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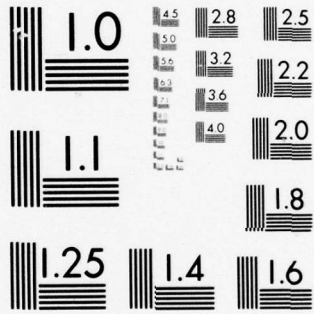
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TECHNICAL REPORT TE-77-1

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PPABLK-A COMPUTER SIMULATION OF THE
VELOCITY RESPONSE OF MOVING-TARGET
INDICATOR RADARS USING PULSE OR BLOCK
STAGGER

Advanced Sensors Directorate
Technology Laboratory

1 February 1977

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The program PPABLK is designed to analyze the velocity response of a moving-target indicator radar processor. The processor consists of identical in-phase and quadrature N_m -tap transversal filters, whose outputs are combined as the square-root of the sum of squares. The incoming pulse train consists of N_t pulses per beam position structured in N_b blocks of N_p ($=N_t/N_b$) sub c sub b sub p sub T sub B ABSTRACT (Continued)		

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ABSTRACT (Concluded)

pulses/block. The individual interpulse spacings can be staggered and a new set of N_m tap gains, interpulse spacings, and transmitter frequency can be assigned to each block. The program can be used to simulate processors with moving-window filters ($N_p > N_m$) or fixed-window ($N_p = N_m$) filters and N_p ($N_p - N_m + 1$) successive outputs are added in an integrator. The processor amplitude response as a function of target velocity is computed and displayed using either a graphics terminal or line printer. Output data, in addition to a velocity response, includes a histogram of the amplitude response over a user-specified range of target velocities and a tabulation of the improvement factor, i.e., ratio of signal-to-clutter power ratios before and after filtering, as a function of the standard deviation of the Gaussian clutter power-density spectrum.



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I. BACKGROUND

It is well known that the velocity response of a digital moving target indicator (MTI) is zero at multiples of that doppler velocity known as the blind velocity (v_b) which corresponds to the radar pulse repetition frequency (f_p). The relationship also depends on the transmitter frequency (f_t) and is given by

$$v_b = \frac{\lambda}{2} f_p = \frac{3 \times 10^8}{2 f_t T} \quad (1)$$

where λ is the radar wavelength and T is the pulse repetition interval ($1/f_p$). Although the location of the first velocity blind could be increased by reducing T , the minimum value of T is determined by the maximum range (R_m) at which it is desirable to detect a target return, i.e., $R_m = cT/2$, where c is the velocity of light (3×10^8 m/sec).

Consequently, alternative procedures for extending the first velocity blind have been proposed. These can be subdivided into block stagger [1, 2] and pulse-to-pulse stagger [3-6] techniques.

A. Block Stagger

Block stagger implies that the number of pulses (N_c) transmitted during a particular beam position are subdivided into N_b blocks of N pulses each. For the j^{th} block of pulses, it follows from Equation (1) that a specified velocity blind $v_b(j)$ can be generated by choosing either a unique transmit frequency $f_t(j)$ or an interpulse spacing $T(j)$. The first technique is referred to as frequency agility, the latter as block stagger. The composite velocity response consisting of the N_b individual block responses has the first true blind velocity when

$$v_b = M_j v_b(j) \quad j = 1, 2, \dots, N_b \quad (2)$$

holds for all N_b blocks and M_j is a unique integer for each block. The velocity response for an MTI processor using two blocks of three pulses is shown in Figure 1 for $T(1) = 1.0$ msec and $f_t(1) = 5.5$ GHz. The staggered response is achieved by a 20% increase in either the transmit frequency or the interpulse spacing for the second block.

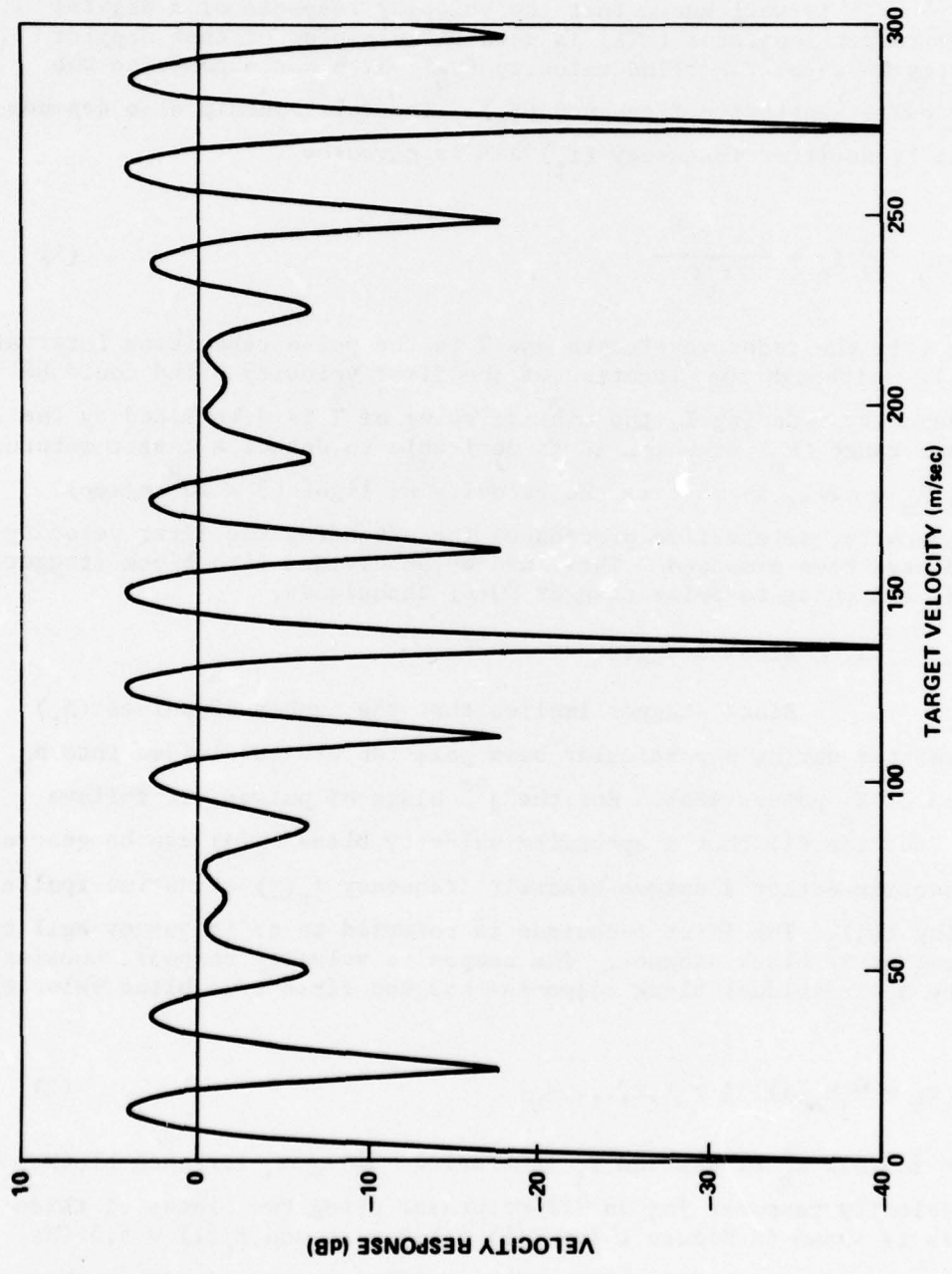


Figure 1. Velocity response of three-pulse canceller using block stagger.

It is evident that while the original blind velocity has been extended by a factor of five, the response contains a considerable number of intervals with poor response, referred to as velocity "dips" versus a true "blind." In fact, 15% of the sampled response values are less than -10 dB and 34% below -4 dB.

B. Pulse-to-Pulse Stagger

Pulse-to-pulse stagger implies a change in the interpulse spacing $\Delta T(i)$ between each successive transmitted pulse, typically alternating between increased and decreased intervals. Sometimes, the intervals are specified in terms of stagger ratios $\{R(i)\}$, i.e.,

$$\Delta T(i) = \frac{R(i)}{R} T \quad , \quad (3)$$

where T is the unstaggered interpulse spacing corresponding to the original v_b in Equation (1) and R is the average stagger ratio; i.e.,

$$R = \frac{1}{S} \sum_{k=1}^S R(k) \quad , \quad (4)$$

where S is the number of unique stagger ratios used and $S \leq N_p - 1$. Consequently, the staggered-PRF velocity blind \bar{v}_b is given by

$$\bar{v}_b = v_b R. \quad (5)$$

An example of pulse-to-pulse stagger is shown in Figure 2 for a set of 10 pulses with a stagger set $\{11,16,13,17\}$ which generates $\bar{v}_b = 14.25 v_b$ where the response has been plotted assuming $v_b = 1$ m/sec.

C. MTI Signal Processor

The purpose of the MTI signal processor is to remove the clutter spectrum while minimizing attenuation of the doppler signal. A block diagram of the MTI processor is shown in Figure 3. Because the return signal is not phase-coherent with the IF mixer frequency (i.e., an unknown phase error ϕ exists), it is necessary to employ two similar channels (I & Q) to process the baseband spectrum. The I-channel processor heterodynes the IF signal to baseband using $\cos(\omega_I t)$, where ω_I is the angular IF frequency, and attenuates the clutter spectrum using an N_m -tap transversal filter with coefficients $\{A(i,j)\}$.

