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## **DIGITAL PHASE-LOCATION SYSTEM FOR MARINE APPLICATIONS**

### **ABSTRACT**

This paper presents concept and implementation of digital phase-location system, de-signed as a navigational aid for marine applications. Main feature of proposed system is the ability to work in both synchronous mode, with one master station and set of slave stations synchronized with master, and in asynchronous mode with independent clocking of all stations.

Key words:

radiolocalization, radionavigation, asynchronous systems, phase-location.

### **INTRODUCTION**

Precise and reliable estimation of watercraft position is crucial not only for effectiveness of maritime operations, but first of all for safety. For more than a hundred years maritime navigation and positioning is aided by various radio-based methods, from omnidirectional beacons and radio direction finders to global navigation satellite systems (GNSS). Satellite systems, such as GPS and GLONASS are nowadays the most frequently used sources of maritime positioning and navigational data. But as these systems are controlled by governments of other countries, relying only on satellite navigation may lead to some security threats, such as limited or restricted availability of navigational service, degradation of position estimation accuracy or even intentional errors in navigational data. Taking it into account, development of independent, ground-based radiolocalization and radionavigation systems for domestic use

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should be considered as important part of national security. Nowadays the Polish section of Baltic Sea is not covered by any fixed, ground-based positioning system. Swedish chains of Decca [3] have been switched off at the end of XX century, most of transmitters in European eLoran network ceased operation in 2015, and the east-European chain of Russian system Chayka does not cover the Baltic Sea area. But Polish Navy is still using an analogue phase-location system called Jemiołuszka, developed over 30 years ago. Unfortunately, parameters and capabilities of Jemiołuszka are limited and cannot fulfill users' expectations, especially in the field of accuracy and reliability. Taking into account limitations of Jemiołuszka, experience gained during tests of radiolocation system with spread spectrum signals [1] and requirements for medium-range mobile radionavigation system, defined by Polish Ministry of National Defence, authors decided to build a digital phase-location system for marine applications. Unfortunately, medium range positioning systems with ground transmitters are not widely described in literature. Majority of publications in field of radio-based position estimation focus on indoor positioning or improvement of satellite-based solutions. Only few papers can be found which presents modern implementation of outdoor positioning systems, for example in [4] the Doppler frequency principle is used to estimate position of moving receiver, while in [2] a new method of aircraft position estimation is presented, based on synchronous hyperbolic location principle. None of these solutions fits requirements defined by Ministry and these systems cannot be treated as direct replacement of analogue system Jemiołuszka. Taking it into account a new digital phase-location system for marine application has been developed in laboratories of Gdansk University of Technology. Unique feature of proposed system is the ability to work in two modes: synchronous — classic solution with designated master transmitter and chain of synchronized slave transmitters, and asynchronous — where all the base stations are clocked from free-running oscillator, without synchronization [7]. Asynchronous emission allows to improve system reliability due to elimination of a single point of failure, which is the master station in synchronous systems.

## PRINCIPLE OF OPERATION

Digital phase-location system in medium frequency (MF) band was designed to combine the advantages of measurements of phase differences between signals received from a set of transmitters in fixed positions (high resolution of measurements,

wide range of operation) with high reliability of asynchronous solutions. Unfortunately positioning systems based on phase measurements have one major drawback, caused by ambiguity of distance estimation due to periodicity of phase measurements as a function of position. The same value of phase differences, recorded by mobile receiver, may refer to wide range of propagation path length (distance) differences from base stations to receiver. In classic phase-location systems this disadvantage results in need to estimate initial position of receiver using other sources (e.g. manual data entry), and after that the receiver must count occurrences of zero phase difference measurements which designates next hyperbolas of possible position. It means that the accuracy of initial position data in classic solution is comparable to half of a radio wavelength, so for medium-wave system it must not be worse than several tens of meters. Simultaneous transmission of positioning signals on two different frequencies allows to decrease required accuracy of initial position estimation, but the problem of dependence on external sources of positioning data remains. All these drawbacks can be found in Jemiołuszka system: initial position of receiver is taken from integrated GPS receiver or is manually entered, and since that position of receiver is estimated using unmodulated pulses transmitted by base stations on two frequencies on MF band with ratio between them equal to 10:9. Data transmission between base stations and mobile receivers is not possible, so the receiver operator must also enter the coordinates of transmitters.

