Universal ranging code generator of GNSS signals

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Abstract: *This paper reviews PRN code generation methods. Generated codes are used as ranging codes in the existing GNSSs. These codes are used to improve the accuracy of the ranging measurements. We present the structure of the universal code generator which can be used in the satellite navigation systems: NAVSTAR GPS, GLONASS, Galileo, Beidou. This generator provides the ability to generate ranging codes for almost 70% of all open navigation signals. Universal generator was implemented as a SystemVerilog module as part of the navigation receiver software. Using the receiver including this module, we have successfully received navigation signals that use different PRN codes. We also compared hardware resource utilization by universal generator and by GPS C/A ranging code generator. This analysis showed that the universal generator module uses less than 4 times more FPGA resources than the special GPS C/A generator module. However, the resource utilization of the correlator channel increases by only 5 percent.*

1. Introduction

Navigation systems are gradually evolving: the number of satellites in constellations increases, control segment is modified and extended, new types of navigation (GNSS) signals are introduced. The number of navigation signal types used is growing rapidly, for example, the new GLONASS-K2 satellites will broadcast 14 different signals! A similar trend is observed in other navigation systems such as NAVSTAR GPS, Galileo, Beidou, QZSS. Often different pseudo-random sequence types are used as ranging codes for different signal types. But, the variety of code types causes additional issues that complicate the development of navigation devices and reduce the flexibility of device configuration. Generation of ranging codes for GPS and GLONASS signals using a universal generator was considered in the article [1]. However, such sequences are used not only for GNSS signals, but also for local navigation systems signals [2].

2. Classification of ranging code generators

The ICD (interface control document) of different GNSS for each signal present the recommended structure of the ranging codes generation. All signals can be divided into three groups according to the type of ranging code generators used:

- generation via linear-feedback shift register(LFSR).

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- using pseudo-random memory code sequences.
- generation of ranging codes with using hash functions.

The third group of signals includes closed signals, such as GPS M-code or GPS Y-code. The second group includes for example Galileo E1 and E6 signals [3]. The first group is the most numerous, various combinations of shift registers are used to generate ranging codes. Let's focus on this group, because about 70% of all open signals use this method.

The signal GLONASS L1OF uses a simplest structure of the PRN code generator. It contains one nine-bit shift register with feedback taps 5th and 9th bits. The start value of the register is all "1". The output sequence is an M-sequence.The period of this sequence is $L = 2^9 - 1 = 511$ characters [4].

The GPS L2C signal uses a truncated M-sequence generator. This generator consist of one shift register. The initial state is set every $L = 767250$ cycles [5].

The ranging codes of other open navigation signals are generated using two or more registers, by XOR the output sequences.

For example, the GPS L5 ranging code is the modulo-2 sum of two sub-sequences [6]. The first sequence is generated using a 13-bit register with an initial condition of all 1s. The feedback polynomial – $X = 1 + X + X^9 + X^{10} + X^{12} + X^{13}$. Forced reset occurs or when achieving the state of the register "1111111111101", or when counter reaches a values 10230 character (i.e. the end of epoch of the ranging code). The second sequence is generated using a 13-bit register. The feedback polynomial – $X = 1 + X + X^3 + X^4 + X^6 + X^7 + X^8 + X^{12} + X^{13}$. Reset to the initial state occurs at the end of each epoch. The second shift register is initialized to a code vector peculiar to the PRN code number (CDMA).

The ranging codes generated as the modulo-2 sum of two M-sequences are divided into two types: Kasami codes and Gold codes. Kasami codes are generated as the modulo-2 sum of