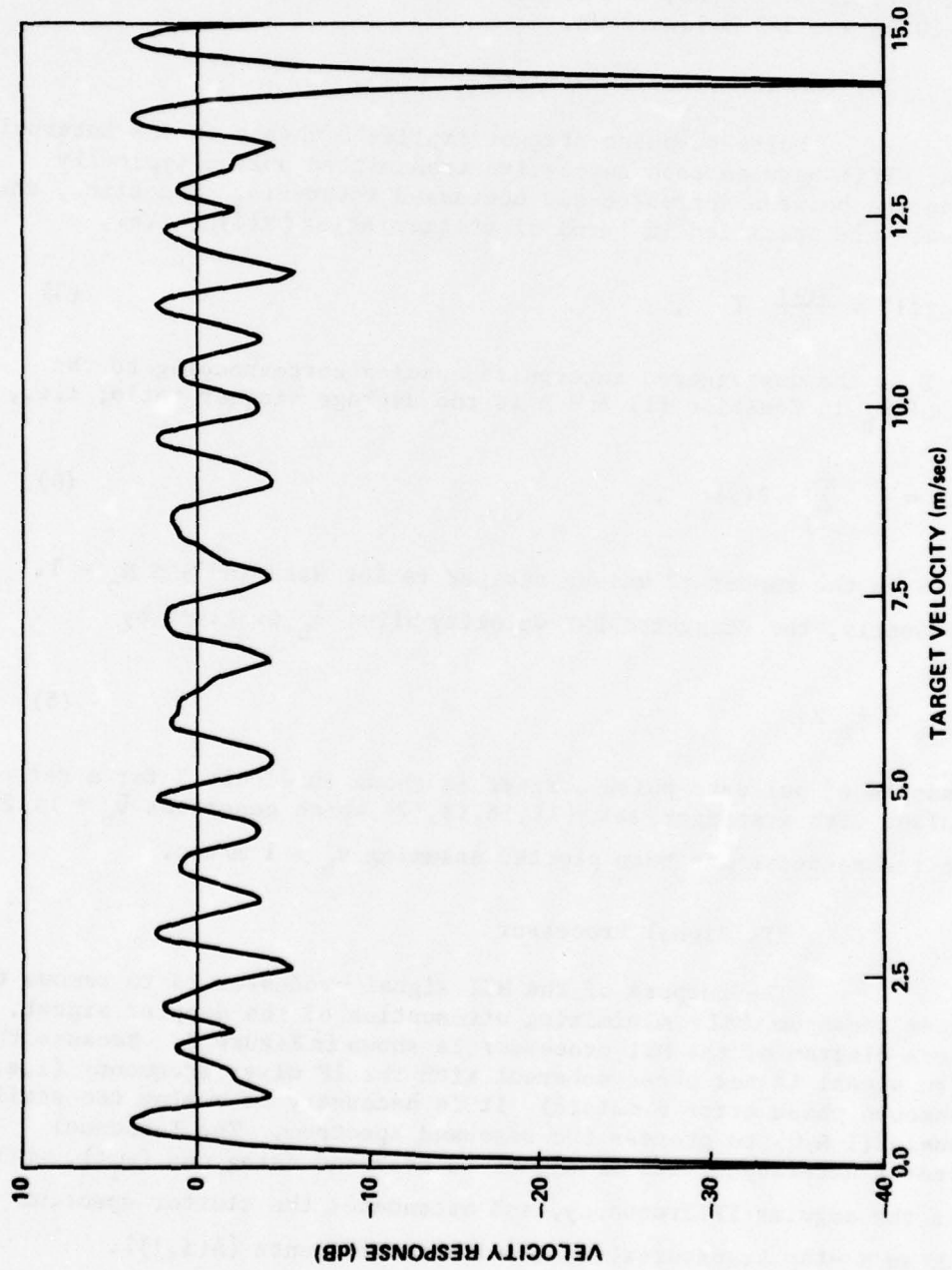


Figure 2. Normalized velocity response using pulse-to-pulse stagger.

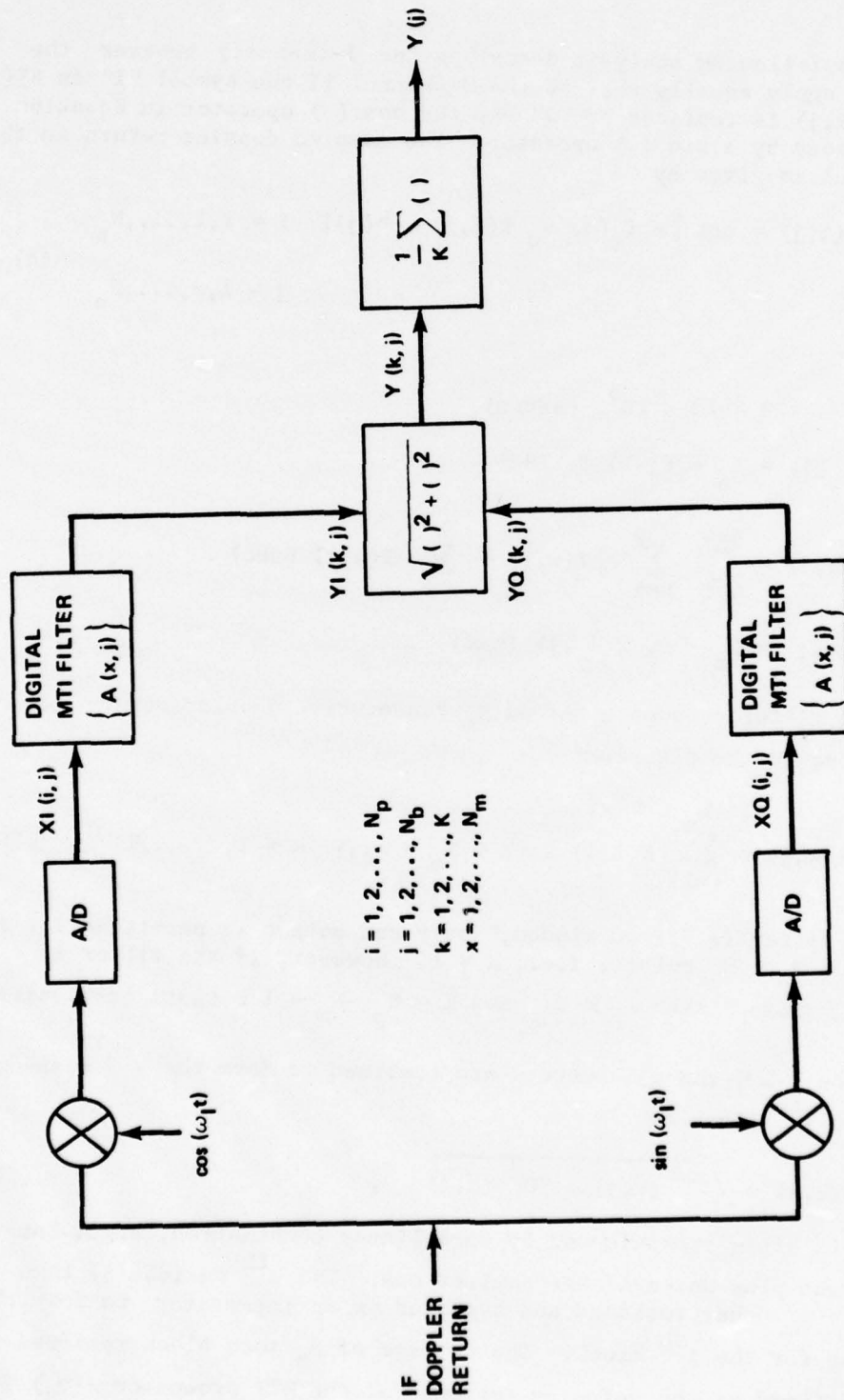


Figure 3. Digital MTI signal processor for one block of N_p returns.

The following analysis describes the I-channel; however, the results apply equally well to the Q-channel if the symbol "I" in XI(i,j) and YI(k,j) is replaced by "Q" and the cos () operator in Equation (6) is replaced by a sin () operator. The sampled doppler return in the I-channel is given by

$$\begin{aligned}
 XI(i,j) = \cos [a f_t(j) v_d T(i,j) + \phi(j)] \quad i = 1,2,\dots,N_p \\
 j = 1,2,\dots,N_b
 \end{aligned} \quad (6)$$

where

$$\begin{aligned}
 a &= 4\pi/3 \times 10^8 \quad (\text{sec/m}) \\
 f_t(j) &= f_o + (j-1)\Delta f \quad (\text{Hz}) \\
 T(i,j) &= \sum_{y=1}^{j-1} \sum_{x=1}^{N_p} \Delta T(x,y) + \sum_{x=1}^i \Delta T(x,j) \quad (\text{sec}) \\
 \phi(j) &= R_o - v_d T(N_p, j) \quad (\text{rad}) .
 \end{aligned}$$

The MTI filter acts on a set of N_m consecutive doppler-return samples according to the algorithm

$$YI(k,j) = \sum_{x=1}^{N_m} A(x,j) XI(k + N_m - x, j) \quad k = 1,2,\dots,K \quad (7)$$

If the filter is "fixed window," only one output is permitted for each block of $N_p = N_m$ pulses; i.e., $K = 1$. However, if the filter is "moving window" then $N_p > N_m$, and $K = N_p - N_m + 1$ outputs are available.

The I & Q channel outputs are combined to form the k^{th} residue for the j^{th} block as

$$Y(k,j) = \sqrt{YI^2(k,j) + YQ^2(k,j)} \quad , \quad (8)$$

which is often approximated by some linear combination, e.g., larger magnitude plus one-half the smaller one. The k^{th} residue is then added to $N_p - N_m$ other residues and averaged in an integrator to form the residue for the j^{th} block. The average of N_b such block residues is then defined as the velocity response of the MTI processor $H(v_d)$ for that particular doppler velocity.

D. Improvement Factor Considerations

The improvement factor (I) by definition is the difference in decibels of the signal-to-clutter ratio (SCR) after passing through the MTI signal processor of Figure 3 to the SCR prior to MTI filtering, i.e.,

$$I = SCR_o - SCR_i \text{ (dB)}. \quad (9)$$

Equation (9) can be rearranged as an expression of signal gain (\bar{S}) minus clutter gain (\bar{C}), i.e.,

$$I = \bar{S} - \bar{C} \text{ (dB)} \quad (10)$$

where

$$\bar{S} = \frac{1}{v_b} \int_0^{v_b} |H(v)|^2 dv \text{ ,}$$

$$\bar{C} = 2 \int_0^{v_b} |H(v)|^2 C_i(v) dv \text{ ,}$$

$$C_i(v) = \frac{1}{\sqrt{2\pi} \sigma} \exp [-v^2/2\sigma^2] \text{ ,}$$

and $|H(v)|$ is the amplitude response of the N_m -tap transversal filter while σ is the standard deviation (in m/sec) of the Gaussian clutter spectrum at the MTI input. Actual signal and clutter spectral density scale factors are irrelevant since the ratios of output over input are considered in Equation (10). Although the doppler signal basically exists at one velocity, the definition of I is based on the average signal gain (\bar{S}) over the entire velocity response of the MTI filter, i.e., zero to v_b . The contribution of \bar{S} to I is negligible compared to \bar{C} in most practical MTI processors, \bar{S} typically being restricted to the range ± 1 dB as compared to -20 to -50 dB range for \bar{C} . Consequently, I is, practically speaking, a measure of clutter suppression ($-\bar{C}$). Barton [7] has developed an expression for the improvement factor as a function of the N_m -tap filter using binomial coefficients. For $N_m = 3$, this becomes

$$I = 3 + 40 \log_{10} [v_b/2\pi\sigma] \text{ (dB)} \text{ .} \quad (11)$$

A limitation on I due to pulse staggering is given by Shrader [8]

$$I = 20 \log_{10} \left[\frac{0.66 \bar{v}_b}{(\gamma - 1)\sigma} \right] \text{ (dB)}, \quad (12)$$

where \bar{v}_b is the unstaggered blind velocity and γ is the ratio of the maximum interpulse spacing to the minimum spacing or, equivalently, the maximum stagger ratio to minimum ratio. For wideband clutter ($\bar{v}_b/\sigma < 1000$), I is limited to 50 dB or less by either formula. The MTI improvement is also limited by the number of bits in the A/D converter, e.g., $I \leq 52.9$ dB for $n = 9$ bits. Consequently, values of I exceeding 50 dB are meaningless for MTI signal processors and effort should be directed toward exchanging excess improvement for better overall frequency response [9].

