We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

4,800
Open access books available

122,000
International authors and editors

135M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

3

Wideband Noise Radar based in Phase Coded Sequences

Ana Vázquez Alejos[1], Manuel García Sánchez[1], Iñigo Cuiñas[1] and Muhammad Dawood[2]
[1]University of Vigo
[2]New Mexico State University
[1]Spain
[2]USA

1. Introduction

At present, widely-used radar systems either use very short pulses or linear frequency modulated waveforms, and are based on either mono- or bi-static configurations. These systems suffer from having stronger sidelobes, thereby masking weaker returns from subtle changes and making it difficult to detect these changes. To overcome the problem of stronger sidelobes, various coding techniques have been proposed with varying degrees of success.
One such technique is based on the transmission of pseudorandom binary sequences (PRBS). Although, PRBS are considered a good option in terms of their autocorrelation function, these sequences are not optimal if sidelobes level is taken into account. This problem can be overcome if the transmit process is composed of complementary binary series of sequences known as Golay series [Golay, 1961; Sivaswamy, 1978; Alejos, 2005; Alejos, 2007; Alejos, 2008]. Golay codes are pairs of codes that have non-periodic autocorrelation functions with null sidelobes levels.
In the present chapter, we propose the improvement of PRBS-based noise radar sounders by using pairs of complementary binary series of Golay sequences series. We demonstrate, in qualitative and quantitative forms, the improvement reached by employing Golay sequences.
The larger dynamic range of the sounder and the better precision in wideband parameter estimation are the main benefits due to the use of Golay sequences. This is important when dealing with large attenuation, as at millimeter frequency bands.
Different schemes are explained in order to implement this kind of radar sounders, as well as the measurement procedure is detailed. The processing gain is also explained. Measurements, using both kinds of sequences, have been performed in actual scenarios. Channel functions and parameters have been calculated and compared. Finally the Fleury's limit [Fleury, 1996] is introduced as a formal way of checking the availability of the obtained results.

2. Fundamentals of wideband noise radar

A generic modulation technique habitually used in radar systems is the one known as noise modulated radar. This technique offers large number of advantages to the radar systems

Source: Radar Technology, Book edited by: Dr. Guy Kouemou,
ISBN 978-953-307-029-2, pp. 410, December 2009, INTECH, Croatia, downloaded from SCIYO.COM

designers due to its robustness to the interferences. Nevertheless, until a few years ago it was very difficult to find practical implementations of these systems. One of the main problems with them is the ambiguity zone and the presence of sidelobes.
The development of the random radar signals generation techniques has impelled the development of systems based on this type of noise modulation. The ultrawideband random noise radar technique has received special importance. It is based on the transmission of a UWB signal, such as the Gaussian waveforms.
Other implementations of the ultrawideband random noise technique use waveforms based on pseudorandom binary sequences with maximum length, also named PRBS sequences (Pseudo Random Binary Sequences) or *M*-sequences, where *M* denotes the transmitted sequence length in bits. This technique, known as *M*-sequence radar, offers great advantages related to the hi-resolution of targets and its large immunity to detection in hostile surroundings but also against artificially caused or natural interferences.
Nevertheless, the radar technique by transmission of *M*-sequences presents serious limitation in the dynamic range offered, which goes bound to length *M* of the transmitted sequence. It makes difficult the detection of echoes, which in some scenes with large attenuation values will be confused with noise. These PRBS sequences present in addition a serious problem of large power sidelobes presence, which aggravates the problem of false echoes detection habitual in the applications radar.
The level amplitude of these sidelobes is directly proportional to length *M* of the sequence, so that if this length is increased with the purpose of improving the dynamic range, the sidelobes amplitude level will be also increased in addition. As well, an increase in the length of the transmitted sequence reduces the speed of target detection, limiting the answer speed of the radar device.
In this chapter it is considered the application to the noise modulation techniques of a type of pseudorandom binary sequences that contributes a solution to the problematic related to the *M*-length of the transmitted sequence. The used pseudorandom sequences are known as Golay series and consist of a pair of pseudorandom binary sequences with complementary phase properties. The autocorrelation properties of a pair of Golay sequences produces the sidelobes problem disappearance and in addition they cause that the dynamic range of the system is double to which would correspond to a PRBS sequence with the same length. This allows the use of smaller length sequences to increase the target detection speed.

3. Coded sequences

In this section, we introduce some of the more known sequences used for radio channel sounding and their main features. All sequences described present autocorrelation properties that try to fit the behaviour of white noise. So they are usually named as like-noise sequences.

3.1 Fundamentals

The radio channel impulse response is obtained by transmission of a signal which autocorrelation equals a delta function, like white noise autocorrelation function. As replication of a white noise signal for correlation at the receiver end is difficult, pseudo noise (PN) sequences are used instead. PN sequences are deterministic waveforms with a noise-like behaviour, easily generated by using linear feedback shift registers. They exhibit good autocorrelation properties and high spectral efficiency [Sarwate, 1980; Cruselles, 1996]. The

best known examples of such waveforms are maximal length pseudorandom binary sequences (*m*-sequences or PRBS).
For a maximal length code, with chip period T_C and length M, its autocorrelation can be expressed by (1) and (2):

$$p(t) = \sum_{n=1}^{M} a_n c(t - nT_c) \quad (1)$$

$$R_p(t) = \begin{cases} -(t+T_c)\dfrac{(M^2+1)}{MT_c} + M & 0 \le t \le T_c \\ (t+T_c)\dfrac{(M^2+1)}{MT_c} - \dfrac{1}{M} & -T_c \le t \le 0 \\ -\dfrac{1}{M} & otherwise \end{cases} \quad (2)$$

In (1) *p(t)* denotes a train of periodic pulses with period T_C and amplitudes a_n=±1, *c(t)* is the basic pulse with time duration T_C and amplitude unitary.
An adequate sequence for channel sounding, which will reassure efficient path delay recognition, should have an autocorrelation function with a narrow main lobe and low sidelobes. Traditionally, PRBS are considered a good option for channel sounding. However, if sidelobe level is taken into account, these sequences are not optimal. The sidelobe level for the correlation of PRBS is constant and equals *-1/M*, or *-1* if normalization is not applied. The shape of the autocorrelation function can be seen in Fig. 1, for a PRBS with length M = 7 and chip period T_C = 1.
There are binary phase codes with non-periodic autocorrelation functions that have minimum sidelobe levels. **Barker** codes [Nathanson, 1999] are the binary phase codes which non-periodic autocorrelation exhibits minimum possible sidelobe levels. The peak of the sidelobes at their autocorrelation functions are all less than or equal to 1/M, where M is the code length.

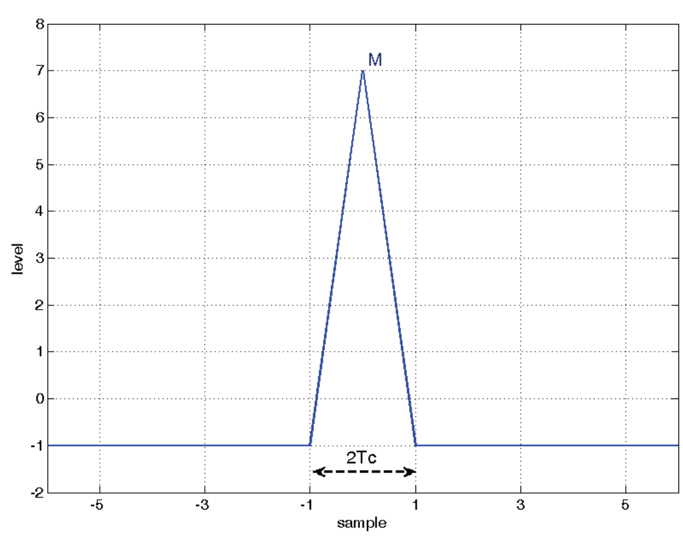


Fig. 1. Autocorrelation of a *m*-sequence. M = 7, T_C = 1

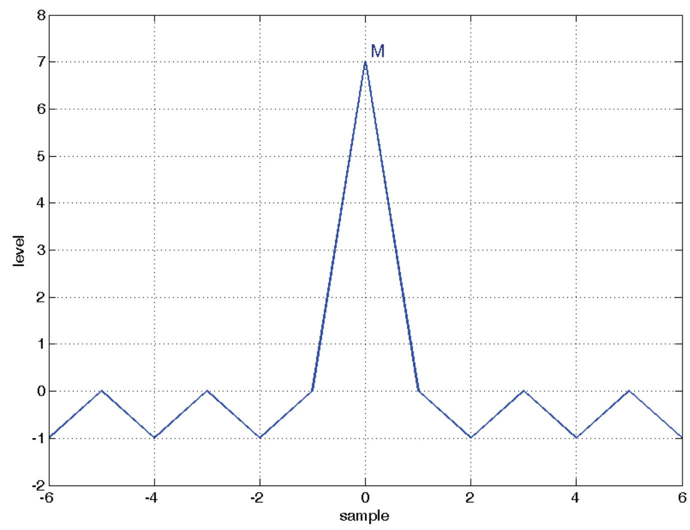


Fig. 2. Autocorrelation of a Barker sequence. $M = 7$, $T_C = 1$

The interesting properties of the Barker codes are that, firstly, the sidelobe structures of their autocorrelation function contain, theoretically, the minimum possible energy; and secondly, this energy is uniformly distributed among all the sidelobes. Barker codes are called perfect codes. An example of the autocorrelation function of a Barker code with $M = 7$ is shown in Fig. 2.

