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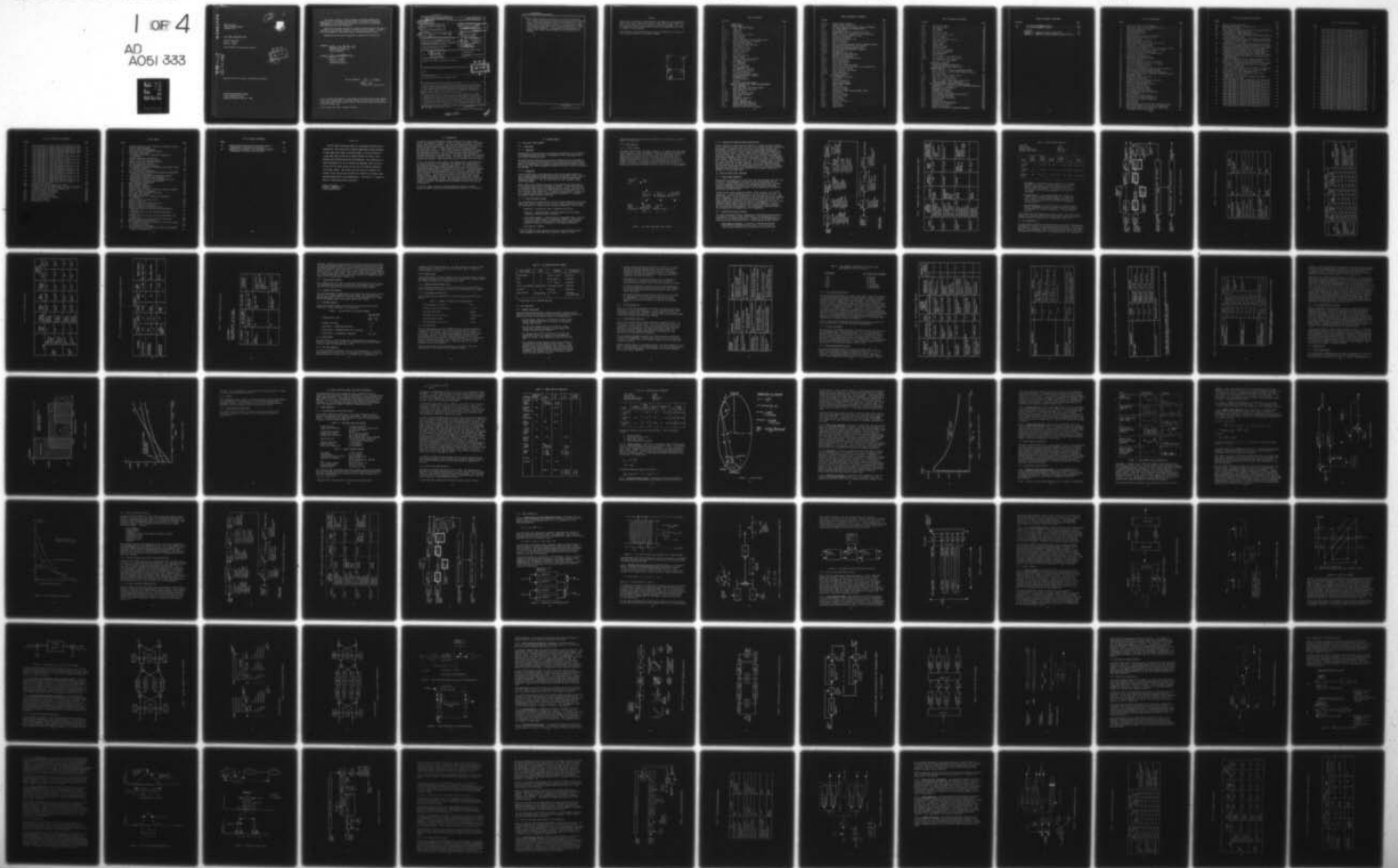
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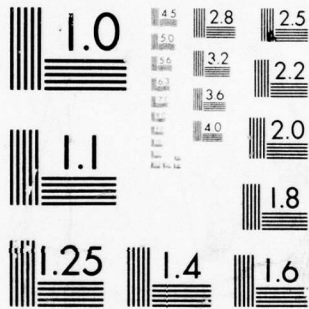
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Final Technical Report
December 1977

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CCD SIGNAL PROCESSOR STUDY

Lloyd W. Martinson
Brian P. Gaffney
Gerard J. Mayer

RCA/Government and Commercial Systems

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report presents the results of a study of the application of charge coupled devices (CCD's) to radar signal processing systems. The particular radar problem considered was the detection of satellites at ranges of up to 25,000 NM. A CCD baseline design and tradeoffs are given for this problem. CCD devices were characterized in sufficient detail to construct an accurate computer simulation of their operation. The simulation included all known noise effects in CCD's in addition to the basic functional properties such as		

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↙ charge transfer inefficiency and dark current. Delay line and matched filter configurations were then synthesized from the CCD model and performance of various CCD subsystems ascertained as CCD parameters were varied. Parameter variations included CCD length, clock rate, gate size, tapped weight accuracy, charge transfer inefficiency, and temperature. Results are presented relating study results to achievable performance for various signal processing subsystems. Programmability, bandwidth limitations, sidelobe levels, dynamic range and signal-to-noise considerations are addressed.

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PREFACE

This report was prepared by RCA/Government and Commercial Systems Division, Missile and Surface Radar, Moorestown, NJ under USAF contract F30602-76-C-0280, Project 4506, Task 01 in response to contract item A002. This work was administered under the direction of Rome Air Development Center, OCTS, W. Simkins, Project Engineer.

Contributions to this final technical report were made by F.P. Papasso and G.R. Stevens in addition to the listed authors.

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EVALUATION

The CCD Signal Processing Study has investigated the applications, capabilities, and limitations of Charge Coupled Device (CCD) technology in long range radar signal processing systems. To be cost-effective, a long range radar system must be highly flexible in terms of power budgeting and waveform generation and processing. New technologies are being investigated for use in flexible and adaptable signal processors not only for new radar systems but also for cost-effective upgrading of existing systems. This effort has shown that CCD technology has promise in this area and has evaluated the tradeoffs for various signal processing applications and implementations. This work is in support of TPO R1C, "Surveillance Sensor Technology".

William Lee Simkins, Jr.
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1.0 INTRODUCTION

The rapidly evolving technology of charge coupled devices (CCD's) holds promise for substantial reduction in the size, power consumption and ultimate cost of radar signal processors. The CCD Signal Processor Study, Contract F30602-76-C-0280, had the overall objective of ascertaining the capabilities and limitations of CCD's to signal processors for long range satellite detection radar systems. A radar system concept was developed which used a two step detection process. Initial detection with coarse range and doppler was determined on the first step with high resolution range and doppler estimates being made on the second step. The radar system was used to develop alternative CCD signal processor concepts from which a baseline, or preferred approach was selected. These results are given in Section 3.0 of the report.

In the initial phases of the program it was apparent that a determination of the state-of-the-art of CCD technology was necessary for identification of realizable CCD parameters in specific applications. The results of this study together with internal RCA measurements were used to characterize CCD operating parameters which are discussed in Section 4.0. A detailed computer simulation of CCD operation described in Section 5.0 was then constructed which included all of the CCD noise sources in addition to the basic charge transfer process. The CCD device was used as the building block for the synthesis of more complex CCD structures such as on delay lines, storage registers and transversal filters. The performance limitations of CCD's as a function of operating parameters were then determined by iteration of the computer simulation. The results of the parameter variations are provided in Section 6.0.

All of the program results are brought together in Section 7.0 which summarizes specific application and projected performance of CCD processors.

2.0 PROGRAM SUMMARY

2.1 STUDY GOALS* AND APPROACH

2.1.1 Study Goals

2.1.1.1 Objective

The objective of this study was to determine the capabilities and limitations of Charge-Coupled Devices (CCD's) as components of very long range pulsed radar signal processing systems.

The effort on the program was to be primarily theoretical with the emphasis placed on the analysis and simulation of device and processor characteristics. Specific orientation was to be placed on the processing of waveforms suitable for the very long ranges and Doppler frequencies involved in satellite detection and tracking.

2.1.1.2 Background

To be cost-effective a long range radar system must be highly flexible in terms of power budgeting and waveform selection, among other things. Both of these requirements imply flexible transmitters and sophisticated computer hardware and software. They also imply flexible and/or adaptable signal processing schemes.

Recent studies have indicated that the cost of building new radars with all of the desired capabilities is probably prohibitive. A viable alternative is to investigate ways and means for updating existing systems. This approach will provide at least some of the needed capability, at reasonable cost. One way to increase range capability is to improve the transmitter. Another way is to improve receiver and/or signal processing components or subsystems. CCDs appear to have promise in this area.

2.1.1.3 Specific Areas of Study

The investigation of the application of CCDs to signal processing for the long range radar included virtually all of the basic signal processing functions for the extraction of range, velocity and angle information. These include:

- o Components - tapped delay lines, integrators and filters.
- o Functions - adaptive matched filtering, coherent and non-coherent integration, correlation and convolution.
- o CCD System Parameters - signal storage or integration time, signal-to-noise ratio, dynamic range, instantaneous bandwidth, insertion and processing losses, pattern noise and clock noise, stage isolation, waveform flexibility or adaptability, CCD imposed constraints.
- o Cost/Benefits Tradeoffs.

* The study goals as given here are contained in the CCD Signal Processor Study statement of work, RADC PR No. A-6-1063, October 22, 1975.

A baseline system specification was provided for the study which is given in Table 17 in Section 3.0.

2.1.2 Study Approach

2.1.2.1 Study Elements

The study effort elements are shown in Figure 1. A review of the long range satellite detection radar requirements was made and converted to alternative signal processing system architectures. These were then broken down to alternative CCD techniques for each functional subsystem such as pulse compression and spectral filtering. Also feeding into this effort was a review of the CCD state-of-the-art and the development of a CCD model for computer simulation. Key elements of the baseline CCD architecture were selected for parametric performance tradeoffs with the CCD simulator, and the results provide system performance levels as a function of the CCD parameters.

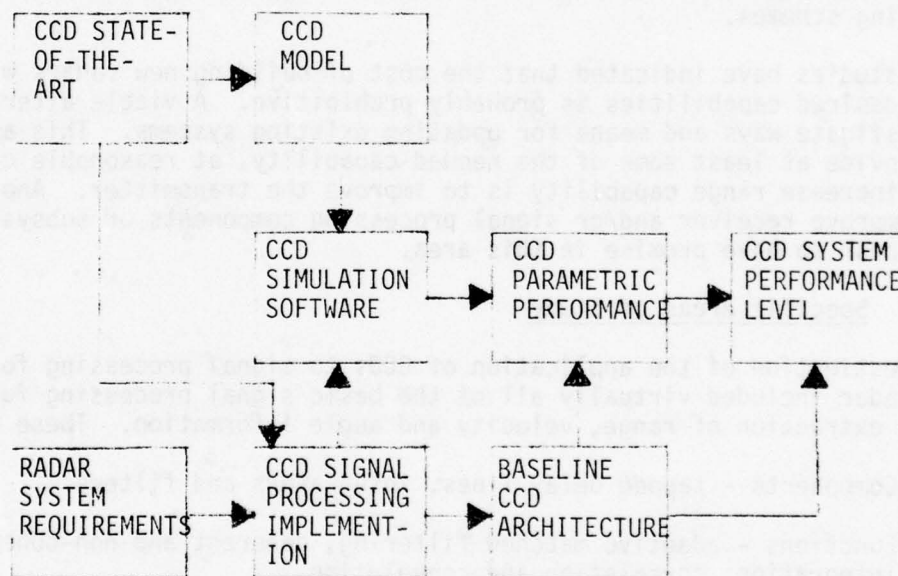


FIGURE 1. CCD SIGNAL PROCESSOR STUDY ELEMENTS

2.1.2.2 General CCD Signal Processing Applications

A broad spectrum of signal processing functions is shown in Figure 2 together with an indication of which ones are felt to be potential CCD signal processing applications. In general, CCD's are suitable for storage functions and those which have fairly high data rates and computational requirements such as most types of filters. Figure 2 shows that the potential applications of CCD's are broad. Most of the given applications involve delay, storage and transversal filtering. These functions are listed in Table 1 with the range of performance parameters which can be encountered in current or developmental radar systems. This parameter range is of course much larger than is required for a long range satellite detection radar. It is, however, useful to consider CCD applications from a broader viewpoint. Many of the requirements which have been derived for the long range radar do not stress the CCD technology. The study has concentrated on the performance of CCD's in the basic functional elements and these results can be applied to other specific applications in addition to the long range radar.

2.2 BASELINE RADAR SIGNAL PROCESSOR

2.2.1 Radar System Parameters

Representative parameters for a long range satellite detection radar are given in Table 2. These parameters were derived from the characteristics of existing long range radars and are thus achievable within today's technology. To maximize detection performance at 25,000 NM, the system losses were reduced by eliminating range and doppler sidelobe weighting on receive and eliminating the CFAR function.

A general radar signal processing system is shown in Figure 3 for the long range radar. A two step detection process was developed for the radar. An uncoded 500 μ sec pulse was transmitted on the first step with sixty to eighty pulses integrated. On the second step, a 200 kHz linear FM pulse was employed which increased the range resolution from 40 NM to less than 1.0 NM. One hundred twenty 250 μ sec pulses were coherently integrated in this case. These parameters differ somewhat from the baseline radar parameters. The final baseline parameters were revised and the system tradeoffs were completed with the given two-step parameters. Any differences are not significant in the consideration of the application of CCD technology.

2.2.2 Baseline CCD Signal Processor

The signal processing functions implemented in the baseline system included input doppler filtering, corner turning memory, pulse compression (up to 10,000 to 1) and coherent integration. A number of CCD implementations for these systems were considered and the following approaches were selected.

- o Input Doppler Filtering - An approach is used which minimizes the number of separate CCD doppler channel filter designs by using a separate demodulating frequency source for each filter.

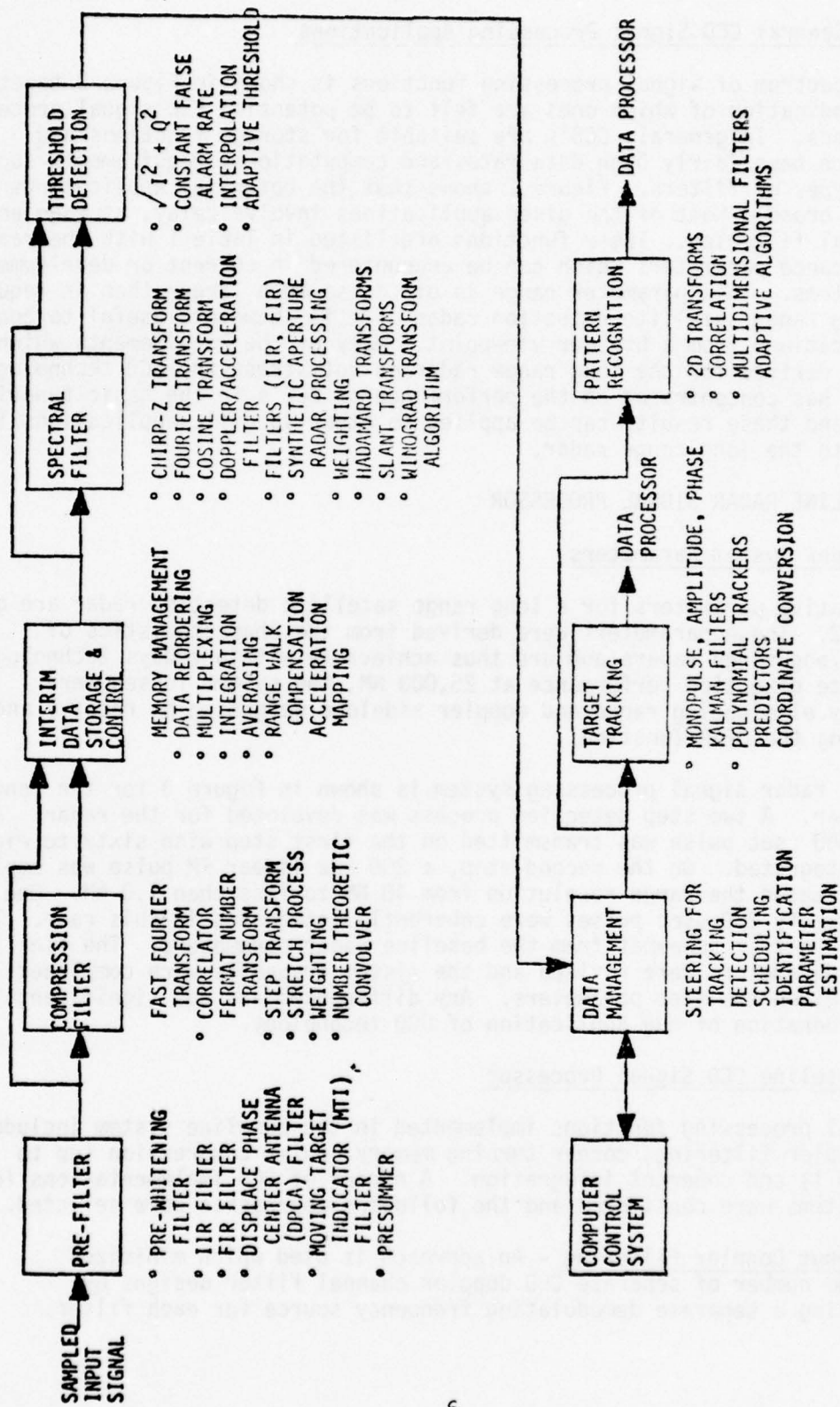


FIGURE 2. GENERALIZED RADAR SIGNAL PROCESSING FUNCTIONS

TABLE 1. PARAMETER RANGES OF SIGNAL PROCESSING FUNCTIONAL ELEMENTS

ELEMENT	SIGNAL PROCESSING FUNCTIONS	CLOCK RATE	NUMBER OF DATA SAMPLES	DYNAMIC RANGE	SPECIAL FEATURES DESIRABLE FOR SOME APPLICATIONS
Delay	Time Alignment and Data Reordering In Most Signal Processing Functions	50 kHz- 100 MHz	1-1000	30 - 80 dB	<ul style="list-style-type: none"> ◦ Programmable Delay ◦ Data Recirculation
Storage	Data Storage Up To Length of Time Data is in Signal Processor e.g., Target Dwell Time	<u>Load/Unload</u> 50 kHz- 100 MHz <u>Store</u> Up to 12 sec.	10-100,000	30 - 80 dB	Random Access
Transversal Filter	FIR Filters, CFAR IIR Filters, Averaging Convolvers, Correlators, Transforms, Interpolation	50 kHz- 100 MHz	10-25,000	<u>Input</u> 30 - 60 dB <u>Output</u> 40 - 80 dB	<ul style="list-style-type: none"> ◦ Programmable Weights ◦ Internal Reference Store ◦ Variable Length
Operations	Switching, Arithmetic Functions, Integration	50 kHz- 100 MHz	-	30 - 80 dB	

TABLE 2. BASELINE RADAR PARAMETERS

Peak Power: 32 MW
 Average Power: 300 kW
 Maximum Energy/Pulse: 10000 Joules
 Maximum Pulse Length: 500 μ sec

RANGE	PULSES INTE- GRATED	TARGET CROSS SECTION	SYSTEM LOSSES	INTE- GRATION TIME	PRF	PULSE LENGTH
3,440 NM Case	7	1.0 m ²	11 dB	.35 Sec	20 Hz	500 μ sec
7,000 NM Case	80	1.0 m ²	11 dB	4 Sec	20 Hz	500 μ sec
25,000 NM Case	180	12 m ²	7.5 dB	10 Sec	30 Hz	312 μ sec

- o Bulk Memory - The length of the CCD memories (up to 36,000 samples) ruled against a serpentine design and dictated an approach which employs input and output multiplexing to moderate length CCD memories. The storage time requirement of 6 seconds or more for these memories is a critical requirement.
- o Pulse Compression - For moderate length pulse compression $\leq 500:1$, a basic quadrature tapped delay line filter can be used. However, for the alternate wideband requirement of 10,000:1 pulse compression the step transform algorithm was most appropriate.
- o Coherent Integration - The basic simplicity of the CCD transversal filter makes the chirp-Z transform technique preferable for implementing a coherent integration, or spectrum analysis, function.

The baseline subsystem parameters are given in Table 3 while the tradeoff summaries for the input, bulk corner turning memory, pulse compression and coherent integration alternatives are summarized in Tables 4-7.

2.3 CCD CHARACTERISTICS

The CCD physical and electrical characteristics interrelate to determine the performance of the device in a signal processing application. In the analysis and simulation, electrons per CCD storage well have been used as the common measure of CCD performance. That is, the maximum signal level to which all other measures can be normalized is the maximum capacity of a storage well in

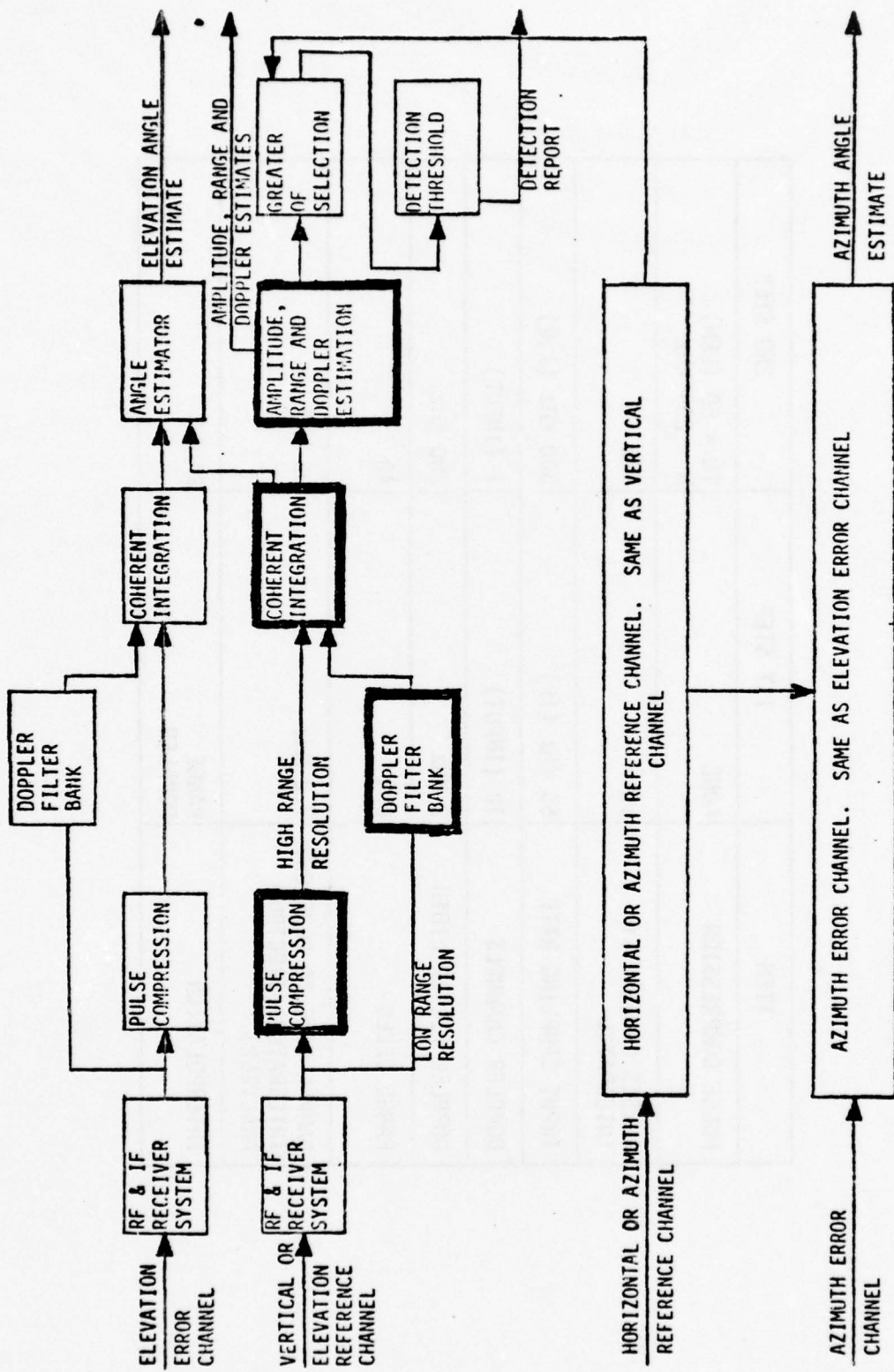


FIGURE 3. RADAR SIGNAL PROCESSING SYSTEM

TABLE 3. BASELINE SUBSYSTEM REQUIREMENTS

ITEM	1ST STEP	2ND STEP
PULSE COMPRESSION	NONE	TW = 50 (LFM) W = 200 KHZ
PULSES COHERENTLY INTEGRATED	60	120
INPUT SAMPLING RATE	55 KHz (IF)	300 KHz (I,Q)
DOPPLER CHANNELS	10 (INPUT)	1 (INPUT)
DOPPLER FILTER WIDTH	2 KHz	200 KHz
RANGE CELLS	600	40
SAMPLE RATE TO COHERENT INTEGRATOR (SPECTRUM ANALYZER)	7.2 MHz	96 KHz
INTERPOLATION	RANGE DOPPLER	RANGE

TABLE 4. FIRST STEP INPUT AND DOPPLER FILTERING

TYPE	INPUT PROCESS			DOPPLER FILTERS				REMARKS
	MAX. VELOCITY FT/SEC	SAMPLE RATE (KHz)	FREQ. SOURCES	TOTAL CCD UNITS	CCD FILTER DESIGNS	NO. OF TAPS		
LOW FREQ. IF INPUT	10,000	5.5	1	40	20	28	<ul style="list-style-type: none"> ◦ SIMPLEST INPUT PROCESSING ◦ MOST FILTER DESIGNS 	
	35,000	19.3	1	140	20	97		
FIXED DOPPLER LOW FREQ. IF INPUT	10,000	5.5	10	40	2	28	<ul style="list-style-type: none"> ◦ MINIMUM FILTER DESIGNS ◦ REQUIRES FREQUENCY SYNTHESIZER 	
	35,000	19.3	10	140	2	97		
I/Q DEMODULATION	10,000	26.5	1	40	10	14	<ul style="list-style-type: none"> ◦ LOWEST SAMPLE RATE ◦ SMALLEST CCD FILTERS 	
	35,000	92.8	1	140	10	40		

TABLE 5. BULK MEMORY REQUIREMENTS

CASE	NUMBER OF UNITS	ORGANIZATION (FUNCTION)	SAMPLES PER UNIT	TOTAL SAMPLES	MAXIMUM STORAGE TIME	MAXIMUM SAMPLE RATES (KHz)	
						INPUT	OUTPUT
FIRST STEP	40	CORNER TURNING (60x600)	36,000	1.44×10^6	~6 SEC	5.5	7200
	140	CORNER TURNING (60x600)	36,000	5.04×10^6	~6 SEC	19.3	7200
SECOND STEP	4	CORNER TURNING 40x120	4,800	19,200	~6 SEC	300	100
	4	CORNER TURNING 1000x120	120,000	480,000	~6 SEC	7500	2500

TABLE 6. CCD PARAMETERS FOR $TW = 10,000$ PULSE COMPRESSION ALTERNATIVES

TECHNIQUE	CCD FILTERS		CCD DELAYS		CLOCK RATE	RANGE COVERAGE
	LENGTH	NUMBER	SAMPLES	NUMBER		
STEP TRANSFORM	200	16	2-6000	60	7.4 MHz	FULL RANGE SEARCH
SUB-APERTURE CZT TRANSFORM	1000	192	1000-23,000	46	12 MHz	FULL RANGE SEARCH
	24	192				
SUB-APERTURE CONVOLUTION	1000 (PROGRAM-MABLE)	20	1000-4000	8	6 MHz	44 NM

TABLE 7. COHERENT INTEGRATION ALTERNATIVES

REQUIREMENTS:

INPUT SAMPLE RATE: UP TO 7.2 MHZ
 APERTURE SIZE: 23, 60, 120 SAMPLES

ALTERNATIVE	CCD LINE LENGTH FOR 120 SAMPLES	CCD CLOCK RATE	SPECIAL CCD REQUIREMENTS
CHIRP-Z FILTER	120 FILTER, 120 DELAY	3 TIMES REAL TIME INPUT RATE	
STORED COEFFICIENT	120	REAL TIME INPUT RATE	<ul style="list-style-type: none"> ◦ SERIAL-PARALLEL BUFFER ◦ N x N COEFFICIENT STORAGE MULT. ◦ ANALOG MULTIPLIER ON CHIP
DELTIC	120	120 TIMES REAL TIME INPUT	LOW TRANSFER LOSS DUE TO RE-CIRCULATION (DELAY ONLY)

electrons. Similarly, noise sources are also given in terms of rms electrons and the maximum dynamic range of a CCD, the peak signal to rms noise, can be calculated by taking the ratio of the well capacity in electrons to the total rms noise electrons. Other factors will act to reduce the operating dynamic range of the CCD. These include charge transfer inefficiency, input sampling non-linearities and dark current. Dark current effects are especially important in applications which require charge to be stored for extended periods of time in a CCD or moved slowly through a CCD.

2.3.1 Signal Sample Storage

The storage capacity of a CCD is proportional to gate area and clock voltage. This parameter, which determines the maximum signal dynamic range, varies from 10^5 to 10^8 electrons for typical gate areas and clock voltages.

2.3.2 Transfer Inefficiency

The small percentage of charge which is left behind with each charge transfer sets the CTI or charge transfer inefficiency level. This varies in the general range from 3×10^{-4} to 2×10^{-5} with the buried channel CCD's (BCCD) performing somewhat better than surface channel CCD's (SCCD).

2.3.3 CCD Noise Sources

Table 8 lists typical values of rms electrons for the CCD noise sources identified as being significant in CCD operation.

TABLE 8. TYPICAL VALUES FOR CCD NOISE SOURCES

	<u>RMS ELECTRONS</u>
o TRANSFER NOISE (α CTI)	SCCD ~ 100 BCCD ~ 20
o THERMAL SHOT NOISE	1 - 13
o TRAP NOISE (α TEMPERATURE AND AREA)	~ 50
o INPUT NOISE (α TEMPERATURE AND INPUT TECHNIQUE)	~ 35
o OUTPUT NOISE (α TEMPERATURE, BANDWIDTH)	100 - 200

2.3.4 Dark Current

The dark current is primarily dependent on temperature and accumulates in a given well to reduce well capacity. A typical well will fill due to dark current in about 10 seconds at 25°C to 50°C .

2.3.5 CCD Input Sampling

The sampling aperture requirements are not firmly established. If the CCD input sampling structure acts as a true averager over the aperture time, the aperture width can be larger than if a random noise is introduced as is

assumed for A/D converter operation. The input structure is the main source of non-linearity in CCD's and can limit the dynamic range to as much as 20 dB less than a full well.

2.3.6 Dynamic Range

Using the definition of dynamic range as the ratio of peak signal to rms noise, the dynamic range of a typical CCD delay line is about 65 dB. Dynamic range will depend on temperature, bandwidth and clock rate.

2.3.7 Signal Isolation Between Cells

Signal isolation between cells is controlled by potential charge barriers used in the physical construction of the CCD and is generally not a problem.

2.3.8 CCD Summary Characteristics

Table 9 summarized CCD characteristics which have been achieved with CCD devices.

TABLE 9. SUMMARY OF REPORTED CCD CHARACTERISTICS

o Maximum Number of Stages	910
o Minimum Transfer Inefficiency	$1 * 10^{-5}$
o Maximum Sample Rate	180 MHz
o Minimum Dark Current Density	$1.5 \frac{nA}{CM^2}$ @ 25°C
o Maximum Dynamic Range	75 dB
o Minimum Harmonic Distortion	-45 dB

2.4 CCD SIMULATION

The CCD simulation was written in FORTRAN IV using a modular programming structure for a PDP-11/40. The CCD noise, dark current and CTI are introduced as the electron packets are transferred from one potential well to the next. The CCD noise sources were modeled as Gaussian noise with non-standard variances. The dark current electrons are added to each potential well as an average with a Rayleigh distribution. The CCD functions which were modeled are a delay line, tapped delay line filter, storage register and linear FM matched filter. Table 10 summarizes the noise parameters used in the simulation.