II. PROGRAM PPABLK

Coding documentation for this MTI simulator is found in the appendix. The main program PPABLK, which is reproduced in Table A-1, is designed to read the input specifications regarding the choice of MTI tap gains $\{A(i,j)\}$, stagger ratios $\{R(i,j)\}$, and unstaggered interpulse spacing $\{T_j\}$ for the j^{th} block of N_p pulses processed. The program converts the set of S unique stagger ratios and T_j into a set of N interpulse spacings $\{\Delta T(i,j)\}$ for the j^{th} block and normalizes the tap gain set $\{A(i,j)\}$ to have 0 dB noise power gain. Alternatively, the interpulse spacings for the j^{th} block can be read instead of the stagger ratios by setting $T_j = 1$. These parameters plus values of initial range (R_0), initial transmit frequency (f_0), and frequency agility (Δf) are passed to subroutine SIGPRO, which is reproduced in Table A-2, for calculation of the velocity response. Successive calls to SIGPRO provide amplitude values which are used to compute the average signal gain over a user specified passband, signal-gain histogram, velocity response in decibels (dB), and the improvement factor for various values of Gaussian clutter standard deviation (σ). The program is described in more detail in the following subsections. Program parameters are indicated in parenthesis to coordinate discussion with the coding presented in the appendix.

A. Input Data

A flowchart of the input segment of PPABLK is found in Figure 4. The first card is simply a descriptive label (AL) which identifies the particular run and is printed with the output data. The second card consists of eight parameters which describe the pulse

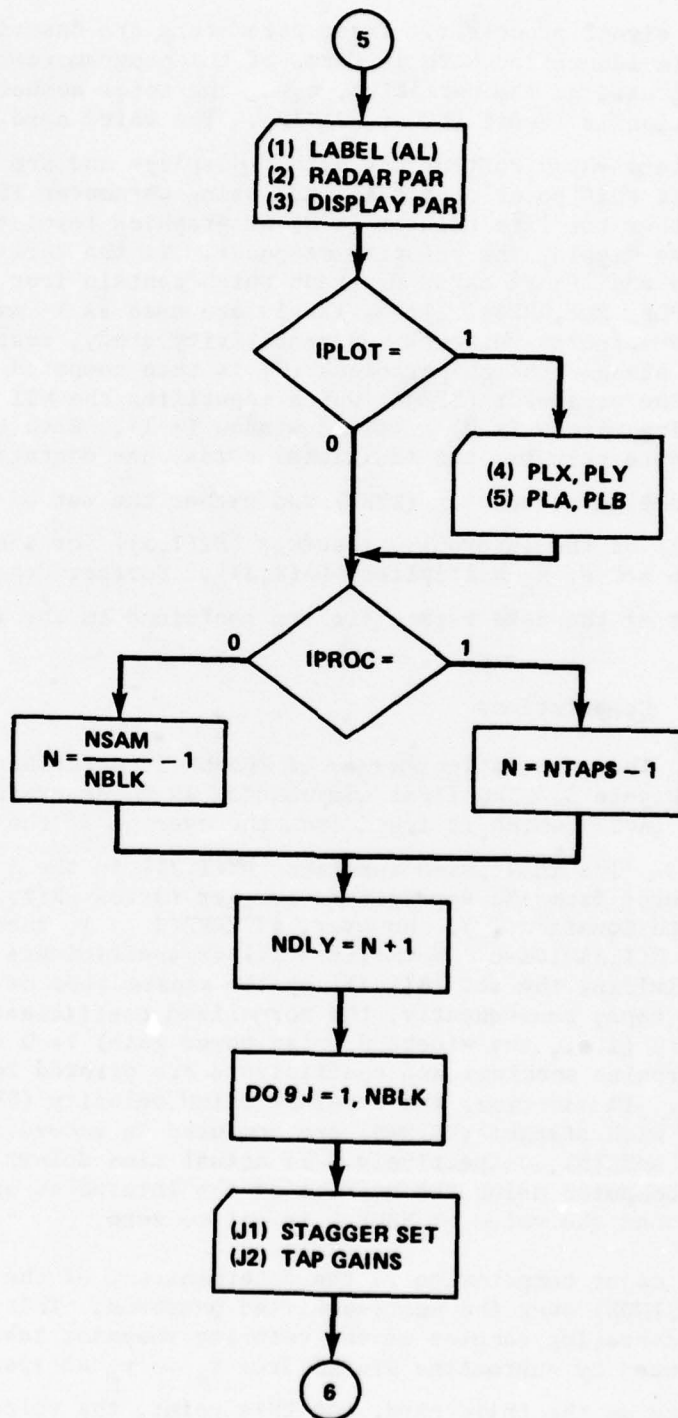


Figure 4. Input segment of program PPABLK.

train and the signal processor. These parameters are described in Table 1 and are identified both in terms of the program (card) symbol and the symbol used in the narrative, e.g., the total number of pulses per beam position is identified as $NSAM/N_t$. The third card contains eleven parameters which control the output displays and are described in Table 2. At this point a test is made using parameter IPLOT to determine whether the line printer (= 0) or graphics terminal (= 1) will be used to display the velocity response. If the terminal is used, then two additional cards are read which contain four additional labels (PLX, PLY, PLA, PLB). These labels are used as X- and Y-axis labels for the velocity response and sensitivity study, respectively. The number of stagger ratios per block (N) is then computed according to a test of the parameter (IPROC) which identifies the MTI processor either as moving window (= 0) or fixed window (= 1). Each of the N_b blocks of data requires two additional cards, one containing the unstaggered interpulse spacing (TPRF) and either the set of N stagger ratios $\{R(I,J)\}$ or the interpulse spacings $\{DT(I,J)\}$ for the j^{th} block, the second the set of N_m multipliers $\{A(I,J)\}$. Further details regarding the format of the data parameters are contained in the program listing.

B. Computations

The computation portion of PPABLK is described by the flowchart of Figure 5. The first computation is to determine the average stagger ratio (AVGR) which is found from the average of the S unique stagger ratios. The interpulse spacings $\{DT(I,J)\}$ in the j^{th} block are then computed from the appropriate stagger ratios $\{R(I,J)\}$ in accordance with Equation (3). However, if $TPRF(J) = 1$, then $AVGR = 1$ and $DT(I,J) = R(I,J) * 10E-6$. Normalized filter coefficients are obtained by dividing the set $\{A(I,J)\}$ by the square root of the sum square of the taps; consequently, the normalized coefficients sum square to unity (i.e., the wideband noise power gain) is 0 dB. The computed interpulse spacings and coefficients are printed for each block of data. In addition, the original blind velocity (VBLD) and the new blind with stagger (VBLDWS) are computed in accord with Equations (1) and (5), respectively. If actual time delays are entered, then VBLD is computed using the average of the interpulse spacings (TAVG) for T, and the value of VBLDWS is set to zero.

The next major computation is the determination of the average signal gain (SIGDB) over the user-specified passband. This gain is determined by averaging samples of the velocity response taken every v_h m/sec computed by subroutine SIGPRO from v_m to v_f as specified by user input data on the third card. At this point, the velocity response

TABLE 1. DATA ELEMENTS FOR SECOND CARD

No.	Card/Report Symbol	Description
1	NSAM/ N_t	Number pulses per beam position (≤ 150)
2	NTAPS/ N_m	Number multiplications (taps) MTI filter (≤ 15)
3	NBLK/ N_b	Number pulse blocks per beam position (≤ 10)
4	NSTRA/S	Number of unique pulse stagger ratios ($\leq N$)
5	IPROC	Type of MTI window, fixed (= 1), moving (= 0)
6	DEL/ Δf	Fractional change transmitter frequency between blocks
7	FOGHZ/ $f_o \times 10^{-9}$	Initial transmitter frequency (GHz)
8	ROKM/ $R_o \times 10^{-3}$	Initial target range (km)

TABLE 2. DATA ELEMENTS FOR THIRD CARD

No.	Card/Report Symbol	Description
1	AMIN	Minimum response-plot velocity (dB)
2	AMAX	Maximum response-plot velocity (dB)
3	VO/ v_o	Initial velocity for response plot (m/sec)
4	VINC/ Δv	Velocity increment for response plot (m/sec)
5	VUP/ v_u	Final velocity for response plot (m/sec)
6	VMIN/ v_m	Minimum velocity for histogram (m/sec)
7	VMAX/ v_f	Maximum velocity for histogram (m/sec)
8	VHIS/ v_h	Velocity increment for histogram (m/sec)
9	DELSGV/ $\Delta \sigma$	Initial value and increment for clutter σ (m/sec)
10	NUMVL/ N_i	Number of velocity points to compute improvement factor
11	I PLOT	Output display; printer (= 0), terminal (= 1)

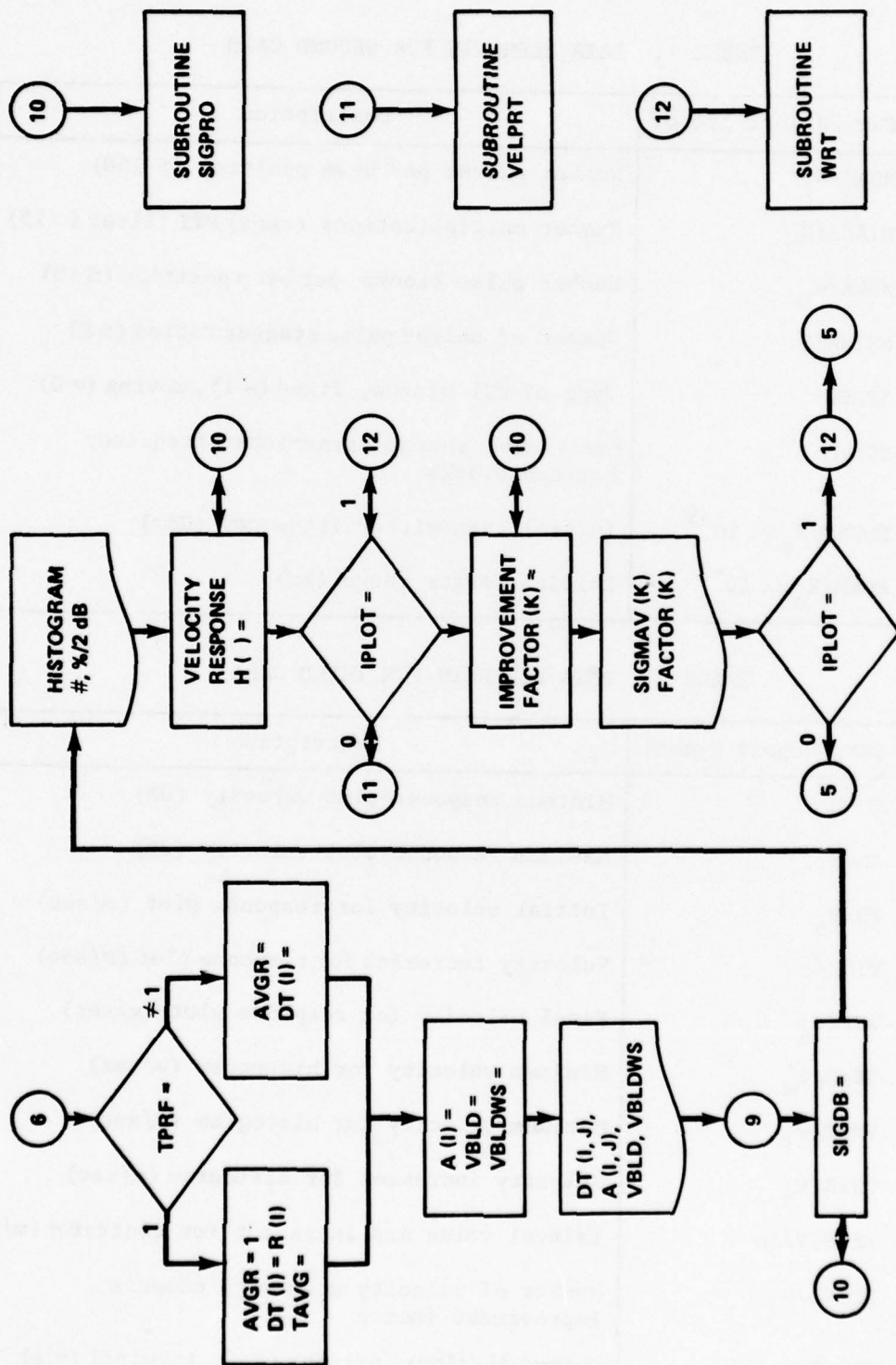


Figure 5. Computation and output segments of program PPABLK.

values $\{H(NV)\}$ (≤ 1001) are converted to decibels and a histogram calculation is performed to determine in which 2-dB interval ranging from < -10 dB to $> +6$ dB the sample belongs. The histogram information, including the total, plus number and percentage in each interval is printed. The average signal gain is used later in the computation of improvement factor.