The disadvantage of Barker codes is that there exist no more than eleven known sequences with the longest one only having 13 elements. The relation of all known Barker codes, according to [Cohen, 1987], is given in Table I. In the second column, +/- represent two different code elements.

An important kind of binary phase codes are complementary codes, also known as **Golay** codes [Golay, 1961; Sivaswamy, 1978]. Complementary codes are a pair of equal length sequences that have the following property: when their autocorrelation functions are algebraically added, their sidelobes cancel. Moreover, the correlation peak is enlarged by the addition.

Length of the code	*Code elements*
1	+
2	+ - + +
3	+ + - + - +
4	+ + - + + + + -
5	+ + + - +
7	+ + + - - + -
11	+ + + - - - + - - + -
13	+ + + + + - - + + - + - +

Table 1. Barker codes known according to [Cohen, 1987].

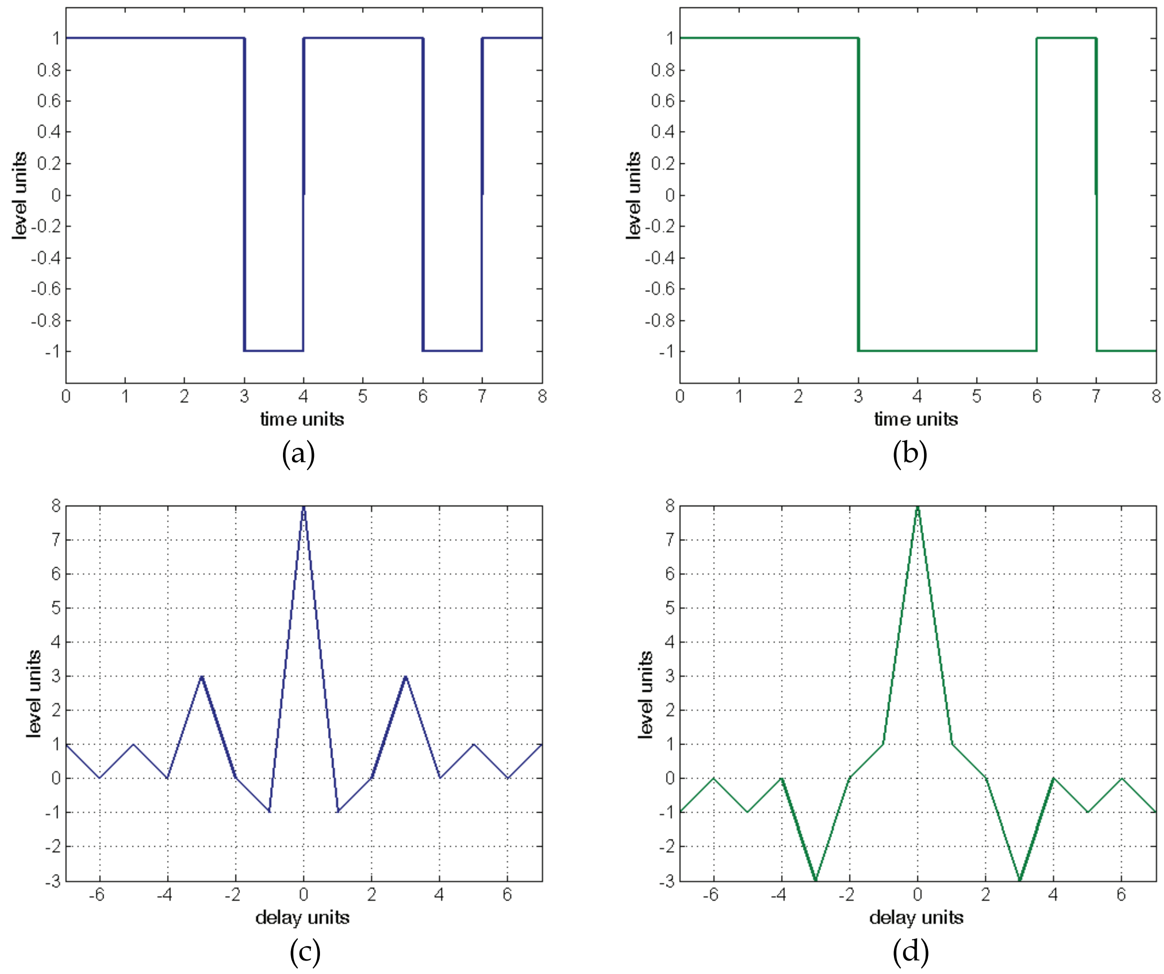


Fig. 3. (a) Complementary Code Golay A; (b) Complementary Code Golay B; (c) Autocorrelation of Code Golay A; (d) Autocorrelation of Code Golay B.

An example of these codes can be seen in Fig. 3(a-d), altogether with their autocorrelation functions. As shown in Fig. 4, the addition of both autocorrelation functions results in total cancellation of the sidelobes, because the correlation sidelobes complement each other. This correlation property of complementary sequences is used in communications systems, as spreading sequences, to allow several communication channels to use simultaneously the same frequency band [Golay, 1961; Díaz, 2002; Wong, 2003], for data encoding [Chase, 1976; Weng, 2000], and even for PAPR (Peak-to-Average-Power-Ratio) reduction [Popovic, 1999; Gil, 2002] in CDMA systems.

3.2 Comparison of complementary series and pseudonoise sequences

Complementary series present certain characteristics that do them more adequate than PRBS for some applications [Budisin, 1992]. These benefits are found only when Golay sequences are used in pairs, because the advantages arise from the complementary properties. Their individual properties are rarely considered. Some of the most important characteristics are:

i. *Autocorrelation properties*: the sum of the autocorrelation of the sequences is exactly zero everywhere except at the origin. Therefore, they exhibit better performance than feedback shift register sequences, including PRBS.

SEQUENCE LENGTH	GOLAY SEQUENCE	PERIODIC PRBS
4/3	4	1
8/7	24	2
16/15	192	2
32/31	1920	6
64/63	23040	6
128/127	322560	18
256/255	5160960	16
512/511	92897280	48
1024/1023	1857945600	60
2048/2047	40874803200	176
4096/4095	980995276800	144

Table 2. Number of different PRBS and Golay sequences

ii. *Sequence length*: the length of Golay sequences is 2^N, whereas the length of pseudorandom sequences is 2^N -1. Since power-of-two length is simpler to implement, complementary sequences are preferable to PN sequences.
iii. *Number of different sequences*: the number of different Golay sequences is larger than the number of different PRBS. Moreover, this number increases more quickly with sequence length, as can be seen in Table 2.
iv. *Spectral properties*: spectral peaks of Golay sequence are not larger than 3 dB over the average of the spectrum. Although the spectrum of PN sequences is theoretically flat, the actual spectrum of the PN sequence is far from constant. The peak values of the spectrum of PN sequences often exceed the average value by more than 3 dB.
v. *Merit Factor*: defined by Golay [Golay, 1983] as a qualitative measure to facilitate analytical treatment. It is closely related to the signal-to-noise ratio, and is defined as (3):

$$F = \frac{L^2}{2E} \quad (3)$$

where L is the sequence length, and E can be seen as an energy term because it is the quadratic sum of all autocorrelation functions (4):

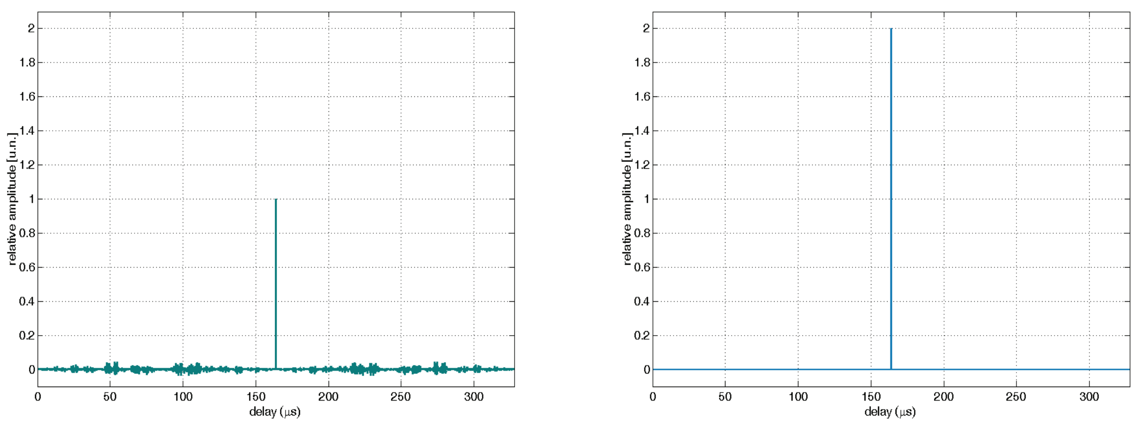
$$E = \sum_{k=1}^{L-1} R_k \quad with \quad R_k = \sum_{i=1}^{L-k} s_i \cdot s_{i+k} \quad (4)$$

The merit factor for a Golay pair of codes doubles the merit factor of a PRBS sequence, and therefore the signal-to-noise ratio will be 3dB higher for the Golay case. This is a very interesting characteristic when dealing with impulse responses with low power echoes, as is the case for measurements in millimeter wave frequency band, where the contributions resulting from first or second-order reflections [García, 2003; Hammoudeh, 2002] may be difficult to detect. Due to the increased dynamic range, weak multipath can be detected.