The CCD's were varied in their operation as a function of clock rate, temperature, CTI, tap weight error and number of stages.

TABLE 10. CCD SIMULATION NOISE SOURCES

NOISE SOURCE	MEAN	VARIANCE	DISTRIBUTION
Input/Output	0	$2K_3 K T C_i/q^2$	Gaussian
Shot	0	$J_D A K_2/q f_c$	Gaussian
Trap	0	$.7 K T N_{SS} A$	Gaussian
Filter Tap Weights	Weight Value	(Percent Error) ²	Gaussian
Transfer	0	$2 e N_S$	Gaussian
Dark Current*	$J=J_{gd}+J_{gn}+J_{gs}$	$J^2/(\pi/2)$	Rayleigh (J_{gs} term only)

* See Section 4.5 for expanded equation.

2.5 CCD SIMULATION

2.5.1 General Conclusions

Specific device characterization results are given in Section 4.0 and simulation results are provided in Section 6.0 and excerpted in Section 7.0. General conclusions of the program include the following points.

- o The performance capability of CCD devices provides usable dynamic ranges of from 50 to 70 dB which is satisfactory for most applications.
- o The clock rate capability of up to 10 MHz for surface channel CCD's and over 100 MHz for buried channel CCD's provides wide application potential.
- o The storage time of CCD's should be held to less than 1 second unless cooling is used and can be extended well beyond 10 seconds if the temperature is held to less than 0°C.
- o The simulation program revealed unique results relative to CCD performance in the presence of dark current. In the operation of a linear FM matched filter, the dark current build-up creates an output dynamic range floor which first encompasses the region outside the matched filter response followed by the sidelobes and finally envelopes the main-lobe as the dark current increases.

- o Charge transfer inefficiency (CTI) will be stable and at levels which do not degrade performance over the full clock rate of CCD devices provided that the control and clock levels are properly maintained. In the event that the CCD is operated at a high CTI, the bandwidth capability is reduced and amplitude dispersion of signals will result.
- o Programmability is a desirable feature to be incorporated in CCD's because it eliminates chip design costs for special applications and can permit signal processor parameter variations.
- o A digital microprocessor rather than a CCD is most appropriate for the post detection processing functions which do not include delay and storage and which do not operate with a 100% signal sample duty factor.
- o The external control and amplification circuitry in a CCD system in large measure limits the CCD performance and application. The development of on-chip controls is therefore of primary importance and should be included in any new CCD chip developments.

2.5.2 CCD Programmability

Table 11 lists the CCD programmability functions, the means for achieving them and the status of the technology. The most important feature is the achievement of electrically programmable weights which can be held for an extended length of time (seconds). Industry effort is being concentrated on this area and some success has been reported.

2.5.3 CCD Bandwidth Limitations

There is both a high and low frequency bandwidth limitation of CCD's. At the high end they are limited by the clock rate at which the devices can be operated. A useful rule of thumb is that surface channel CCD's can be operated at clock frequencies up to about 10 MHz while buried channel or peristaltic CCD's have usable clock frequencies beyond 100 MHz. No discernible frequency dependent degradation in performance has been measured below the maximum clock frequencies.

The low operating frequencies of CCD's are limited by dark current which increases with temperature. Assuming dark current filling 20% of the well as being the limiting threshold the maximum storage time versus temperature is given in Table 12.

Another important factor in the operation of CCD's at high frequencies is the design of the peripheral circuits and packaging. The practical application of CCD's is probably limited more by these problems at very high frequencies than by basic device capability.

TABLE 11. CCD PROGRAMMABILITY CONSIDERATIONS

TECHNIQUE CATEGORY	TECHNIQUES	TECHNOLOGY STATUS
Electrically Variable Weights	<ul style="list-style-type: none"> ◦ Floating Gate Taps ◦ Integrated Multipliers ◦ Analog Storage 	<ul style="list-style-type: none"> ◦ Storage Time is Limited ◦ Multiplier is Problem ◦ Floating Gate Taps are Developed
Semi-Programmable Weights	<ul style="list-style-type: none"> (a) Split Gate Weighting (b) Electrically Programmed Permanent Weights 	<ul style="list-style-type: none"> (a) Established But Not Truly Programmable (b) Technique Not Developed
Switching and Shifting Charge	Use of Transfer Gates and Barrier Controls	<ul style="list-style-type: none"> ◦ Developed for Binary Signals ◦ Analog Technology Not Established
Variable Length	<ul style="list-style-type: none"> ◦ Setting Weights to Zero ◦ Control Length by Switching 	Requires Switching or Programmable Weights
Function Select	◦ Reconfiguration of Chip	Requires Extensive Development
Digital Logic Approach	Basic Digital Gate Functions Implemented with CCD Controls	<ul style="list-style-type: none"> ◦ May be in Laboratory Stage ◦ Suitable for Pipelined Functions such as Digital Filters and FFT's

TABLE 12. LOW FREQUENCY LIMITATIONS OF CCD DELAY LINES
(DARK CURRENT FILLING 20% OF WELL)

<u>TEMPERATURE</u>	<u>MAX STORAGE TIME (SECONDS)</u>
- 55 °C	>12 Seconds
- 25 °C	>12 Seconds
+ 5 °C	>12 Seconds
+ 35 °C	6 Seconds
+ 65 °C	0.75 Seconds
+ 95 °C	< 0.1875 Seconds
+125 °C	< 0.1875 Seconds

2.5.4 Post Processing Functions

The post processing functions in a radar signal processor generally refer to those following the basic matched filtering operation. Doppler processing is generally considered with the pulse compression system since it forms a matched filter for a target with a specific doppler. Post processing functions include: thresholding, range and angle estimation, bulk filtering, constant false alarm rate (CFAR) processing, interpolation, predictors and various pattern recognition procedures. Many of the functions are identified in Figure 2. The application of CCD's is possible in those cases where the computations can be pipelined. Implementation of many post processing functions with CCD's is even more dependent on achieving programmability and adaptability than the pre-post processor functions. An important consideration relative to the appropriateness of CCD processing is the processing rate requirements of specific functions and whether digital microprocessor based techniques will ultimately be the best approach.

Table 13 summarizes the principle post processing functions and rates CCD's and microprocessors as to the most appropriate implementation.

2.5.5 On-Chip CCD Controls

The feasibility of incorporating on-chip clocking and controls to CCD devices has been demonstrated. This technology step is a key to the practical implementation of CCD's in many applications. It is expected that development of on-chip peripheral circuitry will continue and lead to CCD's with stable performance characteristics which will permit their application in the field. An important facet of this is CCD replaceability. CCD performance must be characterized and predictable to permit field replacement without readjustment of the operating timing or control values.

2.5.6 Sub-System Performance Levels

The expected performance levels of the key CCD elements; delay lines, memories, and transversal filters is summarized in Tables 14 - 16. These results are based upon measurements, the published literature and the simulation. The simulation results in Section 6 provide a large number of specific cases demonstrating the operation of the CCD functions. In the

TABLE 13. POST PROCESSOR CCD CANDIDATES

POST PROCESSING FUNCTION	COMPUTATION RATE	DUTY CYCLE	PRINCIPAL PROCESSING ELEMENTS (ARCHITECTURE)	REMARKS RE CCD IMPLEMENTATION	ADVANTAGE TO	
					CCD	MICRO-PROCESSOR
Threshold Detection	Video Sample Rate	100%	Amplitude Comparison	Peripheral CCD, Analog Circuitry	X	
Normal Threshold Computation	<< Sample Rate	~ 1%	Weighting & Adding Several Sensor Inputs	Requires Programmability		X
Interpolation	Sample Rate or Greater	100%	Transversal Filter	Programmability of Weights is Desirable	X	
CFAR	Sample Rate or Greater	100%	Transversal Filter	Programmable Weights for Adaptive CFAR	X	
Range & Angle Estimation	<< Sample Rate	< 1%	Add, Subtract, Mult., Divide, Small Delays	Specialized Analog Functional Would Do Mult. & Divide Operation		X
Pattern Recognition (Correlation, 2D Transform)	High	< 1%	Programmable Transversal Filter for 2D Transform	Computation Rates Are High Since Waveforms are Wideband	X	
Predictors, Coordinate Conversion, Kalman Filters	<< Sample Rate	Small	General Arithmetic Operations	Required Wide Programmability		X

TABLE 14. EXPECTED CCD DELAY LINE PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE	95 dB	512 STAGES SR = 100 kHz, T = +5°C INPUT LINEAR TO FULL WELL (CASE A)
	70 dB	512 STAGES SR = 1000 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
	50 dB	512 STAGES SR = 100 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
NOISE FIGURE	1.5 dB	DELAY LINE (CASE A)
INSERTION LOSS	UP TO 26 dB	DEPENDS ON INPUT/OUTPUT STRUCTURES
LINEARITY (HARMONIC DISTORTION)	-45 dB	TYPICAL LEVEL WITH STANDARD INPUT TECHNIQUE (MEASURED RESULTS)

TABLE 15. EXPECTED CCD STORAGE REGISTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE*	45 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, RE FULL WELL
	18 dB	STORAGE TIME = 12 SEC TEMPERATURE = 35°C, RE FULL WELL
	65 dB	STORAGE TIME = 1 SEC TEMPERATURE = 5°C, RE FULL WELL
	25 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, -20 dB RE FULL WELL
INSERTION LOSS LINEARITY	SAME AS DELAY LINE CASE	

* THE DYNAMIC RANGE FOR CCD'S IN A STORAGE MODE IS LOW BECAUSE OF THE BUILD-UP OF DARK CURRENT VARIATIONS WHICH ARE AVERAGED OUT IN THE DELAY LINE CASE.

TABLE 16. EXPECTED CCD TRANSVERSAL FILTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC*	MEASURE	CONDITIONS	
		TAP ERRORS = 1%	T = 5°C CLOCK RATE (f_s) = 10 ⁵ Hz
MAX SIDELobe LEVEL (IDEAL = -39.6, TW PRODUCT = 65)	-39.5 dB	TAP ERRORS = 1%	ZERO TAP WEIGHT ERRORS
	-39.3 dB	TAP ERRORS = 3%	
	-35.6 dB	TAP ERRORS = 10%	
DYNAMIC RANGE (OUTPUT) CCD FILTER = 129 STAGES, TW = 65	-36 dB	$f_s = 10$ kHz TEMP. = 95°C	RE FULL WELL
	-38.5 dB	$f_s = 10$ kHz TEMP. = 65°C	
	80 dB	$f_s = 100$ Hz TEMP. = -25°C	
	60 dB	$f_s = 100$ Hz TEMP. = 5°C	
INSERTION LOSS	60 dB	$f_s = 300,000$ Hz TEMP. = 65°C	RE FULL WELL
	110 dB	$f_s = 3000$ Hz TEMP. = -25°C	
LINEARITY (HARMONIC DISTORTION) CCD FILTER = 129 STAGES, TW = 65	UP TO 26 dB	INPUT/OUTPUT STRUCTURES	
	-63 dB	RE OUTPUT	
	-45 dB	RE INPUT	

* THESE MEASUREMENTS APPLY TO CORRELATORS, CONVOLVERS, MATCHED FILTERS AND CZT SPECTRUM ANALYZERS IN SO FAR AS FUNDAMENTAL CCD IMPOSED LIMITATIONS.

examples in Section 6.0 examples were generally chosen which show performance variation with a parameter such as temperature. Thus many examples involve low clock rates and high temperatures which begin to show adverse CCD performance. Many, if not most, applications of CCD's will not see these problems simply because dark current will not be significant.

Noise figure will depend upon the application of the CCD. We can consider the delay line case for an example. The factor kTB yields an output voltage level into a 1000 ohm resistance of about 6.3×10^{-7} volts for a bandwidth of 100 kHz. A CCD peak output voltage with a full well measured at the drain of 0.05 volts gives a maximum dynamic range of 98 dB relative to thermal noise or about 92 dB relative to receiver noise. Thus the effective CCD noise figure is about 1.5 dB in this case since the delay line CCD self noise is -95 dB relative to a full well. On the other hand in those applications such as the storage mode the operating dynamic range of the CCD is severely reduced due to dark current build-up. Thus the noise figure is increased accordingly. In these applications, the operating range of the system would be set to minimize system losses while operating over the dynamic range. Setting the receiver system noise 10 dB below the CCD noise level gives an effective noise figure of 0.3 dB. In the CCD operation, generally the CCD self noise is greater than the thermal noise level.

2.5.7 CCD Cost/Performance Tradeoffs

General projections on CCD system costs relative to other technologies can be made, but specific tradeoffs will depend on the application and the competing technology. For low data rate applications, microprocessor techniques will prevail as most cost-effective. As the data rates and processing requirements increase to the hundreds of kilohertz up to 10 MHz, CCD's will find increasing application. Buried channel CCD's operate up to and beyond 100 MHz. Figure 4 indicates general speed performance categories for various technologies. The line of demarcation between different approaches will fluctuate depending on the specific application. Note that every category of processor can be built with special purpose digital hardware. This involves paralleling at the very high rates.

Costs can be expected to follow the basic pattern of Figure 5. A standard implementation using MSI digital technology will be relatively low in cost but as the number of units to be constructed increases, the parts cost will become dominant. Thus initial investments in either LSI or CCD development will produce substantial savings in the end. Since fewer chip designs are required for CCD's and fewer parts will be required in the system, the CCD unit costs will be lowest for large volumes. The crossovers of "break-even" costs indicated in Figure 5 can not be assumed to hold in general. Each application will produce a different tradeoff.

2.6 RECOMMENDATIONS

2.6.1 Device Developments

On a device level programmable features should be emphasized. A need exists for improvement of the linearity of the input sampling structure. CCD clocking, control and amplification functions should be incorporated on the

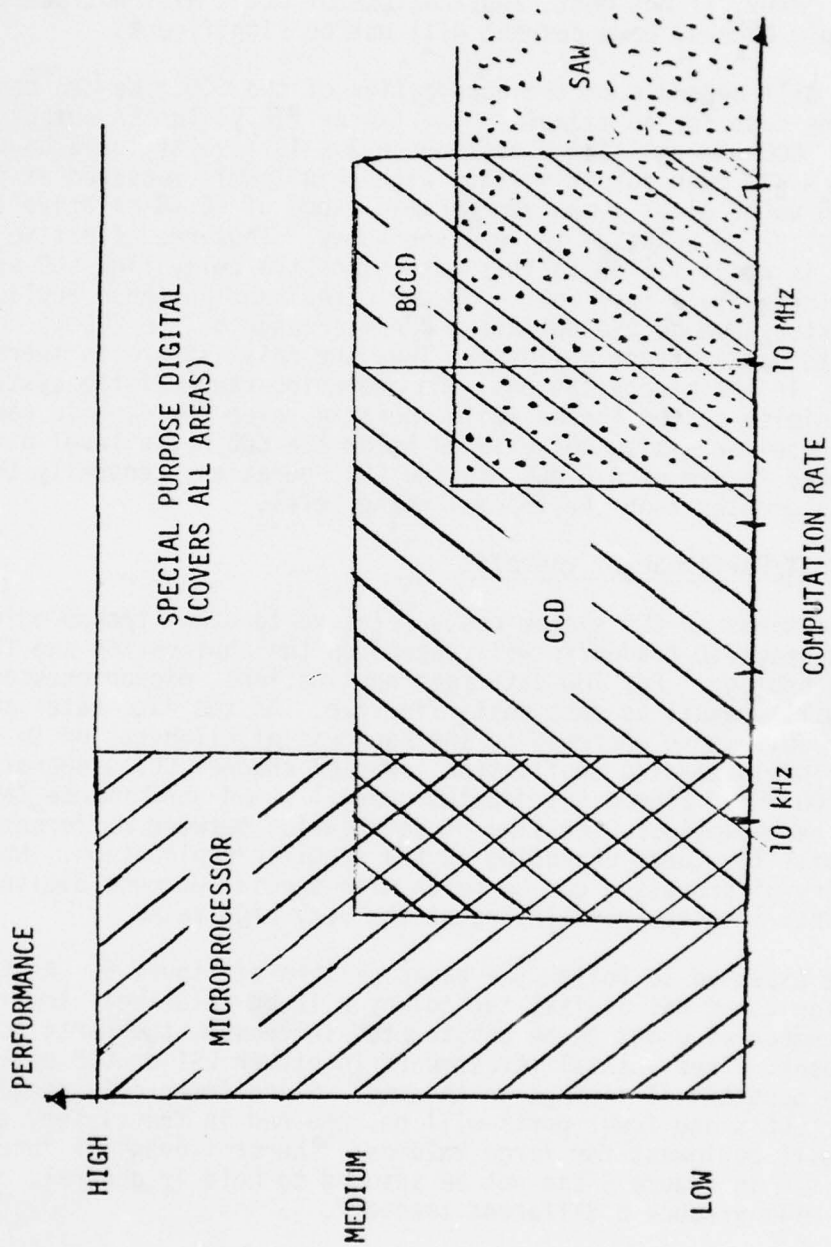


FIGURE 4. TECHNOLOGY CATEGORIES

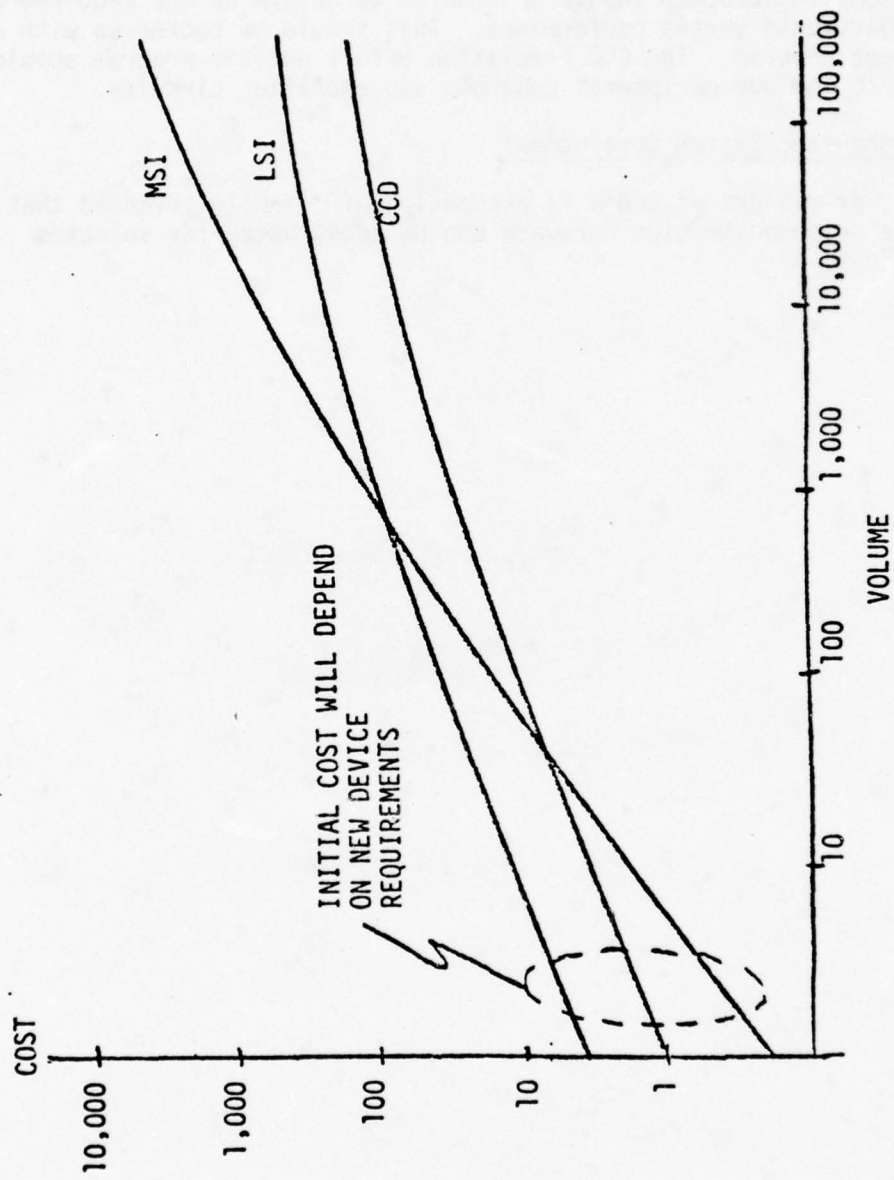


FIGURE 5. TECHNOLOGY COST TRENDS

CCD chip. Tests are necessary to more completely characterize CCD's in terms of reliability and temperature stability.

2.6.2 Analysis

The CCD sampling process should be studied to determine the required aperture time requirements versus performance. This should be backed up with a measurement program. The CCD simulation effort on this program should be extended to include peripheral controls and amplifier circuits.

2.6.3 Subsystem-System Development

The state-of-the-art of CCD's is presently sufficiently advanced that prototype or demonstration hardware can be constructed for selected applications.

3.0 RADAR SYSTEM AND SIGNAL PROCESSING REQUIREMENTS

The stated objective of this program has been to determine the major capabilities and limitations of CCD's as components in very long range pulsed radar signal processors. This objective has served as a base from which the application of CCD's to a broad range of signal processing functions can be derived. It will be shown in this section that possible signal processor subsystems for the long range radar applications comprise a representative set of the subsystems of general interest for wider applications.

3.1 RADAR PARAMETERS

3.1.1 Long Range Radar System Requirements

The contract Statement of Work lists a set of radar characteristics for meeting long range satellite detection requirements. These are listed in Table 17. The bounds on key radar parameters of several long range radars currently in use is listed in Table 18.

TABLE 17. LONG RANGE RADAR REQUIREMENTS

Target Altitude	100 NM to 25,000 NM
Target Radial Velocity	$\pm 10,000$ ft/sec to $\pm 35,000$ ft/sec for Elliptical Orbits
Transmission Frequency	435 MHz
Target Cross Section	1.0 Sq. Meter @ 435 MHz
Probability of Detection	50% to 90% @ 3440 NM 50% @ 7000 NM, Max. Range 25,000 NM
Range Resolution	1 NM for Two Targets with Up to 10 dB Differential Amplitude
Velocity Resolution	$< + 50$ ft/sec
Angular Accuracy	$+ 1/10$ Beamwidth
False Alarm Probability	10^{-6} (Assumed)

TABLE 18. RADAR* PARAMETER BOUNDS

Peak Power	1.2 MW to 32 MW
Average Power	25 KW to 300 KW
Transmitted Energy Per Pulse	2400 to 10000 Joules
Transmission Frequency	Around 435 MHz One of the Systems at 1300 MHz
PRF	20 to 30 PPS
Pulse Lengths (Coded)	250 μ sec to 2000 μ sec
Waveform Bandwidths	500 Hz to 5 MHz
Range Resolution	200 Feet to ± 1 NM

The foregoing radar requirements and radar parameter bounds can be combined by use of the radar equation to define a baseline satellite detection radar. The radar range equation can be expressed for the signal-to-noise ratio (S/N) of a single pulse.

* Based on FPS-17, FPS-49, FPS-79, FPS-80, FPS-85 and Cobra Dane.

$$S/N = \frac{P_t \tau G_T G_R \lambda^2 \sigma_t (1.07)}{NF R^4 L}$$

The equation is diagrammed in Table 19 to derive a set of appropriate radar parameters. The table indicates that a 1.0 square meter target has a S/N of 4.71 dB for a single transmitted pulse 500 μ sec in length using a peak power of 20 MW and antenna gains of about 42 dB. The S/N required for $P_d = 90\%$ and $P_{fa} = 10^{-6}$ is about 13 dB. Thus the coherent integration of 7 pulses is required to meet the 3440 NM range requirement.

At 7000 NM the single pulse S/N is -7.69 dB. To achieve a P_d of 0.5 with a false alarm probability of 10^{-6} requires a S/N of 11.2 dB. Thus a S/N enhancement of 18.83 dB is required, or the integration of 78 pulses. An integration time of about 4 seconds provides the 78 pulses. The losses used in the range equation are estimated, and probably on the high side. Thus the 4 seconds of integration time specified is more than adequate for the 7000 NM detection range and 1 square meter target.

To reach a range of 25,000 NM requires 20.06 dB more gain than the 7000 NM case. The duty factor for the 20 Hz PRF and a pulse length of 500 μ sec is 100 to 1. Thus a peak power of 32 MW matches the 300 kW average power limitation. However, the energy per pulse in this case is 16,000 joules, or more than the 10,000 limit of the bounds in Table 18. In order to stay within the average power limitation of 300 kW and the maximum energy per pulse of 10,000 joules with a 32 MW peak power, the pulse length must be 312 μ sec and the PRF increased to 30 Hz. The only variables left are the target size, losses and the number of pulses integrated unless the basic radar parameters are improved. The loss budget in the long range search mode can be altered in the signal processor. In the 11 dB total loss budget 1.3 dB is typically due to matched filter weighting, 1.6 dB may be due to doppler (coherent integrator) filter weighting and 0.6 dB may be due to a CFAR function loss. All of these losses totalling 3.5 dB can be eliminated in a mode change if the radar has sufficient programmability. If a limit of 10 seconds of integration time is placed on the system due in part to dark current build up in a CCD storage or integration device the maximum number of pulses per dwell at a PRF of 30 is 300. This represents a signal integration improvement over the 78 lower power longer pulses used in the 7000 NM mode of 5.8 dB. Under the foregoing assumptions, the baseline radar can detect a target with a cross section of $20.06 - (3.5 + 5.8) = 10.76$ dB or 11.9 m².

In summary, the baseline radar parameters for the system incorporates the radar parameter bounds of Table 18. The overall baseline parameters meeting the minimum performance goals at 3440 NM and 7000 NM are summarized in Table 20.

3.1.2 Radar System Considerations

The baseline CCD signal processor will be used for long range satellite detection and tracking radar applications. A basic characteristic of these radars is a very low PRF along with very high pulse energy. The satellites of interest are often non-cooperative and in non-powered flight. Thus the satellite path will follow predictable orbits.

A signal processor configuration for these satellite radars will have

TABLE 19. RANGE EQUATION TABULATION

PARAMETER	EQUATION SYMBOL	VALUE	(+) dB	(-) dB	OUTPUT S/N dB
Transmit Power (Watts)	P_t	A,B: 20×10^6 C: 32×10^6	73.01 75.05		
Antenna Gain (Transmit)	G_T	-	42.10		
Antenna Gain (Receive)	G_R	-	41.70		
Wave-length (cm)	λ^2	69	36.77		
Target Cross Section (m^2)	σ_t	1.0	0		
System Noise Factor	\overline{NF}_0	2.37		3.75	
Pulse Length (Sec)	τ	A,B: 500×10^{-6} C: 312×10^{-6}		33.01 35.05	
Range (NM)	R	A: 3440 B: 7000 C: 25000		A: 141.4 B: 153.8 C: 175.9	
Losses	L			11	
Constant		1.07	0.29		
		TOTALS	195.91	A: 189.16 B: 201.56 C: 223.66	4.71 -7.69 -27.75

TABLE 20. BASELINE RADAR PARAMETERS

Peak Power: 32 MW
 Average Power: 300 kW
 Maximum Energy/Pulse: 10000 Joules
 Maximum Pulse Length: 500 μ sec

RANGE	PULSES INTEGRATED	TARGET CROSS SECTION	SYSTEM LOSSES	INTEGRATION TIME	PRF	PULSE LENGTH
3,440 NM Case	7	1.0 m ²	11 dB	.35 Sec	20 Hz	500 μ sec
7,000 NM Case	80	1.0 m ²	11 dB	4 Sec	20 Hz	500 μ sec
25,000 NM Case	300	12 m ²	7.5dB	10 Sec	30 Hz	312 μ sec

constraints imposed by the satellite environment. These constraints include:

1. Satellite Orbits
2. Satellite Velocity Limits
3. Radar Power Limits
4. Range Resolution Requirements

3.1.2.1 Satellite Orbits - Satellites in non-powered flight follow an orbit that is a conic section with one focus at the earth's center. A simplified derivation of the equations of motion developed by C. S. Lerch [1] will be used. Figure 6 shows a typical orbit and gives the applicable equations of motion of this orbit. It can be shown that the maximum range rate at the radar occurs when the radar is in the plane of the orbit and when θ is plus or minus 90°. It follows that:

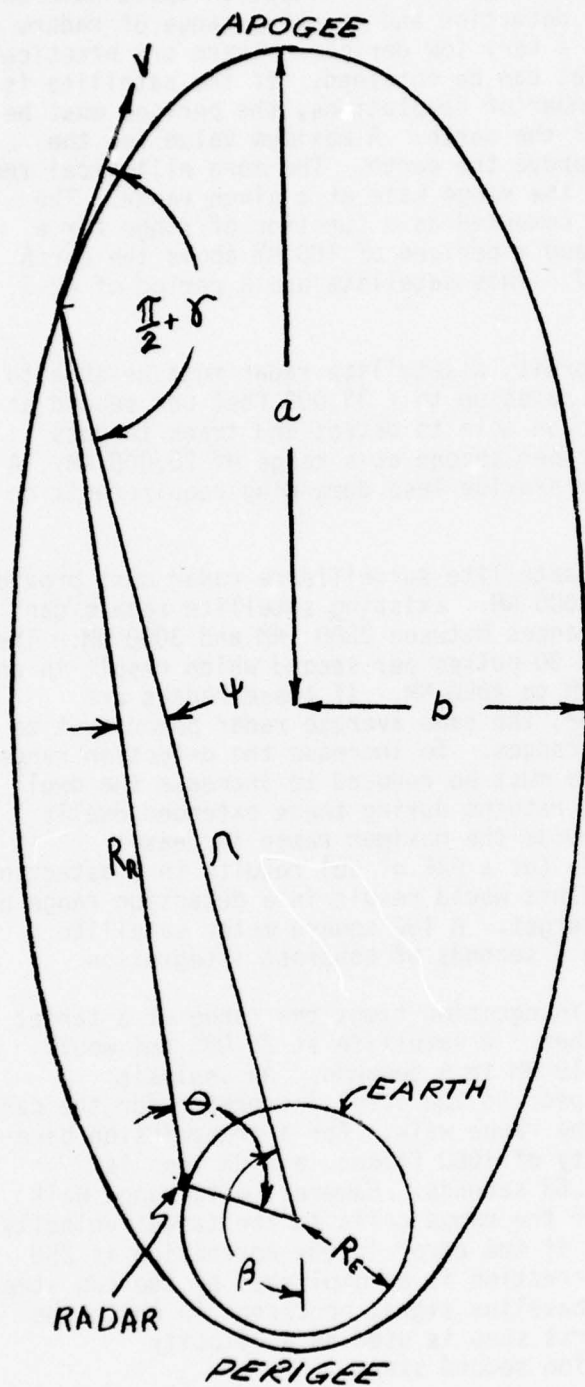
$$R_R = \sqrt{\Omega^2 - R_E^2}$$

$$\sin \psi = R_E/\Omega$$

The maximum range rate (V_{RM}) at the radar is:

$$V_{RM} = V \cos \left(\frac{\pi}{2} + \gamma + \psi \right) = -V \sin (\gamma + \psi)$$

3.1.2.2 Satellite Velocity Limits - Satellites can have very elliptical orbits particularly if the prevention of detection of the satellite is of



EQUATIONS OF MOTION

$$e = 1 - \left(\frac{b}{a}\right)^2$$

$$v^2 = 62740 \left(\frac{2}{r} - \frac{1}{a}\right)$$

$$r = a \frac{(1-e)^2}{1+e \cos \beta}$$

$$\tan \gamma = \frac{e \sin \beta}{1+e \cos \beta}$$

$$\frac{d\beta}{dt} = \frac{62740 a^{3/2} (1+e \cos \beta)^2}{b^2}$$

FIGURE 6. SATELLITE ORBIT

primary concern. Thus a satellite that is to elude detection could have an apogee that is well beyond the skin detection and tracking range of radars and would speed past the earth with a very low perigee. There are practical limits to the apogee and perigee that can be obtained. If the satellite is to maintain an orbit for a large number of revolutions, the perigee must be at least 100 NM above the surface of the earth. A maximum value for the apogee seems to be about 60,000 NM above the earth. The more elliptical the satellite orbit, the higher will be the range rate at a given range. The maximum range rate at the radar was computed as a function of range for a satellite with an apogee 60,000 NM and a perigee of 100 NM above the earth. These results are shown in Figure 7. This satellite has a period of 42.7 hours.