The velocity response is computed from v_o to v_u every Δv m/sec by a second call to SIGPRO. The response is converted to decibels, with -100 dB set as a lower bound, and printed or X-Y plotted depending on the user parameter IPLOT. If $IPLOT = 0$, the printout is obtained by calling subroutine VELPRT (see Table A-3), whereas if $IPLOT = 1$ the plot is obtained via a call to subroutine WRT (see Table A-4) which puts the output in a temporary file for later processing by TEK 4015 graphics terminal. Every tenth response point is also tabulated on the line printer. The program is currently limited to computing 1001 data points for the velocity response.

The final computation is a determination of the improvement factor (FACTOR) which is a measure of signal-to-clutter power ratio before and after processing. This calculation is performed in decibels in accord with Equation (10) and involves a computation of the clutter gain (which is really a loss) after MTI filtering. The clutter gain is computed by a numerical approximation to Equation (10) using N_1 velocity points equally spaced between zero and 5σ m/sec. The improvement factor is computed for 20 values of clutter standard deviation (σ) equally spaced between $\Delta\sigma$ and $20 \Delta\sigma$. The resulting sensitivity-study data are tabulated, and if $IPLOT = 1$ is also stored for plotting on the TEK 4015.

C. Subroutine SIGPRO

The subroutine simulates the operation of the MTI signal processor shown in Figure 3 and described in Section I.C. The project of filter coefficients $\{A(i,j)\}$, normalized for 0 dB noise gain, and the set of interpulse spacings $\{DT(i,j)\}$ are passed from the main program via a COMMON statement together with the pertinent descriptive parameters read from input data by the main program. The initial doppler velocity (V_0), velocity increment ($VDEL$), and number of velocity points ($NUMVL$) to be computed are passed in the subroutine call. The computed amplitude-squared response $\{H(NV)\}$ for the $NUMVL$ velocity points is returned to the main program by the COMMON statement. The computations are executed in double precision to provide sufficient accuracy, although $\{H(NV)\}$ is returned to the main program as a single-precision array of size 1001 for processing by subroutines VELPRT and WRT.

The flow chart for SIGPRO is shown in Figure 6 and the program listing in Table A-2. The outer DO loop generates the NUMVI velocity samples and corresponding amplitude-squared response (H). The next pair of DO loops generates the individual I & Q channel input samples (XI and XQ) for all NBLK blocks of samples. The remaining nest of three DO loops computes the individual filter outputs (YI and YQ), the resultant residue (RES) for the j^{th} block, and the final sum (T) of the NBLK residues.

D. Subroutine VELPRT

Subroutine VELPRT is used to display the amplitude response $\{H(v)\}$ in dB as a function of velocity using NPTS values beginning at VO m/sec in increments of VINC m/sec. The ordinate is limited to the range AMIN to AMAX in decibels. All aforementioned parameters are included in the subroutine call. The coding for this subroutine is included in Table A-3.

E. Subroutine WRT

Subroutine WRT is used to write data generated by PPABLK on a data file, designated as Unit 3, in such a format that it can be used by a plot routine on a TEK 4015 graphics terminal. The call to WRT includes two data arrays (X DATA & Y DATA), the number of points in the arrays (NPTS), a curve designator (TYPLT) which is set to zero for the first curve on a given plot or to 1 designating other than the first curve, a horizontal-axis label (HL), a vertical-axis label (VL), minimum and maximum values (XMIN, XMAX, YMIN, YMAX) for the X-axis and Y-axis, respectively, and the number of curves (NCURVE) to be drawn on a given plot. Before running PPABLK with the graphics option (IPLOT = 1.) the user must state that Unit 3 should be used as a data file and assign Unit 3, i.e., the statements "@ USE 3, DATA*FILE." and "@ ASG,A 3." are inserted prior to the @XQT card in the executive control language cards. The coding for subroutine WRT is included as Table A-4 of the appendix.

F. Program PLOT

The program PLOT is designed for use with a TEK 4015 graphics terminal. The program reads data from a file using the same format employed by subroutine WRT to initiate the file. The program then calls a set of advanced graphics subroutines [10] to display the data in graphic form. The graphs are labeled with the horizontal and vertical labels (HL, VL) read into PPABLK. The axes are scaled according to the values (XMIN, XMAX, YMIN, YMAX) read from the data. If more than one curve is drawn on a given plot, each curve will be drawn using a unique identification symbol. After each plot is drawn the program will

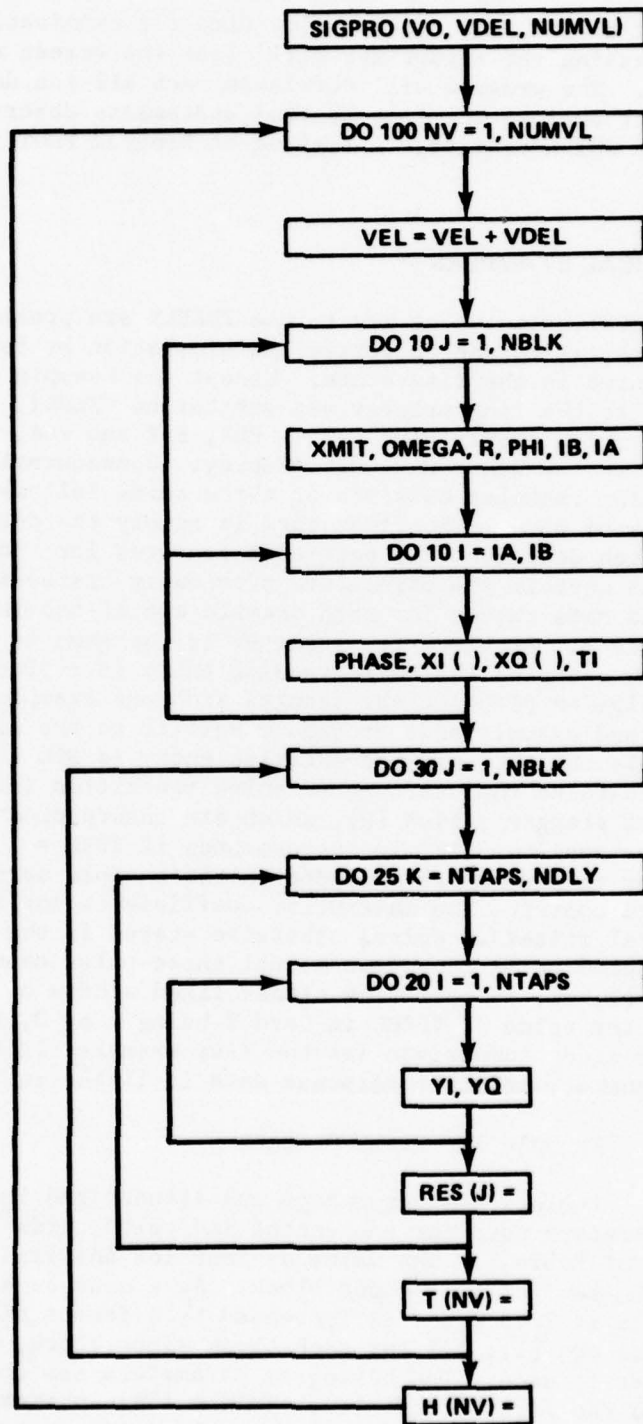


Figure 6. Flowchart for subroutine SIGPRO.

return control to the keyboard to allow time for examination or to make a copy. Depressing the return key will clear the screen and initiate the next plot. The program will terminate when all the data have been read. The user employs the same control statements described in the aforementioned WRT narrative. A listing of Program PLOT is found in Table A-5.

III. TYPICAL EXAMPLES

Several examples of how to use PPABLK are presented to illustrate its versatility and to verify the simulation by comparing to results presented in the literature. Except for Example 5, all plot calls will be to the line printer via subroutine VELPRT, thus eliminating the two cards which supply plot labels PLX, PLY and PLA, PLB used in conjunction with the Tektronix 4015 display. Consequently, the input for the remaining examples consists of three cards followed by two more for each block of data. The first card is simply the descriptive label (AL) which describes the pertinent features for that design. The next two cards contain the parameters previously listed in Tables 1 and 2, and the data values for each example are listed in the appropriate column of Table 3. If the data parameter is the same as the value used in the previous example, the corresponding entry is replaced by an asterisk (*). This helps to pinpoint the changes from one example to another; e.g., the second example adds frequency agility to the previous block stagger example and the only non-asterisk entry is DEL in Card 2. The fourth card contains the unstaggered pulse repetition interval (TPRF) and the set of stagger ratios {R}, which are interpreted as corresponding interpulse spacings {DT} in microseconds if TPRF = 1. The input parameters for this card are included in the example narrative. Finally, the fifth card contains the multiplier coefficients for the I & Q channel digital filters. Unless otherwise stated in the example, the filter is assumed to be the conventional three-pulse canceller (TPC) with weights {1, -2, 1} operating either fixed window or moving window according to the value of IPROC in Card 2 being 1 or 0, respectively. A sensitivity study comparison for the five examples is tabulated in Table 4 and summary velocity response data is listed in Table 5.

A. Example 1 - Block Stagger

A block stagger design was illustrated in Figure 1. The data parameters used for the second and third cards are found in the first column of Table 3. The value of TPRF for the first block was 1000 and 1200 μ sec for the second block. As a consequence, the original velocity blind at 27.3 m/sec is increased by a factor of five. The stagger ratios are {1., 1.} for each block since block, rather than pulse, stagger is used. The histogram parameters are chosen to cover the region to the first blind, i.e., VMAX = 136., whereas the velocity response is computed to 300 m/sec to clearly demonstrate the repetition

TABLE 3. DATA VALUES FOR CARDS 2 AND 3

Card	1	2	3	4	3
No. 2					
NSAM	6	*	10	*	3
NTAPS	3	*	*	5	3
NBLK	2	*	1	*	*
NSTRA	1	*	4	*	2
IPROC	1	*	0	*	1
DEL	0	0.01	0	*	*
FOGHZ	5.5	*	*	*	1.3
ROKM	5	*	*	*	*
No. 3					
AMIN	-40	*	*	*	*
AMAX	10	*	*	*	*
VO	0	*	*	*	*
VINC	0.5	*	0.05	2	3
VUP	300	*	15	400	600
VMIN	0	*	*	*	*
VMAX	136	*	14.25	385	575
VHIS	1	*	0.25	5	*
DELSGV	0.05	*	0.0018	0.05	*
NUMVL	201	*	*	*	*
IPLLOT	0	*	*	*	1

*Implies no change from previous entry in same row.

of the response at multiples of v_b . It is apparent from Table 4 that block stagger provides excellent clutter attenuation; however, it is also apparent from Table 5 that signal attenuation exists over a wide portion of the velocity response.

