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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

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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 $\sigma_X^2 = \sigma_Y^2 = N_0\Delta f_{noise}$, Δf_{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.

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

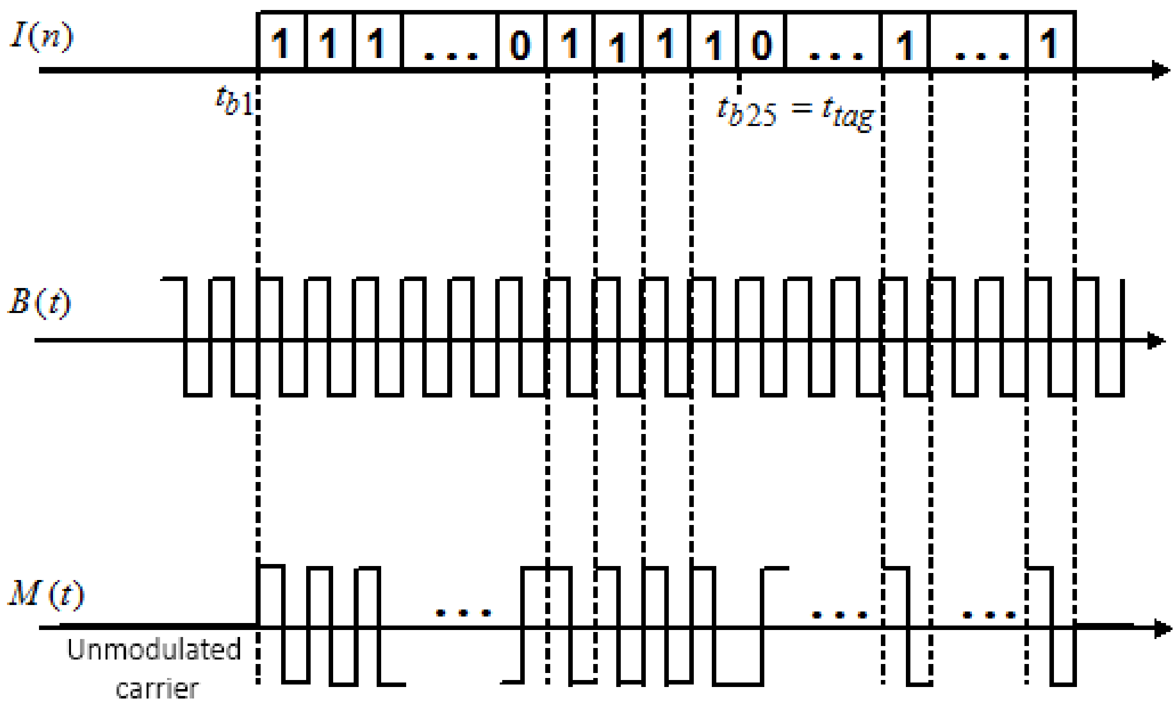

Fig. 1. Diagrams of the functions I(n), B(t), and M(t)

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,

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

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,

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

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 $(C/N_0)^*$, 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).