To meet this worst case elliptical orbit, a satellite radar must be able to detect and track targets with range rates up to $\pm 35,000$ feet per second at short ranges (100 NM). It must also be able to detect and track targets with range rates up to $\pm 10,000$ feet per second at a range of 25,000 NM. A less eccentric orbit would obviously provide less demanding requirements on the radar.

3.1.2.3 Radar Power Management - A satellite surveillance radar must provide detection of targets from 100 to 25,000 NM. Existing satellite radars can detect one square meter targets at ranges between 2500 NM and 3000 NM. These radars use PRF values between 20 and 30 pulses per second which result in an unambiguous range coverage of 2700 NM to 4050 NM. If these radars are modified using a CCD signal processor, the same average radar power must be used to provide detection at longer ranges. To increase the detection range of a fixed power radar, the scan rate must be reduced to increase the dwell time at a given angle position. The returns during these extended dwells must be coherently integrated to provide the maximum range increase. Coherent integration over six seconds (at a PRF of 30) results in a detection range increase of up to 3.31 to 1. This would result in a detection range of about 7000 NM for a 1 square meter target. A 100 square meter satellite could be detected at 25,000 NM using 6 seconds of coherent integration.

3.1.2.4 Range Walk - For very long integration times the range of a target may move from one range cell to another. A satellite at 25,000 nmi would move up to $\pm 50,000$ feet or about ± 10 NM in 6 seconds. An analysis was made of the loss in S/N with respect to the ideal integrator for the case in which no correction is made for the range walk. For a transmission bandwidth of 200 khz and a target velocity of 1000 ft/sec. a 3 dB loss is incurred for an integration time of .68 seconds. However, with range walk correction, (matching the movement of the range cells to the target velocity) a loss of less than .5 dB will occur if the error in the correction is 250 feet/sec or less. The range walk correction is accomplished by the two step detection process described for the baseline signal processor in which the doppler frequency obtained on the first step is used as a velocity correction on the high range resolution second step.

3.1.2.5 Ionospheric Dispersion - Refraction of UHF frequencies through the ionosphere are frequency dependent and vary as a function of time. For wideband waveforms the effect is akin to passing the signal through a filter

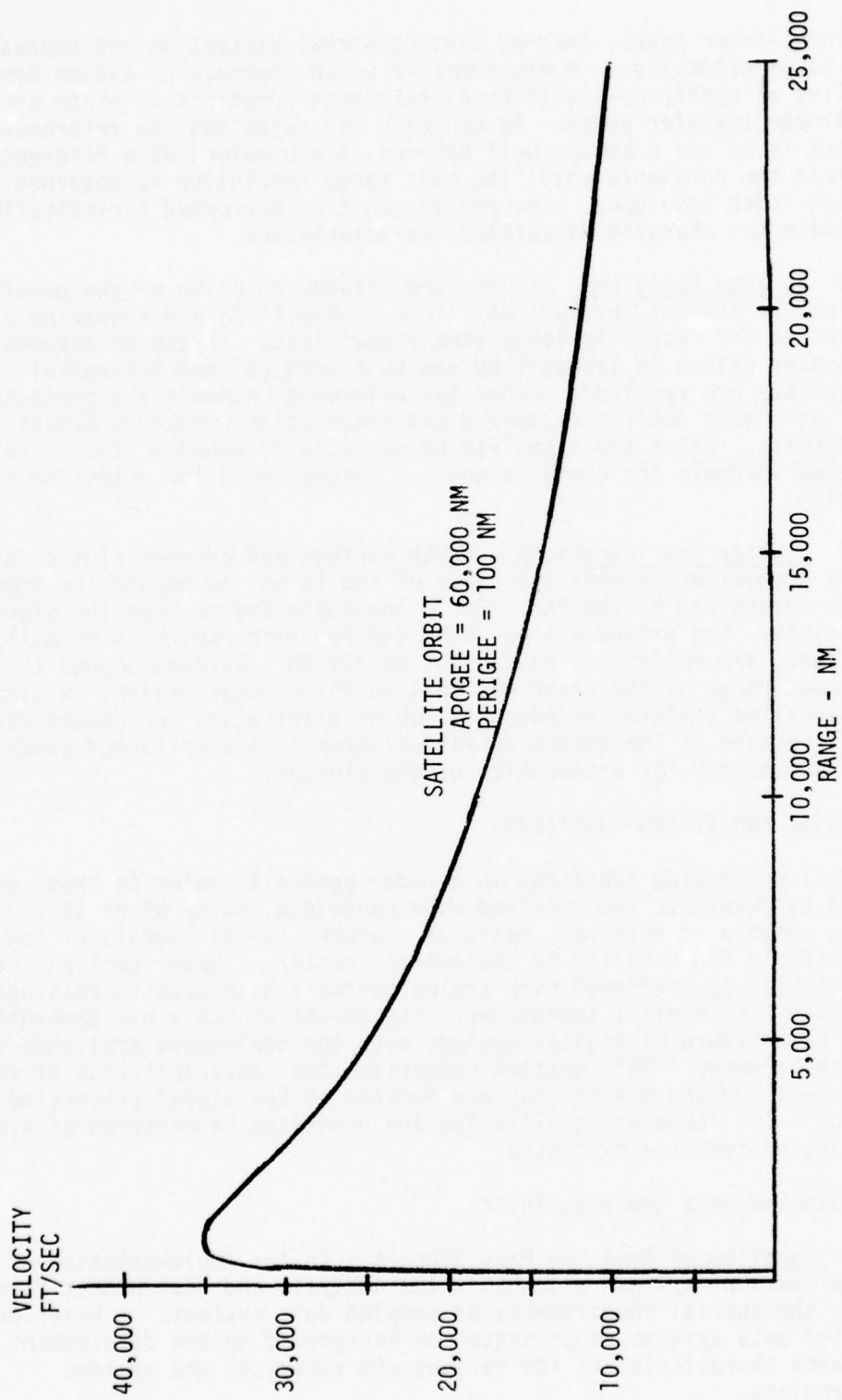


FIGURE 7. MAXIMUM VELOCITY PROFILE FOR A SATELLITE

with a non-linear phase, thereby causing signal distortion and degradation of the range estimation. A programmable pulse compression system has the capability of modifying the internal reference functions so as to synthesize a non-linear transfer phase. An approach for adjusting the reference function constants is to use a known, well behaved, space object as a reference, and manipulate the constants until the best range resolution is obtained (the narrowest video envelope). The process must be performed periodically to accommodate the changing dispersion characteristics.

3.1.2.6 Faraday Rotation - At UHF, the Faraday rotation of the polarization vector can be several revolutions. Thus transmitting and receiving a single polarization can result in large echo signal loss. It can be assumed that linear polarization is transmitted and both vertical and horizontal polarizations are received. Hence two reference channels are processed with all the attendant doppler filtering and integration needed to detect long range targets. After the signal-to-noise ratio is enhanced the signal levels in the two channels are compared and the largest used for detection and range estimation.

3.1.2.7 Clutter Considerations - Earth surface and weather clutter are problems predominately when the range of the target is beyond the unambiguous range as determined by the PRF. For a low angle search beam the significant ground clutter can extend out to 30 NM and for rain, which is normally below 10,000 feet, the return can extend out to 130 NM. Targets beyond the unambiguous range of the radar may fall in the clutter region. A simple two pulse canceller performs an adequate job of eliminating the ground clutter. However, because of the motion of rain clutter a clutter-locked cancellation scheme is required for attenuation of the clutter.

3.2 SIGNAL PROCESSING FUNCTIONS

The signal processing functions in a radar generally refer to those operations required to translate the received wide bandwidth, noisy RF or IF signals from the antenna to detected, measured, labeled target signals of low data rates suitable for handling by the control center. These functions which were historically performed with analog hardware have been increasingly implemented with digital techniques. The advent of CCD's has combined the sampled data nature of digital systems with the continuous amplitude structure of analog hardware. This section summarizes the characteristics of sampled data systems and the manner they are related to key signal processing functions. The important qualitative and quantitative measures of signal processing systems are discussed.

3.2.1 Sampled Data Characteristics

3.2.1.1 Sampling of Real Low Pass Signals - In the implementation of signal processing systems with CCD's the analysis and design must first consider the special requirements of sampled data systems. A brief overview of sampled data systems is presented as background to the development of performance characteristics for various CCD subsystem and systems configurations.

Figure 8 depicts the time waveform and spectrum of a number of sampled data

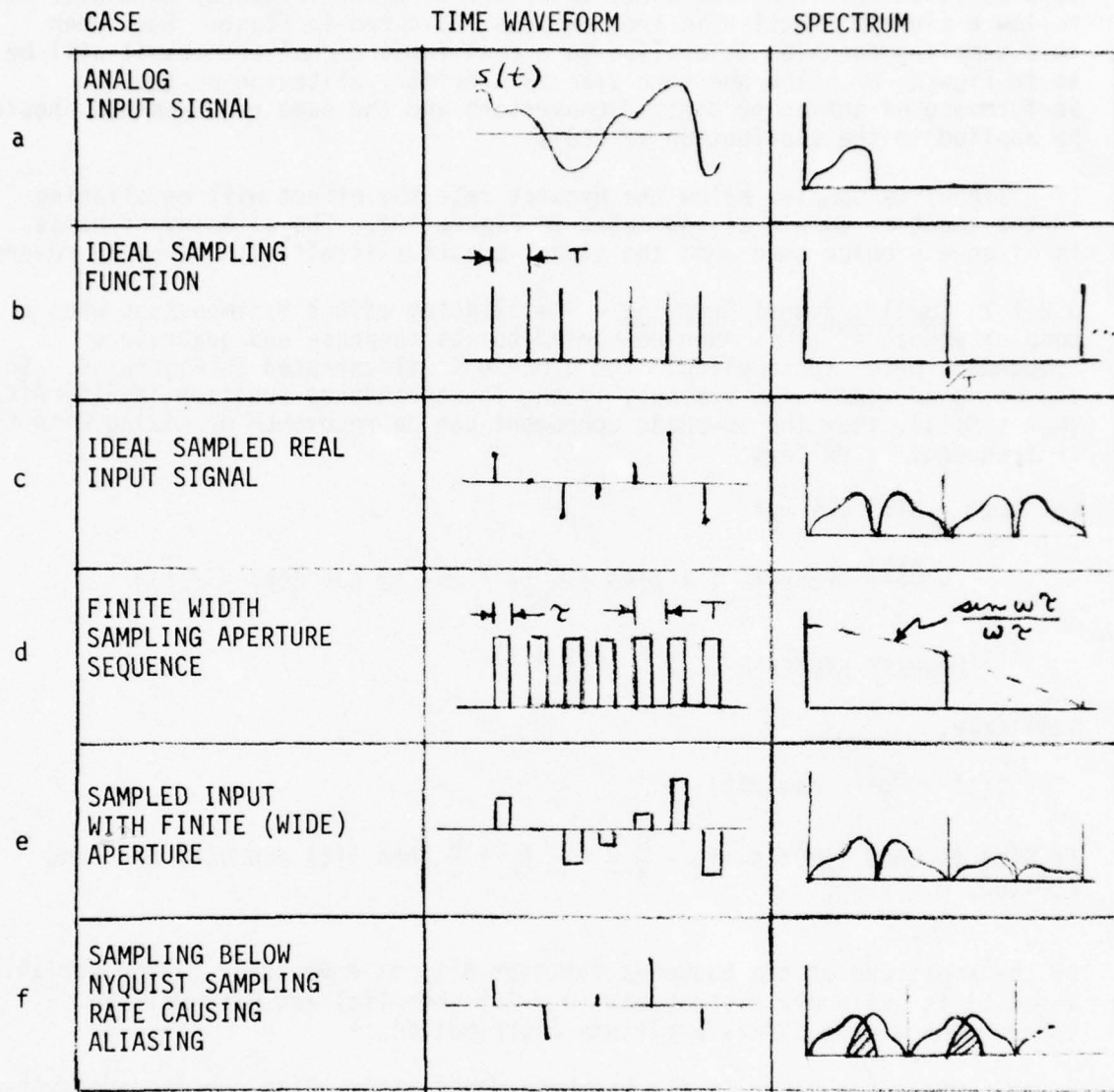


FIGURE 8. BASIC SAMPLED DATA CHARACTERISTICS

situations. In Figure 8a, a simple low frequency video signal with its low frequency signal is shown. A single impulse in the time domain produces a flat frequency spectrum. However, a train of impulse functions representing an idealized sampling function creates a series of line spectra at frequencies which are integral multiples of the sampling frequency. In order to sample a signal of low pass bandwidth B the sampling rate must be greater than or equal to $2B$. This is usually referred to as the Nyquist sampling criterion. The spectrum of an ideal sampled real signal is shown in Figure 8c. The sampling process creates sideband replicas of the sampled signal about the harmonics of the sampling frequency.

The sampling function will generally not be ideal but will have a finite

aperture. This finite aperture will limit the frequency content of the sampled function. The line spectrum of the sampling frequency harmonics will follow a $\sin x/x$ function in frequency as indicated in Figure 8d. When this sampling function is applied to a real input signal the result will be as in Figure 8e. The aperture size is a primary criterion on the performance of analog to digital converters and the same requirements should be applied in the application of CCD's.

If a signal is sampled below the Nyquist rate the effect will be aliasing in the spectral domain as indicated in Figure 8f. The aliasing of noise is often a problem even when the signal spectrum itself is adequately covered.

3.2.1.2 Complex Signal Sampling - The aliasing effect is important when a complex signal at IF is down-converted to its in-phase and quadrature components prior to sampling. The process is illustrated in Figure 9. In the baseband conversion process, if the input bandpass function is $S(t)=A(t) \cos(\omega_c t + \theta(t))$, then the in-phase component can be recovered by mixing with the IF frequency as follows.

$$\begin{aligned} \text{Let } I(t) &= S(t) \cos \omega_c t \\ &= \frac{A(t)}{2} [\cos(\omega_c t + \theta(t) + \omega_c t) + \cos(\omega_c t + \theta(t) - \omega_c t)] \\ I(t)_{\text{LOWPASS FILTERED}} &= \frac{A(t)}{2} \cos \theta(t) \end{aligned}$$

Similarly,

$$Q(t) = \frac{A(t)}{2} \sin \theta(t)$$

If $S(t)$ is band limited, $f_c - \frac{W}{2} \leq f \leq f_c + \frac{W}{2}$ then $I(t)$ and $Q(t)$ are band limited, $0 \leq f \leq \frac{W}{2}$.

If the amplitude of the bandpass function $A(t)$ is a Gaussian random variable and $\theta(t)$ is uniformly distributed ($0 - 2\pi$) then $I(t)$ and $Q(t)$ will be independent with a normal amplitude distribution.

Error sources can occur in the baseband demodulator which can degrade system performance. Quadrature errors are caused by the two mixing IF signals not being precisely shifted in phase relative to each other by 90 degrees. Amplitude and phase tracking errors and low pass filter distortion can also degrade performance.

One can calculate the noise increase from aliasing due to the low pass filter characteristics. An example is shown in Figure 10 for Butterworth and elliptic filters employed with sampling rates close to Nyquist. The noise increase varied up to 0.4 dB for Nyquist sampling and 0.1 dB for a sampling rate 1.1 times Nyquist. This example also assumed the signal spectrum was Hamming weighted in the signal processor. In this example a limit was placed on the phase distortion so that the higher pole filters which have higher phase distortion are used only at the higher sampling rates. The curve indicates the regions where the filters can be used without compensation while supporting sidelobes greater than 40 dB down. It should be noted that appropriate phase compensation will eliminate this limitation.

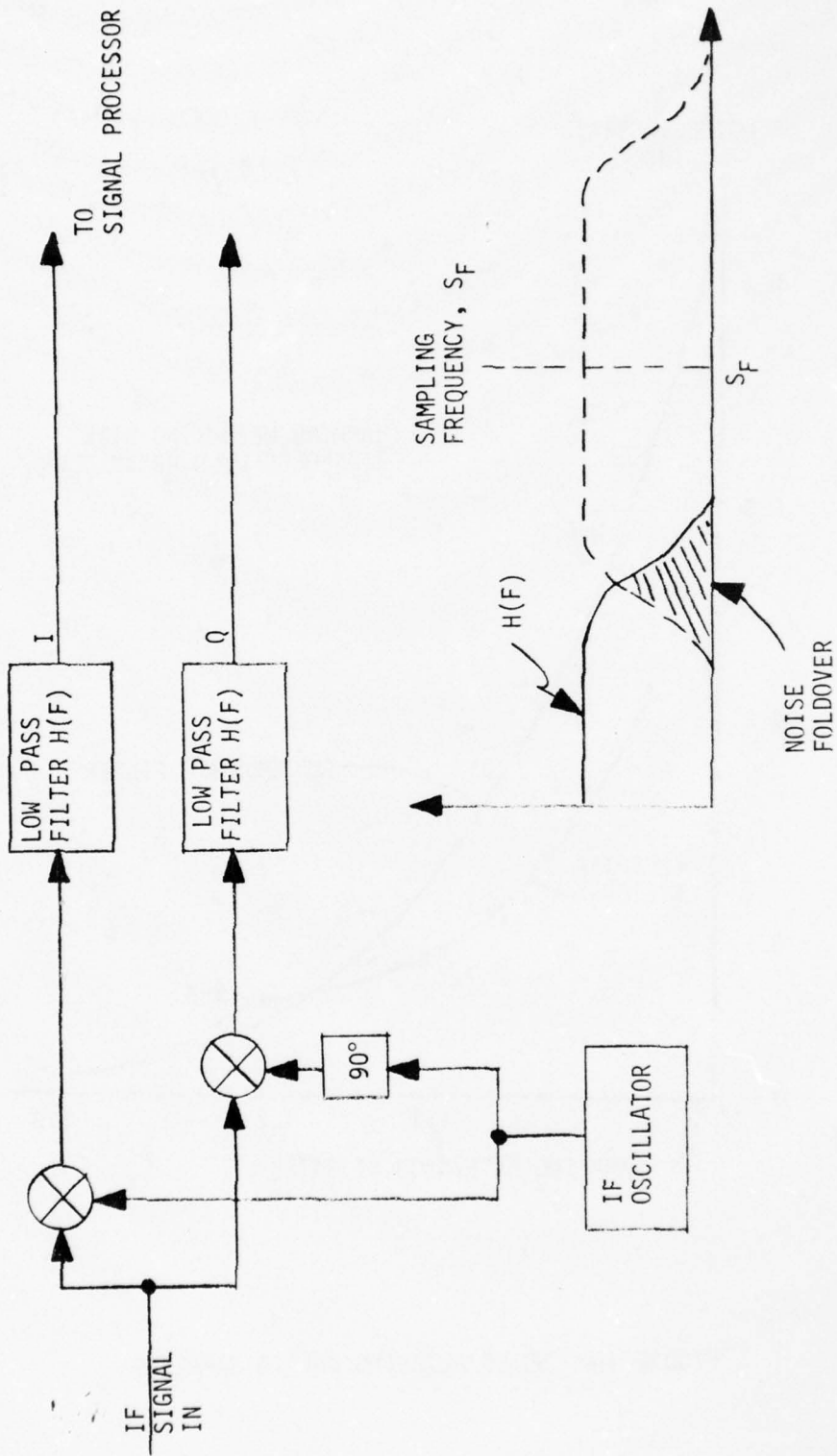


FIGURE 9. BASEBAND CONVERTER

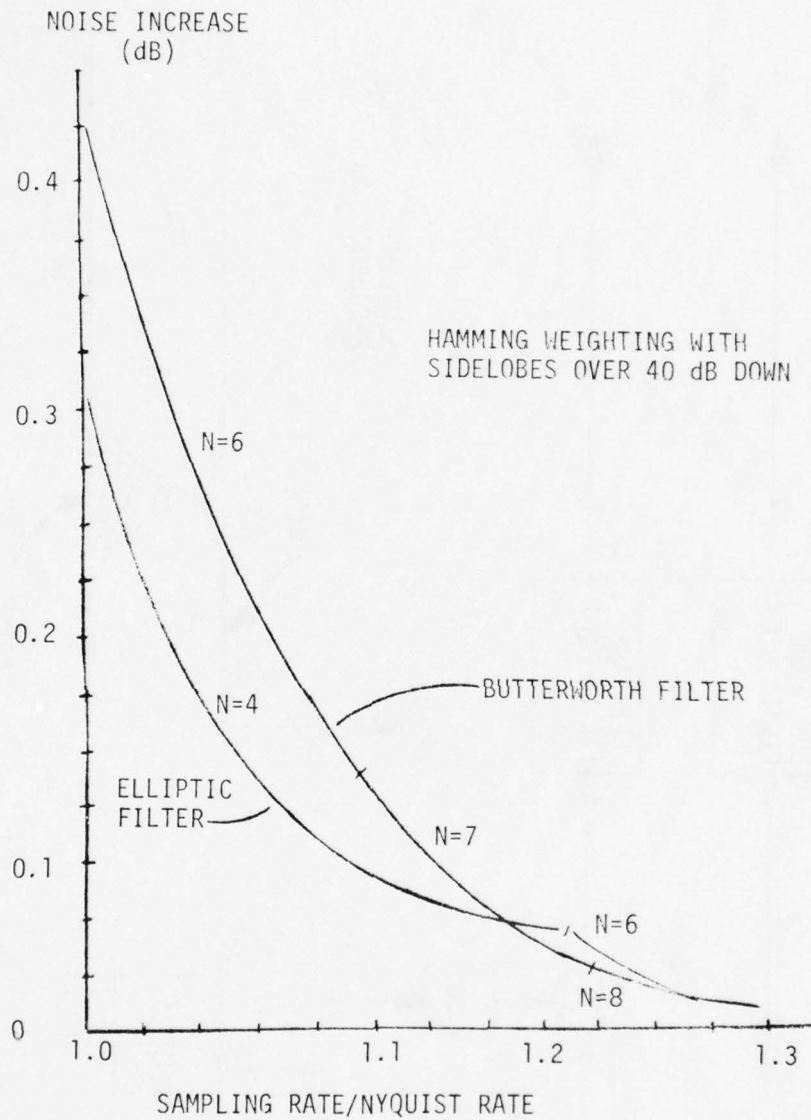


FIGURE 10. NOISE ALIASING DUE TO SAMPLING

3.2.2 Signal Processing Functions

A generalized block diagram of a radar signal processing system is shown in Figure 11. Virtually all of the functions listed can be implemented with CCD's as indicated by the dotted items. If one extends the CCD applications to digital logic implementation, CCD's can be used for all functions. The functions in Figure 11 can be implemented with a basic set of signal processing elements. These are:

- Delay Elements
- Storage Elements
- Integrators
- Arithmetic Functions (Add, Subtract, Multiply, Divide)
- Tapped Delay Lines
- Transversal Filters
- Recursive Filters
- Switches

These elements can either be implemented as part of a CCD or implemented in an analog technique on a CCD integrated circuit. The primary effort relative to CCD performance evaluation for this study has been to identify the key functional elements which are implemented as CCD's and determine their performance as a function of the CCD parameters themselves. The performance level of a full CCD signal processing system can be extrapolated from the constituent elements.

3.2.3 Parameter Ranges of Key Signal Processing Elements

Depending on the radar application, the signal processing functions listed in Figure 11 will have widely varying requirements. The requirements imposed on a signal processor by the long range satellite search radar will not cover the full gamut of potential CCD hardware specifications. Table 21 lists the parameter variations which may be encountered in a large variety of radar systems. Regardless of the level of achievement in a technology toward the implementation of radar signal processing, there will be new applications which cannot be practically met. Thus, the bounds given in Table 21 represent typical requirements rather than extreme. The application of CCD's therefore can best be assessed on an individual case basis. The performance level of CCD's as a function of basic operational parameters as given in Section 6.0 will provide a useful tool in this assessment.

3.3 CCD SIGNAL PROCESSING IMPLEMENTATIONS

Figure 12 shows a typical radar signal processing system with the elements which are candidates for CCD implementation in dark outline. From a hardware viewpoint in typical radar systems, these elements constitute a major part of the signal processor size and cost. This section describes alternative CCD implementation techniques for the principal hardware function of pulse compression, storage and spectral analysis. Details of the CCD structure itself in relation to developing a model for simulation are developed in Section 4.0.

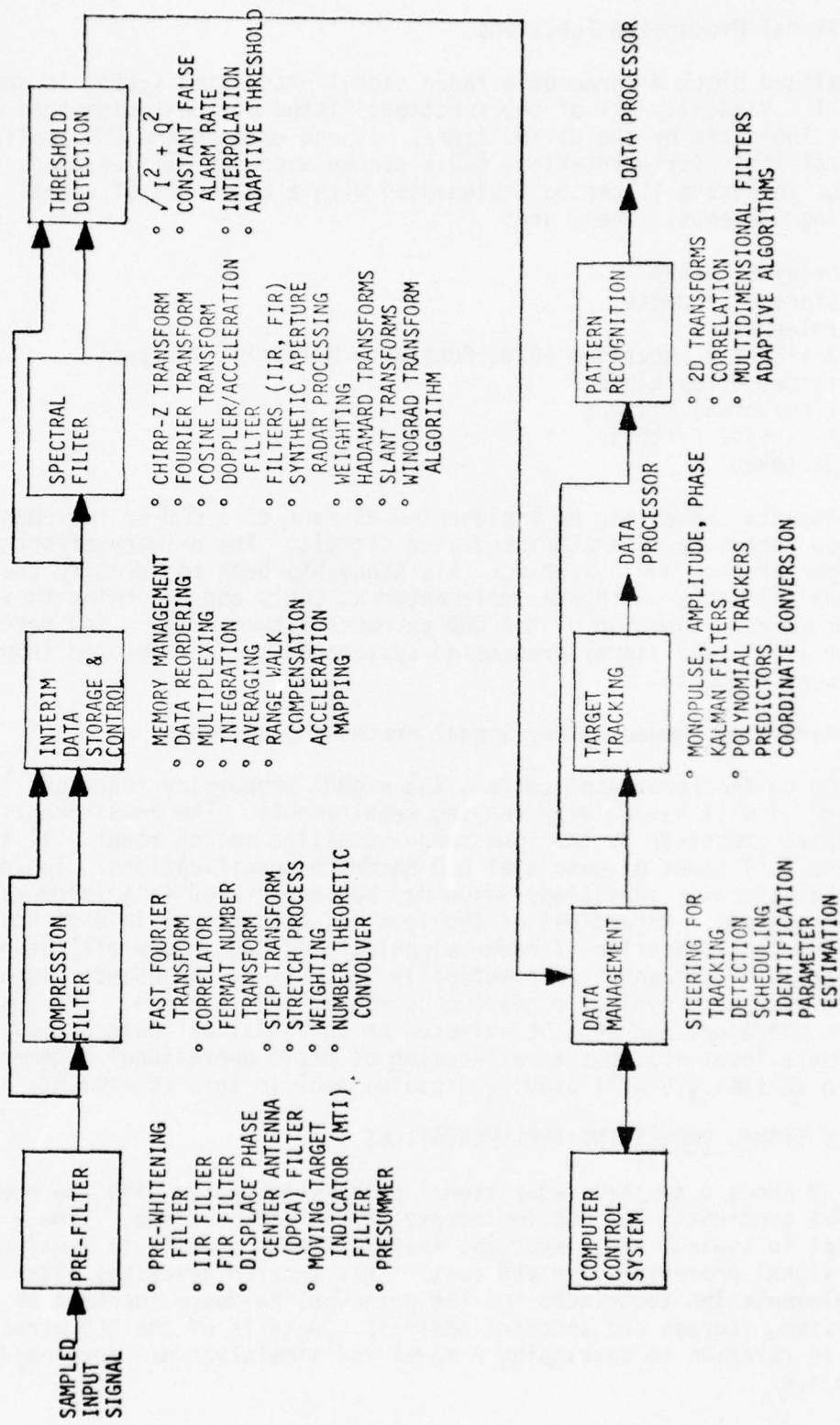


FIGURE 11. GENERALIZED RADAR SIGNAL PROCESSING FUNCTIONS

TABLE 21. PARAMETER RANGES OF SIGNAL PROCESSING FUNCTIONAL ELEMENTS

ELEMENT	SIGNAL PROCESSING FUNCTIONS	CLOCK RATE	NUMBER OF DATA SAMPLES	DYNAMIC RANGE	SPECIAL FEATURES DESIRABLE FOR SOME APPLICATIONS
Delay	Time Alignment and Data Reordering In Most Signal Processing Functions	50 kHz- 100 MHz	1-1000	30 - 80 dB	<ul style="list-style-type: none"> ◦ Programmable Delay ◦ Data Recirculation
Storage	Data Storage Up To Length of Time Data is in Signal Processor e.g., Target Dwell Time	<u>Load/Unload</u> 50 kHz- 100 MHz Store Up to 12 sec.	10-100,000	30 - 80 dB	Random Access
Transversal Filter	FIR Filters, CFAR IIR Filters, Averaging Convolvers, Correlators, Transforms, Interpolation	50 kHz- 100 MHz	10-25,000	Input 30 - 60 dB Output 40 - 80 dB	<ul style="list-style-type: none"> ◦ Programmable Weights ◦ Internal Reference Store ◦ Variable Length
Operations	Switching, Arithmetic Functions, Integration	50 kHz- 100 MHz	-	30 - 80 dB	

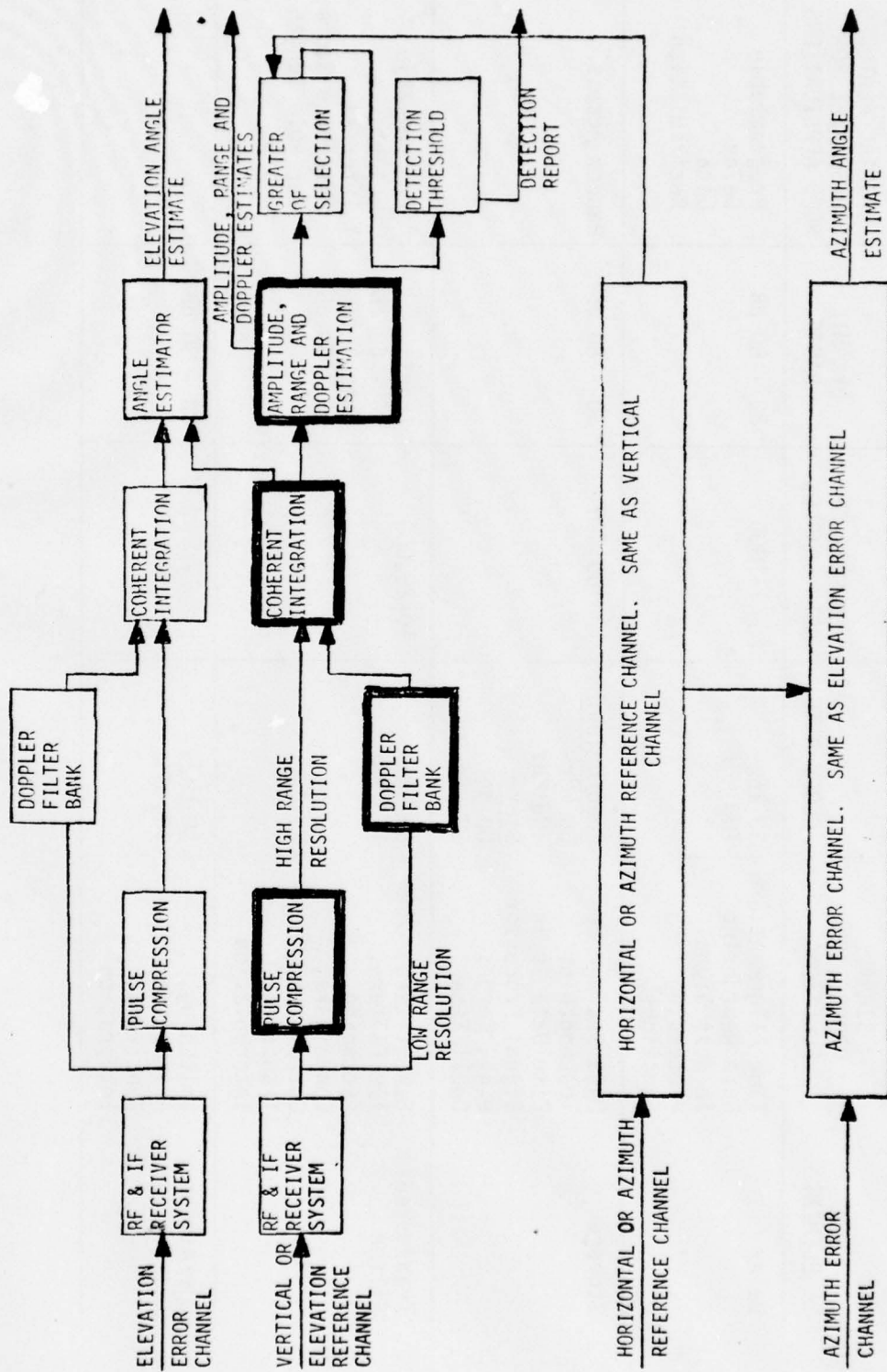


FIGURE 12. RADAR SIGNAL PROCESSING SYSTEM

3.3.1 Pulse Compression

3.3.1.1 Tapped Delay Line Pulse Compression Filters - The output $y(t)$ of a matched filter implemented via convolution of an input signal $s(t)$ with the impulse response of the matched filter $h(t) = x^*(-t)$ where $x(t)$ is the transmitted waveform;

$$y(t) = \int_{-\infty}^{\infty} s(\tau) h^*(t-\tau) d\tau$$

The signal and filter functions are generally represented as complex in-phase and quadrature samples for sample data operations. Thus a physical realization of the filter function must accommodate the complex multiplication operation, which, for a matched filter is

$$(a + jb)(c - jd) = ac + bd + j(bc - ad)$$

A tapped delay line matched filter, therefore, takes the form of Figure 13. CCD's are ideally suited for implementing this function because of their serial structure. The variable weight tapped delay line can be implemented on a CCD using the well known electrode weighting technique [2] shown in Figure 14. In this method, the filter weights are built into the basic physical structure of the CCD gates.

