

1. Classification <i>INPE-COM.10/PE</i> <i>C.D.U. 551.510.535</i>		2. Period <i>December, 1975</i>	4. Distribution Criterion  internal <input type="checkbox"/>  external <input checked="" type="checkbox"/>
3. Key Words (selected by the author) <i>INCOHERENT-BACKSCATTER; IONOSPHERE;</i> <i>RADAR; BARKER CODE; MULTIPLE PULSE</i>			
5. Report No. <i>INPE-827-PE/015</i>	6. Date <i>February 10, 1976</i>	7. Revised by <i>L. A. Vieira Dias</i>	
8. Title and Sub-title  <i>DESIGN OF BARKER CODED MULTIPLE PULSE EXPERIMENTS</i>		9. Authorized by  <i>Fernando de Mendonça</i> Director	
10. Sector <i>CEA-SGO</i>	Code <i>412</i>	11. No. of Copies - <i>4</i>	
12. Authorship <i>Carlos José Zamlutti</i>		14. No. of Pages - <i>27</i>	
13. Signature of first author		15. Price	
16. Summary/Notes  <i>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.</i>			
17. Remarks <i>To be submitted for publication in Radio Science.</i>			

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 strength 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 Zamlutti 1973; Ioannidis, 1973).

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

In order to pursue the studies on 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 the basic principles of both techniques and discuss 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:

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

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

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

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

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

⋮  
⋮  
⋮

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

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

where

$T_b$  is the baud length.

Provided 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:

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

Details 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 b-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:

$$\begin{aligned} X_i &= (+1) \times S_i + (+1) \times S_{i+1} + (+1) \times S_{i+2} + (-1) \times S_{i+3} + (+1) \times S_{i+4} = \\ &= S_i + S_{i+1} + S_{i+2} - S_{i+3} + S_{i+4} = \\ &= V(h_i, t) + V(h_{i+2}, t) + 5V(h_{i+4}, t) + V(h_{i+6}, t) + V(h_{i+8}, t) \end{aligned}$$

It can be observed that the signal,  $X_i$ , available at the output of the Barker decoder enhanced the contribution of altitude  $h_{i+4}$ , 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  $\langle X_i^2 \rangle$ , the true expected value or ensemble average of the signal power corresponding to altitude  $h_i$ . Let's call:

$$S_b = \langle X_i^2 \rangle$$

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:

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

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:



$$n_b = bN \quad (2)$$

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 literature (Farley, 1969; Wand 1969; Wand and Perkins, 1970; Farley, 1972; Zamlutti, 1973; 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 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;  $0, \tau, 4\tau$  and  $6\tau$ , 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:

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

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

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

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

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

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

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  $\langle r(h, \Delta t) \rangle$ , 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:

$$S_p = S' + (p-1)S' = pS' \quad (3)$$

### 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, furthermore, 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,  $\delta$ , defined as:

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

where  $\sigma$  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,  $\sigma$ , 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 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 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:

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

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

$$n_L = p(p-1)/2 \quad (6)$$

where  $p$  is the number of pulses in the scheme.

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

$$n_h = A^2/T_b \quad (7)$$

where  $A$  is a constant.

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

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

#### 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 compared to the term,  $p(b^2+b-1)b^2$ , due to clutter. For these cases we can simplify (8) to:

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

Measurements to compute the autocorrelation functions for the E region during nighttime 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:

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

Presently, due to equipment limitations at Arecibo (Zamlutti 1973; Behhke and Vickrey, 1975) the minimum value that can be used for  $T_b$  is  $4\mu\text{sec}$ . We shall therefore assume  $4\mu\text{sec}$  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  $660\mu\text{sec}$  of round trip). On the other hand, ground clutter returns affect the signal for the first 30 km range (round trip of about  $200\mu\text{sec}$ ). Hence, to compromise both restrictions, we are allowed to a maximum transmission time,  $T_R$ , of about  $460\mu\text{sec}$ . This restriction, 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,  $\tau$ , and to the pulse width,  $T$ , by (Zamlutti, 1973):

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

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  $\tau/T$ . 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 Figure 4 for the case of a 5-baud code. One can observe that range ambiguities will still occur 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 length, 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  $T_b = 4\mu\text{sec}$ . From expression (9) we can define a quantity,  $\eta_1$ , by:

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

where  $\beta = T_b/4$ , ( $T_b$  in  $\mu\text{sec}$ ), is the ratio between the baud length actually used and the  $4\mu\text{sec}$  chosen as reference and  $\gamma$  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,  $\eta_2$ , given by:

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

The experiment is best designed for minimum  $\eta_1$  or  $\eta_2$  according 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 chosen. Both experiments use just one pulse scheme all time,  $T_b = 4\mu\text{sec}$  and  $\tau/T = 2$ . The first experiment using a 5-pulse scheme, each pulse coded by a 5-baud Barker code yields 10 lags at  $40\mu\text{sec}$  intervals out to  $440\mu\text{sec}$  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  $56\mu\text{sec}$  intervals out to  $336\mu\text{sec}$ . Table I shows the quality factor  $\eta_1$  for these two experiments:

TABLE I

p	b	$\eta_1$
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  $416\mu\text{sec}$  in steps of  $52\mu\text{sec}$ . Pulses were coded by a 13-baud Barker code with baud length of  $4\mu\text{sec}$ . The quality factor of it is  $\eta_1 = 2.142$  which is 15% worse than the ones presented in Table I.

When measurements are done during ionospheric modification experiments, the restriction  $T_R = 460\mu\text{sec}$  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 length  $4\mu\text{sec}$ . This experiment yields 21 lags at  $40\mu\text{sec}$  intervals out to  $1000\mu\text{sec}$ , with 4 missing lags in that range. The quality factor for it is  $\eta_1 = 1.772$  which is 3% better than the 5-pulse experiment presented in Table I. The considerable advantage of this 7-pulse experiment is the frequency resolution of 1 KHz, which is 2.25 times better than 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 length of  $5\mu\text{sec}$ . This experiment yields 6 lags at  $70\mu\text{sec}$  intervals out to  $240\mu\text{sec}$ . The third experiment uses a 4-pulse scheme, each pulse coded by a 5-baud Barker code with baud length of  $7\text{ sec}$ . This experiment yields 6 lags at  $70\mu\text{sec}$  intervals out to  $420\mu\text{sec}$ .

The quality factor  $\eta_2$  for each of these experiments is shown in Table II.

TABLE II

$T_b$ (nsec)	p	b	$\eta_2$
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 13 $\mu$ sec. 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 length of 10 $\mu$ sec. It yields lags at 100, 200 and 300 $\mu$ sec. The difference in integration time balances up the difference in baud length so that standard deviation is the same for all lags. The quality factor,  $\eta_2$ , 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 16 $\mu$ sec and filter bandwidth of 125 KHz. It yielded 10 lags at 40 $\mu$ sec intervals out to 440 $\mu$ sec with one missing lag. Its quality factor  $\eta_2$  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.