TABLE 4. SENSITIVITY STUDY COMPARISONS

σ (m/sec)	System, I (dB)				
	Block (2) (TPC) (Fig. 1)	Block (2) / 1% Agility (Fig. 7)	Pulse (10) (TPC) (Fig. 2)	Pulse (10) (5-CHEB) (Fig. 8)	Pulse (3) (OPT) (Fig. 9)
0.05	78.2	78.1	56.5	53.3	47.0
0.25	50.3	50.1	42.1	40.6	46.2
0.50	38.3	38.1	35.1	30.1	44.4
1.00	26.4	26.3	26.6	19.0	40.5

TABLE 5. SIGNAL HISTOGRAM STUDIES

System	Block (2) (TPC) (Fig. 1)	Block (2) / 1% Agility (Fig. 7)	Pulse (10) (TPC) (Fig. 2)	Pulse (10) (5-CHEB) (Fig. 8)	Pulse (3) (OPT) (Fig. 9)
Avg Gain (dB)	-0.8	-0.9	-0.4	-0.3	-0.0
> 0 dB (%)	29	29	34	41	40
\pm 2 dB (%)	38	37	54	69	45
< -4 dB (%)	34	34	12	4	22

B. Example 2 - Frequency Agility

This example illustrates that according to Equation (1) the blind velocity may be altered by changing the transmit frequency; however, large changes are impractical and small changes move the blind by large factors. The effect of frequency agility will be illustrated by a 1% change ($DEL = 0.01$) between the two blocks used in the first example. Only the parameter DEL is changed as reflected in column 2 of Table 3. Comparison of the data in Tables 4 and 5, and the new velocity response shown in Figure 7 with that of Figure 1, clearly demonstrates the effect of 1% frequency agility is minimal although all true blinds are eliminated through 300 m/sec.

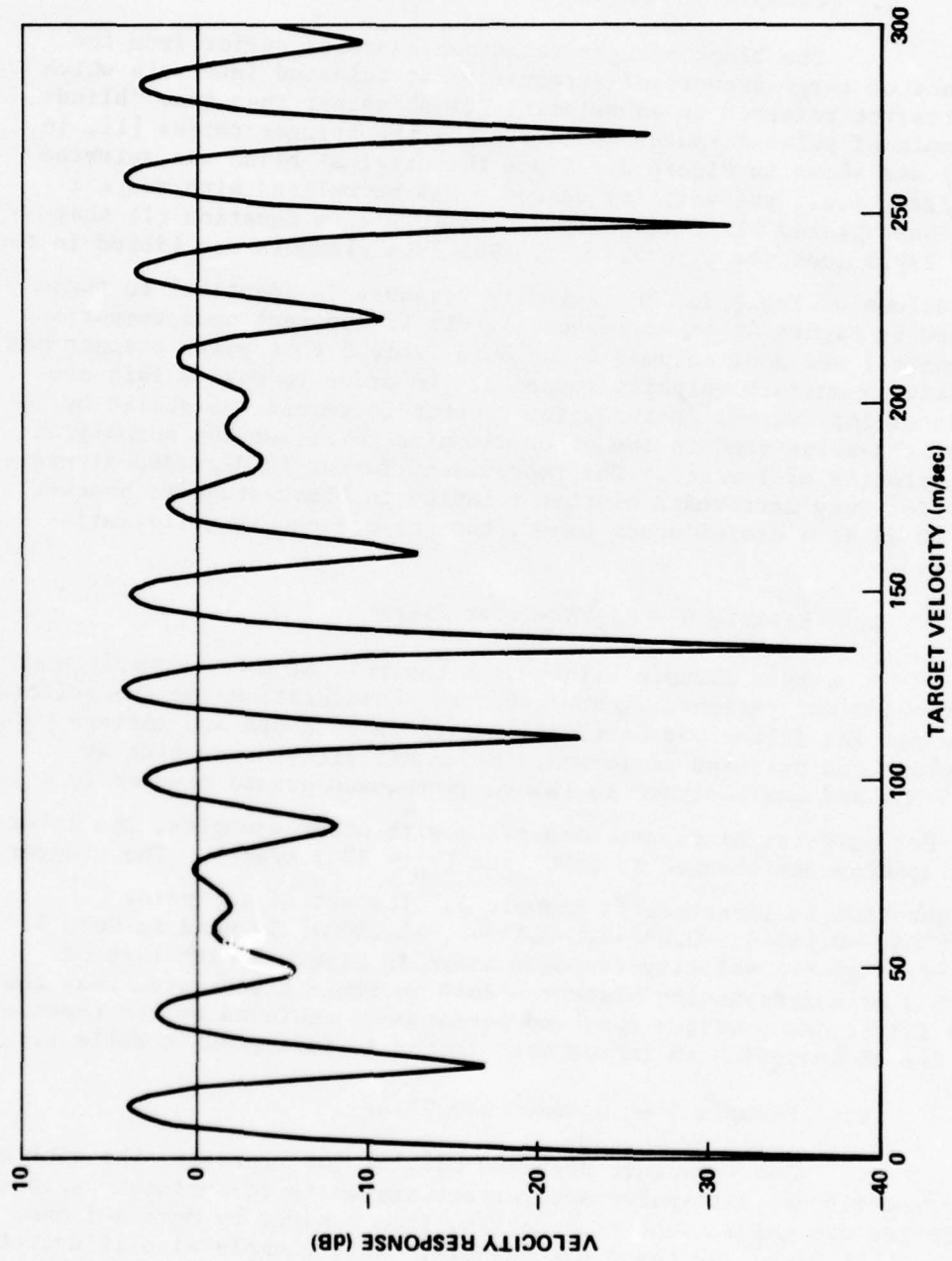


Figure 7. Velocity response using block stagger and frequency agility.

C. Example 3 - Pulse-Pulse Stagger

The block stagger technique examples suffer from the existence of large amounts of attenuation at selected intervals which are hereafter referred to as velocity "dims" rather than true "blinds." An example of pulse-to-pulse stagger using the stagger ratios {11, 16, 13, 17} was shown in Figure 2. Since the original blind was selected as 1 m/sec, i.e., the velocity response was normalized with respect to the unstaggered blind velocity, it follows from Equation (1) that $TPRF = 27273 \mu\text{sec}$ for $f_t = 5.5 \text{ GHz}$. The data elements are listed in the third column of Table 3. The velocity response is identical to that provided by Figure 44 of Reference 11. It is apparent upon comparison of Figures 1 and 2 or columns 1 and 3 in Table 5 that pulse stagger has a relatively uniform velocity response. In order to make a fair comparison of improvement factors, the clutter increment was scaled by 1/27 of the value used in the other examples to offset the normalized blind velocity of 1 m/sec. The improvement factor is degraded significantly for very narrowband clutter relative to block stagger; however, using 50 dB as a useful upper bound, the performance is quite satisfactory.

D. Example 4 - Higher-Order Filter

This example illustrates the role of a five-tap digital filter which was designed without stagger considerations on the velocity response. The filter was originally designed by Houts and Burlage [9] to improve the passband performance of an MTI filter operating at $f_p = 5 \text{ kHz}$ and was designed to remove narrowband ground clutter ($\sigma = 5 \text{ Hz}$). For purposes of closer comparison with other examples, the interpulse spacing was changed to $1000 \mu\text{sec}$ ($v_b = 27.3 \text{ m/sec}$). The stagger configuration is identical to Example 3. The set of tap gains $\{-0.28004, -0.16340, +0.88868, -0.16340, -0.28004\}$ is used in Card 5. Comparison of the velocity response shown in Figure 8 with that of Figure 3 or corresponding histogram data in Table 5 indicates that the 5-tap filter has a better passband performance achieved at the expense of a 2-7 dB reduction in improvement factor as indicated in Table 4.

E. Example 5 - Optimum Tap Gains

One technique proposed [12,13] for improving the clutter rejection for pulse-to-pulse stagger situations is to optimally select the filter tap gains. One such design, from a paper by Murakami and Johnson [13] serves as the final example. This example also illustrates the use of time delays (1000, 1200 μsec) instead of stagger ratios by letting $TPRF = 1$ to signify time delay interpretations of the stagger ratio entries. The set of optimized tap gains is $\{1.0, -1.823, 0.833\}$

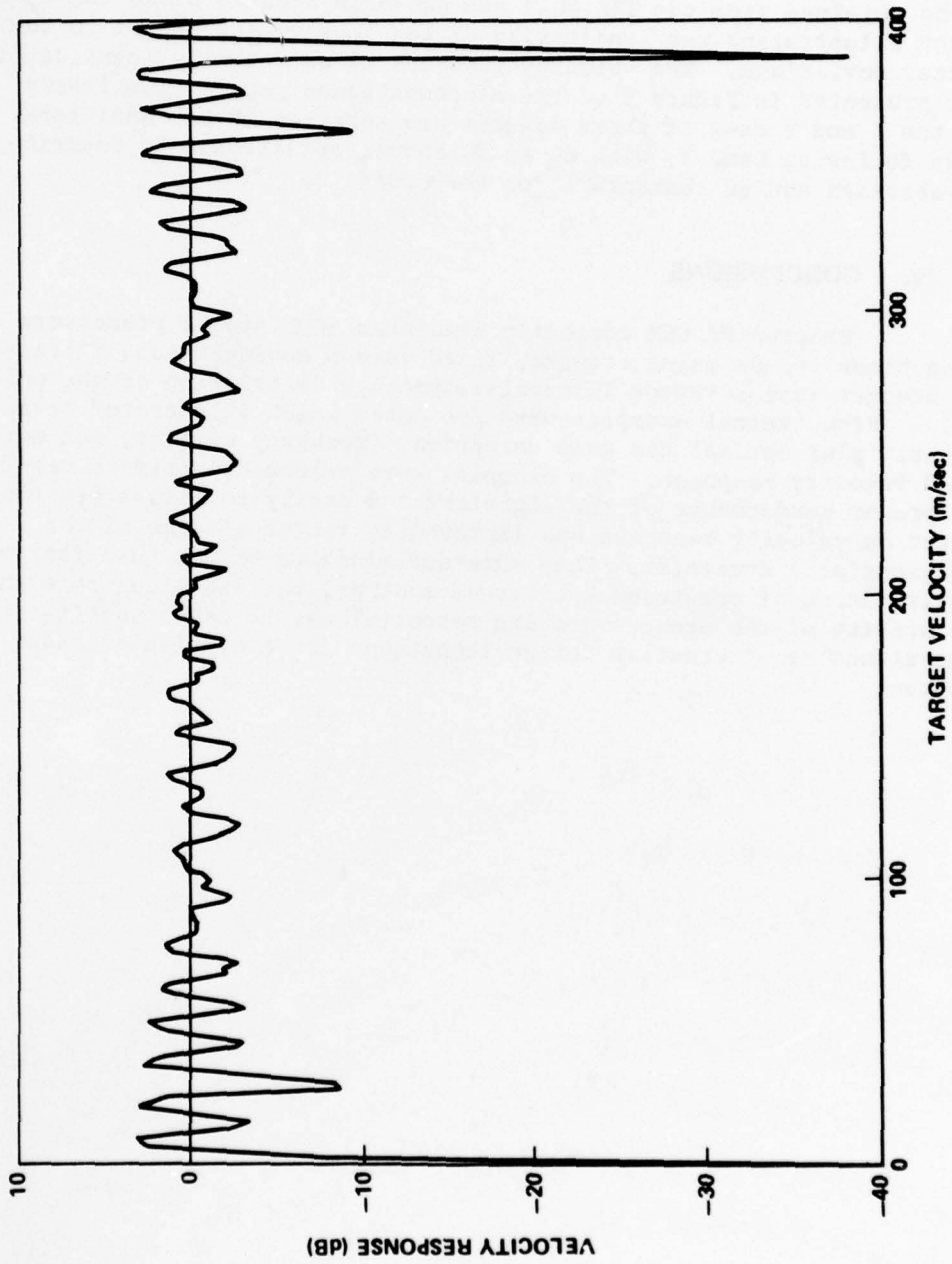


Figure 8. Velocity response using pulse stagger and five-tap Chebyshev filter.