An alternate method for constructing a CCD transversal filter is to place a weight on a CCD floating gate tap output. This latter technique is more amenable to the development of programmable transversal filters. Programmability is a desirable feature in a radar pulse compression system since it permits the tailoring of a transmitted waveform to a specific operational requirement.

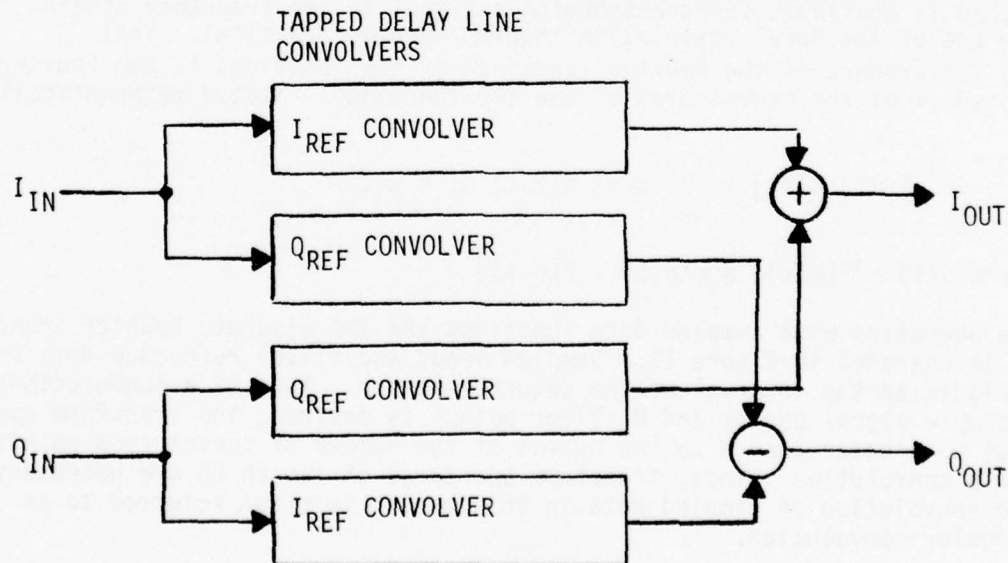


FIGURE 13. TAPPED DELAY LINE MATCHED FILTER

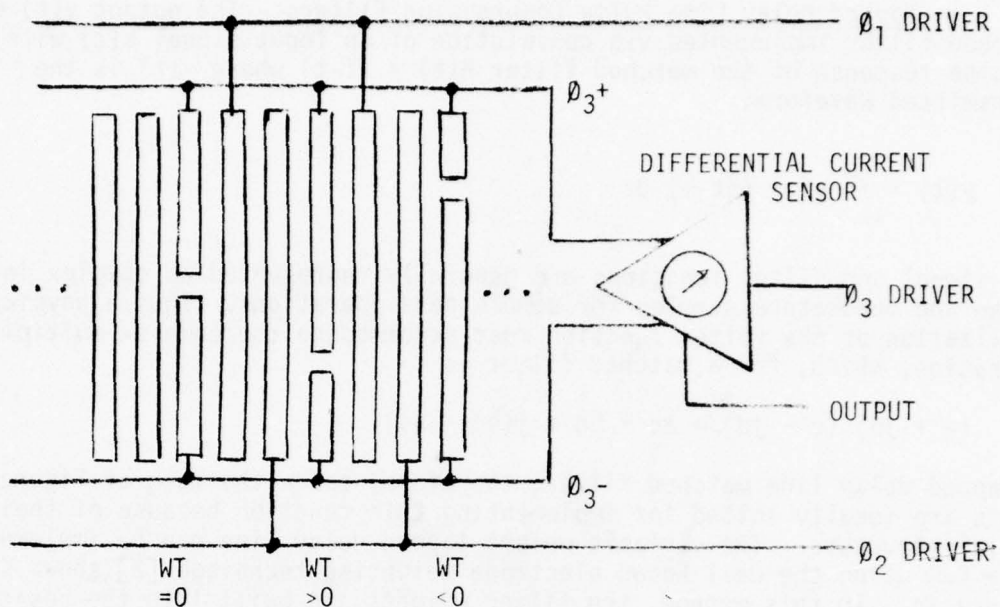


FIGURE 14. SPLIT GATE CCD WEIGHTING TECHNIQUE WITH 3-PHASE CLOCKING

The performance level of CCD transversal filters will depend on the transfer efficiency and noise associated with the charge transfer process and on the realizable tap weight accuracy.

3.3.1.2 Matched Filtering Using Spectral Multiplication - If a convenient method is available for transforming a signal to the frequency domain, the use of the Borel convolution theorem becomes practical. That is, the product of the Fourier transform of two functions is the Fourier transform of the convolution of the two functions. Stated mathematically,

$$F^{-1} [S(f) H(f)] \equiv \int_{-\infty}^{\infty} x(\tau) h(t-\tau) d\tau = y(t)$$

where $S(f) = F[s(t)]$ and $H(f) = F[h(t)]$.

The operation with sampled data functions and the discrete Fourier transform is illustrated in Figure 15. Sampled input and filter reference data are periodic at the interval of the sequence length. Thus if a convolution of N sample signal points and N filter points is desired, the transform aperture must be greater than N to the extent of the number of convolution points. For N convolution points, transform apertures of length $2N$ are necessary. The convolution of sampled data in this manner is often referred to as circular convolution.

The fast Fourier transform (FFT) algorithm has provided an efficient method for calculating the discrete Fourier transform (DFT) of a set of sampled data

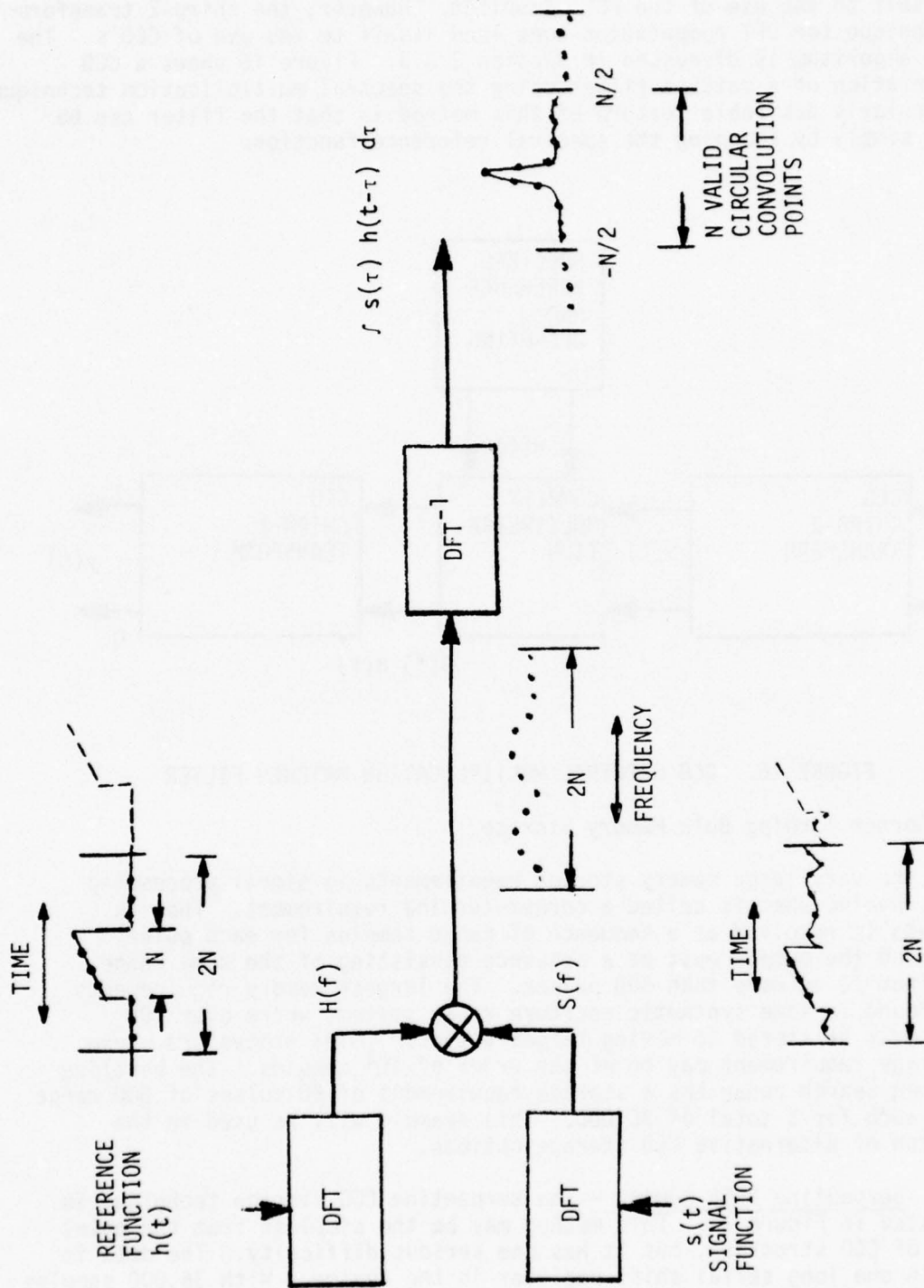


FIGURE 15. ILLUSTRATION OF CONVOLUTION BY SPECTRAL DOMAIN MULTIPLICATION WITH SAMPLED DATA

using digital techniques. The serial structure of CCD's does not lend itself to the use of the FFT algorithm. However, the chirp-Z transform [3] technique for DFT computation does lend itself to the use of CCD's. The chirp-Z algorithm is discussed in Section 3.3.3. Figure 16 shows a CCD implementation of a matched filter using the spectral multiplication technique. A particularly desirable feature of this method is that the filter can be changed simply by changing the spectral reference function.

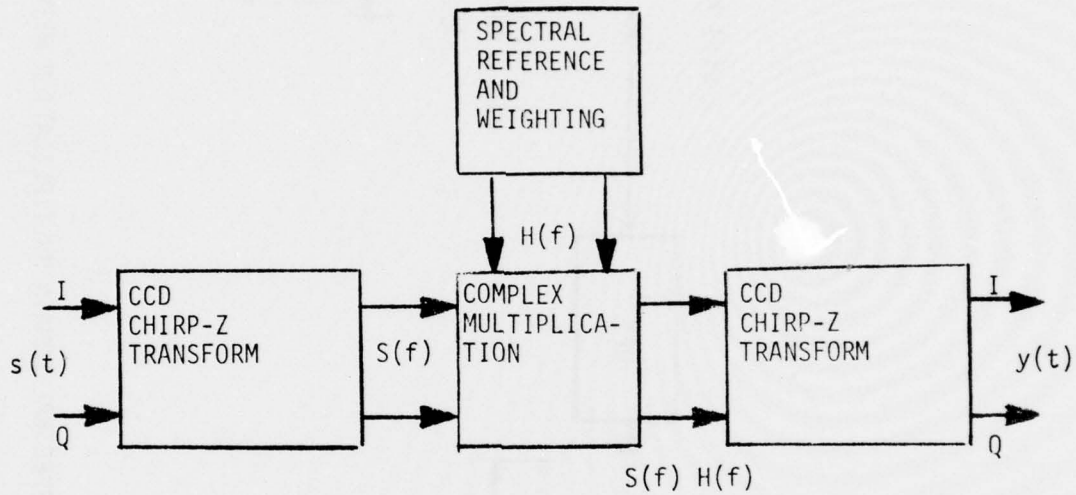


FIGURE 16. CCD SPECTRAL MULTIPLICATION MATCHED FILTER

3.3.2 Corner Turning Bulk Memory Storage

Many of the very large memory storage requirements in signal processing systems involve what is called a corner-turning requirement. That is while data is received as a sequence of range samples for each pulse transmitted the output must be a sequence consisting of the same range sample from 10 to more than 500 pulses. The largest memory requirements can be found in some synthetic aperture radar systems where over 10^6 samples must be stored to moving target detector (MTD) processors where the storage requirement may be of the order of 10^4 samples. The baseline long range search radar has a storage requirement of 60 pulses of 600 range samples each for a total of 36,000. This example will be used in the discussion of alternative CCD storage options.

3.3.2.1 Serpentine Bulk Memory - The serpentine CCD storage technique is illustrated in Figure 17. This method may be the simplest from the point of view of CCD structure, but it has one serious difficulty. The data is loaded in one long serial shift register in the device. With 36,000 samples to be loaded in sequence any transfer inefficiency will seriously degrade the samples passed through the entire device. A 10^{-4} transfer loss which is

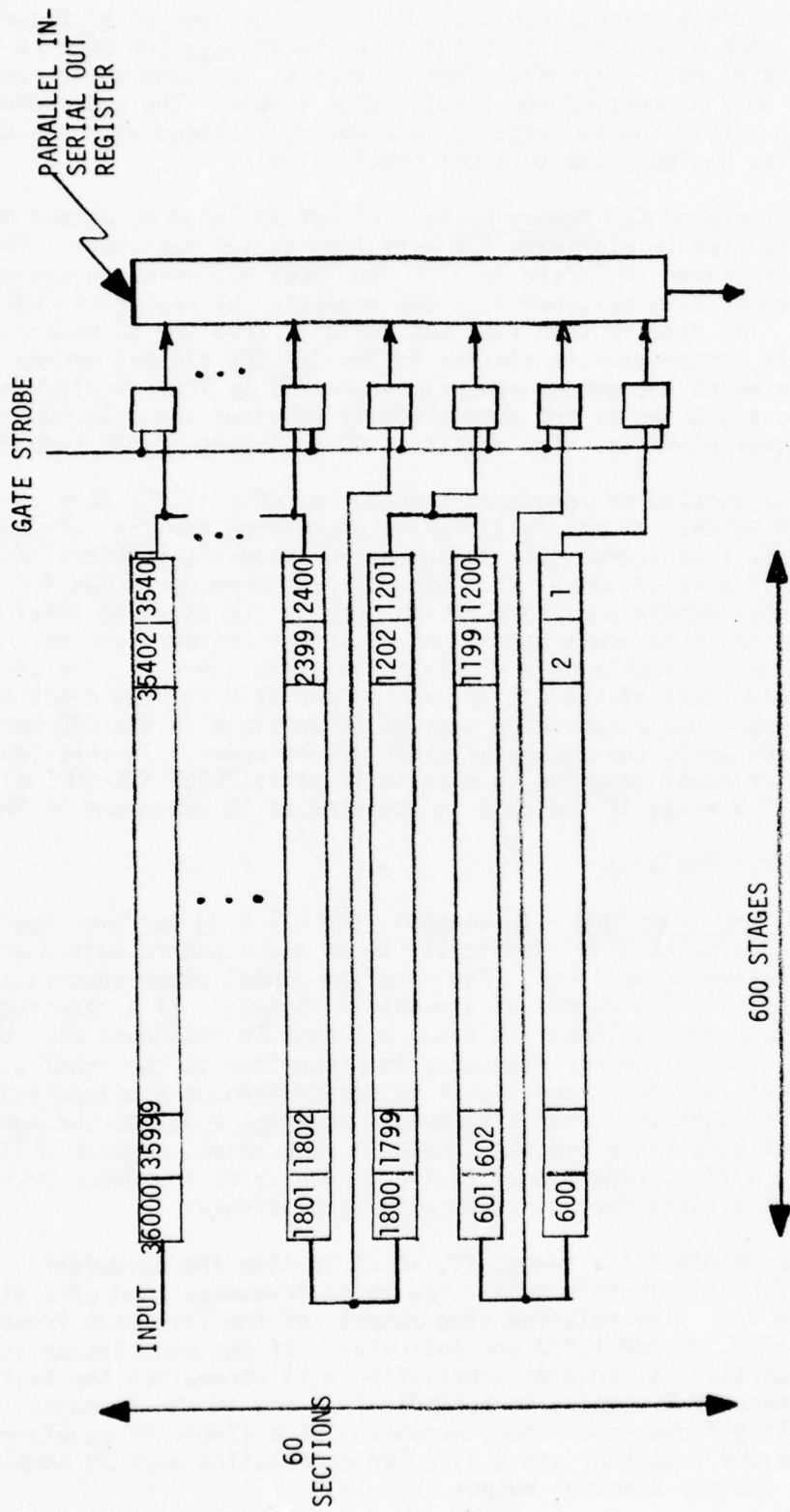


FIGURE 17. SERPENTINE BULK MEMORY

typical for surface channel CCD will result in the loss of 97.2 percent of the leading edge sample of a step function loaded into the CCD. A buried channel CCD will have a transfer inefficiency of 10^{-5} and would result in the loss of 30.2 percent of the leading edge sample. The amplitude distribution across the 60 output points would be skewed with the most recent samples having close to their exact value.

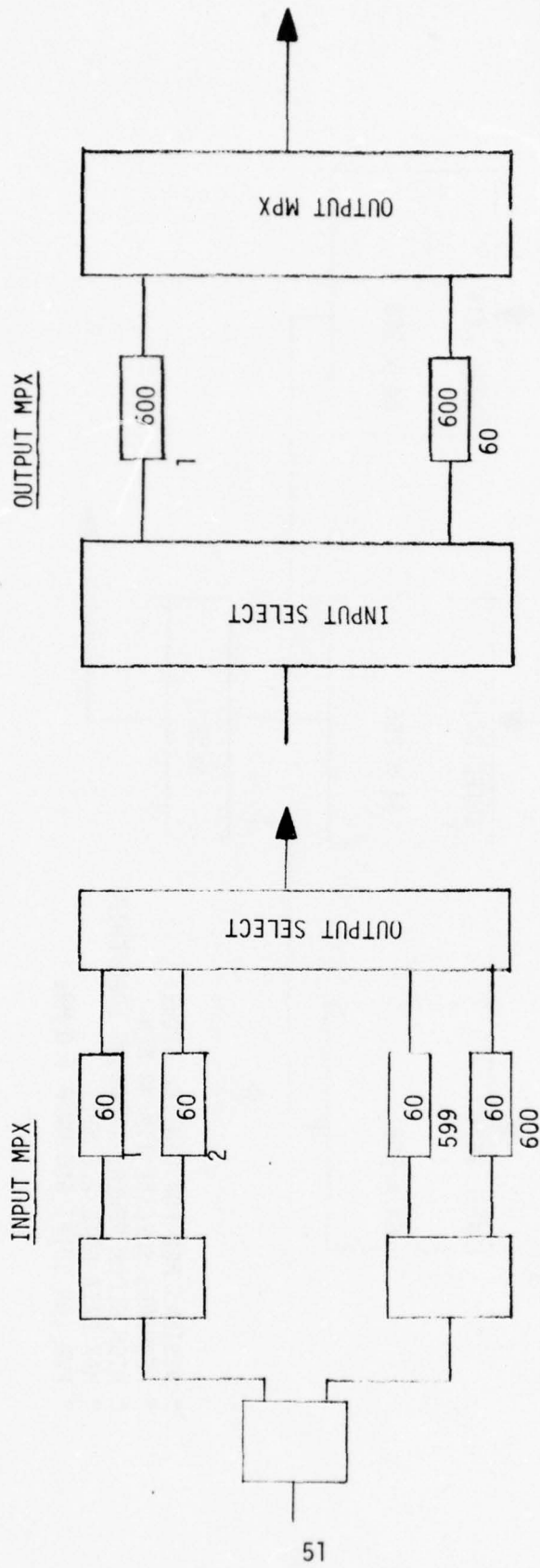
3.3.2.2 Multiplexed CCD Memory Cells - Either an input or output multiplexing method can be used to eliminate the very long serial registers. The two approaches are shown in Figure 18. In the input multiplexing approach, the input is sequentially switched into 600 separate CCD registers, one for each range cell. The data is then read out serially from one 60 sample register at a time. This arrangement is similar to the 32K CCD digital memory design of Fairchild in which the memory dimensions are 256 by 128. Performing a multiplexing operation at the output simply reverses the size and number of CCD register elements. The result is 60 registers of 600 samples each.

The principal problem of long term storage in CCD's is the dark current build up and neither of the multiplexing approaches nor the bulk memory using multiple line addressable random access memories (LARAM's) as indicated in Figure 19 solves it. LARAM's have been developed for use as digital storage mechanisms and a design such as the 64 x 256 Intel 2416 has the required functional operations to perform corner turning. However, these units are currently only viable for digital storage. The Intel design has a very high 2800 pf capacitive load on the chip for the clock input. This high clock capacitance should be avoided if possible in the CCD design as it greatly increases the amount of clock driver power. In this instance, the peak clock power required to operate it using 75365 TTL-CMOS clock drivers is 12.5 watts if the chip is operated at 10 volts and 10 MHz.

3.3.3 Spectral Analysis

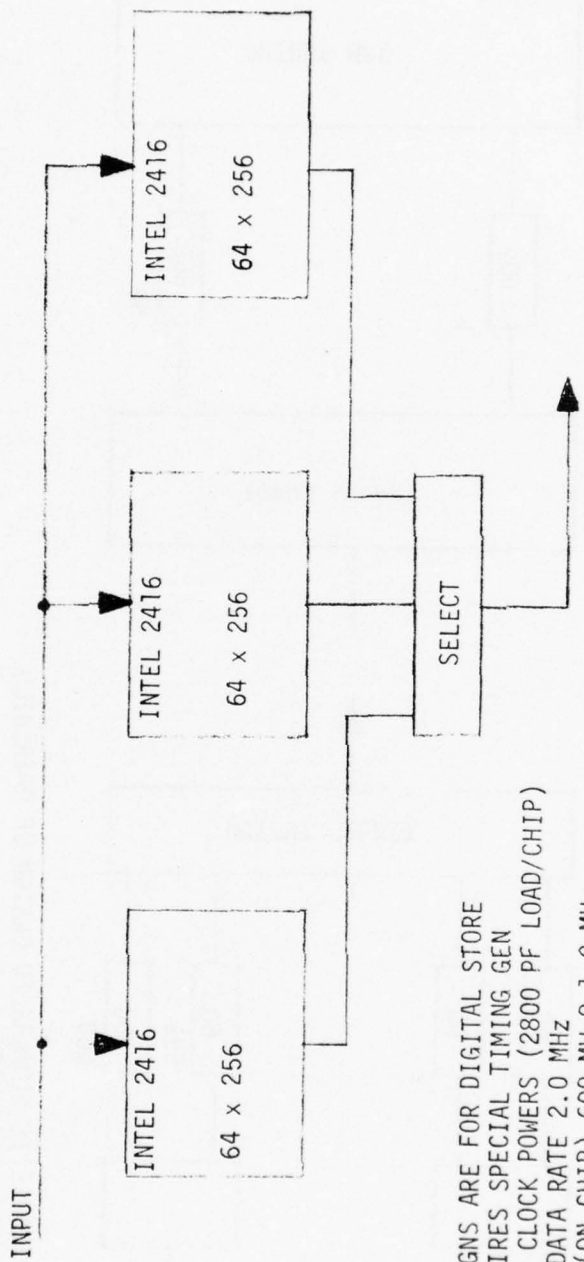
3.3.3.1 Chirp-Z Transform - In concept, the CZT [3] performs spectral analysis with sampled data identically to an old standard method used with analog dispersive delay lines. The received signal whose spectra is to be analyzed consists of a number of sinusoidal signals. If a received CW signal is mixed with a linear FM ramp, a linear FM resultant will be produced which is offset in frequency in proportion to the input signal frequency. If this resultant signal is passed through a dispersive line (or linear FM convolver) with a frequency coverage equal to the sum of the frequency analysis range and the linear FM ramp range, a pulse will be outputted at a time proportional to the frequency of the input CW signal. Figure 20 illustrates the principle with sampled data.

The input bandwidth has a range, Δf , which is also the bandwidth of the LFM function in this case. The total frequency band of a dispersive line must be $2\Delta f$. The relative time outputs of the line with frequency inputs of $-\Delta f/2$, 0, and $+\Delta f/2$ are indicated. If the convolution is done via a sampled function, a circular convolution will accomplish the task. Recall that a sequence of N samples is periodic in N and in the frequency domain at the sampling frequency. Thus, extension of a linear FM waveform occurs in both time and frequency and a circular convolution over 2N samples will provide the desired spectral output.



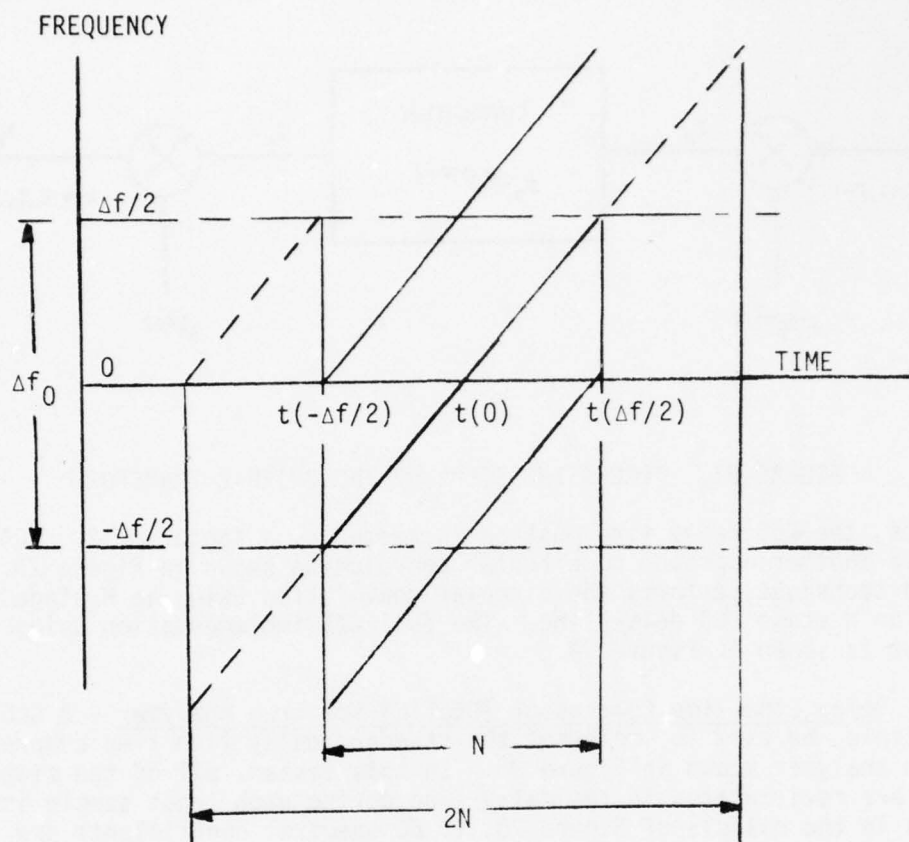
PRINCIPLE IS SIMILAR TO DESIGN OF FAIRCHILD
32K CCD (256 x 128)

FIGURE 18. SIMPLE MULTIPLEXING BULK STORE



- DESIGNS ARE FOR DIGITAL STORE
- REQUIRES SPECIAL TIMING GEN
- HIGH CLOCK POWERS (2800 PF LOAD/CHIP)
- MAX DATA RATE 2.0 MHZ
- PWR (ON CHIP) 600 MW @ 1.0 MHZ

FIGURE 19. BULK MEMORY USING MULTIPLE LARAM



N = TIME SPAN OF LFM FUNCTION
 $2N$ = SUM OF N PLUS RELATED TIME SPAN OF FREQUENCY BAND, Δf

FIGURE 20. CHIRP-Z DFT CONCEPT

The CCD is ideally suited for the computation of the discrete Fourier transform (DFT) via the chirp-Z transform (CZT) because the implementation of the CZT makes use of linear FM convolvers. The basic processing steps of the CZT are shown in Figure 21. The complex input signal (X_p) is mixed with the chirp signal $A \cdot P \cdot B P^2 / 2$ which produces an offset chirp signal output. This signal (Y_p) is convolved with $B \cdot P^2 / 2$ in the convolution filter. The convolution peak at the output of the filter occurs at a time corresponding to the frequency of the input signal. The complex multiplication after convolution corrects the phase bias by multiplication with the reference chirp signal ($B k^2 / 2$). If the phase information is not required, then the output of the convolution can give the power spectrum. Figure 22 shows the CZT process in more detail. The complex CZT requires real and imaginary baseband processing (I and Q).

The circular convolution can be performed in the CZT using a tapped CCD delay line of $2N$ stages, where N is the number of samples for which the z-transform is evaluated. Therefore, to increase the number of points that the CZT

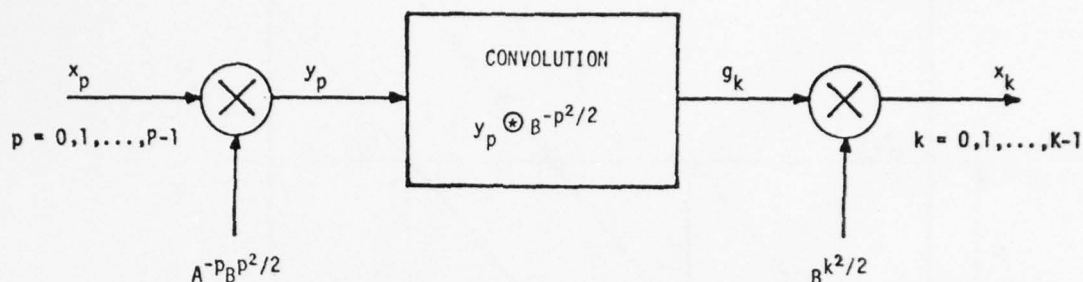


FIGURE 21. PROCESSING STEPS OF THE CHIRP Z-TRANSFORM

evaluates, the CCD delay line must be increased by a factor of 2. RCA has developed another approach to circular convolution shown in Figure 23. This patented technique performs the circular convolution using an N stage tapped CCD and an N stage CCD delay line. The full CZT implementation using the technique is shown in Figure 24.

3.3.3.2 Delay Line Time Compressor (DEL TIC) Spectrum Analyzer - A CCD can, in principle, be used to implement the standard delay line time compressor spectrum analyzer shown in Figure 25. In this system, all of the signal samples are recirculated in the delay line during each input sample interval. Thus, as in the example of Figure 25, if 60 spectral coefficients are analyzed with a 60 time sample interval, the clock rate of the system is 60 times the input sample rate. This technique will be limited with CCD's to small numbers of samples (N) because the number of CCD transfers is N^2 . For wide bandwidth applications, the clock rate becomes prohibitively high.

3.3.3.3 Stored Coefficient CCD Spectrum Analyzer - Another approach to spectrum analysis with CCD's which avoids the high clock rates of the DEL TIC is given in Figure 26. In this case, the samples to be analyzed are loaded into the tapped delay line and held. All of the spectral reference coefficients can be stored on the CCD in a manner similar to a split gate correlator and the coefficients can be read out by impulsing the line. This general method has the advantages of providing any arbitrary transform of the input and operation at clock speeds equal to the sample rate. However, the storage requirement is proportional to N^2 thus limiting the size of the transform.