#### ACKNOWLEDGMENTS

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

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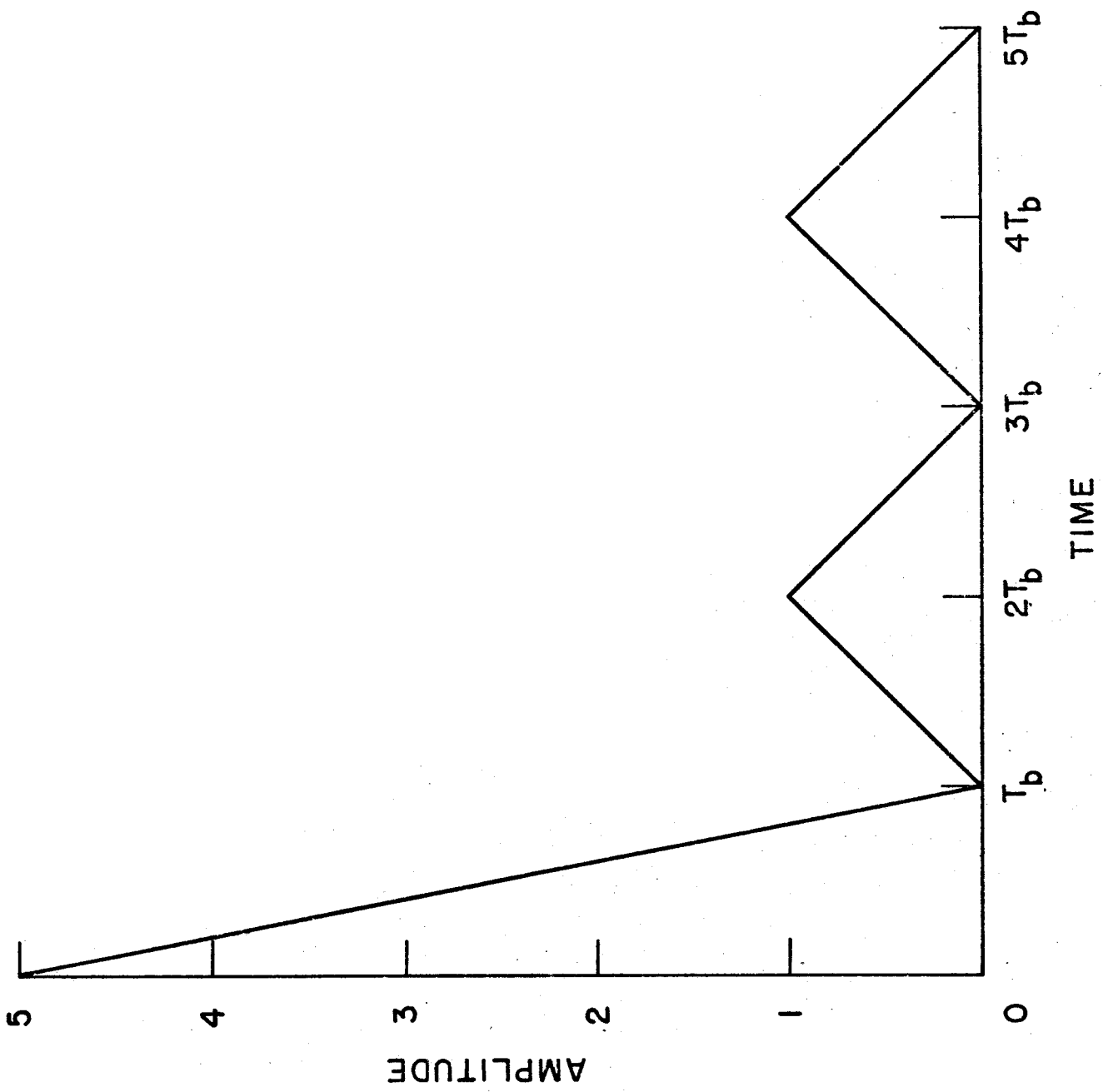
