

A Novel Ranging Code based on improved Logistic Map Chaotic Sequences

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Abstract— Spread-spectrum technology is widely used in communication system particularly in Global Navigation Satellite System (GNSS) to achieve a better ranging accuracy. This makes spreading code (also known as ranging code) so important that any change of it would directly influence positioning accuracy, compatibility, anti-interference, security, and receiver performance. Therefore, research on ranging code could provide theoretical support for the improvement of the performance of ranging codes and extension of their design methods to future satellite navigation signal structures. Chaotic sequence is not predictable and non-periodic so that has great auto-correlation and cross-correlation characteristic. However, the code balance of chaotic sequence is barely satisfactory, in this paper, a novel ranging code is proposed and we will give the details of the ranging code design process based on improved Logistic-map chaotic sequences and m code. Then the code select criteria based on even/odd correlation functions and Welch bound have been set up to compare different code sets which include the proposed code, common GPS code, common Beidou code, and Random code. Theoretical analysis and simulation results show that the proposed ranging code cannot only maintain excellent performance in the acquisition, tracking, and anti-interference performance as the GPS L5I code but also significantly improve balance performance to strong balance constraints and improve code length flexibility.

Keywords— ranging code, chaotic sequence, improve Logistic map, m code, balance

I. INTRODUCTION

The ranging code is the fundamental element of the navigation system. The design goal of the ranging code is to achieve better communication performance and ranging accuracy [10]. It is directly related to the basic functions of location, time service, and velocity measurement as well as to the key performance indexes of positioning accuracy, compatibility, interoperability, security, anti-interference ability, etc. The properties of ranging code have a great influence on the performance of acquisition, tracking, demodulation, anti-jamming, secrecy, and so on[6]. So, the study on the design and evaluation of ranging codes is necessary. Generally speaking, there could be four parts to design a set of ranging code which are code criteria, code design, code select, and code allocation [12].

During the development of GNSS, there are many code design method such as a linear feedback shift register (LFSR), the theory of numbers, etc. [9], [11]. The cross-correlation function of conventional ranging code has large peaks and the correlation function is periodic so that the code has poor anti-multi-access interference performance, poor anti-interception performance, yet the code set is small. Chaotic theory, however, gives us another option to construct a new type of code compared with conventional ones. Chaotic sequences are sensitive to initial values, have strong confidentiality and anti-interception with respect to traditional m pseudo-random sequences[8], and can provide a large number of non-correlated and random-like reproducible signals [1]-[5]. but chaotic sequences also have their shortcomings, especially for poor balance. The balance coefficient is often bigger than 0.02 when sequence length is relatively short, which cannot satisfy the requirement of high-precision positioning systems[10].

The purpose of code selection is to select a subset of code that meets the selection criteria. Different application may have different select criteria. These criteria are mainly based on the auto- and cross-correlation functions [3], except the index of code balance. After the code design, we have a large code set. When the final code selection process finished, we can get the good code set [6], [7].

The ranging code allocation is a process of establishing a ranging code associated with a specific satellite signal. The purpose of the allocation is to further optimize the navigation service performance under the condition that the ranging code, signal structure, and spatial topology keep unchanged. However, the length of the article is limited; the code allocation will not be discussed [12]. In this paper, the selection criteria are set up and a compound ranging code based on chaotic sequences and m code is proposed, then the proposed code performance have been analyzed.

II. CODE CRITERIA

According to Shannon channel capacity theorem, Shannon's best signal theory, A. A. Kharkevich's anti-multipath fading theory, the best spreading signal is white noise, thus the ideal auto-correlation function is impulse function and the ideal cross-correlation function is exactly zero at every delay. So any deviation to ideal characteristics may have a side effect.

A. The communication perspective

In addition to the target signal, the signal entering the receiver also includes the multipath signal, the multiple access signals from other satellites, the external interference signal, and the thermal noise, this section we will focus on analyzing code acquisition in respect of communication perspective. We will discuss the code tracking which is related to ranging performance later on the next section.