3.3 Benefits of employing phase coded sequences

The autocorrelation function of a noise-like *M*-length sequence, with bit period T_c, presents a peak of amplitude M and duration $2 \cdot T_C$. Both PRBS and Golay sequences of length 2^{13} bits with chip period $T_C = 20\,ns$ have been computer generated, using a general purpose mathematical software, and their theoretical correlation functions have been calculated and compared.

The correlation functions associated to each sequence are shown in Fig. 5. In both cases, a main peak can be found. But for the Golay sequence correlation, the main peak has double amplitude and the noise level is lower. This indicates a theoretical improvement in dynamic range of 3dB.



(a) (b)

Fig. 5. Example of correlation functions of (a) PRBS with $M_{PRBS} = 2^{13}$-1, $T_C = 1$ and (b) Golay sequences with $M_{GOLAY} = 2^{13}$, $T_C = 1$.

These properties are kept when actual signals, instead of mathematical sequences, are generated using hardware generators. Other different phenomena may be observed if actual signals are used, main of them is the presence of additional peaks corresponding to the sidelobes problem.

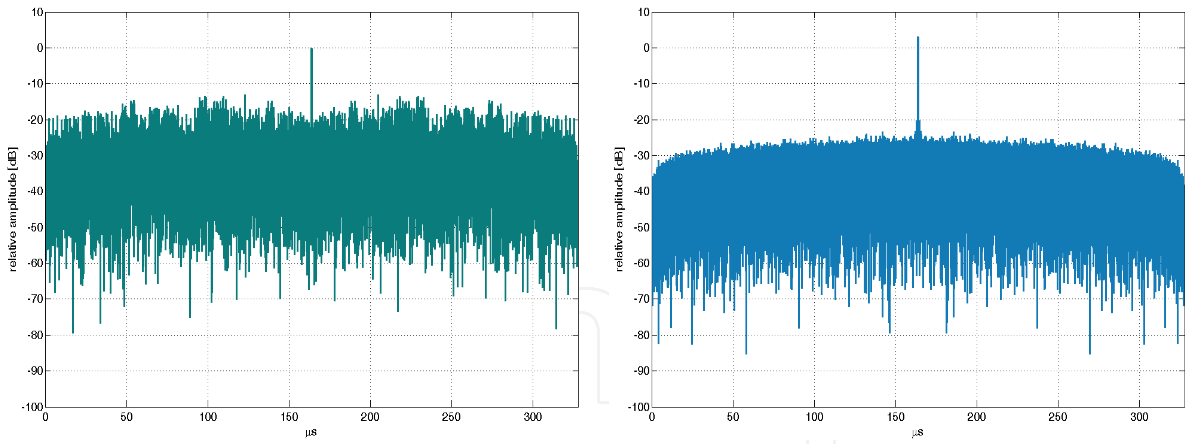
Two signals corresponding to the previous theoretical sequences were generated by a general purpose signal generator and captured with a digital oscilloscope. Later, the correlation functions were calculated off-line. The dependency of the sidelobe level with the ratio E_b/N_0 has tried to be determined.

So, firstly, actual signals were obtained generating both codes with a ratio E_b/N_0 of 20dB and the related results are presented in Fig. 6. PRBS and Golay sequences were generated again, now with a ratio E_b/N_0 of 5dB. Results are shown in Fig. 7. The E_b/N_0 ratio is a configurable parameter of the generator. E_b is the energy in a single chip of the considered code, and N_0 is the power noise spectral density level.

A degradation of dynamic range when E_b/N_0 is reduced can be appreciated for both codes, but it is larger for the PRBS case. We can observe that autocorrelation peak of Golay codes always presents double amplitude independently of the ratio E_b/N_0.

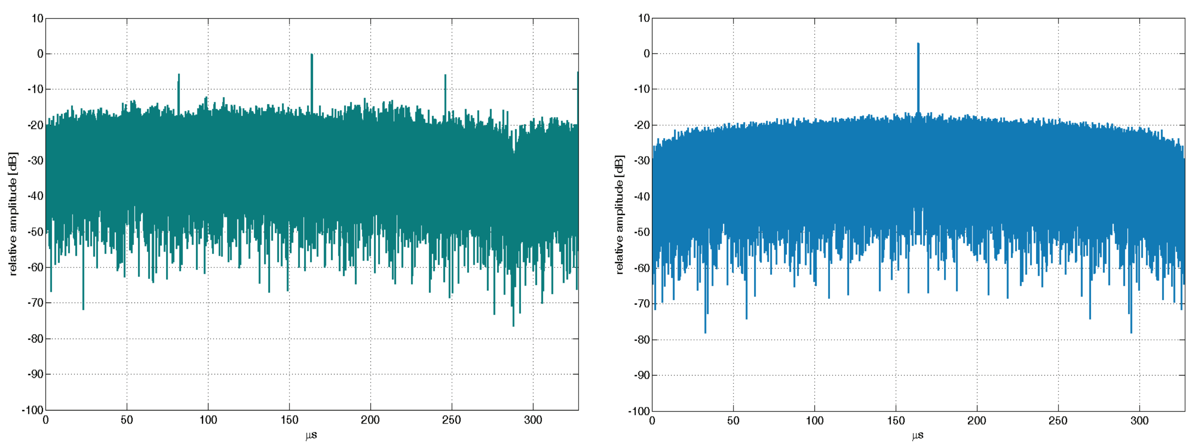
It may be also seen spurious correlation peaks well above the noise level in the PRBS case. Then, we can conclude that theoretical dynamic range improvement is 3dB, but in actual cases, this improvement is larger due to the noise cancellation associated to Golay codes.

Definition given for dynamic range can be used to measure the improvement in the dynamic range. For a ratio E_b/N_0 of 20dB, the dynamic range is 13dB for PRBS and 23dB for Golay. The improvement achieved is 10dB. For a ratio E_b/N_0 of 5dB, the dynamic range values are 5dB and 19dB, respectively. The improvement is 14dB. We can conclude that the improvement achieved is the sum of the 3dB correlation peak increment and the correlation sidelobes reduction.



(a) (b)

Fig. 6. Example of correlation functions of (a) captured PRBS signal with $M_{PRBS} = 2^{13}$-1, T_C = 20 ns, E_b/N_0=20dB and (b) Golay captured signals with $M_{GOLAY} = 2^{13}$, T_C = 20 ns, E_b/N_0=20dB.



(a) (b)

Fig. 7. Example of correlation functions of (a) captured PRBS signal with $M_{PRBS} = 2^{13}$-1, T_C = 20 ns, E_b/N_0=5dB and (b) Golay captured signals with $M_{GOLAY} = 2^{13}$, T_C = 20 ns, E_b/N_0=5dB.

3.4 ISL, SSL and PSL comparison

Some software simulations were performed in Matlab to illustrate the robustness against noise interferences of PRBS and Golay sequences [Alejos, 2008]. Their capabilities will be measured in terms of peak-to-sidelobe, secondary-sidelobe and integrated-sidelobe levels, PSL, SSL and ISL respectively. This will show also better understanding of the advantage provided by reduced sidelobe levels.

Two length 2048 Golay sequences and one length 4096 PRBS sequence were software generated. White Random Gaussian noise was added to the sequences with E_b/N_0 ratio levels in the range of -50dB to 50dB. The correlation functions between noisy and original sequences were obtained. Figure 8 shows a comparison for PSL, SSL and ISL parameters obtained for PRBS and Golay sequences in presence of the mentioned E_b/N_0 ratio level range. None average has been performed.

From this figure, it can be noticed that, for a ratio E_b/N_0 larger than 3dB, the PSL levels of Golay and PRBS sequence are identical. It can be observed that SSL level of Golay sequences is up to 50dB smaller when compared to PRBS sequence. It is also clear that as the E_b/N_0 ratio increases, the SSL level difference between Golay and PRBS sequence decreases.

