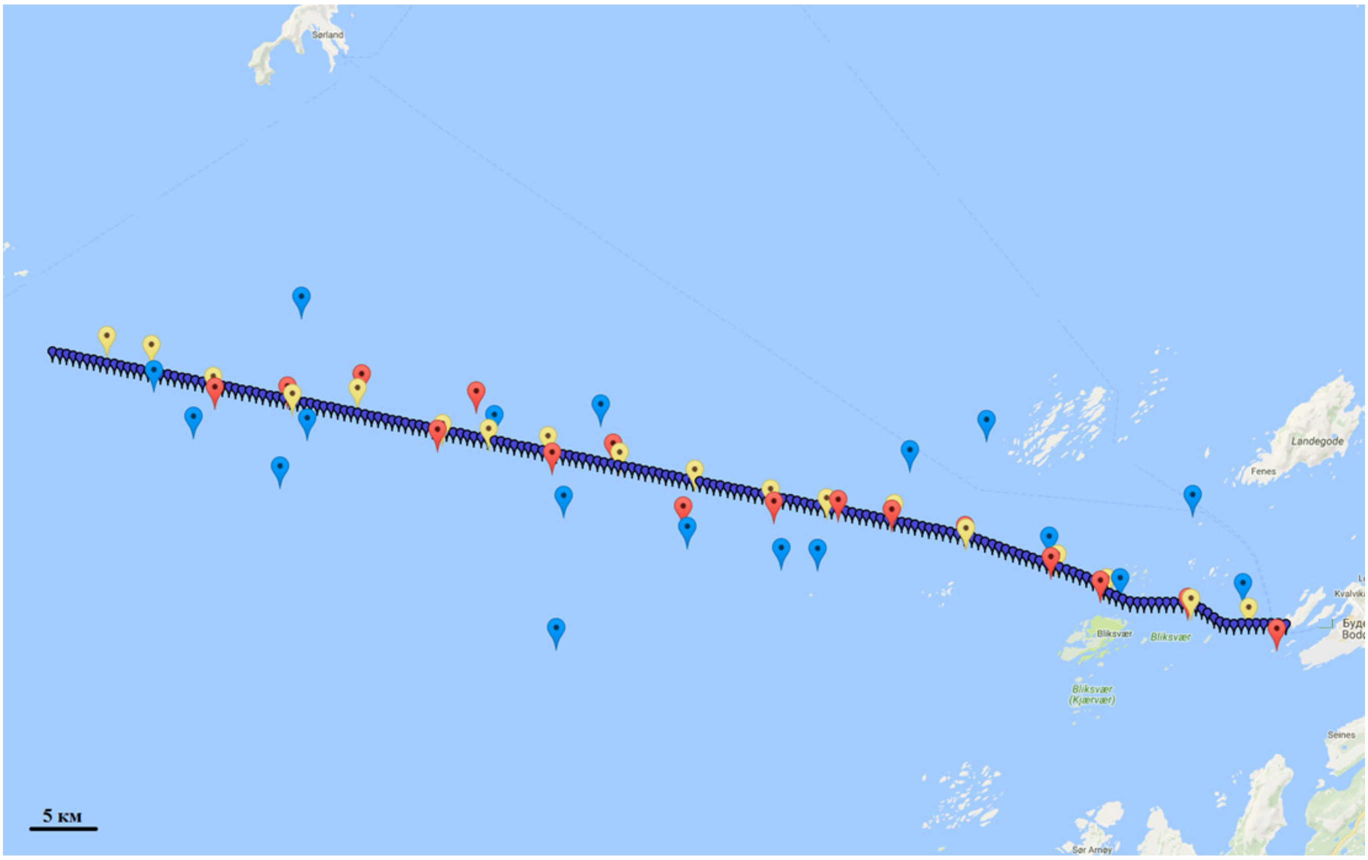

Fig. 4. Solutions received in different scenarios in the map. Blue makers are the 1st scenario (four antennas), red makers are the 2nd scenario (six antennas), yellow makers are the 3d scenario (twelve antennas). Small blue makers are the route of the vessel according to the analyzed period of time

Table 1. Statistics of determination of the coordinates of a slow moving EPIRB

				Solutions on messages received per 10 minutes			
No. of scenario	Number of antennas	Used data	Number of spacecraft in the solution	Number of solutions	Average theoretical accuracy indicator (95%), km	Scattering of the accuracy indicator (95%)	Final error in 95% cases
1	4	Moscow (4)	4	360	11.33	5.80–28.96	10.13
2	6	Moscow (4) + the EU (2) (TOA+FOA)	6	16	3.37	2.47–6.85	3.00
3	12	Moscow (4) + the EU (8) (TOA+FOA)	6–11	18	1.28	0.90–2.12	1.78

Experiment results

The results of the determination of the coordinates of the movable EPIRB depending on the scenario are given in Figs. 3–4 and in Table 1.

As expected, an error of determination of the coordinates of the movable EPIRB according to the TOA measurements of the MEOLUT with four antennas was worse than the required 5 km and was about 10 km.

The MEOLUTs with six and twelve antennas fulfilled the requirements for the accuracy of independent determination of the coordinates. The MEOLUT with twelve antennas, at the same time, showed a considerable stock on accuracy (approximately by 3 times). It should be noted that if the accuracy of the FOA measurement of all measurements would be 0.08 Hz (as on the Moscow MEOLUT), so the accuracy of determination of the coordinates would be even better.

Results

According to the results of the conducted experiment, the possibility of a MEOLUT to determine the coordinates of slowly moving EPIRBs with the required accuracy for the first time was shown, at the same time there were enough TOA/FOA measurements from six relay satellites. The accuracy of determination of the coordinates received on the MEOLUT with four antennas was worse than the required one by 2 times.

The conducted experiment on determination of the coordinates of a slowly moving EPIRB has shown the compliance with the theoretical calculations and mathematical simulations made earlier.

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Integrated Antenna for Second Generation Emergency Radio Beacons of the COSPAS-SARSAT System

S.N. Boyko, *Cand. Sci. (Physics and Mathematics), bosnik2012@yandex.ru*
A branch of "ORKK"-"NII KP", Moscow, Russian Federation
A.V. Isaev
A branch of "ORKK"-"NII KP", Moscow, Russian Federation
D.S. Kosorukov
A branch of "ORKK"-"NII KP", Moscow, Russian Federation
Yu.S. Yaskin, Cand. Sci. (Engineering)
A branch of "ORKK"-"NII KP", Moscow, Russian Federation

Abstract. A built-in antenna for distress beacons of the second generation for search and rescue COSPAS-SARSAT system that consists of a Huygens element in the form of a combined half-wave frame (loop) and dipole is proposed. The formation of the radiation pattern in the cardioid form is achieved by specific excitation of the dipole and loop. An engineering design methodology of the antennas is developed and the comparison of the results of numerical simulation with experimental data is presented. The performance of the antenna meets the requirements of COSPAS-SARSAT to the second generation beacons on a frequency of 406 MHz. An example of application of the developed antenna in the personal distress beacon with its placing on the inner side of the side wall of the frame with the dimensions of 200×75×45 mm is given. The main advantages of this antenna are easy manufacture, protection from external mechanical effects, and low cost.

Keywords: dipole-loop antennas, cardioid pattern, hemispherical radiation pattern, built-in antennas

Introduction

The international search and rescue system COSPAS-SARSAT was established in 1977 for the purpose of distress alerting and the location of personal radio beacons and radio beacons installed on watercraft and aircraft in the event of an emergency. Up to now, the system was based on a low-orbit satellite constellation, and the main type of antenna for transmitting a signal to a satellite at a frequency of 406 MHz was a monopole. The main direction of the development of the COSPAS-SARSAT system is currently the creation of a space segment based on the MEOSAR medium-orbit satellites to create uniform coverage of the entire visible hemisphere of the sky in any part of the globe, which will allow continuous spatial and temporal monitoring of the activated beacon search zone. As a consequence, the main requirement for the antennas of second-generation beacons is the formation of a hemispherical (cardioid) radiation pattern (RP) with linear or circular polarization, the maximum of which is directed to the zenith.

The design of antennas with a cardioid RP shape for personal radio beacons proves to be quite a challenge, since the beacons themselves must have small dimensions and mass. The Expert Group of the COSPAS-SARSAT Committee considered the known types of antennas (spiral, microstrip, planar F-antennas and L-antennas) with a hemispherical shape of the radiation pattern and came to a disappointing conclusion about the inapplicability of these antennas in the personal radio beacons of the second generation: either the dimensions and mass exceed the permissible limits, or the efficiency of radiation is insufficient. Thus, there was no variant of the antenna applicable in the second-generation personal radio beacons.

The search for a solution to this difficult problem by the employees of the NII KP research institute led to a constructive version of the integrated antenna for second-generation beacons, which has acceptable dimensions, mass and DN in the form of a cardioid. This result is achieved due to the combination of a dipole and a shortened loop antenna, which is a practical implementation of the Huygens element.

The algorithm of calculating the dipole-loop antenna with the cardioid shape of the radiation pattern is presented in the article, the stages of its design are described in detail, and the results of computer simulation are compared with the measured characteristics of the antenna model at a frequency of 406 MHz.

Algorithm for calculating an embedded antenna for second generation beacons

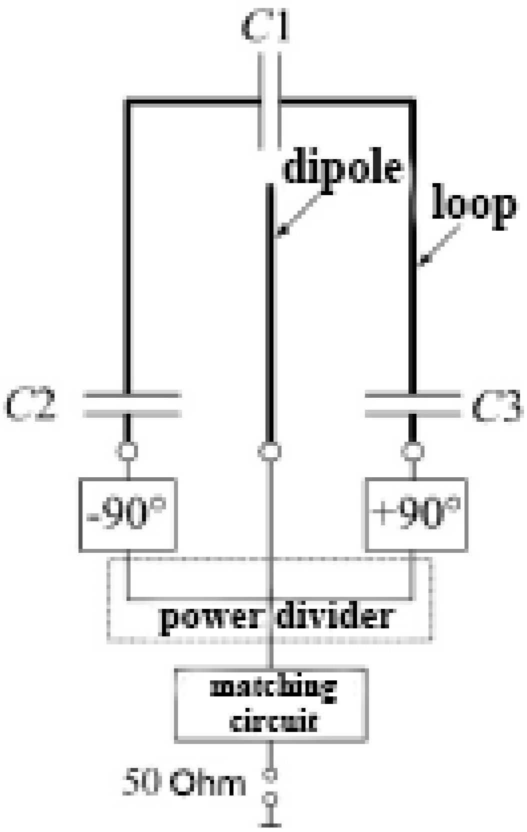
The idea of forming a spherical radiation pattern in the form of a Huygens element was described in many monographs, such as [1]. The Huygens element is an elementary source of unidirectional radiation formed by orthogonal in-phase electric and magnetic dipoles. The field of the Huygens element in the far zone is a spherical wave, and the RP does not depend on the angle φ, and in any plane $\varphi = const$ is determined by the expression $F(\theta) = 1 + \cos\theta$.

The basic implementation of such an antenna, which has a loop antenna with a perimeter equal to the wavelength λ in free space, is not applicable in second-generation beacons because of the large dimensions.

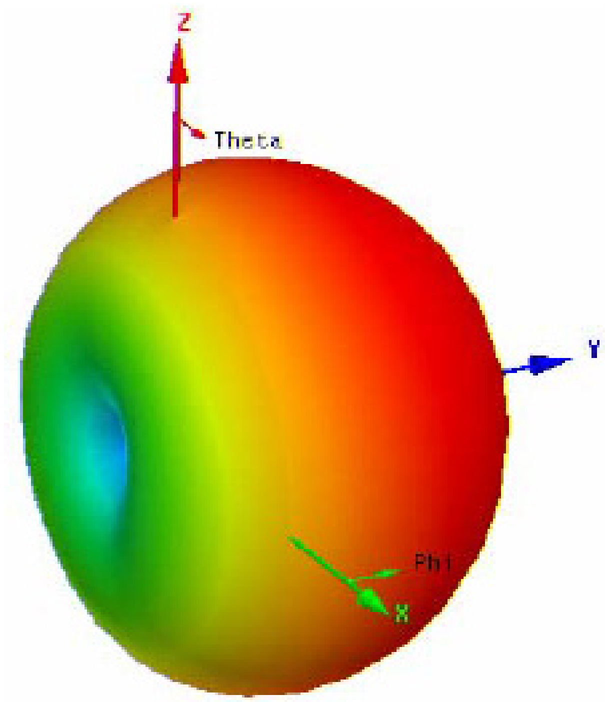
The paper [2] sets forth the theoretical basis for the formation of a cardioid-type radiation pattern with a dipole-loop pair provided that the dimensions of all the radiators are much smaller than the wavelength. In [3], a design variant of an antenna for mobile communication with a RP in the form of a cardioid is proposed, which is a combination of an asymmetric dipole and an electrically small loop, energized in quadrature relatively to the dipole (each arm). However, in [3] the material is illuminated briefly, as a consequence the method for calculating a dipole-loop antenna with a half-wave frame is not presented. The authors of this article tried to fill this gap.

The design of this antenna was taken by us as a basis, in which the changes necessary for this particular application were made.

A schematic diagram of the antenna design is shown in Fig. 1, *a*. A truncated loop with a perimeter of $\lambda / 2$ contains three containers, one of which is included in the center of the loop, and two others - at the beginning of its two arms. The inclusion of capacitance C_1 in the antinode of the voltage makes it possible to shorten the loop with a perimeter equal to the wavelength λ to a loop with a perimeter equal to half the wavelength [4], however, the input impedance of such a frame at the operating frequency will be inductive. To compensate for the inductive component of the input impedance, the capacitances C_2 and C_3 included at the input of the frame. The frame emitter in this form is practically a half-wave dipole with a capacitive load, wound into a loop, fed by a current.



a



b

Fig.1. Schematic diagram of the antenna (a) and the shape of the dipole-loop antenna radiation pattern (b)

In [3] it was noted that for the formation of a spherical radiation pattern of an antenna, the dimensions of all radiators of which are much smaller than the wavelength, it is necessary to observe the following conditions:

1) the centers of emission of the dipole and the loop must coincide, while the mutual influence between the emitters should be minimized;

2) the powers emitted by the dipole and the loop must be equal to each other;

3) the currents flowing in the dipole and the loop must have a phase difference of 90°.

If these conditions are met, the antenna will have a directional diagram in the form of a cardioid with a maximum radiation in the direction of the branch of the frame, energized with a phase of + 90° relative to the dipole, and a minimum radiation in the reverse direction (Fig. 1b).

Antenna consists of several elements, and its calculation and design is a complex task, which must be divided into several stages. We used the following algorithm for designing such an antenna:

Step 1. The calculation of an asymmetric dipole on a printed circuit board is carried out separately;

Step 2. The calculation of a half-wave loop on a printed circuit board is carried out separately;

Step 3. A microstrip power divider is designed with loads in the output arms equal to the calculated resistance of the dipole and loop radiation, provided that the powers of the signals entering the loop and the dipole are equal;

Step 4. Calculation of the balancing transformer on lumped elements is carried out;

Step 5. Calculation of the antenna assembly;

Step 6. The line-building-out network of the antenna is calculated.

Step 7. Optimization of the relative positioning of the antenna and the radio beacon transceiver board is carried out in order to minimize the effect of the board on the form of the RP.

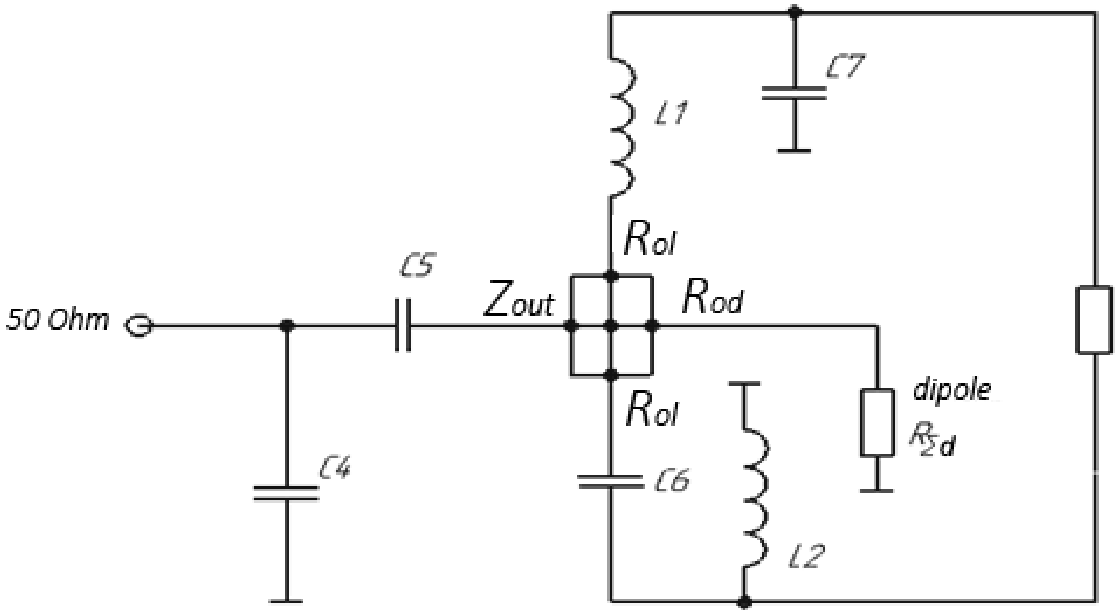


Fig.2. The electric circuit of the dipole-loop antenna

The electrical circuit of the combined antenna is shown in Fig. 2. The diagram shows that the dipole is connected directly to the power divider, and the loop arms are energized with a phase shift of ±90° relative to the dipole through a balanced-unbalanced transformer formed by the pairs of lumped elements L_1, C_7 and C_6, L_2. In this case, the shoulders of the loop are energized opposite in phase to each other. The capacitive L-section matches the input impedance of the antenna with a 50-ohm path.

At the first stage of antenna design, it is necessary to calculate the dimensions of an asymmetrical dipole consisting of a quarter-wave emitter and a coaxial ground plane (counterweight), which are located on one side of the printed circuit board (Fig. 3). In this case, the emitter is located strictly along the longitudinal axis of the board. On the same side of the board is a power divider.

At the next stage, a loop for a working frequency of 406 MHz is designed. The loop antenna is made in the form of a strip on the back side of the printed circuit board along its external contour so that the dipole radiator is located inside the frame on its axis (Fig. 3), which is due to the first condition for the formation of the cardioid type RP above. The perimeter of the frame is a constructive parameter that is determined mainly by the length of the dipole radiator and the width of the board, dictated also by the first condition for the formation of cardioid type RP.

Values of capacitances C_1, C_2, C_3 are calculated by the long-line method applied to the equivalent circuitry of the loop antenna at the resonant frequency (Fig. 4, *a*).

The loop antenna is replaced by a long line of two conductive strips of width *w* spaced a distance *a*, which is loaded at the end by the capacitance C_1 and the radiation resistance $R_{\sum l}$. The power fed to the loop input is calculated using the resistance transformation formula along the transmission line [5]:

$$\dot{z}(b) = Z_{\text{w}} \frac{\dot{z}_{н} + jz_{\text{w}} tg\beta l}{z_{\text{w}} + j\dot{z}_{н} tg\beta l}, \tag{1}$$

where Z_w is the wave impedance of the transmission line, $\dot{z}_i = R_{\sum p} - \dfrac{j}{\omega C_1}$ is the load impedance, l is the length of the transmission line, $\beta = \dfrac{2\pi}{\lambda}$ is the wavelength constant of empty space.

The radiation resistance of the loop $R_{\sum P}$ is found by the formula [6]:

$$R_{\sum p} = 197 \cdot (\Pi_p / \lambda)^4, \tag{2}$$

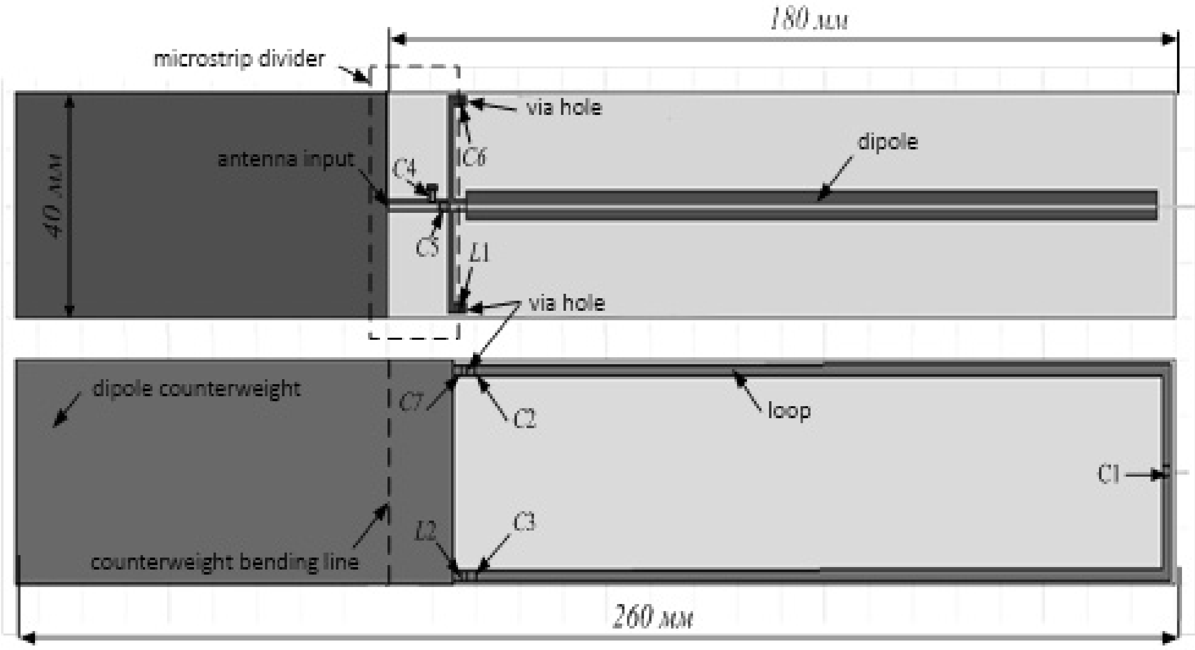
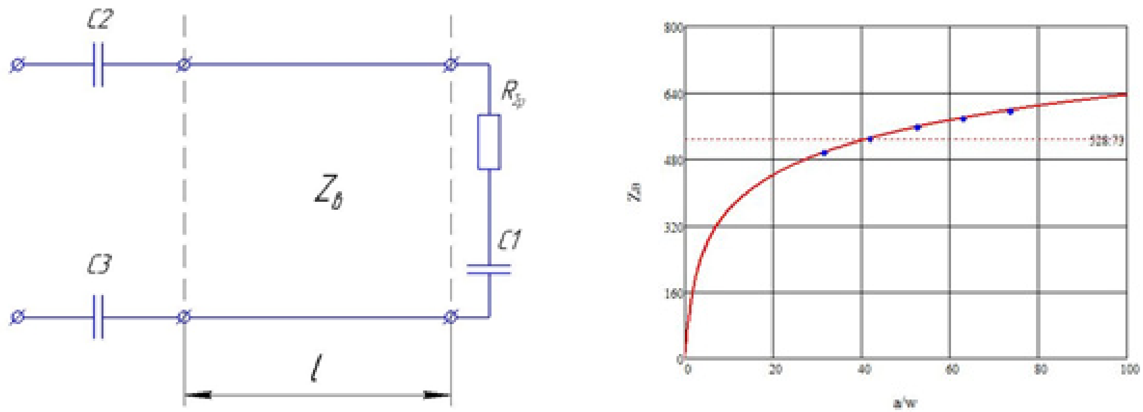


Fig.3. Antenna topology: top and bottom sides of the board



a

b

Fig.4. Equivalent circuit of the loop antenna (a); dependence Zw on a/w (b)

where P_l is the perimeter of the loop.