3.3.4 Extended Time Bandwidth Applications

It was indicated in Section 3.2 that time bandwidths at least as high as 25,000 might be encountered for some radar requirements. In fact, the long range search radar application could include a pulse length of up to 2 msec with a 5.0 MHz bandwidth. With a sample rate of 6.0 MHz, the resulting samples required to define the waveform is 12,000. If the spectral multiplication technique were used for matched filtering, DFT's as large as 24,000

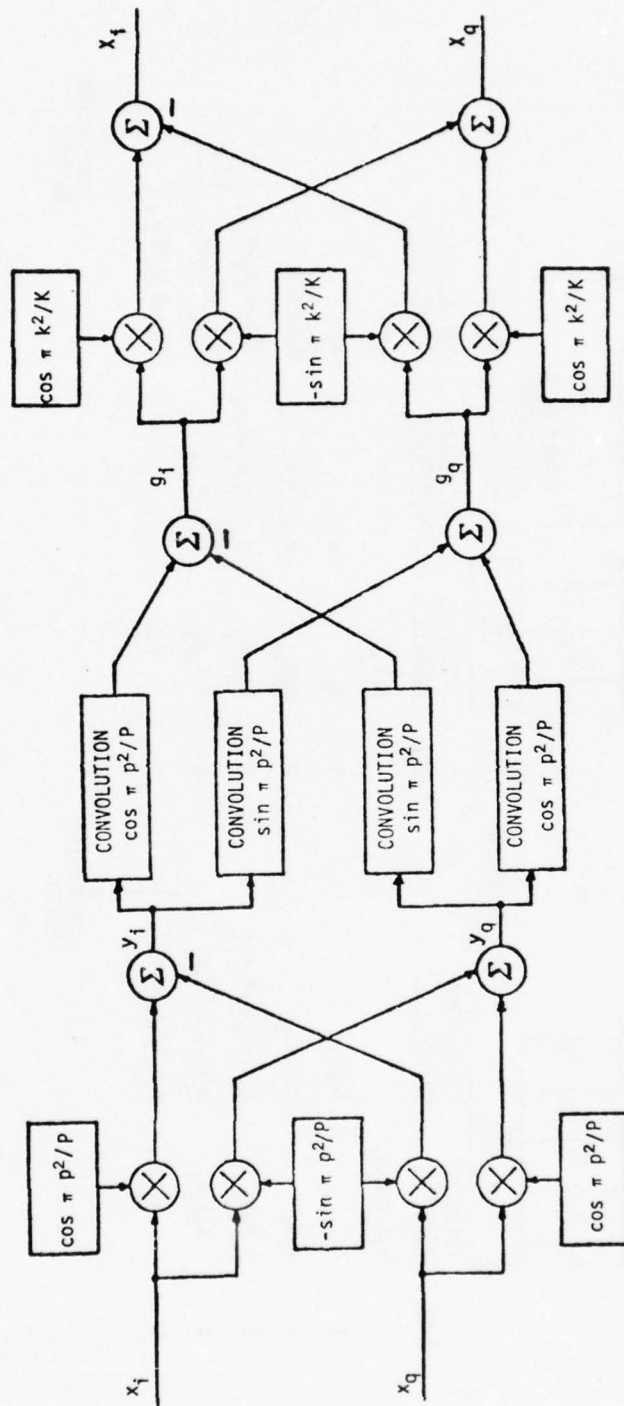
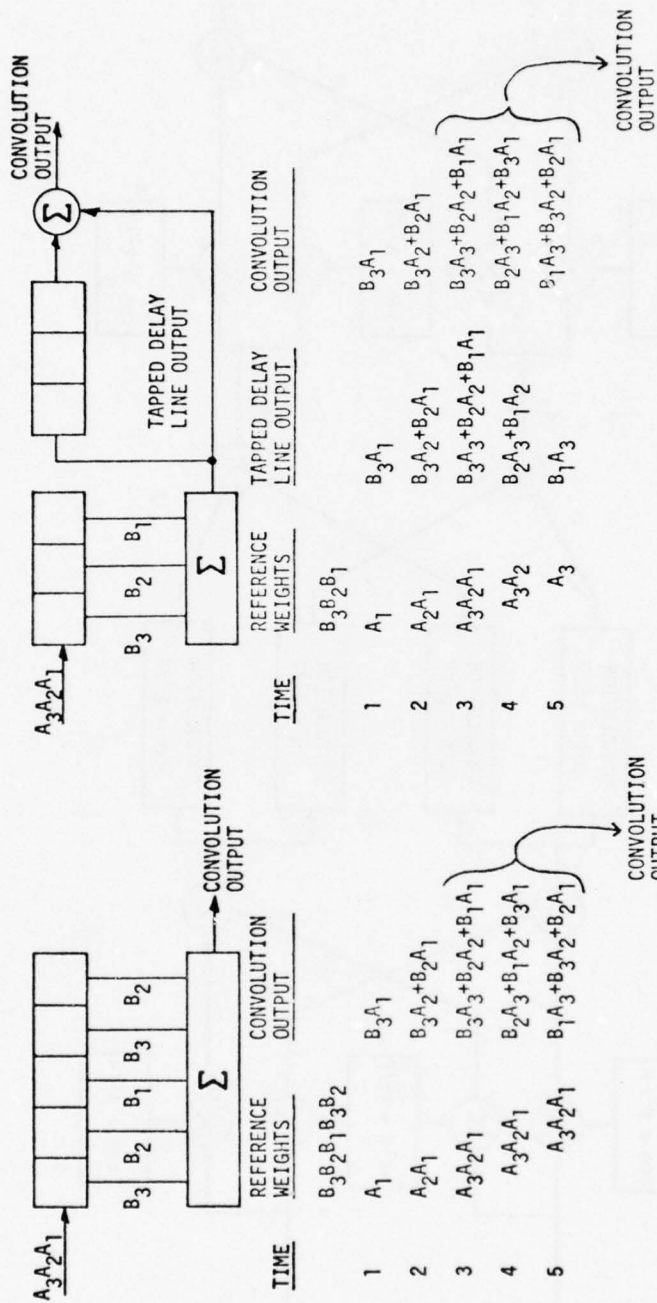
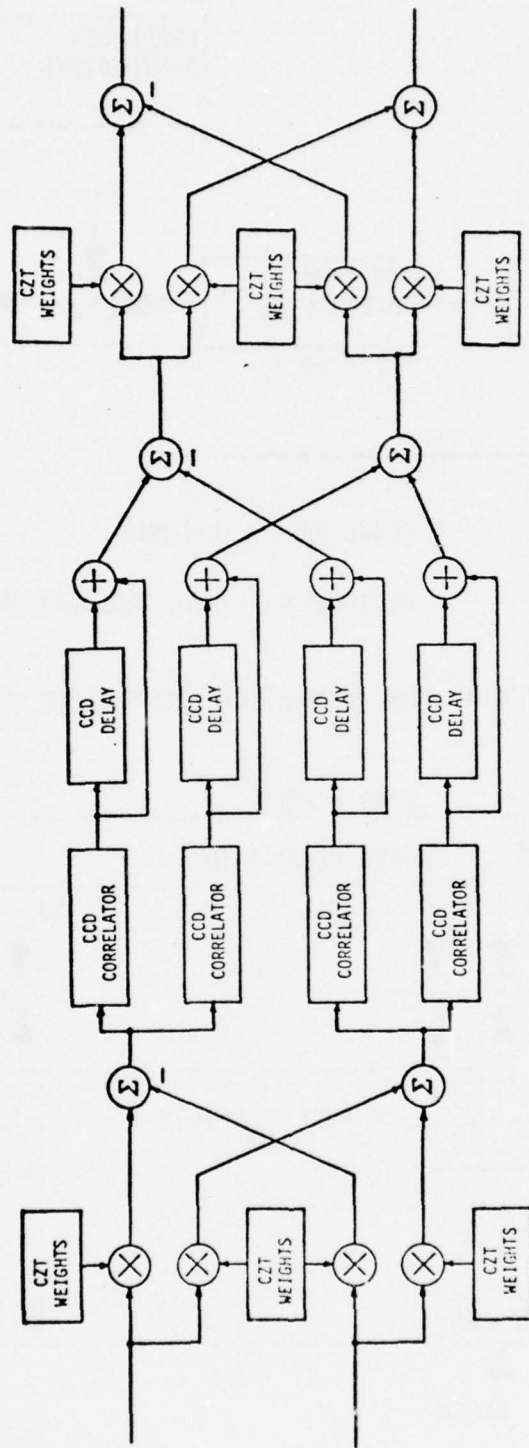


FIGURE 22. FUNCTIONAL DIAGRAM OF THE CHIRP Z-TRANSFORM

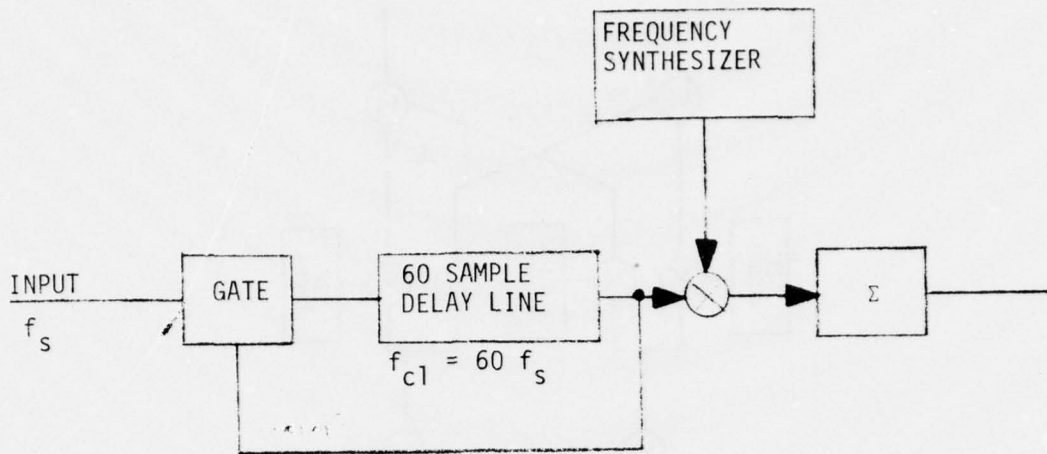


RCA PATENTED PROCESS

FIGURE 23. CIRCULAR CONVOLUTION TECHNIQUE



RCA PATENT PENDING
 FIGURE 24. CCD CHIRP Z-TRANSFORM (CZT)



$f_s \geq 60 \text{ KHz}$

° CLOCK RATE $\geq 3.6 \text{ MHz}$

° RECIRCULATED DATA DEGRADATION

FIGURE 25. DELAY LINE TIME COMPRESSOR (DELTIC) SPECTRUM ANALYZER

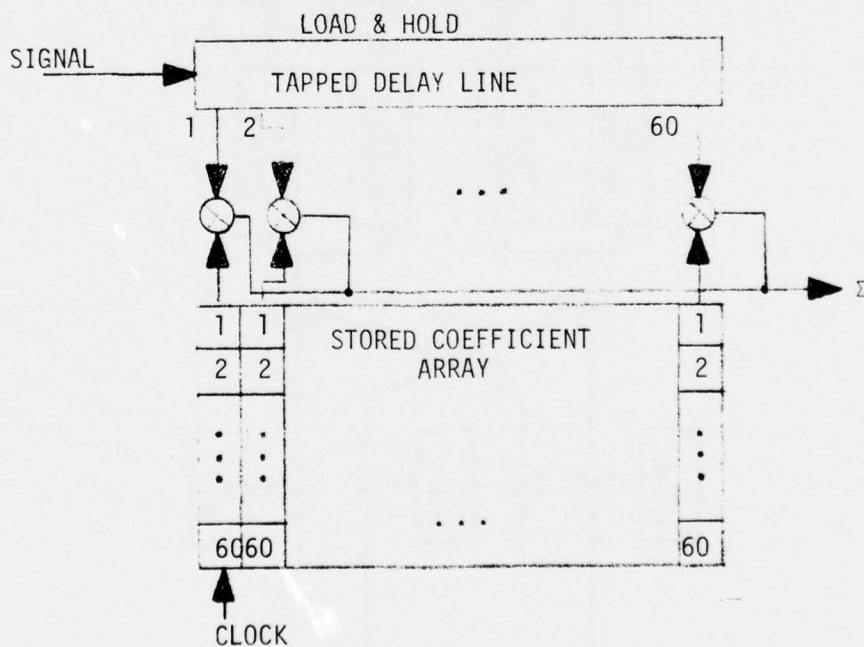


FIGURE 26. STORED COEFFICIENT CCD SPECTRUM ANALYZER

could be required. This section discussed some alternative techniques for processing these large TW products with shorter CCD filters.

3.3.4.1 Step Transform (Sub-Aperture) Technique - The step transform algorithm [4] effectively breaks up a linear FM waveform into sub-apertures which can be more adequately processed with CCD's.

A conceptual diagram of the step transform process is given in Figure 27. The upper portion of the figure indicates the principal functional elements in the processor while a representation of the function itself is given below. The received signal is a linear FM waveform of length T and bandwidth W. This is sampled, A/D converted and multiplied by a linear FM sawtooth whose time bandwidth product of a single "tooth" is approximately equal to \sqrt{TW} . The resultant from this operation is a segmented CW waveform of \sqrt{TW} segments whose overall slope is equal to the slope of the original waveform. Each individual segment is then passed into a DFT spectrum analyzer to obtain its exact spectral characteristics. The number of sample points in the deramping sawtooth is equal to the number of sample points in the input DFT aperture.

Successive DFT analysis windows are stored in the data reordering memory forming a time-frequency matrix. Spectral data from a single received linear FM pulse will have amplitude peaks across the matrix beginning at a point corresponding to the range of the target. Fine range resolution is obtained by processing successive diagonals of the data in the time frequency matrix through the second DFT. The output of the second DFT gives the compressed pulse output with a resolution determined by the bandwidth of the waveform. Weighting is applied prior to entering the second DFT to reduce range side-lobes.

The implementation of the DFT in the step transform process can be done with a CCD-CZT. Many of the CZT and step transform functions can be combined so that a functional diagram will be similar to that shown in Figure 28.

The reorder memory function in the step transform algorithm requires that data received on a column by column basis be read out along a diagonal through successive columns. This process is normally accomplished using random access memories in a digital system. However, a technique for accomplishing the diagonalization using serial shift registers has been developed, and its implementation with CCD's is shown in Figure 29. The total register length is approximately equal to the number of samples in the waveform.

3.3.4.2 Extended TW-CZT - A method can be used as indicated in Figure 30 to synthesize a large CZT with smaller CZT segments. In this case, the objective was to synthesize a 24,000 point transform. It is done by combining 24-1000 point CZT's in a sub-aperture approach somewhat akin to the step transform. An inherent problem with any large TW product signal processor is the requirement for storage of the full TW samples. This is exemplified in the sub-aperture CZT by the size of the delay lines. The maximum length in the example is 23,000 stages.

3.3.4.3 Sub-Aperture Convolution - A sub-aperture convolver can be used to reduce the size of the CCD memories in extended time-bandwidth convolvers if not the number of transfers. The concept is shown in Figure 31 where 12,000

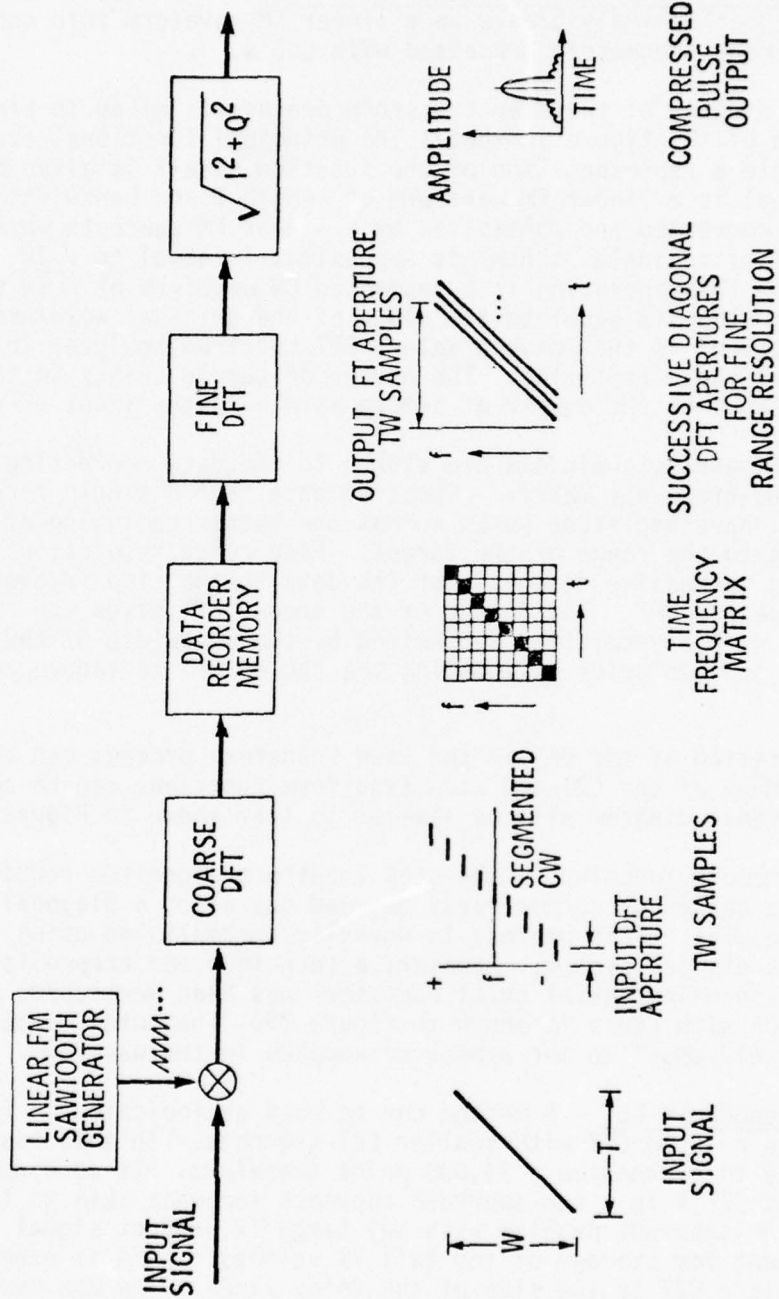


FIGURE 27. STEP TRANSFORM LFM PULSE COMPRESSION PROCESSING

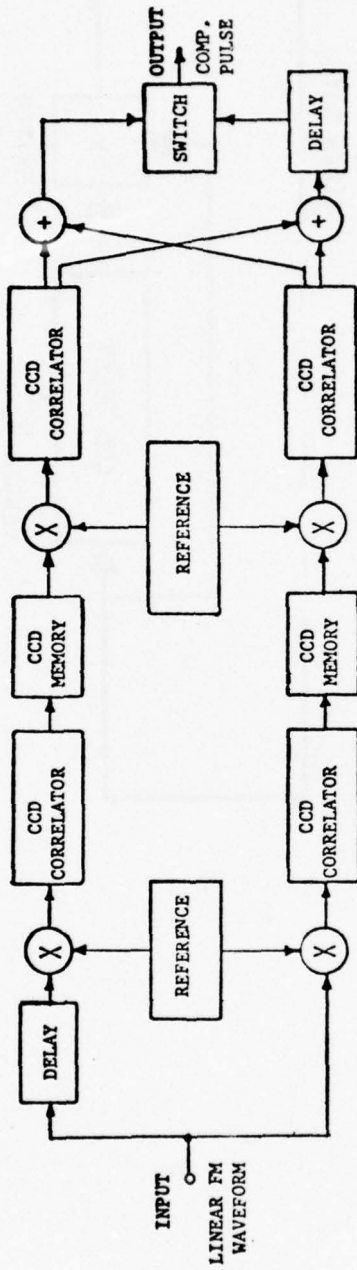
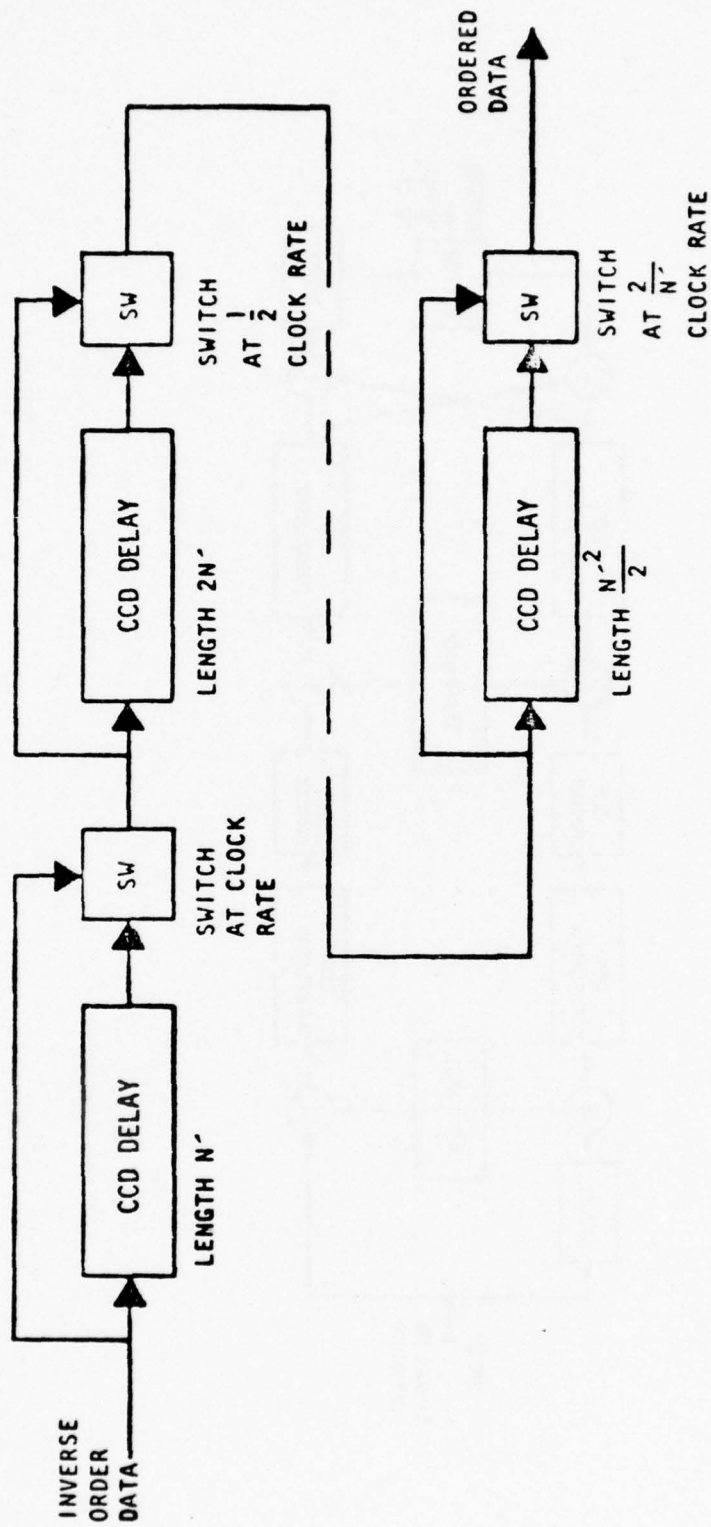


FIGURE 28. FUNCTIONAL BLOCK DIAGRAM OF CCD STEP TRANSFORM PROCESSOR



N' IS APPROXIMATELY EQUAL TO THE SQUARE-ROOT OF THE TIME-BANDWIDTH PRODUCT

FIGURE 29. CCD REORDER MEMORY

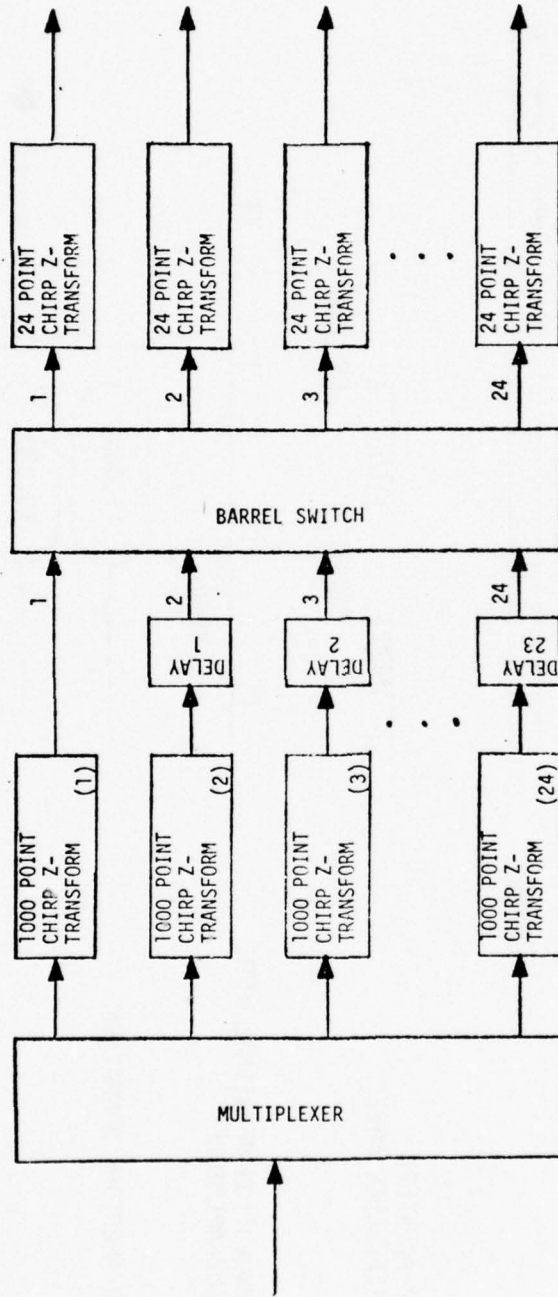


FIGURE 30. 24,000 POINT CHIRP Z-TRANSFORM

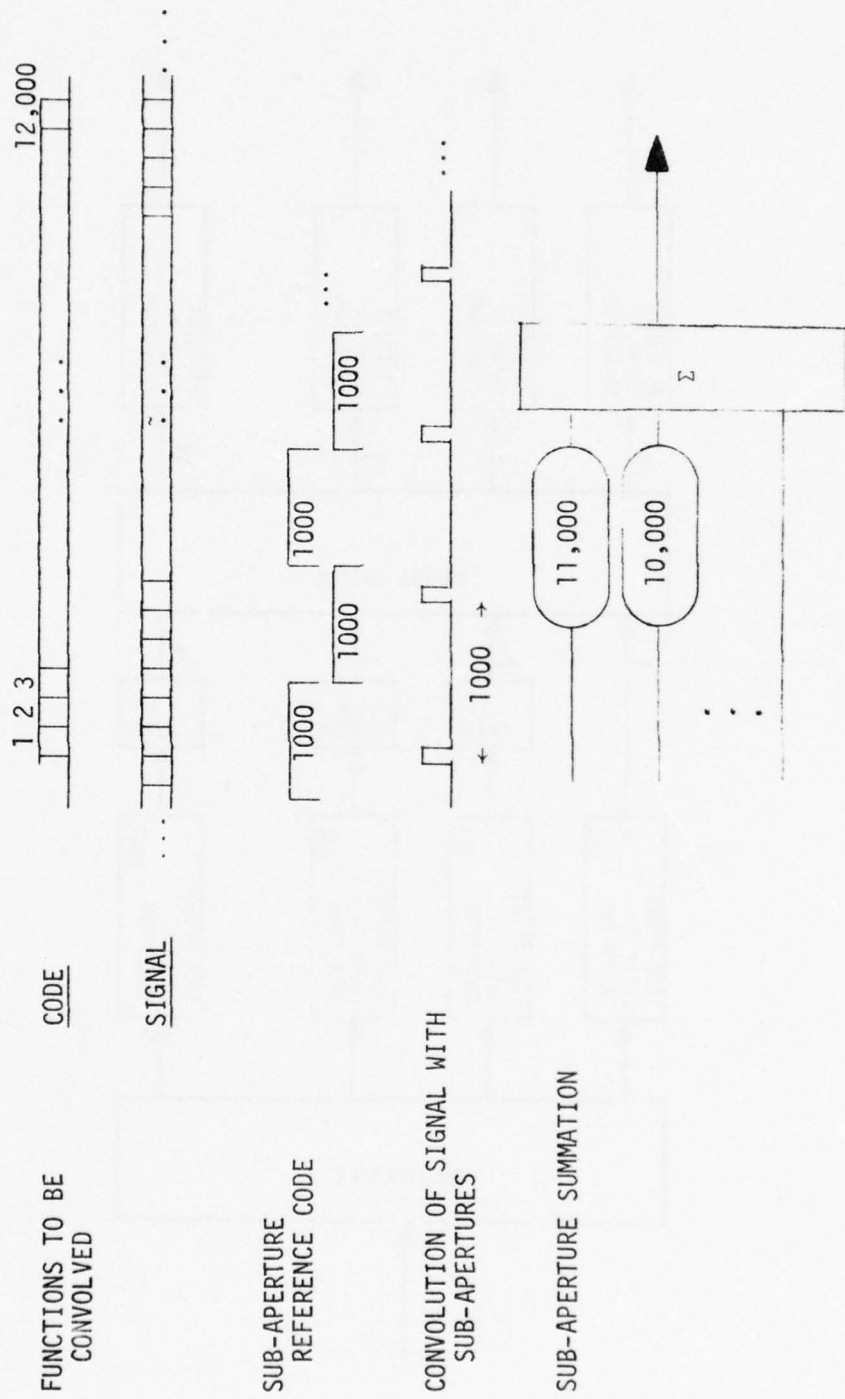


FIGURE 31. SUB-APERTURE CONVOLUTION

sample code and signal samples are to be convolved. If the number of convolution samples desired is limited to 1000 points, the reference code can be broken up into 1000 point samples each of which can be correlated with the appropriate segment of the signal. The resultant is a set of impulses separated by 1000 points which can be summed by the delay line network of Figure 31. An alternative implementation might take the form of Figure 32. In this approach, the input is alternately steered to two programmable CCD convolvers and each 1000 point output is integrated in the recirculating integrator. Here again, the performance limitation due to a large number of transfers in the CCD delay line in the integrator will be a factor.

3.4 BASELINE CCD SIGNAL PROCESSOR

A baseline radar signal processing system was developed from the requirements outlined in Section 3.1. The baseline system features a two step detection process to achieve long coherent integration times for high radial velocity targets. A low range resolution waveform is used on the first step to obtain coarse range and doppler, followed by a high range resolution waveform on the second step with programmed velocity gates for coherent integration with high range resolution.

3.4.1 Baseline System Approach

To achieve coherent integration the target must remain within the range cell during the integration time. For a radial target velocity of 10,000 ft/sec, and a range resolution of greater than 6,070 ft (1NM) the target will pass through the range cell in less than 1 second. In this situation, coherent integration of more than 1 second is not effective. A two step detection process will overcome this range walk problem.

On the first step a low range resolution waveform is transmitted such that the target will not walk through the range cell during the integration interval. A coarse range resolution (≤ 40 NM) and radial velocity resolution (250 ft/sec) will be obtained. In the event of a detection on the first step the second step process is initiated in which a high range resolution waveform (≤ 1 NM) is transmitted.

By using the coarse velocity estimate from the first step, a large part of the target radial velocity can be removed to permit the full coherent integration with the high range resolution. In essence the position of the range cells can be programmed versus time to approximately match the target radial motion and thus reduce the range walk to an acceptable value. The second step provides the desired range and doppler resolution as well as the angle estimates.

The attractiveness of the two step detection approach is that it is not wasteful of radar resources since the second step is not used until a detection is obtained on the first step. Furthermore, since the number of targets beyond 2000 NM is small and normally closely spaced, the second step process is not often repeated as would be the case of widely separated multiple targets.