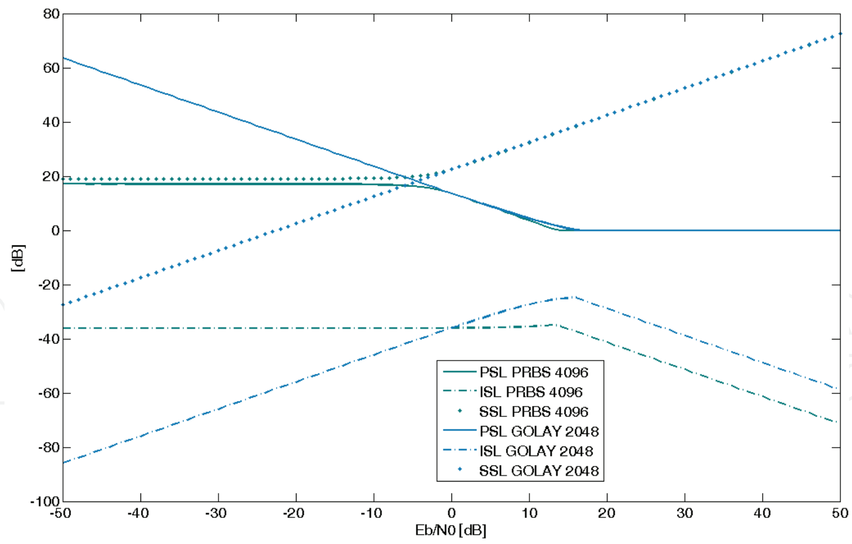


Fig. 8. PSL, SSL and ISL comparison for 2048-Golay and 4096-PRBS sequences.

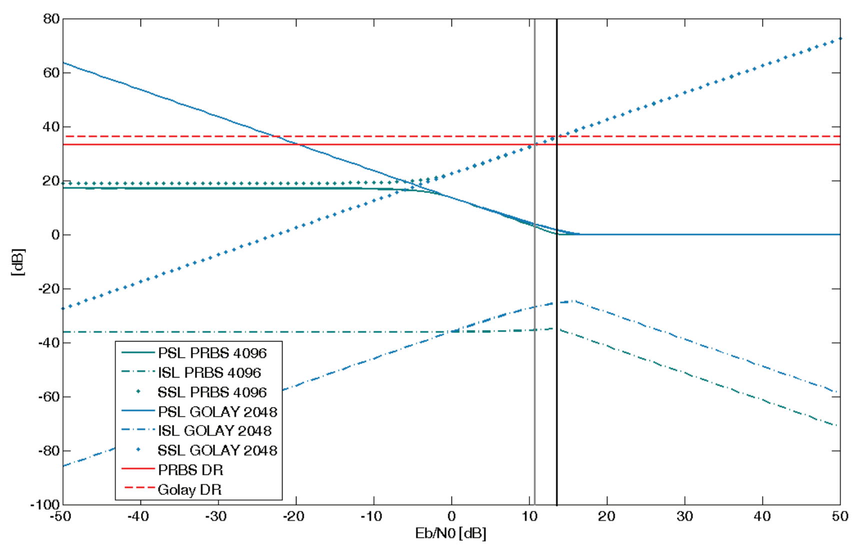


Fig. 9. PSL, SSL and ISL comparison including ideal dynamic ranges.

The figure also shows ISL level vs. E_b/N_0 ratio for PRBS and Golay sequences. It can be observed that the ISL level for PRBS sequence is almost 50dB larger than the ISL level for Golay case. Moreover, as the E_b/N_0 ratio increases the ISL level difference between Golay and PRBS sequences decreases. Whereas as the E_b/N_0 ratio level is increased to 16dB, the Golay case shows slightly larger ISL level than PRBS sequence. At this same point the PSL level is zero. It is produced when the AWGN power is larger than the sequence power, so the noise masks the signal.

In plots of Figure 9, we have included the ideal dynamic ranges corresponding to both codes. We can notice that the cross point between the DR and SSL lines for the Golay case is 3dB larger than for the PRBS case.

4. Estimation of improvement achieved by using Golay codes in noise radar

A controlled experiment of propagation was conducted in order to estimate the improvement achieved in the estimation of channel parameters. Two signals, one based in

PRBS and other resulting from Golay codes, were generated with a general purpose pattern generator, with chip period T_C = 20 *ns.* The signals were generated with two different values of E_b/N_0 ratio, which are 20dB and 5dB. Signals were captured with a digital oscilloscope. In order to reduce the effect of system noise, one hundred captures are taken for each signal and then averaged. These measured signals were correlated off-line with a replica of the original one.

The obtained impulse response was used to estimate the *mean delay*, τ_{mean}, and *rms delay*, τ_{rms}. Applying a Fourier transform to the averaged power-delay profile, an estimation of the frequency correlation function and the *coherence bandwidth*, *CB*, were calculated.

From each code, Golay and PRBS, six signals were created. The first one consisted in a simple sequence corresponding to single path propagation, whereas the other five include multipath components. In this way the second signal includes one echo; the third, two echoes; and successively until the sixth signal, which includes five multipath components.

The time delays and the relative levels and phases of the multipath components were established by setting the function generator properly. It was decided to assign to each new multipath component a level 3dB lower to the prior component. No phase distortion was added. The distribution of the echoes and their amplitudes can be seen in Fig. 10. This graphic represents the ideal impulse response for a signal with five multipath components.

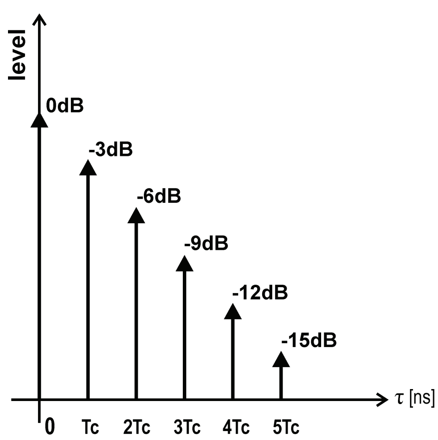


Fig. 10. Impulse response generated for improvement estimation with multipath components, T_C = 20 ns.

The error in the estimation of the parameters has been measured in terms of a mean quadratic error, *MSE*, and relative error *e·100%*, according to the following expressions (5) to (8):

$$MSE(\tau_{mean/rms}) = \sqrt{\sum_{i=1}^{n=5ecos} \left(\tau_{mean/rmsPRBS/Golayi} - \tau_{mean/rmsIDEALi}\right)^2 \Big/ n\cdot(n-1)} \tag{5}$$

$$e\cdot 100\%(\tau_{mean/rms}) = MSE\,\tau_{mean/rmsPRBS/Golayi} \Big/ <\tau_{mean/rmsIDEALi}> \tag{6}$$

$$MSE(CB_\alpha) = \sqrt{\sum_{i=1}^{n=5ecos} \left(CB_{\alpha PRBS/Golayi} - CB_{\alpha IDEALi}\right)^2 \Big/ n\cdot(n-1)} \tag{7}$$

$$e\cdot 100\%(CB_\alpha) = MSE(CB_\alpha) \Big/ < CB_{\alpha IDEALi} > \tag{8}$$

Values obtained for errors *MSE* and $e\cdot 100\%$ are shown in Tables 3 and 4. The errors achieved are lower for the case of Golay codes, even when the ratio E_b/N_0 is as high as 20dB. From these values, we can predict a better performance of Golay codes for the measurements to be made in actual scenarios.

		E_b/N_0 =20dB		E_b/N_0 =5dB	
Sequence	***Error***	*mean delay*	*rms delay*	*mean delay*	*rms delay*
PRBS	*MSE* [ns]	1.2	1.6	1.4	2.4
	$e\cdot 100(\%)$	8.9%	11.5%	10.3%	15.4%
GOLAY	*MSE* [ns]	1.0	1.4	1.1	1.9
	$e\cdot 100(\%)$	7.5%	9.9%	8.2%	13.6%

Table 3. Mean Square Error, in *ns*, and Relative Error *(%)*, for time parameters estimations resulting from the experiment described in section 4, obtained with a ratio E_b/N_0 of 20dB and 5dB.

		E_b/N_0 =20dB		E_b/N_0 =5dB	
Sequence	***Error***	$CB_{0.9}$	$CB_{0.5}$	$CB_{0.9}$	$CB_{0.5}$
PRBS	*MSE* [MHz]	0.8	1.6	0.7	1.7
	$e\cdot 100(\%)$	17.6%	13.6%	18.6%	14%
GOLAY	*MSE* [MHz]	0.5	1.6	0.6	1.6
	$e\cdot 100(\%)$	13.7%	13.2%	16.4%	13.3%

Table 4. Mean Square Error, in *MHz*, and Relative Error *(%)*, for Coherence Bandwidth estimations resulting from the experiment described in section 4, obtained with a ratio E_b/N_0 of 20dB and 5dB.

5. Channel sounding procedure based in Golay series

Two important questions must be considered to employ Golay codes for channel sounding. The first of these questions is relative to the facility of generation of Golay sequences. Marcell Golay [Golay, 1961] developed a method to generate complementary pairs of codes. These codes have the following general properties:

i. The number of pairs of similar elements with a given separation in one series is equal to the number of pairs of dissimilar elements with the same separation in the complementary series.
ii. The length of two complementary sequences is the same.
iii. Two complementary series are interchangeable.
iv. The order of the elements of either or both of a pair of complementary series may be reversed.

