1.Classification *INPE.COM 4(RPE)* *CDU: 551.510.535*	2.Period *May 1980*	4.Distribution Criterion internal ☐ external ☒
3.Key Words (selected by the author) *BARKER CODE;* *MULTIPLE PULSE.*		
5.Report Nº	6.Date *May 1980*	7.Revised by *Barclay Robert Clemesha*
8. Title and Sub-title *DESIGN OF BARKER CODED MULTIPLE PULSE EXPERIMENTS*		9.Authorized by *Nelson de Jesus Parada* *Director*
10.Sector *DCE/DGA/GIO*	Code *30.371*	11.Nº of Copies
12.Authorship *C.J. Zamlutti*		14.Nº of Pages
J.SOBRAL p/ 13.Signature of the responsible		15.Price

16.Summary/Notes

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17.Remarks *This work was partially supported by the "Fundo Nacional de Desenvolvimento Científico e Tecnológico (FNDCT)", Brazil, under contract FINEP-537/CT. This work is a revison of (INPE-708-RRE/018, August 1975).*

DESIGN OF BARKER CODED MULTIPLE PULSE EXPERIMENTS

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ABSTRACT

Barker code and multiple pulse constitute two of 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 good quality data. The implementation of experiments combining the benefits of the two techniques is discussed and suggestions are made in some particular cases.

1. INTRODUCTION

Incoherent scatter studies of the lower ionosphere were drastically limited by the capabilities of the radars to satisfy the severe constraints imposed by the medium (Evans, 1969). In order to improve the quality of data, considerable work has been done, in the last few years, on the hardware and software of radar facilities (Farley, 1972; Hagen, 1972; Gray and Farley, 1973; Ioannidis, 1973; Ioannidis and Farley, 1973; Zamlutti, 1973; Rino et al, 1974; Zamlutti and Farley, 1975). As a result, good quality measurements of the ionospheric autocorrelation function are now possible at the E region during daytime (Rino et al., 1974; Zamlutti and Farley, 1975), and measurements of the signal power are made down to the D region (Ioannidis and Farley, 1973).

Some data collected at Arecibo, Puerto Rico, in experiments designed for the D and E regions, suggest that these experiments can also yield information about:

a) The daytime sporadic E layer dynamics and composition (Ioannidis, 1973; Zamlutti, 1973; Rowe, 1974).

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

c) The nighttime aspects of the E region (Rowe, 1973; Zamlutti, 1973).

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

In this paper we review, briefly, only the basic principles of both techniques, that are relevant to the design of experiments combining them together. An application is made to the radar at Arecibo (430 MHz). The theory is, however, general enough to be used for any monostatic radar, above 400 MHz, of similar design.

2. GENERAL PRINCIPLES

2.1. BARKER CODE TECHNIQUE

Pulse compression techniques, in radar astronomy, have been used 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, 1973; Ioannidis, 1973). The basis for the use of pulse compression techniques in these experiments has been discussed in detail by Gray and Farley (1973).

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

We are interested in phase-coded pulses, particularly in 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 Fig. 1. Let $V(h, t)$ be the voltage due to returns from altitude h, at instant t, and let T_b be the baud length. The samples of the received signal are:

$$A_1 = V(h_1, t_1) - V(h_2, t_1) + V(h_3, t_1) + V(h_4, t_1) + V(h_5, t_1)$$

$$A_2 = V(h_2, t_1+T_b) - V(h_3, t_1+T_b) + V(h_4, t_1+T_b) + V(h_5, t_1+T_b) + \\ + V(h_6, t_1+T_b)$$

$$A_3 = V(h_3,\ t_1+2T_b) - V(h_4,\ t_1+2T_b) + V(h_5,\ t_1+2T_b) + V(h_6,\ t_1+2T_b) +$$

$$+ V(b_7,\ t_1+2T_b)$$

....

$$A_{n+1} = V(h_{n+1},\ t_1+nT_b) - V(h_{n+2},\ t_1+nT_b) + V(h_{n+3},\ t_1+nT_b) + \dots$$

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

Provided that the total code duration ($5\,T_b$, in our example) is much shorter than the correlation time (which is the first zero crossing, T_X, of the autocorrelation function, or a time T_K, after which correlation becomes negligible, viz., in the case that no zero crossing is present), one can assume that:

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

for any interval of time Δt shorter than the total code duration. Details of the effect of the code 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 equal to the baud length, the cross-correlation operation (for a b-baud code) becomes just the multiplication of b consecutive samples by the signs of the transmitted sequence, and addition of the products. In our example, a generic sample, X_i, of the output of the decoder will be:

$$X_i = (+1)A_i + (+1)A_{i+1} + (+1)A_{i+2} + (-1)A_{i+3} + (+1)A_{i+4} =$$

$$= A_i + A_{i+1} + A_{i+2} - A_{i+3} + A_{i+4} = V(h_i,\ t) + V(h_{i+2},t) +$$

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

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

It has become common practice to analyse the behavior of any pulse or code scheme, by its weight function. This weight function can be thought of as the response of the a thin slab of the ionosphere, to the exciting pulse or code scheme, processed continuously in analog form. A 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 Fig. 1, is shown in Fig. 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 expected value or ensemble average of the signal power corresponding to altitude h_i. Let us call

$$S_b = <X_i^2>$$

For a b-baud Barker code, considering the scattering volume as 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:

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

The noise power, N_b, at the output of the Barker decoder will be b times the noise power, 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:

$$N_b = bN$$

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

2.2. MULTIPLE PULSE TECHNIQUE

The use of multiple pulse schemes has already been discussed, in full detail, in the incoherent scatter literature (Farley, 1969; Wand, 1969; Wand and Perkins, 1970; Farley, 1972; Zamlutti, 1973; Rino et al, 1974; Zamlutti and Farley, 1975). It is one way of making possible the computation of long lags, in the autocorrelation function, without losing height resolution. The technique consists of transmitting pulses spaced in such a way that, when averaging lagged products, no correlated contribution comes from more than a single height at a time. One way of generating such schemes was presented by Zamlutti (1973).

As 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 perfom 6 different lagged products:

$$r(h,\tau) = X(t)\ X(t+\tau)$$
$$r(h,2\tau) = X(t+4\tau)\ X(t+6\tau)$$
$$r(h,3\tau) = X(t+\tau)\ X(t+4\tau)$$
$$r(h,4\tau) = X(t)\ X(t+4\tau)$$
$$r(h,5\tau) = X(t+\tau)\ X(t+6\tau)$$
$$r(h,6\tau) = X(t)\ X(t+6\tau)$$

where X(.) denotes the sample of the voltage available at the receiver output; $h = ct/2$, where c is the speed of light in free space. Since the instantaneous power scattered by the plasma for length-scales larger than one Debye length, λ_d, exhibit no mutual correlation, for $c\ \tau > \lambda_d$, the average over many transmissions yields an estimate of $< r(h, \Delta t) >$, the expected value or ensemble average of the cross product. Details of the effect of the pulse duration on the behavior of the pulse scheme are given by Zamlutti (1973).

Fig. 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 desired height, and (p-1) times that power, from other undesired heights. One can then write:

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

This signal power is not useful for evaluation of the zero lag of the autocorrelation function which is obtained by other means (Zamlutti and Farley, 1975; Rino et al. 1974).

2.3. BARKER CODED MULTIPLE PULSE TECHNIQUE

This tecnhique 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.

The first part of the design consists of satisfying the physical constraints, imposed by the phenomena to be observed. These constraints determine the baud length, to obtain the desired height resolution, and the transmission time, for satisfactory spectral resolution. Once these variables are fitted to the constraints, the remaining ones can be adjusted to improve the quality of the data.

A final balance, between data quality and integration time, to follow the motion of the phenomena under observation, is then made. In the case of very poor signal-to-noise ratio, it is sometimes necessary to strike a compromise among baud length, quality of data and integration time, in order to draw reliable conclusions from the experiment.

Following Zamlutti and Farley (1975), assumption will be made that all computed lags of the autocorrelation function are equally useful in determining the parameters of interest and, furthermore, that each altitude sampled gives an independent piece of information about the ionosphere. With these assumptions and the physical constraints, the design of an experiment becomes a matter of suitably choosing the variables that minimize a quantity, δ, defined as:

$$\delta = \sigma n_L^{-1/2} \, n_h^{-1/2} \qquad (4)$$

where 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 the particular range of altitudes.

For just one measured height, equation (4) expresses the decreasing of uncertainty, with the increase in the number of computed lags. For a single computed lag, it expresses the improvement obtained by sampling more heights within the chosen range of altitudes.