and the other pertinent changes are listed in column 5 of Table 3. The graphs obtained from the TEK 4015 are shown in Figures 9 and 10, the latter illustrating the sensitivity of the improvement factor to the clutter deviations. The velocity response is essentially identical to that presented in Figure 9 of the aforementioned paper. The labels for the X and Y axes of these figures are supplied by two additional cards following Card 3, with up to 50 characters allowed to describe the abscissa and 30 characters for the ordinate.

IV. CONCLUSIONS

Program PPABLK correctly simulates MTI signal processors using block versus pulse stagger, fixed versus moving window filters, and stagger ratios versus interpulse spacings description of the pulse train. Five typical examples were presented which illustrated these features plus optimal tap gain selection, frequency agility, and normalized velocity response. The examples were selected partly to verify the proper performance of the algorithm and partly to illustrate the effect on velocity response and improvement factor of some of the aforementioned tradeoffs. They were not meant to be the quantitative justification of one technique versus another, but did illustrate the versatility of the program and its potential use to make quantitative comparisons of alternative design techniques for a particular radar problem.

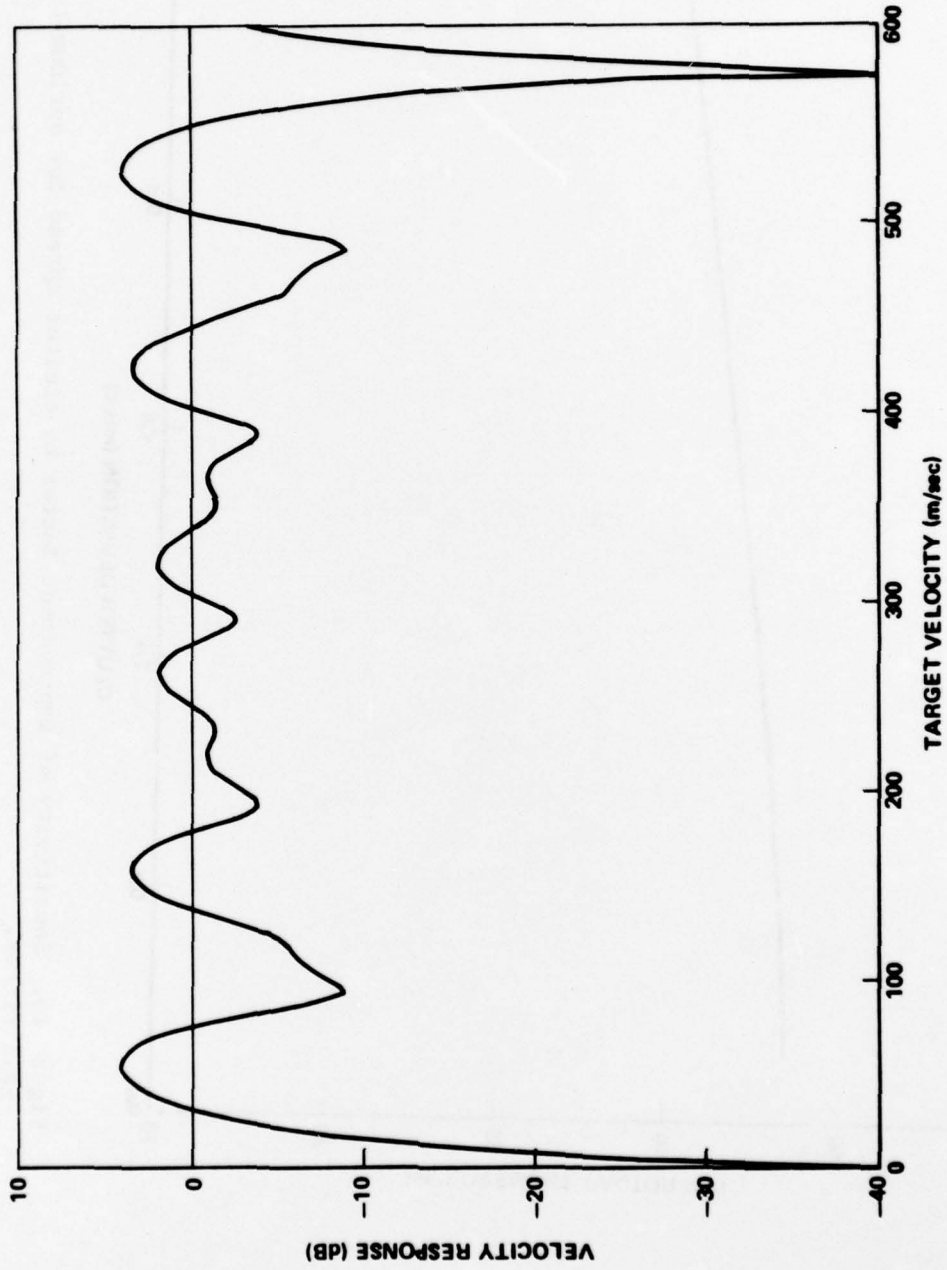


Figure 9. Velocity response using pulse stagger and optimal three-tap filter.

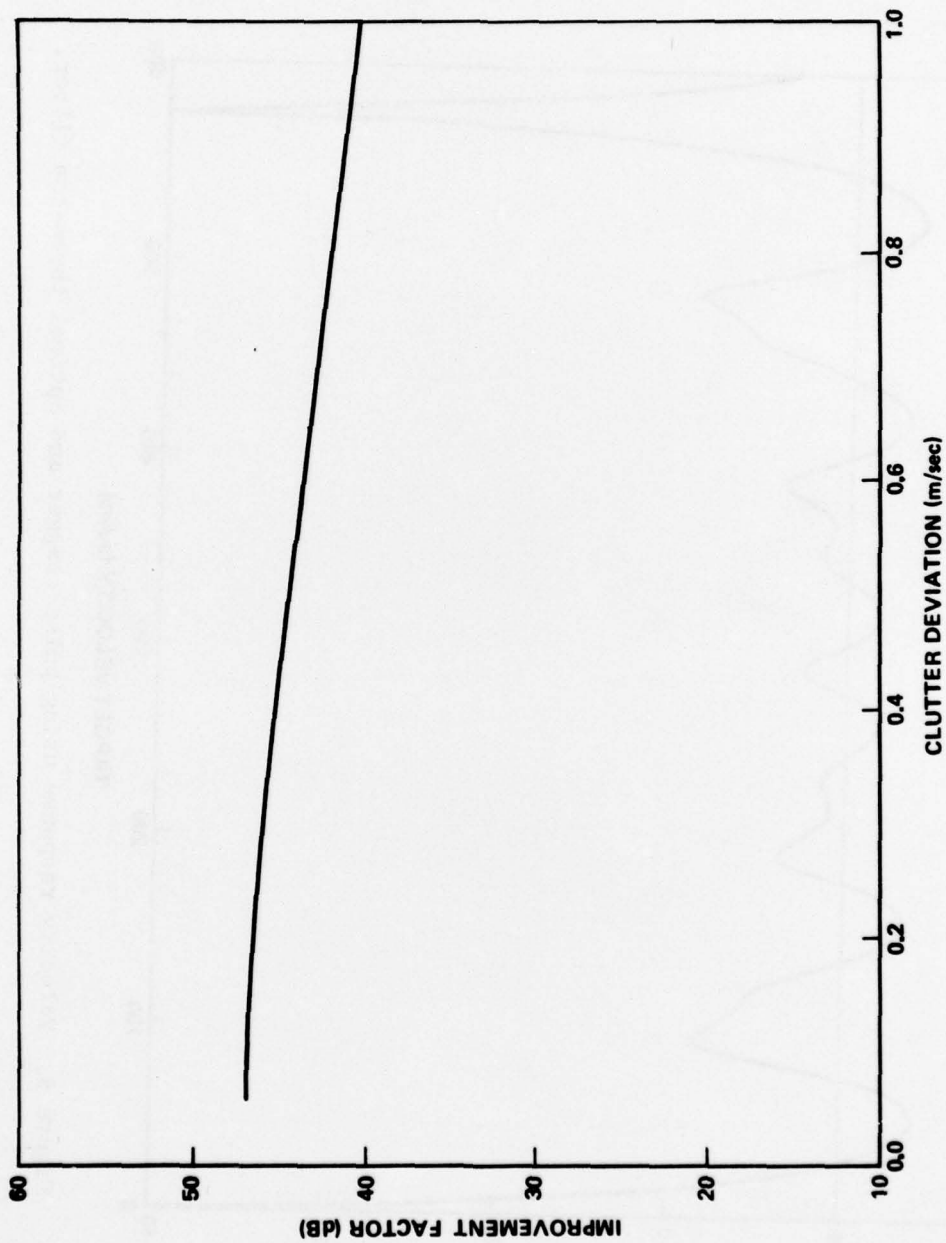


Figure 10. Sensitivity of improvement factor to clutter spread for optimum-tap-gain filter.

Appendix. COMPUTER LISTINGS FOR PPABLK

The computer listings for the simulation of an MTI signal processor using pulse-to-pulse or block are contained in the five tables found in this appendix. These routines have been described in the main text and further amplification is found in the comment statements contained within the program listings. The main program PPABLK is described in Table A-1 and subroutines SIGPRO, VELPRT, and WRT are described in Tables A-2 through A-4. Table A-5 describes program PLOT which is used in conjunction with the Tektronix 4015 graphic display terminal. The routines identified by call statements in program PLOT are described in Reference 10.