In order to generate Golay sequences $\{a_i\}$ and $\{b_i\}$, the properties enunciated lead us to an iterative algorithm. It starts with the Golay pair $\{a_i\}_1 = \{+1, +1\}$, $\{b_i\}_1 = \{+1,-1\}$, and the following calculation is repeated recursively:

$$\begin{aligned} \{a_i\}_{m+1} &= \{\{a_i\}_m | \{b_i\}_m\} \\ \{b_i\}_{m+1} &= \{\{a_i\}_m | \{-b_i\}_m\} \end{aligned} \quad (9)$$

where | denotes sequence concatenation.

The second question to take into account is the procedure to be applied to obtain the channel impulse response. A method to measure impulse response of time invariant acoustic transducers and devices, but not for the time varying radio channel, has been proposed in [Foster86, Braun96] based on the use of Golay codes. In those occasions, the authors intended to employ the benefits of autocorrelation function of a pair of Golay codes to cancel a well known problem in magnetic systems. Along this chapter we present the benefits of the application of Golay codes in radio channel characterization to obtain more precise estimations of main parameters such as delay spread and coherence bandwidth. This method consists in three steps:

i. Probe the channel with the first code, correlating the result with that code. This yields the desired response convolved with the first code.
ii. Repeat the measurement with the second code, correlating the result whit that code and obtaining the response convolved with the second code.
iii. Add the correlations of the two codes to obtain the desired sidelobe-free channel impulse response.

For time variant radio channel sounding a variation of this method can be considered. A sequence containing in the first half, the first Golay code, and in a second part the complementary code is built. Between both parts a binary pattern is introduced to facilitate the sequence synchronization at reception, but this is not absolutely necessary. In any case the two sequences can be identified and separated with an adequate post processing, so each one can be correlated with its respective replica. Finally, the addition of the two correlation functions provides the channel impulse response.

The total sequence containing the two Golay codes, and the optional synchronization pattern, will present a longer duration that each one of the complementary codes. This increases the time required for the measurement and, consequently could reduce the maximum Doppler shift that can be measured or the maximum vehicle speed that can be used.

6. Processing gain

In the practical cases, we have to take care of one aspect which affects to the amplitude of the autocorrelation. This factor is the sample rate. The autocorrelation pertaining to the ideal sequences takes one sample per bit. But, in sampled sequences, there will be always more than one sample per bit, since we must have a sample rate, at least, equal to the Nyquist frequency to avoid the aliasing. This causes that we have more than two samples per bit and the amplitude of the autocorrelation of a sampled sequence will be double of the ideal. It takes place a processing gain due to the sampling process. It appears a factor that multiplies the autocorrelation peak value that is related to the sample rate. We have named this factor '*processing gain*'.

The value of the autocorrelation peak for a case with processing gain, M', can then be written as:

$$\left.\begin{array}{l} F_S \geq F_{Nyquist} = 2 \cdot \dfrac{1}{T_c} \\ M' = F_S \cdot T_C \cdot \left(2^n - 1\right) \end{array}\right\} \Rightarrow M' \geq 2 \cdot \left(2^n - 1\right) \Rightarrow M' \geq 2 \cdot M \qquad (9)$$

If we employ a sample rate s times superior to the minimum necessary to avoid aliasing, $F_{Nyquist}$, we will increase the gain factor according to (10):

$$s = \frac{F_S}{F_{Nyquist}} \Rightarrow gain = 2 \cdot s \Rightarrow M' = gain \cdot M \tag{10}$$

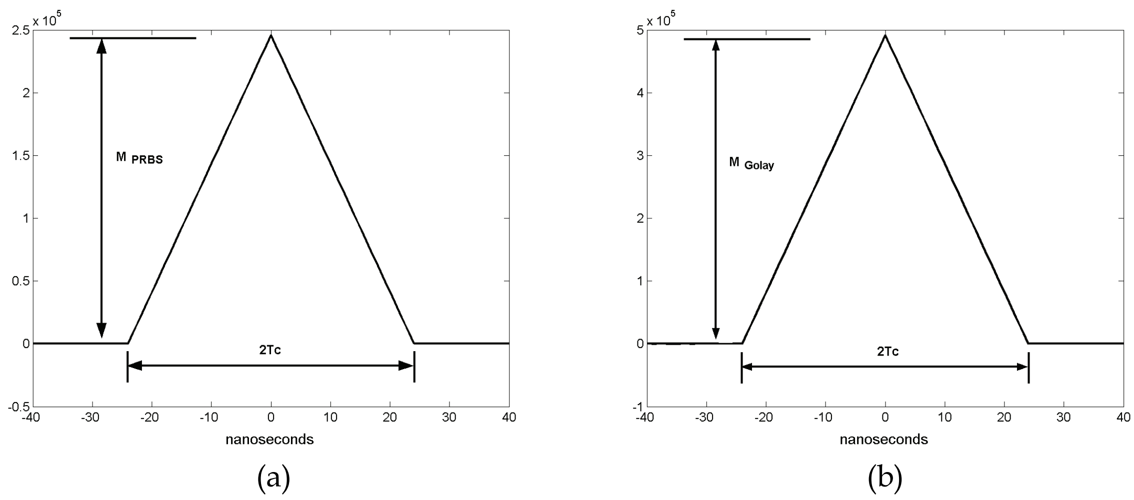


Fig. 11. Example of processing gain due to oversampling: (a) ideal PRBS signal with $M_{PRBS} = 2^{13}-1$, T_C = 24 ns, Fs=1.25GS/s, and (b) ideal Golay signals with $M_{GOLAY} = 2^{13}$, T_C = 24 ns, Fs=1.25GS/s.

In our particular case, the sample rate was 1.25GS/s, so we wait to obtain an autocorrelation peak value $M' = 2 \cdot 15 \cdot M$, where $M=2^{13}-1=8191$ for the PN sequence and $M=2^{13}=8192$ for the Golay codes. In below Fig. 11, we can see that, for the Golay case, this peak amplitude is double in relation to the expected value. We can give then the next expression:

$$M_{GOLAY} = 2 \cdot (2 \cdot s \cdot M) = 2 \cdot M_{PRBS} \qquad where: \quad M = 2^n \tag{11}$$

Giving values to the variables of equation (11) we obtain

$$M_{GOLAY} = 2 \cdot (2 \cdot 15 \cdot 2^{13}) = 491520 \qquad M_{PRBS} = (2 \cdot 15 \cdot 2^{13}) = 245760$$

We can effectively test that the maximum of the peak autocorrelation is double in the Golay sequence case.

7. Noise radar set-up by using Golay codes

In the previous sections, we have analyzed the improvements introduced by Golay sequences. The most important among them is the double gain in the autocorrelation function. This gain is achieved with no need of changes in the hardware structure of classical PN radar sounders with respect to the hardware structure of a PRBS-based sounder.

Next section presents the adaptation of the radio channel sounder built described in [Alejos, 2005; Alejos, 2007] in order to obtain a radar sounder [Alejos, 2008]. The general measurement procedure has been detailed in previous section 5, but it will experience slight variations according to the selected type of hardware implementation. This question is analyzed in section 7.2.

7.1 Hardware sounder set-up

The wideband radar by transmission of waveforms based on series of complementary phase sequences consists in the transmission of a pair of pseudorandom complementary phase sequences or Golay sequences. These sequences are digitally generated and they are modulated transmitted. In their reception and later processing, the phase component is also considered and not only the envelope of the received signal.

For this purpose, different receiving schemes can be adopted, all focused to avoid the loss of received signal phase information. This receiver scheme, based on module and phase, is not used in UWB radars where the receiving scheme is centred in an envelope detector.

In the receiver end it is included, after the radio frequency stage, a received signal acquisition element based on an analogue-digital conversion. By means of this element, the received signal is sampled and the resulting values are stored and processed.

The radiating elements consist of antennas non-distorting the pulses that conforms the transmitted signal, arranging one in the transmitter and another one in the receiver. Three main types of antennas can be considered: butterfly, Vivaldi and spiral antennas.

The operation principle of the system is the following one. A pair of complementary sequences or Golay sequences is generated, of the wished length and binary rate. The first sequence of the pair is modulated, amplified and transmitted with the appropriate antenna. A generic transmitter scheme is shown in Figure 12.

This scheme is made up of a transmission carrier (b), a pseudorandom sequence generator(c), a mixer/modulator (d), a bandpass filter (e), an amplifier (f), and the radiation element (g).

In the receiver end, a heterodyne or superheterodyne detection is carried out by means of a baseband or zero downconversion. Any of the two receiving techniques can be combined with an I/Q demodulation.