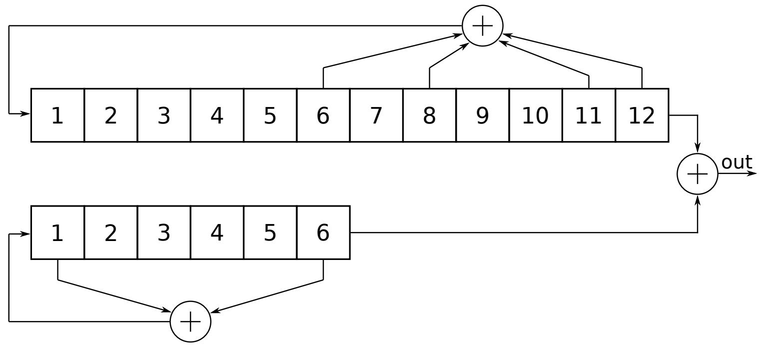


Figure 1: Structural scheme Gln L1OCp ranging code generator

two sequences from registers, the length of one of them is twice as short. For example, the signal GLONASS L1OC used as a ranging code the truncated Kasami codes [7]. This generator contains of 12-bits register and 6-bits register (see fig. 1).The truncated Kasami codes are also used by GLONASS L2OCp and L1OC signals [8, 9].

Gold codes generated as the modulo-2 sum of two sequences from two registers of the same length, but with different initial states and different feedback taps. Gold codes are used, for example, by GPS C/A, Galileo E5, BeiDou B1I, GlnL1OCd [3, 5, 7, 10]. Beidou B1I PRN code generator consist of two registers the same length (see fig. 2). Output sequence is the modulo-2 sum of two sequences from registers G1 and G2.

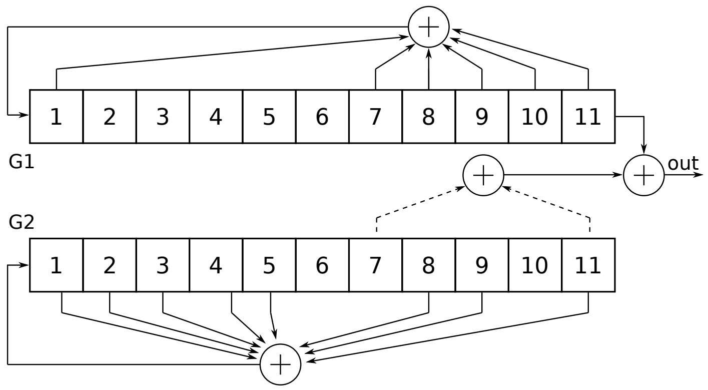


Figure 2: Structural scheme BeiDou B1I ranging code generator

The LFSR-generators of ranging codes may uses different number of registers, different initial states and different feedback taps. We analyzed the structures of the generators of different signals of different GNSS systems. And present a universal code generator which can be used in the GNSS and provides the ability to generate ranging codes for almost 70% of all open navigation signals.

3. Proposed structure of the universal ranging code generator

Universal ranging code generator (see fig. 3) consists of two 14-bit linear feedback shift registers SR_1 and SR_2. Reset to the initial state occurs at the beginning of each epoch. The initial states of the shift registers are in the corresponding registers CODE_STATE_1 and CODE_STATE_2. The bitmask in the registers CODE_BITMASK_1 and CODE_BITMASK_2 sets the feedback taps. The bitmasks in the registers CODE_OUT_BITMASK_1 and CODE_OUT_BITMASK_2 defines output taps. At each cycle of operation, one character of the ranging code is generated. Controlling the frequency of clock pulses to the generator allows controlling the rate of bit generation.

To save resources used by the structure of the universal ranging code generator, two modes of operation are used:

1. two separate 14-bit registers
2. two registers are combined into one and form a 28-bit shift register

