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DESIGN OF BARKER CODED MULTIPLE PULSE EXPERIMENTS

by

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ABSTRACT

Barker code and multiple pulse constitute the main techniques for incoherent scatter studies of the lower ionosphere. The possibility of coupling these two techniques has been suggested as an important step towards better quality data. The problems concerning the implementation of experiments collecting the benefits of the two techniques are discussed and solutions suggested in some particular cases.

INTRODUCTION

Incoherent scatter measurements have been considerably improved in the past few years, particularly as far as the monostatic type radar at Arecibo is concerned. A new line feed, installed in early 1972 improved its backscatter gain by almost one order of magnitude. A hybrid autocorrelator (hagen, 1972) matched up the speed of its data processing with that of data taking for F-region measurements. Successful application of pulse compression techniques (Ioannidis and Farley, 1972) make it possible to extend measurements of signal power down to D-region heights. A compromise design of multiple pulse experiments (Zamlutti, 1973; Zamlutti and Farley, 1975) balanced up the requirements for adequate height resolution with those of signal strenght allowing good quality data to be collected at E region altitudes during daytime.

Some data collected at Arecibo, using the experiments designed for D and E region, suggested that these experiments could also yield information, about the following topics:

a) The daytime sporadic E layer dynamics and composition (Ioannidis, 1973; Zamlutti, 1973; Rowe, 1973a).

b) The effect of modifications in the ionosphere introduced by high power HF waves (Hagfors and Zamluttim 1973; Ioannidis, 1973).

c) The night-time aspects of E region (Rowe, 1973b; Zamlutti, 1973).

In order to pursue the studies os these three topics, in fair detail, better quality data is required. It was felt that it would be necessary to collect together the benefits of improved range resolution, of pulse compression techniques, with that of a satisfactory spectral resolution obtained by using the multiple pulse technique. In fact, successful measurements of sporadic E layers have been recently made (Behnke and Vickrey, 1975) using a Barker-coded double pulse experiment.

In this paper we shortly review tha basic principles of both techniques and disscuss the important points governing the design of experiments coupling them together. The purpose is to find a way of collecting better data for the studies of the three topics mentioned above. The design is particularly applicable to the radar at Arecibo. The basic considerations are, however, general enough to be extended to other radars of monostatic type that operate in similar way.

GENERAL PRINCIPLES

Barker Code Technique

Pulse compression techniques have been used in radar astronomy to improve range resolution (e.g., Cook and Bernfeld, 1967; Evans and Hagfors, 1968). Only recently their application to incoherent scatter experiments has been put into practice (Ioannidis and Farley, 1972; Ioannidis, 1973). The basis for their use in these experiments has been discussed in detail by Gray and Farley (1973).

Pulse compression techniques work properly provided that phase coherence of the received signal is not lost. This has been a limitation to their application in incoherent scatter experiments (Ioannidis and Farley, 1972; Gray and Farley, 1973).

We are interested on phase-coded pulses, particularly on the convenient compression scheme known as Barker coding. The way these schemes work is fairly simple. As an example consider the 5 baud Barker code whose range time diagram is presented in Figure 1. Let V (h, t) be the voltage due to the returns from altitude h at instant t. The samples of the received signal will be in this case:

$$S_1 = V(h_1, t_1) - V(h_2, t_1) + V(h_3, t_1) + V(h_4, t_1) + V(h_5, t_1)$$

$$S_2 = V(h_2, t_1+T_b) - V(h_3, t_1+T_b) + V(h_4, t_1+T_b) + V(h_5, t_1+T_b) + V(h_6, t_1+T_b)$$

$$S_3 = V(h_3, t_1+2T_b) - V(h_4, t_1+2T_b) + V(h_5, t_1,2T_b) + V(h_6, t_1+2T_b) + V(h_7, t_1+2T_b)$$

$$S_4 = V(h_4,\ t_1+3T_b)-V(h_5,\ t_1+3T_b)+V(h_6,\ t_1+3T_b)+V(h_7,\ t_1+3T_b)+V(h_8,\ t_1+3T_b)$$

$$S_5 = V(h_5,\ t_1+4T_b)-V(h_6,\ t_1+4T_b)+V(h_7,\ t_1+4T_b)+V(h_8,\ t_1+4T_b)+V(h_9,\ t_1+4T_b)$$

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$$S_{n+1} = V(h_{n+1},t_1+nT_b)-V(h_{n+2},t_1+nT_b)+V(h_{n+3},t_1+nT_b)+V(h_{n+4},\ t_1+nt_b)+$$

$$V(h_{n+5},\ t_1+\ nT_b)$$

where

T_b is the baud length.

