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Time Delay and Range Estimation of Received Signals in Deep Space PN Ranging

Athira Thulaseedharan[1], Indhu Gopan[2*]

[1]Department of Electronics and Communication Engineering, SCMS School of Engineering and Technology, India

[2]RFSD/RFSG/AVN, VSSC-ISRO, Trivandrum, Kerala, India

Abstract: The trajectory models of spacecraft tracked by the Deep Space Network are improved by using Range measurements. A stable acoustic time of flight in low SNR is acquired by adopting a time delay estimation method of cross correlation and auto correlation. In this article the PN sequence is first introduced, and then the commonly used m- sequence and its application for time delay measurement is summarized. Linear Feedback Shift Registers are used for the implementation of PRBS signals. In this project, the entire design of the PRBS generator and correlation technique was implemented using VHDL programming language and the simulation were done and tested on the LIBERO IDE v9.0 simulator. Simulation is made by Matlab as well as VHDL and has compared the same.

Keywords: Pseudo random binary sequence, Linear feedback shift registers, M-sequence, Correlation

I. INTRODUCTION

The basic principle behind the working of ranging systems is based basically on measuring the time of flight of an electromagnetic wave in vacuum. The most common configuration of this system consists, of a known ranging signal which is modulated onto an uplink, retransmitted by the spacecraft and is then detected on the downlink. The measurement of the range can be yielded by the round trip light time, which is measured by correlating the received signal with a replica of what was transmitted.

Three types of signals are sent between spacecraft and the ground station. The signals that are sent from the ground to the spacecraft are the command signal. Signals that are sent from the spacecraft to the ground are the telemetry signals. Signals that are sent both from the ground to the spacecraft and from the spacecraft to the ground are the ranging signals. Exact location of the spacecraft can be determined, using these signals [1,2].

In a Deep Space Station (DSS), an uplink carrier is transmitted whose phase is modulated by a ranging signal. The uplink carrier is demodulated, and the downlink carrier is then phase modulated by the recovered ranging signal, within the spacecraft transponder. Now, the round-trip delay of the ranging signal is measured by DSS, by receiving and demodulating the downlink carrier.

Two types of ranging signals are used in deep space, sequential ranging and PN ranging. Sequential ranging is nothing but sending a series of square waves for fixed periods of time. The disadvantage with this method is that, the starting of the ranging signal must be known by the correlator, since it must properly sequence through all of the tones. Whereas, PN ranging involves sending a sequence, resulting in a unique sequence of length 1,009,470 bits, which is built from PN components of length 2, 7, 11, 15, 19, and 23. It overcomes the problem of sequential ranging by eliminating the requirement to know when the sequence started [2-4].

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Correlation Technique

Suppose we have two signal sequences x(n) and y(n). x(n) represents, sampled version of transmitted signal and y(n) represents the sampled version of the received signal at the output of the ADC. If, target is present in the space, the received signal then consist of a delayed signal of the transmitted signal, and will be corrupted by additive noise w(n). Received signal sequence can be represented as:

$$y(n) = \alpha\, x(n - D) + w(n) \quad (1)$$

The received signal is delayed (by D), noisy, and attenuated. The objective is to determine the time delay between the transmitted and received signal. This important information can be extracted from y(n) by means of correlation. The information that is to be transmitted from one point to another is usually converted to a binary form (a sequence of zeros and ones), in case of digital communications, which is then transmitted to the intended receiver.

Maximal length sequence or m-sequence is the simplest PN sequence to generate. These are generated by LFSR (Linear Feedback Shift Registers). An m stage shift register, described by a polynomial of order m, can generate a periodic m-sequence of period 2^ (m^{-1}).

The rest of this paper is organized as follows. Section II describes correlation and its types, in detail. In Section III, the proposed method to generate the m-sequence is presented. In Section IV, presents the experimental results of both VHDL and MATLAB software based simulation. Finally, conclusions of this paper are summarized in Section V.

II. CORRELATION

By estimating the cross-correlation or auto-correlation of the received signal with the transmitted signal x(t), we can compute the time delay D. By plotting these functions between the transmitted and received signals, we get only one peak value that occur at τ=D. The time argument that corresponds to the maximum peak in the output, after correlating, is the estimated time delay.

Correlation is a mathematical operation which is similar to convolution. Operation between a signal and a filter is usually convolution, and we think of it as a system with single input and a stored coefficient, whereas cross-correlation is between two signals, that is a system with two inputs and no store coefficients. There are two types of correlation: auto-correlation and cross-correlation. Cross-correlation is nothing but a measure of similarity between two signals, whereas auto-correlation is a measure of how similar a signal is to itself.