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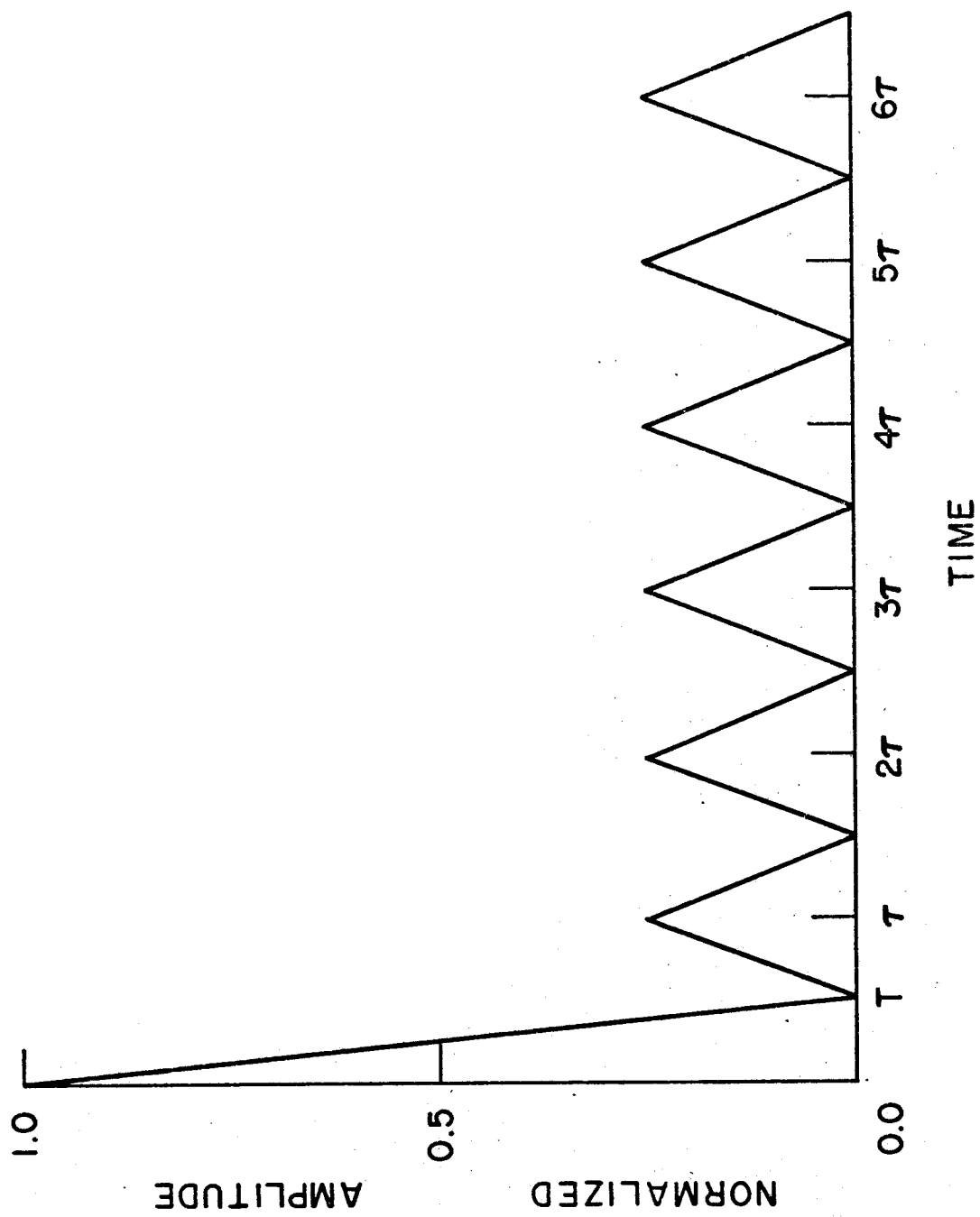
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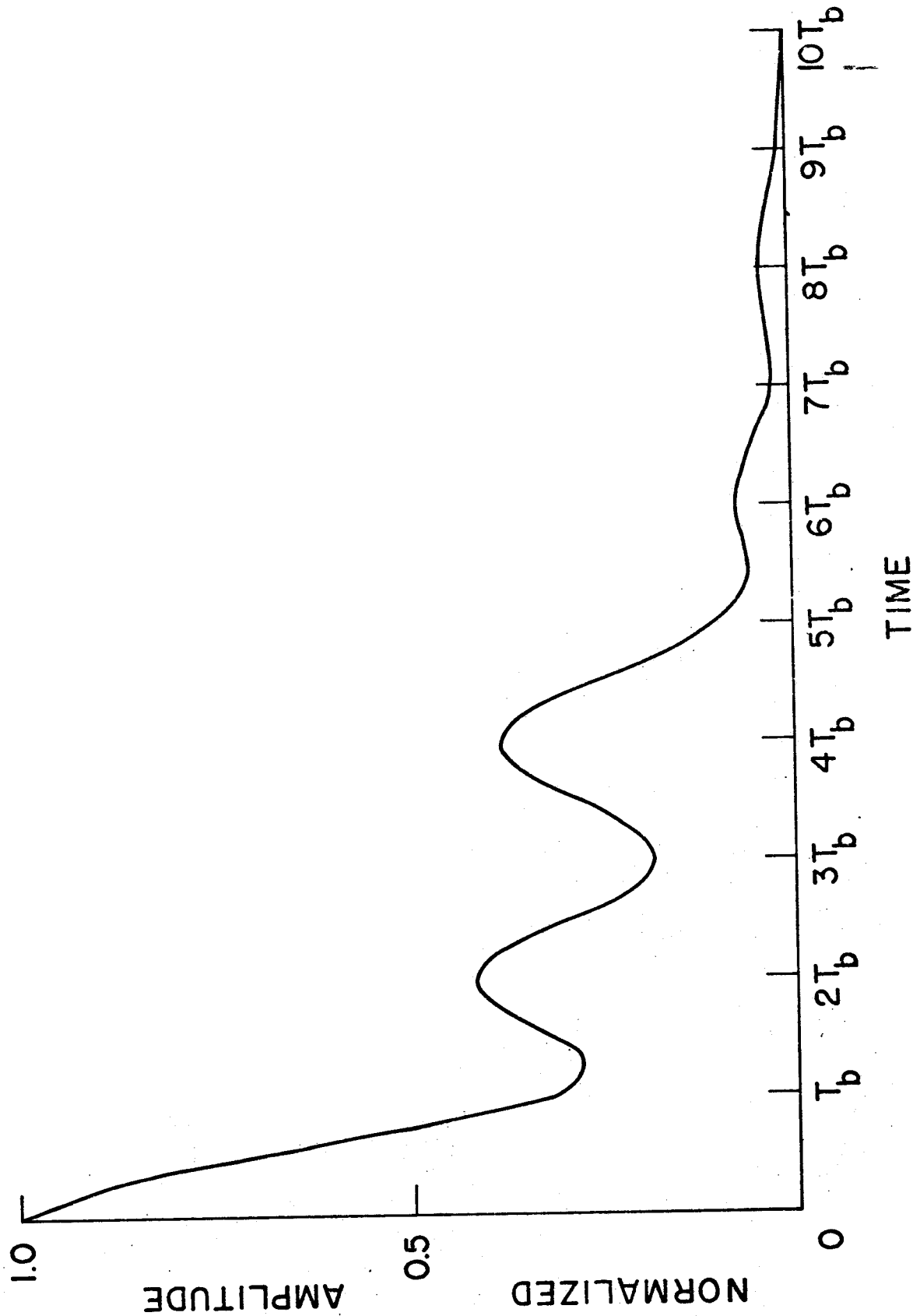
## FIGURE CAPTIONS