A physical picture of the equation can be obtained by thinking of an experiment with the measured lags close together, near the origin, and all sampled heights within an homogeneous scattering volume. For this case, only the electron density (or signal power) can be determined and its uncertainty will be the δ of equation (4) when the standard deviation for each individual lag is σ.

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

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

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 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 useful 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:

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

When just one lagged product is performed relative to each pair of pulses the number of lags is given by (Farley, 1972; Zamlutti, 1973):

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

The number of heights is inversely proportional to the baud length, except when computer limitations occur (Zamlutti, 1973). We can, thus, write:

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

where A is a constant.

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

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

3. 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 of 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 in expression (8), can be neglected as compared to the term $p(b^2+b-1)/b^2$, because of clutter. For these cases we can approximate (8) by

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

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

$$\delta_2 = AK^{-1/2} (N/bS) \left[p(p-1)/2\right]^{-\frac{1}{2}} T_b^{-\frac{1}{2}} \qquad (10)$$

The assumption of a homogeneous medium is not satisfied when enhanced layers are present. In the case of very thin layers, like the ones treated here, when the total electron content of the scattering volume is not affected,the assumption can still to be used.

3.1. APPLICATION TO THE RADAR AT ARECIBO

(a) Basic considerations

Presently, owing to equipment limitations at Arecibo (Zamlutti, 1973; Behnke and Vickrey, 1975), the minimum value that can be used for T_b is 4 μsec. We shall, therefore, take 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 660 μsec of round trip). On the order hand, ground clutter returns affect the signal for the first 30 km range (round trip of about 200 μsec). Hence, to satisfy both restrictions, we are limited to a maximum transmission time, T_R, of about 460 μsec. This limitation can, of course, be relaxed for regular ionospheric modification experiments, when measurements 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 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 concerns 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 because 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 Fig. 4, when $\tau = 5T_b$, for the case of a 5-baud code. One can observe that range ambiguities will still occur if $\tau/T<2$. It is important to note that coding the pulses is equivalent to changing its rectangular shape by a triangular compressed shape, as that of Figure 2, for purposes of computing the weight function.

For $\tau/T = 2$ a negligible contribution to range ambiguities, as that shown from $5T_b$ to $10T_b$, in Figure 4, will still be present, but that can be ignored for all practical purposes.

In our design we will use $\tau/T = 2$, to transmit more pulses during the transmission time.

The signal-to-noise ratio for one individual pulse, when matched filters are used, varies with the square of the pulse width (or baud length, if the pulses are coded). In our case:

$$N/S \;\alpha\; T_b^{-2} \tag{12}$$

As far as the transmission is concerned, we can transmit the same pulse scheme all the time, like Zamlutti and Farley (1975) did for uncoded multiple pulse, or transmit two or more different schemes alternately, during the integration time, like Behnke and Vickrey (1975), did with double coded pulse.

In order to compare different experiments, we assume the same integration time chosen as normalization $T'_b = 4$ μsec. From expression (9) we can define a quantity, η_1, by:

$$\eta_1 = A^{-1}(K_1 T_b)^{1/2}\,\delta_1 = \left[p(b^2+b-1)/b^2\right]\left[p(p-1)/2\right]^{-1/2}\beta^{-1/2}\gamma^{1/2} \tag{13}$$

where $\beta = T_b/4$, (T_b in μsec) is the ratio between the length, actually used, and the 4 μsec chosen as reference; and γ is the ratio, K_1/K, of samples, K_1, that are obtained when transmitting the same pulse scheme all the time, to the number of samples, K, obtained with the transmission procedure actually used.

Analogously, for the case of low signal-to-noise ratio, we define, from expressions(10) and (12), the quantity, η_2, given by:

$$\eta_2 = A^{-1} K_1^{1/2} (T_b)^{3/2}\,\delta_2 = b^{-1}\left[p(p-1)/2)\right]^{-1/2}\beta^{-3/2}\gamma^{1/2}$$

(b) Examples

Experiments will be compared having in mind that they are designed to satisfy the physical constraints as much as possible.

The criterion adopted to compare experiments is, first, to examine the way that physical constraints are satisfied and, then, look at the quality factors, η_1 and η_2, when experiments equally satisfy these constraints. The smaller the values for η_1 and η_2, the samaller will be the integration time to obtain good quality data.