The wave impedance of the transmission line can be determined from the expression for Z_w a two-wire transmission line [5]:

$$z_B = 276\lg(a/d + \sqrt{1+(a/d)^2}), \qquad (3)$$

where d is the diameter of the wire, assuming that the width of the conductive strip w is equal to twice the value of d, i.e.

$$w = 2d \qquad (4)$$

Relation (4) is determined empirically, namely by comparing the values Z_w calculated from formula (3) with the values obtained with strict electrodynamic calculations. The dependence of the wave resistance of a two-wire transmission line Z_w on the magnitude of a/w is shown in Fig. 4, *b* the solid line is the graph $z_B(a/w)$ calculated by formulas (3), (4), the points are the calculations of z_B in the software package HFSS15 for the width of the strip w = 1.9 mm and a number of values of the distance between the strips a = {28 ; 38; 48;

58; 68} mm; It can be seen that the calculation according to formula (3) assuming (4) completely agrees with the values of the wave impedance obtained with strict electrodynamic calculations.

After recalculation $\dot{z}_i$ to the input of the loop by the formula (1), the nominal values of the elements C_1, C_2, C_3 are found from the condition that the imaginary parts of the total resistance of the loop are equal to zero:

$$\mathrm{Im}\{\dot{z}(b)\} + \frac{1}{j\omega C_2} + \frac{1}{j\omega C_3} = 0 \tag{5}$$

When the elements C are equal, the equation has two unknown parameters: $C_2 = C_3 = C$ and C_1. This indicates that the nominal value of one of the elements can be specified, and the second one is found from the solution of equation (5). Figure 5 shows a plot of C as a function of C_1, which was obtained by numerically solving equation (5). This graph can be used to select a pair of matching capacitors $\{C_1, C\}$.

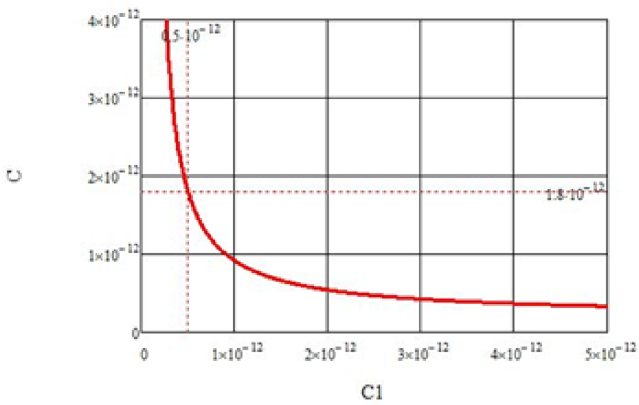


Fig.5. The calculated dependence of C on C1

Calculation of the power divider is carried out from the condition of equality of powers radiated by the loop and the dipole (the second condition for the formation of a cardioid type RP):

$$P_{\sum p} = P_{\sum Д}$$

$$\text{or } I_{a\_p}{}^2 \cdot R_{\sum p} = I_{a\_Д}{}^2 \cdot R_{\sum Д} \tag{6}$$

where $I_{a\_Д}$ and I_{a_p} are the effective values of the dipole current and the loop at the connection points.

The resistance of the radiation of the loop $R_{\sum p}$ is given by the previously given formula (2), and the resistance of the dipole radiation is [1]:

$$R_{\sum Ä} = 80\pi^2 \cdot (l_Ä / \lambda)^2 , \tag{7}$$

where $l_Ä$ is the length of the dipole.

Taking into account (2), (7) and (6), we obtain a formula for the ratio of the currents at the points of connection of the dipole and loop antennas:

$$\frac{I_{a\_Д}}{I_{a\_p}} = \sqrt{\frac{R_{\sum p}}{R_{\sum Д}}} . \tag{8}$$

When designing a power divider, the relation for power is used. Since the input power is proportional to the square of the current, the expression for the ratio of input powers is:

$$m = \frac{P_{âõ\_Ä}}{Đ_{âõ\_ð}} = \left(\frac{I_{a\_Ä}}{I_{a\_p}}\right)^2 = \frac{R_{\sum p}}{R_{\sum Ä}} . \tag{9}$$

The alignment of the loop arms with ports 2 and 3 of the divider is performed using a balanced-unbalanced transformer, its arms are essentially a high-pass filter (HPF) and a low-pass filter (LPF), which in addition to the phase-shifting circuit function also play the role of resistance transformers [5].

The characteristic impedance Z_p of a length of a long line equivalent to the stages of the LPF and HPF, ensuring the transformation of the loading resistance R to the input resistance R_{0l} is [7]:

$$Z_{\Pi} = \sqrt{2R_{0p}\frac{R}{2}} = \sqrt{R_{0p}R} = \sqrt{\frac{L}{C}} \tag{10}$$

In addition, the following condition must be met:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} , \tag{11}$$

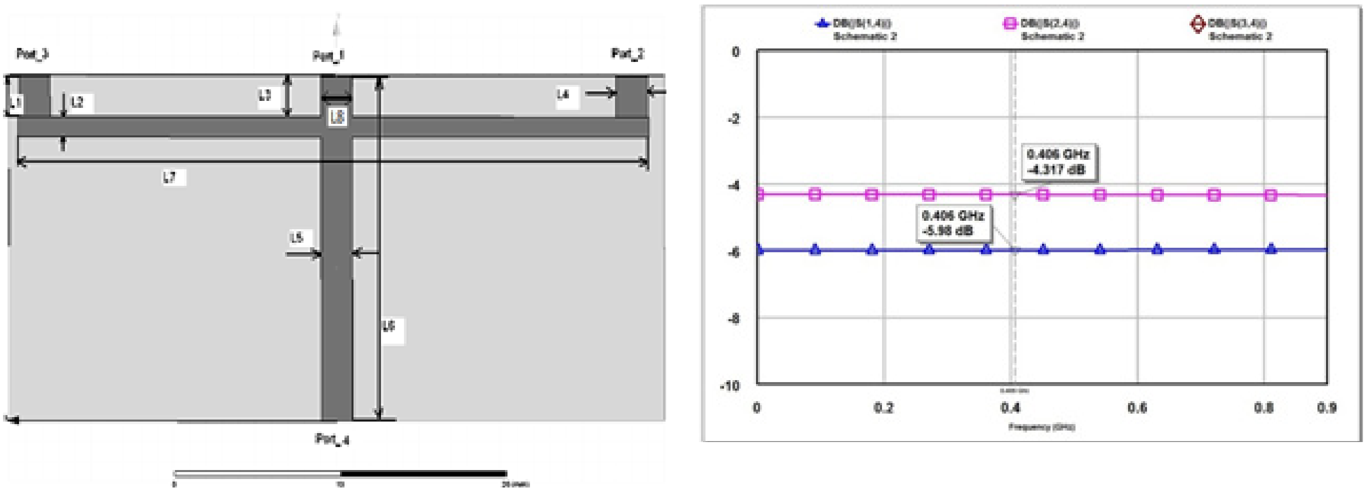
where f_0 is the center frequency of the operating range.

From the formulas (12) and (13) we obtain formulas for calculating the L *and* C elements that make up the balanced-unbalanced transformer:

$$L_1 = L_2 = \frac{Z_{\Pi}}{2\pi f_0} , \tag{12}$$

$$C_6 = C_7 = \frac{1}{2\pi f_0 Z_{\Pi}} . \tag{13}$$

If the L *and* C elements are equal in the arms of the balanced-unbalanced transformer, the HPF specifies a phase shift of minus 90 degrees, and the LPF shifts the



a b

Fig.6. Topology of the microstrip power divider (a); the dependence of the moduli of the transmission coefficients on the frequency (b)

phase by plus 90 degrees. Thus, the third condition for the formation of a hemispherical (cardioid) radiation pattern is met automatically.

Calculation of the dipole-loop antenna

As the material of the antenna board was chosen FR-4 glass fiber 1 mm thick with a relative permittivity $\varepsilon_r = 4.4$. According to the calculation performed with the software package HFSS15, the length of an asymmetric vibrator with a resonant frequency of 406 MHz for a strip width of 5 mm was 162 mm with a counterweight of 100x40 (mm)^2. Taking into account the length of the asymmetric dipole, the calculated perimeter of the loop was $P_l = 366$ mm with a loop width $a = 38$ mm and a loop length $l = 164$ mm. As a result, the overall dimensions of the antenna board, taking into account the counterweight, were 260 mm (length) x 40 mm (width).

For the selected width, the loop strip $w = 1.9$ mm at $a = 38$ mm, the calculated value of the loop wave impedance calculated from formulas (3), (4) was $z_B = 528.73$ Ohm.

For the dimensions of the asymmetrical dipole and the loop given above, formulas (2), (7) and (9) calculate the values of the radiation resistance and the power division coefficient: $R_{\sum Ä} = 37.5$ Ohm, $R_{\sum p} = 12$ Ohm, $m = 0.32$. As a result, the power divider must divide the input power in the following ratios:

$$P_{вх\_Д} = 0.25 \cdot P_{вх}$$

$$P_{вх\_p1} = P_{вх\_p2} = 0.375 \cdot P_{вх},$$

where $P_{вх\_p1}, P_{вх\_p2}$ is the power coming into each shoulder of the loop.

The power division is executed using microstrip lines. The topology of the power divider is shown in Fig. 6, *a*. The loop is connected to the power divider through segments of identical microstrip lines, and the dipole is connected directly to the breakout of the power divider. Loads of the three outputs of the divider are the radiation resistances of the loop $R_{\sum p}$ (half of each output of the divider connected to a loop arm) and the dipole $R_{\sum Ä}$.

The criteria for the synthesis of the power divider were conditions (10), (11), namely, the modulus of the transmission coefficient between the divider input (port 4) and the dipole connection point (port 1) is equal to $|s_{14}| = -6$ dB; The transmission coefficient modules between the divider input and the connection points of the loop arms (ports 2 and 3) are equal to $|s_{24}| = |s_{34}| = -4.3$ dB. The required power splitting was achieved by selecting the width *L*2 and the length *L*7 of two identical microstrip lines in the arms of the power divider. As a result of the synthesis, the following widths and lengths of the intermediate transmission lines were obtained: *L*2 = 0.01 mm, *L*7 = 38 mm.

Due to the technical impossibility to manufacture divider arms 0.01 mm in width, it was decided to increase the *L*2 value to a physically realizable value of 0.5 mm. With this topology, the output impedance of port 1 is

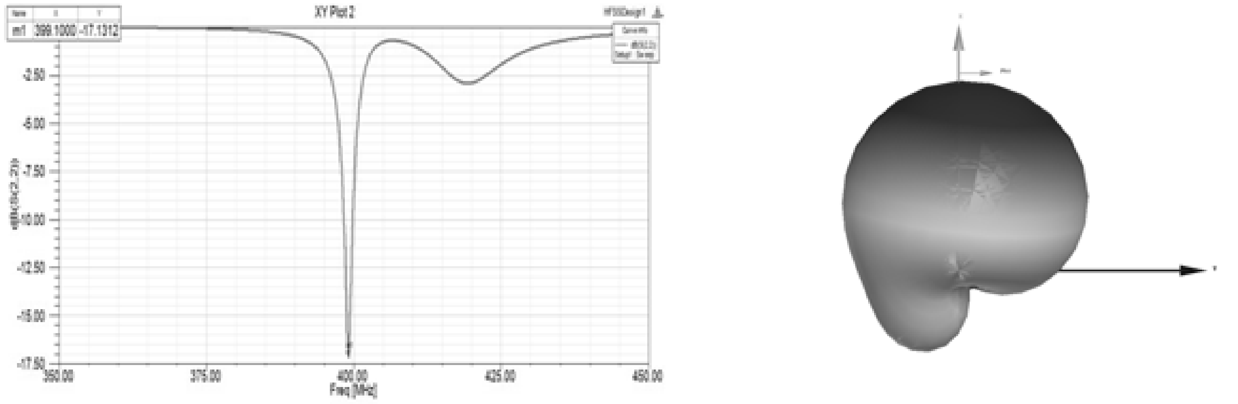


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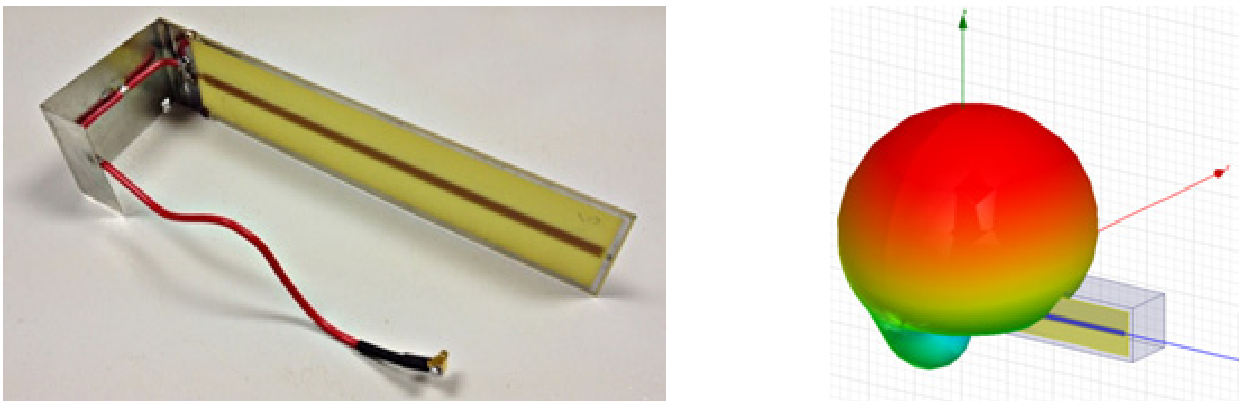
Fig.7. Calculated characteristics of the antenna: a - the modulus of the reflection coefficient at the antenna input; b - radiation pattern at resonant frequency



a b

Fig.8. Dipole-frame antenna model (a); form of RP during operational position of the antenna (b)

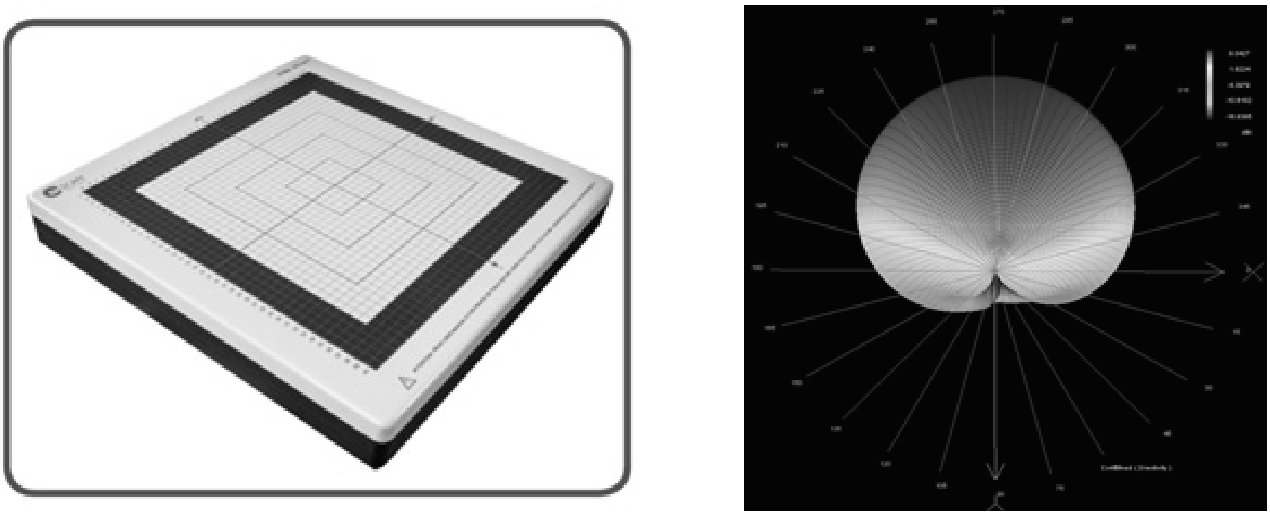
R_{0d} = 200 Ohm, and the output impedances of ports 2 and 3 are R_{0l} = 72.5 ohms each. For these values of load resistances, the necessary power division is provided (the calculated dependences of the transmission coefficient moduli on frequency are shown in Fig. 6 *b*), but it becomes necessary to match the radiation resistance of the dipole and the loop with the above-mentioned resistances of outputs (ports) of the power divider.

The matching of the dipole with port 1 of the divider was achieved by introducing a step transition with a width L8 = 2 mm and a length L3 = 4 mm.

The matching of the loop with ports 2 and 3 of the power divider is carried out using a matching-balancing transformer. The nominal values of the lumped elements of the loop transformer are calculated by the formulas (10) - (13) for the load resistance $R=R_{\Sigma l}/2$ = 6 Ohm, calculated by formula (1) of the input resistance of the loop, R_{0l}=72.5 Ohm, were: $L_1=L_2$= 4.7nH, $C_6=C_7$=32.6 pF.

Calculation of the input impedance of the antenna assembly (dipole + loop with a balanced-unbalanced transformer + power divider) was carried out in the software package HFSS15. The calculated value of the input impedance was $z_{\hat{a}\tilde{o}} = 8 + j6$ Ohm. Since the input impedance has a low value of the active component and a non-zero value of the inductive component, a matching transformer is needed to match the antenna input to the 50-ohm path. In our case, it was implemented in the form of a L-shaped matching circuit, consisting of a serial and parallel capacitances. The calculation of these capacitances was carried out according to the method described in [8], [9]. As a result, the capacitance values were: C_4=15 pF, C_5= 7.5 pF.

The calculated reflection coefficient $|s_{11}|$ at the antenna input and its radiation pattern are shown in Fig. 7 (*a*) and 7 (*b*), respectively. The modulus of the reflection coefficient at the resonant frequency is -26 dB, which



a b

Fig.9. Photo of the RFxpertRFX2 scanner (a) and the type of PR of the dipole-frame antenna measured on the scanner (b)

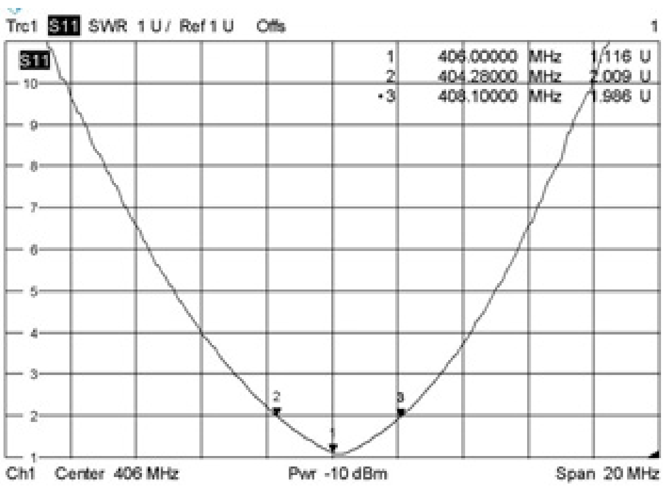


Fig. 10. The experimental frequency dependence of the VSWR at the antenna input

corresponds to the input VSWR = 1.1. The K_u value of the antenna at the maximum of the RP was 2.8 dB. It can be seen from Fig. 7 (b) that in the lower part of the diagram there is a small parasitic radiation, which is connected with the presence of a counterweight to the antenna, which is undesirable for the frame emitter.

On this the antenna design process could be considered complete, but the resulting longitudinal antenna size (260 mm) is clearly large and does not allow it to fit into the dimensions of the personal radio beacon. Therefore, in order to incorporate the antenna into the beacon casing, the counterweight of the dipole was bent at an angle of 90 degrees to the board in such a way that the longitudinal dimension of the board with the topology of the antenna does not exceed 180 mm (the fold line is shown in Fig. 3). In the simulation, it was determined that with such a counterweight configuration, the changes in the shape of the radiation pattern are negligible and can be compensated for by a small change in the capacitances C_6, C_7 in the frame matching circuits.