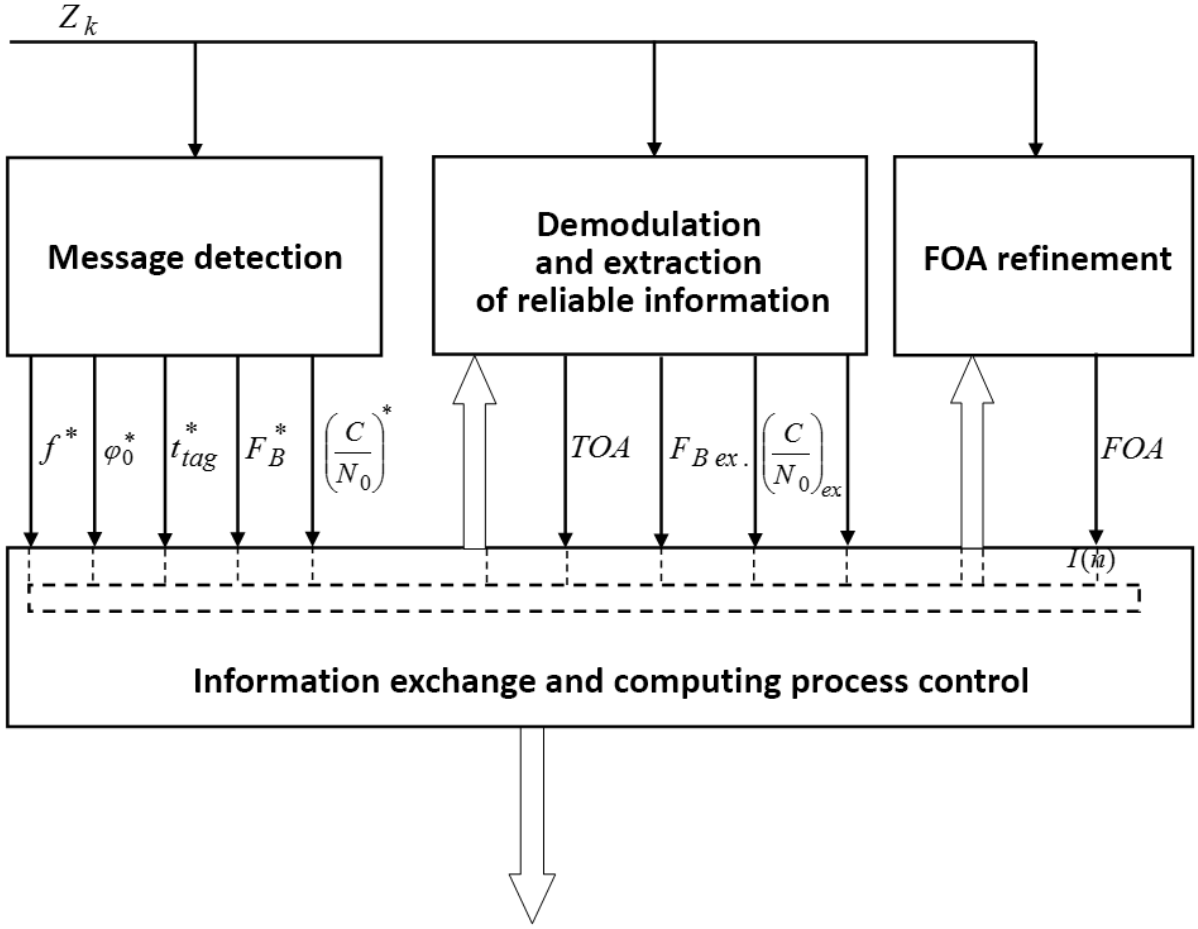

Fig. 2. Functional scheme of the algorithm for processing the complex digital readings from the output of one MEOLUT channel

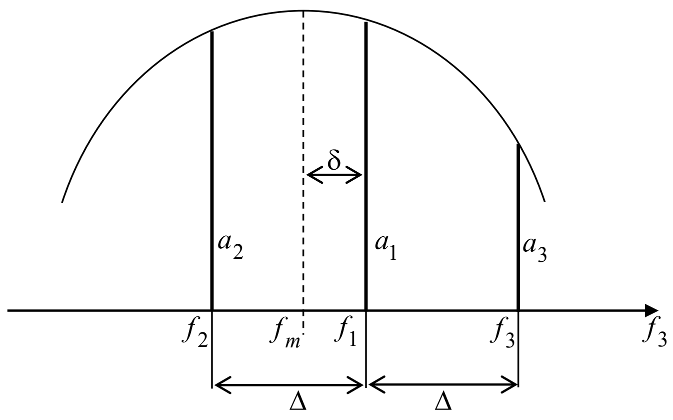

Fig. 3. Readings of the spectrum amplitudes received by FFT in the field of the maximum of its envelope

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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