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TABLE A-1. MAIN PROGRAM PPABLK

```
C*****
C** PROGRAM SIMULATES PULSE-TO-PULSE AND/OR BLOCK STAGGER MTI SYSTEM. **
C** INPUT COEFFICIENTS A(I,J) ARE RESCALED TO YIELD 0 DB NOISE GAIN. **
C** SIGNAL GAIN IS MEASURED EVERY VTHIS FROM VMIN TO VMAX **
C** SIGNAL GAIN IS HISTOGRAMMED FROM .LE. -10 DB TO .GE. +6 DB EACH 2 **
C** IMPROVEMENT FACTOR COMPUTED FOR 20 VALUES OF SIGMAV. **
C** SEE FORMAT 40 FOR ADDITIONAL DETAILS. **
C** EACH VELOCITY PLOT REQUIRES 3 LEAD CARDS **
C** 1. LABEL FOR PLOTS (13A6) **
C** 2. EIGHT PARAMETERS (5I5, 3F5.2) **
C**   A. NSAM - TOTAL NUMBER OF SAMPLES (NDLY * NBLK .LE. 150) **
C**   B. NTAPS - NUMBER OF FILTER TAPS. (.LE.15) **
C**   C. NBLK - NUMBER OF BLOCKS (GROUPS). (.LE.10) **
C**   D. NSTRA - NUMBER OF UNIQUE STAGGER RATIOS (OR INTERPULSE **
C**     INTERVALS) **
C**   E. IPROC - TYPE OF PROCESSOR, MOVING WINDOW (=0) OR FIXED (=1) *
C**   F. DEL - FREQUENCY AGILITY (FDEL = DEL * F0). **
C**   G. F0GHZ - TRANSMITTER FREQUENCY (GHZ) **
C**   H. ROKM - INITIAL TARGET RANGE (KM) **
C** 3. ELEVEN PARAMETERS (4F5.0, 2(F10.0, F5.0), F5.0, 2I5) **
C**   A. AMIN - MINIMUM VELOCITY RESPONSE (DB) **
C**   B. AMAX - MAXIMUM VELOCITY RESPONSE (DB) **
C**   C. V0 - INITIAL VELOCITY VALUE (M/S) **
C**   D. VINC - VELOCITY INCREMENT FOR RESPONSE (M/S) **
C**   E. VUP - FINAL VELOCITY VALUE (M/S) **
C**   F. VMIN - MINIMUM VELOCITY FOR HISTOGRAM DATA **
C**   G. VMAX - MAXIMUM VELOCITY FOR HISTOGRAM DATA **
C**   H. VTHIS - HISTOGRAM INCREMENT (DEFAULT = 1 M/S) **
C**   I. DELSGV - CLUTTER STD. DEV. (M/S) INCREMENT **
C**   J. NUMVL - NUMBER OF VELOCITY POINTS COMPUTED (.LE.1001) FOR **
C**     SENSITIVITY STUDY. ACCURACY LOSS OF 0.2 DB FOR 201 **
C**     PTS VS. 1001, WITH FACTOR OF 4 TIME SAVINGS. **
C**   K. I PLOT - (=0) CALL VELPRT FOR LINE PRINTER PLOT OF VELOCITY **
C**     RESPONSE AND TABLE OF SENSITIVITY STUDY DATA **
C**     (=1) CALL WRT FOR GRAPHICS TERMINAL. **
C**       (1) VELOCITY RESPONSE V0 TO VUP EVERY VINC **
C**       (2) SENSITIVITY STUDY IMP. FACTOR VS. SIGMAV **
C**   IF GRAPHICS TERMINAL IS USED (I PLOT = 1) THEN TWO **
C**     ADDITIONAL LABEL CARDS (50A1,30A1) ARE INSERTED **
C**     HERE FOR VELOCITY RESPONSE ΔPLX(50),PLY(30) AND **
C**     CLUTTER SENSITIVITY STUDY (PLA,PLR) **
C** EACH VELOCITY PLOT REQUIRES 2 * NBLK ADDITIONAL CARDS. **
C** 1. A DESCRIPTION OF THE PULSE-TO-PULSE STAGGER IN BLOCK NO.1 **
C**   A. UNSTAGGERED PRF INTERVAL IN MICROSECONDS (F5.0) **
C**   B. A SET OF N STAGGER RATIOS, R(I,J), (NF5.0) **
C**     N = NSAM/NBLK - 1 IF IPROC = 0, OR **
C**     N = NTAPS - 1 IF IPROC = 1. **
C**   NOTE. THE ACTUAL TIME DELAYS IN MICROSEC CAN BE READ IN **
C**     PLACE OF STAGGER RATIOS IF TPRF(J) = 1. IN PART A **
C** 2. A SET OF TAP GAINS FOR THE FIRST BLOCK (17X, 7F4.5/8F8.5) **
C** 3. ADDITIONAL PAIRS OF CARDS LIKE 1 AND 2 FOR NBLK-1 BLOCKS **
C*****
```

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TABLE A-1. (Continued)

```
DIMENSION R(14,10),TPRF(10),VELC(1001),PLA(50),PLB(30),PLX(50),PLY
S(30),PB(10),NB(10),CLUT(20),SIGMAV(20),FACTOR(20),AL(13)
COMMON FO,RO,NTAPS,NDLY,NBLK,FDEL,H(1001),A(15,10),DT(15,10)
SRT2PI = 2.506628275
5 READ(5,10,END=100) AL
10 FORMAT(13A6)
READ(5,20) NSAM,NTAPS,NBLK,NSTRA,IPROC,DEL,F0GHZ,ROKM
20 FORMAT(5I5,3F5.2)
READ(5,30) AMIN,AMAX,V0,VINC,VUP,VMIN,VMAX,VHIS,DELSGV,NUMVL,IPL0T
30 FORMAT(4F5.0,2(F10.0,F5.0),F5.0,2I5)
FO = F0GHZ * 1.0E+9
RO = ROKM * 1000.
IF(IPL0T.EQ.0) GO TO 34
READ(5,33) PLX,PLY,PLA,PLB
33 FORMAT(50A1,30A1)
34 WRITE(6,40) AL, F0GHZ, DEL, NSAM, ROKM
40 FORMAT(1H1, //50X, ' PROCESSOR DYNAMIC FREQUENCY RESPONSE ' // 15X,
$ ' PROCESSOR CONSISTS OF I AND Q CHANNEL MTI, DETECTOR AND RECOMBIN
$ ATION CIRCUIT, AND POST-DETECTION INTEGRATOR.' // 15X, ' BOTH PULSE
$ TO PULSE AND/OR BLOCK STAGGERING ARE PERMITTED USING AVERAGE PRF
$ AND STAGGER RATIO PARAMETERS.' // 15X, ' FREQUENCY AGILITY CAN BE
$ SIMULATED BY A FREQUENCY INCREASE (FDEL = DEL X FO) EACH BLOCK.' //
$ // 15X, ' UP TO 15 TAPS/BLOCK AND 10 BLOCKS CAN BE SIMULATED.' //
$ 20X,13A6, // ' TRANS. FREQ. = ',F3.1, ' GHZ, FREQ.AGILITY = '
$ ,F4.2, ', PULSES / DWELL = ',I3,', INITIAL TARGET RANGE = '
$ ,F3.1, ' KM.' //)
IF(IPROC.EQ.0) GO TO 42
N = NTAPS - 1
WRITE(6,41)
41 FORMAT(34H0 SIGNAL PROCESSOR IS FIXED WINDOW)
GO TO 44
42 N = NSAM/NBLK - 1
WRITE(6,43)
43 FORMAT(35H0 SIGNAL PROCESSOR IS MOVING WINDOW)
44 NDLY = N + 1
C** READ STAGGER RATIOS AND TAP GAINS, COMPUTE INTERPULSE SPACINGS
DO 9 J=1,NBLK
READ(5,50)TPRF(J),(R(I,J),I=1,N)
50 FORMAT(15F5.0)
READ(5,60) (A(I,J),I=1,NTAPS)
60 FORMAT(17X,7F9.5 / 8F8.5)
ITEST = IFIX(TPRF(J))
AVGR = 0.
DO 1 I=1,NSTRA
1 AVGR = AVGR + R(I,J)
AVGR = AVGR / FLOAT(NSTRA)
IF(ITEST.NE.1) GO TO 7
TAGV = AVGR * 10.**(-6)
AVGR = 1.
7 CONST = TPRF(J) * 10.0**(-6) / AVGR
DO 2 I=1,N
2 DT(I,J) = R(I,J) * CONST
```

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TABLE A-1. (Continued)

```

DT(NDLY ,J) = TPRF(J) * 10.0**(-6)
IF (ITEST.EQ.1) DT(NDLY,J) = TAVG
WRITE(6,70)J,(DT(I,J),I=1,NDLY)
70  FORMAT(9H0BLOCK NO,I2,' - TIME DELAYS(SEC) ',8F10.6 / 31X,7F10.6)
WRITE(6,80) (A(I,J),I=1,NTAPS)
80  FORMAT(13X,' ORIGINAL TAP GAINS ',8F9.5 / 34X, 7F9.5/)
C** COMPUTE NORMALIZED FILTER COEFFICIENTS WITH 0 DB NOISE GAIN
AVGS = 0.
DO 4 I=1,NTAPS
4  AVGS = AVGS + A(I,J)**2
SRAVGS = SQRT(AVGS)
DO 8 I=1,NTAPS
8  A(I,J) = A(I,J) / SRAVGS
WRITE(6,90) (A(I,J),I=1,NTAPS)
90  FORMAT(13X,' NORMALIZED TAP GAINS ',8F9.5 / 34X, 7F9.5/)
VBLD = 0.15/(F0GHZ * (1.+FLOAT(J-1)*DEL)*DT(NDLY,J))
VBLDWS = VBLD * AVGR
IF(ITEST.EQ.1) VBLDWS = 0.
9  WRITE(6,36) VBLD,VBLDWS
36  FORMAT(1H0,10X,' ORIGINAL BLIND VELOCITY = ',F6.1,' M/S AND
$ NEW BLIND = ',F6.1,' M/S.')
FOEL = DEL * FO
C** COMPUTE AVERAGE SIGNAL GAIN FROM VMIN TO VMAX IN STEPS OF VHIS.
IF(VHIS .EQ. 0.) VHIS = 1.
NHIS = 1 + IFIX((VMAX - VMIN) / VHIS)
GAIN = 0.
CALL SIGPRO(VMIN,VHIS,NHIS)
C** HISTOGRAM OF SIGNAL GAIN FROM -10 TO +6 DB / 2 DB STEPS, NHIS PTS.
DO 21 I = 1,10
21  NB(I) = 0
DO 26 NV = 1,NHIS
GAIN = GAIN + H(NV)
IF(H(NV) .GT. 1.0 E-10) GO TO 22
H(NV) = -100.
GO TO 23
22  H(NV) = 10. * ALOG10(H(NV))
23  BL = - 10.
IF(H(NV) .LT. BL) NR(1) = NB(1) + 1
DO 24 I= 2,9
BU = BL + 2.
IF(H(NV) .GE. BL. AND. H(NV) .LT. BU) NB(I) = NB(I) + 1
24  BL = BU
26  IF(H(NV) .GE. BU) NB(10) = NB(10) + 1
SIGAIN = GAIN / FLOAT(NHIS)
SIGDB = 10. * ALOG10(SIGAIN)
WRITE(6,25) VMIN, VMAX, (NB(I),I=1,10), NHIS
25  FORMAT(1H0, 20X, ' HISTOGRAM DATA FOR VMIN = ',F3.0,' M/S TO VMAX
$= ',F5.0,' M/S//', AMPLITUDE INTERVAL (DB) .LT.-10 -10/-8 -8
$/-6 -6/-4 -4/-2 -2/-0 +0/+2 +2/+4 +4/+6 .GE.+6 (ALL I
$N DB) '//' NUMBER OF SAMPLES/INTERVAL ',10(I5,3X),', TOTAL = ',I4)
DO 29 I=1,10
29  PB(I) = FLOAT(NB(I)*100) / FLOAT(NHIS)