In proposed, digital phase-location system, the base stations (BS) are transmitting positioning signals on almost any two frequencies in range 1.6 MHz to 2 MHz (ratio 10:9 no longer needed). These signals are BPSK-modulated and all the base stations in one network are working on the same pair of channels using TDMA technique. Transmitted signals contains data packets with coordinates of all the base stations and parameters of mathematical models allowing to predict phase differences between signals from any pair of transmitters. One emission on one frequency lasts 120 ms (total time, including transmitter switch on/switch off, synchronization preamble, useful data and forward error correction) and is transmitted in 125 ms long time slot. In a network consisting  $N_{BS}$  base station (minimal number of transmitters:  $N_{BS} = 3$ , but in order to improve system reliability by redundancy, real system should be built with at least 4 stations) emission of signal by a given transmitter on a given frequency is repeated every  $2 \cdot N_{BS} \cdot 125$  ms. Figure 1 presents example of emission arrangement on two frequencies in the network made by four base stations.

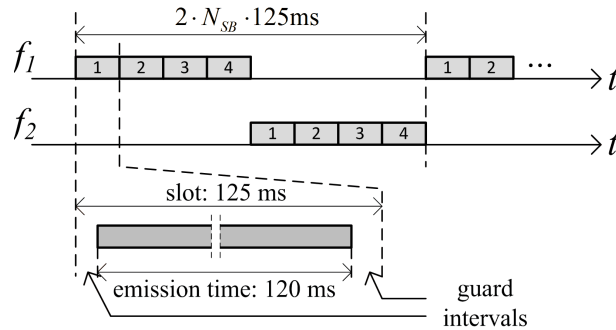


Fig. 1. Structure of positioning signals emission in time and frequency domain [own study]

In the classic, synchronous systems, time of emission of all signals from set of synchronized transmitters will be automatically maintained during whole time of operation. In contrary, in asynchronous version, independent clocking of all base stations will cause slow, but systematic drift of not only initial phases of transmitted signals, but also position of transmitted packets in TDMA time slots. In order to ensure possibility of interference-free reception of all signals by mobile receivers and estimation of its' position, all the base stations contains additional receivers for reception of signals from other base stations. It allows all stations to track carrier phase differences and time of emission of all received signals, estimation of phase and time change rates, and finally to model these changes by prediction models in a form of linear equations. It has been verified in laboratory, that when transmitters are clocked by reference clock with short term stability of  $10^{-9}$  or better (see data in table 1), even simple linear prediction models are sufficient for accurate prediction of phase differences during time up to several tens of seconds since last update of linear equations coefficients, while in proposed system models are updated at least once per 5 seconds. Parameters of prediction models are then broadcasted by all base stations, alternately with its' coordinates and system messages to all other nodes: base stations and mobile receivers. Therefore the base stations maintains two-way communication on the basis of broadcasts (one to all), while communication of base stations and mobile terminals is one way only, so the network may provide positioning service to unlimited number of mobile receivers. The concept of data exchange in proposed system is presented on figure 2 [5].

In order to get fully automatic system operation, the problem of unknown initial position of receivers had to be solved. It was achieved by additional measurements of differences in time of arrival of all radio packets based on correlation of samples of received radio signals with locally generated templates, consisting the same

stream of bits (modulated, baseband signal regenerated from decoded data packets). Time of signal reception is estimated with subsample resolution using bank of fractional delay filters [6]. But even in case of high signal to noise ratio, estimation of time of reception by correlation is performed with accuracy two orders of magnitude worse than measurements of phase differences. So in order to combine data from both methods of measurements, the receiver generates histogram of time of reception for several tens of data packets, which is then approximated by Gaussian function. Maximum of this function indicates the most probably value of distance differences expressed by measured difference of received phases and variable integer multiplicity of half wavelength, after subtraction of predicted difference in emission of signals from base stations using linear prediction models.