Proveided that the total code duration ($5T_b$ in our example) is much shorter than the correlation time (first zero crossing, T_x, of the autocorrelation function) one can assume that:

$$V(h_i,\ t_i) = V(h_i,\ t_i + \Delta t)$$

Detais of the effect of the coded duration on the compression were discussed by Gray and Farley (1973).

The received signal is cross-correlated with the transmitted signal at the Barker decoder. When the returned signal is sampled at intervals that equal the baud length, the cross-correlation operation (for- 5-baud code) becomes just the multiplication of 5 consecutive samples by the signs of the transmitted sequence and addition of the products. In our example the output, X_i, of the decoder will be:

$$X_i = (+1)xS_i + (+1)xS_{i+1} + (+1)xS_{i+2} + (-1)xS_{i+3} + (+1)xS_{i+4} =$$

$$= S_i + S_{i+1} + S_{i+2} - S_{i+3} + S_{i+4} =$$

$$- V(h_i,t) + V(h_{i+2},t) + 5V(h_{i+4},t) + V(h_{i+6},t) + V(h_{i+8},t)$$

It can be observed that the signal, X_i, available at the output of the Barker decoder enhanced the contribution of alttitude h_{i+4}, in the considered example. This is equivalent to having one short pulse with duration equals to the baud length, T_b, and the amplitude five times larger.

It became common practice to analyse the behavior of any pulse or code scheme by means of its weight function. The weight function can be thought of as the response of a thin slab of the ionosphere to the exciting pulse or code scheme, processed continuously in analog form. Mathematical description of this is given by the convolution of the pulse or code scheme with itself. One side of the symmetric weight function, corresponding to the 5-baud Barker-code of Figure 1, is shown in Figure 2. Actually, in practice, signals are not processed continuously in analog form, but sampled, digitized and then processed. Still, the weight function is a helpful tool to visualize the smearing produced by the pulse or code scheme.

From an average of the results of many transmissions we obtain an estimate of $<X_i^2>$, the true expected value or ensemble average of the signal power corresponding to altitude h_i. Let's call:

$$S_b = <X_i^2>$$

For a b-baud code, considering the scattering volume homogeneous, S_b is composed of b^2 times the power, S, from the desired height and (b-1) times that power from other (undesired) heights. This last contribution is often called self-clutter. We can then write S_b as:

$$S_b = b^2 S + (b-1) = (b^2 + b - 1)S \qquad (1)$$

The noise, N_b, at the output of the Barker decoder will be b times the noise, N, coming at the receiver output. This happens because when using matched filters the phase coherence for the noise is lost in a much shorter time than the baud length. We can then write:

$$n_b = bN \tag{2}$$

For a large b we can then appreciate an improvement of roughly a factor of b in signal-to-noise ratio. The signal- to-clutter ratio is also close to b.

Multiple Pulse Technique

The use of multiple pulse schemes has already been discussed in full detail in the incoherent scatter litterature (Farley, 1969; Wand 1969; Wand and Perkins, 1970; Farley, 1972; Zamlutti, 1973; Zamlutti and Farley, 1975). It is one way of making possible tha computation of long lags in the autocorrelation function without loosing height resolution. The technique for that consists of transmitting pulses spaced in such a way that when averaging lagged products no correlated contribution comes from more than one single height at a time. One way of generating such schemes was presented by Zamlutti (1973).

As an example consider a 4-pulse scheme, with pulses starting at relative times; 0, τ, 4τ and 6τ, each pulse with duration T. By sampling the received signal at relative times: t, $t+\tau$, $t+4\tau$ and $t + 6\tau$ one can perform 6 different lagged products:

$$r(h,\tau) = X(t) \quad X(t+\tau)$$

$$r(h,2\tau) = X(t+4\tau)\ X(t+6\tau)$$

$$r(h,3\tau) = X(t+\tau)\ X(t+4\tau)$$

$$r(h,4\tau) = X(t)\ X(t+4\tau)$$

$$r(h,5\tau) = X(t+\tau)\ X(t+6\tau)$$

$$r(h,6\tau) = X(t)\ X(t+6\tau)$$

where $X(\cdot)$ denotes the sample of the voltage available at the received output, $h = ct$ where c is the velocity of light in free space. From an average of many transmissions we obtain estimates of $<r(h,\Delta t)>$, the true expected value or ensemble average of the cross product. Details of the effect of the pulse duration on the behavior of the pulse scheme were given by Zamlutti (1973).

Figure 3 shows one side of the symmetric weight function corresponding to the case $\tau/T = 2$ for this 4-pulse scheme.