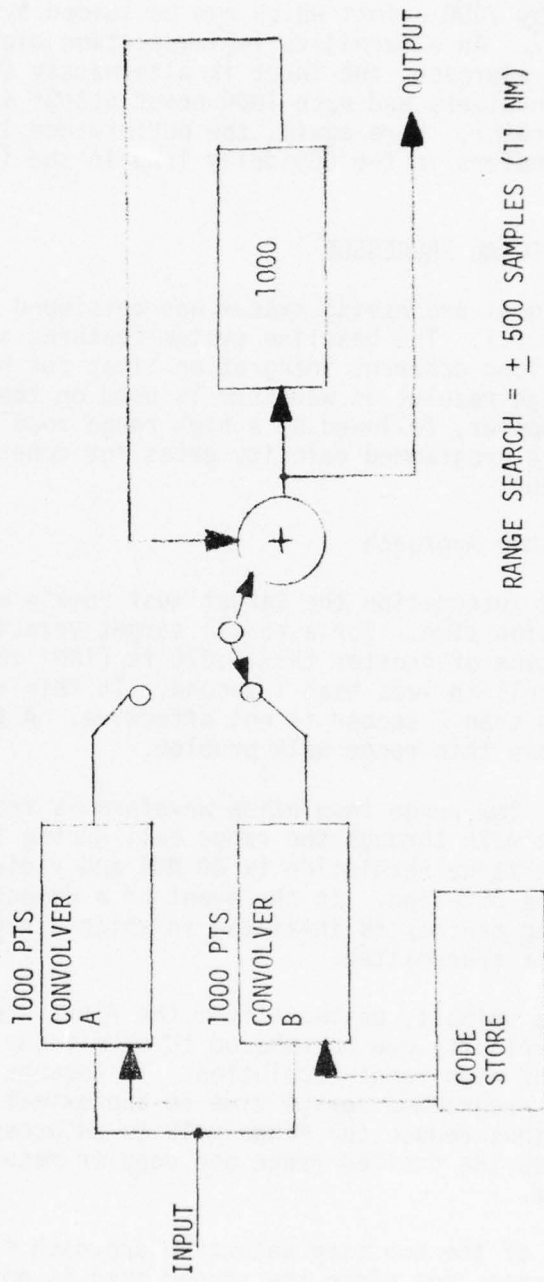


FIGURE 32. IMPLEMENTATION OF SUB-APERTURE CONVOLUTION

3.4.2 Waveforms for the Baseline System

Figure 33 provides a summary of the waveforms proposed in the two step approach. The range resolution of the first step waveform, Figure 33a, is low enough so that the target remains substantially in the range cell for the entire integration interval. In addition the waveform provides a coarse doppler estimation which is used on the second step process to program the range cell such that the target remains in the high range resolution cell over the integration interval.

The higher range resolution on the second step is achieved with a linear FM waveform, Figure 33b, having a bandwidth of 200 KHz. This bandwidth provides a resolution of 1 NM between two targets with an amplitude differential of 10 dB. Resolution in doppler is a function of the coherent integration interval which for a 6 second integration interval is 1/6 Hz. This doppler resolution permits separation of targets within the same range cell but with different velocities.

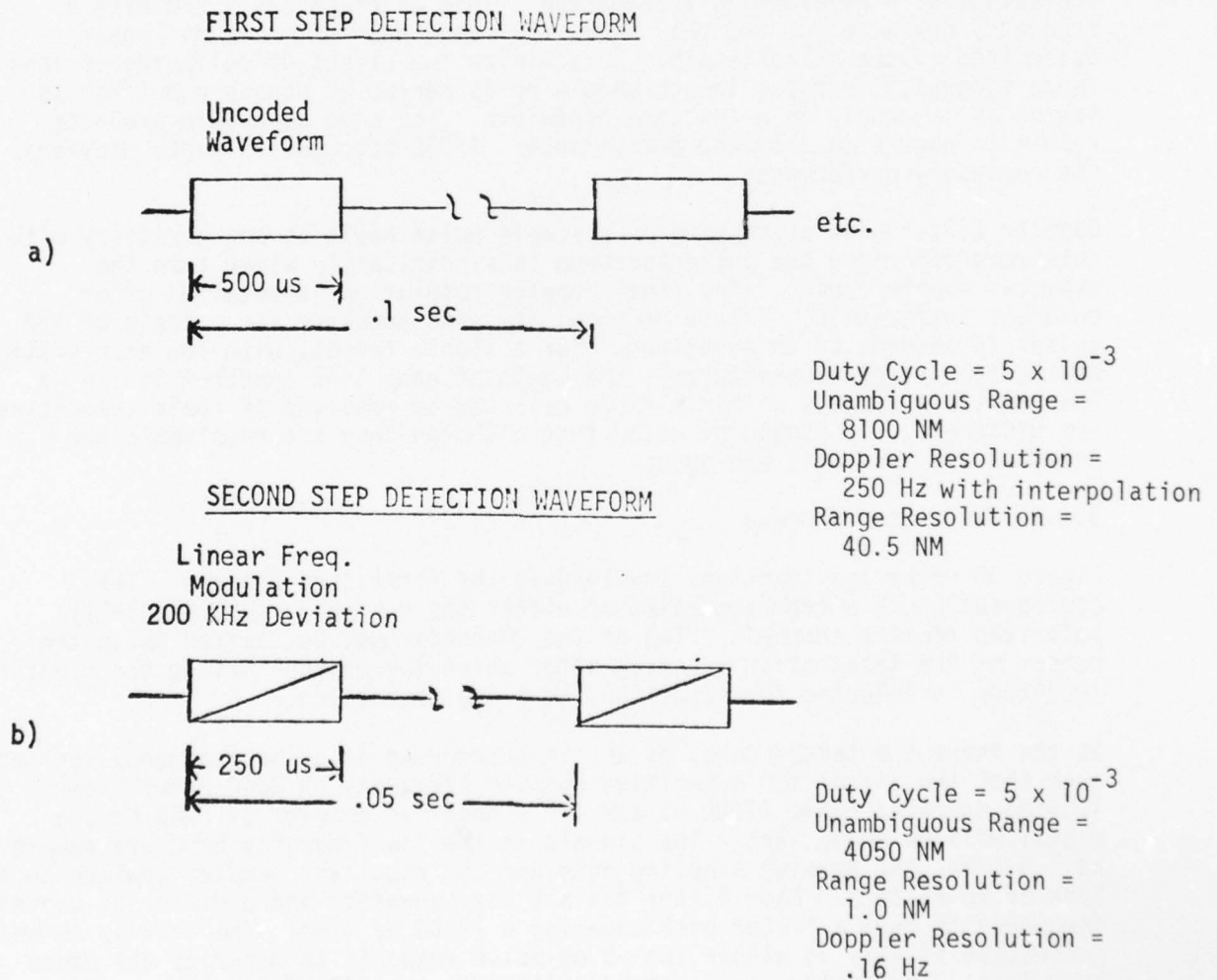


FIGURE 33. SUMMARY OF BASELINE WAVEFORMS

3.4.2.1 First Step Waveform - The first step waveform was established on the basis of using a low bandwidth waveform so that a target moving at 10,000 ft/sec would remain within a range resolution cell over a 6 second integration interval. The low bandwidth waveform is provided by using an uncoded pulse of 500 usec. The resolution of this waveform is determined by the auto correlation function shown in Figure 34a. A 10,000 ft/sec target over a 6 second integration interval will have an average loss in sensitivity due to the target motion of approximately 1.1 dB. A smaller loss can be realized by making the waveform longer. However, the range accuracy would suffer thus requiring processing of a larger range window on the second step detection process.

The spectrum of the waveform is shown in Figure 34b. At the -3.9 dB response the spectral width is 2 KHz. For target velocities of $\pm 10,000$ ft/sec the doppler frequency is ± 8840 Hz. Thus to optimally process a single pulse a doppler filter bank (or equivalent) is used having approximately 10 filters, 2 KHz bandwidth each, covering the ± 8840 Hz band.

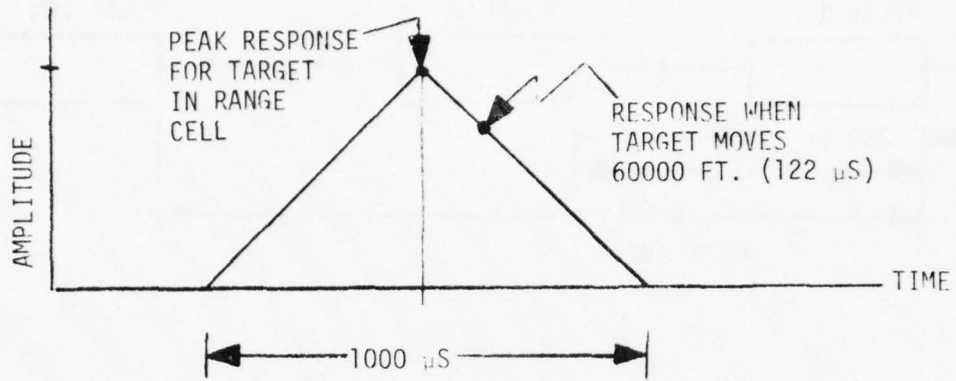
3.4.2.2 Second Step Waveform - After a detection on the first step process the second step waveform is transmitted. This waveform has a LFM with a frequency deviation of 200 KHz, hence the range resolution is no longer determined by the pulse length. To minimize the effect of eclipsing of long range targets, the pulse length should be as narrow as possible but not so narrow as to result in a low time bandwidth. Low time bandwidth products result in poor time sidelobe performance. A 250 usec pulse length provides the necessary performance.

Doppler filter bank processing on a single pulse basis is not necessary with this waveform since the pulse spectrum is significantly wider than the expected doppler shift. The final doppler resolution is obtained after coherent integration. Figure 35 shows the line spectrum for a train of 120 pulses (6 seconds of integration). For a stable target, with low acceleration during the integration interval, the width of each line spectrum is 1/6 Hz. Thus multiple targets within a range cell can be resolved if their velocities are different. It should be noted that although they are resolvable the dopplers are generally ambiguous.

3.4.3 First Step Process

Figure 36 shows the functions involved in the first step process. The configuration is a representation of either the vertical or horizontally polarized receive channels. Two of the channels must be carried up to the output of the integration function after which the channel having the greatest amplitude is selected for detection and range estimation.

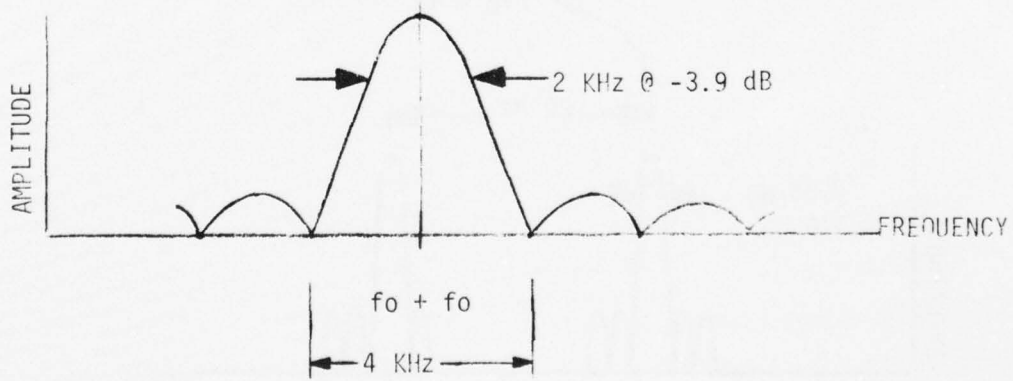
At the input the target echo, at IF, is heterodyned to a low frequency carrier such that the signal for a positive doppler frequency of 8840 Hz will be located somewhat above 17680 Hz and for a negative doppler of 8840 Hz the signal will be below zero. The signals in the low frequency band are sampled at 1.5 times the Nyquist sampling rate and the resultant samples applied to a bank of 10 filters. Each filter has a 2 KHz bandwidth and a different center frequency to form a filter bank covering a 17680 Hz band. The overlap between successive filters is within the -3 dB pulse response to minimize the cross-over loss. Each filter is a matched filter to the 500 usec pulse.



AVERAGE LOSS DUE TO VELOCITY MISMATCH IS

$$L = \frac{1}{2} \left[1 + \left(\frac{378}{500} \right) \right] = .878 \rightarrow 1.1 \text{ dB}$$

A) AUTOCORRELATION FUNCTION



B) PULSE SPECTRUM

FIGURE 34. FIRST STEP WAVEFORM CHARACTERISTICS

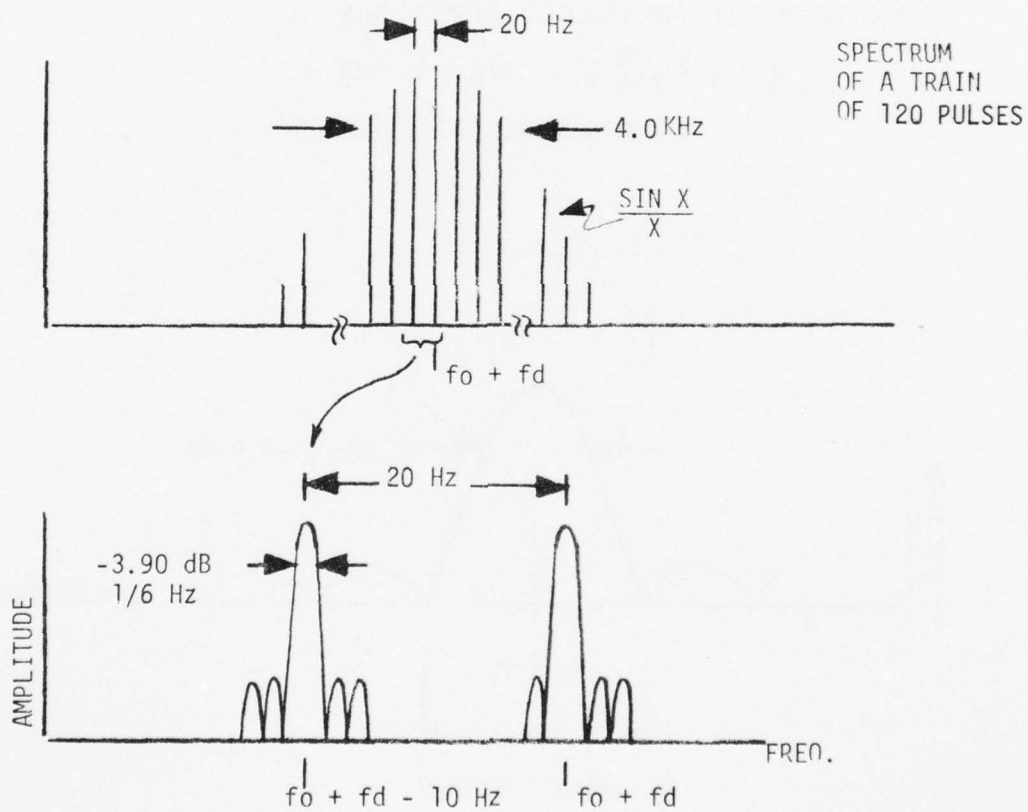
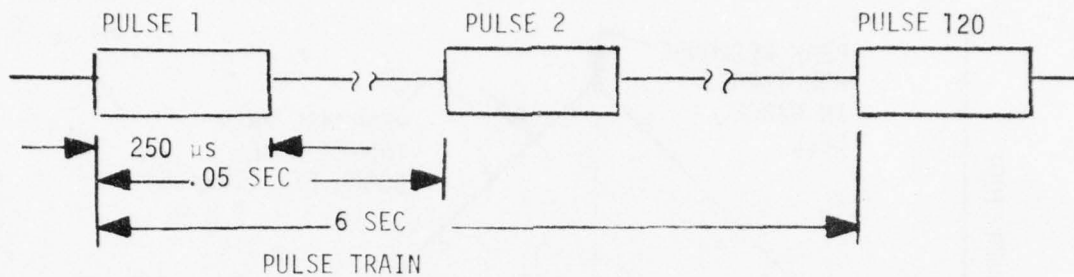


FIGURE 35. SPECTRUM OF A PULSE TRAIN

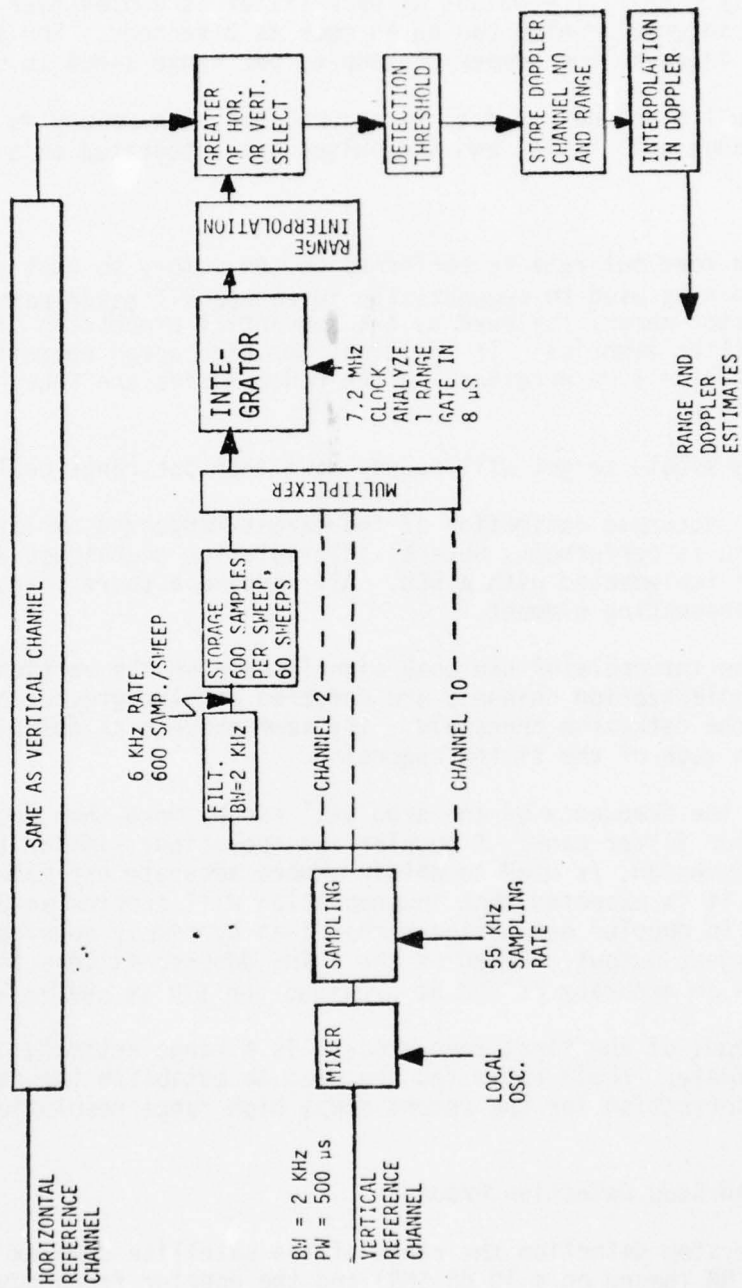


FIGURE 36. FIRST STEP DETECTION PROCESS

The entire group of samples at the filter outputs representing the range sweep is placed in storage. Although the input sample rate with each filter is 55 KHz the sample rate at the output of each filter can be reduced to approximately 6 KHz. The output of each filter is stored over the coherent integration interval, which can be as much as 6 seconds. For a .05 sec range sweep interval the number of samples per range sweep is 600.

After the full 6 seconds of data is accumulated, the memory is rapidly read out, on a range cell basis, and the pulses are integrated on a range cell basis.

A high speed read out rate is performed on the memory so that a single integrator can be used to sequentially integrate all range samples from one filter memory followed by the sequential processing of the data from the other filter memories. In addition, the high speed operation minimizes the total storage time necessary in the CCD memories and thus reduces dark current build-up.

In general a single target will occupy more than one range cell.

To obtain an accurate estimation of the target range and amplitude an interpolation is performed. Several interpolation techniques are possible which can be implemented with a CCD. All involve a short transversal filter as the key processing element.

Following the interpolator the peak signals between the vertical and horizontal polarization channels are compared and the greater of the two applied to the detection threshold. The same process as described above is performed on each of the filter channels.

In general, the frequency of the echo will occupy more than one of the filters in the doppler filter bank. A doppler interpolation, similar to that used in the range dimension, is used to obtain a more accurate estimate of the doppler frequency. It is expected that interpolation will provide an 8 to 1 improvement in doppler estimation rather than by simply considering the filter with the largest output. Based on the 2 KHz doppler filters the interpolation will provide an accuracy of 250 Hz provided the S/N is sufficiently high.

Thus the output of the first step process is a range estimate and a coarse doppler estimate. These estimates are used to establish the range window and range walk correction for the second step, high range resolution, detection process.

3.4.4 Second Step Detection Process

On the first step detection the range of the satellite complex is determined to within 6 NM (based on a 10 dB SNR) and the doppler frequency determined to within 250 Hz (\approx 283 ft/sec). In order to resolve closely spaced targets the second step detection process uses a linear FM waveform with a 200 KHz bandwidth. Based on the range estimates made on the first step process a reduced range window (\approx 10 NM) is processed on the second step. Since the same detection sensitivity is required on the second step as was used on the first

step, the integration time on the second step is the same as on the first step. To minimize the effects of the range walk due to the higher range resolution the coarse doppler estimate obtained from the first step is used to program the movement of the range samples. In effect the range samples, over the 10 NM range window, are moved in range to match the target velocity such that the target remains within the range cell over the 6 seconds of integration time. If the uncertainty in target velocity is 250 ft/sec then in 6 seconds the differential motion between the moving range gate and the target will be 1500 feet. For a linear frequency modulated transmission, with Hamming weighting on reception, the average signal-to-noise loss due to the velocity mismatch is less than 1 dB.

The loss can be reduced by obtaining a finer estimate of doppler on the first step; this, however, is accomplished at the expense of using a lower bandwidth transmission on the first step and thereby requiring processing of a larger range window on the second step.

Figure 37 shows the functional flow diagram of the second step process. Identical channels are carried for the vertical and horizontal polarization channels. The target echo at IF is connected to its in-phase (I) and quadrature (Q) components. Each baseband channel I and Q has a bandwidth of approximately 100 KHz. The channels are sampled and applied to a pulse compression process.

Over a 6 second interval 120 range sweeps will be obtained from the pulse compression process. The 120 samples for each range cell are read out of memory and integrated in the spectrum analyzer. A range interpolation and selection of the greater of the horizontal and vertical channels is performed and the output applied to the detection threshold circuit.

The 1/6 Hz resolution of the spectrum analyzer is used for doppler resolution and the interpolated range is used as the range estimates. These estimates are used to initiate the tracking mode.

3.4.5 Baseline Processor Requirements and Implementation

Table 22 summarizes the processing requirements for the baseline system. The principal subsystem CCD implementation which is identified is: the input doppler filtering and I,Q demodulation in the first step processor, the corner turning or bulk filter requirements in first and second step, pulse compression and the coherent integrator or spectrum analyzer. These functions can be considered for both the narrow band and wideband cases and for handling the $\pm 10,000$ ft/sec or $\pm 35,000$ ft/sec doppler cases.

3.4.5.1 Input Doppler Filtering - The input signal handling in the first step process illustrates the option of processing signals at a low IF frequency or at baseband. Figure 38 is an implementation of the input doppler filtering with a low IF frequency sampled directly. Each doppler filter in this case consists of a pair of I and Q CCD correlators and a total of 10 filters are required. Figure 38 is an implementation requiring 20 distinct CCD filter designs. The number can be reduced to two by employing a system whereby separate mixers and reference frequency sources are used for each filter and all of the ten doppler filters are identical.

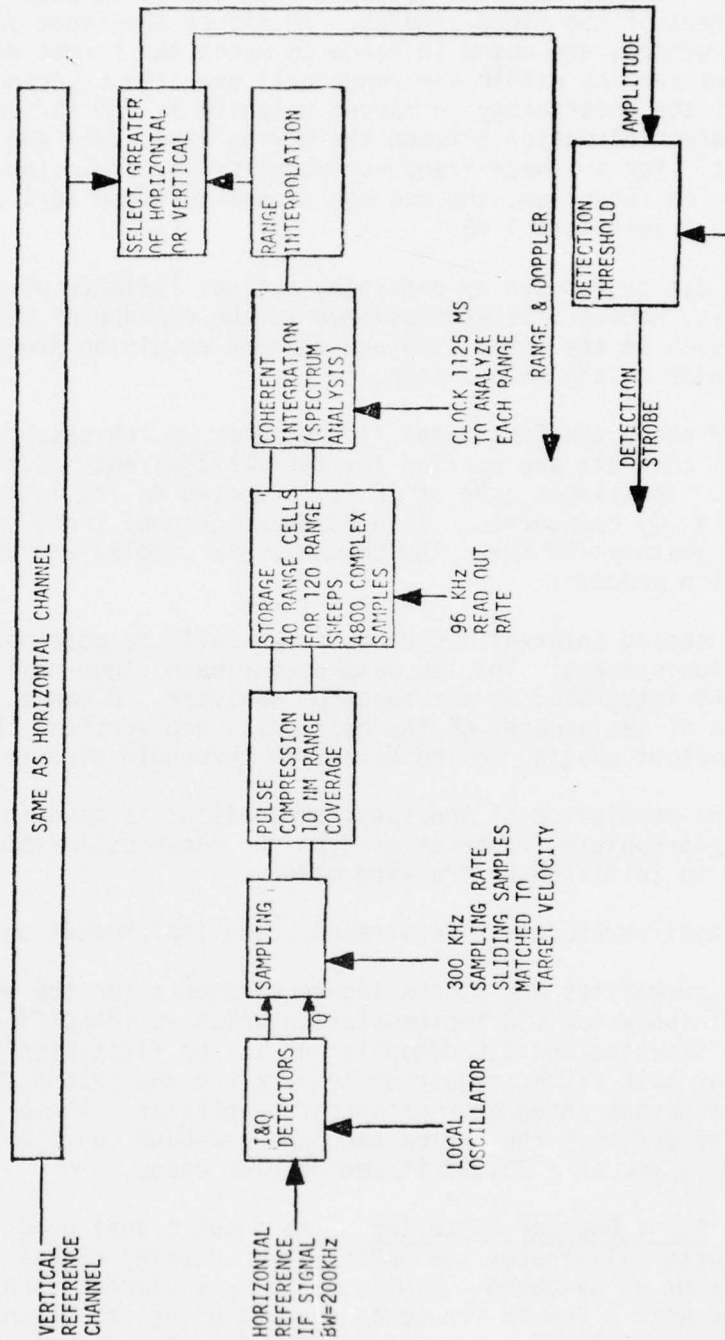


FIGURE 37. SECOND STEP DETECTION PROCESS

TABLE 22. BASELINE SUBSYSTEM REQUIREMENTS

ITEM	1ST STEP	2ND STEP
PULSE COMPRESSION	NONE	TW = 50 (LFM) W = 200 KHZ
PULSES COHERENTLY INTEGRATED	60	120
INPUT SAMPLING RATE	55 KHz (IF)	300 KHz (I,Q)
DOPPLER CHANNELS	10 (INPUT)	1 (INPUT)
DOPPLER FILTER WIDTH	2 KHZ	200 KHZ
RANGE CELLS	600	40
SAMPLE RATE TO COHERENT INTEGRATOR (SPECTRUM ANALYZER)	7.2 MHz	96 KHZ
INTERPOLATION	RANGE DOPPLER	RANGE

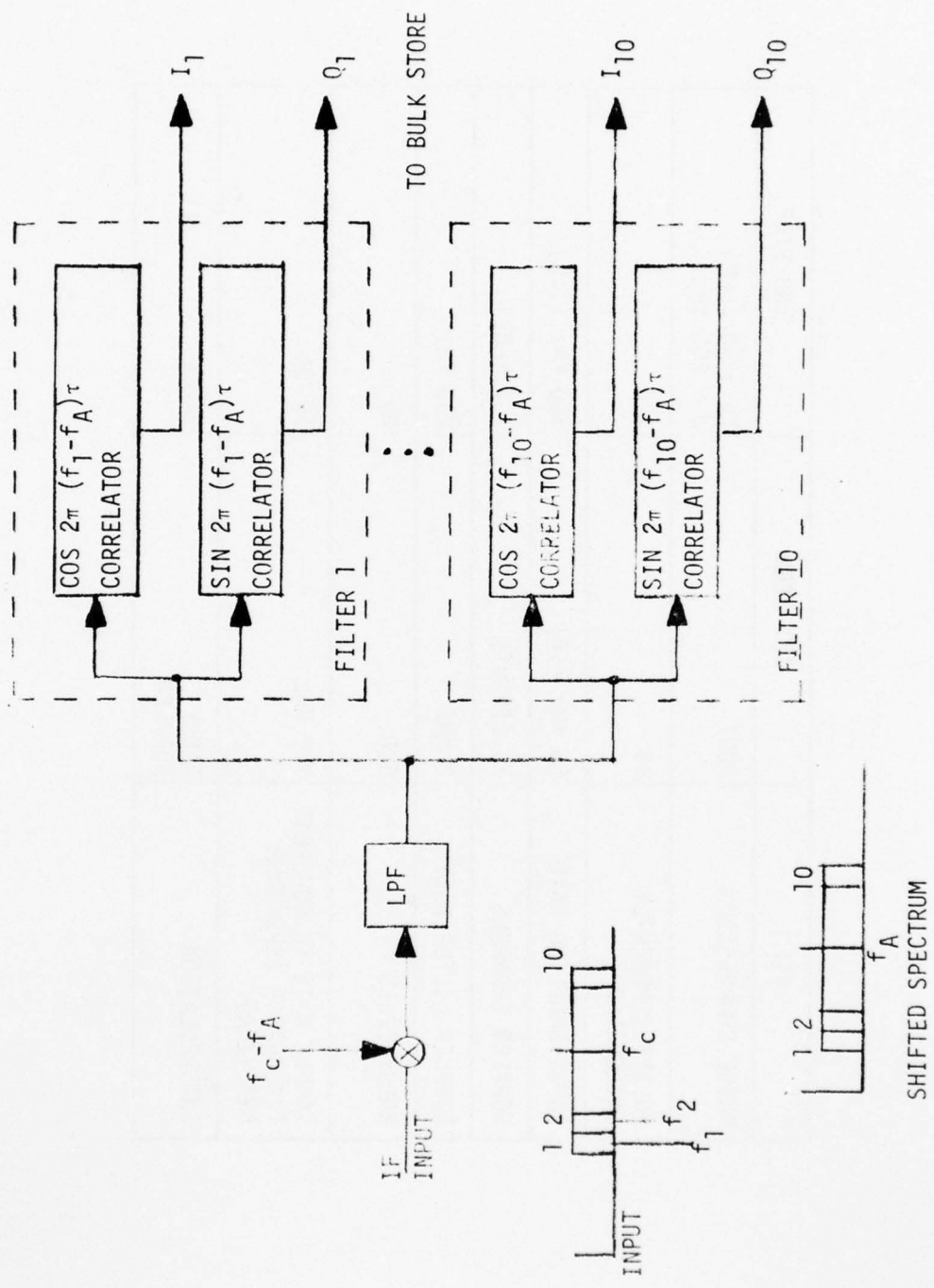


FIGURE 38. LOW FREQUENCY IF INPUT FILTERING

An I/Q baseband equivalent of the input processing is shown in Figure 39. In this case, four CCD lines are required for each doppler filter unit. However, if the ten filters are identical in shape and are symmetrically situated around the sample rate, a second filter can be realized with each unit by changing the signs of the Q summation.

Table 23 summarizes the choices for the first step input and doppler filtering. The second one was selected as the baseline approach since it offered the fewest distinct CCD designs.

3.4.5.2 Corner Turning - Bulk Memory - The requirements imposed on the bulk-corner turning memory by the various system options are listed in Table 24. Although the maximum storage time listed is 6 seconds, as noted in Section 3.2, system requirements for very long range detection could impose times of 12 seconds or more. The length of storage time is the most critical requirement from the point of view of the basic CCD physics and as shown in Section 6.0, it can only be achieved if the devices are cooled. Either input or output multiplexing as described in Section 3.3 is a satisfactory approach for the corner turning memory.

3.4.5.3 Pulse Compression - The low bandwidth pulse compression requirement with a time-bandwidth product of 200 can be met with a straightforward implementation of a transversal matched filter with four elements as discussed in Section 3.3. However, for the long TW products three alternates are possible; the step transform, a sub-aperture CZT approach giving a large DFT-DFT⁻¹ matched filter and a sub-aperture convolver with minimum range. The CCD hardware impact of these alternatives are tabulated in Table 25. The step transform approach is most attractive in this case because it minimizes the size and number of the CCD's relative to the sub-aperture CZT and avoids the requirement for programmability as in the case of the sub-aperture convolver. Full range search is an additional advantage.