The results of measurements of the prototype of the antenna and comparison with the calculated data

To test the proposed technique for designing a dipole-loop antenna, a model was made, consisting of an antenna board and a counterweight connected to it. The antenna board was made on a material of FR-4 (ε_r= 4,4) with a thickness of 1 mm, the counterweight was made of tinned sheet 0.2 mm thick. The topology of the antenna board is made according to the calculations carried out by the algorithm described above. The matching capacitors C_1, C_2, C_3 were selected according to the chart in Fig. 5 and are equal to: $C_2 = C_3 = 1.8$ pF, $C_1 = 0.5$ pF (dotted markers in Figure 5). Other options are also possible C_1, C_2, C_3 according to the chart in Fig. 5, for example: C_1 = 0.25 pF, C_2 = C_3 = 3 pF or C_1= 1 pF, C_2 = C_3 = 0.9 pF.- The capacitors in the balanced-unbalanced transformer are variable to fine-tune the phase difference in the loop

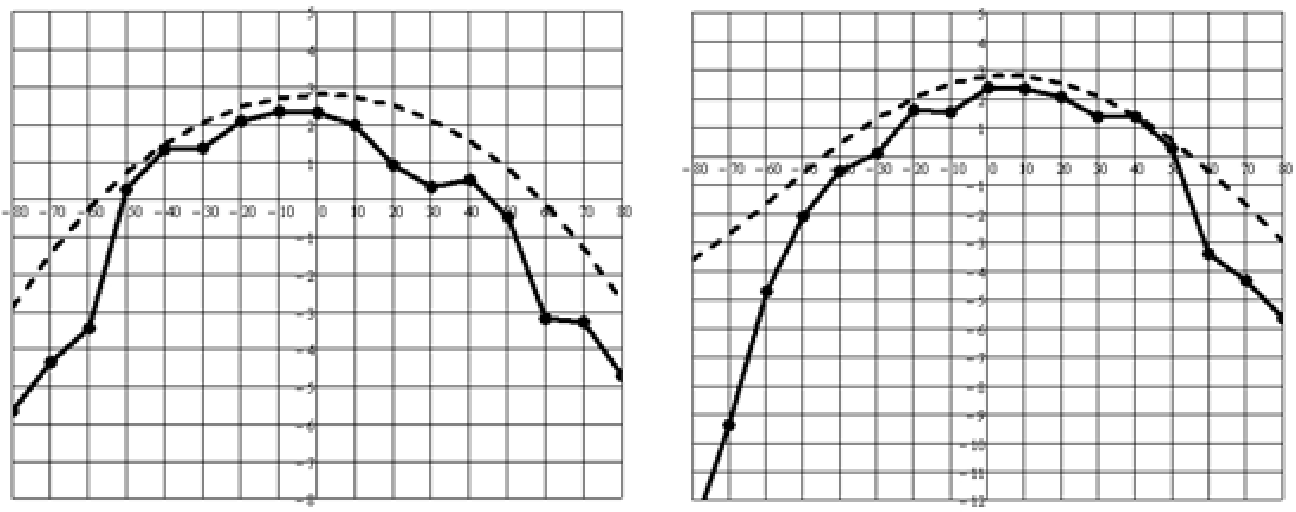


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Fig.11. Measured in the anechoic chamber (solid lines) and calculated (dotted lines) antenna RP: a - for φ = 0 °, b - for φ = 90 °

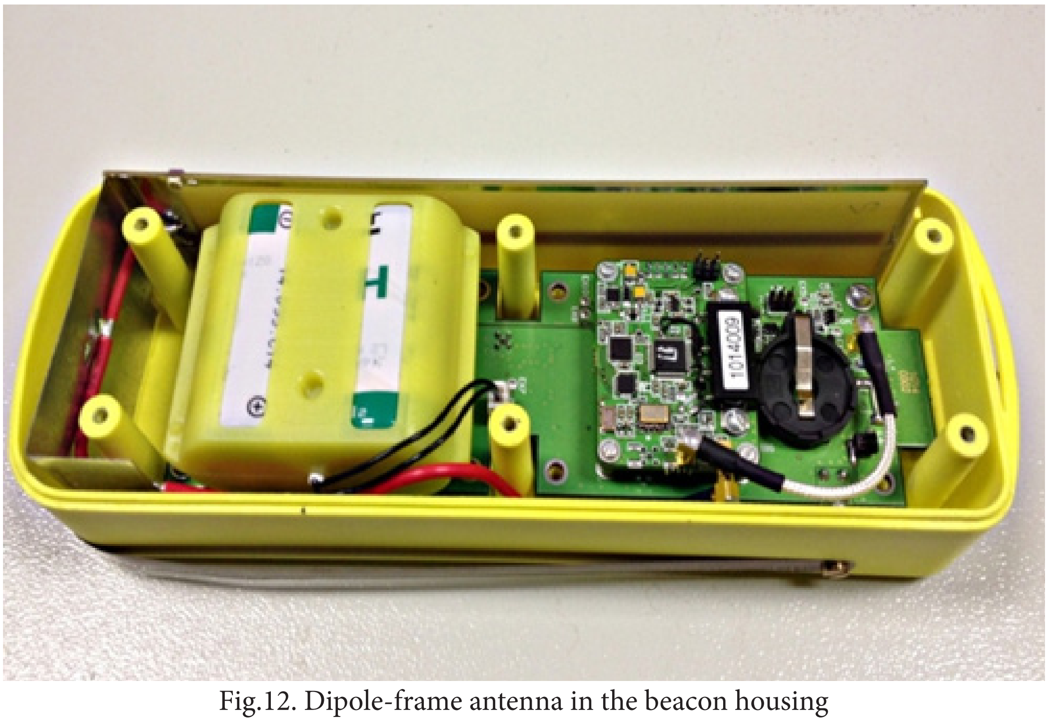

Fig.12. Dipole-frame antenna in the beacon housing

arms. The photograph of the antenna layout is shown in Fig. 8 (a), the calculated three-dimensional RP in the operational position of the antenna is shown in Fig. 8 (b). An additional (second) bending of the antenna's counterweight at an angle of 90 degrees is due to the need to incorporate the antenna into the projected body of the second generation personal radio beacon. The antennas are located on three narrow sides of a rectangle with dimensions (180x65x40) mm^3.

The final testing and tuning of the antenna was carried out by the form of RP with the RFxpertRFX2 scanner by EMScan, which allows to determine the shape of the antenna radiation pattern in real time directly at the workplace [10]. This device measures the near field of the antenna and recalculates it into a far zone field with a RP display in three-dimensional form with a sufficient accuracy for tuning the antenna. The combined antenna was placed on the working surface of the scanner by the plane of the board (counterweight up), then a small adjustment of the capacitances C_6, C_7 was made in the balanced-unbalanced transformer to achieve a cardioid shape of the RP. A photograph of the scanner and the radiation pattern of the antenna measured with it are shown in Fig. 9, *a* and 9, *b*, respectively. Then, the VSWR and PR of the scanner-tuned antenna were measured in the far zone in an anechoic chamber.

The measured dependence of the VSWR at the antenna input on the frequency is shown in Fig. 10.

It follows from the figure that at the operating frequency of 406 MHz the value of the VSWR is 1.1, which fully coincides with the calculated value. The RP of the antenna in the upper hemisphere at φ=0° and 90°, measured in an anechoic chamber, are shown in Fig. 11 (a) and 11 (b), respectively. Also in these figures, the dashed line shows the results of calculating the RP in the software package HFSS15. The measured value of gain at the maximum of the RP is 2.5 dB, and the calculated value is 2.8 dB. From the above analysis it can be seen that a good rate of coincidence of the calculated and experimental data has been achieved.

It should be noted that according to the requirements of the COSPAS-SARSAT standard on the second-generation radio beacons in 90% of the radiation pattern, the antenna gain should be in the range from minus 7 to plus 4 dB for elevation angles from 15 ° to 90 °. The obtained experimental values of gain (θ) satisfy this requirement: the values of gain vary in the range from minus 6 dB to plus 2.5 dB in a given range of angles (see Figure 11).

When the antenna is placed inside the radio beacon its board is located along one of its long side walls, and the counterweight is along the adjacent short side wall, with a small overlapping with the opposite long wall (Fig. 12).

Since there is a transmitter-receiver board perpendicular to the antenna board in the radio beacon, it was necessary to measure its effect on the characteristics of the antenna. Therefore, computer simulation and experiments determined the best position of the transmitter-receiver board with respect to the antenna board for the operation of the antenna, in which the shape of the RP is retained (Fig. 8, b*)*.

The dipole-loop antenna has several advantages as a built-in antenna. Firstly, because of the lack of radiation in the lower hemisphere, it makes it possible to reduce the negative influence of the underlying surface on the DN shape. Secondly, it is protected from external mechanical influences by the radio beacon housing. Thirdly, it has a simple manufacturing technology and low cost.

Conclusion

In this article:

- A dipole-frame antenna is proposed for use in the new (second) generation of the COSPAS-SARSAT personal rescue beacon.
- A detailed description of the design stages of such an antenna is given and an engineering procedure for its calculation is proposed.
- The input standing wave ratio of the antenna (SWR = 1.1) and the hemispherical RP of the antenna at a frequency of 406 MHz with a gain = 2.5 dB were calculated experimentally.
- By changing the configuration of the counterweight, the antenna is embedded in the radio beacon with dimensions (200 × 75 × 45) mm^3.
- The influence factor of the transmitter board on the form of the antenna RP is taken into account. Its best position in the radio beacon casing is chosen.

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Analysis of the Concepts for Design of Complexes for Receiving, Processing and Retransmitting of Information from the International COSPAS-SARSAT System and the Prospects for Their Development

A.A. Romanov, *Dr. Sci. (Engineering), Prof., romanov_alal@risde.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.S. Kondrashov, *Cand. Sci. (Engineering), kondrashov_as@risde.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
D.A. Belov
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
S.A. Bukin
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. This paper describes the operation principles of various complexes of onboard systems of the search and rescue spacecraft deployed in the low, medium, highly elliptical and geostationary orbits.

An analysis of the basic technical characteristics of the existing airborne complexes of various segments has been carried out. It has been shown that it is possible to form generalized requirements for on-board equipment that meet the requirements of the international search and rescue system COSPAS-SARSAT, taking into account the performance features of the equipment.

A possible future design of a unified complex is presented, which, with a minimal reconfiguration, can be used in the spacecraft of all the segments of the international search and rescue system COSPAS-SARSAT.

Keywords: COSPAS-SARSAT, medium-orbit search and rescue system, geostationary search and rescue system, on-board unified SAR complex

Introduction

The international search and rescue system COSPAS-SARSAT has been successfully developing since the late 80s of the 20th century, when the basic agreement regulating mutual obligations of the parties (the USSR, the USA, France and Canada) was signed [1]. The system, according to [1], included a space segment consisting of a minimum of 4 low-Earth orbiting spacecraft that must receive and process signals from emergency beacons and transmit them to ground stations.

Subsequently, the search and rescue system was modernized. Initially, it was augmented by spacecraft in the geostationary orbit (1998), as an addition to the low-orbit segment relaying data packets from radio beacons to ground stations without signal processing on board. In 2000, consultations were started and a decision was made to start the development of a fundamentally new (medium-orbit) search and rescue system (MEOSAR), which in future should replace the low-orbit segment. At the end of 2016, it was decided to start the phase of early operational readiness of the MEOSAR system anticipating its final commissioning, which, according to the current development plans, is scheduled for 2020.

The MEOSAR in theory combines the advantages of the low-orbit (LEOSAR) system (the ability to independently determine the coordinates of a beacon – the geostationary system (GEOSAR) is deprived of this capability) while eliminating its shortcomings: the alert signal retransmission service becomes available to the consumer in almost real time, since there is no need to wait for a communication session with the spacecraft.

Successive modifications and expansion of the number of segments of the search and rescue system COSPAS-SARSAT, in fact, led to the actual creation of several different types of onboard equipment, which, with the exception of the LEOSAR, performs the same task: relaying of the signal from an emergency beacon located in the range of the spacecraft to a ground station.

At the present time, the signaling function of the search and rescue system is implemented on the low-Earth space vehicles such as Meteor-M (RK-SM-MKA equipment), geostationary spacecraft of the Electro-L type (channel 8 of the onboard radio unit) and Louch (COSPAS-SARSAT channel of the RDATS), prospective highly elliptical spacecraft of the Arktika-M type (COSPAS-SARSAT onboard radio unit channel) - (the complex is at the stage of ground testing), as well as medium-orbit GLONASS-K spacecraft of different generations (BRKS, BRKS-K2 and the prospective BRKS-2-M).

Within the scope of this article, technical characteristics of the search and rescue equipment are analyzed, and a way of development of these complexes is proposed: the unification of onboard equipment for all segments of the COSPAS-SARSAT system, taking into account the need for additional processing of signals onboard low-earth orbit spacecraft.

Description and principle of operation of COSPAS-SARSAT onboard equipment of various space segments

Below is a brief description of the space complexes used in the current configuration of the system.

The RK-SM-MKA complex

The RK-SM-MKA (modernized rescuing radio complex for small-sized spacecraft) is intended for installation on low-earth orbit spacecraft and in accordance with the latest decisions of the SC Roskosmos will be installed onboard Meteor-M No. 2-1 and No. 2-2 spacecraft.

Similar to the RK-SM complexes [2, 3, 4], a more modern RK-SM-MKA product is designed to receive COSPAS-SARSAT emergency beacon signals at a frequency of 406 MHz, measure the Doppler frequency shift of the package with simultaneous recording of the receiving start time, acquisition of the information part of the message, as well as the formation of a data frame with its subsequent transmission to a ground station.

The basic principles of operation of the complex are presented in Figure 1 [2].

From the antenna-feeder system (AFS), the beacon signal of COSPAS-SARSAT system in the frequency range 406.01 ... 406.09 MHz is fed into the linear section of the receiver, where the frequency is halved (IF1-46.05 MHz and IF2-35 kHz, where IF is an intermediate frequency). At the first intermediate frequency (IF1), the working band of the 90 kHz signal is formed. At the output of the linear section of the receiver, the signal at the second intermediate frequency (IF2) is digitized and enters the digital section of the receiver.

In the digital section of the receiver, algorithms for detecting the signals of emergency beacons, information

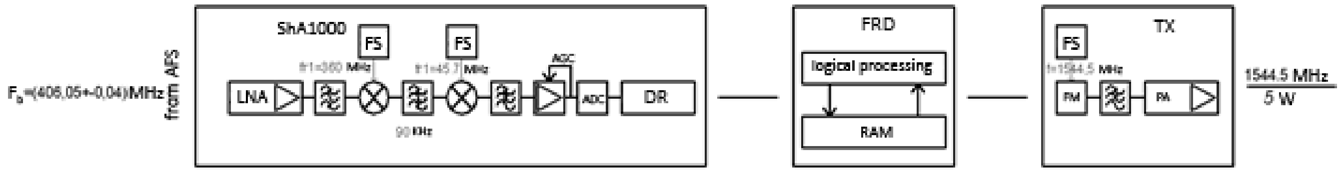

Fig. 1. Functional diagram of the complex RK-SM-MKA. where

FS - frequency synthesizer;
AFS - antenna-feeder system;
LNA - low noise amplifier;
AGC - automatic gain control;
DR - digital receiver;
ADC - analog-to-digital converter;
FRD - framing and recording device;
RAM - random access memory;
FM - phase modulator;
PA - power amplifier;
TX - transmitter.

extraction, as well as measuring the Doppler frequency and time shift of the sending are implemented. The received information is sent to the frame formation and recording unit (FRD), where an information packet is formed for data output to the complex transmitter (TX). In the TX, phase modulation is performed at the carrier frequency of 1544.5 MHz and the gain is 5 ± 1 W. The FRD also records up to 2000 beacon transmissions in the RAM.

The COSPAS-SARSAT channel from the onboard radio unit of the Elektro-L spacecraft

In Fig. 2 the simplified functional scheme of the channel 8 fulfilling the function of relaying the signals of the COSPAS-SARSAT system [5] is presented.

The channel C8 (COSPAS-SARSAT) is combined with the channels C6 and C7 at the input of the onboard radio unit of the Electro-L spacecraft [5, 6]. For all three channels (C6, C7, C8), the LNA is common. Channels C7 and C8 have a common converter CONV-0.4, which performs the first frequency conversion. The LNA has a wide reception bandwidth, since it provides reception of signals at 402 MHz (channel C7), 406.05 MHz (channel C8) and 465 MHz (channel C6). Structurally, the LNA is made as a separate device with external power supply (+15 V), but not removed to the AFS. In CONV-0,4 preliminary frequency selection and the initial frequency reduction are carried out. The signal of the C8 channel is transferred to the frequency of 26.05 MHz and without narrowband filtering fed to the RSC8 unit. The RSC8 unit performs frequency selection by external commands:

- Fnom - 26.05 MHz, 2ΔF - 120 kHz;
- Fnom - 26,025 MHz, 2ΔF - 30 kHz.

The spectrum of the signal thus formed is shifted to the low-frequency end (at a central frequency of 50 or 25 kHz) and as a modulating signal is fed to the LFM with a carrier frequency of 1544.5 MHz. Taking into account the modulation index, the signal efficiency in the spectrum does not exceed 20%. The generated signal is fed to the PA, where it is amplified up to 5 W and is fed to the AFS.

The COSPAS-SARSAT channel from the prospective onboard radio unit of the Arktika-M spacecraft

Radio unit servicing the relay channel for search and rescue information (BRTK-VE) of the Arktika-M spacecraft is a logical upgrade of the radio unit of the Electro-L spacecraft and is intended for installation on a high-elliptical orbit spacecraft. Figure 3 shows the enlarged structural diagram of the Arktika-M radio unit providing the COSPAS-SARSAT relay channel

The main difference between the BRTK-VE equipment and the radio relay installed on the Electro-L spacecraft is the absence of the C6 channel. In addition, the center frequency of reception, transmission and the intermediate frequency of the channel C7 (DATS) is shifted upwards by 500 kHz. However, these differences did not affect the functional circuit of the COSPAS-SARSAT BRTK-VE channel, which repeats the scheme of the C8 channel of the Electro-L spacecraft radio unit. All the devices included in the channel pipeline are kept intact and for unification purposes the broadband LNA remains unchanged, despite the redundancy of

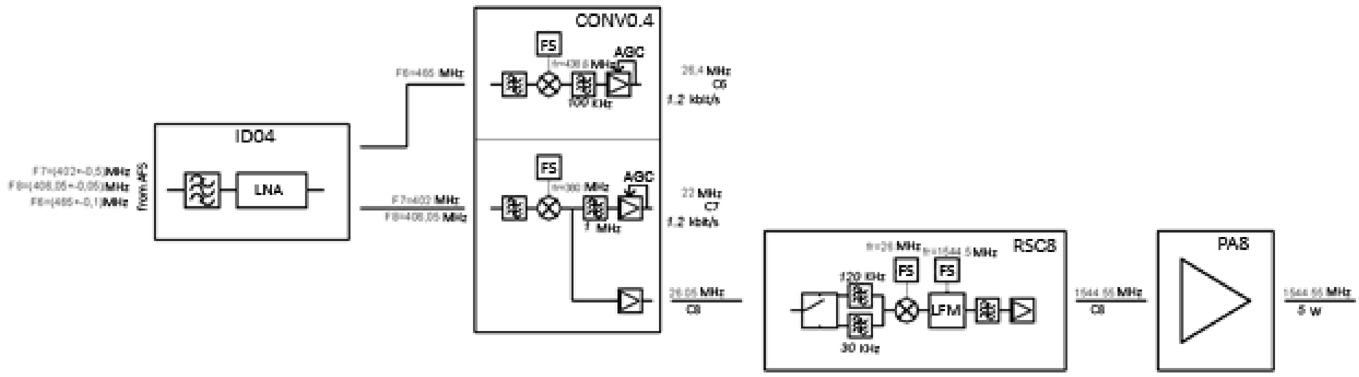

Fig. 2. Enlarged functional diagram of the COSPAS-SARSAT channel of the onboard radio unit of the Electro-L spacecraft, where

ID04 - an input device of the 0.4 GHz band;
CONV0.4 - down converter from the 0.4 GHz band to the 20 MHz band;
RSC8 - response signal conditioner of channel 8;
UM8 - power amplifier of channel 8;
LFM - linear phase modulator;
F6 - the input frequency of the channel C6 - 465.0 ± 0.05 MHz;
F7 - input frequency of the channel C7 - 402.0 ± 0.5 MHz;
F8 - the input frequency of the channel C8 - 406.05 ± 0.05 MHz;
C6 - channel 6 - channel for retransmission of data from data acquisition platforms (DAPs) obtained via low-orbit satellites;
C7 - channel 7 - channel for direct retransmission of data acquisition and transmission system (DATS);
C8 - channel 8 - the COSPAS-SARSAT channel.

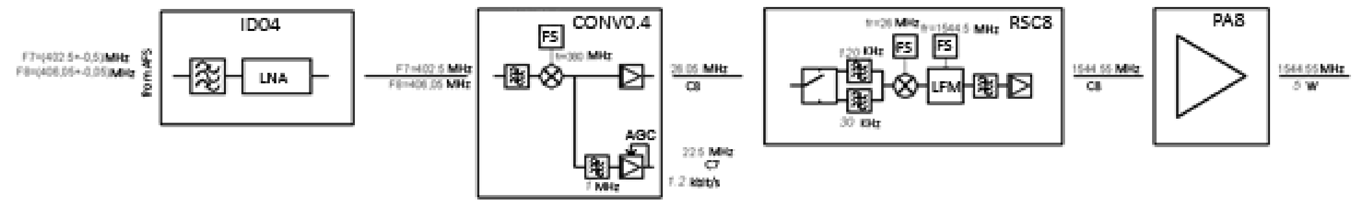

Fig. 3. Enlarged functional diagram of the COSPAS-SARSAT channel of the radio unit of the Arktika-M spacecraft

the bandwidth. Thus, the operation principle of the C8 channel, given in the previous section, is also similar for the COSPAS-SARSAT channel of the Arktika-M onboard radio unit.

The COSPAS-SARSAT channel from the SC of the multifunctional relay space system (MRSS) Luoch-5 series

Meteorological geostationary spacecraft of the Electro-L type are not the only ones equipped for relay of signals from the international search and rescue system COSPAS-SARSAT. Currently, the Louch-5A, Louch-5B and Louch-5V spacecraft, which are part of the Louch MRSS, operate successfully in the geostationary orbit. The Luch-5A and Luch-5V spacecraft have channels for relay of COSPAS-SARSAT signals [6].

Figure 4 shows the enlarged functional scheme of the COSPAS-SARSAT channel from the composition of the Louch-5 spacecraft from the MRSS Luch

According to [6], the relay of the data acquisition and transmission system (RDATS) provides simultaneous retransmission of the signals of the two systems: COSPAS-SARSAT with receive frequency of 406.05 MHz and DATS with receive frequency of 402 MHz. Receipt from AFS is carried out by the RX unit. The RX unit is a low-noise input amplifier that provides the minimum effective noise temperature of the product and a down-converter that shifts the signal spectra from the input frequency range to the IF range (41.375 ± 0.5) MHz for the

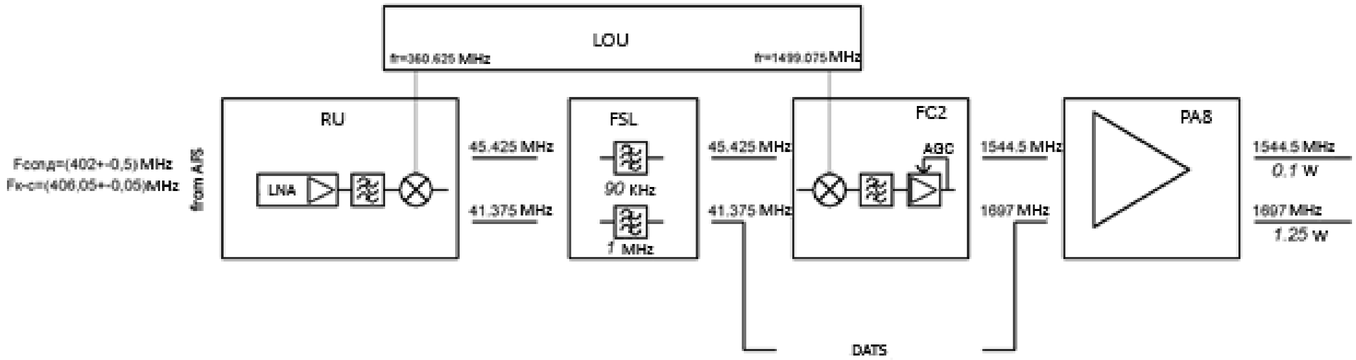

Fig. 4. Enlarged functional scheme of the COSPAS-SARSAT channel from the RDATS of the Louch-5A spacecraft, where
LOU - local oscillator unit;
RU – receiver unit;
FSL - frequency-selective limiter;
FC2 - frequency converter;

DATS channel and (45.425 ± 0.04) MHz for the COSPAS-SARSAT channel. Signals at intermediate frequencies are fed to the FSL unit, which provides narrow-band frequency selection and separation of signals. From the FSL, the COSPAS-SARSAT signal at the center frequency of 45.425 with a 90 kHz band is fed to the FC2 unit, where it is converted to the center frequency of 1544.5 MHz and is fed to the PA. The PA provides simultaneous amplification and transmission of two signals: the DATS signal at a transmission frequency of 1697 MHz and the COSPAS-SARSAT signal at a frequency of 1544.5 MHz. In this case, the output level of the COSPAS-SARSAT signal should be up to 100 mW. Frequencies of the local oscillators, in contrast to the previously considered systems, are formed in a separate LOU.