For a p-pulse scheme, the total returned power, S_p, assuming an homogeneous scattering volume, is composed of the signal power, S', from the described height and (p-1) times that power from other undesired heights. This last contribution is called self clutter. One can then write:

$$S_p = S' + (p-1)S' = pS' \tag{3}$$

Barker Coded Multiple Pulse Technique

This technique consists of coding each pulse of the multiple pulse scheme by a b-baud Barker code. The received signal is sampled, digitized, decoded and then lagged products are performed.

The basic features of multiple pulse technique remain unchanged. One can thus analyse the performance of any Barker coded multiple pulse experiment using the same considerations used before for uncoded multiple pulse experiments.

Following Zamlutti and Farley (1975) we shall assume that all computed lags of the autocorrelation function are equally useful in determining the parameters of interest and, futhermore, that each altitude sampled gives an independent information of the ionosphere. With these assumptions the design of an experiment becomes a suitable choice of the parameters that minimizes a quantity, δ , defined as:

$$\delta = \sigma \; n_L^{-1/2} \; n_h^{-1/2} \tag{4}$$

were σ is the standard deviation of each individual lag, n_L is the number of computed lags and n_h the number of heights sampled in a particular range of altitudes.

The standard deviation, σ, can be assumed to be th same for all computed lags (Zamlutti, 1973) and given by:

$$\sigma = K^{-1/2} \quad S_T/S_U$$

where K is the total number of transmissions performed, S_T the total power and S_U the power of the useful signal. The total power is composed of the total signal power, S_p, and an additional noise power. The total signal power for a multiple pulse scheme is given by (3), with S' being the total power corresponding to one pulse in the scheme. When the pulses are Barker coded S' is given by (1) and we then get:

$$S_p = pS' = p(b^2+b-1)S$$

where S is the signal power from the desired height. The usegul signal power for Barker coded pulses is b^2S. The noise power at the output of the decoder, given by (2) is bN. The standard deviation then becomes:

$$\sigma = K^{-1/2} \left[p(b^2+b-1)S + bN \right] /(b^2S) \tag{5}$$

The number of lags is given by (Farley, 1972; Zamlutti, 1973):

$$n_L = p(p-1)/2 \tag{6}$$

where p is the number of pulses in the scheme.

The number of heights is inversely proportional to the baud lenght, i.e.:

$$n_h = A^2/T_b \tag{7}$$

where A is a constant.

With (5), (6) and (7) substituted into (4) we get:

$$\delta = AK^{-1/2} \left[p(b^2+b-1) \,/b^2+N/bS \right] \left[p(p-1)/2 \right]^{-1/2} T_b^{-1/2} \tag{8}$$

DESIGN CONSIDERATIONS

Measurements to compute the autocorrelation function during occurrence of daytime sporadic E layers and during ionospheric modification experiments have one common feature: the returned signal is fairly strong but comes from a very thin layer in the ionosphere. Under these circumstances height resolution becomes the main point to be considered in the design. Also in this case the noise term, N/bS, of expression (8) can be neglected campared to the term, $p(b^2+b-1)b^2$, due to clutter. For these cases we can simplify (8) to:

$$\delta_1 = AK^{-1/2} \left[p(b^2+b-1)/B^2 \right] \left[p(p-1)/2 \right]^{-1/2} T_b^{-1/2} \qquad (9)$$

Measurements to compute the autocorrelation functions for the E region during nightime are characterized by extremely poor signal-to-noise ratios (Zamlutti, 1973). For this case only the noise term will matter in expression (8) which can be simplified to:

$$\delta_2 = AK^{-1/2} (N/bS) \quad p(p-1)/2^{-1/2} \; T_b^{-1/2} \qquad (10)$$

Presently, due to equipment limitations at Arecibo (Zamlutti) 1973; Behhke and Vickrey, 1975) the minimum value that can be used for T_b is 4μsec. We shall therefore assume 4μsec as a lower boundary for T_b in our design.

Computation of autocorrelation functions for E region altitudes at Arecibo requires measurements to be made as low as 100 km (about 660μsec of round trip). On the other hand, ground clutter returns affect the signal for the first 30 km range (round trip of about 200μsec). Hence, to compromise both restrictions, we are allowed to a maximum transmission time, T_R, of about 460μsec. This restriction, can, of course, be relaxed for regular ionospheric modification experiments, when meausrementes are important above 200 km (Hagfors and Zamlutti, 1973; Gordon and Carlson, 1974).