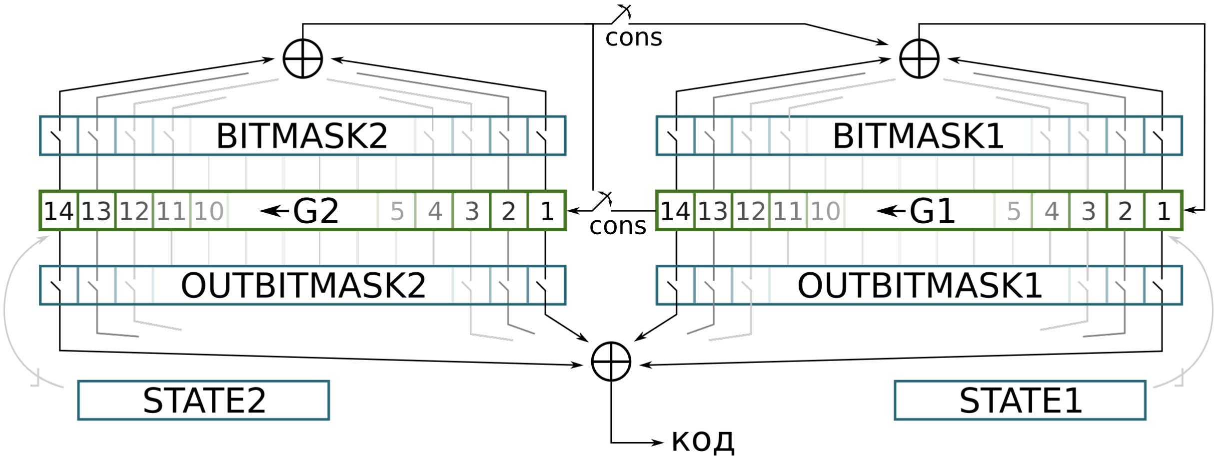


Figure 3: Structural scheme of the universal code generator

The shift registers SR_1 and SR_2 are combined by the flag – "cons". At the beginning of work registers are initialized by initial states. Further, the operation of the generator depends on the selected mode.

In the first mode structure of PRN code generator consist of two m-sequence generators with different initial states and different feedback taps. At each step, the bits defined by the registers CODE_BITMASK_1 and CODE_BITMASK_2, are summed modulo 2. Further, registers SR_1 and SR_2 are shifted to the left. The calculated bits are written to the lower digits of the corresponding shift registers.

In the second mode, two shift registers are combined into one. Thus we get one 28-bit shift register. This structure allows the generation ranging code of signals that require a 27-bit register.

Shift registers SR_1 and SR_2 are shifted to the left during each operation cycle. Bits defined by the bitmasks in registers CODE_BITMASK_1 and CODE_BITMASK_2 are modulo-2 summed. The calculated bit is written to the least significant bit SR_1. And the most significant bit of SR_1 is written to the least significant bit of SR_2.

In each mode the output sequence is formed by modulo-2 sum of bits defined by the bitmasks in registers CODE_OUT_BITMASK_1 and CODE_OUT_BITMASK_2.

4. The initialization parameters of the universal ranging code generator

To generate PRN sequence using a universal generator, it necessary to configure it by writing the appropriate control words in to registers.

Tables 1-4 show the initializing parameters of the universal generator for different GNSS signals. All control words can be divided into two groups. The first three words: bitmask1, bitmask2, out bitmask1 — depend only on the type of signal, while: out bitmask2, code state1, code state2 depend on the signal type and on the number of PRN sequence (i.e., the number of satellite).

For control words that depend on the number of PRN sequence, the cumulative mask is shown in the table. This mask allows identify which bits are used to generate codes for all PRN code numbers. The row ”Summary” shows all bits used for generation all signal types of each system and all PRN code numbers. This value is useful for analyzing the usage of bits of the register.

Table 1: The initialization parameters – GLONASS

Signal	***bitmask1***	***bitmask2***	***out bitmask1***	***out bitmask2***	***code state1***	***code state2***
LxOF	00000100010000	–	00000001000000	–	00000111111111	–
L1OCd	00001001000000	00001101000100	00001000000000	00001000000000	00000001001100	{00001111110000}
L1OCp	00110010100000	00000000100001	00100000000000	00000000100000	00101000110000	{00000000111111}
L2OCp	11000010001000	00000001100000	10000000000000	00000001000000	00011100101100	{00000001111111}
L3OCd	11000010001000	00000001100000	10000000000000	00000001000000	00011100101100	{00000001111110}
L3OCp	11000010001000	00000001100000	10000000000000	00000001000000	00011100101100	{00000001111110}
Summary	11111111111000	00001101100101	10101001000000	00001001100000	00111111111111	{00001111111111}

Table 2: The initialization parameters – GPS

Signal	***bitmask1***	***bitmask2***	***out bitmask1***	***out bitmask2***	***code state1***	***code state2***
L1 C/A	00001000000100	00001110100110	00001000000000	{00001111111111}	00001111111111	00001111111111
L2C CM	01001001010010	01010100111100	01000000000000	00000000000000	{01111111111111}	{11111111111111}
L2C CL	01001001010010	01010100111100	01000000000000	00000000000000	{01111111111111}	{11111111111111}
L5 I	01101100000000	01100011101101	01000000000000	01000000000000	01111111111111	{01111111111111}
L5 Q	01101100000000	01100011101101	01000000000000	01000000000000	01111111111111	{01111111111111}
Summary	01101101010110	01111111111111	01001000000000	{01001111111111}	{01111111111111}	{11111111111111}