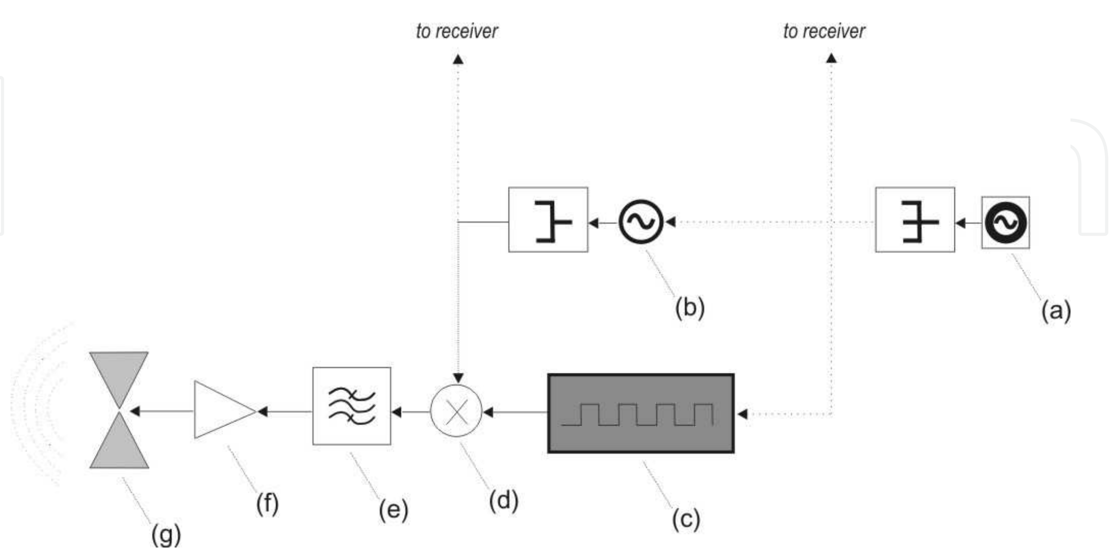


Fig. 12. Generic transmitter scheme for noise radar sounder

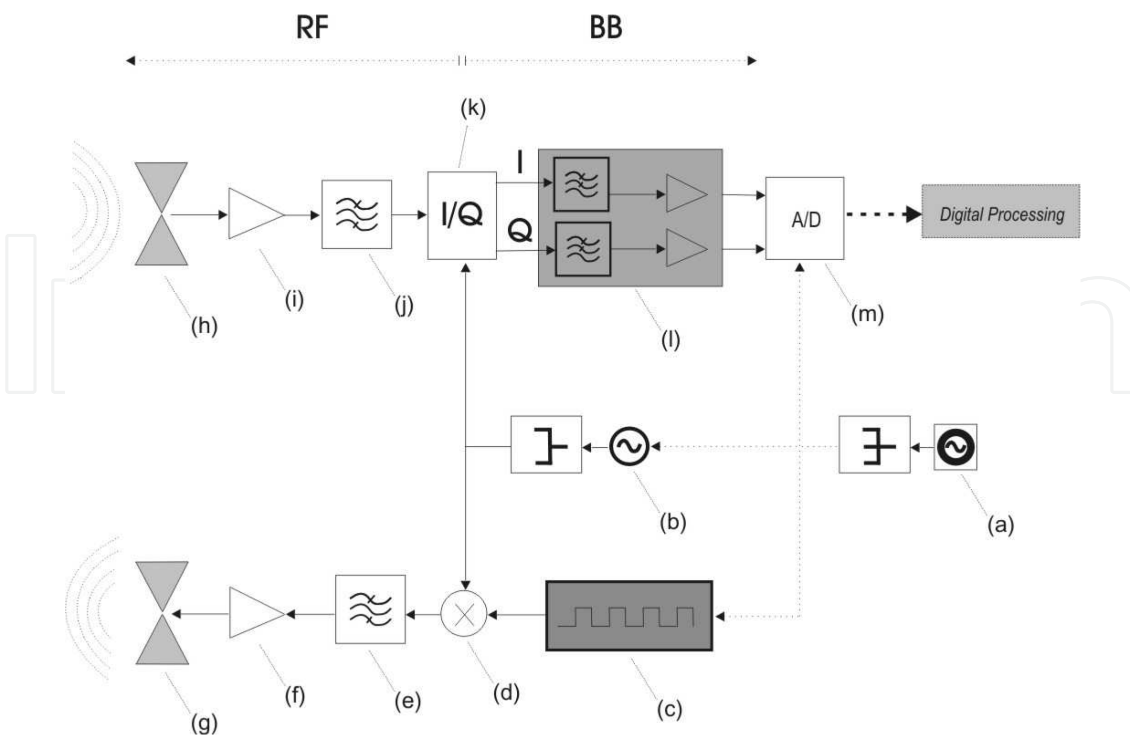


Fig. 13. Receiver scheme for noise radar sounder: I/Q superheterodyne demodulation to zero intermediate frequency

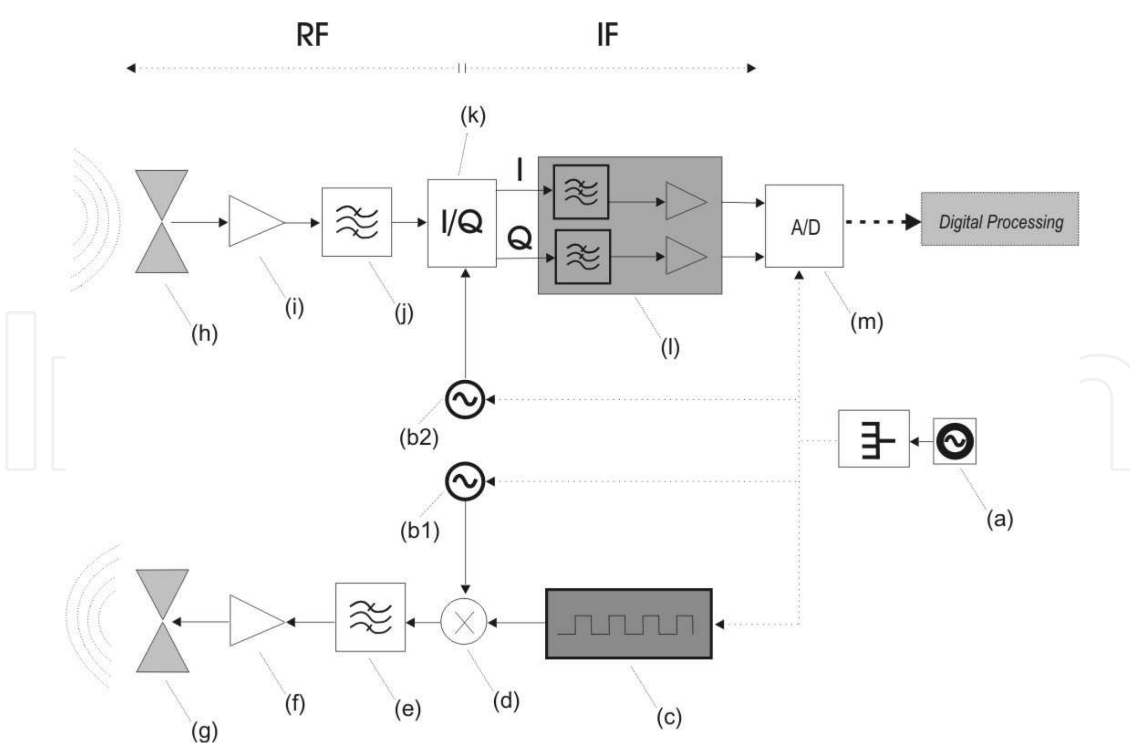


Fig. 14. Receiver scheme for noise radar sounder: I/Q superheterodyne demodulation to non-zero intermediate frequency

Four different schemes are proposed to implement the system, being different by the reception stage (Figures 13-15). All have in common the transmission stage and the used antennas. The diverse schemes can be implemented by hardware or programmable logic of type FPGA (Field Programmable Gate Array) or DSP (Digital Signal Processor).
In Figures 13-15, the transmission stage is included to emphasize the common elements shared by both ends of the radar. The main common element between transmitter and receiver is the phase reference (a), composed generally by a high stability clock, such as a 10 or 100MHz Rubidium oscillator.
The schemes of figures 13-15 have in common one first stage of amplification (f) and filtrate (h). Next in the scheme of Figure 13 is an I/Q heterodyne demodulation (h) to baseband by using the same transmitter carrier (b). The resulting signals are baseband and each one is introduced in a channel of the analogue-digital converter (m), in order to be sampled, stored and processed. Previously to the digital stage, it can be arranged an amplification and lowpass filtered stage (l).
In the scheme of Figure 13, an I/Q superheterodyne demodulation (k) with a downconversion to a non-zero intermediate frequency is performed. The outcoming signals are passband and each one of them is introduced in a channel of the analogue-digital converter (m) for its sampling, storing and processing. An amplification and passband filtered stage (l) can also be placed previously to the acquisition stage.