The total transmission time, T_R, is related to the lag spacing, τ, and to the pulse width , T, by (Zamlutti, 1973):

$$T_R = (n_L + n_M)\,\tau + T \qquad (11)$$

where n_L is the number of lags in the autocorrelation function and n_M is the number of missing lags (Farley, 1972; Zamlutti, 1973).

Another consideration deals with the ratio τ/T. To avoid range ambiguities (Zamlutti and Farley, 1975) this ratio must be larger than 2 for uncoded multiple pulse schemes. For coded multiple pulse schemes one could think that this restriction could be relaxed bacause of the compression. This, however, is not the case. In fact, when pulses are Barker coded the triangular shape of the weight function, as that shown in Figure 3, changes to another symmetric shape, one half of which is shown in Figure 4 for the case of a 5-baud code. One can observe that range ambiguities will still occurs if $\tau/T<2$. In our design we will use $\tau/T = 2$, for better use of the transmission time.

The signal-to-noise ratio, when matched filters are used varies with the square of the pulse width (or baud lenght, if pulses are coded).

As far as the transmission is concerned we can transmit the same pulse scheme all the time or, transmit two or more different schemes in an alternative way.

In order to compare the different experiments we assume same integration time and choose as normalization T_b = 4μsec. From expression (9) we can define a quantity, η_1, by:

$$\eta_1 = \left[p(b^2+b-1)/b^2 \right] \left[p(p-1)/2 \right]^{-1/2} \beta^{1/2} \gamma^{1/2} \qquad (12)$$

where $\beta = T_b/4$, (T_b in μsec), is the ratio between the baud lenght actually used and the 4μsec choosen as reference and γ is the ratio of the number of samples that are obtained when transmitting the same pulse scheme all the time to the number of samples obtained with the transmission procedure actually used.

For the case of low signal-to-noise ratio we can define from expression (10) a quantity, η_2, given by:

$$\eta_2 = b^{-1} \left[p(p-1)/2 \right]^{-1/2} \beta^{-3/2} \gamma^{1/2} \qquad (13)$$

The experiment is best designed for minimum η_1 or η_2 acording to the signal-to-noise ratio.

RESULTS

Based on the considerations of the precedings sections we selected some competitive experiments to present here.

For measurements during occurence of sporadic E layers two experiments were choosen. Both experiments use just one pulse scheme all time, T_b = 4μsec and τ/T = 2. The first experiment using a 5-pulse scheme, each pulse coded by a 5-baud Barker code yields 10 lags at 40μsec intervals out to 440μsec with one missing lag in that range. The second experiment using a 4-pulse scheme, each pulse coded by a 7-baud Barker code yields 6 lags at 56μsec intervals out to 336μsec. Table I shows the quality factor η_1 for these two experiments:

TABLE I

p	b	η_1
5	5	1.834
4	7	1.833

With no additional consideration both experiments are equally good. If one looks also for good frequency resolution the experiment using 5 pulses is, however, better.

For the case of E_S measurements, experiments using different pulse schemes to compute different lags are unlike to compete with the experiments presented above. In one such experiment (Behnke and Vickrey, 1975) transmitted pulses were sent off in pairs with variable time separation, cycled from 0 to 416μsec in steps of 52μsec. Pulses were coded by a 13-baud Barker code with baud lenght of 4μsec. The quality factor of it is η_1 = 2.142 which is 15% worse than the ones presented in Table 1.

When measurements are done during ionospheric modification experiments, the restriction T_R = 460μsec can be relaxed. For these measurements we also look for good frequency resolution (Hagfors and Zamlutti, 1973; Gordon and Carlson, 1974). It is, therefore, possible to increase the transmission time. From the possible experiments we choosed the one that seems more convenient for these measurements. It uses one 7-pulse scheme, each pulse coded by a 5-baud Barker code with baud lenght 4μsec. This experiment yields 21 lags at 40μsec intervals out to 1000μsec, with 4 missing lags in that range. The quality factor for it is η_1 = 1.772 which is 3% better than the 5-pulse experiment presented in Table I. Tha considerable advantage of this 7-pulse experiment is the frequency resolution of 1 KHz, which is 2.25 times better that used by Hagfors and Zamlutti (1973).

For measurements during nighttime we have 3 competitive experiments that uses just one pulse scheme all time. The first experiment is the 5-pulse experiment presented before. The second experiment uses a 4-pulse scheme, each pulse coded by a 7-baud Barker code with baud lenght of 5μsec. This experiments yields 6 lags at 70μsec intervals out to 240μsec. The third experiment uses a 4-pulse scheme, each pulse coded by a 5-baud Barker code with baud lenght of 7 sec. This experiment yields 6 lags at 70μsec intervals out to 420μsec.