The BRKS-K1 system from the GLONASS-K1 spacecraft

The BRKS-K1 system installed on board the GLONASS-K 11L and 12L spacecraft [7, 8] is equipped with an integrated LNA providing reception of signals with the minimum standing wave ratio (SWR) and noise factor (NF) at a frequency of 406.05 MHz (Fig. 5). The relay system is autonomous and has no connections with the broadcast signals of other systems. The relay [8] is built on a circuit with a double frequency conversion. The intermediate frequency is 44.9 MHz. At the intermediate frequency, frequency selection is performed by selecting a filter:

- F_{nom} - 44.9 MHz, 2ΔF - 120 kHz;
- F_{nom} - 44.893 MHz, 2ΔF - 90 kHz.

The generated signal is transferred to a frequency of 1544.9 MHz and is fed to the power amplifier.

The BRKS-K2 system from the GLONASS-K2 spacecraft

The BRKS-K2 system, planned for installation onboard the future spacecraft GLONASS-K2 13L and 14L, is currently at the stage of ground tests. Thus, before the completion of the ground tests, it should be considered only as a prospective one.

One of the differences between BRKS-K2 and BRKS-K1 is the removed LNA, which is part of the AFS of the spacecraft. In addition, in BRKS-K2 equipment there are no switchable filters at the intermediate frequency. The signal is selected by a single filter with the Fnom of 44.9 MHz, 2ΔF - 90 kHz. Otherwise, the data relay circuit is similar to the one used in the BRKS-K1 system.

The essential difference between the systems is the presence of a return channel with processing of the acknowledgment signal (AS) onboard for transmission as part of the navigation signal L1OC. From a separate LNA output, the noise-like signal of the AS at the central frequency of 405.928 MHz is fed to the receiver-processor (RX-PRC), which processes, extracts and stores the target information, then the packet is sent to the on-board control complex via the multiplexed exchange channel (MEC) for insertion in the appropriate line of the navigation frame. In addition, the signal from the LNA output goes to another adjacent special purpose system with a similar functional and operating principle.

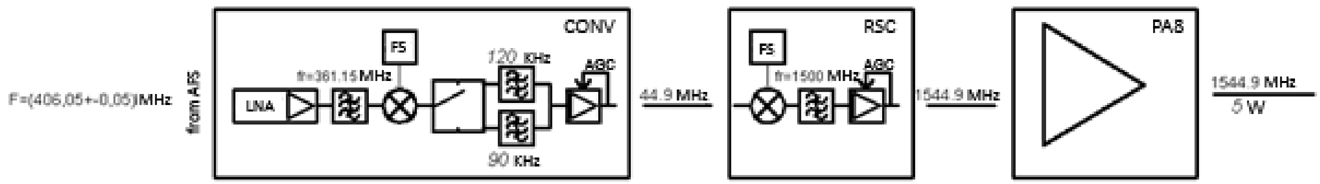

Fig. 5. The enlarged functional diagram of the BRKS SC GLONASS-K1 where CONV - converter; RSC - response signal conditioner.

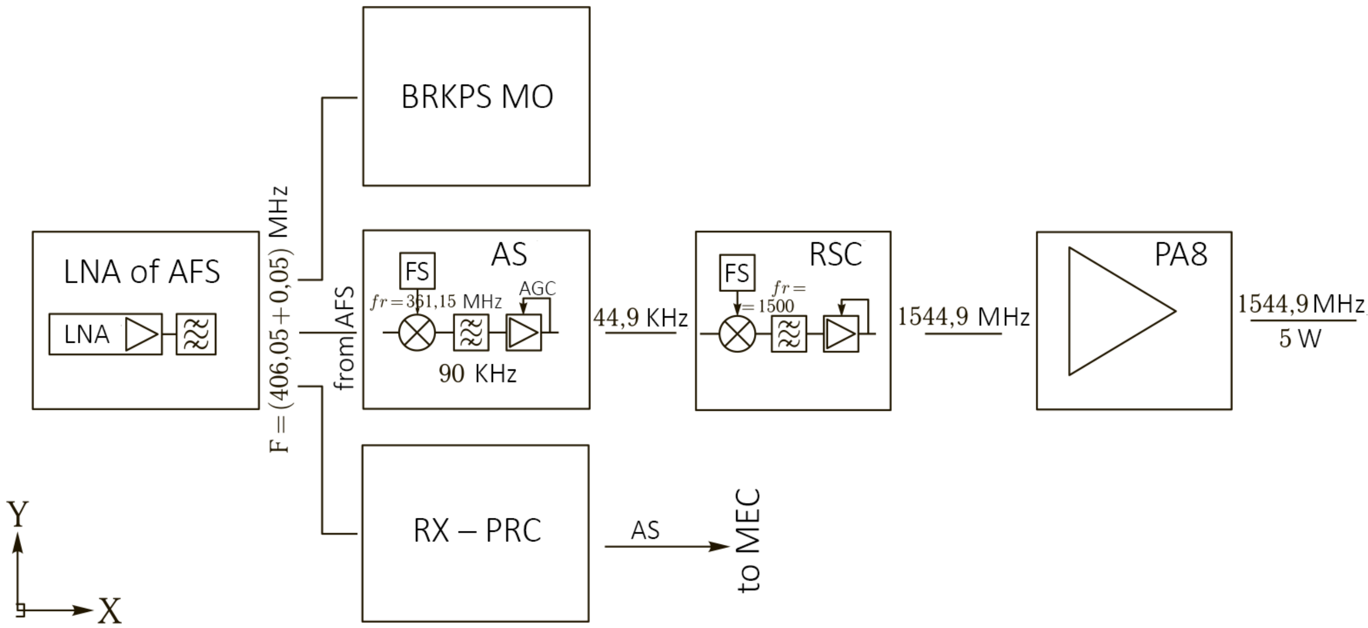

Fig. 6. The enlarged functional scheme of the prospective BRKS-K2 of the GLONASS-K2 SC

Figure 6 shows the enlarged functional diagram of the prospective BRKS-K2 system for the GLONASS-K2 spacecraft.

The BRKS-K2-M system from the GLONASS-K2 spacecraft

At the moment, the modernized BRKS-K2-M system is being developed at the stage of preliminary design, the main difference from BRKS-K2 system is the substitution of imported components with the promising Russian components. The technical characteristics of the system, the operating principle and the functional scheme of the upgraded system are assumed to be unchanged compared to the BRKS-K2 system. Completion of the design and development work is planned for 2020.

Analysis of the characteristics of the onboard equipment of the COSPAS-SARSAT system of various space segments (LEOSAR, MEOSAR and GEOSAR)

As already mentioned above, at present all the complexes for receiving and relaying of the signals of the search and rescue system are created to comply with various requirement specifications, moreover, the products (since they are placed on various spacecrafts) are created at the request of various head enterprises. Therefore, the requirements specification for this equipment, as a rule, do not coincide.

As an example, we can cite the requirements for switching the bus of the onboard network of spacecraft manufactured at various industrial enterprises. Lavochkin

Table 1 The main technical characteristics of COSPAS-SARSAT relays for different satellites

	Channel 8 of Electro-L RU	Channel 8 of Arctic-M RU	BRKS-K1 of GLONASS-K1 SC	BRKS-K2 of GLONASS-K2 SC	COSPAS-SARSAT channel of the Louch-5A RDATS	RK-SM-MKA of Meteor-M No. 2-1 and No. 2-2 SC
Transmission frequency, MHz	1544.55	1544.55	1544.9	1544.9	1544.5	1544.5
Radiation power, W	>4	>4	3-5	3-5.5	0.01-0.1[1]	4-6
Direct retransmission	LFM modulation	LFM modulation	yes	yes	yes	LFM modulation
Processing on board	no	no	no	optional processing of the acknowledgment signal	no	data acquisition, measurement of Doppler frequency offset and the reception time of the packet, data framing
Reverse channel	no	no	no	yes	no	no
Receive bandwidth, kHz	120/30	120/30	120/90	90	90	90
Intermediate frequency, MHz	26.05/26.025	26.05/26.025	44.9/44.893	44.9	45.425	46.05
NF, K^0	160	160	190	150	140	requirements are not imposed
Receiving sensitivity, dBW	-173-173	-173-173	-160	-160	-155	-161
Autonomy	Reception multiplexing with the DATS channel in the range of 402 MHz and MLS in the range of 465 MHz	Reception multiplexing with a DATS channel in the range of 402 MHz	Autonomous system	AS in the L1OC signal, is integrated by reception (LNA) with adjacent special-purpose system	Integration by reception (402 MHz) and transmission (1697 MHz) with the DSP channel	Autonomous system
LNA form factor	Dedicated device with external power supply (+15 V)	Dedicated device with external power supply (+15 V)	Integrated	Autonomous device as a part of AFS	Integrated into RX	Integrated
Service life, years	10	7	10	10	10	5
Operating conditions (orbit)	GSO	HEO of the Molniya type	medium-high circular (h = 19,100 km, i = 64.8)	medium-high circular (h = 19,100 km, i = 64.8)	GSO	Low close to circular (h = 900 km, i = 81.2)

Table 2. Proposals on the unification of COSPAS-SARSAT equipment requirements for various platforms.

Parameter	Value
Transmission frequency, MHz	1544.5 (for the on-board data frame for the LEOSAR and for direct relay for the GEOSAR and HEOSAR) 1544.9 (for direct re-broadcast of the MEOSAR)
Radiation power, W	4-6
Relay type	Direct
Processing on board	1. Data acquisition, measurement of Doppler frequency offset and the reception time of the packet, data framing 2. Acknowledgment signal processing, data framing
Reverse channel	yes
Receive bandwidth, kHz	90
Intermediate frequency, MHz	44.9
NF, K^0	140
Receiving sensitivity, dBW	-173
Autonomy	Reception multiplexing with the DATS channel in the 402 MHz band, with the special-purpose system and a channel for retransmission of DAP data acquired by the LO satellites in the 465 MHz band
LNA form factor	A dedicated stand-alone device with separate power supply, not integrated in the AFS

(the head company for the creation of the Electro-L and Arktika-M) adheres to the principle of switching the negative bus, while the Reshetnev (the head enterprise for the creation of spacecraft of the GLONASS and Luch series) switches the positive bus.

In this paper, the above questions will not be considered. Also, the requirements for complexes for the resistance to the effects of external factors, including mechanical vibration, temperature regime and the impact of space factors, are not considered. Obviously, these characteristics are determined by the type of target orbit and means of launching the spacecraft. When creating the equipment of the COSPAS-SARSAT system, in relation to the specified types of effects, it is necessary to take into account the most stringent requirements currently imposed for each of their types.

The aim of this work is to analyze the technical requirements for the COSPAS-SARSAT equipment intended for installation on various space vehicles of various segments of the international system in order to determine the possibility of their harmonization in the development of the maximally unified solution. The basic requirements for the space complexes of all segments of the COSPAS-SARSAT system are determined by the system documents of the Program [4, 5, 7].

Let us consider the main technical characteristics of the COSPAS-SARSAT signal relay complexes. Table 1 summarizes all the main hardware requirements for different segments: receive and transmit frequencies, sensitivity, modulation type of the output signal, and conditionally (in the form of orbit types) gives the operating conditions.

Analysis of the table shows that the basic hardware requirements for all segments of the international search and rescue system are similar: the complexes must receive signals from beacons in the 406.0-406.1 MHz range, emit a signal in the 1544.0-1545.0 MHz range, the radiated power should be of the order of 5 W.

Nevertheless, there are differences. For example, the level of the output signal of the Louch-5A and Louch-5V SC is significantly lower than 5 W and is 0.1 W at maximum. However, even in this case, the repeater signal is received by the LUT with the signal-to-noise ratio necessary for decoding the information, since the

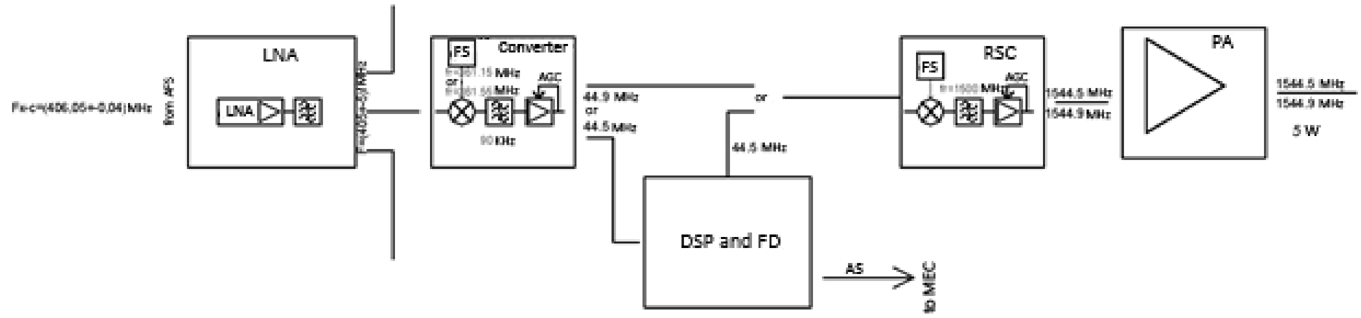

Fig. 7. Enlarged functional diagram of the unified on-board complex of the COSPAS-SARSAT system, where

LNA - low noise amplifier;
AFS - antenna-feeder system;
RSC - response signal conditioner;
PA - power amplifier;
DSP - digital signal processing;
FD - framing device;
FS - frequency synthesizer;
MEC - multiplex exchange channel;
AS - acknowledgment signal;
AGC - automatic gain control.

antenna parameters of the receiving stations were chosen with a significant margin in the design.

In addition, there are differences in the requirements for sensitivity of the equipment. Such a difference can be determined by the altitudes of the orbits on which the corresponding repeaters are supposed to be used. However, the difference, for example, in the types of modulation of the relayed signal is not easy to explain.

It should be noted that design solutions differ, which is clearly demonstrated by the example of LNA implementation. In the case of Electro-L or Arktika-M spacecraft, as well as BRKS-K2 on GLONASS-K2, this is an external device with a dedicated power supply. In the case of the RDATS on the Louch-5A or Louch-5V and BRKS-K1 on the GLONASS-K1, the LNA is integrated directly into the radio units. There is a lack of a systematic approach and a unified scientific and technical policy in the design of onboard equipment for search and rescue systems.

In order to further develop the system to reduce the cost of developing and manufacturing of equipment for different platforms, it is advisable to develop a single and maximally uniform set of requirements taking into account the selection of the most stringent requirements for equipment operating in different orbits.

Based on the analysis of the performance characteristics of the equipment for various platforms, the criteria for maximum suitability and the worst case were used to formulate the general requirements with a view to its unification for future projects. These proposals are presented in Table 2.

The produced requirements take into account the need for signal emission at different frequencies, which is determined by the system requirements of COSPAS-SARSAT for the equipment of LEOSAR, GEOSAR and MEOSAR. In addition, the characteristics of the power of the output signal, the input band, the sensitivity of the intermediate frequency of conversion, and the basic performance requirements are suggested.

Fig. 7 presents the enlarged functional diagram of the proposed unified onboard complex of the COSPAS-SARSAT system.

In accordance with Fig. 7, on the LNA, which provides a noise temperature of not more than 140 K °, the signal is received in the frequency range 400-410 MHz. The LNA should have a sufficient number of outputs to support the operation of the COSPAS-SARSAT system, as well as the DATS system and the adjacent special purpose system.

Currently, the option of creating a unified common converter for the COSPAS-SARSAT and DATS channels is under consideration.

In the converter, the COSPAS-SARSAT signal is converted to the central frequency of 44.9 MHz or 44.5 MHz (depending on the version) and its filtering at the intermediate frequency is performed. Thus, the converter designs differ in the frequency of the local oscillator formed by the frequency synthesizer (FS), and in the filter with a band of 90 kHz at intermediate frequencies.

Therefore, for relays for geostationary spacecraft, such as the Electro-L and Louch series or spacecraft in a highly elliptical orbit, such as Arktika-M, a converter modification with a local oscillator frequency of 361.55 MHz and an intermediate frequency of 44.5 MHz with the appropriate filter setting is required. For a relay for medium-orbiting spacecraft of the GLONASS series, a converter with a local oscillator frequency of 361.15 MHz and an intermediate frequency of 44.9 MHz is required. It is assumed that such a configuration can be implemented through software modifications.

From the output of the converter, the signal is fed to the DSP, where it is digitally processed and information is extracted. DSP will also require different execution of software for different projects due to different input frequencies of the devices. In FRD, a data frame is formed and modulated at 44.5 MHz.

Internal switching of the devices can also be implemented in different ways. So, for the LEOSAR SC of the Meteor series, the signal to the RSC comes from the FRD. That is, relaying is carried out by signal processing followed by modulation. Therefore, direct HF communication between CONV and RSC is not required. In other cases, the signal to the RSC comes directly from the CONV, since only such a link provides direct relaying without processing. In general, DSPs and FDs are not used on relays for the GEOSAR. On-board systems of these spacecraft (the Electro-L, Arktika-M, Louch series) do not provide signal processing on board. DSP and FR are used on GLONASS SC, because they require a reverse channel with on-board processing of the acknowledgment signal (AS) for transmission as part of the L1OC signal. The generated sequence, however, is fed into the onboard control complex through the MEC for insertion into the corresponding row of the navigation frame.

In the RSC, the signal (44.5 MHz or 44.9 MHz) is transferred to the 1544 MHz band (the local oscillator frequency is 1500 MHz), then it is fed to the power amplifier (PA), where it is amplified up to 5 W and is fed to the AFS.

Taking into account the above, it can be concluded that the proposed variant of design of a prospective relay provides all the necessary options for signal transmission under a single unified scheme with the performance characteristics proposed in Table 2 with minimal modifications.

Conclusion

In the article technical characteristics of the existing and future complexes of the search and rescue system COSPAS-SARSAT intended for installation on various space vehicles are considered.

As a result of the analysis, unified requirements for prospective on-board equipment are formed, which, if developed and implemented as a part of the advanced DDWs within the framework of the Russian Federal Space Program 2016-2025 or the GLONASS Federal Target Program, can be installed on low-orbit, medium-orbit, geostationary and highly elliptical spacecraft of the system.

Taking into account the design of COSPAS-SARSAT advanced equipment in the form of a complex of basic elements with severely limited functionality, and also taking into account the need to implement the signal processing function for emergency beacons onboard low-earth orbiting spacecraft, it becomes possible to create a maximally unified search and rescue complex that with minimal reconfiguration can be used onboard any segment of the search and rescue system.

The development of the most unified complex will not only increase its reliability and reduce the costs of development and production, but also fundamentally reduce the time for adaptation to various spacecraft, reduce the required range of electronic products, expanding the list of used Russian-made components, and demonstrate the advantages of using a unified control and verification equipment.

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The Usage of Continuous Engineering Approaches in the Adaptation of the RK-SM-MKA Receiving Complexes for Installation on Board the Meteor-M No. 2-1 and 2-2 Spacecraft

A.A. Romanov, *Dr. Sci. (Engineering), Prof., romanov@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.A. Romanov, *Dr. Sci. (Engineering), Prof., romanov_alal@risde.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
N. N. Bulgakov
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A. N. Ershov
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A. S. Kolobaev
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. The paper gives the results of using the system engineering methods, more precisely, continuous engineering, its relatively new trend, when performing the adjustment of the search and rescue onboard complex for the Meteor-M type spacecraft. The article offers the description of the method for project management aimed at adaptation of the search and rescue complex (item RK-SM-MKA) for installation on board of the Meteor-M No. 2-1 and No. 2-2 spacecraft. The results of its application are also discussed.

It is shown, that building of a separate unit for interface transformation made it possible to install the onboard radio complex as soon as possible, within the scheduled time before the spacecraft launch.

Keywords: system engineering, project management, V-diagram, life cycle phases, continuous verification, continuous engineering

Introduction

To date, we can state that Moore's law is still being implemented, that is, the number of transistors in processors increases twofold every two years. The natural consequence of this law is the ever-increasing complication of products for various purposes, which utilizes the increasing capabilities of the electrical, electronic, and electromechanical (EEE) parts.

At present, the complexity of space technology products has also grown significantly. In addition, the product requirements are constantly increasing in terms of reliability, active life, etc. In some other countries, the 1970-ies were the starting point of the development of the approaches of system engineering [1] (which are now being gradually introduced in Russia), rigidly regulating the phases of the life cycle of the product creation in conjunction with the control procedures of each stage, as well as the verification and validation of the output products, as a part of the design process of products for various purposes. Special visual programming environments and object programming languages [2] are formed that simplify the process of system design of products or the creation of complex systems.

Based on this foundation, many additional approaches are already being developed that make it possible to improve the efficiency of solving problems arising in the design of new products. Within the framework of the present paper, it is proposed to consider the application of "continuous engineering" [3, 4] approaches to the adaptation of the search and rescue complex RK-SM-MKA (Modernized Rescuing Radio Complex for Small-Sized Spacecraft) for its installation on the spacecraft of the "Meteor-M" series.

Continuous engineering (CI) offers methods for the development of enterprises for the successful development of innovative products with ever-increasing complexity and connectivity, taking into account the current (or ever-changing) requirements of the consumer and the market. CI is not a general replacement for system engineering approaches or existing project management techniques. In the framework of CI methods, key project management approaches are being revised through the introduction of activities such as continuous verification, the unblocking of engineering knowledge, and the strategic reuse of the results of previous development projects.

The RK-SM-MKA complex is designed for reception and processing of COSPAS-SARSAT beacon signals [5, 6] and was originally developed for installation on the Sterkh and Obzor-OA spacecraft, which, in accordance with the international obligations of the Russian Federation under the COSPAS-SARSAT [7] program, were to be launched into the orbit, forming the basis of the Russian low-orbit segment. Due to the termination of the Sterkh and Obzor-O projects in 2015, it was decided to install the RK-SM-MKA on board the Meteor-M spacecraft No. 2-1 and 2-2, provided that the aforementioned devices were launched no later than 2017 or 2018.

Taking into account the fact that the time for adaptation of the complex for spacecraft launch was extremely limited, it was suggested to use the "Continuous Engineering" approaches to plan the works on this project, which allows providing a timely delivery of equipment to the head enterprise.

Thus, within the framework of the present work, we propose a description of the methodology for managing the adaptation of the RK-SM-MKA equipment for its installation on board the Meteor-M No. 2-1 and 2-2 spacecraft, and discuss the results of its application.

Continuous engineering

Currently, a system approach to the design of complex products, known as "system engineering", is widely used. Within the framework of the "system engineering" approach, all aspects of product development are considered from the very beginning of the design process and are consistently applied for continuous improvement of the created product [1].

Obviously, during the adaptation of a product originally intended for another spacecraft, taking into account the requirements of the new spacecraft platform, it is necessary to start the design process from the very beginning: to revise and change (if necessary) the basic requirements for the product. However, in this case, it becomes clear that, perhaps, it will be necessary to implement a full cycle of reworking of the complex, which will require considerable time and financial resources.

The well-known modern physicist Stephen Hocking said: "Intelligence is the ability to adapt to change." Accordingly, it is necessary to find such an approach to the product development process, which would at least not reject the changes at various stages of product design [3].