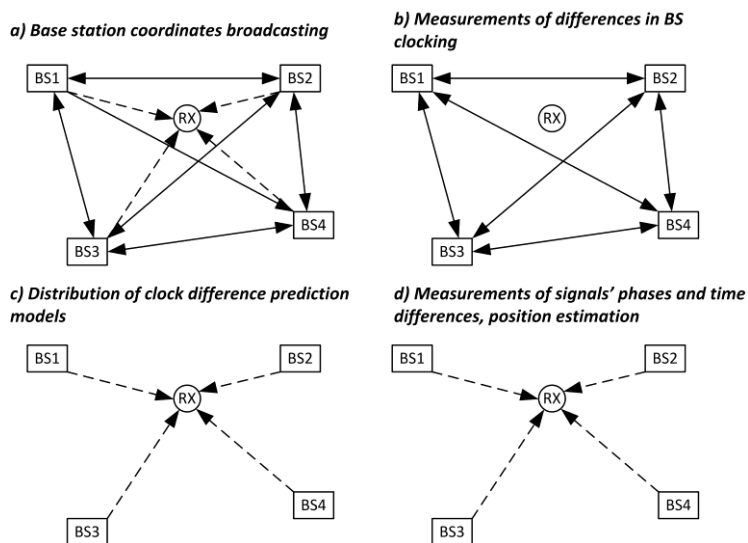


Fig. 2. Measurements and data transmission in phase-location system in asynchronous mode [own study]

### PROTOTYPE OF DIGITAL PHASE-LOCATION SYSTEM

Prototype of digital phase-location system was built in mixed form. The transmitters are based on dedicated hardware, while receivers were made using commercial, general purpose receivers EM550 from Rohde&Schwarz, equipped with additional frequency converters allowing to extend range of reception to cover band 1.6 MHz to 2 MHz. The prototype consists of four base stations, all of them consisting

transmitting and receiving part, and one mobile positioning receiver, with the same structure as receiving part of base stations. Block diagram of phase-location system base station is presented on figure 3, while figure 4 shows one exemplary base station used for laboratory tests. All the prototypes may work in both synchronous (master-slave) and asynchronous modes.

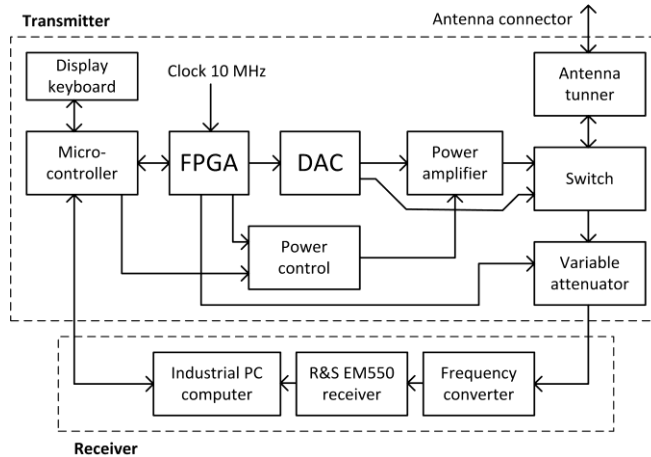


Fig. 3. Block diagram of phase-location base station [own study]



Fig. 4. Base station prototype: dedicated transmitter (top) and commercial receiver (bottom) [authors' photos]

Positioning signals are generated in digital form by FPGA. Signal generation chain in FPGA consists of carrier generator based on digital direct synthesis (DDS), packet generator, coder, digital modulator and filter. Stream of samples at the input of digital to analog converter (DAC) represents signal on desired transmission frequency, not in the baseband, so the output signal from DAC is directly amplified and transmitted without need for analog modulation or frequency conversion. This allows to achieve high repeatability of parameters of all transmitters, required by correlator-based estimation of time of signals' reception in receivers.

Mobile positioning receiver and all receivers in base stations were made using software defined radio (SDR) concept. Stream of I/Q samples from EM550 receiver is transmitted via Ethernet interface to industrial PC computer. Dedicated software, written in C, is responsible for demodulation, detection of packets, data interpretation, as well as measurements of differences in phases of received carriers and measurements of differences in time of reception of data packets via correlation. In addition, SDR receiver software in base stations calculates parameters of models used for prediction of differences in base station clocking. Software of mobile receiver is also responsible for final estimation of differences in distances from base stations, calculation of current coordinates and position presentation in selected coordinate system.

### LABORATORY TESTS

Laboratory tests were performed using prototypes of four base stations and one mobile receiver. All devices were connected only using antenna connectors via variable attenuators, allowing to change level of received signals in range between  $-114$  dBm (limited by packet error rate equal  $10^{-1}$ ) and  $-50$  dBm. Transmitters were working on frequencies  $f_1 = 1.8$  MHz and  $f_2 = 1.85$  MHz with independent sources of reference clocks: rubidium oscillators, crystal oscillators with temperature stabilization (ovenized) and crystal oscillators without stabilization. All the tests were performed in stable state, after preparation of prediction models in asynchronous mode or after slave synchronization in synchronous mode (approx. 95 seconds). Mobile receiver is able to return first position estimate 5 seconds after cold start and to update results after reception of any new radio packet (up to 8 times per second).