The quality factor η_2 for each of these experiments is shown in Table II.

TABLE II

T_b (ηsec)	p	b	η_2
4	5	5	0.0632
5	4	7	0.0583
7	4	5	0.0353

The last experiment in Table II is by far the best one. It sacrifices height resolution to achieve better quality data.

From the possible experiments combining different schemes to compute different lags there is one that can be used for measurement of the nighttime E layer. It uses two pulse schemes. The first pulse scheme transmitted during 7/27 of the total integration time is a 3 pulse scheme, each pulse coded by a 5 baud Barker code with baud length of 13μsec. The second pulse scheme transmitted during 20/27 of the total integration time is a 3 pulse scheme, each pulse coded by a 5-baud Barker code with baud lenght of 10μsec. It yields lags at 100, 200 and 300ηsec. The difference in integration time balances up the difference in baud lenght so that standard deviation is the same for all lags. The quality factor, η_2 , for this experiment is 0.0251, which is 30% better than the best quality factor in Table II.

Preceding measurements made at Arecibo, during nighttime (Zamlutti, 1973) used a 5-pulse scheme with pulse width of 16μsec and filter bandwidth of 125 KHz. It yielded 10 lags at 40μsec intervals out to 440μsec with one missing lag. Its quality factor η_2 was 0.0791 which is about 3.3 times worse than the one obtained with the 3 pulse schemes presented before.

CONCLUSIONS

The results presented here show that the measurements of important features of the ionosphere, can be improved by using Barker coded multiple pulse experiments.

One main achievement with the present design is a frequency resolution of 1 KHz for measurements during ionospheric modification experiments, together with a height resolution of 600 m. The improvement by a factor of 3.3 in the quality of data for nighttime E region measurements is other significant achievement of the proposed design.

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FIGURE CAPTIONS

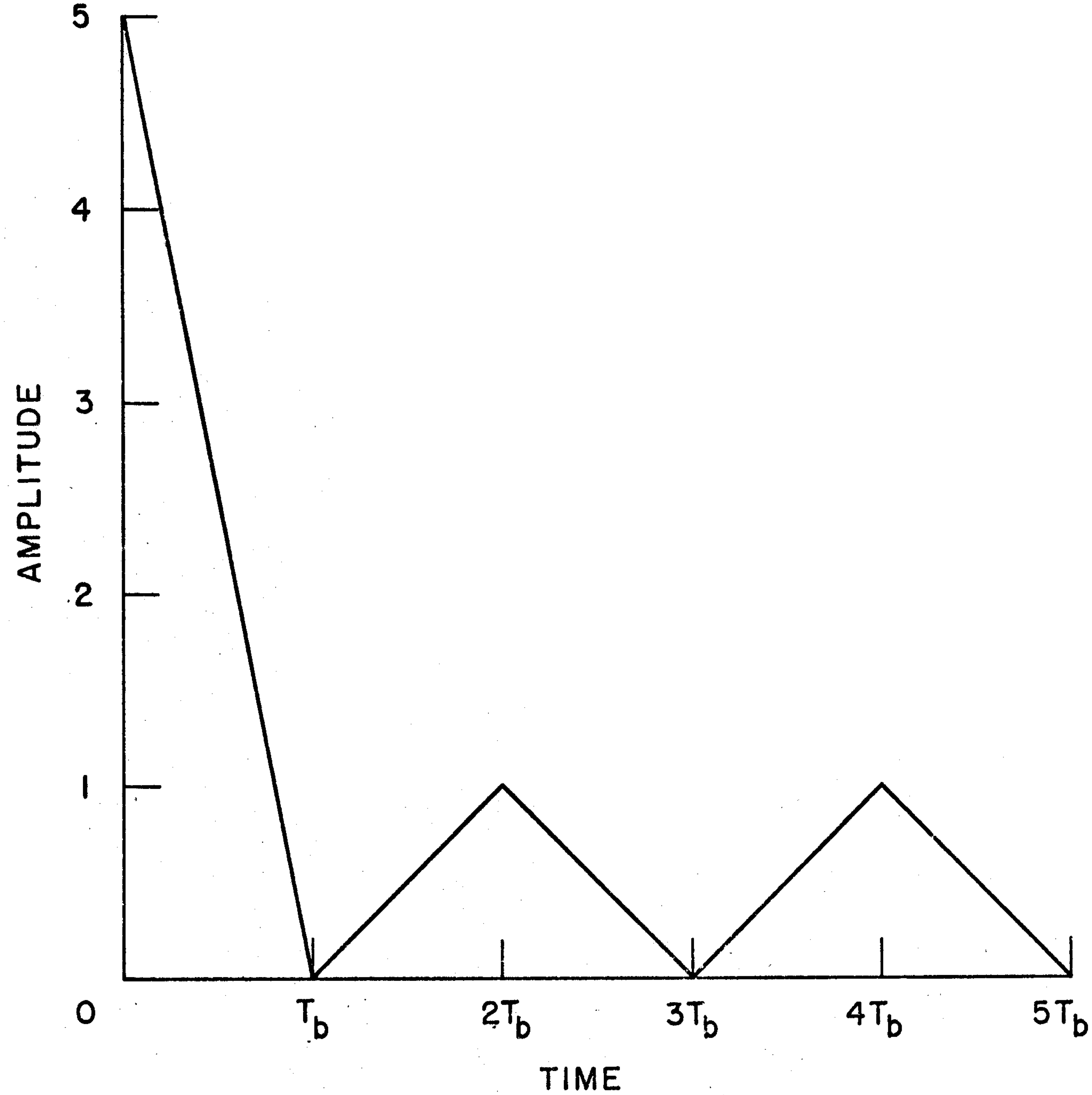
Figure 1 - Range time diagram for a 5-baud Barker coded pulse transmission (the finite width of the pulses and receiver gates is not shown).