Based on the considerations of the preceding section, we have selected some competitive experiments to present here.

(b.1) Experiments for observations of E_s layers:

Sporadic E layers, observed at Arecibo in the range 100-120 km, are likely to be due to heavy ions (Zamlutti, 1973; Behnke and Vickery, 1975) with correlation time above 400 μsec. This imposes the first physical constraint, which is a frequency resolution better than 2.5 KHz. These layers have a width of a few hundred meters, so one looks for the best possible height resolution. In our case we are limited to 600 m height resolution.

To compare different experiments, the same integration time and repetition frequency are assumed.

With the considerations of the preceding sections, two experiments were chosen. Both experiments use just one pulse-scheme all the time T_b = 4 μsec 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 40 μsec intervals, out to 440 μsec, 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 56 μsec intervals, out to 336 μsec. Table 1 shows the quality factor η_1 for these two experiments:

TABLE 1

P	b	η_1
5	5	1.834
4	7	1.833

Both experiments are competitive, however, frequency resolution constraint excludes the second experiment.

For the case of E_S measurements, experiments using different pulse schemes, to compute different lags, are unlikely 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 416 μsec in steps of 52 μsec. Pulses were coded by a 13-baud Barker code with baud length of 4 μsec. The quality factor is η_1 = 2.142, which is 15 % worse than the ones presented in Table 1.

(b.2) Experiments for observations of man-made ionospheric modifications:

The characteristics of the so called heating experiments is the production of a thin region of enhanced scattering in the ionosphere. The frequency spectrum of this region shows up as an spike, superimposed on the ion frequency spectrum. Physical contraints for its observation are, therefore, good height and frequency resolutions, so far not obtained together (Hagfors and Zamlutti, 1973; Gordon and Carlson, 1974).

When measurements are made during ionospheric modification experiments, the restriction T_R = 460 μsec can be relaxed. For these measurements we look for good frequency resolution (Hagfors, and Zamlutti, 1973; Gordon and Carlson, 1974). It is, therefore, desirable to increase the transmission time.

From the possible experiments, we chose one that seemed more convenient for the measurements. It uses one 7-pulse scheme, each pulse coded by a 5-baud Barker code, with 4 μsec baud length. This experiment yieds 21 lags at 40 μsec intervals, out to 1000 μsec, with 4 missing lags in that range. The quality factor for it, η_1 = 1.772, is 3% better than the 5-pulse experiment presented in Table 1. The considerable advantage of this 7-pulse experiment is the frequency resolution of 1 kHz, which is 2.25 times better than that used by Hagfors and Zamlutti, (1973). The height resolution is also 4 times better than that of Hagfors and Zamlutti (1973).

(b.3) Experiments for observations of the E layer during nighttime:

Previous measurements made at Arecibo (Zamlutti, 1973); during nighttime, presented evidence of an ionized layer, with no more than 5 km total width, peaked around 100 km, when a sporadic E layer was observed in the ionograms. To distinguish between the sporadic E layer and the background ionization, we have the same physical constraints imposed for observation of daytime sporadic E layers. Nighttime measurements are characterized by very poor signal-to-noise ratios, and data analysis complexity increases with the decrease of ionization (Zamlutti, 1973). Under these circumstances, we must compromise between the baudlength and quality of data, to obtain meaningful results, within reasonable integration times.

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

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

TABLE III

T_b(μsec)	p	b	η_2
4	5	5	0.0632
5	4	7	0.0417
7	4	5	0.0353

The third experiment is the best one, as far as the quality of data is concerned. With its height resolution of 1.05 km, some information can still be obtained about the sporadic E layer (Zamlutti, 1973).

If we decide not to sacrifice the height resolution when examining the sporadic E layers, we may use the first experiment and take the average of two consecutive heights outside the E_S range. This procedure will decrease η_2 by a $\sqrt{2}$ factor outside the E_S range, allowing a quality of data comparable to that of the third experiment for the background ionization.

Preceding measurements, made at Arecibo, during nighttime (Zamlutti, 1973) used a 5-pulse scheme with a pulse width of 16 μsec and filter band-width of 125 kHz. It yielded 10 lags at 40 μsec intervals, out to 440 μsec, with one missing lag. The integration time less than 30 minutes was acceptable, but the height resolution of 2.4 km and the quality factor η_2 = 0.0791 did not allow conclusions to be drawn from the data.