```

TABLE A-1. (Concluded)

```

WRITE(6,35) (PB(I),I=1,10)
35 FORMAT( 29H0 PERCENTAGE IN EACH INTERVAL , 10(F5.1,3X)/)
C** FIND VELOCITY RESPONSE (DB) FROM V0 TO VUP IN STEPS OF VINC (M/S)
NPTS = IFIX(1.+(VUP-V0)/VINC)
CALL SIGPRO(V0,VINC,NPTS)
DO 32 NV = 1,NPTS
IF( H(NV).GT.1.0E-10 ) GO TO 31
H(NV) = -100.
GO TO 32
31 H(NV) = 10.* ALOG10(H(NV))
32 CONTINUE
VELC(1) = V0
DO 37 K = 2,NPTS
37 VELC(K) = VELC(K-1) + VINC
IF(IPL0T.EQ.1) GO TO 38
CALL VELPRT(AMIN, AMAX,NPTS, V0,VINC, H)
GO TO 39
38 CALL WRT(VELC,H,NPTS,0.,PLX,PLY,V0,VUP,AMIN,AMAX,1)
WRITE(6,46) (VELC(K),H(K),K=1,NPTS,10)
46 FORMAT(1H0,10X,'VELOCITY RESPONSE DATA PAIRS-VELC(M/S),RESPONSE(DB
$)',,/(2X,8(F6.2,',',F6.1,3X)))
39 CONTINUE
C** COMPUTE IMPROVEMENT FACTOR I FOR SIGMAV = DELSGV TO 20 * DELSGV
C** VARY SIGMAV FROM DELSGV TO 20 * DELSGV
DO 12 K = 1,20
CLUT(K) = 0.
FACTOR(K) = 0.
SIGMAV(K) = DELSGV * FLOAT(K)
VDEL = 5.* SIGMAV(K) / FLOAT(NUMVL-1)
CALL SIGPRO(0.,VDEL,NUMVL)
C** COMPUTE CLUTTER GAIN FROM 0. TO 5*SIGMAV (M/S) USING NUMVL PTS.
VEL = 0.
DO 11 NV = 1,NUMVL
VEL = VEL + VDEL
ARG = 0.5 * (VEL / SIGMAV(K) )**2
CLUT(K) = CLUT(K) + H(NV) * EXP(-ARG)
11 CONTINUE
CLGAIN = 2. * VDEL * CLUT(K) / (SRT2PI * SIGMAV(K) )
CLUTDB = 10. * ALOG10(CLGAIN)
12 FACTOR(K) = SIGDB - CLUTDB
WRITE(6,45) NUMVL,SIGDB
45 FORMAT(1H0, 5X,' SENSITIVITY STUDY DATA ( NUMVL = ',15,',AVG. PAS
$SBAND SIGNAL GAIN = ',F6.3,' DB)')
WRITE(6,55) (SIGMAV(K), K=1,20 )
55 FORMAT(20H CLUTTER SIGMA (M/S) , 20F5.2/)
WRITE(6,65) (FACTOR(K), K=1,20 )
65 FORMAT(20H IMP. FACTOR (DB) , 20F5.1 )
IF(IPL0T .EQ. 0) GO TO 5
CALL WRT(SIGMAV,FACTOR,20,0.,PLA,PLB,0.0,SIGMAV(20),10.,60.,1)
GO TO 5
100 STOP
END

```

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TABLE A-2. SUBROUTINE SIGPRO

```
      SUBROUTINE SIGPRO(V0,VDEL,NUMVL)
      C*****
      C** SIMULATES I AND Q CHANNEL MTI SIGNAL PROCESSOR USING TWO NTAPS **
      C** TRANSVERSAL FILTERS WITH RESIDUE = SQRT(I**2+Q**2). NDLY-NTAPS+1 **
      C** SUCH RESIDUES ARE SUMMED FOR EACH OF NBLK BLOCKS OF VELOCITY **
      C** RETURNS. FOR FIXED-WINDOW PROCESSOR, NDLY = NTAPS. VELOCITY **
      C** RESPONSE = AVERAGE OF NBLK*(NDLY-NTAPS+1) RESIDUES IS COMPUTED **
      C** VS. VELOCITY (M/S) FROM V0 TO V0 + (NUMVL-1)*VDEL. **
      C*****
      DOUBLE PRECISION OMEGA,PHASE,PHI,RES,T,XI,XG,YI,YQ
      DIMENSION XI(150),XG(150),RES(10),T(1001)
      COMMON F0,R0,NTAPS,NDLY,NBLK,FDEL,H(1001),A(15,10),DT(15,10)
      FPIOVC = 4.191689E-8
      C** GENERATE VELOCITY RESPONSE H(NV)
      DO 100 NV = 1,NUMVL
      VEL = V0 + FLOAT(NV-1) * VDEL
      TI = 0.
      T(NV) = 0.00
      C** GENERATE I AND Q-CHANNEL VELOCITY-RETURN SAMPLES
      DO 10 J=1,NBLK
      XMIT = (F0 + FLOAT(J-1) * FDEL) * FPIOVC
      OMEGA = XMIT * VEL
      R = R0 - VEL * TI
      PHI = XMIT * R
      IB = J * NDLY
      IA = IB - NDLY + 1
      DO 10 I = IA,IB
      PHASE = OMEGA * TI + PHI
      XI(I) = DCOS(PHASE)
      XG(I) = DSIN(PHASE)
      10 TI = TI + DT(I-IA+1,J)
      C** FILTERS I AND Q CHANNELS USING IN-PHASE AND QUADRATURE FILTERS
      DO 30 J = 1,NBLK
      RES(J) = 0.00
      C** PROCESSOR IS FIXED WINDOW IF NTAPS = NDLY.
      DO 25 K = NTAPS,NDLY
      YI = 0.00
      YQ = 0.00
      DO 20 I = 1,NTAPS
      L = (J-1) * NDLY + K - I + 1
      YI = YI + A(I,J) * XI(L)
      20 YQ = YQ + A(I,J) * XG(L)
      25 RES(J) = RES(J) + DSQRT( YI**2 + YQ**2 )
      30 T(NV) = T(NV) + RES(J)
      100 H(NV) = ( SNGL(T(NV)) / FLOAT( NBLK * ( NDLY - NTAPS + 1 ) ) )**2
      RETURN
      END
```

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TABLE A-3. SUBROUTINE VELPRT

```

SUBROUTINE VELPRT(AMIN,AMAX,NUMVL,V0, VDEL, H)
C*****
C** PRINTS VELOCITY RESPONSE (H - IN DB) OF MTI SIGNAL PROCESSOR **
C** FROM V0 TO V0 + (NUMVL-1)*VDEL (M/S) IN INCREMENTS OF VDEL. THE **
C** RESPONSE IS LIMITED TO RANGE AMIN TO AMAX IN DB. **
C*****
DIMENSION H(NUMVL)
REAL LINE(101)
DATA DASH,AI,STAR,AX,BLANK/1H-,1HI,1H*,1HX,1H /
WRITE (6,500) AMIN,AMAX
500 FORMAT (1H0,45X,30HMAGNITUDE(DB) VS VELOCITY(M/S),//,7X,2HDR,6X,
$F5.1,95X,F5.1,4X,3HM/S)
IZERO=IFIX(-AMIN*100./(AMAX-AMIN))+1
DO 510 J=1,NUMVL
VEL=V0+FLOAT(J-1)*VDEL
IF(J.NE.1) GO TO 503
DO 501 I=1,101
501 LINE(I)=DASH
GO TO 504
503 DO 502 I=1,101
502 LINE(I)=BLANK
504 IF((IZERO.GT.101).OR.(IZERO.LT.1)) GO TO 505
LINE(IZERO)=AI
505 K=IFIX(H(J)*100./(AMAX-AMIN))+IZERO
IF(K.GT.101) GO TO 506
IF(K.LT.1) GO TO 507
LINE(K)=STAR
GO TO 510
506 K=101
GO TO 508
507 K=1
508 LINE(K)=AX
510 WRITE (6,520) H(J),LINE,VEL
520 FORMAT (1X,F13.3,8X,101A1,F9.2)
RETURN
END

```

TABLE A-4. SUBROUTINE WRT

```
SUBROUTINE WRT(XDATA,YDATA,NPTS,TYPLT,HL,VL,XMIN,XMAX,  
$YMIN,YMAX,NCURVE)  
DIMENSION XDATA(1025),YDATA(1025),HL(50),VL(30)  
IF(TYPLT.EQ.1.) GO TO 100  
WRITE(3,50) (HL(I),I=1,50)  
WRITE(3,70) (VL(I),I=1,30)  
50 FORMAT(50A1)  
70 FORMAT(30A1)  
WRITE(3,80) NPTS,NCURVE,XMIN,XMAX,YMIN,YMAX  
80 FORMAT(2I5,4F10.4)  
WRITE(3,150) (XDATA(I),I = 1,NPTS)  
100 WRITE(3,150) (YDATA(I),I = 1,NPTS)  
150 FORMAT(6E13.6)  
RETURN  
END
```

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TABLE A-5. PROGRAM PLOT

```

DIMENSION XDATA(1025),YDATA(1025),HL(50),VL(30)
50 READ(3,100,END=999) (HL(I),I=1,50),(VL(I),I=1,30)
100 FORMAT(50A1/30A1)
READ(3,150) NPTS,NCURVE,XMIN,XMAX,YMIN,YMAX
150 FORMAT(2I5,4F10.4)
M=NPTS+1
READ(3,250) (XDATA(I),I=2,M)
READ(3,250) (YDATA(I),I=2,M)
XDATA(1)=YDATA(1)=NPTS
250 FORMAT(6E13.6)
CALL INITT(30)
CALL BINITT
CALL TERM(3,1024)
CALL CHRSTZ(3)
CALL XFRM(3)
CALL YFRM(3)
CALL XMFRM(1)
CALL YMFRM(1)
CALL FRAME
CALL DLIMX(XMIN,XMAX)
CALL DLIMY(YMIN,YMAX)
CALL TSEND
CALL MOVABS(310,60)
DO 300 I=1,50
300 CALL ACUTST(1,HL(I))
CALL MOVABS(30,600)
DO 350 I=1,30
CALL ACUTST(1,VL(I))
CALL LINEF
CALL BAKSP
350 CONTINUE
CALL CHECK(XDATA,YDATA)
CALL DISPLAY(XDATA,YDATA)
IF(NCURVE.EQ.1) GO TO 550
L=NCURVE-1
M=NPTS/5
DO 500 K=1,L
READ(3,250) (YDATA(I),I=2,M)
YDATA(1)=NPTS
CALL STEPS(N)
CALL SYMBL(K)
CALL CPLOT(XDATA,YDATA)
500 CONTINUE
550 CALL TIMPUT(M)
GO TO 50
999 CALL FINITT(0,720)
STOP
END
```

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