Such an approach called "continuous engineering" was introduced by IBM in 2014. It was viewed by the

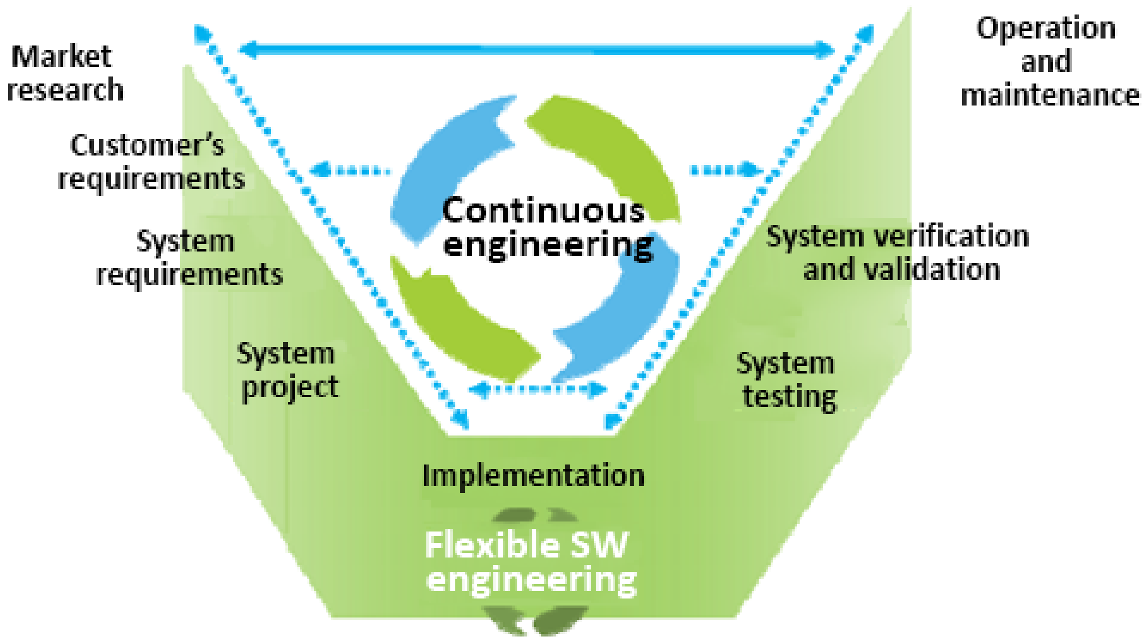

Fig. 1. V-diagram in the representation of CI [3]

specialists of the corporation as the enterprise's ability to create complex electronic products in the interests of the development of approaches and implementation of the Internet of things (IOT) concept [4]. "Continuous engineering" was based on IBM's over 25-years of experience of offering solutions within the framework of the concept of system engineering and the development of software for various manufacturers, including manufacturers from the aerospace industry [8].

CI represents the logical development of approaches to system engineering. It preserves the focus on the system, the levels of abstraction and the basic processes that form the basis of system engineering, but adds a new perspective on how the actions are interconnected [3].

In the framework of continuous engineering, the V diagram of the product or system development process (Figure 1) is no longer a consecutive series of steps; on the contrary, it involves performing actions that are performed iteratively (and most probability in parallel) through the entire product development process, and connects actions and interconnections between engineering, operational and marketing data [3].

The main idea of the CI is to reduce the distance between the current development plans and the current (or newly arising) requirements imposed on the product.

As already mentioned above, the fundamental difference of the CI approaches from the traditional approaches to product design is their focus on the constantly changing requirements for the product, as the commercial success of the product is substantially determined by market requirements that are subject to serious variations. Applying the methods proposed as a part of the CI, it would be possible to change the design of the product in a timely manner if there arises a discrepancy between the technical implementation of the product and its requirements in the process of the continuous verification process.

In order to be maximally ready for constant changes in requirements, a mechanism was proposed (and its advantage is that it does not go beyond the "system engineering" approaches) for reusing the developed products or their components. Moreover, such an approach can be extremely effective for adapting existing products to the changed conditions of their use.

A simple example, given in [3]. If the software product in the product "B" subsystem performs almost the same functions as in the "A" subsystem, it may seem that you just need to copy the program code of the "A" product and modify it to meet the requirements for the product "B" subsystem. At first glance, the proposed mechanism for accomplishing the task will speed up the process of adaptation.

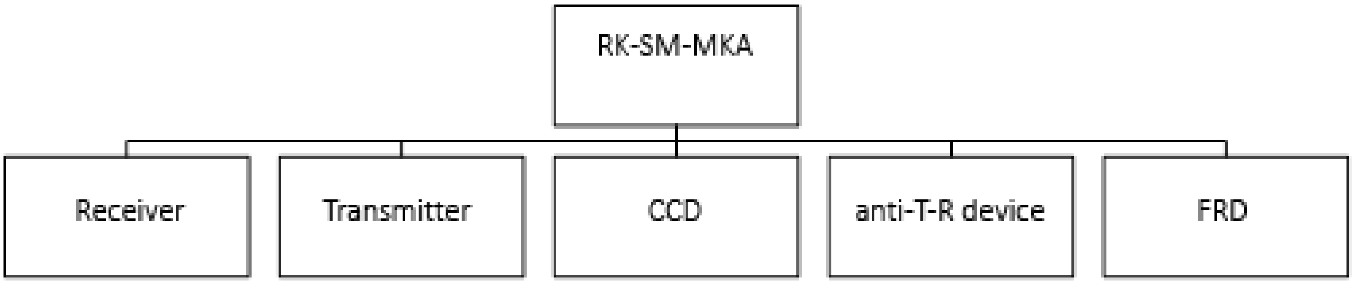

Fig. 2. Structural diagram of the RK-SM-MKA complex

However, if the product code "A" is simply copied and adapted for use in the product "B", the latter product acquires a modified code, and all verification tests with this software will be performed as part of the product "B" verification. One cannot just assume that the results of verification of the product "A" code apply to the product "B", because the product "A" code has been changed. Moreover, if a defect in the product "A" code is found, it will be difficult to determine whether this defect has been eliminated in the product "B" code or vice versa, without carrying out the corresponding work to correct the software of each of the products. That is, in any case, it is necessary to carry out work to eliminate this defect twice. Consequently, the effectiveness of this solution is clearly low.

It is from this point of view that it is more efficient to go by borrowing previously created products. If, while developing the subsystems of the product "A", it is known that the subsystems of the product "B" require approximately the same functionality, one can create technical or design solutions in such a way that the product "B" uses parts of the product "A" design systematically, that is including requirements, test programs, software and other elements, without modifications. In this case, certain components of the product "A" are simply introduced into the design of the product "B", and, as can be seen from the above, such an approach of reusing the results of previous development projects will be much more effective.

In accordance with CI, it is necessary to separate the concepts of "creation of an innovative product" from "development of basic elements or technologies". In the process of creating an innovative product, it should be created by taking advantage of borrowing of the existing technologies or elements that will provide it with competitive advantages in the commercial market.

Development of the basic technologies must be performed independently and before the creation of consumer products, clearly focusing on the needs of consumers or the market as a whole.

Description of the RK-SM-MKA complex

The RK-SM-MKA complex (Fig. 2) is a set of devices for various purposes: a receiving device, a transmitting device, a command-distributing device (CDD), an anti-T-R device, as well as a framing and recording device (FRD), which prepares the information for transmission to the transmitting device of the complex.

The main problem in the adaptation of the RK-SM-MKA complex that occurs when it is placed onboard a Meteor-type spacecraft is the need to transform the interfaces for the exchange of telemetric and command information by modifying or re-designing the FRD of the complex for new requirements, taking into account the changed spacecraft bus. In any case, since the documentation for the complex was previously completely verified and the designation "O" was received, such changes in the equipment of the complex would lead to the need to repeat the cycle of ground testing of the product.

Description of the proposed methodology

When installing spacecraft products on spacecraft that were not originally designed to accommodate the aforementioned complexes, as a rule, it becomes necessary to make significant changes to the design of the finished product, because of the uniqueness of each individual space bus. Unification issues are an extremely important aspect of modern space device engineering, which has finally been given the necessary attention [9], but they are not to be considered in detail in this article.

Changes in design documentation for the adaptation of complexes are caused, among other things, by potential changes in the requirements to layout, interfaces of equipment, as well as resistance to external influences from outer space.

Therefore, when planning and implementing the necessary improvements, as a rule, they begin with the modification of the existing documentation and modernization of the components of the complex to meet the changed requirements, which, as a consequence, leads to the repetition of the entire procedure for ground-based experimental testing of not only the upgraded components, but also the complex in whole. Unfortunately, the optimization process takes a very long time and requires considerable financial resources.

Due to the established practice in the design of the spacecraft, the antenna-feeder complex is functionally a part of the radio complex; therefore, it is developed and manufactured by the space bus manufacturer. For this reason, within the framework of this work, the issues of creating an antenna-feeder complex are not considered, and only the considerations of the development of on-board equipment are given.

During the adaptation of the RK-SM-MKA on board a spacecraft of the Meteor-M type, it became necessary to change the design documentation for the length and structure of the cable network of the complex (due to the re-arrangement of the product for installation on the new bus), the introduction of additional protective casings for some devices to meet more stringent requirements for external influencing factors (IAF) taking into account the changed altitude of the orbit. In addition, the most serious challenge in solving this problem was the need for substantial reworking of the RK-SM-MKA interface to make it compatible with the service subsystems of the spacecraft.

The most obvious solution in this situation was the revision of the FRD device, which carries out information exchange when receiving commands from the spacecraft and transmitting the target information to the radio link. It is necessary to take into account that the RK-SM-MKA complex was manufactured according to the documentation approved for the batch production. Provided that the decision was made to finalize the FRD instrument, taking into account the seriousness of the modifications not only of the on-board equipment, but also of the control equipment, it would be more likely to repeat the cycles of ground-based experimental testing to confirm the corrections to the approved documentation.

In accordance with the contractual documents for the RK-SM-MKA complex, a full cycle of tests and other necessary work is about 24 months, which does not satisfy the delivery time of the equipment required by the bus manufacturer, taking into account the limited time before the scheduled launch of the spacecraft.

Therefore, in accordance with the CI approach, it was decided not to modify the RK-SM-MKA complex in terms of changing the functionality of its devices and to deliver the RK-SM-MKA unchanged.

To ensure the adaptation of the complex, it was decided to develop a special and relatively simple device to perform an extremely specialized interface transformation function which would ensure the transfer of commands to the RK-SM-MKA complex, as well as the information output from the complex to the service systems of the space bus.

Description of the interface conversion unit

The interface conversion unit (ICU-K) is a separate unit, which consists of two independent packages, main and backup, according to the scheme of cold redundancy, which provides the required level of reliability.

The ICU-K accepts the relay commands, a serial 17-bit code of the on-board time scale (OBTS), in the format of the on-board control system of the Meteor-M spacecraft and converts it into a format that provides the RK-SM-MKA equipment control (Figure 3).

ICU-K performs the following functions:

– reception of the second timestamp from the OBCC of the “Meteor-M” SC and its transfer with other pulse parameters to the RK-SM-MKA;

– reception of the serial 17-bit code of the OBTS from the OBCC of the “Meteor-M” SC once per second and saving it in the buffer of the ICU-K (when saving, the previous code is overwritten);

– reception of relay commands from the OBCC of the “Meteor-M” SC and output of an information frame (digital command) with the code of the accepted relay command and the code of the on-board time stored in the buffer of the ICU-K to the RK-SM-MKA via the RS232 interface;

– reception from the RK-SM-MKA of the acknowledgment of the command transmission;

– output of the telemetry about the command transmission to the “Meteor-M” spacecraft.

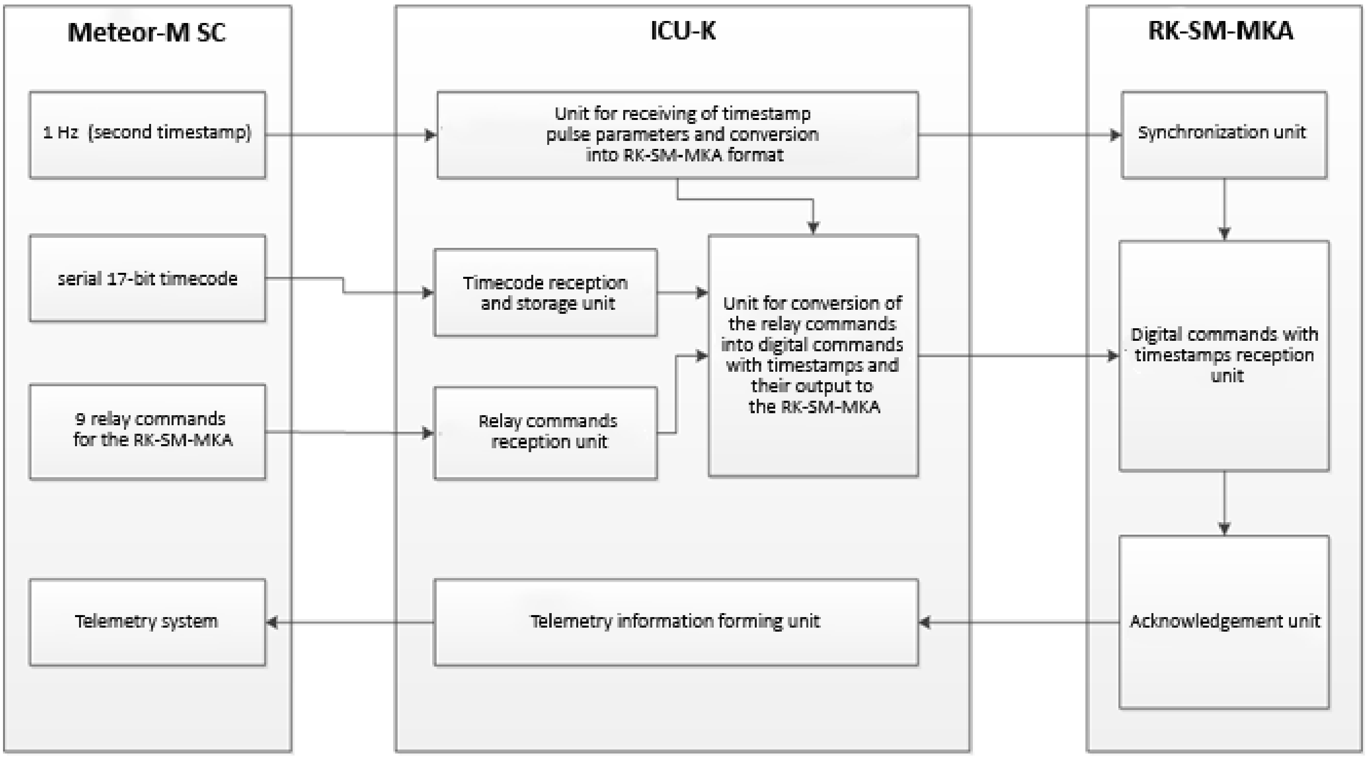

Fig. 3. Scheme of operation of ICU-K

Results of application of the CI approaches

The abandonment of the classical scheme of execution of activities within the framework of system engineering approaches, readiness for a flexible change in the requirements for the system or the final product, made it possible to shorten the delivery time of the equipment significantly. Thus, the term for manufacturing the interface transformation unit (excluding the time of the procurement of the components) was no more than 9 months, including the cycles of ground-based experimental testing.

Taking into account the minimum necessary modifications to the RK-SM-MKA complex, delivery of the equipment was ensured within the timeframe necessary for the scheduled launch of the spacecraft. The forthcoming launch of the "Meteor-M" No. 2-1 spacecraft is very important, because for the first time in many years, a spacecraft with a payload of search and rescue will appear in the low Earth orbit, which will allow Russia to renew its international obligations to the COSPAS-SARSAT Program.

In addition, as part of the import substitution program, when designing the equipment for the interface transformation unit, the basic technologies of programming and functional use of the Russian-made electrical, electronic and electromechanical parts were worked out, which in the future will be used in other development projects of JSC "Russian Space Systems".

Taking into account the gained experience, the developed software (both technological and target), circuit solutions, EEE parts and technological equipment for the use of the Russian-made EEE parts, it can be summarized that a set of engineering "artifacts" was obtained that will improve the efficiency of advanced space device development projects, which is especially important when using the domestic EEE parts.

Conclusion

In conclusion, it should be noted that in this situation, the space industry, both in the Russian Federation and in the world, increasingly loses its "driver" positions in the application of the cutting-edge technologies in device engineering.

Taking into account the rapid development of consumer electronics markets, as well as the change in the current techno-economic paradigm and the constant complication of the developed products, it becomes clear that it is necessary to change the management approaches to the organization of scientific research work and space technology development projects, orienting and adapting (indisputably) the experience of creating devices for the mass market.

It is shown that the application of the continuous engineering approaches based on the basic principles of the classical system engineering can shorten the time of the adaptation of RK-SM-MKA equipment for installation onboard a spacecraft of the "Meteor-M" type.

A method of project management using the approach of strategic re-use of the previously completed CI development projects is proposed. In accordance with the above methodology, it was decided not to modify the RK-SM-MKA complex and to implement the delivery in accordance with the approved documentation. To implement the necessary changes in the adaptation of the product, it was suggested to develop a relatively simple device that performs a substantially limited function: the transformation of interfaces.

As a result, it was ensured that the search and rescue complex was adapted for installation on the new spacecraft within a period not exceeding 9 months, taking into account the need to fundamentally rework the interfaces of interaction with the service subsystems and the complete layout rearrangement onboard the spacecraft.

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Approaches to Accuracy Improvement of GNSS Independent Determination of Position Data of Emergency Radio Beacons in the Medium Earth Orbit Segment of the COSPAS-SARSAT System

V.A. Arkhangel'skiy, *Cand. Sci. (Engineering), varhangelskij@gmail.com*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
V.V. Seleznev, *Cand. Sci. (Engineering)*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. This article analyzes the approaches to improve the accuracy of GNSS independent determination of position data of COSPAS-SARSAT radio beacons by the MEOLUT stations. It describes the differences in the locating process of the Medium Earth Orbit segment of COSPAS-SARSAT and conventional satellite radio navigation systems. A method to improve significantly the frequency measurement accuracy is provided. Increasing the frequency measurement accuracy leads to an improvement in the location accuracy of narrowband radio beacons (the first generation beacons). It is shown that an improvement in the measurement accuracy can be achieved by utilizing the measurements of signal arrival times to a relay satellite and an optimization of the relay satellite selection for pointing of the ground station antennas. Broadband beacons (the second generation beacons) are considered, with the accuracy of their location being significantly higher than that of the narrowband beacons.

Keywords: COSPAS-SARSAT, MEOSAR, frequency measuring method, accuracy, navigation task

Introduction

The most important issue for the Medium Earth Orbit Search and Rescue (MEOSAR) system being created nowadays is the accuracy of determination of the locations of emergency position indicating radio beacons (EPIRBs) independent of global navigation satellite systems (GNSS). A more than 30 years long experience of using Low Earth Orbit segment (LEO) during search and rescue (SAR) operations showed that the accuracy of the independent determination provided in it is not less than 5 km in 95 % of cases is enough to carry out the search of the people in distress. Obtaining the same or better accuracy in the MEOSAR system involves great difficulties, which are caused by greater altitudes of the orbits of spacecraft (SC) in MEOSAR and the signals of short duration and narrow band radiated by distress beacons. Today there is more than 3 million emergency beacons in the world. This paper is devoted to searching the ways to overcome these difficulties and describing the methods, approaches, and algorithms obtained in the result of this research to process the data of the MEO segment of COSPAS-SARSAT received by Medium Earth Orbit Local User Terminals (MEOLUTs).

Preliminary analysis of the methods of the independent determination of the locations of distress beacons in the MEOSAR system

There are two methods to determine the beacon locations by LUTs in the COSPAS-SARSAT system. The first is independent of GNSS, when EPIRB locations are determined based on navigation measurements of its radiated signal. The second is dependent on GNSS, when EPIRB determines itself its locations by means of the GNSS-receiver and encodes them in the digital message, and then these positions are taken from the digital message in a LUT.

It should be noted that not all EPIRBs are equipped with a navigation receiver. Moreover, in course of years, an independent method for determination of positions has showed more reliability than the dependent one. The MEOSAR requirements (5 km in 95% of cases within 10 min after EPIRB activation) are put forward exactly to independent solutions while dependent solutions are considered optional and no requirements are put forward to them. Further, in the article, the determination of locations will be meant as the determination of positions by the independent method.

The MEOSAR space segment are repeaters of EPIRB signals. Such repeaters are placed onboard GLONASS, GPS, and Galileo SC. According to the COSPAS-SARSAT terminology, these systems are SAR/GLONASS, SAR/Galileo, SAR/GPS, and DASS/GPS (SC of the DASS/GPS system are not standard for MEOSAR, however they can be used optionally). For the independent determination of EPIRB locations, MEOSAR has the measurements of time of the reception of the EPIRB signal to relay satellites (RS) (this time is designated as *TOA*) and the measurements of the frequencies of this signal (*FOA*). Each MEOLUT is equipped with four and more information and measurement complexes (IMC), where each IMC receives retranslated EPIRB signals from one of the RS that enables one to have *TOA* and *FOA* measurements from the same EPIRB message, but retranslated over different SC.

Well-known and widely used in space navigation systems methods to solve navigation tasks, i.e., the methods of the independent determination of locations radiated by radio beacons. Actually, with the signal spectrum width equal to 1.6 kHz [1] and real energy potentials of the signals received by a MEOLUT H = 30–35 dBHz, an error of the measurement of the time of signal propagation from the EPIRB to SC will be ~ 20 μs, and, hence, an error to determine pseudorange is σ_D = 6 km. At such an error of the pseudorange, to obtain the accuracy of determination of the location of 5 km with the probability of 95% at the reception of all EPIRB messages within 10 min is possible only at the geometric factor H $DOP < 1$. In fact, this can be obtained very seldom [2].

Using the Doppler method to determine locations in MEOSAR is hindered because of the small duration of the interval, on which it is possible to measure the frequency of the received signal by the ordinary method (0.16 s total) and considerably less derivatives of the Doppler shifts in frequency according to the beacon locations due to a high altitude of the orbits of the MEOSAR SC.

However, the possibility and effectiveness of the solution of the navigation task only on the basis of the frequency measurements of the signals received from several navigation SC was shown quite long ago [3], it is necessary to increase the accuracy of the measurements of the frequencies of the radio beacon signals retranslated by several SC for the application of this concept in MEOSAR.

History of the issue

Since the beginning of the research and development of the MEOSAR system, Russia has paid a great attention for providing a high accuracy of determination of radio beacon locations. The first results of this research were demonstrated at the second meeting of the DASS-SAR/GLONASS (WG-2) working group on March 10, 2006, in Joint Stock Company "Russian Space Systems", Moscow. The more complete results of the research were presented at the fourth meeting of WG-2 DASS-SAR/GLONASS on June 6–8, 2007, in Zheleznogorsk, Russia.

These reports contained the following:

1. At a high measurement accuracy of *FOA* ($\sigma_{FOA} = 0.04\,Hz$), completely deployed space segment (24 SC), and presence of the measurements of all SC in the EPIRB visibility area, the required accuracy for the location determination (≤ 5 km with the probability of ≥ 0.95) is provided at any movements of a radio beacon in any time moment in any part of the Earth. Under such conditions, the obtained accuracy of the locations determination is by 3–8 times better.