Black circles correspond to positive signal and white circles to negative signal. By negative signal we mean phase reversed signal.

Figure 2 - One side of the symmetric weight function for a 5-baud Barker coded pulse with unit amplitude.

Figure 3 - One side of the symmetric normalized weight function for a 4-pulse scheme. With transmitted pulses at telative times: $0, \tau, 4\tau, 6\tau$.

Figure 4 - One side of the symmetric shape that substitutes the triangular pulses of a multiple pulse weight function when pulses are coded by a 5-baud Barker code. It results from the convolution of the weight function of this code with itself.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$5T_b$
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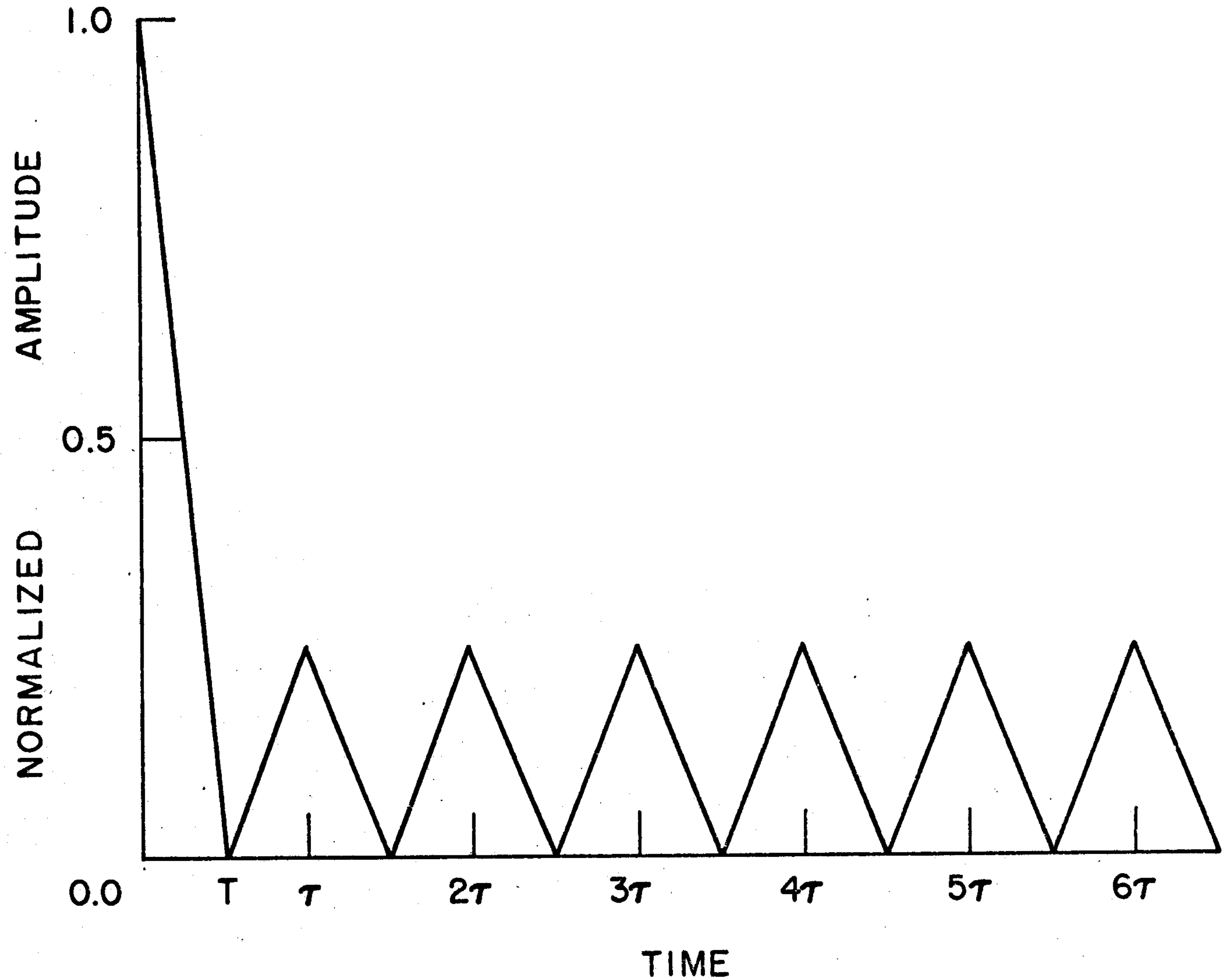
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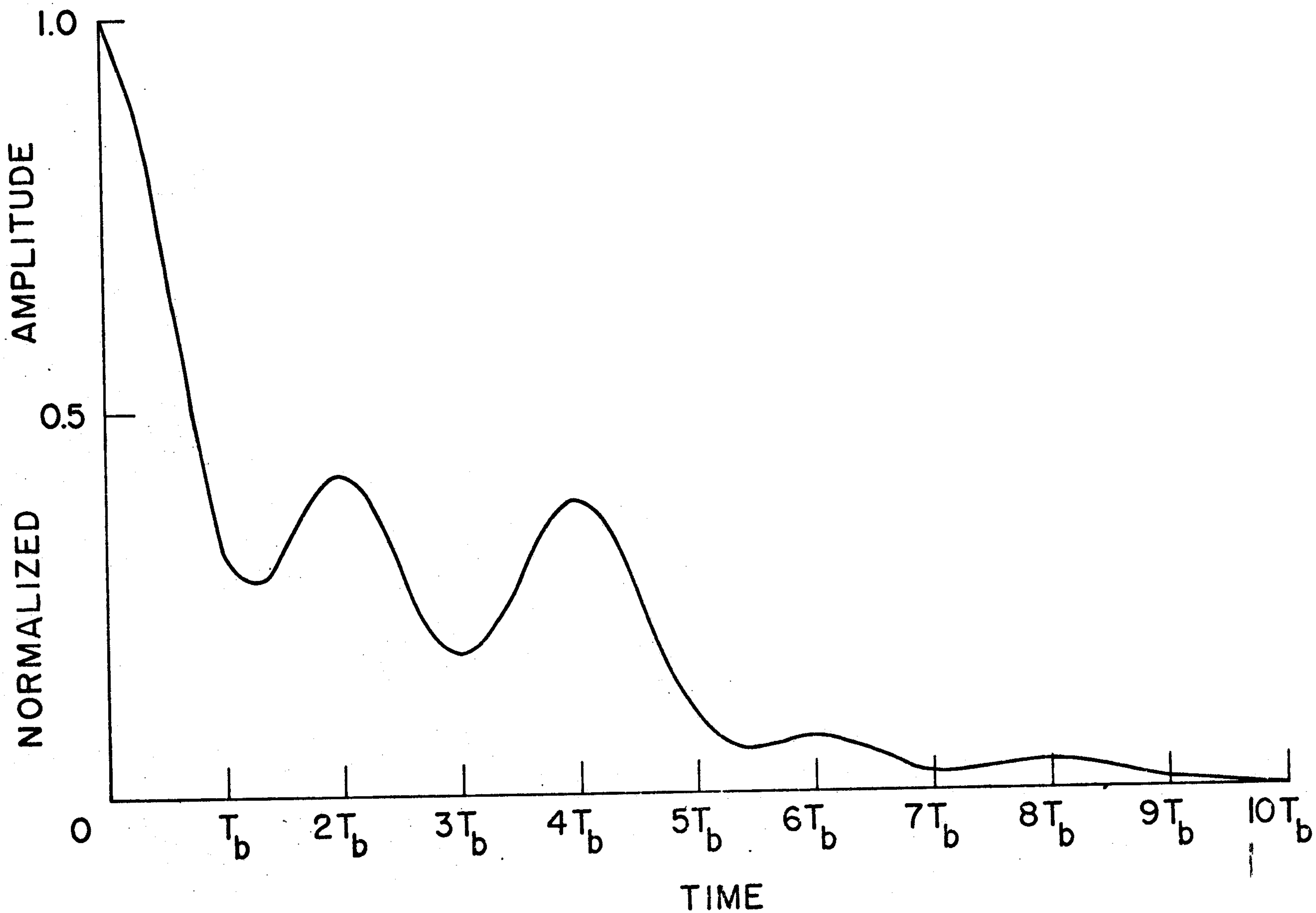