Continually transmitting a pseudo random binary sequence (PRBS), towards a potential target, is the general principle of correlation ranging. Its distance and relative speed, is determined by, the signal received back after reflection from the target. The auto-correlation function is defined as:

$$Rxx(\tau) = \lim_{T\to\infty} 1/2T \int_{-T}^{T} x(t).x(t+\tau)dt \quad (2)$$

And cross-correlation is defined as:

$$Rxy(\tau) = \lim_{T\to\infty} 1/2T \int_{-T}^{T} x(t).y(t+\tau)dt \quad (3)$$

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Comparing one waveform with a different one is the function involved in cross-correlation (and this is different from auto-correlation, where we compare the signal with itself). The property of this process is that, when the two signals match, we get a peak in the function, at the time shift where they match. Computing the cross-correlation function of the received signal with the transmitted signal x(t), is one of the common method of estimating the time delay D. E is the expectation factor.

$$Ryx(\tau) = E\{y(t)x(t+\tau)\} \quad (4)$$

$$E\{[ax(t-D)+w(t)][x(t+\tau)]\} \quad (5)$$

$$E\{ax(t-D)x(t+\tau)+w(t)x(t+\tau)\} \quad (6)$$

Hence,

$$Ryx(\tau) = aRxx(\tau - D) + Rwx(\tau) \quad (7)$$

Therefore, the cross correlation $Ryx(\tau)$ is equal to the sum of the scaled autocorrelation function of the transmitted signal (i.e. $\alpha Rxx(\tau)$) and the cross correlation function between x (t) and the contaminated noise signal w(t). α is the scaling factor. If we now assume that the noise signal w (t) and the transmitted signal x (t) are uncorrelated then,

$$Rwx(\tau) = 0 \quad (8)$$

Hence the cross-correlation function between the transmitted signal and the received signal may be written as:

$$Ryx(\tau) = aRxx(\tau - D) \quad (9)$$

The operation of auto-correlation and cross correlation done between the transmitted and the received noisy signal is shown in Fig. 1.

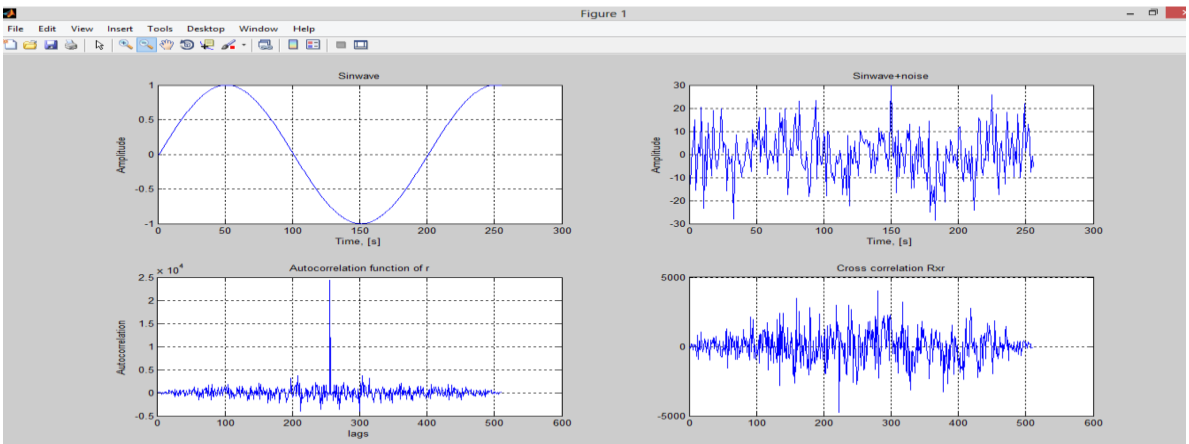

Fig. 1. (a) Pure sine wave, (b) Sine wave + noise, (c) Autocorrelation of pure sine wave, (d) Cross-correlation of noisy delayed signal.

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We can observe the one and only one peak value at τ=D in the waveform.

III. PRBS GENERATION

PRBS or Pseudo Random Binary Sequence is nothing but a random sequence of binary numbers. PRBS generator is implemented with linear feedback shift registers (LFSR), which consists of 'n' master slave flip-flops. The PRBS generator generates a predefined sequence of 1's and 0's, with 1 and 0 occurring with the same probability. PN sequences is unique for good auto-correlation property, and hence two similar PN sequences can easily be phase synchronized, even when one of them is corrupted by noise [5,6].