Welch bound is the theoretical minimum of the maximum value of auto- or cross-correlation functions that can be obtained for a given set of M codes of length N . It is defined as:

$$\phi_{min} = N \sqrt{\frac{M-1}{MN-1}} \quad (1)$$

1) AMEWS_{MP}

The acquisition process is a three-dimensional search in the code phase space, the frequency space, and the code set space. Any non-zero autocorrelation sidelobe and non-zero cross-correlation values will have an impact on the capture performance, and the greater of the value beyond the Welch boundary, the larger of the effect. The mean value (EWSD) corresponds to the autocorrelation sidelobe and cross-correlation function, which can be divided into EWSD_{MP} describing the influence of multipath signals on the acquisition. EWSD_{CT} describing the effects of the multiple access signals on the acquisition.

$$MEWSD_{MP} = \frac{1}{n_{fd}} \sum_{n_{fd}} \frac{1}{2} \left[\sum_{l=1}^{n-1} \left(\frac{AC^e(l, fd) - \phi_{min}}{AC^e > \phi_{min}} \right)^2 + \sum_{l=1}^{n-1} \left(\frac{AC^o(l, fd) - \phi_{min}}{AC^o > \phi_{min}} \right)^2 \right] \quad (2)$$

The AMEWS_{MP} can be obtained from the average of all ranging codes in a code set:

$$AMEWS_{MP} = \frac{1}{M} \sum_{i=1}^M MEWSD_{MP,i} \quad (3)$$

where AC^e and AC^o are the even and odd auto-correlation function.

2) AMEWS_{CT}

The impact of different satellites on the acquisition can be calculated by MEWSD_{CT} and AMEWS_{CT}:

$$MEWSD_{CT} = \frac{1}{n_{fd}} \sum_{n_{fd}} \frac{1}{2} \left[\sum_{l=0}^{n-1} \left(\frac{CC^e(l, fd) - \phi_{min}}{CC^e > \phi_{min}} \right)^2 + \sum_{l=0}^{n-1} \left(\frac{CC^o(l, fd) - \phi_{min}}{CC^o > \phi_{min}} \right)^2 \right] \quad (4)$$

$$AMEWS_{CT} = \frac{1}{M(M-1)} \sum_{i=1}^M \sum_{j=1}^M MEWSD_{CT,i,j} \quad (5)$$

where CC^e and CC^o are the even and odd cross-correlation function.

B. The ranging perspective

In a navigation signal, any sidelobe of auto-correlation function equates to the noise in a coherent spread decoder.

3) AMF_{MP}

$$MF_{MP} = \frac{1}{n_{fd}} \sum_{n_{fd}} \frac{1}{2} \left[\sum_{l=1,2,n-2,n-1} (AC^e(l, fd))^2 + \sum_{l=1,2,n-2,n-1} (AC^o(l, fd))^2 \right] \quad (6)$$

$$AMF_{MP} = \frac{1}{M} \sum_{i=1}^M MF_{MP,i} \quad (7)$$

The impact of other satellites on the tracking process can be calculated by MF_{CT} and AMF_{CT}.

4) AMF_{CT}

$$MF_{CT} = \frac{1}{n_{fd}} \sum_{n_{fd}} \frac{1}{2} \left[\sum_{l=0}^{n-1} (CC^e(l, fd))^2 + \sum_{l=0}^{n-1} (CC^o(l, fd))^2 \right] \quad (8)$$

$$AMF_{CT} = \frac{1}{M(M-1)} \sum_{i=1}^M \sum_{j=1}^M MF_{CT,i,j} \quad (9)$$

C. The anti-interfering perspective

The Excess Line Weight (ELW) is a measure of the robustness against narrow-band signals.

5) AELW

$$ELW = 10 \log_{10} \left[\frac{1}{n} \sum_{k=-n/2}^{n/2} (A_k - \sqrt{n})^2 \right] \quad (10)$$

$$AELW = \frac{1}{M} \sum_{i=1}^M ELW_i \quad (11)$$

where A_k is the k -th value of FFT of ranging codes.

6) CB(Code Balance)

Another criterion is code balance, it is denoted as:

$$CB = \frac{A-B}{A+B} \quad (12)$$

where A and B are respectively the “+1” and “-1” bit of ranging code.

III. CODE DESIGN

The footstone of ranging code design in this paper is combined chaotic sequence with m sequence.

Chaotic behavior is present in many systems. It has many interesting properties. One of these properties is sensitivity to initial values and system parameters. Another property is the noise-like feature of chaotic signals. The discrete chaotic signal can be generated from chaotic maps which represent a non-linear dynamical system. There are many chaotic maps

studied before such as Chebyshev map, Tent map, Bernoulli map, Logistic map, improve Logistic map, etc. In this paper improve Logistic map has been chosen:

$$x_{n+1} = 1 - 2 \times x_n^2 \quad (13)$$

Where x_n is chaotic value and $-1 < x_0 < 1$.

Changing the initial value alters the dynamics of the system which makes chaotic maps ideal for generating ranging code of the desired length. The real-valued sequence is obtained by cyclic iterative chaotic mapping dynamic equation, and then the binary chaotic ranging sequence consisting of “-1” and “+1” is obtained by binary quantization according to the quantization threshold which in this case is zero.