Due to fact, that emulation of variable delay of radio signals in laboratory is not an easy task, authors decided to test the prototype of phase-location system with equal propagation delay between all transmitters and mobile receiver. Assuming that all four transmitters broadcast their coordinates corresponding to corners of a square, mobile receiver should return its position in the centre of square, which simplifies evaluation of system errors. The value  $MEd$  in table 1 is a mean value while  $RMSEd$  is a root mean squared value of distance difference estimation error. Values  $ME_{xy}$  and  $RMSE_{xy}$  are mean and root mean squared values of final position estimation error respectively. Values presented in table 1 were calculated from a series of 1000 consecutive measurements, during which mobile receiver was clocked from EM550 internal oscillator while receivers and transmitters in base stations were clocked by independent oscillators of various kind.

In most cases (except asynchronous mode with transmitters clocked from low quality crystal oscillators without temperature control, short term stability limited to  $10^{-7}$ ), RMSE values are limited to much less than half meter, reaching few centimeters when transmitters are clocked from stable frequency sources (short term stability  $10^{-9}$  or better). Performance of phase-location system in both synchronous and asynchronous modes is comparable, with little predominance of asynchronous one. It is mainly caused by limited step of phase correction in DDS frequency synthesizers in FPGA. Due to fact, that most sources of reference frequency 10MHz doesn't allow for fine tuning, synchronization of emission in slave transmitters in synchronous mode is performed in DDS with step of phase correction equal  $0.36^\circ$  which limits accuracy of synchronization. In contrary, in asynchronous mode, all receivers performs phase measurements with resolution better than  $0.1^\circ$ , therefore allowing for higher precision of modelling differences in clocking in asynchronous mode.

Tab. 1. Distance difference measurement errors and position estimation errors measured in laboratory [own study]

Reference frequency source	MEd [m]	RMSEd [m]	MExy [m]	RMSExy [m]
<b>Synchronous mode</b>				
Rubidium frequency standard ( $10^{-11}$ )	-0.141	0.199	0.153	0.160
Ovenized crystal oscillator ( $10^{-9}$ )	-0.098	0.168	0.118	0.129
Crystal oscillator without temperature control ( $10^{-7}$ )	-0.126	0.283	0.175	0.203
<b>Asynchronous mode</b>				
Rubidium frequency standard	-0.052	0.106	0.071	0.080
Ovenized crystal oscillator	-0.073	0.110	0.080	0.085
Crystal oscillator without temperature control	0.026	1.051	0.764	0.858

## CONCLUSIONS

Presented prototype of digital phase-location system has all the advantages such as high resolution and accuracy of position estimation, without disadvantages caused by unknown initial estimate of position in other systems of such kind. In addition, ability to work in asynchronous mode, without selection of master station and



synchronization of all slave transmitters, improves system reliability. Fully automatic estimation and compensation of all the possible phase/time delays caused by various components of base stations significantly reduces list of tasks which needs to be performed by transmitter operators, while mobile receivers don't require any supervision at all.

It should be noted that all the tests and results of error analysis were performed only in laboratory. Therefore, presented values of position estimation accuracy don't include negative effects, which may be introduced by radio propagation phenomena in real environment. Therefore, some further tests are needed to evaluate full parameters of proposed system in real scenarios in maritime environment.

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# CYFROWY SYSTEM FAZOŁOKACYJNY DO ZASTOSOWAŃ MORSKICH

## STRESZCZENIE

Artykuł zawiera opis działania oraz budowy prototypu cyfrowego systemu fazolokacyjnego. System ten został zaprojektowany do obsługi nawigacji morskiej, przy czym jego cechą charakterystyczną jest możliwość pracy zarówno w trybie synchronicznym, z wyróżnioną stacją główną oraz zestawem stacji podległych, jak i w trybie asynchronicznym, w którym wszystkie stacje bazowe są taktowane niezależnie z własnych generatorów wzorcowych.

Słowa kluczowe:

radiolokalizacja, radionawigacja, systemy asynchroniczne, fazolokacja.