Some of the important properties of PN sequences are:

- Run length: Considering any length of a PN sequence, the number of '1's and '0's, differ only by one, that is, the number of '1's is just one more than the number of '0's.
- Shift and add: When a shifted PN sequence is modulo-2 added with the un-shifted sequence, the result we get is the same PN sequence with some other shift.
- Correlation: By comparing the two binary sequences bit-by-bit using XNOR gates, and by counting the places they match, we can obtain the correlation of these two serial bit sequences over a length L. XNOR produces a bit '1' at the output, if the two bits are identical, and otherwise a '0'. Now, we can obtain the correlation by, counting all the '1's and dividing the sum by the total number of bits, L. Thus the correlation equation for the digital bit sequence can be written as:

$$R(m) = \frac{number\ of agreements}{total\ number\ of\ bits} \quad (10)$$

PN sequence has an auto-correlation of 1 at zero phase, and 0.5 at all other phases. Synchronization, or acquisition, of PN sequences uses this property.

Generation of PN Sequence

Three well known PN sequence families are:

- M-sequence
- Gold sequence
- Kasami sequence

M-sequence is the commonly used pseudo-random sequence and is the longest linear sequence shift register. The longest periodic sequence of the shift register has a period, which does not exceed 2N-1. The sequence we need, known as maximal length sequences (MLSs), are the one whose periods are exactly 2N-1 units long.

The implementation of PRBS generator is based on the linear feedback shift register, consisting of 'n' master slave flip-flops. The two main parts of an LFSR is the shift register and the other being the feedback part.

Clock is one of the inputs to a shift register. Whenever clock input changes its state from zero to one (or from one to zero, depending on the implementation), a shift occurs in the register. Depending on the design of the device, a shift register can shift its contents in either direction. A shift involves the bit on the far right end of the shift register to move out of the register. The shifted out bits of the register are also referred to as output bits. The bit on the left end of the shift register is left empty after a shift, unless a new bit is moved into it.

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Feedback in a shift register is taken from a selection of points (taps) in the register chain and performs the XORing of these taps to provide tap(s) back into the register. The cause of the register to loop through repetitive sequences of pseudo-random value is these feedbacks. How many values are there in a given sequence before the sequence repeats is determined by the choice of taps. Feedback is done mainly to make the system more stable and error free [7].

Design

Linear feedback shift registers, associated with its characteristic polynomial *G(x)* of order n can generate a good random like binary variable of periodicity (2n-1). The LFSR structure with the polynomial *x4+x1+1* is shown in Fig. 2.

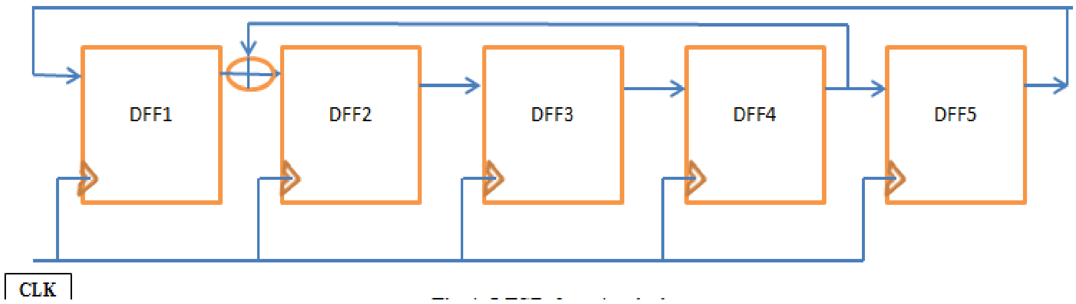

Fig. 2. LFSR for polynomial *x4+x1+1*.

The pattern of PN sequence produced by the LFSR is represented as a table of register states and their output stream for the corresponding polynomial *x4+x1+1* and is shown in Table 1 and its corresponding state flow is shown in Fig. 3.

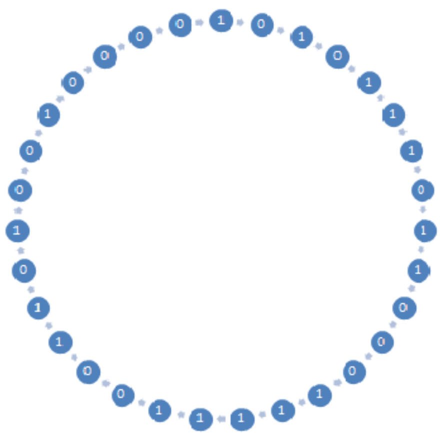

Fig. 3. State flow of output for Fig. 2.

Properties of m-sequence

- An even number of taps is the basic criteria for m-sequence, but all registers with an even number of taps are not maximal.
- By reversing the order of the taps, we can generate the reciprocal codes.
- 'Shift and add' property: By adding an m-sequence to a phase shifted version of itself, then the resulting sequence is another shift of the original sequence.

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- Balance Property: One more 1 than 0 is present (result of not having an all zeros state), in one period of an m-sequence (Table 1).

Table 1. BIT pattern for the lfsr shown in Fig. 2.