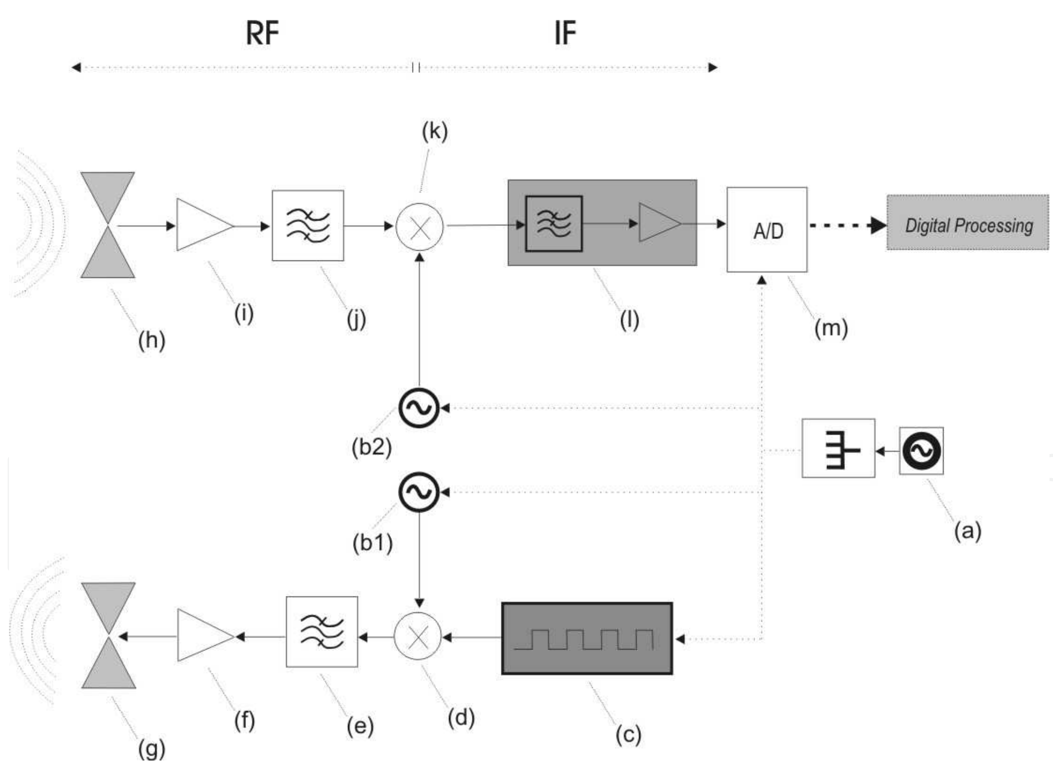


Fig. 15. Receiver scheme for noise radar sounder: superheterodyne demodulation to non-zero intermediate frequency

In scheme of Figure 15 a superheterodyne mixer (k) with downconversion to non-zero intermediate frequency is used. The resulting signal is passband and it is the input to a channel of the analogue-digital converter (m), to be sampled, stored and processed. The previous amplification and passband filtered stages (l) are also optional.

7.2 Measurement procedure

The processing algorithm is based on the sliding correlation principle, employee in the sector of radio channel sounding systems based on the transmission of pseudorandom binary sequences of PRBS type.
This processing can be implemented to work in real time or in off-line form. The processing requires the existence of a version previously sampled and stored of the transmitted signal. This version can also be generated in the moment of the processing, whenever the transmitted signal parameters are known. The first process to implement consists of carrying out a cross-correlation between the received signal and its stored version. From this first step, the time parameters and received echoes amplitudes are extracted.
The processing implemented in this description obtains an echo/multipath time resolution superior to the provided one by classic schemes. For that it is necessary to consider all the samples of the received and sampled signal. In the classic processing a sample by transmitted bit is considered. The fact to consider all the samples will allow obtaining a larger accurate parameter estimation of the channel under study.
From the sample processing, the corresponding radar section images are obtained. Algorithms widely described in literature will be used for it. When lacking sidelobes the received signal, many of the phenomena that interfere in the obtaining of a correct radar image, such as the false echoes, will be avoided.
The part corresponding to the processing and radar images obtaining closes the description of the hardware set-up implementation presented here. Following we will describe some experimental results corresponding to measurements performed in actual outdoor scenarios for a receiver scheme for the noise radar sounder similar to Figure 14.

8. Experimental results

The previously described wideband radar sounder was used to experimentally compare the performance of PRBS and Golay sequences in actual scenarios. Some results are here introduced from the measurement campaign performed in an outdoor environment in the 1GHz frequency band.
In the transmitted end, a BPSK modulation was chosen to modulate a digital waveform sequence with a chip rate of 250Mbps. The resulting transmitted signal presented a bandwidth of 500MHz. In the receiver end, an I/Q superheterodyne demodulation scheme to non-zero intermediate frequency (125MHz) was applied according to description given in section 7.1 for this hardware set-up.
Transmitter and receiver were placed according to the geometry shown in Fig. 16, with a round-trip distance to the target of 28.8m. The target consisted in a steel metallic slab with dimensions $1m^2$. The experiment tried to compare the performance of Golay and PRBS sequences to determine the target range. Results with this single target range estimation are shown in Table 4.
From measurement it has been observed also the influence of the code length M in the detection of multipath component. As larger the code as larger number of echoes and stronger components are rescued in the cross-correlation based processing.

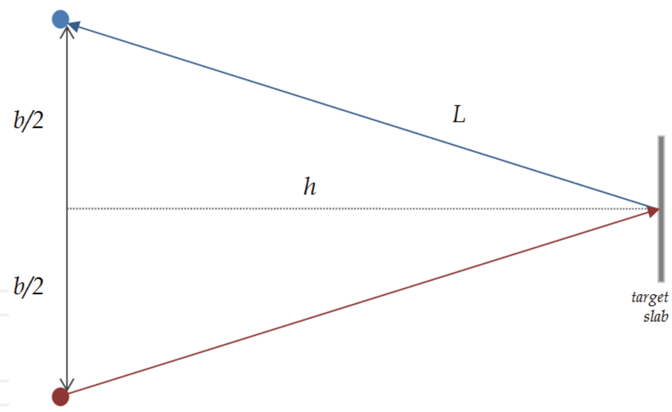


Fig. 16. Geometry of measurement scenario (*b*=2.25m, *h*=14.447m, *L*=14.4m)

Sequence transmitted		GOLAY	PRBS
M (sequence length)		4096	8192
Link range [m]		28.8	28.8
Link range [ns]		96	96
Measured Delay [ns]	*vertical*	97	94
	horizontal	97	94
Estimated range [m]	*vertical*	29.1	28.2
	horizontal	29.1	28.2
Relative error [%]	*vertical*	1.04	2.1
	horizontal	1.04	2.1

Table 4. Single target range estimation results.

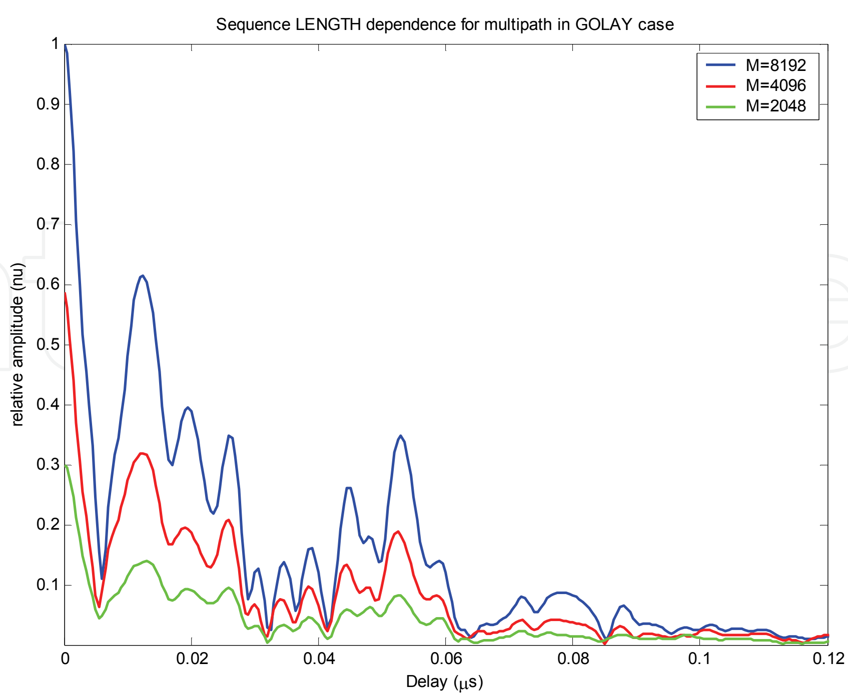


Fig. 17. Code length influence on multipath detection.

9. Relation between channel parameters: Fleury Limit

The only restriction to be satisfied by the values of *CB* is the known as *Fleury limit* [Fleury, 1996]. The expression for this limit is (12):

$$CB \geq \arccos(c)/(2 \cdot \pi \cdot \tau_{rms}) \tag{12}$$

where c is the level of correlation, and verifies $c \in [0,1]$. The theoretical values of the Fleury limit for the 0.5 and 0.9 correlation levels can be found by (12). These limit values can be later compared with those experimentally achieved. The results for values of coherence bandwidth measured should verify the theoretical limit given in [Fleury, 1996] to ensure the reliability of the experimental outcomes.

This limit for 50% and 90% CB is defined according to equation (12) and plotted in graphic of Fig. 18.