4. CONCLUSIONS

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

The major achievement of the present design is the possibility of having together height and frequency resolution, more appropriate to the observation of thin layers that have narrow frequency spectra, like some sporadic E layers and the layer resulting from the excitation of the ionosphere by high power HF waves.

ACKNOWLEDGMENTS

The author appreciates the help of the Arecibo staff in 1972 when first ideas for this paper started being developed. This work was fully supported by the Instituto de Pesquisas Espaciais (INPE), Brazil.

FIGURE CAPTIONS

Figure 1 - Range time diagram for a 5 baud Barker coded pulse transmission (the finite width of the pulse and receiver gates is not shown). Black circles correspond to positive signal. By negative signal we mean phase reversed signal. Notice that the number of samples A_i is not necessarily 7 as shown in the figure.

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 of a 4-pulse scheme. With transmitted pulses at relative times: $0, \tau, 4\tau, 6\tau$. Note that $T = \tau/2$.

Figure 4 - One side of the symmetric shape that substitutes each one of the triangular pulses of the 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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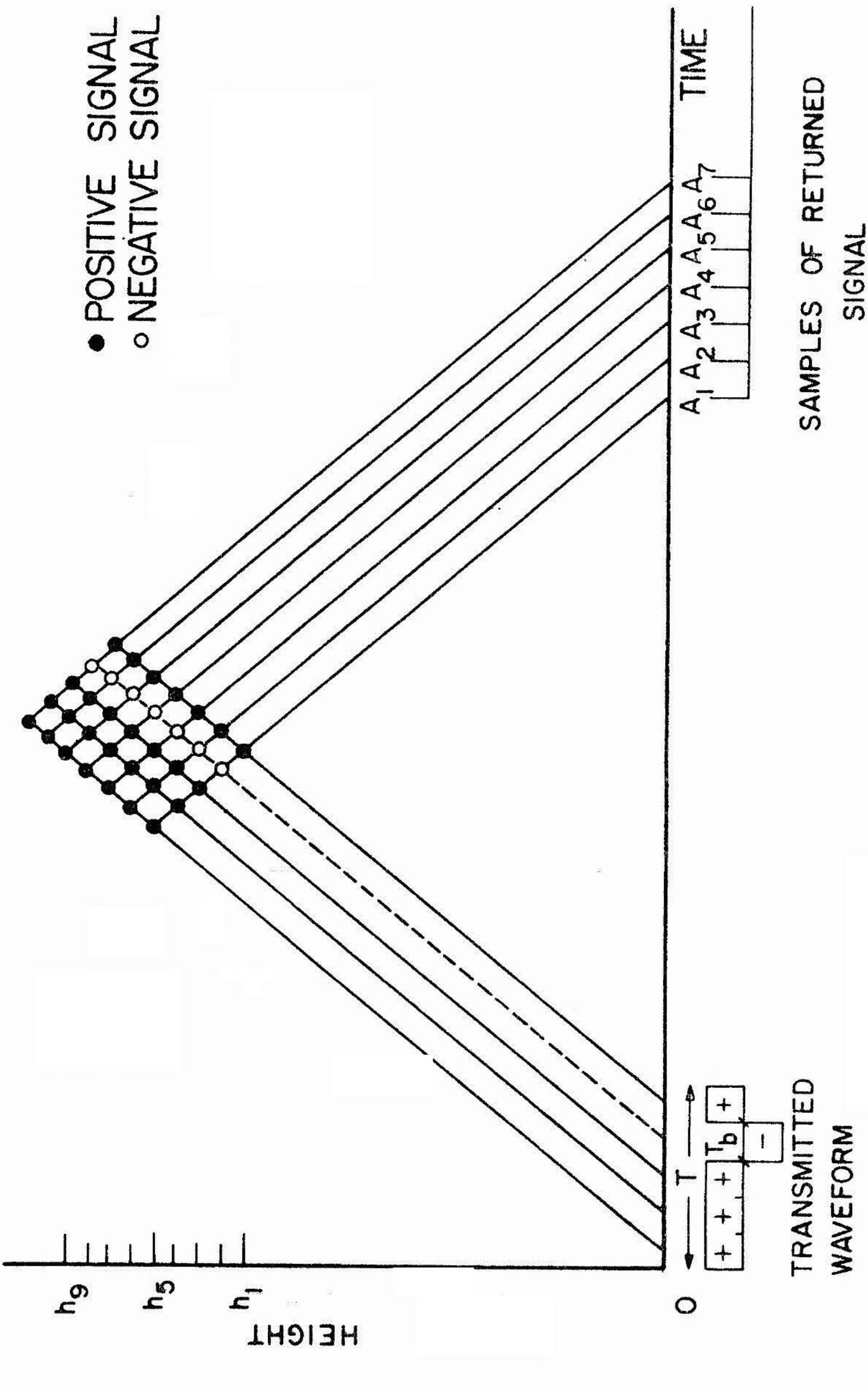
POSITIVE SIGNAL
NEGATIVE SIGNAL
TIME
A_1 A_2 A_3 A_4 A_5 A_6 A_7
SAMPLES OF RETURNED SIGNAL
HEIGHT
h_9
h_5
h_1
O
T
T_b
+ + + - +
TRANSMITTED WAVEFORM