3.4.5.4 Coherent Integration - The coherent integration alternatives are listed in Table 26. A chirp-Z transform implementation is optimum at this point because of the well developed split-gate tap weight technique. As the methods of parallel data transfer and switching control on CCD's are improved, further performance advances in CZT's and stored coefficient analyzers will ensue.

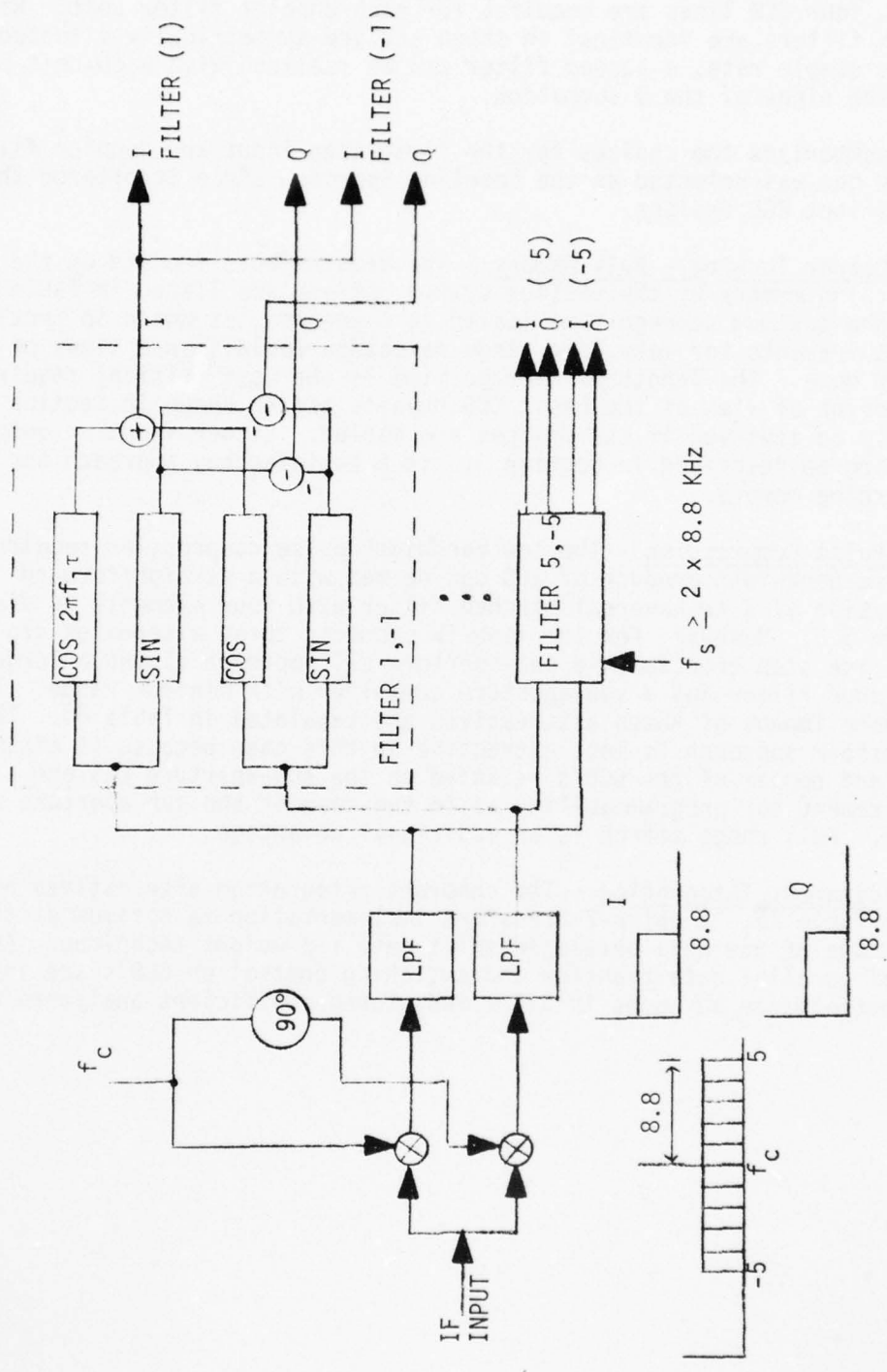


FIGURE 39. I/Q BASEBAND SAMPLING WITH I/Q FILTERS

TABLE 23. FIRST STEP *INPUT AND DOPPLER FILTERING

TYPE	INPUT PROCESS			DOPPLER FILTERS				REMARKS
	MAX. VELOCITY FT/SEC	SAMPLE RATE (KHz)	FREQ. SOURCES	TOTAL CCD UNITS	CCD FILTER DESIGNS	NO. OF TAPS		
LOW FREQ. IF INPUT	10,000	5.5	1	40	20	28	<ul style="list-style-type: none"> ◦ SIMPLEST INPUT PROCESSING ◦ MOST FILTER DESIGNS 	
	35,000	19.3	1	140	20	97		
FIXED DOPPLER LOW FREQ. IF INPUT	10,000	5.5	10	40	2	28	<ul style="list-style-type: none"> ◦ MINIMUM FILTER DESIGNS ◦ REQUIRES FREQUENCY SYNTHESIZER 	
	35,000	19.3	10	140	2	97		
I/Q DEMODULATION	10,000	26.5	1	40	10	14	<ul style="list-style-type: none"> ◦ LOWEST SAMPLE RATE ◦ SMALLEST CCD FILTERS 	
	35,000	92.8	1	140	10	40		

TABLE 24. BULK MEMORY REQUIREMENTS

CASE	NUMBER OF UNITS	ORGANIZATION (FUNCTION)	SAMPLES PER UNIT	TOTAL SAMPLES	MAXIMUM STORAGE TIME	MAXIMUM SAMPLE RATES (KHz)	
						INPUT	OUTPUT
FIRST STEP	40	CORNER TURNING (60x600)	36,000	1.44×10^6	~6 SEC	5.5	7200
	140	CORNER TURNING (60x600)	36,000	5.04×10^6	~6 SEC	19.3	7200
SECOND STEP	4	CORNER TURNING 40x120	4,800	19,200	~6 SEC	300	100
	4	CORNER TURNING 1000x120	120,000	480,000	~6 SEC	7500	2500

TABLE 25. CCD PARAMETERS FOR TW = 10,000 PULSE COMPRESSION ALTERNATIVES

TECHNIQUE	CCD FILTERS		CCD DELAYS		CLOCK RATE	RANGE COVERAGE
	LENGTH	NUMBER	SAMPLES	NUMBER		
STEP TRANSFORM	200	16	2-6000	60	7.4 MHz	FULL RANGE SEARCH
SUB-APERTURE CZT TRANSFORM	1000	192	1000- 23,000	46	12 MHz	FULL RANGE SEARCH
	24	192				
SUB-APERTURE CONVOLUTION	1000 (PROGRAM- MABLE)	20	1000- 4000	8	6 MHz	44 NM

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DEC 77 L W MARTINSON, B P GAFFNEY, G J MAYER F30602-76-C-0280
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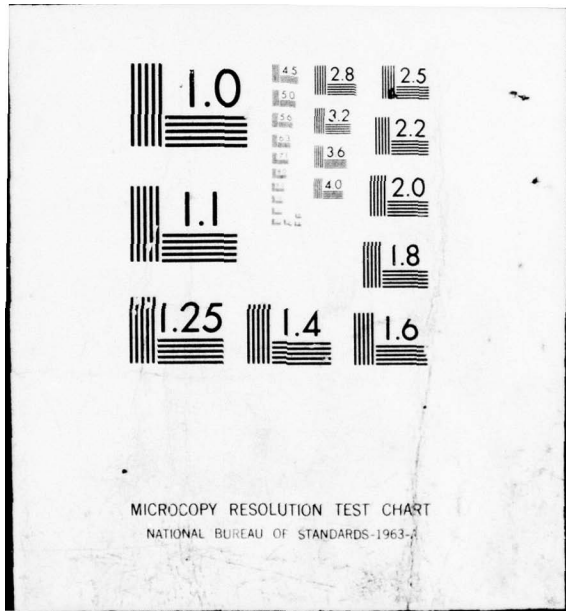


TABLE 26. COHERENT INTEGRATION ALTERNATIVES

REQUIREMENTS:

INPUT SAMPLE RATE: UP TO 7.2 MHz
 APERTURE SIZE: 23, 60, 120 SAMPLES

ALTERNATIVE	CCD LINE LENGTH FOR 120 SAMPLES	CCD CLOCK RATE	SPECIAL CCD REQUIREMENTS
CHIRP-Z FILTER	120 FILTER, 120 DELAY	3 TIMES REAL TIME INPUT RATE	
STORED COEFFICIENT	120	REAL TIME INPUT RATE	<ul style="list-style-type: none"> ◦ SERIAL-PARALLEL BUFFER ◦ N x N COEFFICIENT STORAGE MULT. ◦ ANALOG MULTIPLIER ON CHIP
DELTA TIC	120	120 TIMES REAL TIME INPUT	LOW TRANSFER LOSS DUE TO RE-CIRCULATION (DELAY ONLY)

4.0. CCD CHARACTERISTICS

4.1 CCD OPERATING PRINCIPLES*

4.1.1 Background

In 1970, W. S. Boyle and G. E. Smith of Bell Laboratories, reported the concept of semiconductor charge coupled devices (CCD's).[5] Since that time, progress in CCD development has been rapid. The technology has advanced from laboratory demonstration of eight-stage CCD delay lines, which lost 1-2 percent of the stored charge with every transfer [6], to 500-800 stage CCD delay line/transversal filters, which lose .01-.02 percent with every transfer.[7 ,8] As CCD performance has increased, so also have device design variations.

The characteristics by which CCD's are characterized include:

- Surface or Buried Channel.
- The Number of Clock Phases (Three, Two, and One-Phase).
- Various Input/Output Techniques.
- Clock Swing Voltages.
- Gate Areas.

All of the above characteristics directly affect device performance. In addition, any CCD can be operated with different parameters that alter device performance. An example is the percent of input background charge which directly affects the charge transfer efficiency. The large variation in CCD operating conditions have made many performance reports in the literature difficult to correlate, usually due to the lack of complete experimental descriptions. It is apparent, however, that certain CCD designs and operating conditions are becoming typical of good operation.

In order to realistically describe CCD performance, the theoretical considerations will be presented along with typical operating conditions. The CCD as a delay line and as a tapped delay line has been modeled and a computer simulation described in Section 5.0 has been developed. A substantial amount of literature has been generated describing CCD operation and performance, with much of it containing sophisticated analyses. These analyses lead to CCD performance predictions with first, second, and higher order effects. The scope of the computer simulation of this program incorporates first and second order effects of the predominate CCD variables. Higher order effects were not included since their impact on CCD performance was minimal.

Many references were consulted in the development and verification of the CCD model. Internal RCA laboratory measurements were also used as a validation of the model and the computer simulation. Limitations of the model and simulation will be noted where they apply.

4.1.2 Basic CCD Operation

An analog signal connected to the CCD input is sampled and a charge packet is generated by the input structure. The magnitude of this charge packet is

* A glossary of CCD terms is provided at the end of this section.

proportional to the analog signal sample. The charge packet is attracted to the region with the minimum potential energy. This region, called potential well, occurs under an MOS gate when a voltage is applied to the gate. A linear array of closely spaced MOS gates with properly controlled adjacent gate voltages allows the charge packet to be transferred down the gate array. When the charge packet has been transferred through the entire gate array, its magnitude is sensed by the output structure.

Referring to Figure 40, when two adjacent transfer gates have the same voltage applied, the charge packet will be equally distributed under the two (Time 1). When the voltage is removed from one gate, the charge packet will be distributed under the second transfer gate (Time 2). The process is repeated (Time 3 and 4) until the charge packet resides under the desired transfer gate. In this example, three gates are used to provide direction to the transfer. This shows that a three or higher-phase clock system can be used to control charge transfer. A two-phase clock system can be used if direction is built into the clock structure. This is shown in Figure 41 with the aid of a potential profile line.

The first and second gates are connected to the same phase clock with the first gate voltage reduced by ΔV . Gates three and four are connected in a like manner. The ΔV bias gives direction to the charge transfer. One stage of a three-phase clock CCD consists of three gates which involves three transfers. One stage of a two-phase clock CCD consists of four gates with two transfers. Charge is not stored under the first or third gates, but under the second and fourth. The clock frequency and the number of stages determines the time delay of the CCD.

There are many CCD input and output techniques that have been published.[9 , 10] A given input structure can be operated in different ways to inject charge into the CCD, but each method operates by generating charge and forming charge packets. Some input structures are more linear than others, while some allow larger charge packets to be formed, or are less noisy. CCD output techniques operate by detecting the change of charge present in the output structure. As in the input, linearity, signal amplitude and noise are factors that must be considered.[9]

4.1.3 Physical Description

CCD's are solid-state devices usually constructed on silicon substrates. They can be fabricated using standard MOS processing. A cross-section of a surface-channel CCD is shown in Figure 42. The charge transferred down the CCD physically resides at the $S_i-S_iO_2$ interface. A buried-channel CCD is shown in Figure 43.

A buried-channel CCD uses an epitaxial or ion-implanted silicon layer (N-layer) of polarity opposite to that of the substrate (P-substrate). This layer shifts the transferred charge away from the $S_i-S_iO_2$ interface into the bulk of the N-layer material.

The charge packets are contained under specific transfer gates by the appropriate gate voltages. The charge packets are prevented from being

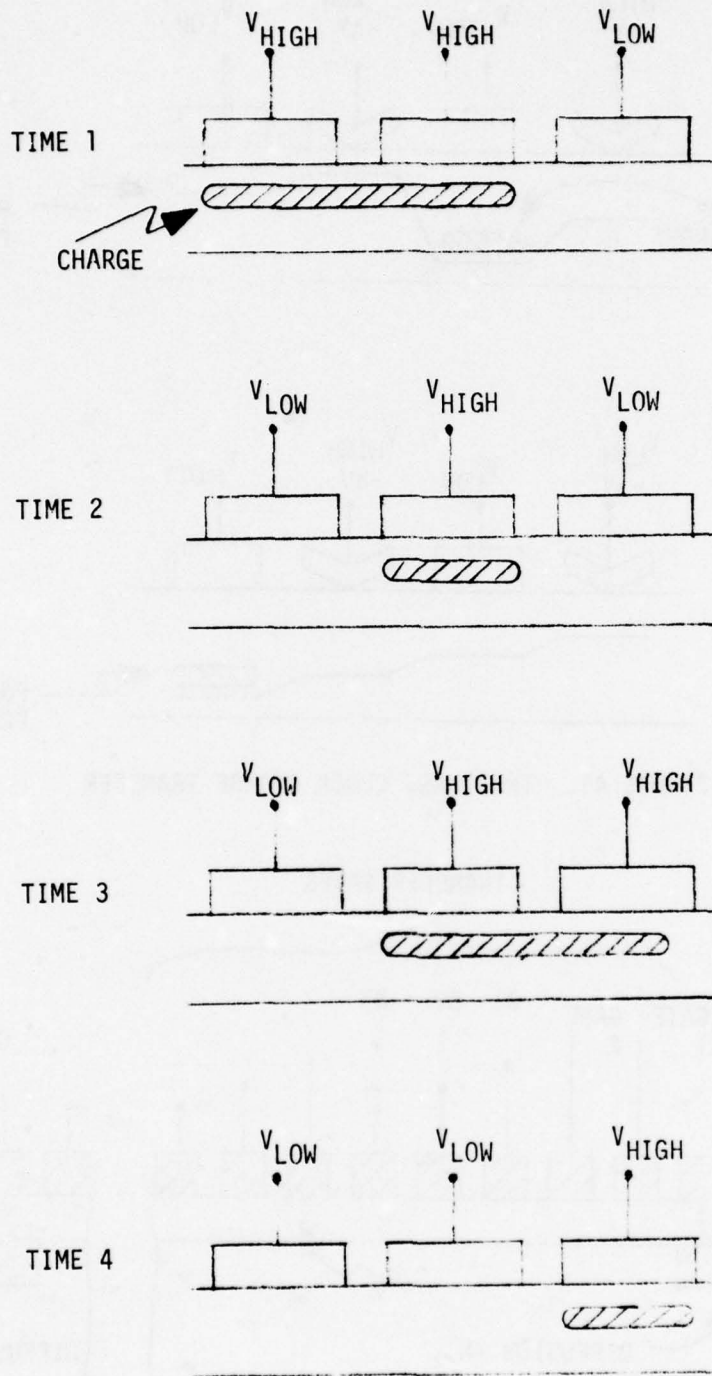


FIGURE 40. CHARGE TRANSFER

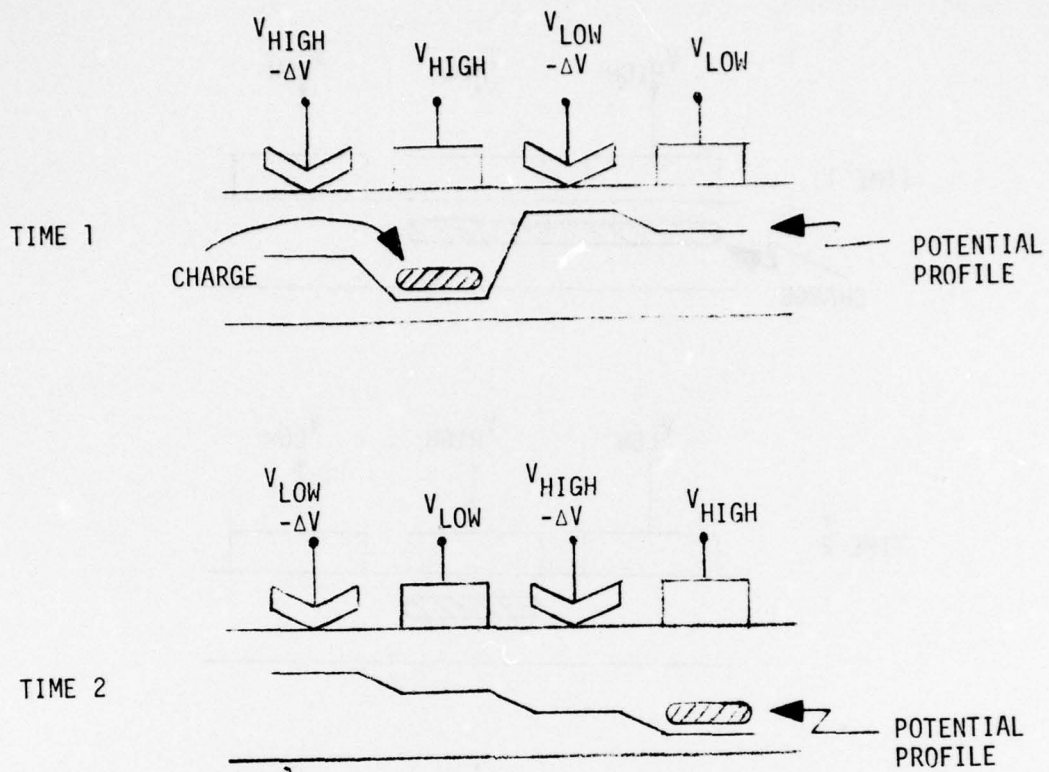


FIGURE 41. TWO-PHASE CLOCK CHARGE TRANSFER

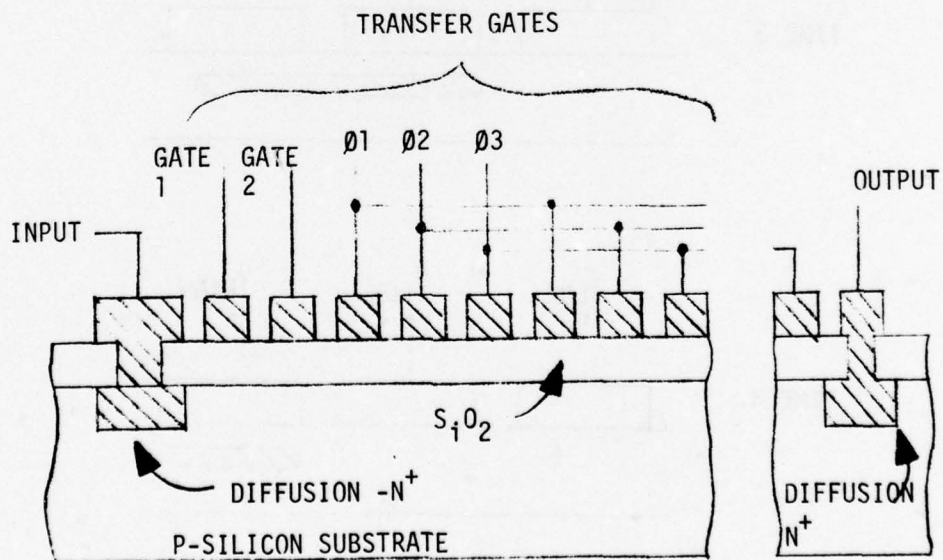


FIGURE 42. CROSS SECTION OF SURFACE CHANNEL CCD

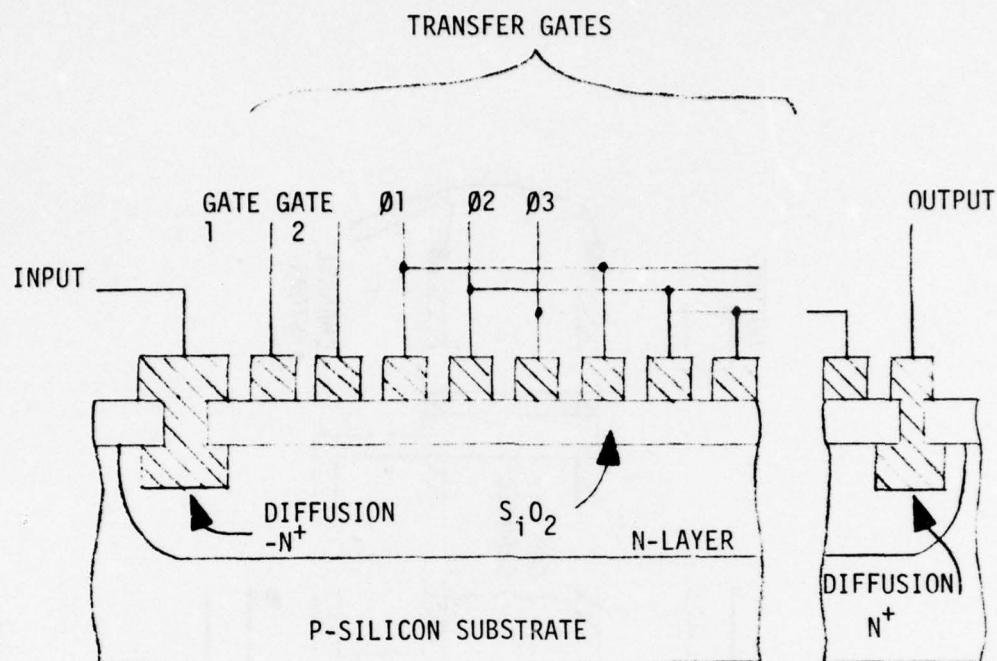


FIGURE 43. CROSS SECTION OF BURIED CHANNEL CCD

laterally dispersed by channel stops shown in Figure 44 which define the CCD channel. In addition to confining the charge packets, the channel stops also keep the charge packets physically separated from the clock bus lines.

The input structure consists of the input diffusion and gates 1 and 2 of Figures 42 and 43. Input structures can also be constructed with an input diffusion and only gate 1 or, as an additional variation, it can contain an additional gate (Gate 3). The output structure shown in Figures 42 and 43 consists simply of the output diffusion. A variety of output structures exist, however, the split-gate structure is described since it is an important technique in the fabrication of a tapped CCD delay line.

The transfer gates can be used to sense the charge passing beneath them as well as causing the charge to transfer. In order to implement a weighted tapped delay line, transfer gates can be split as shown in Figure 45.

The phase three (ϕ_3) gates are shown split into ϕ_3^+ and ϕ_3^- . The amount of charge detected by a given split gate depends directly on its area. The charge packet proportional to the input signal sample is equally distributed across the CCD channel. Therefore, the charge packet under the split gate is weighted by the relative area of the ϕ_3^+ gate to the ϕ_3^- gate. The ϕ_3 clock bus lines act here as summers for the plus contributions and for the minus contributions. The plus and minus buses are then applied to the appropriate inputs of a differential amplifier. If the split of a particular gate occurs at the middle, the corresponding weight at that gate is zero. If the split occurs closer to the minus side of the CCD channel, the weight will be positive for that gate. An analog weight from +1 to -1 can thus be obtained.

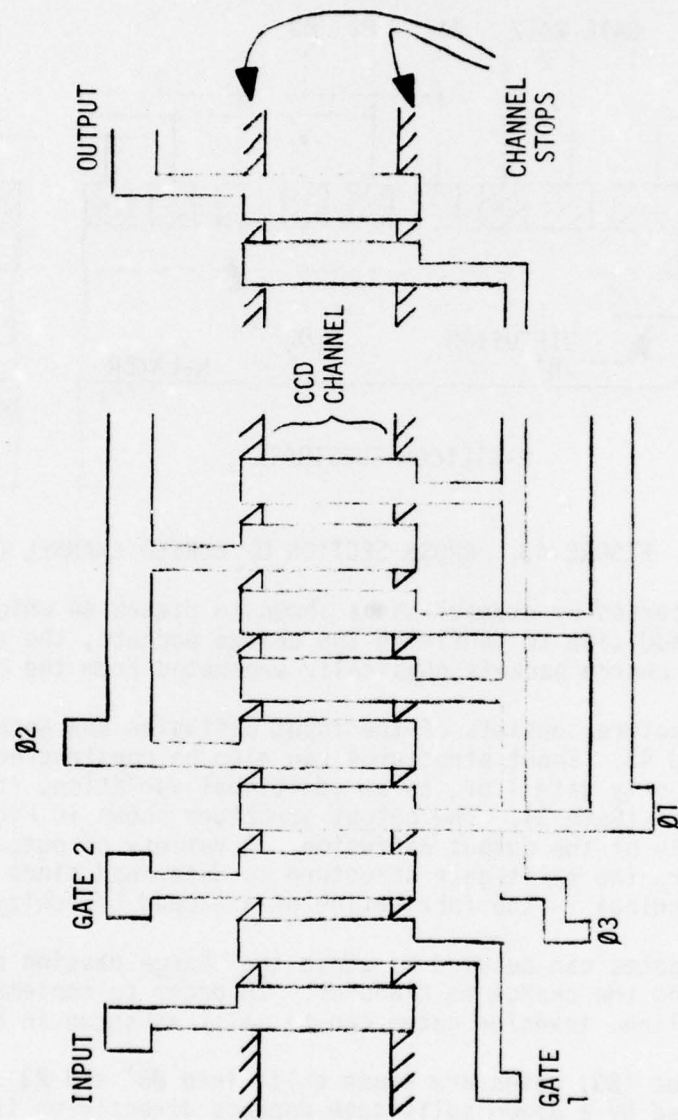


FIGURE 44. CCD (TOP VIEW)

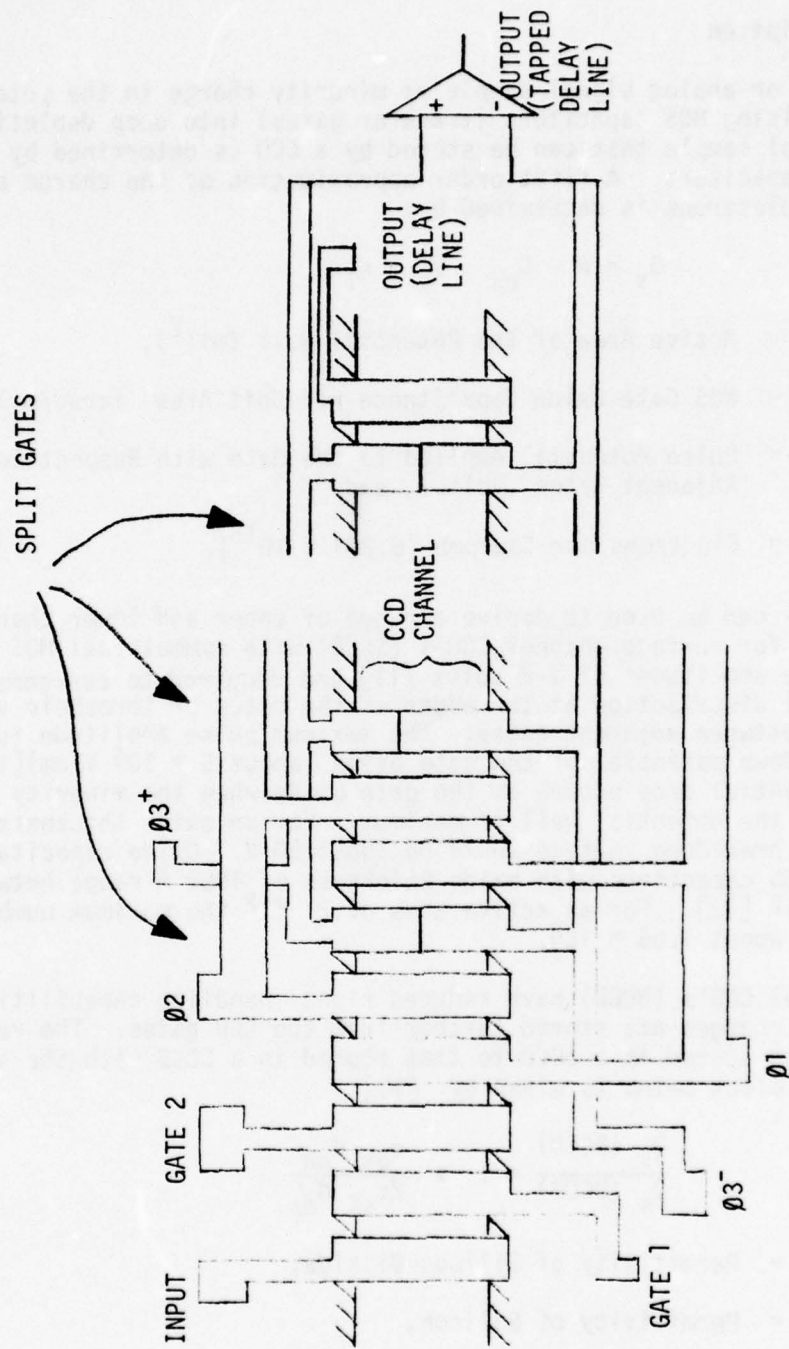


FIGURE 45. SPLIT-GATE CCD

4.2 SIGNAL SAMPLE STORAGE

4.2.1 Description

A CCD stores an analog signal sample as minority charge in the potential wells formed by pulsing MOS capacitors (transfer gates) into deep depletion. The maximum signal sample that can be stored by a CCD is determined by the size of the MOS capacitors. A first order approximation of the charge stores (Q_s) measured in electrons is determined by:

$$Q_s = A \cdot C_{ox} \cdot V_p \cdot K_1 \quad (1)$$

- where: A = Active Area of the Potential Well (mil^2),
 C_{ox} = MOS Gate Oxide Capacitance per Unit Area ($\text{farad}/\text{mil}^2$),
 V_p = Pulse Potential Applied to the Gate with Respect to the Adjacent Gates (Volts), and
 K_1 = Electrons per Coulomb ($6.284 \cdot 10^{18}$).

Equation (1) can be used to derive a range of upper and lower charge handling capabilities for surface channel CCD's (SCCD) with symmetrical MOS gates. Minimum pulse amplitudes of 1-2 volts [11] are required to overcome anomalies in the potential distribution at the edges of the gates or threshold voltage differences between adjacent gates. The maximum pulse amplitude is determined by the breakdown potential of the gate oxide (about $5 \cdot 10^6$ V/cm)[11] because the main potential drop occurs at the gate oxide when the minority charge contained in the potential well is maximum. For an oxide thickness of 1000 Å (100 nm) the breakdown voltage would be about 50 V. Oxide capacitance (C_{ox}) levels for MOS capacitors with oxide thickness of 1000 Å range between .225 and .3 pf/ mil^2 [12]. For an active area of 2 mil^2 the maximum number of electrons is about $1.65 \cdot 10^8$.