2. A combined usage of two completely deployed systems 24 DASS/GPS and 24 SAR/GLONASS in all cases ensures the accuracy of determination of beacon locations not less than 500 m.

3. The accuracy of determination of beacon location based on the measurements only of *TOA* with the error σ_{TOA} = 10 μs is considerably worse.

Several additional results of the research on the accuracy of determination of radio beacon locations for the separate Moscow MEOLUT are given in [4]. The experimental data on the accuracy of the positions of orbitographical, test, and distress radio beacons received by the Moscow MEOLUT in April–May 2014 were presented at the 28th meeting of the COSPAS-SARSAT Joint committee in June 2014.

These data completely proved the above-mentioned results of the theoretical research and simulations. It should be noted that the accuracy of determination of beacon positions received by the Moscow MEOLUT is by 3–5 times better than the accuracy of other countries received by a MEOLUT during "Demonstration and Evaluation" (D&E) phase of MEOSAR in 2015 [5].

The key problem to obtain a high accuracy of determination of locations is obtaining a high (better than 0.1 Hz) accuracy of the *FOA* measurement on the MEOLUT. The issues regarding the methods to calculate *FOA* and the accuracy of its measurement were discussed in details at C/S EWG-2/2009 in March 2009 and at the 23d COSPAS-SARSAT Joint committee. Canada, the USA, the European Commission, and Russia expressed their suggestions on the method and accuracy of the *FOA* measurement, which they implemented in MEOLUTs and concepts on their development. Unfortunately, the discussions of these issues did not result in the agreed opinion of all the participants, and the issue remained open.

Accuracy of *FOA* measurements

The method of the *FOA* measurement implemented on the Russian MEOLUT was described briefly in the C/S JC-23/8/18 document presented by Russia in June 2009. Thus, apparently, the essence of this method and error of measurements influencing the accuracy of radio beacons locations were not quite obvious for the participants of the discussions of the 23d Joint committee, this article gives a more detailed description showing both its methodological and technical sides.

A mathematical definition of *FOA*, as well as the equation of the navigation problem are given in [6]. This paper also shows that to determine beacon positions, it is enough to know the differences of *FOA* (*DFOA*) formed according to the measurements from the same EPIRB message but received through different SC. In this case, the errors of the *FOA* measurements caused by instability of the EPIRB frequency for the same message retranslated through different SC **are completely excluded**.

A potential accuracy of the *DFOA* measurement is determined by the Cramer-Rao inequality equals:

$$\sigma_{DFOA\min} \geq \frac{\sqrt{6}}{2\pi}\left(\frac{1}{(\tilde{N}/N_0)_1 T^3}+\frac{1}{(\tilde{N}/N_0)_2 T^3}\right)^{\frac{1}{2}} \quad (1)$$

where $(\tilde{N}/N_0)_1$ and $(\tilde{N}/N_0)_2$ are the energy potentials of the beacon signals retranslated by the two satellites (the 1st and 2nd respectively);

T is the duration of the measurement interval.

At $(C/N_0)_1 = (C/N_0)_2$ = 35 dBHz and T =0.44 s:

$\sigma_{DFOA\,\min}$ = 0.034 Hz

At $(C/N_0)_1 = (C/N_0)_2$ = 30 dBHz and T =0.44 s:

$\sigma_{DFOA\,\min}$ = 0.06 Hz

Considering the necessary "stock" and losses for realization, the following can be taken: the required accuracy of the *D FOA* measurement should be not less than 0.15 Hz.

Method to measure *FOA* allowing one to obtain the accuracy of determination of *D FOA* close to optimal

As it was shown in [6], to determine beacon positions, it is enough to know only the differences of *FOA* (*D FOA*). It is technically more convenient in the receivers of each channel of the MEOLUT to measure *FOA*, and to obtain their differences when processing these measurements in the algorithm of positions determination. Hence, the paper describes the method to measure *FOA* implemented in the Russian MEOLUT, however, when estimating the errors of measurement, only the errors occurring because of own noises of repeaters and less due to the MEOLUT noises will be considered.

The method described below is patented in Russia [7]. The main idea of the *FOA* measurement used in the Russian MEOLUT, which was written in the C/S JC-23/8/18 document dated 09.06.2012, is the following:

1. Restoration of the pure carrier along the whole length of the beacon owning to the phase modulation with the index message 1.1 rad of the received signal of the message of the reliable information with a reversed sign (remodulation).

2. Measurements of the frequency of this remodulated message using the algorithm providing a potential accuracy.

For better understanding of the concept, below are given a detailed description of this method.

An input information for the algorithm of the *FOA* frequency measurement are complex digital readings of the signal received by the MEOLUT receiver and then transmitted by RS heterodyned in the field of zero frequencies:

$$Z_k = Z(t_k) = S(t_k) + N(t_k) = A_{sk}e^{i2\pi f t_k} + N_k \quad (2)$$

where $t_k = k\Delta t$, $\Delta t = 10\ \mu s$, $A_{sk} = a(t_k)e^{i2\pi\varphi_k}$, $N_k = X_k + iY_k$, $a_s(t_k)\ \varphi_k(t_k)$ is the amplitude and phase of the beacon signal, X_k, Y_k are independent random values with $\sigma_X^2 = \sigma_Y^2 = N_0\Delta f_{noise}$, $\Delta f_{noise} = 80$ kHz is the noise band of the receiver.

This formula has the signal $S(t_k)$ only for one beacon. Actually, signals of several beacons and several interferences can enter Z_k. Further in the description of the algorithm for processing of the Z_k readings, it will be mentioned only the signal of one beacon for simplification of the description. The necessary instructions on the changes or supplements to the algorithm occurring because of the presence of the signals of several beacons and interferences without changing the essence of the algorithms under description will be given in the paper as often as required.

The frequency *f* of the signal $S(t_k)$ in the formula (2) equals:

$$f = (FOA + f_{b.o.RS})(1 - \frac{\dot{D}}{c} + \Delta_{rel.}) - f_{b.o.MEOLUT} \quad (3)$$

where $f_{b.o.RS}$ is the frequency of the beat oscillator of RS,

$f_{b.o.MEOLUT}$ is the frequency of the beat oscillator of the MEOLUT receiver,

$\Delta_{rel.}$ is the relativistic correction,

$\dot{D}$ is the radial velocity of SC relative to the MEOLUT,

v is the light velocity.

The frequency of the beat oscillator of RS is formed from the frequency of the high-stable oscillator of the navigation signal of the satellite and the frequency of the beat oscillator of the MEOLUT receiver radiated by this satellite and equals:

$$f_{b.o.MEOLUT} = (406.05 \cdot 10^6 Hz + f_{b.o.RS})(1 - \frac{\dot{D}}{c} + \Delta_{rel.}) \quad (4)$$

Substituting this value into (3) and taking into account that the sampling frequency of the digital readings of Z_k in the formula (2) $F_{samp} = \frac{1}{\Delta t}$ is also formed from the frequency of the navigation signal received by a MEOLUT, the following is obtained:

$$f = FOA - 406.05 \cdot 10^6\ Hz \quad (5)$$

The possible values of *f* are in the range of $\pm 40\ kHz$.

The phase of the beacon signal $\varphi(t_k)$ equals:

$$\varphi_k = \varphi(t_k) = \varphi_o + 1.1 rad \cdot \grave{I}\ (t_k) \quad (6)$$

where φ_o is the initial signal phase, i.e., the signal phase in the time moment of the beginning of the 25th bit of the digital information of the beacon message (t_{tag}),

$\grave{I}\ (t_k)$ is the function defined by the information put into the beacon message.

$$M(t_k) = \begin{cases} 0 & at\ -22000 \le k < -6000 \\ B(t_k)[2I(n)-1] & at\ -6000 \le k \le 22000 \end{cases} \quad (7)$$

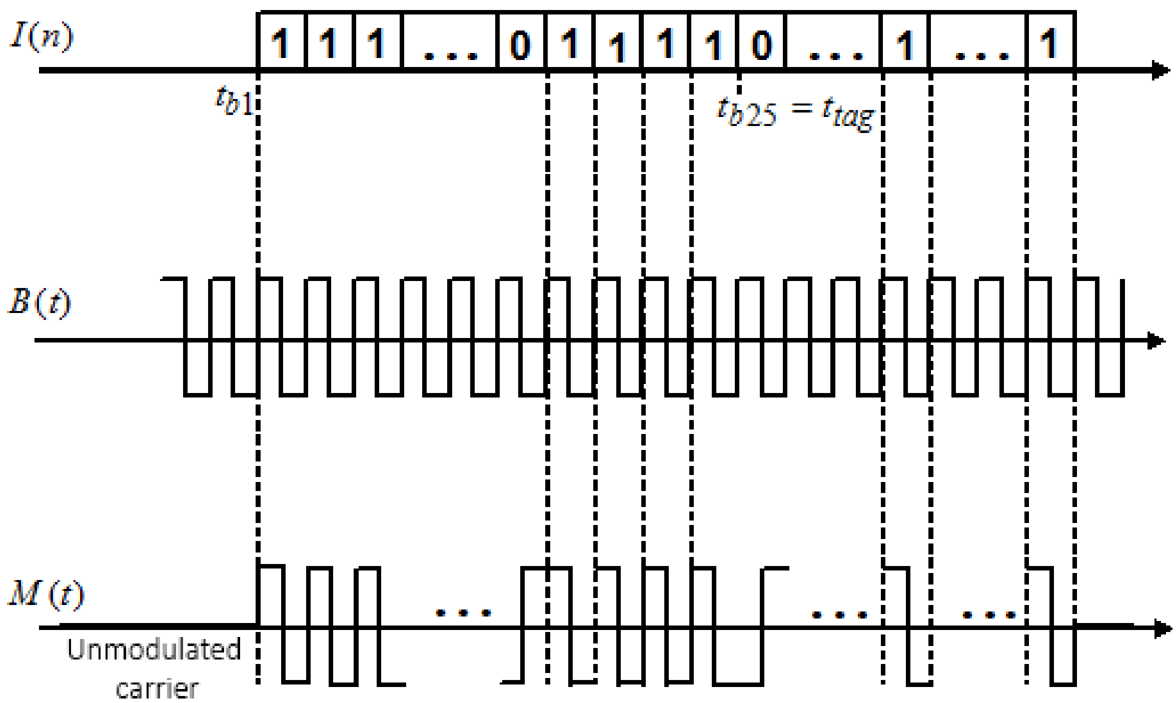

Fig. 1. Diagrams of the functions I(n), B(t), and M(t)

where $I(n) = \begin{cases} 1 \\ 0 \end{cases}$ is the binary digital sequence of the beacon message,

n is the bit number of this sequence,

$B(t_k)$ is the square wave with the frequency $F_B \approx 400\,Hz$, i.e., the period equal to the duration of one bit 2.5 *ms* = 250 Δt,

$$B(t_k) = \begin{cases} 1 & at \;\; t_{bn} \le t_k \le t_{bn} + 125\Delta t \\ -1 & at \;\; t_{bn} + 125\Delta t \le t_k \le t_{bn} + 250\Delta t \end{cases} \quad (8)$$

where t_{bn} is the moment of the beginning of the n^{th} bit,

$t_{b25} = t_{tag}$ is the beginning of the readings of the time in the message, i.e., the time moment $t_0 = t_{tag}$ is taken as the beginning of the reading of the sequence t_k,

$$t_{bn} = t_{tag} - 6250\Delta t + 250 n \Delta t \quad (9)$$

Fig. 1 depicts the diagrams of the functions *I*(*n*), *B*(*t*), and *M*(*t*). These diagrams do not show the time moments t_k.

The algorithm for processing the complex digital readings Z_k from the output of each IMC of the MEOLUT can be divided into four interacting units. Their interacting functional scheme is shown in Fig. 2. An input stream Z_k is received by all units in packets. The beginning of each packet is locked to the timescale of the navigation signal. To do this, one uses the time received from the receiver of the navigation signal received from the same satellite as the MEOLUT signal. The sample rate of the inquiry (100 kHz) is also formed from the received navigation signal. Thus, any Z_k value is precisely locked to the onboard time of RS.

A unit for message detection consists of two algorithms solving the tasks of detection and preliminary (approximate) measurement of their parameters:

1. The algorithm of fast Fourier transform (FFT), which detects a carrier frequency of the message and defines its value (f^*), phase φ_0^*, and $\left(C/N_0\right)^*$, that is the signal-to-noise ratio of the message.

2. The algorithm of the correlation analysis of the presence of Word Clock (the first 24 bits of the digital part of the message that are the same for all messages) and the definition of t_{tag}^*.

Hereinafter, the upper index "*" designates the approximate values of the message parameters. To obtain more precise values of f^* and t_{tag}^*, a quadratic approximation of the discreet values of the main peak of the FFT result and the correlation function (Fig. 3).

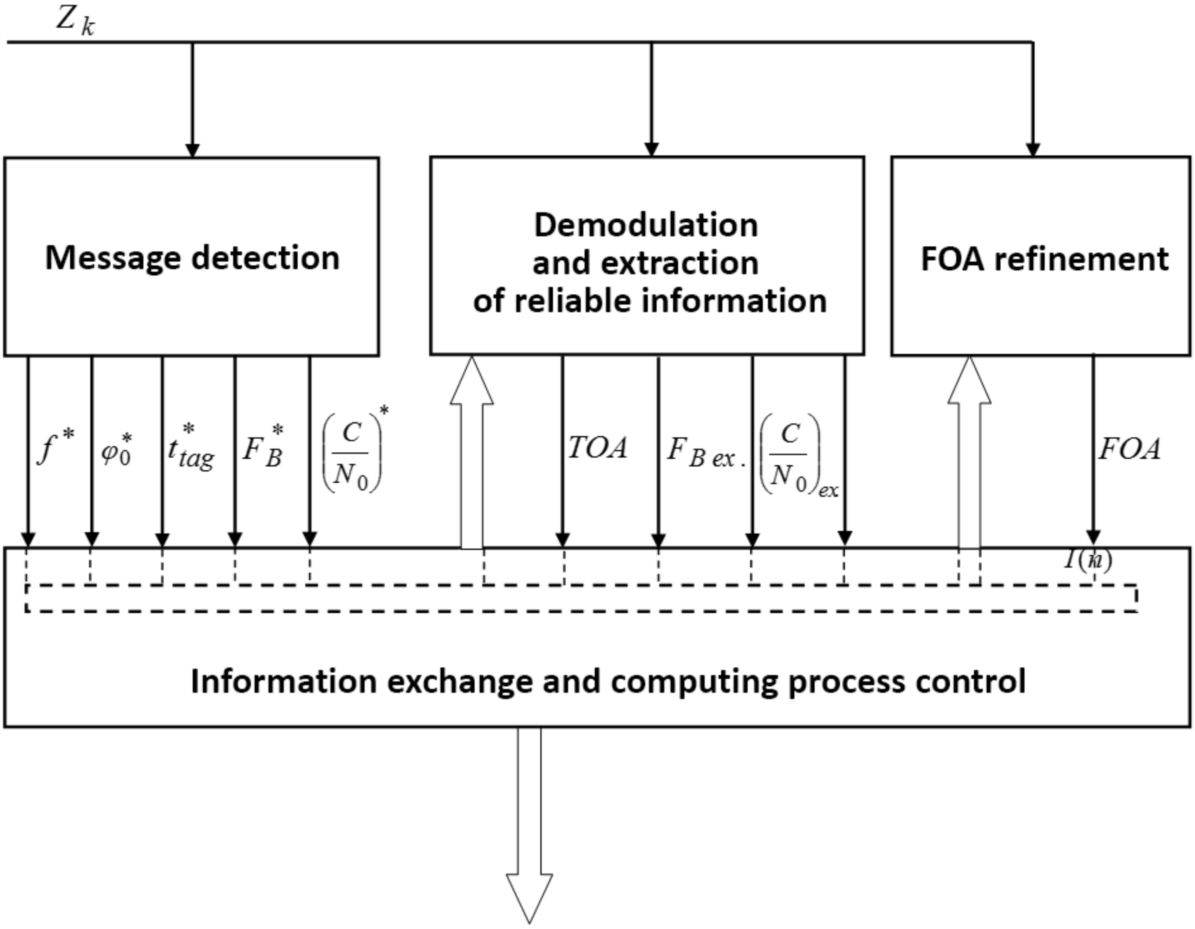

Fig. 2. Functional scheme of the algorithm for processing the complex digital readings from the output of one MEOLUT channel

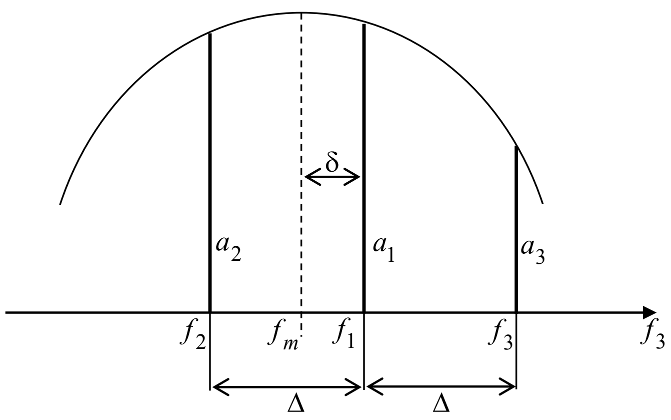

Fig. 3. Readings of the spectrum amplitudes received by FFT in the field of the maximum of its envelope

Three values of the amplitude of the spectrum readings of FFT are used:

1. The maximum – a_1 with the frequency f_1.
2. Lagging behind it by $-\Delta$ at the frequency – a_2.
3. Lagging behind a_1 by $+\Delta$ at the frequency – a_3.

The value of the frequency maximum a in the spectrum is calculated by the formula:

$$f_m^* = f_1 + \delta = f_1 - \frac{a_2 - a_3}{a_1 - \frac{a_2 + a_3}{2}} \tag{10}$$

The same way $t_{tag.m}^*$ is calculated.

Apart from these functions, a unit for the message detection defines the value of the clock frequency of the message (F_B^*) and checks the message for the authenticity, its duration, and position of the time stamp t_{tag}^* in the middle of the message.

The approximate values of the message parameters f^*, φ_0^*, t_{tag}^*, F_B^*, and $(C/N_0)^*$ obtained in the result of the operation of this unit are used by the successive units as the necessary initial data.

A detection unit should detect all messages from all beacons available in the stream of the input data Z_k received from this RS, $(C / N_0)^*$ of which exceeds the set threshold.

A unit of demodulation and extraction of the reliable message using the parameters of f^*, φ_0^*, t_{tag}^*, F_B^*, $(\tilde{N}/N_0)^*$ demodulates the message as it is done in the geostationary segment extracting the information $I^*(n)$ from it and then by means of the BCH decoder corrects all false bits in $I^*(n)$. If this correction was made right, i.e., not more than 2 errors are corrected and, moreover, in Word Clock all 9 bits beginning from 16 to 24 are right, then a message is considered reliable, and it can be denoted as $I(n)$ (without *). If in the result of the BCH decoding and checking Word Clock a reliable message was not able to be obtained, than a process for signal accumulation by summing the corresponding values of Z_k received from two or more adjacent in time messages is activated.

Detection of the messages from the same beacon is made according to the parameters f^* and t_{tag}^*. The message demodulation received in the result of the summation gives a more reliable information ($I^*(n)$), which after the BCH decoding and verification of Word Clock gives a right $I(n)$.

Apart from this main function, the unit for demodulation and extraction of the reliable message specifies the necessary parameters of the message $t_{tag\ exact} = TOA$ and $F_{B\ exact}$ for the exact demodulation.

A unit for *FOA* refinement using the message parameters f^* and φ_0^* defined by the detection unit, and $I(n)$, $t_{tag\ exac}$, $F_{B\ exact}$ received from the unit for demodulation and extraction of the reliable message specifies f^* obtaining in the result a pore exact value f_{exact}, i.e., *FOA*.

The *FOA* value is calculated for **each** detected message including the messages, that do not contain any reliable information received ($I^*(n) \neq I(n)$), and the reliable information $I(n)$ is received after the summation of the signals of several messages.

The received information sequence $I(n)$ can be used to calculate the *FOA* of any message of this beacon, including in the channels of the reception of the signals of this beacon through other RS. Such usage of $I(n)$ considerably increases the number of messages, the *FOA* and *TOA* of which can be measured and, hence, increases the reliability and accuracy of the beacon positions.

The revised *FOA* value is calculated by the formulae, which are the realization of the least squares method for this case:

$$FOA = f^* + F \tag{11}$$

where

$$F = \frac{3I_m\left[\sum_{k=-N}^{+N} Z_k S_0^*(t_k)k\right]}{2\pi a^* N(N+1)(2N+1)\Delta t} \cong \frac{6}{2\pi TN} \cdot \frac{\mathrm{Im}\left[\sum_{k=-N}^{+N} Z_k S_0^*(t_k)k\right]}{\mathrm{Re}\left[\sum_{k=-N}^{+N} Z_k S_0^*(t_k)\right]} \tag{12}$$

In these formulae,

$F = f_{ex.} - f^*$ is the refinement of the preliminary estimation of the frequency f^*,

a^* is the estimation of the amplitude of the beacon signal

$$a^* = \frac{1}{2N}\mathrm{Re}\left[\sum_{k=-N}^{+N} Z_k S_0^*(t_k)\right] \tag{13}$$

Z_k is the complex digital readings of the signal from the input of the receiver,

K is the number of the reading of Z_k.

The time moment $t_{tag\ exact}^* = TOA$ is taken as the zero number ($k = 0$),

$\Delta t = 10\mu s$ is the interval of quantization,

$$N = \frac{T}{2\Delta t} = 22000,$$

$T = 2N\Delta t$ is the duration of the beacon message (440 ms),

$S_0^*(t_k)$ is the standardized (with the amplitude equal to 1) complex-conjugate value of the signal with the values of the frequency f^*, phase φ_0^*, and $I(n)$, i.e.,

$$S_0^*(t_k) = e^{-i[2\pi f^* t_k + \varphi_0^* + 1.1M(t_k)]} \tag{14}$$

$\mathrm{Re}[\ ]$, $\mathrm{Im}[\ ]$ are the real and supposed parts of the complex expression in square brackets.

The formulae (12) and (13) give a rather high accuracy in the determination of *FOA* and a^*, if the error of the preliminary estimation of f^* does not exceed $0.5\,Hz$ that is provided by the detection algorithm described above at $\frac{C}{N_0} \geq 30\, dBHz$. At higher errors of the preliminary determination of f^*, it is possible to make the second approximation to calculate FOA_2 using the *FOA* of the first approximation (FOA_1) in the formulae (11) and (14) instead of f^*.

A mean-root-square error (RMSE) of the measurement of *FOA* due to the noises of the repeater and a MEOLUT equals:

$$\sigma_{FOA} = \frac{\sqrt{6}}{2\pi T\sqrt{(C/N_0)T}} \tag{15}$$

and the RMSE of the message amplitude is

$$\frac{\sigma_a}{a} = \frac{1}{\sqrt{2(C/N_0)T}} \tag{16}$$

At $C/N_0 = 26\ dBHz$, $\sigma_{FOA} = 0.067\ Hz$, a $\frac{\sigma_a}{a} = 5.33\%$

At such estimations, worsening caused by nonideality of the form of the modulating signal and also caused by the errors $t^*_{tag\ exact} = TOA$ and $F_{B\ exact}$ are not taken into account. Thus, the real values of σ_{FOA} and $\frac{\sigma_a}{a}$ are by 1.5 times worse.