Fig. 1

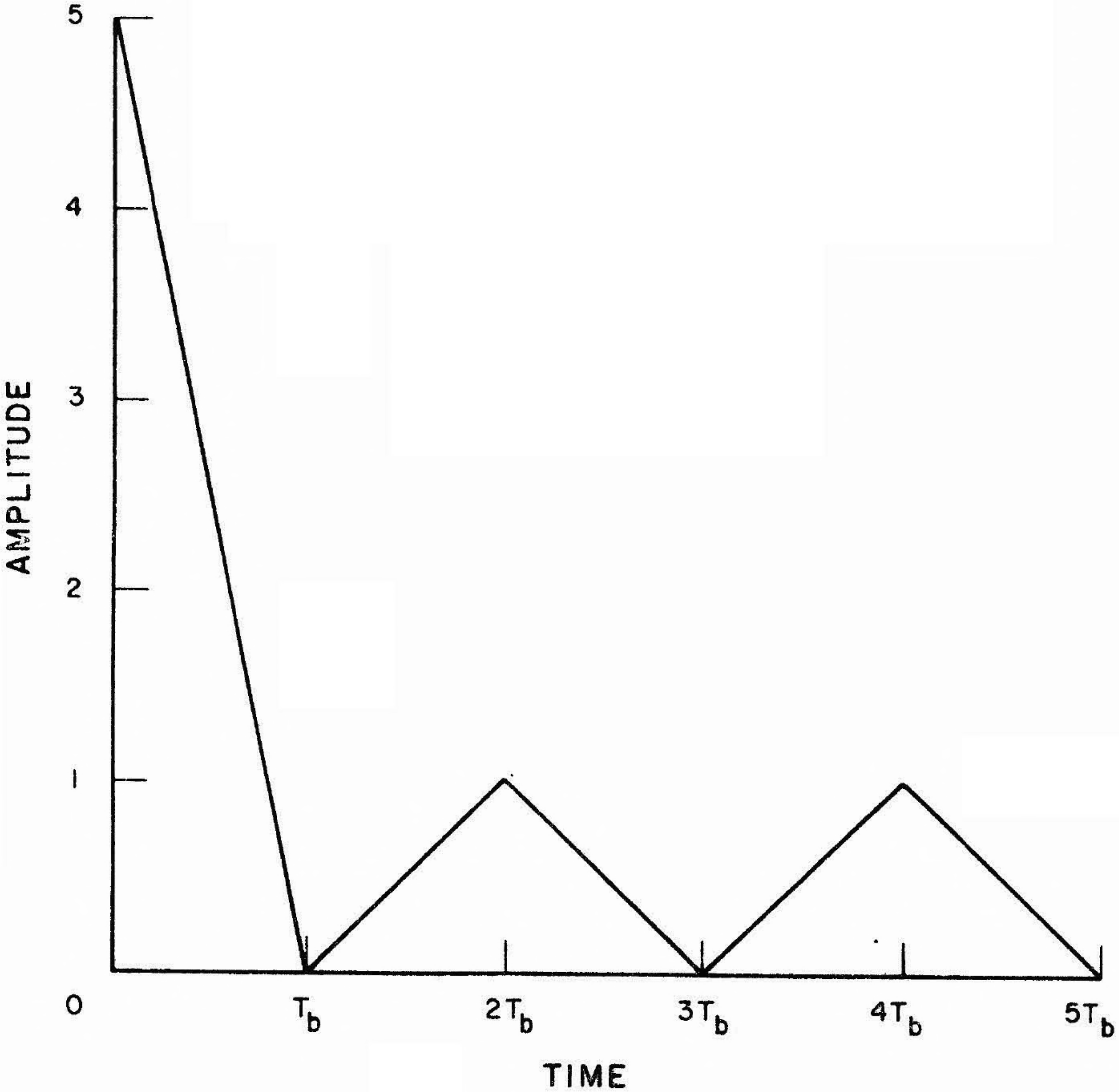

Fig. 2

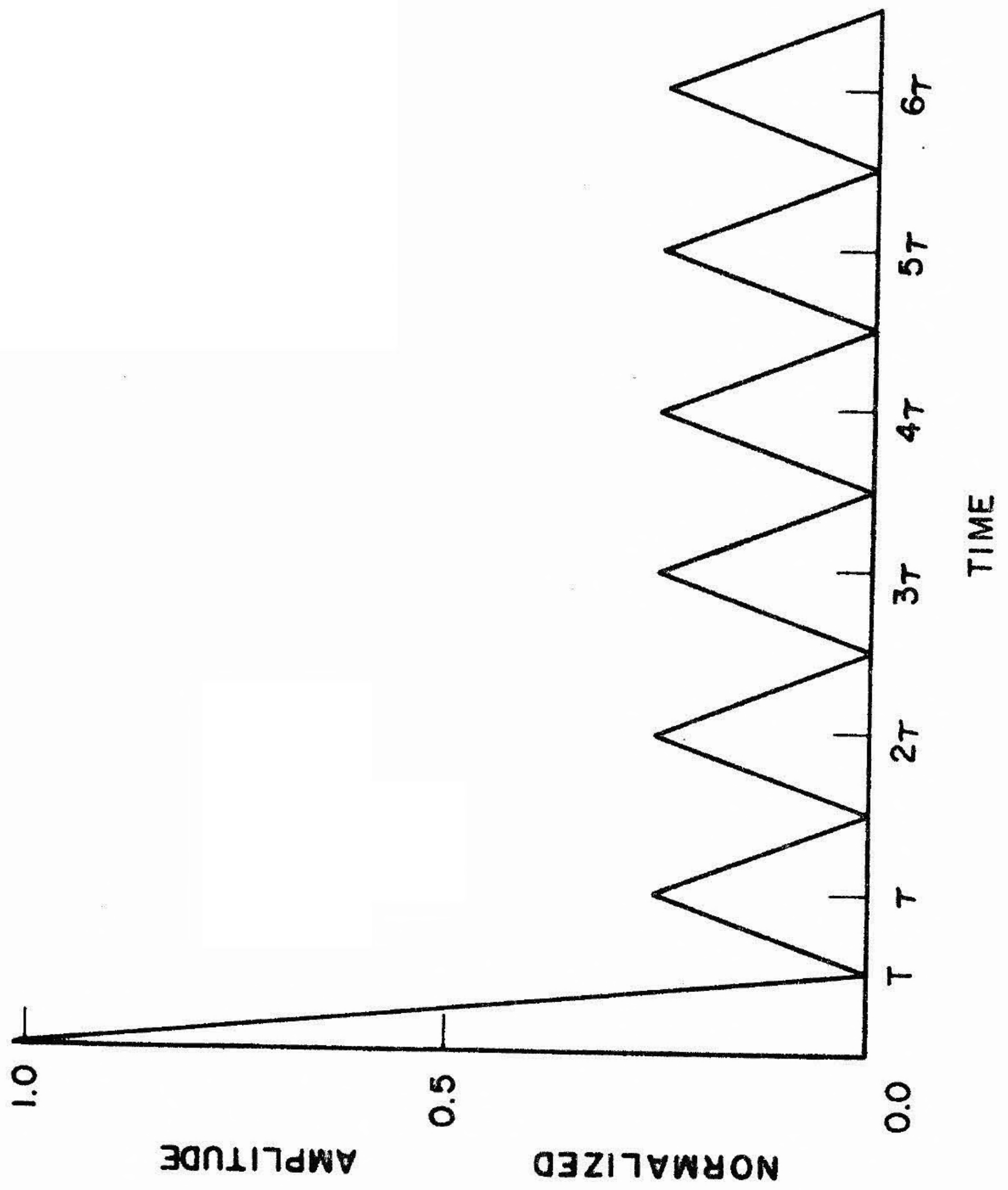