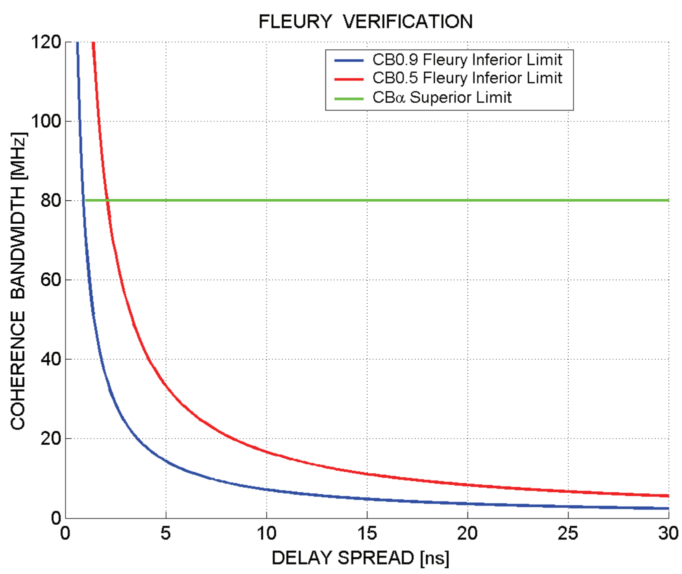


Fig 18. Graphical illustration of Fleury limit.

10. Conclusion

The improvement introduced by the hereby introduced noise radar in dynamic range thematic and sidelobes suppression is based on the autocorrelation properties of the used pseudorandom sequences: the Golay series.

The binary phase codes are characterized by a nonperiodic autocorrelation function with minimum sidelobes amplitude level. An important class of these binary codes is the denominated complementary codes, also known as Golay codes. The complementary codes consist of a pair of same length sequences that present the following property: when their respective autocorrelation functions are algebraically added, their sidelobes are cancelled. In addition, the amplitude level of the autocorrelation peak is increased by this sum doubling its value.

The complementary series have certain features that make them more suitable than PRBS sequences for some applications. Among them most important it is the double gain in the autocorrelation function. This increased gain is obtained with no need to introduce an additional hardware structure.

This behaviour of the Golay codes will provide a significant improvement at the detection level of the signal in the receiver. When increasing the dynamic range, is allowed to suitably separate the echoes level of background noise, avoiding the false echoes and allowing better target estimation. The improvement in the dynamic range is obtained thanks to a double effect: the autocorrelation peak is of double amplitude and the sidelobes are cancelled. This behaviour is very useful in extreme situations, like a scene where the transmitted and the reflected signals experience a large attenuation, as it is the case of ground penetrating radars application surroundings.

In [Alejos, 2007] it has been demonstrated, in quantitative and qualitative form that the improvement reached when using Golay sequences in the radio channel parameters estimation reaches values of up to 67.8% with respect to PRBS sequences. The only cost resulting of use Golay sequences is the double time required for the sequence transmission, since a pair of sequences instead of a single one is used.

The sounders or radar systems, for any application, that use binary sequences have been traditionally used because they are of easy implementation to obtain wide bandwidth. The sounders based in binary sequences implied the use of hardware shift registers of bipolar technology ECL (Emitter Coupled Logic), with reduced logical excursion, low switching speed and with non good noise threshold. All this makes difficult the attainment of quality sequences, greater level, low noise level and high binary rate.

Nowadays, nevertheless, it is possible to use hardware for arbitrary waveform generation of cheaper implementation and with a faster and versatile operation. In the present invention authors had boarded the generation of the used Golay sequences by means of the combination of algorithms programmed on a FPGA and a later analogue-digital conversion stage of great bandwidth and large amplitude resolution. As result, to use Golay sequences, previously stored or instantaneously generated, is easier and precise than it used to be.

Some advantages of the Golay codes have been practically demonstrated by means of the measurements described in section 8. The single target range estimation offers better outcomes for the Golay case even for the short round-trip here shown. It has been practically stated the influence of the code length in the multipath detection. This fact seems be due to that a longer code yields to a higher dynamic range cross-correlation.

11. References

A. Alejos, M. García Sánchez, I. Cuiñas (2005). "Benefits of Using Golay Sequences in Channel Swept Time Cross-Correlation Sounders", Proceedings of the *35th European Microwave Conference*, Paris, ISBN 2-9600551-2-8.

A. Alejos, M. García Sánchez, I. Cuiñas (2007). "Improvement of wideband radio channel swept time cross-correlation sounders by using Golay sequences". *IEEE Transactions on Vehicular Technology*, vol. 56, nº 1, ISSN 00189545.

A. Alejos, Dawood Muhammad, Manuel García Sánchez, Russell Jedlicka, Iñigo Cuiñas, Habeeb Ur Rahman Mohammed (2008). "Low Sidelobe Level Radar Techniques Using Golay Based Coded Sequences", Proceedings of the *2008 IEEE International Symposium on Antennas and Propagation*, San Diego (USA), ISBN 978-1-4244-2041-4.

Budisin, S. (1992). “Golay complementary sequences are superior to PN sequences”, *IEEE International Conference on Systems Engineering 1992*, pp. 101-104, ISBN 0-7803-0720-8.

Cohen, M. N. (1987). *“Pulse compression in radar systems”*. Principles of modern radar, Van Nostrand Reinhold Company Inc., ISBN 0-9648312-0-1, New York.

Cruselles Forner Ernesto, Melús Moreno, José L. (1996). *“Secuencias pseudoaleatorias para telecomunicaciones”*, Ediciones UPC, ISBN 8483011646, Barcelona.

Chase D. (1976). “Digital signal design concepts for a time-varying Rician channel”. *IEEE Transactions on Communication*, vol. COM-24, no. 2, pp. 164–172, ISSN 0090-6778.

Díaz, V. D., Hernández and J. Ureña (2002). “Using complementary sequences for direct transmission path identification,” in *Proceedings of the 28th Annual Conference IEEE IECON*, vol. 4, pp. 2764–2767, ISBN 0-7803-7474-6.

Fleury, Bernard Henri (1996). “An uncertainty relation for WSS processes and its application to WSSUS systems”. *IEEE Transactions on Communications*, vol. 44, issue 12, pp. 1632–1634, ISSN 00906778.

Gil, V.P., Jimenez, M.S. Fernandez, A.G. Armada (2002). “Study and implementation of complementary Golay sequences for PAR reduction in OFDM signals”, *MELECON 02, 11th Mediterranean Electrotechnical Conference*, pp. 198-203, ISSN 0-7803-7527-0.

Golay, M. J. E. (1961). “Complementary series”. *IEEE Transactions on Information Theory*, vol. 24, pp. 82-87, ISSN 0018-9448.

Golay, M.J.E. (1983). “The merit factor of Legendre sequences”. *IEEE Transactions on Information Theory*, vol. IT-29, no. 6, pp. 934–936, ISSN 0018-9448.

Hammoudeh, Akram, David A. Scammell and Manuel García Sánchez (2003). “Measurements and analysis of the indoor wideband millimeter wave wireless radio channel and frequency diversity characterization”. *IEEE Transactions on Antennas and Propagation*, vol. 51, issue 10, pp. 2974–2986, ISSN 0018-926X.

M.O. Al-Nuaimi and Andreas G. Siamarou (2002). “Coherence bandwidth characterisation and estimation for indoor Rician multipath wireless channels using measurements at 62.4GHz”, *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 149, issue 3, pp. 181-187, ISSN 1350-2417.

Nathanson, F. E. ,M. N. Cohen and J. P. Reilly (1999). *“Phase-coding techniques. Signal processing and the environment (2nd edition)”*. SciTech Publishing, ISBN 978-1-891121-09-8, New York.

Popovic, B. M. (1999). “Spreading sequences for multicarrier CDMA systems”. *IEEE Transactions on Communications*, vol. 47, no. 6, pp. 918–926, ISSN 0090-6778.

Sarwate, D. and M. Pursley (1980). "Crosscorrelation properties of pseudorandom and related sequences". *Proceedings of the IEEE*, vol. 68, no. 5, pp. 593--619, ISSN 0018-9219.

Sivaswamy, R. (1978). “Multiphase Complementary Codes”. *IEEE Transactions on Information Theory*, vol. 24, no. 5, pp. 546-552, ISSN 0018-9448.

Weng, J. F. and Leung, S. H. (2000). “On the performance of DPSK in Rician fading channels with class A noise”. *IEEE Transactions on Vehicular Technology*, vol. 49, no. 5, pp. 1934–1949, ISSN 00189545.

Wong, K. K. and T. O'Farrell (2003). "Spread spectrum techniques for indoor wireless IR communications". *IEEE Wireless Communications*, vol. 10, no. 2, pp. 54–63, ISSN 1536-1284.

Radar Technology
Edited by Guy Kouemou

ISBN 978-953-307-029-2
Hard cover, 410 pages
Publisher InTech
Published online 01, January, 2010
Published in print edition January, 2010

In this book “Radar Technology”, the chapters are divided into four main topic areas: Topic area 1: “Radar Systems” consists of chapters which treat whole radar systems, environment and target functional chain. Topic area 2: “Radar Applications” shows various applications of radar systems, including meteorological radars, ground penetrating radars and glaciology. Topic area 3: “Radar Functional Chain and Signal Processing” describes several aspects of the radar signal processing. From parameter extraction, target detection over tracking and classification technologies. Topic area 4: “Radar Subsystems and Components” consists of design technology of radar subsystem components like antenna design or waveform design.