At greater (C/N_0), the errors of σ_{FOA} and σ_a will decrease.

Apart from the errors from the noises of the receivers on RS and MEOLUTs, as well as the errors from the frequency instability and phase of the beacon receivers, the *FOA* measurements are also caused by instabilities of the conditions of radio waves propagation in the ionosphere on the routes of their propagation from the beacon to satellites, so called ionospheric errors. Due to different regions of the ionosphere, through which the propagation routes lie, these errors are only partially compensated, and their fluctuations on the interval of the message duration are almost independent.

The conducted estimations of these errors showed that in the periods of a huge solar activity, RMSD of the ionospheric errors of *FOA* can reach

$$\sigma_{FOA\ ion.} = 0.05\ Hz$$

Thus, the sum value of the differencing of *FOA* (*DFOA*) at $C/N_0 = 30\ dBHz$ can reach

$$\sigma_{FOA\ sum} = 0.093\ Hz$$

Other methods to increase the accuracy of determination of beacon locations

As it was mentioned above, such accuracy of the *FOA* measurements (σ_{FOAsum} = 0.093 Hz) will allow one to determine the locations of the immovable beacons at the completely deployed RS system (≥ 24 SC) in any moment of time, in any part of the world with an error of ≤ 2 km with the probability of ≥ 95% when using the *FOA* measurements received from 3-4 SC.

To determine the locations of the beacons moving at the sea under the influence of currents, wind, and rolling of the sea to solve the 6th navigation task (two locations, frequency uncertainty, and three components of the vector of the beacon speed), one needs the *FOA* measurements, received in general case not less through 6 RS being in not less than three different orbital planes. This is possible only at the completely deployed space segment – not less than 24 SC in orbits and not less than 6 antennas in MEOLUTs.

In some cases, the required accuracy of determination of beacon locations moving at the sea with the speed of 3 m/s (6 knots), one can obtain when using a less number of antennas in MEOLUT owning to applying the *TOA* measurements apart from the *FOA* measurements.

To make *TOA* measurements give the required or close to the required accuracy of determination of beacon locations, it is necessary to take all the measures to decrease the errors of their measurements.

The first measure is using the averaged *TOA* measurements within 10–15 min, i.e., receiving about 12–18 measurements through each RS. Such averaging will permit one when there are no nongaussian noises to decrease the error of the *TOA* measurement by 3.5-4 times, i.e., up to the values of 6-8 μs except the achieved ones in all MEOLUTs 20-30 μs. To average *TOA* measurements (as well as *FOA* measurements), there is no necessity in using special algorithms and programs, since this averaging the most optimally realizes the algorithm of the least squares method, which is used for the EPIRB determination in a MEOLUT.

Moreover, it is necessary to reduce the systematic errors of *TOA* measurements caused by uncertainty and instability of delays in signals in the onboard equipment of RS. To do this, the offer of France on an adjustment of RS on signals of the orbitografical and test beacons with the known positions seems the most acceptable. At the same time it should be noted that at such adjustment, a high precision of a binding of the moments of radiation of these beacons is not required, as only the errors of measurements of the *TOA (DTOA)* differences received through various RS, but not the absolute values of the *TOA* errors caused by the delays of each repeater influence the error of determination of beacon locations according to *TOA* measurements (as well as according to *FOA* measurements). When realizing such adjustment of the delays of the signal in repeaters, it is necessary to consider that because of their narrowband, the size of the delays depends on the frequency of the retranslated signal (the phase and frequency characteristic of a repeater is not linear). Therefore, the adjustment needs to be carried out at several frequencies of the beacons operation. The technique of carrying out and processing of an adjustment of the delays has to be developed.

The advantage of this method is that to determine the positions of slow moving EPIRBs at the sea under the influence of wind, rolling, and currents, the measurements received at the same time via 6 RS (since *TOA* measurements do not depend on the speed of the EPIRB) are not required. To receive an error of determination of the positions ≤ 5–7 km with the probability of 95%, *TOA* measurements received from only 4 RS are enough. It significantly simplifies implementation of this method at the not completely developed space segment of MEOSAR. The results of the simulation of determination of moving beacons positions due to the usage of the *TOA* measurements in addition to *FOA* are given in the article [6]. Unfortunately, this method has not received yet an experimental confirmation.

One more method to increase the accuracy of determination of beacon positions is the optimum selection of RS, on which MEOLUT measurements from all visible ones are taken. This method is effective at the insufficient number of antennas on the MEOLUT. The algorithm of the optimum planning of retargeting of MEOLUT antennas on the RS implementing this method is described in [8].

In addition, a very effective method to increase the accuracy of beacon locations, which can and has to be realized in the farther prospect, is a transition in the COSPAS-SARSAT system to use broadband beacons [9]. Except the increase in accuracy of determination of positions to the values about 200–300 m with the probability of 95% beacons moving with any speed (including aviation in falling), this method will allow one to reduce the influence of narrowband interferences from the radio facilities, which are illegally working in the range of the COSPAS-SARSAT frequencies. Unfortunately, the transition of the COSPAS-SARSAT system to completely broadband radio beacons will demand considerable time, apparently, not less than 7–10 years. It is necessary to use above-mentioned ways before this time.

Conclusion

An essential increase in the accuracy of determination of the locations of the first generation beacons in MEOSAR can be received owning to the reduction of the errors of the measurements of the *FOA* frequency caused by own noise of receivers of RS and MEOLUTs by means of the increase in an interval of the FOA measurement up to the full duration of a beacon message. A mean square error of the differences of the *FOA (DFOA)* measurements should not exceed 0.15 Hz that corresponds to the errors of the FOA measurements caused by own noise of RS and MEOLUTs $\sigma_{FOA\text{noise}} < 0.1$ *Hz*.

Some improvement of the accuracy of determination of the locations of the first generation beacons can be reached by means of *TOA* measurements. It is expedient to make averaging of these measurements in 10–15 min and an adjustment of onboard delays of signals in RS according to the signals orbitographical and test beacons. This approach demands the development of the corresponding technique of an adjustment and experimental check. The accuracy of determination of beacons positions only based on *TOA* measurements is much lower, than when using *FOA*, however, under certain conditions, it can be about the required 5 km in some area.

A certain help in the increase of the accuracy of determination of beacon locations can give optimization of the planning of retargeting the MEOLUT antennas to RS minimizing the errors of detection in the MEOLUT service area.

In remote future, an effective method to achieve a high accuracy of determination of the positions (200–300 m) is applying COSPAS-SARAST broadband beacons of the second generation.

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Present State and Main Characteristics of the Geostationary Relay Satellites of the COSPAS-SARSAT System Based on the Louch-5A and Louch-5V Spacecraft

V.A. Arkhangel'skiy, *Cand. Sci. (Engineering), varhangelskij@gmail.com*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
N.V. Dedov, *dedovnik2009@mail.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.I. Litvin, *litvin49@gmail.com*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.I. Ostanniy, *ai-ost@mail.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
V.I. Semin, *semin.50@list.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.V. Fedoseev, *andrewxf@gmail.com*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
M.Yu. Novikov, *munov@mail.ru*
ISS-Reshetnev Company, Zheleznogorsk, Russian Federation
V.A. Portnyagin, *pva@iss-reshetnev.ru*
ISS-Reshetnev Company, Zheleznogorsk, Russian Federation
S.M. Roskin, *rsm@iss-reshetnev.ru*
ISS-Reshetnev Company, Zheleznogorsk, Russian Federation
N.A. Testoedov, *Dr. Sci. (Engineering), testoedov@iss-reshetnev.ru*
ISS-Reshetnev Company, Zheleznogorsk, Russian Federation

Abstract. The paper presents the results of the flight tests of the Russian geostationary segments of the COSPAS-SARSAT system built on the base of the relay satellites Louch-5A and Louch-5V of the Multifunctional relaying space system (MRSS) Louch and ground stations for reception of the data from EPIRBs. The tests have shown high performance characteristics of the relay satellites and the ground stations that are considerably greater than that of the geostationary segments of the countries-manufactures of similar equipment. The geostationary complex included into the Louch-5A spacecraft and into the ground stations in Khabarovsk is ready to operate in the COSPAS-SARSAT system. In 2017, it is planned to put into operation the ground stations for reception in Zheleznogorsk for future introduction into service of the complex based on the Louch-5V spacecraft.

Keywords: COSPAS-SARSAT, search and rescue operations, Russian segment, relay satellite, geostationary complex

Introduction

The geostationary segments (GEOSAR) of the COSPAS-SARSAT system were created by different countries of the world (the USA, the European Union, India, and Russia) in the 90th of the last century as an additional segment of the system for the LEOSAR system. The GEOSAR systems considerably increase the efficiency of detecting the messages of the emergency beacons (EPIRB) comparing to the present LEOSAR systems. Excluding the polar regions, the maximum time of receiving a reliable message in the GEOSAR systems does not exceed 10 minutes that it is significantly less than in the LEO segment where it reaches up to 1.5–2 hours.

Inclusion of the user navigation equipment (UNE) of the global navigation satellite systems (GLONASS, GPS) into the EPIRB makes it possible to detect the EPIRB's coordinates with the accuracy up to tens of meters. If an EPIRB has no UNE, so geostationary satellites of the COSPAS-SARSAT system allow one in due time to distress alerting while the coordinates of the EPIRB in distress are received by means of the LEOSAR system with delay.

The geostationary segment consists of spacecraft in the geostationary orbit with the repeater of EPIRB signals and ground receiving stations. An onboard repeater of EPIRB signals receives messages in the range of frequencies of 406.0–406.1 MHz and relays these signals in the range of frequencies of 1544.5 ± 0.05 MHz to the ground receiving stations, which detect the relayed EPIRB messages and allocate a reliable information from them.

The COSPAS-SARSAT repeaters of signals are established usually on the satellites of another mission as an additional payload. Nowadays the repeaters of EPIRB signals of the geostationary segments of the COSPAS-SARSAT system are placed on the Russian spacecraft Louch-5A (167°east longitude) and Louch-5V (95°*east longitude*) of the Multifunctional relaying space system (MRSS) Louch, the Electro-L spacecraft No. 2 (76° east longitude), and on the foreign spacecraft: the European Union — spacecraft of the MSG series (3.4° west longitude; 0°; 9.5° east longitude); the USA — spacecraft of the GOES series (75° west longitude; 105° west longitude; 135° west longitude), and India — the INSAT-3D spacecraft (82° east longitude).

The ground distress beacon data receiving stations (DBDRS) that successfully underwent tests with Electro-L are used as ground receiving stations for the geostationary ground segment based on Louch-5A and Louch-5V.

The article presents the results of the flying tests of the Russian geostationary segments of the COSPAS-SARSAT system created on the base of the Louch-5A and Louch-5V relay satellites (RS) and DBDRS as well as the results of the international tests of the geostationary satellite search and rescue system based on the Louch-5A spacecraft.

Dependence of the main functional parameter of the geostationary system (SC+ DBDRS) on the characteristics of the relay-satellite

The main functional parameter of the COSPAS-SARSAT geostationary segment is **the probability of receiving a reliable message** ($P_{reliable}$) from the EPIRB which is in the visibility area of the RS for the set time (not more than 5 minutes) [1].

When using RS, the radio line, over which an EPIRB signal is transmitted to DBDRS, is made of two lines: EPIRB–RS and RS–DBDRS.

A general view of the ground DBDRS, as well as of the Louch-5A and Louch-5V spacecraft, are given in Figs. 1, 2.

The probability of $P_{reliable}$ depends on the energy potential (H), i.e., the relation of the signal power P_s to the spectral density of the noise power N_{noise} on the input of the DBDRS receiver, as well as on the parameters of the message signal: the number and duration of the symbols (“bit”) in the message, type and index of the modulation, and method and parameters of the applied code for detection and correction of mistakes. These parameters of a signal of the message in the COSPAS-SARSAT system were chosen in the 70th of the last century when designing a LEO segment of this system [2], i.e., long before the beginning of designing a geostationary segment. By the beginning of this design, a rather big fleet of EPIRBs consisting of several hundred thousand pieces had been created. Therefore, real methods to obtain the required high probability of the reliable message during the creation of the geostationary segments are:

1. Increase in energy potential of the radio lines of EPIRB – RS – DBDRS.

2. Optimization of processing of the signals received by DBDRS, including the opportunity to accumulate the energy of the signals of messages by means of their coherent summation.

Fig. 1. RSDBD placed on the operation station in the Khabarovsk region

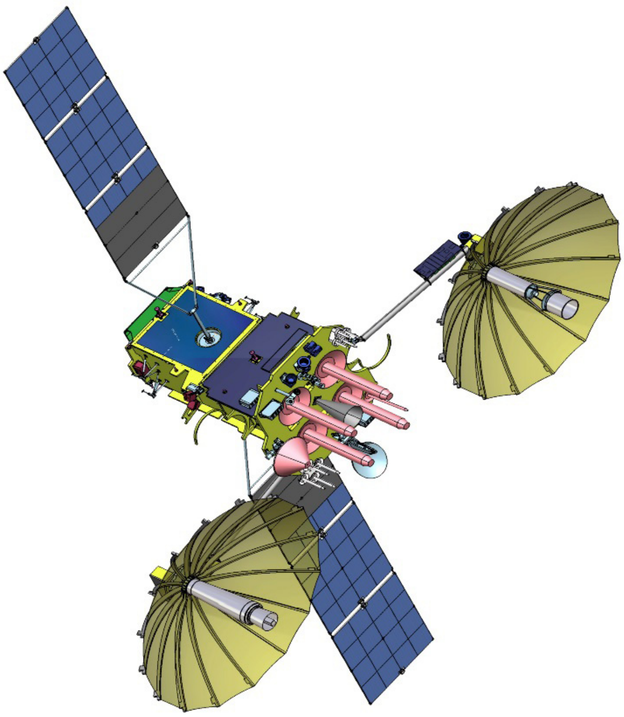

Fig. 22. A general view of the Louch-5A and Louch-5V spacecraft

The Bose-Chaudhuri-Hocquenghem (BCH) error-correcting code chosen in COSPAS-SARSAT contains 82 symbols, from which 61 are information and 21 are for testing, corrects up to three mistakes and detects the even number of errors equal or bigger than four [3].

This code cannot find and, especially, correct an odd number of errors bigger than three, and for any odd number of errors more than three will correct any three and consider this message reliable. To exclude such false messages, only those messages in which no more than two errors are corrected and more than two even errors are not detected are considered reliable in COSPAS-SARSAT. The message with the corrected three errors is considered doubtful.

At such decoding algorithm for the BCH code (82, 61), the probability of the reliable message equals *(allowing for the received message has already undergone checking for the presence of the right bit [15 bits] and frame synchronization):*

$$P_{reliable} = \sum_{k=0}^{k=2} C_{82}^{k} (1 - p_1)^{82-k} p_1^{k} \quad (1)$$

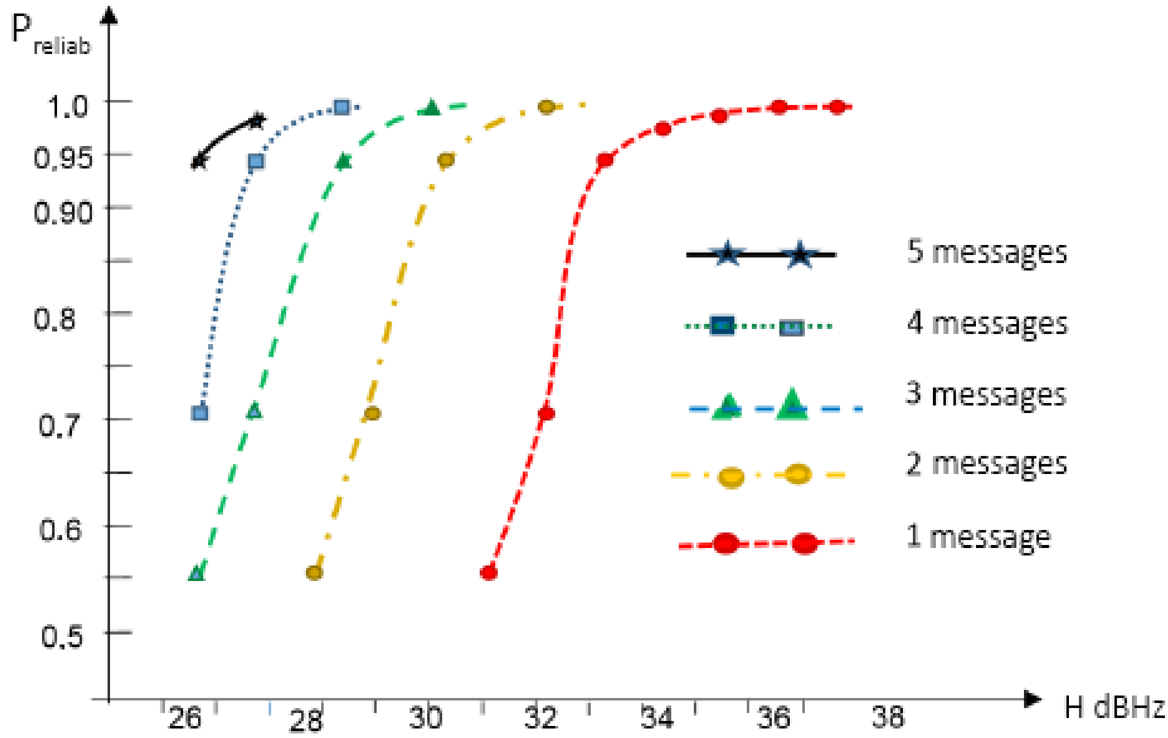

Fig. 33. Dependence of the probability of receiving a reliable distress beacon message on energy potential of the end-to-end radio line and the number of messages in accumulation

where C_{82}^{k} is the number of combinations from 82 on k;

p_1 is the probability of the error of one message bit.

At the optimum processing of the received DBDRS signal, the probability of the error in one bit is [4]

$$p_1 = 1 - F\left(\sqrt{\frac{2E_1 n}{N_{noises}}}\right) = 1 - F\left(L_E\, H \tau\, n\right) \qquad (2)$$

where $E_1 = l_E\, P_c\, \tau$ is the energy of one bit of the received signal;

H is the energy potential on the input of the DBDRS receiver;

τ is one bit duration (τ = 1/s, where s is the speed of information transmission from the EPIRB equal 400 bit/s);

$L_E = m\, l_{realiz}$ is the coefficient of the energy losses of one signal, i.e., a share of the signal power for modulation of its useful information taking into account the losses for realization;

m is the share of the power for modulation of its useful information from the sum signal;

$l_{realization}$ is the losses for realization;

N_{noise} is the spectral density of the power noise in the input of the DBDRS receiver

$$F(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{x^2}{2}} dx \text{ - is the probability integral;} \qquad (3)$$

n is the number of EPIRB messages coherently summed to receive a rather few errors in the message to provide its validity checking when decoding of the BCH code.

Taking in the formulae (1), (2), (3) the values of the loss coefficients m = ‑ 1 dB that corresponds to the losses at the phase modulation with the index 1.1 rad received in the EPIRB [1];

$l_{realiz} = -2\, dB$,

the following is obtained:

$$\frac{E}{N_{noise}} = H - 10\, lg\, c + 10\, lg\, n = H - 26 + 10\, lg\, n. \qquad (4)$$

The calculation results by the formulae (1)–(4) are given in Fig. 3.

As this figure shows, P_{reliab} is defined by the H and n values.

The energy potential of the EPIRB→RS→ DBDRS end-to-end radio line can be calculated by the formula:

$$\frac{1}{H_\Sigma}=\frac{1}{H_1}\left(1+\frac{N_{\text{int}1}}{N_{noiseRS}}\right)+\frac{1}{H_2}\left(1+\frac{P_{\text{int}\Sigma}}{P_{S\,receiver\,RS}}\right)+\frac{\Delta f_{RS}}{H_1 H_2} \quad (5)$$

where H_1 is the energy potential of the DBDRS-RS radio line;

H_2 is the energy potential of the RS-DBDRS radio line;

Δf_{RS} is the bandwidth of the repeater to RS;

$N_{\text{noise RS}}$ is the spectral density of the noises power in the input of the RS receiver;

$N_{\text{int}1}$ is the spectral density of the broadband interference power in the input of the RS receiver;

$P_{\text{int}\Sigma}$ is the sum power of the broadband interference and narrowband interferences operating in the receiving band of RS;

$P_{S\,receiver\,RS}$ is the signal power of the EPIRB message in the RS input.

The formula (5) is a kind of modification of the formula for calculating the energetics of the radio lines in the satellite communications radio systems [5]. When there are no external interferences, this formula is the following:

$$\frac{1}{H_\Sigma}=\frac{1}{H_1}+\frac{1}{H_2}+\frac{\Delta f_{RS}}{H_1 H_2} \quad (5a)$$

The energy potentials of the EPIRB-RS-(H_1) and RS-DBDRS-(H_2) lines are calculated according to the formulae:

$$H_1 = EIRP_{EPIRB}+(G/T)_{RS}+20\lg\left(\frac{\lambda_1}{4\pi D}\right)+L_{mp.}+L_{pol}-228.6\ dBHz/K \quad (6)$$

$$H_2 = EIRP_{RS}+(G/T)_{DBDRS}+20\lg\left(\frac{\lambda_2}{4\pi D}\right)+L_{losses}-228.6\ dBHz/K \quad (7)$$

In these formulae,

EIRP is the equivalent isotropic radiated power of the EPIRB or RS respectively;

G/T is the quality parameter of the reception system of RS or DBDRS;

$\lambda_1 = 73.88\ cm$ is the wavelength in the EPIRB-RS radio line;

$\lambda_2 = 19.42\ cm$ is the wavelength in the RS-DBDRS radio line;

$L_{mp.}$= −2.0 dB is the losses due to the multipath effect in the EPIRB-RS radio line;

$L_{pol.}$ = −4.1 dB is the polarization losses in this line;

L_{losses} = −1 dB is the additional sum losses in the RS-DBDRS radio line.

The losses due to signal propagation in the atmosphere will be considered in additional sum losses in the RS- DBDRS radio line.

All values in the formula (5) are expressed in natural values and the values in (6) and (7) are expressed in decibels.

The analysis of the formula (5) shows that the maximum possible value H_Σ is always less than H_1. If the following is fulfilled:

$$H_2 >> H_1 \text{ and } H_2 >> \Delta fRS \quad (8)$$

with interferences being rather small:

$$N_{\text{int}} << N_{nRS} \text{ and } P_{\text{int}\ \Sigma} << P_{s receiver\ \ RS}\cdot\frac{H_2}{H_1} \quad (9)$$

and the following is met: $H2 > 10H1$, $\Delta f_{RS} < 0.1H_2$, so

$H_\Sigma = H_1 - 1.1$ dBHz.

If the conditions $H_2 > 3H_1$, $\Delta f_{RS} << 0.1H_2$ are met, so

$H_\Sigma \cong H_1 - 3$ dBHz.