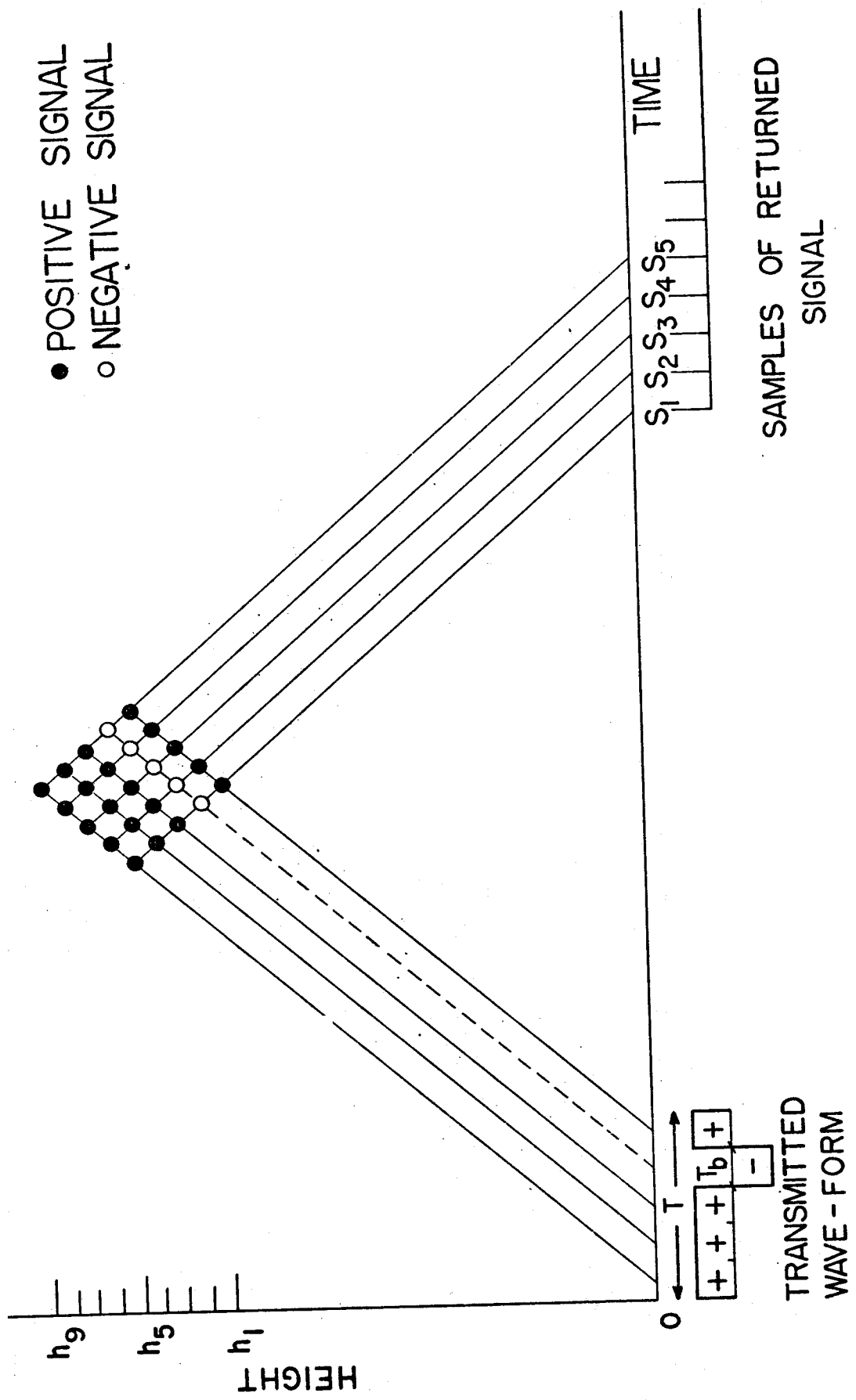
- Figure 1 - Range time diagram for a 5-baud Barker coded pulse transmission (the finite width of the pulses and receiver gates is not shown).  
Black circles correspond to positive signal and white circles to negative signal. By negative signal we mean phase reversed signal.
- Figure 2 - One side of 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 relative 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.













DESIGNED AND PRINTED IN  
INSTITUTE FOR SPACE RESEARCH (INPE)  
BRAZIL