Table 3: The initialization parameters – Galileo

Signal	***bitmask1***	***bitmask2***	***out bitmask1***	***out bitmask2***	***code state1***	***code state2***
E5aI	10000010100001	10100011011000	10000000000000	10000000000000	11111111111111	11111111111111
E5aQ	10000010100001	10100011011000	10000000000000	10000000000000	11111111111111	11111111111111
E5bI	11010000001000	10100110010010	10000000000000	10000000000000	11111111111111	11111111111111
E5bQ	11010000001000	10001100110001	10000000000000	10000000000000	11111111111111	11111111111111
Summary	11010010101001	10101111111011	10000000000000	10000000000000	11111111111111	11111111111111

As shown in tables 1 - 4, registers bitmask1, bitmask2 and out bitmask1 accepts only 14 different states. Thus, the initialization of these registers can be presented as a 4-bit word. This replacement can reduce the resource consumption when implementing the universal generator in a ASIC.

Table 4: The initialization parameters – Beidou

Signal	*bitmask1*	*bitmask2*	*out bitmask1*	*out bitmask2*	*code state1*	*code state2*
B1I/B2I	00011111000001	00011111001101	00010000000000	00011111111111	00001010101010	00001010101010
B3I	01000000001101	01101101110001	01000000000000	01000000000000	01111111111111	01111111111111
B2ad	01010000010001	01110100010100	01000000000000	01000000000000	01111111111111	01111111111111
B2ap	01000001100100	01100011010001	01000000000000	01000000000000	01111111111111	01111111111111
Summary	01011111111101	01111111111101	01010000000000	01011111111111	01111111111111	01111111111111

5. Correlation functions of the GNSS signals

The universal ranging code generator was implemented as the SystemVerilog module as part of the navigation receiver software. We conducted experiments to receive different types of navigation signals with different types of ranging codes. The stand (see fig. 4) consisting of the FPGA-based navigation receiver Clonicus based on SoC Zynq-7030 developed by the Navigation Systems Laboratory, the imitator and the PC was used to conduct the experiments.