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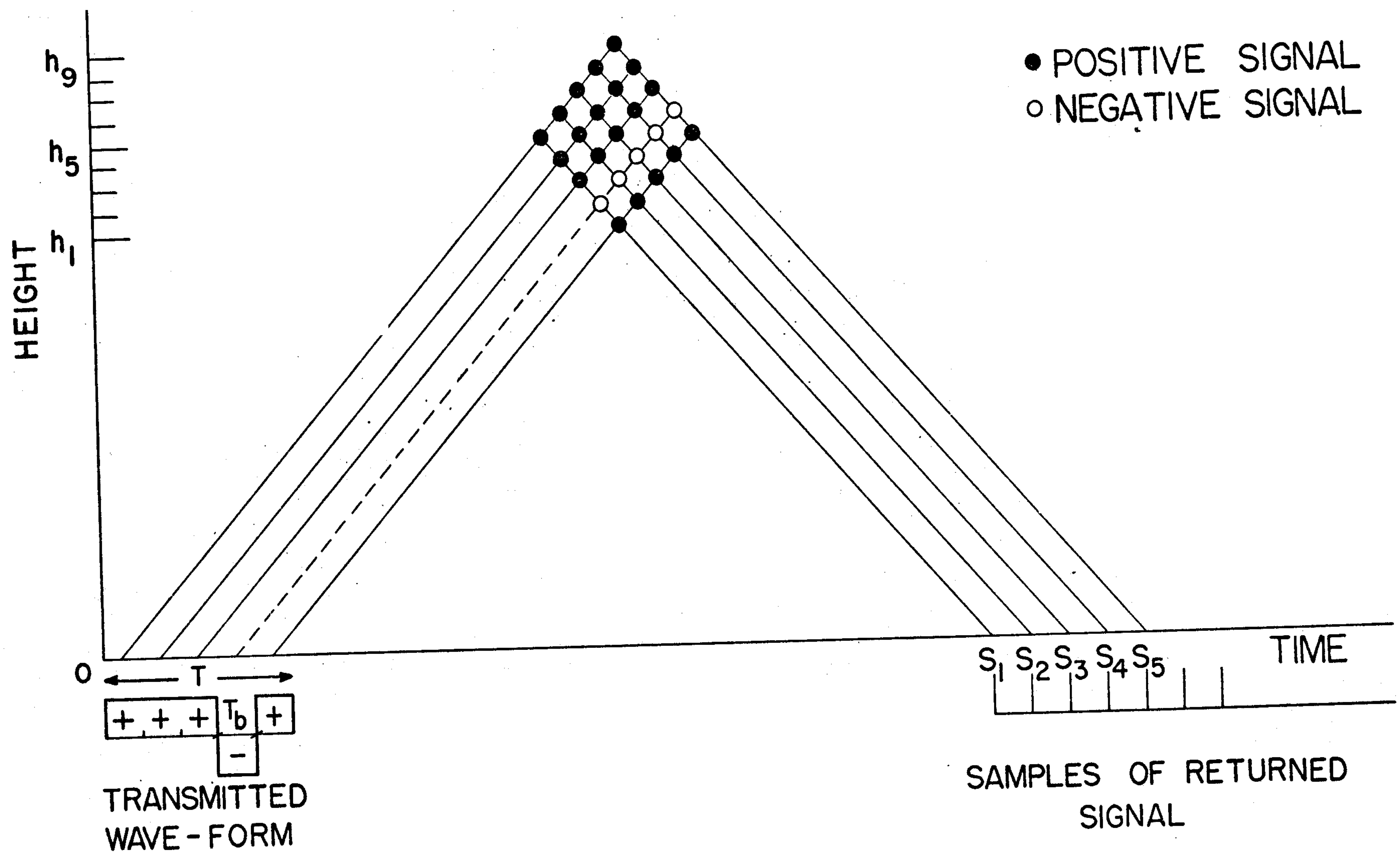

POSITIVE SIGNAL
NEGATIVE SIGNAL
HEIGHT
h9
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h1
0
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Tb
TIME
S1 S2 S3 S4 S5
TRANSMITTED WAVE-FORM
SAMPLES OF RETURNED SIGNAL

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