Excluding the interference coinciding in the spectrum with the message signal, which cannot be decreased by any increase in H_1 or H_2, other inequalities in (8) and (9) are amplified with the grow of H_2. Hence, to increase the probability of receiving a reliable message, it is necessary to increase H_1 and H_2.

As it can be seen from the formulae (6) and (7), the key parameters that define H_1 and H_2 in the geostationary segment of the COSPAS-SARSAT system and can be changed when creating its separate parts (RS and DBDRS) are $(G/T)_{RS}$, $EIRP_{RS}$, and $(G/T)_{DBDRS}$.

Results of the flight tests of the geostationary segments of the COSPAS-SARSAT system based on the Louch-5A and Louch-5V relay satellites

The *G/T* measurements and definition of the EIRP repeater, as well as the calculation of the probability of reception of the reliable message were carried out based on the Programme and Methodology of COSPAS-SARSAT C/S T.013 [1].

Prior to these tests, the parameter of quality (*G/T*) of the Moscow DBDRS equal 9.8 dB/K was determined. As a result of the taken measurements, the following results were received:

- The equivalent isotropic radiated RS power: EIRP = 26.9 dBmW.
- The parameter of quality of RS: $G/T = -9.2$ dB/K.
- The transmission bandwidth of the repeater according to the level of 3 dB: $\Delta f_p = 80$ kHz.

The probabilities of receiving reliable messages depending on the EIRP of a test radio beacon ($EIRP_{TEPIRB}$) are given in Table 1.

Table 1. Probabilities of receiving a reliable EPIRB message when accumulating the energy of the messages within 5 minutes ($P_{5message}$) and one message ($P_{1message}$)

$EIRP_{TEPIRB}$, dBmW	H_{mean}, dBHz	MSD, H_{mean}, dBHz	$P_{5message}$	$P_{1message}$
32.4	42.2	1.5	1.0	0.97
29.0	37.2	1,3	1.0	0.98
28.0	36.3	1.4	1.0	0.94
26.0	34.9	0.7	1.0	0.90

H_{mean} is the value of the mean energy potential on all radiated message measured on DBDRS, and MSD H_{mean} is its mean quadratic value (σ).

The probability of receiving a reliable message according to the C/S T.009 standard within 5 minutes is 0.99 that is carried out for all values of the radiated power of the test EPIRB. The requirements to receiving a reliable message on the first radiated one in the COSPAS-SARSAT documents are not raised, however the values given in Table 1: $P_{1mess} = 0.98$ for $EIRP_{TEPIRB} = 29$ dBmW, and $P_{1message} = 0.9$ for $EIRP_{TEPIRB} = 26$ dBmW are very good.

The energy store of the COSPAS-SARSAT geostationary complex based on the Louch-5A spacecraft is:

The store of the system is 11 dB (37 dBmW–26 dBmW), where 37 dBmW is the nominal value of $EIRP_{TEPIRB}$ (C/S T/.001 [2]), and 26 dBmW is the smallest value of the $EIRP_{TEPIRB}$, at which the set probability of P ≥ 0.99 to obtain a reliable message established at the tests is provided.

According to the data of Table 1, the actual store of the system is even more. The requirements to the energy store are not made by the COSPAS-SARSAT documents; however, they contain the recommendation to have this store as large as possible, since it will allow one to receive emergency messages at unsuccessful locations of EPIRBs:

- At the location of the beacon's axis close to the direction on RS.
- Presence of the EPIRB in the woods or other powerful vegetation.
- Presence of overshadowing or reflecting objects of the EPIRB radiation close to the EPIRB.

The results of the tests show a very high level of the main characteristics of the geostationary segment on the basis of the Louch-5A spacecraft. To prove this statement, Table 2 will be considered, which includes the main characteristics of the operating geostationary segments of the developments of the USA, the EU, and Russia together with the characteristics of the segment based on Louch-5A.

Table 2. Comparing characteristics of the main parameters of the geostationary segments of the COSPAS-SARSAT system

System / Parameter	GOES, the USA	MSG, the EU	Electro-L, Russia	Louch-5A, Louch-5V, Russia
G/T, dB/K	–18.5	–21.3	–16.5	–9.2
$EIRP_{mean}$, dBmW	45.0	–20.0	50.1	26.9
Δf_p – broadcast bandwidth, kHz	100	180	138	80

This Table shows that the key parameter (G/T) defining the probability of a validated reception of the emergency message at the bad energetics of the of EPIRB-RS radio line, **RS of Louch-5A is much better** than that of all other spacecraft used in other geostationary segments. According to other parameters, Louch-5A corresponds to the requirements and to the level of other RS. The exception makes only a small value of $EIRP_{RS}$. For RS MSG, this value is even less, but the last one uses ground reception antennas with the diameter of 9 m and only 5 m on DBDRS. The influence of a small EIRP on the quality of a geostationary segment will be considered in the following section.

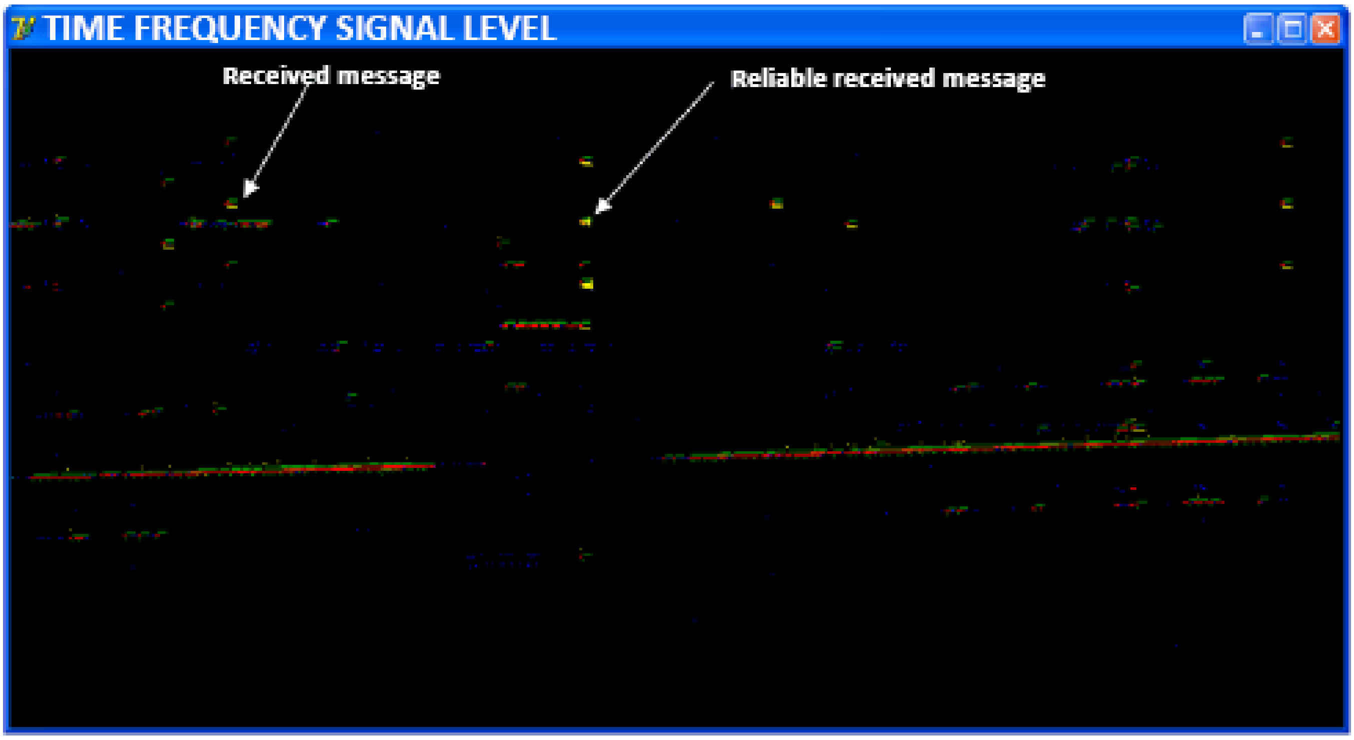

Fig. 4. Frequency and time panorama of the signals spectrum in the input of the DBDRS processor. 26.09.2012, 2 p.m. MSK

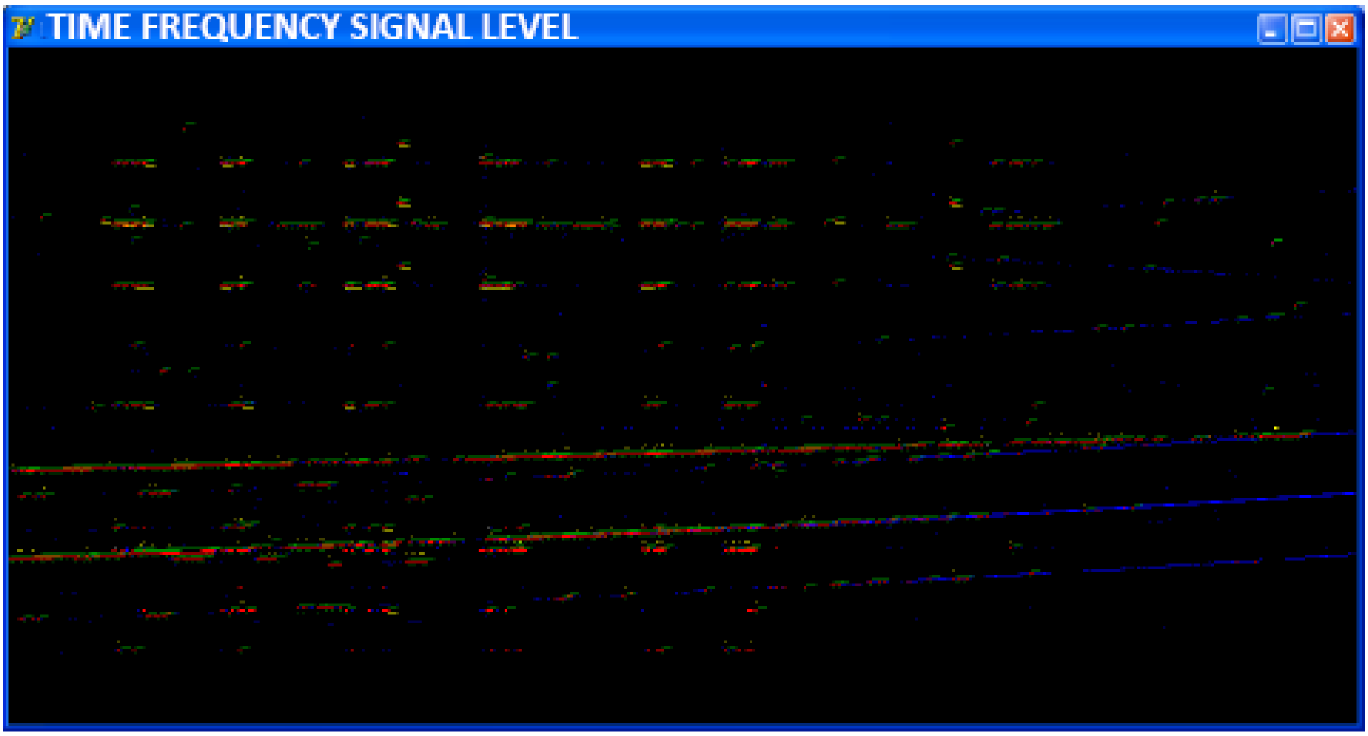

Fig. 5. Frequency and time panorama of the signals spectrum in the input of the DBDRS processor. 26.09.2012, 7 p.m. MSK

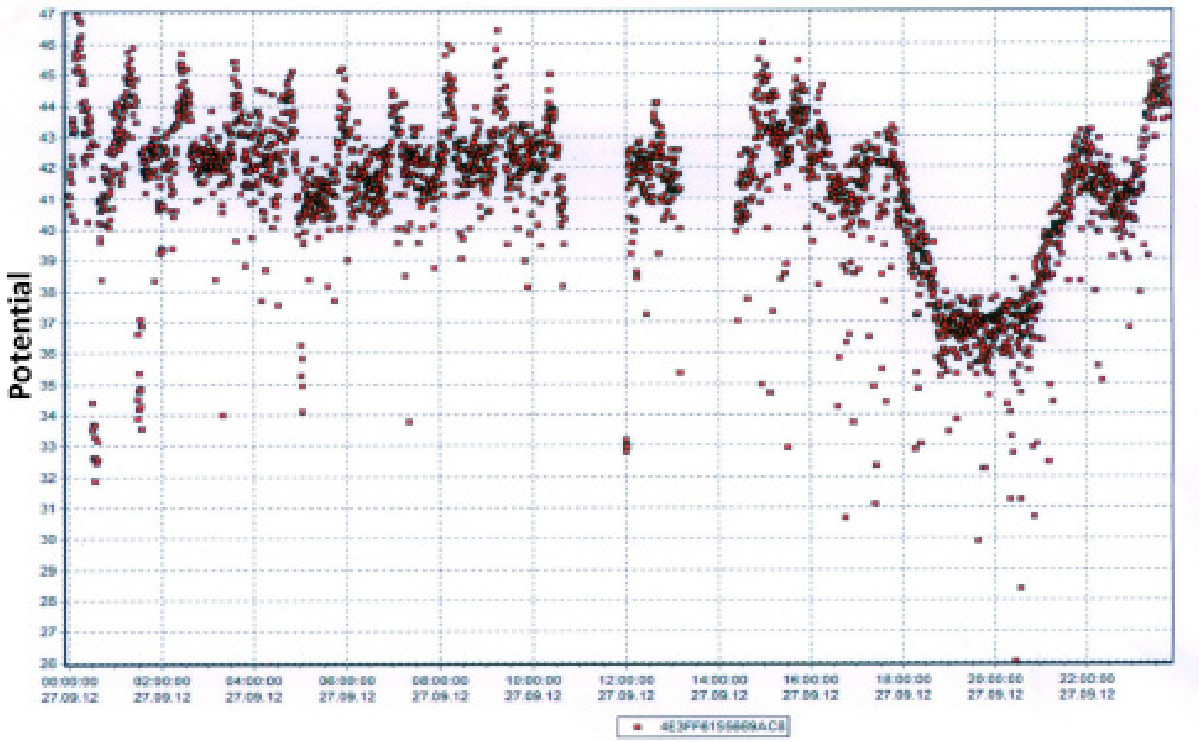

Fig. 6. Energy potential of the ORB of the Kerguelen Islands retranslated by Louch-5A on 27.09.2012

Estimation of the level and influence of interferences on the geostationary segment of COSPAS-SARSAT based on the Louch-5A spacecraft

The research of interferences in the range of the working frequencies of COSPAS-SARSAT 406.01–406.09 MHz and their influence on the operation of the geostationary segment was conducted by two ways:

• A visual observation and the analysis of the time-and-frequency panorama of the accepted DBDRS signal;

• A measurement on rather extended intervals of time the level of the signals received by DBDRSs from the orthographic radio beacon (ORB) placed on the Kerguelen Islands (70° east longitude, 50° south latitude) and constantly, with the period of 30 s, radiating rather powerful (with EIRP ~ 38–40 dBm) signals. When there are no interferences, the energy potential of the received signals of the ORB has to be 48–50 dBHz. Reducing the actually received energy potential of the ORB arises because of the action of interferences. By the value of reduction of the actually received energy potential of the ORB relative to the energy potential of the ORB when there are no interferences, it is possible to estimate the sum power of the last ones.

Figs. 4 and 5 present the examples of time and frequency panoramas received by DBDRS from Louch-5A. The frequency is on the vertical axis and the time (MSK) is in on the horizontal one. The level of interferences is colored: blue is weak, yellow-green is average, and red is big. This level is measured in the band of the elementary filter of fast Fourier transform ≈ 10 Hz. (Figs. 4, 5). The yellow short lines depict the received beacon messages, the yellow horizontal line with the same vertical one after the horizontal one presents the received validated messages.

Fig. 4 is a frequency and time panorama in daytime (2 p.m. MSK 26.09.2012) and Fig. 5 is in evening (7 p.m. MSK 26.09.2012). The analysis of these figures shows that a number and intensity of interferences in daytime are significantly bigger and many messages cannot be reliably allocated.

Fig. 6 shows the dependence of the measured energy potential in the radio line ORB–RS Louch-5A–DBDRS from 12 a.m. to 11 p.m. on 27.09.2012. As this figure shows, in evening (from 6.30 p.m. to 9 p.m. MSK), the potential of the messages was considerably lower (by 5–6 dB) than in another time. This decrease can be explained by the presence in the frequency band of rather strong interferences not coinciding on the spectrum with the messages of the ORB of the Kerguelen Islands.

Fig. 66. Energy potential of the ORB of the Kerguelen Islands retranslated by Louch-5A on 27.09.2012

The sum power of these interferences is about –48 dBW, i.e., by 6 times more than the power of own interferences of a repeater. The same decreases in the potential were observed in other days in almost the same hours. Such decrease of the potential for the ORB placed the Kerguelen Islands due to a big EIRP in no way influenced the probability of a correct reception of its messages. However, for the emergency beacons, which because of the unsuccessful location can have a small EIRP (29 dBmW and less), the decrease in the potential due to such interferences will not allow one to receive the validated messages of these EPIRBs.

Since the increase in the share of the power of the repeater of the transmitter taken for retranslation of the COSPAS-SARSAT signals in the manufactured and placed into orbit Louch-5A is not possible, then it was decided to increase the G/T antenna of DBDRS. This increase could have been done by means of the change of the antenna exciter, LNA, and input filter. The corresponding improvement tests of the DBDRS were made in 2013, and in 2014 two DBDRSs were produced to be placed in the regions of Khabarovsk and Zhelezlogorsk according to the improved documentation.

After installation and putting into operation of DBDRS in Khabarovsk in November 2015, the tests of the geostationary segment consisting of this DBDRS and Louch-5A in the orbital position of 167° east longitude, as well as the tests of this DBDRS and Louch-5V in the orbital position 95° east longitude, were conducted.

The conducted tests completely validated high technical specifications of the RS Louch-5A and Louch-5V obtained during the tests in 2012. A significant (by 5 dB and more) decrease in the potential of the received messages due to the interferences that was detected in 2012 during the tests of the RS Louch-5A with the Moscow DBDRS on the improved DBDRS was not detected. All characteristics of the geostationary segment of Louch-5A and DBDRS in Khabarovsk completely meet the COSPAS-SARSAT requirements T.013 [1], and this segment can be given to the COSPAS-SARSAT Council to put into normal operation.

To put into normal operation in the COSPAS-SARSAT system of the Louch-5V geostationary segment and a DBDRS in Zheleznogorsk, it is planned in 2018 to put into operation this DBDRS and repeat the tests of this segment against correspondence of the C/S T.013 recommendations.

International tests of the geostationary satellite search and rescue system based on the Louch-5A spacecraft

In 2012, the decision of the 57th session of the COSPAS-SARSAT Council approved the intentions of national administrations of the Russian Federation, New Zealand, and the USA to carry out the tests to evaluate the characteristics of the geostationary satellite search and rescue system based the Louch-5A spacecraft to introduce an onboard repeater of this SC to the COSPAS-SARSAT system.

In 2017, after numerous specifications of the terms these tests were launched. The test objectives are:

1) The evaluation of the characteristics of the Louch-5A–DBDRS radio line.

2) The detailing of the COSPAS-SARSAT specifications and standards regarding the requirements to LUT ground stations, which are to carry out reception of signals from the SC of the Louch series.

Carrying out of the tests is made according to the programme and a technique given in the COSPAS-SARSAT document: C/S R.020. According to this programme, Russia is a coordinator of the tests and responsible for functioning of the onboard repeater during the tests and also provides ground reception facilities. New Zealand provides reception through its ground station, and the USA ensures functioning of the simulator of beacon's signals located on the Hawaiian Islands.

Up to the beginning of June 2017, the following tests out of the planned ones had been fulfilled:

1) Test No. 1 "Threshold characteristics of reception, system stock, and efficiency of processing of EPIRB messages".

2) Test No. 2 "Time necessary to form reliable and validated messages".

3) Test No. 4 "Capacity of the channel Louch-5A DBDRS".

Based on the preliminary estimation of the results of the tests No. 1 and No. 2, it is possible to make the following conclusions:

1) The system stock in the geostationary satellite search and rescue system (GEOSAR) according to the

Russian and New Zealand DBDRS makes not less than 11 dB (the difference between the EIRP of a standard beacon in 37 dBmW and the EIRP of the EPIRB at the threshold of reception of messages by the DBDRS) that by 3–6 dB better than a stock in other GEOSAR (MSG, Electro-L, and GOES).

2) The average time of obtaining a reliable message in 95% of cases did not exceed 2 minutes for all EIRP levels of a beacon (from 24 to 37 dBmW).

It should be noted that the obtained preliminary results testify an obvious advantage of the radio line under estimation over the available ones in COSPAS-SARSAT (particularly over the SC of MSG, Electro-l, and GOES series). An indisputable fact also is that the contribution to the improved characteristics of the geostationary segment of COSPAS-SARSAT based on Louch-5A is provided by the COSPAS-SARSAT repeater on the Louch-5A SC.

In the nearest future after completion of the tests, the report on the tests and the recommendation of introducing the repeater into the COSPAS-SARSAT system will be sent for consideration to the COSPAS-SARSAT Joint committee.

Conclusion

The results of the flight tests of the Russian geostationary segments of the COSPAS-SARSAT system created on the basis of the Louch-5A and Louch-5V RS of the MRSS Louch and DBDRSs carried out in 2012–2013 showed a high level of the main characteristics of a geostationary segment based on Louch-5A.

Thus, based on one of the key parameters – G/T defining the probability of the reliable reception of the distress message, Louch-5A is considerably better (up to 10 dB) than the SC used in other geostationary segments of the COSPAS-SARSAT system (SC of MSG, GOES, and Elektro-L series). An energy stock of the radio line (a system stock), i.e., a difference between the EIRP of the nominal emergency radio beacon satisfying the COSPAS-SARSAT [2] specifications and the EIRP values when DBDRS still can fulfill the COSPAS-SARSAT requirements on the probability of allocation of the reliable message made not less than 11 dB that is by 3–6 dB more than for other RS of the COSPAS-SARSAT system.

In 2017, the international tests on the estimation of GEOSAR based on Louch-5A were carried out with the participation of the USA and New Zealand. The preliminary results testified an obvious advantage of Louch-5A over available ones in COSPAS-SARSAT. An indisputable fact is that the significant contribution to the improvement of the quality of characteristics of the COSPAS-SARSAT geostationary segment based on Louch-5A is provided through the relaying equipment available on board the Louch-5A SC. In the nearest future, the report on the tests and the recommendation of introduction of the SC into the COSPAS-SARSAT system will be sent for consideration to the COSPAS-SARSAT Joint committee.

Thus, high tactical and technical characteristics of Louch-5A and Louch-5V RS and ground stations confirmed by the results of national and international tests allow one to make a conclusion that the geostationary segments as a part of these RS and their ground stations are ready to be included into the COSPAS-SARSAT system.

The geostationary segment as a part of the Louch-5A spacecraft and the DBDRS placed in Khabarovsk from the technical point of view are ready to be put into operation in the COSPAS-SARSAT system in 2017. Commissioning of the complex based on Louch-5V will be carried out after putting into service of a DBDRS in Zheleznogorsk.

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