Register States					
BIT5	**BIT4(TAP)**	**BIT3**	**BIT2**	**BIT1(TAP)**	**Output Stream**
0	0	0	0	1	1
1	0	0	0	0	0
0	1	0	0	0	1
1	0	1	0	0	0
0	1	0	1	0	1
1	0	1	0	1	1
1	1	0	1	0	1
1	1	1	0	1	0
0	1	1	1	0	1
1	0	1	1	1	1
1	1	0	1	1	0
0	1	1	0	1	0
0	0	1	1	0	0
0	0	0	1	1	1
1	0	0	0	1	1
1	1	0	0	0	1
1	1	1	0	0	1
1	1	1	1	0	1
1		1	1		0
0		1	1		0
0		1	1		1
1		0	1		1
1		0	0		0
0		1	0		1
1		1	1		0
0		0	1		0
0		1	0		1

IV. EXPERIMENTAL RESULTS

The code for implementing the required PRBS and correlation concept is realized by writing VHDL as well as Matlab program. In the program the logic implemented is very simple. A 32-bit sequence is realized using the LFSR by shifting the input through the D-flip flops and feed backing the outputs of some registers known as taps again into the first register after passing them through an XOR gate.

In the developed code tapping is taken from the first and fourth taps so as to obtain the maximum length of binary digits produced.

When the reset is kept at zero initially, the outputs of each of the register are uninitialized and hence the output is also uninitialized. As soon as the reset is made high the output of all registers starts coming out.

We assume that, both the transmitter and the receiver are synchronized, then we can first get the delay and hence the time of transmission of the signal from a particular satellite. Hence, the pseudo-ranges can be calculated as:

$$R = c\,(T2 - T1) \qquad (11)$$

Where T1: transmission time at the satellite.
T2: reception time at the receiver.
C: velocity of light.

The received code is compared with a replica, and the difference in time gives us the amount of delay.
However if the clocks are not synchronized and there is an error which has to be taken, then the true geometric range becomes:

$$R = c[(Tu - tu) - (Ts - ts)]$$
$$= c[Tu - Ts] + c[ts - tu]$$
$$= r + c\Delta t \qquad (12)$$

Where,
$\Delta t = ts - tu$
Tu: reception time of the signal at the receiver.
Ts: transmission time of the signal from satellite
ts: satellite clock offset from system time
tu: receiver clock offset from system time.
c: velocity of light in vacuum (3×10^8 m/s).

Behavioral codes have been written for PRBS and correlation as well, and their corresponding waveforms are plotted in Fig. 4.

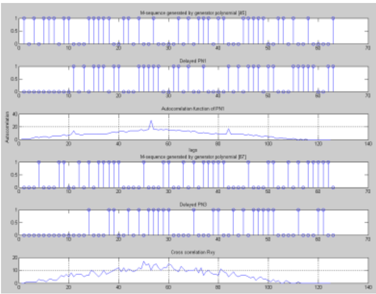

Fig. 4. (a) m-sequence generated using polynomial of length 45, (b) delayed sequence of (a), (c) Auto-correlation output between (a) and (b), (d) m-sequence generated by polynomial of length 67, (e) delayed sequence of (d), and (f) Cross-correlation between (a) and (e).

Output waveform obtained for the VHDL code is shown in Fig. 5.

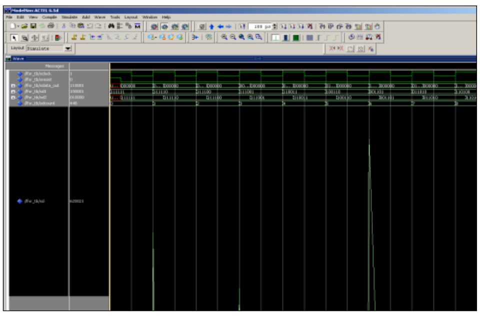

Fig. 5. Correlation output obtained for VHDL code.

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V. CONCLUSION

The code for implementing the required PRBS and correlation concept is realized by writing VHDL as well as Matlab program. In the program, the logic implemented is very simple. A 32-bit sequence is realized using the LFSR by shifting the input through the D-flip flops and feed backing the outputs of some registers known as taps again into the first register after passing them through an XOR gate. The time delay D can be computed by estimating the cross-correlation function or auto correlation function of the received signal with the transmitted signal x(t). These functions between the transmitted signal and the received signal is plotted, and it will have only one peak value that will occur at $\tau = D$. After correlating, the time argument that corresponds to the maximum peak in the output is the estimated time delay. We assume that, both the transmitter and the receiver are synchronized, then we can first get the delay and hence the time of transmission of the signal from a particular satellite can be determined. Hence, the pseudo-ranges can be calculated as $R = c\,(T2 - T1)$ as described above. The code for implementing the above circuit was written and hence the simulation results were generated and tested.

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