To ensure chaotic stability and confidentiality, first L_0 symbols can be discarded. A chaotic sequence initial value vector X_0 is randomly generated, and each initial value is not equal to each other, and the initial value precision is 10^{-4} . A chaotic sequence set $G1$ is generated according to the initial value vector, the sequence set contains 16 sets of chaotic sequences, and the sequence code length is 200, and the sequence of each group is uncorrelated. The inverse of each element of the sequence in $G1$ is obtained as $G2$.

In the spread spectrum communication system, the balance of the spread spectrum sequence is closely related to the carrier suppression capability. The unbalance of the sequence may cause the leakage of the carrier information of the spread spectrum communication system, which deteriorates the error rate or information loss. therefore, good sequence balance is extremely important for spread spectrum communication systems. To improve chaotic sequence balance, we combine chaotic code with m code.

A set of binary m sequences consist of “+1” and “-1” is then generated. Check the m-sequence balance, and add a bit to the even-numbered period at the end of the sequence to make the code balance coefficient 0. The sequence code length is L .

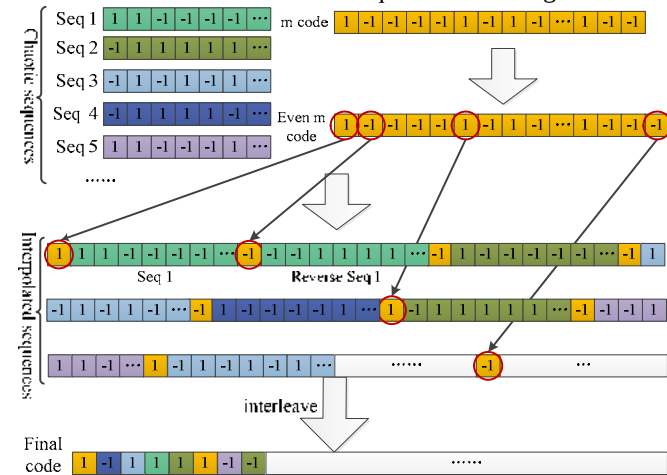


Figure 1. Ranging code generation flow

The sequence of the chaotic code set is cyclically inserted into each bit of the even-period m-sequence. The specific insertion method is: first determining the m-sequence symbol, and if the symbol is “+1”, the sequence of the chaotic code set $G1$ is inserted and if the symbol is “-1”, the chaotic sequence

set $G2$ is inserted. It is repeated until all chaotic code is inserted after each even-period m-sequence symbol.

The interpolated sequences are interleaved to obtain the final optimized sequence. It should be noted that if matrix interleaving is selected, the interleaving depth cannot be L . The total generation flow is depicted as figure 1.

IV. COMPARISON OF CODE PERFORMANCE

Based on the five criteria of the correlation function, the effects of multipath signals and other satellite signals on the performance of acquisition, tracking, and anti-jamming are analyzed. To evaluate a ranging code set, it is best to be one index. Therefore, the index R_i can be written as:

$$R_i = \sum_{j=1}^5 w_j \frac{\overline{cv_j} - cv_{i,j}}{\overline{cv_j}} \quad (14)$$

where $i = 1, 2, \dots, M$, w_j is the weight factor of single criteria, $cv_{i,j}$ is i -th code set of j -th criteria related to correlation function. $\overline{cv_j}$ is the average value of j -th criteria in all code sets.

Generally speaking, we let $w_j = 1/5$, as there are no special requirement for single criteria.

In order to select the best code within M code sets, 13 different sets of GNSS ranging code including the proposed code will be considered. Some basic information of these code sets are presented in Table 1.

TABLE 1. CHARACTERISTICS OF CANDIDATE CODE FOR COMPARISON

Code sets	Family	Type	f_c (MHz)	Length	Size
C/A	GPS	Gold code	1.023	1023	32
L1C	GPS	Weil code	1.023	10230	10
L5I	GPS	Compound LFSR	10.23	10230	63
L5Q	GPS	Compound LFSR	10.23	10230	63
Random	Galileo	Galileo Random	1.023	4092	15
B1I	BDS	Balance Gold	2.046	2046	32
B3I	BDS	Truncation Gold	10.23	10230	32
B2a Data	BDS	Compound code of Gold & Fix	10.23	10230	32
B2a Pilot	BDS	Compound code of Gold & Weil	10.23	10230	32
B1C data	BDS	Truncation Weil	1.023	10230	32
B1C pilot	BDS	Compound of truncation Weil	1.023	10230	32
proposed	---	Compound of chaotic code & m	1.023	10230	32

For consistency, the proposed code length is set up to 10230 and code size is 32. Following the code design flow, the detail of the proposed code generation process is described as follow.