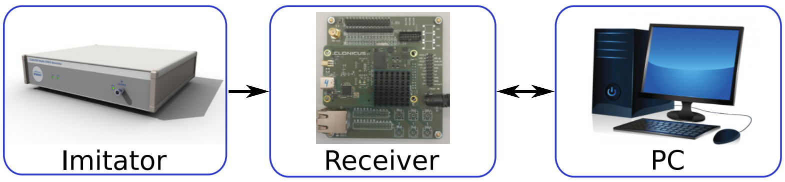


Figure 4: Structural scheme of the stand

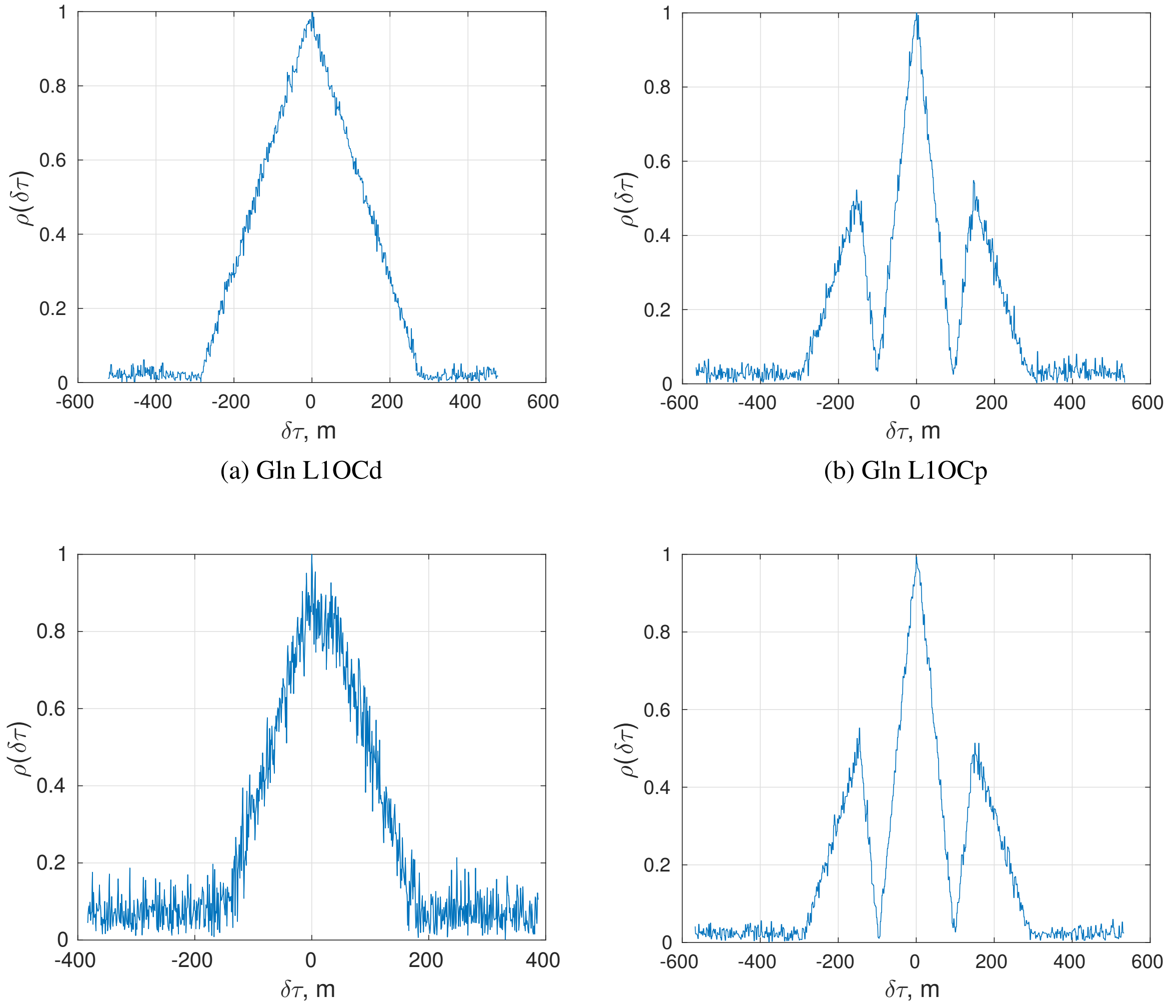
To exchange data with the receiver, a binary information exchange protocol is used. This protocol supports the transmission of 1-ms correlation sums of a selected channel to a PC. Correlation functions of envelopes of different signals were produced from these data. The figure 5 show the results for GLONASS L1OCd, L1OCp, Beidou B1I and L2OCp, respectively.

The form of correlation functions corresponds to the expected. This confirms the correct generation of ranging codes.

6. Analysis of generator resource usage in FPGA implementation

We have implemented two types of generators as FPGA-based modules: universal PRN code generator and GPS C/A code generator. Figure 6 shows the utilization of FPGA resources dependent on the number of included modules for two types of generators. The number of used FPGA blocks "LUT" and "Slice Register" is chosen as a numerical characteristic. Since the shortage of these blocks limits the number of channels placed in the receiver.

The figures 6 show that resource consumption increases linearly as the number of included modules increases. Which means that resource intensity of each module can be assessed as increment of resource.