Fig. 3

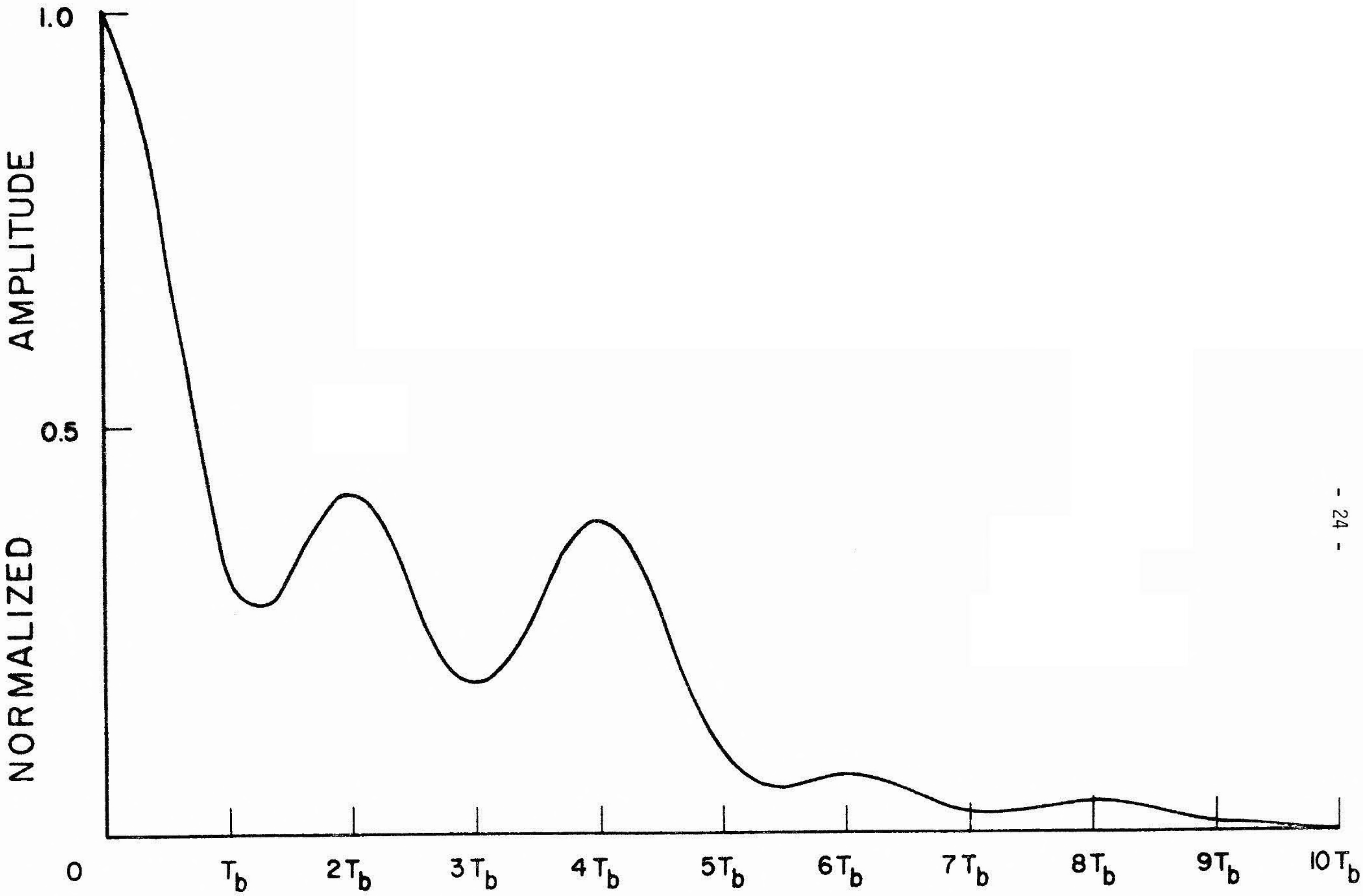
NORMALIZED AMPLITUDE
1.0
0.5
0
T_b
$2T_b$
$3T_b$
$4T_b$
$5T_b$
$6T_b$
$7T_b$
$8T_b$
$9T_b$
$10T_b$
TIME

Fig. 4