Step1, generate m code. The polynomial of LFSR is:

$$f(x) = 1 + x^2 + x^5 \quad (15)$$

Then add a “-1” at the end of m code, after which the balance coefficient of even-period m code is zero. The length of m code is 32. Step2, generate chaotic sequence. The size of $G1$ is 16, the code length of 11 sequences among $G1$ are 319 and 5 sequences among $G1$ are 318. To obtained the binary chaotic

sequence, first, we generate the random initial vector, second, the system dynamic equation will be iterated 518 or 519 times if L_0 is set to 200, and the sequence we get is real number instead of binary, so the sequences need to be quantized and the quantization threshold is zero. After quantization, we now have $G1$, and then by reverse the polarity of $G1$, we have $G2$. Step3, Combine the chaotic sequence with m code. Step4, Interleaving the compound sequence.

After 4 steps, we have obtained the final code. Taken the ranging code of existing GPS and Beidou navigation systems into account, we can analysis all these ranging code with same criteria. The Doppler frequency cannot ignore during the acquisition and tracking process, in this paper, the simulation of f_d is set between 0 and 4KHz. Figure 2 show the $MEWSD_{MP}$ performance versus signal Doppler.

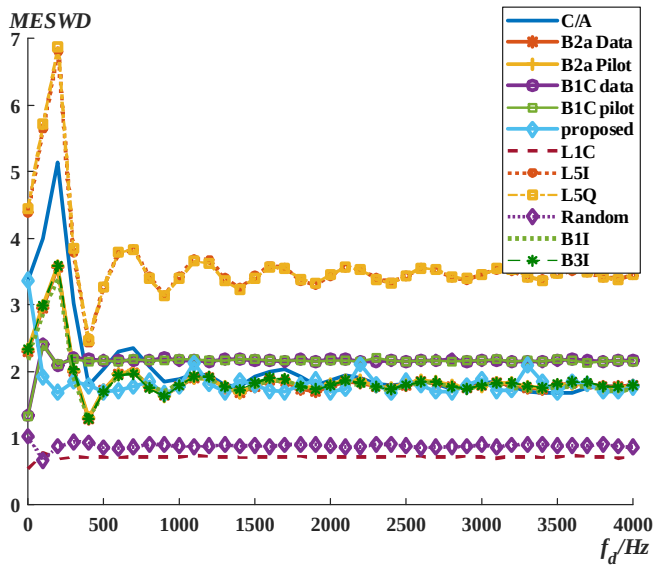


Figure 2. $MEWSD_{MP}$ of the candidate ranging code

Table 2 and Table 3 summarize the different criteria based on correlation functions for the 13 code sets.

TABLE 2. CRITERIA FOR CANDIDATE CODE (PART 1)

Code sets	$AMEWSD_{MP}$	$AMEWSD_{CT}$
C/A	0.064424	0.064015
L1C	0.071660	0.062856
L5I	0.057197	0.057449
L5Q	0.057278	0.057427
Random	0.059070	0.059225
B1I	0.057952	0.058071
B3I	0.058914	0.058733
B2a Data	0.058540	0.058663
B2a Pilot	0.058882	0.058686
B1C data	0.067252	0.056204
B1C pilot	0.067162	0.056241
proposed	0.057268	0.056756

TABLE 3. CRITERIA FOR CANDIDATE CODE (PART 2)

Code sets	AMF_{MP}	AMF_{CT}	$AELW$
C/A	0.003915	0.999935	18.02427
L1C	0.000349	0.999939	26.95511
L5I	0.000370	1.000034	27.38525
L5Q	0.000395	0.999871	27.34434
Random	0.000946	0.999648	23.39950
B1I	0.001897	0.999252	20.35822
B3I	0.000394	0.999933	27.33842
B2a Data	0.000410	0.999808	27.37819
B2a Pilot	0.000389	0.999650	27.39729
B1C data	0.000385	0.999919	26.93416
B1C pilot	0.000389	1.000060	26.94361
proposed	0.000397	1.000041	27.91193

The index R_i and CB are shown in Figure 3 - 5.