(a) Gln L1OCd

(b) Gln L1OCp

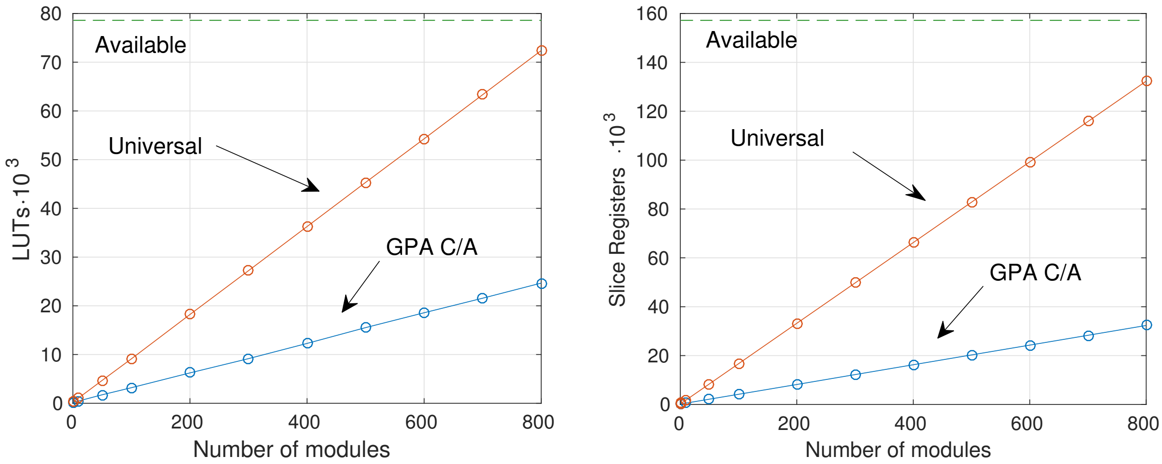
(c) BdsB1I

(d) Gln L2OCp

Figure 5: Correlation function of several GNSS signals

FPGA-based implementation on Xilinx Zynq-7030 of universal generator module (with the interface) requires roughly 88 LUTs and 167 slice registers. Meanwhile, FPGA-based implementation of the specialized module of the ranging code generator for GPS C/A signal, including only two 10-bit shift register and an interface with a reduced number of control words required: 26 LUTs and 40 slice registers. This analysis shows that the universal generator module uses approximately 4 times more FPGA resources than the special GPS C/A generator module.

In comparison the correlator channel including the universal generator module requires: LUT – 1384, slice register – 2558. In this case, the universal generator module (with interface) takes only 6% of the LUTs and 7% of slice registers from the number of resources used by the correlator channel. Although the universal generator module utilized much more resources than the specialized GPS C/A generator, the total increase in the resource utilization of the correlator channel does not exceed 5%. This is the price of versatility.



(a) LUTs (b) Slice registers

Figure 6: FPGA resources usage

7. Versatility of the universal ranging code generator

The structure of the universal generator allows to generate ranging codes for the majority of navigation signals which use LFSR based PRN code generators, but, nevertheless, not all. This structure doesn't allow the generation of GPS P-code. Table 5 shows the total number of signal types in each system, as well as the number supported by the proposed generator.

Table 5: Open GNSS signals which covered by the universal PRN code generator

Signal	*Open signals*	*Signals with LFSR-based generator*	*Possible to generate*	*Unable to generate*
GLONASS	7	7	7	0
GPS	9	7	5	4
Galileo	8	4	4	4
Beidou	7	5	5	2
Summary	31	23	21	10

As shown in table, the universal generator supports 75% of types of all open signals.

8. Conclusion

Proposed structure of universal generator provides the ability to generate ranging codes for almost 70% of all open navigation signals systems GLONASS, GPS, Galileo and BeiDou. Initialization parameters of the universal ranging code generator for signals are given: Gln L1OF, GlnL2OF, Gln L1OCd, Gln L1OCp, Gln L3OCd, Gln L3OCp, GPS C/A, GPS L2 CM, GPS L2 CL, GPS L5 I, GPS L5 Q, Gal E5aI, Gal E5aQ, Gal E5bI, Gal E5bQ, Bds B1I, Bds B2I, Bds B3I, Bds B2ad, Bds B2ap. These parameters can be used to configure the universal generator to generate PRN codes for each signal.

The universal ranging code generator was implemented as a FPGA-based module as a part of the navigation receiver software. The experiment to receive different types of navigation signals using the receiver, which as a PRN code generator used a universal generator was provided. The results confirm the correct generation of ranging codes.

The analysis of the FPGA resources utilization by the universal generator module shows that compared with a specialized GPS C/A PRN code generator module consumption of FPGA resources increases by 4 times. However, the resource utilization of the correlator channel increases by only 5 percent.

Acknowledgment

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