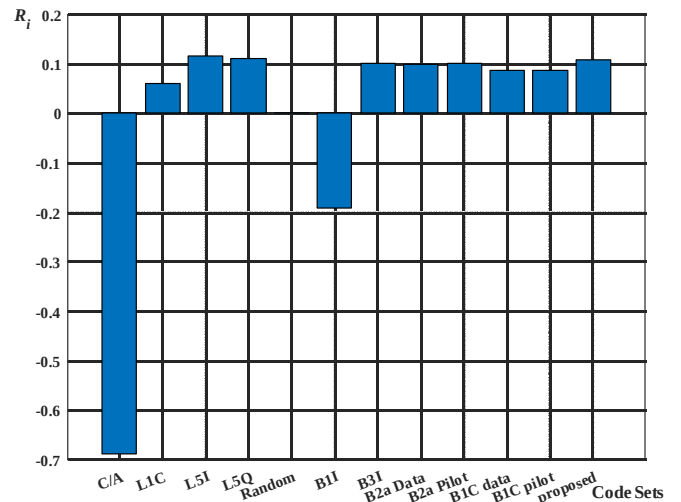


Figure 3. R_i of the candidate ranging code

It is easy to find that R_i stands for the result of performance, if R_i is greater than 0, it means code set i is R_i percentage better than average. As shown in Figure 3, the proposed code is as good as GPS L5I ranging code that is 10% better than average.

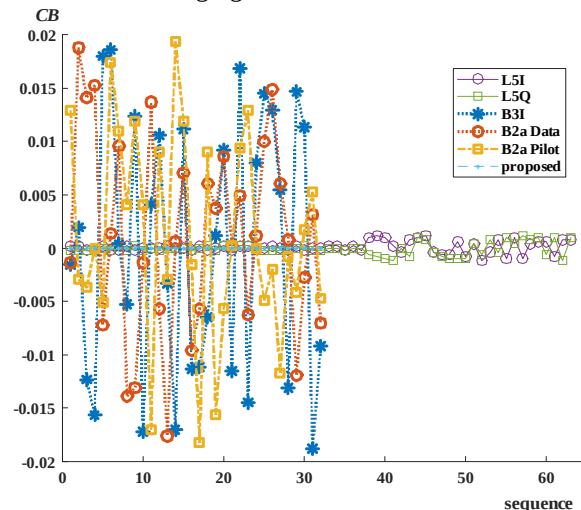


Figure 4. Code Balance of candidate ranging code (Part 1)

From Figure 4 and 5, we could know that the code balance of B1C, Random, code are also satisfies strong balance constraints, but only the proposed code is the best with R_i index while satisfies strong balance constraints, Moreover, the code set size of the proposed code is much bigger if setting parameters properly.

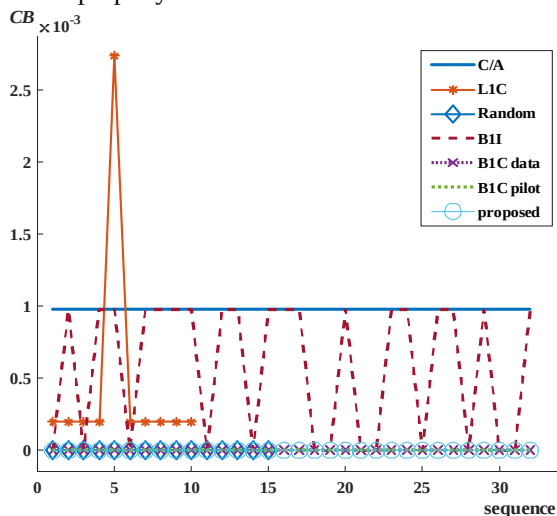


Figure 5. Code Balance of candidate ranging code(Part 2)

V. CONCLUSIONS

In view of the disadvantage of conventional chaotic sequences in terms of balance, a novel ranging code is proposed, which is constructed by combine improved Logistic map chaotic sequence with m code. From the construction process, we can see that m code has optimized the balance of chaotic sequence and the interleave process have optimized the correlation properties. Based on the above analysis and simulation, it is obvious that the problem of poor balance of common chaotic sequence is effectively solved. The balance coefficient of proposed code is zero; therefore, carrier leakage problem of the spread spectrum signal can be well solved compared with the ordinary chaotic sequence, GPS code, or Beidou ranging code. Compared with a single chaotic sequence, the final optimized sequence has strong randomness, high security, strong anti-interception, and good anti-interference ability.

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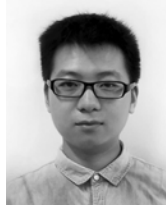
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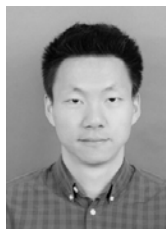
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