Buried channel CCD's (BCCD) have reduced signal handling capabilities since the minority charges are stored further from the CCD gates. The ratio of maximum charge stored in a SCCD to that stored in a BCCD with the same gate geometry and clock swing is given by: [10]

$$\frac{Q_s (\text{SCCD})}{Q_s (\text{BCCD})} = 1 + \frac{\epsilon_{ox} d_{ch}}{2\epsilon_{si} d_{ox}} \quad (2)$$

- where: ϵ_{ox} = Permittivity of Silicon Dioxide,
 ϵ_{si} = Permittivity of Silicon,
 d_{ch} = Effective Thickness of Channel Implant, and
 d_{ox} = Oxide Thickness.

For a device with $d_{ox} = .1 \mu\text{m}$ and $d_{ch} = .6 \mu\text{m}$ the ratio Q_s (SCCD)/ Q_s (BCCD) is about 2. Thus a BCCD has approximately one-half the number of electrons in a full well as a similar SCCD.

4.2.2 Typical Parameters

Although the charge storage per potential well increases as the voltage applied to the transfer gate, most CCD's are not driven with the maximum level of 50 volts, but with voltages between 9-15 volts. This is primarily due to power dissipation limitations in the CCD clock drivers. The CCD gates appear as large capacitances; therefore, the power to drive the clock gates is mainly reactive. The power is dissipated in the driver according to:

$$P = f_c \cdot C \cdot V_p^2 \quad (3)$$

where: f_c = Clock Frequency,

C = Gate Capacitance, and

V_p = Pulse Potential Applied to the Gate.

The power increases with the square of the drive voltage and for high frequency operation (>1 MHz) commercial switch-transistor integrated circuits reach their power dissipation limit at drive voltages around 10-15 volts.

Typical SCCD full potential wells hold a maximum of $3.29 \cdot 10^7$ electrons at 9 volts to $4.95 \cdot 10^7$ electrons at 15 volts for a 2 mil^2 gate area. Typical BCCD potential wells would hold about half that number of electrons ($1.64 \cdot 10^7 - 2.47 \cdot 10^7$ electrons).

Gate area is the product of the gate length and the channel width. Most CCD's have been built with gate areas between $.32$ and 3.2 mil^2 . However, it is feasible to construct dense CCD's, with gate areas as low as $.02 \text{ mil}^2$; and future predictions of $.01 \text{ mil}^2$ have been made. [14] Gate areas larger than 4 mil^2 can be built for applications requiring large charge storage capability such as accumulators.

Oxide capacitance per unit area depends on the thickness and permittivity of the oxide as follows: [12]

$$C_{ox} = 8.85 \cdot 10^{-10} \frac{\epsilon_{ox}}{d_{ox}} \frac{\text{pf}}{\mu^2} \quad (4)$$

where ϵ_{ox} is between 2.7 and 4.2.

Oxide Thickness d_{ox} (Å)	Oxide Capacitance, C_{ox} (pf/mil ²)
1000	.225 - .30
1500	.150 - .20
2000	.112 - .15

According to Equation (1), the amount of stored charge increases as the oxide capacitance per unit area and the oxide thickness should therefore be minimized for maximum charge storage. For oxide thickness less than 1000 Å pinhole failure modes begin to reduce the yield of fully operational CCD's.

4.2.3 Simulation - Model

Electrons are the common variable for all the CCD factors considered. The maximum number of electrons a potential well can hold (a full well) sets the largest signal sample amplitude that can be input to the CCD. The full well electrons (Q_s) determined by Equation (1) and the following parameters:

A = Simulation Parameter Input (mil^2)

C_{ox} = .262 (pf/ mil^2) for 1000 Å Thick Oxide

V_p = Simulation Parameter Input (Volts)

K_1 = $6.28 * 10^{18}$

SCCD or BCCD = Simulation Parameter Input (Q_s (BCCD) = $1/2 Q_s$ (SCCD))

Shown below are the number of electrons for a full well as calculated by the simulation.

<u>TYPE</u>	<u>GATE AREA (mil^2)</u>	<u>CLOCK VOLTAGE (Volts)</u>	<u>FULL WELL ELECTRONS</u>
SCCD	2	10	$3.29 * 10^7$
SCCD	2	15	$4.94 * 10^7$
SCCD	4	10	$6.59 * 10^7$
SCCD	4	15	$9.89 * 10^7$
SCCD	.3	10	$4.95 * 10^6$
SCCD	.02	10	$3.29 * 10^5$
SCCD	.01	10	$1.65 * 10^5$
BCCD	2	10	$1.64 * 10^7$
BCCD	2	15	$2.47 * 10^7$
BCCD	4	10	$3.29 * 10^7$
BCCD	4	15	$4.94 * 10^7$
BCCD	.3	10	$2.47 * 10^6$
BCCD	.02	10	$1.65 * 10^5$
BCCD	.01	10	$8.24 * 10^4$

4.3 TRANSFER EFFICIENCY AND BACKGROUND CHARGE

4.3.1 Description

When the charge packet is transferred from one potential well to the next, a small fraction of the charge packet is left behind. Two mechanisms contribute to this charge transfer inefficiency (CTI), free charge transfer and signal charge interaction with traps. The trapping is due to interface state and bulk traps in SCCD's and bulk traps only in BCCD's.

Free charge transfer is the process that describes the movement of charge from one potential well to the next. The amount of charge transferred is time dependent. If the time allowed for charge transfer is too short, not all of the charge will be transferred. The trapped charge will either be forced backward or into the substrate where it is lost. The speed and amount of charge transferred strongly depends upon the CCD gate length and substrate doping. Keeping the substrate doping less than 10^{15} cm^{-3} and gate length less than 10 microns gives a charge transfer efficiency (CTE) of 99.99% for clock frequencies greater than 10 MHz considering the effects of free charge transfer only.[15] Therefore, keeping these design considerations in mind, CTI can be considered independent of frequency for most CCD applications.

The effect of traps (interface state and bulk) is independent of frequency. SCCD's are primarily affected by interface state traps as most of the signal charge resides in about 10 nm of the interface. In BCCD's, the signal charge resides entirely in the bulk. Empty traps capture signal charge as it comes in contact with them in less than 1 ns. Full traps release this signal charge at a much slower rate. This results in a smearing of the input signal. BCCD's experience less CTI from traps than SCCD's because the bulk traps are less dense than the interface state traps.

In order to reduce the CTI, it is common practice to continuously input an amount of charge which will fill up the traps. This allows the signal charge to transfer down the CCD and not encounter any empty traps. This background bias charge is referred to as "fat zero" in SCCD's and "slim zero" in BCCD's. The amount of fat or slim zero is given in % of the full well electrons.

The use of fat or slim zero reduces the number of full well electrons that can be used for signal charge. To obtain the best CTE from a CCD some reduction in the input signal sample range must be made.

4.3.2 Typical Parameters

SCCD's typically require about 10-15% fat zero to fill the interface state traps. The number of electrons required to fill the bulk traps is less and therefore the slim zero level for BCCD's is usually between 5% and 10%. The relationship of fat or slim zero to CTE depends on the device. The range of fat (10-15%) and slim (5-10%) zero given above was obtained from the published literature. The corresponding levels given for CTE are 0.9999 for SCCD's and 0.99999 for BCCD's.

Since charge transfer efficiency is a function of background charge, it is desirable to obtain a functional relationship between the two. The fraction

of signal lost in passing through a CCD as a function of background charge for SCCD's and BCCD's has been measured.[16] The fraction of signal lost is related to charge transfer inefficiency (CTI) as follows:

$$CTI = \frac{\text{Fraction of Signal Lost in CCD}}{\text{Number of Transfers}} \quad (5)$$

For Tompsett's results, the number of transfers is 256 stages x 3 phases per stage or 768. Figure 46 shows the measured results and the linear piecewise approximation made. The expressions used for the linear approximation are shown below.

SCCD

<u>Section of Curve</u>	<u>Background Charge (%)</u>	<u>Signal Fraction Lost (%)</u>	<u>CTI</u>
A	0-4	28	$3.6 * 10^{-4}$
B	4-5	$-21x + 112$	$-2.7 * 10^{-4} + 1.4 * 10^{-3}$
C	5-10	$-.8x + 11$	$-1.0 * 10^{-5} + 1.4 * 10^{-4}$
D	10 →	3	$3.9 * 10^{-5}$

BCCD

<u>Section of Curve</u>	<u>Background Charge (%)</u>	<u>Signal Fraction Lost (%)</u>	<u>CTI</u>
E	0-4	$-1.25x + 8.9$	$-1.6 * 10^{-5} + 1.1 * 10^{-4}$
F	4-13.5	$-.16x + 4.5$	$-2.1 * 10^{-6} + 5.8 * 10^{-5}$
G	13.5 →	2.2	$2.8 * 10^{-5}$

Tompsett's results give a good indication of the CTI/background charge relationship. However, his results are not definitive. A fat zero of 10% for a SCCD gave the same CTE as a slim zero of 7% for a BCCD; CTE = .999961. These results are good for a SCCD, but poor for a BCCD.

4.3.3 Simulation - Model

The simulated device is a two-phase CCD, as shown in Figure 41. The second and fourth gates in each stage function are the storage gates. The first and third gates act as barriers to prevent the backward flow of charge. Due to the gate functions, only the second and fourth gates need to be simulated as long as the charge transfer direction is correct. The simulation has the device type specified (SCCD or BCCD) as indicated in Section 4.2.3. The simulation gives the option of either specifying the CTI as a parameter or by specifying a percent of background bias charge which then computes the CTI. Typical values for CTI as a function of background charge percentage derived from the linear approximation in Figure 46 are given in Table 27.

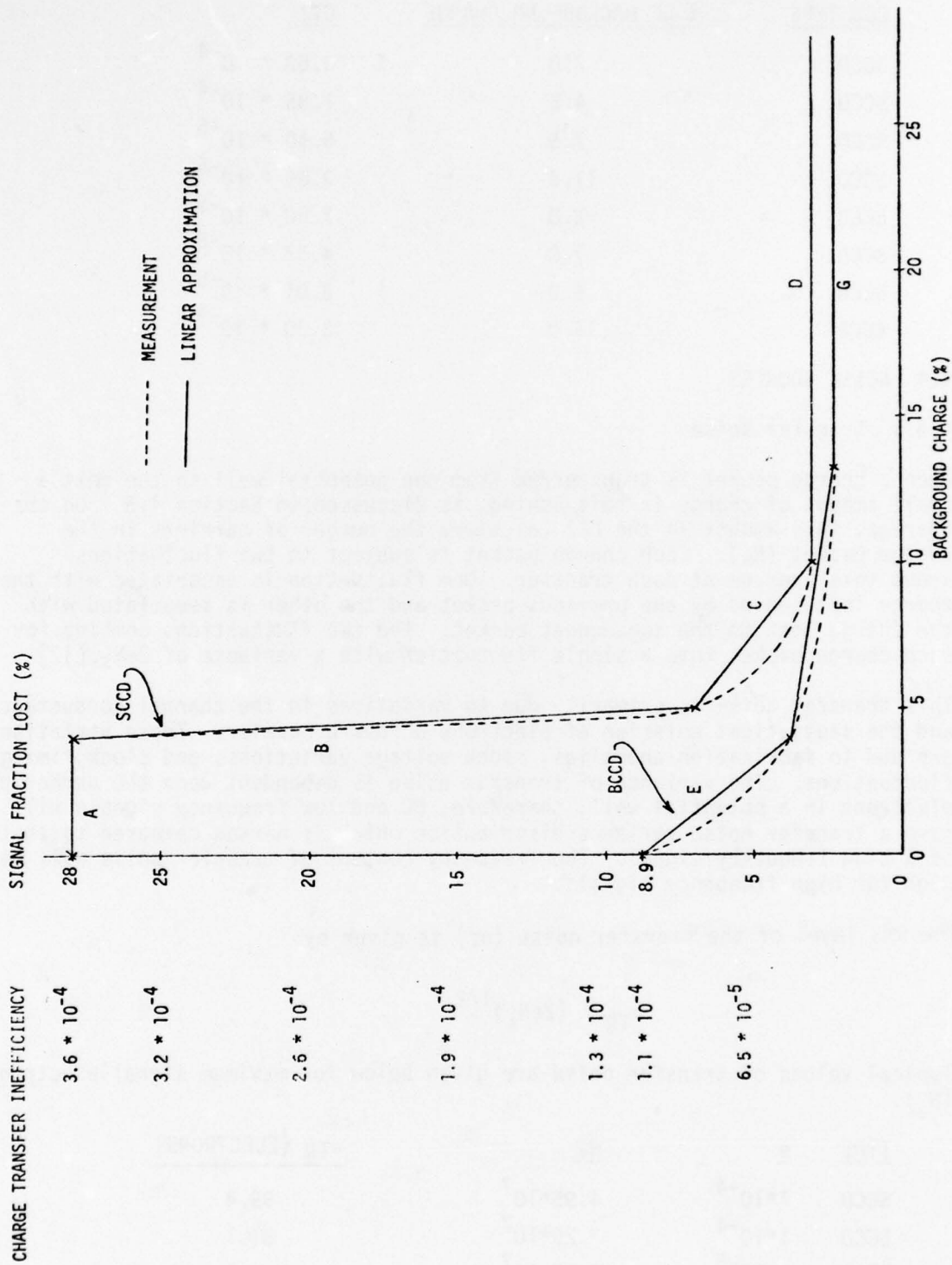


FIGURE 46. CHARGE TRANSFER INEFFICIENCY VERSUS BACKGROUND CHARGE

TABLE 27. TYPICAL VALUES OF CTI

CCD TYPE	% OF BACKGROUND CHARGE	CTI
SCCD	2.0	$3.60 * 10^{-4}$
SCCD	4.5	$1.85 * 10^{-4}$
SCCD	7.5	$6.50 * 10^{-5}$
SCCD	11.0	$3.89 * 10^{-5}$
BCCD	2.0	$7.80 * 10^{-5}$
BCCD	7.0	$4.33 * 10^{-5}$
BCCD	9.0	$3.91 * 10^{-5}$
BCCD	14.0	$2.80 * 10^{-5}$

4.4 NOISE SOURCES

4.4.1 Transfer Noise

When a charge packet is transferred from one potential well to the next a small amount of charge is left behind, as discussed in Section 4.3. On the average, this amount is the CTI (e) times the number of carriers in the charge packet (N_s). Each charge packet is subject to two fluctuations about this average at each transfer. One fluctuation is associated with the charge left behind by the previous packet and the other is associated with the charge lost to the subsequent packet. The two fluctuations combine for each charge packet into a single fluctuation with a variance of $2eN_s$. [17]

This transfer noise is primarily due to variations in the channel conductance and the statistical emission of electrons across a barrier. These variations are due to fabrication anomalies, clock voltage variations, and clock timing fluctuations. The variance of transfer noise is dependent upon the number of electrons in a potential well; therefore, DC and low frequency signals will have a transfer noise variance distribution which is narrow compared to that of a high frequency signal. The frequency content of transfer noise will be high for high frequency signals.

The RMS level of the transfer noise (σ_T) is given by:

$$\sigma_{TR} = (2eN_s)^{1/2}$$

Typical values of transfer noise are given below for maximum signal electrons (N_s).

TYPE	e	N_s	σ_{TR} (ELECTRONS)
SCCD	$1 * 10^{-4}$	$4.95 * 10^7$	99.4
SCCD	$1 * 10^{-4}$	$3.29 * 10^7$	81.1
BCCD	$1 * 10^{-5}$	$2.47 * 10^7$	22.2
BCCD	$1 * 10^{-5}$	$1.64 * 10^7$	18.1

4.4.2 Thermal Shot Noise

Since a CCD is normally operated in deep depletion, there is a thermal generation of electrons which will re-establish an equilibrium condition. These electrons generated as a function of time are referred to as "dark current". There is an average dark current with spatial variations described in Section 4.5. Associated with this is a thermal shot noise with a variance, σ_{SN}^2 , of: [18]

$$\sigma_{SN}^2 = \frac{J_D A K_2}{q f_c} \quad (6)$$

where: J_D = Dark Current Density (A/cm^2)
 A = Area of Potential Well (cm^2)
 q = Electron Charge (Faraday)
 f_c = Clock Frequency (H_z)
 $K_2 = (1.0363 \cdot 10^{-5})$

Thermal shot noise is completely uncorrelated from charge packet to charge packet and this results in a white frequency spectrum. The thermal shot noise variance increases as temperature due to the dark current density (J_D) increase with temperature. Substituting the following parameters in Equation (6):

$$\begin{aligned} J_D &= 2 \cdot 10^{-9} \text{ A/cm}^2 \\ A &= 1.29 \cdot 10^{-5} \text{ cm}^2 \text{ (2 mil}^2\text{)} \\ K_2 &= 1.0363 \cdot 10^{-5} \\ q &= 1.64 \cdot 10^{-24} \text{ Faraday} \end{aligned}$$

we obtain the following values for σ_{SN} in electrons.

f_c (Hz)	σ_{SN} (ELECTRONS)
1,000	12.7
10,000	4.0
100,000	1.3

4.4.3 Trap Noise

SCCD interface state traps and BCCD bulk traps capture signal charge and then release the captured charge back into the CCD channel as described in Section 4.3. There will be fluctuations in the total number of carriers (signal charge) trapped at any instant of time. These fluctuations cause a SCCD trap noise with variance σ_{TP} [17] of:

$$\sigma_{TP} = .7 k T N_{ss} A \quad (7)$$

where: k = Boltzmann's constant (eV/°K)
 T = Temperature (°K)
 N_{ss} = Density of Fast States (cm² - eV)⁻¹
 A = Area of Potential Well (cm²)

The variance of the trap noise for BCCD is about 1/5 the variance described by equation (7).[19] This is due to the lesser density of bulk traps compared to interface state trap.

A typical trap noise level can be obtained by letting,

$$\begin{aligned} k &= 8.617 \times 10^{-5} \text{ eV/°K} \\ T &= 300 \text{ °K} \\ N_{ss} &= 1 \times 10^{10} \text{ (cm}^2 \text{ - eV)}^{-1} \\ A &= 1.29 \times 10^{-5} \text{ cm}^2 \end{aligned}$$

to give $\sigma_{TP} = 48.3$ electrons.

4.4.4 Input Noise

The amount of noise introduced at the input strongly depends on the input technique. Noise results from fluctuations in the associated voltage levels, the pulse width that determines the amount of charge injected, the dynamic setting of charge, the distribution of signal charge, and capacitive pick-up from clock pulses. The lowest-noise input technique has produced noise variance σ_{IN}^2 approaching:[9]

$$\sigma_{IN}^2 = \frac{1}{q^2} \left(\frac{2}{3} K_3 k T C_i \right) \quad (8)$$

where: q = Electron Charge (Coulomb)
 K_3 = eV → Coulomb-Volt (1.602×10^{-19})
 k = Boltzmann's Constant (eV/°K)
 T = Temperature (°K)
 C_i = Input Capacitance (Farad)

The input noise RMS electrons σ_{IN} are typically 33 for the following parameters.

where: $q = 1.602 \cdot 10^{-19}$ Coulomb
 $K_3 = 1.602 \cdot 10^{-19}$
 $k = 8.617 \cdot 10^{-5}$ eV/°K
 $T = 300$ °K
 $C_i = 1 \cdot 10^{-14}$ Farad

4.4.5 Output Noise

The noise at the output depends directly upon the output technique. Although floating gate and MOSFET outputs can theoretically be expected to be the least noisy, most CCD outputs have noise measured at the level predicted for floating diffusion and RC-bandwidth limited outputs.[10] This noise level is thermal RC noise whose variance is the same as that given for the input noise variance. Typical RMS electrons are about 100 to 180, which is higher due to higher capacitance.

4.4.6 Miscellaneous Noise

Clock noise is not clock feedthrough at the fundamental clock frequency, but is essentially white noise in the signal frequency spectrum. This noise source is suspected to be due to feed-through capacitance of the clock voltage to floating diffusions. There has been little discussion in the literature of this noise and no quantitative measurements.[20]

1/f noise has been predicted to be absent in CCD's [17] and has not been observed. 1/f noise is present in MOSFET's and will contribute to the overall noise if they are used at the output of CCD's.

4.4.7 Simulation - Model

Transfer, thermal shot, trap, input, and output noise is incorporated in the simulation. The standard deviation (RMS electrons) for the noise sources are those described in the respective sections. Rather than adding the noise effects in at the output, they are incorporated where they would occur in an actual device. The transfer, thermal shot, and trap noise is added in at each transfer. The noise is Gaussian with standard deviation determined separately for each noise source.

The transfer noise standard deviation depends upon the CTI(e) which is incorporated in the simulation as described in Section 4.3.3. The number of carriers in a charge packet (N_s) changes at each transfer, therefore, the variance is changed at each transfer in the simulation.

The thermal shot noise standard deviation is a function of dark current density (J_D) whose average value is determined in the simulation and described in Section 4.5. Potential well area (A) and clock frequency are simulation inputs.

Trap noise standard deviation depends upon potential well area (A) and

temperature (T) which are simulation inputs. The density of fast states (N_{SS}) is incorporated in the simulation.

Input and output noise standard deviation requires temperature (T) as a simulation input. The input capacitance (.01 pF) and output capacitance (.1 pF) are incorporated in the simulation.

4.5 DARK CURRENT

4.5.1 Description

Since a CCD is normally operated in deep depletion there is a thermal generation of electrons which, with time, will reestablish an equilibrium condition (dark current). Thermal generation of electrons originate principally from three sources; the bulk depletion region, the neutral bulk, and the S_i - S_iO_2 interface.

The dark current density in amp/cm² due to generation in the bulk depletion region (J_{gd}) is given by:

$$J_{gd} = \frac{q n_i x_d}{2 t_d} \quad (9)$$

where: q = Electron Charge (Faraday F)
 n_i = Intrinsic Carrier Concentration (cm⁻³)
 x_d = Depletion Width (cm)
 t_d = Carrier Lifetime (sec.)

The dark current density due to generation in the neutral bulk (J_{gn}) is given by:

$$J_{gn} = \frac{q n_i^2 L_n}{N_R t_d} \quad (10)$$

where: L_n = Carrier Diffusion Length (cm)
 N_R = Density of Recombination-Regeneration Centers in the Bulk (cm⁻³)

The dark current density due to generation at the S_i - S_iO_2 interface (J_{gs}) is given by:

$$J_{gs} = \frac{q n_i a_T v_{th} N_{st}}{2} \quad (11)$$

where: a_T = Trap Capture Cross Section (cm²)
 v_{th} = Carrier (Electron) Thermal Velocity (cm/s)
 N_{st} = Concentration of Recombination-Regeneration Centers at the interface (cm⁻²)

The total dark current density (J_D) is:

$$J_D = J_{gd} + J_{gn} + J_{gs} \quad (12)$$

The dark current density is temperature dependent due to the temperature dependence of the intrinsic carrier concentration (n_i). The functional relationship between n_i and temperature has been empirically determined to be:[21]

$$n_i = 1.5 * 10^{33} T^3 \exp\left(\frac{-1.21}{kT}\right) \quad (13)$$

where: T = Temperature ($^{\circ}K$)
 k = Boltzmann's Constant ($eV/^{\circ}K$)

This expression is valid down to 250 $^{\circ}K$. [22] Below this temperature, the carrier concentration reaches a fixed level (exhaustion region). [23]

Spatial variation in dark current generation is primarily due to spatial variation of interface recombination-regeneration centers (N_{st}). N_{st} can range between $1 * 10^9$ to $1 * 10^{11} \text{ cm}^{-2}$. Good control over device processing variables leads to a Rayleigh distribution of N_{st} skewed toward values of $1 * 10^9 \text{ (cm}^{-2}\text{)}$. This leads to a reduction in average dark current generation and to a minimization of dark current variations.

The dark current leads to a collection of electrons in a potential well according to:

$$\# \text{ of Electrons} = \frac{J_D A}{g f_c}$$

where: A = Area of Potential Well (cm^2)
 f_c = Clock Frequency (Hz)

Typical values for dark current calculations are:

q	$= 1.64 * 10^{-24} \text{ F}$	a_T	$= 1 * 10^{-15} \text{ cm}^2$
n_i	$= 1.6 * 10^{10} \text{ cm}^{-3}$	v_{th}	$= 8 * 10^5 \text{ cm/s}$
x_d	$= 1 * 10^{-4} \text{ cm}$	N_{st}	$= 1 * 10^{10} \text{ cm}^{-2}$
t_d	$= 1 * 10^{-4} \text{ s}$	A	$= 1.29 * 10^{-5} \text{ cm}^2$
L_n	$= 5.6 * 10^{-2} \text{ cm}$	f_c	$= 1 * 10^4 \text{ Hz}$
N	$= 5 * 10^{14} \text{ cm}^{-3}$		

These values give:

$$J_{gd} = 1.27 \text{ nA/cm}^2$$

$$J_{gn} = .046 \text{ nA/cm}^2$$

$$J_{gs} = 10.18 \text{ nA/cm}^2$$

The total dark current density is:

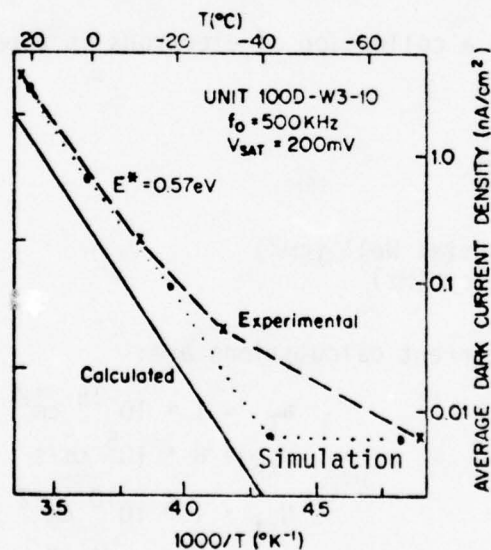
$$J_D = 11.496 \text{ nA/cm}^2$$

and the number of elections in the potential well is 81.8.

4.5.2 Simulation - Model

The dark current calculations require as inputs; temperature, potential well area, and clock frequency. All other variables are contained in the simulation.

Figure 47 shows experimental, calculated, and simulation dark current density as a function of temperature.[24]



- Calculated [24]
- x-----x Measured [24]
-• Simulation Characteristics

FIGURE 47 . DARK CURRENT DENSITY AS A FUNCTION OF TEMPERATURE

As Figure 47 indicates the dark current density, as simulated, closely follows experimental measurements down to -20°C (250°K). At lower temperatures the simulation starts to deviate as discussed in Section 4.5.1 (Equation 13). For temperatures below -40°C the dark current density in the simulation is constant.

The number of electrons that fill the potential wells due to dark current is a function of time (clock frequency). Figure 48 is the result of simulation runs showing the effects of temperature and clock frequency on dark current density (J_g) and number of electrons per well.

4.5.3 Reduction of Dark Current

Cooling can be used to drastically reduce the dark current density. Section 4.5.2 shows that cooling the CCD to -20°C from room temperature results in two orders of magnitude reduction in dark current density. CCD's as IR detectors and CCD's for signal processing from IR detectors are under development by many companies. Cooling containers developed for IR systems are commercially available [25] and could be used for cooling CCD signal processing sub-systems to desired temperatures.

Dark current density can also be reduced by adequately controlling the fabrication process. In particular, the largest contributor to the total dark current density is the interface dark current density. This source can be reduced by reducing the number of recombination-regeneration centers at the interface. This is accomplished by choosing the optimum type of silicon and the type of oxidation, and using the proper annealing procedures.

Another method of reducing the effects of dark current is to subtract the accumulated background charge from the charge packets. *This technique should be made adaptable to changes that increase in temperature and clock period and be sensitive to differences in dark current densities from device to device.*

4.5.4 Radiation Effects

The most serious limitation on CCD performance is the increased dark current density levels which are observed in the neutron environment. Indications are that BCCD's are superior to SCCD's in an ionizing radiation environment. Transfer efficiency is also worse for SCCD's at lower radiation levels.[26]

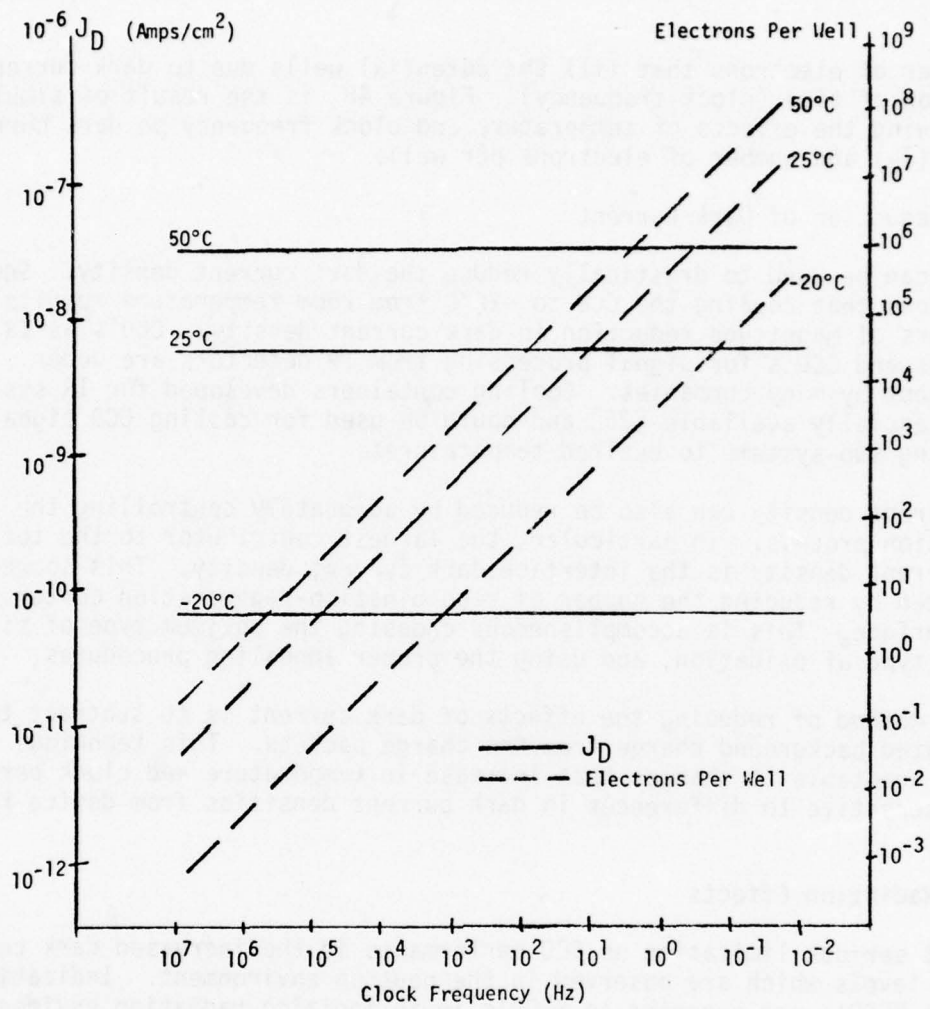


FIGURE 48 . DARK CURRENT DENSITY AND ELECTRONS PER WELL VERSUS TEMPERATURE AND CLOCK FREQUENCY

4.6 CCD INPUT SAMPLING

The input sampling technique used in CCD's is critical to their performance. An important problem is attaining a charge packet in the CCD which is a linear function of the input signal amplitude. In addition, the sampling process in CCD's will have the same general specifications applicable to analog-to-digital converters.

4.6.1 Input Structure and Linearity

Figure 49 shows a typical CCD input structure. It is characterized by a diffusion source of electrons and perhaps two input sampling gates which transfer the desired charge to the potential well formed by clock voltage ϕ_1 . If a signal is applied directly to the source and is strobed into the CCD by pulsing the gates, the result is inherently non-linear. Although there are other variations, the technique which has provided the best linearity, of up to 50 percent of the full potential well, is called the "fill and spill" method.[8-20] In this technique, the signal is applied to the first gate G_1 , and a DC level or the signal is placed on the second gate G_2 . A sampling pulse applied to the source will inject an excess of charge into the device. As the clock voltage and pulse is removed, the excess charge is extracted from the CCD, limited by the signal gate potential.

A method has been suggested [27] which uses a feedback approach to achieve a linear input to a CCD. In this method, a tap is placed after the input gates which senses the magnitude of the sampled charge. The tap output is fed back to a differential amplifier which subtracts the tap value from the input. The resultant is fed to the signal gate of the CCD. During a sample interval, the sampled charge is thus forced to be proportional to the input sample value. Although this method greatly increases the linear range of the full potential well, its bandwidth capability for wideband applications is limited.

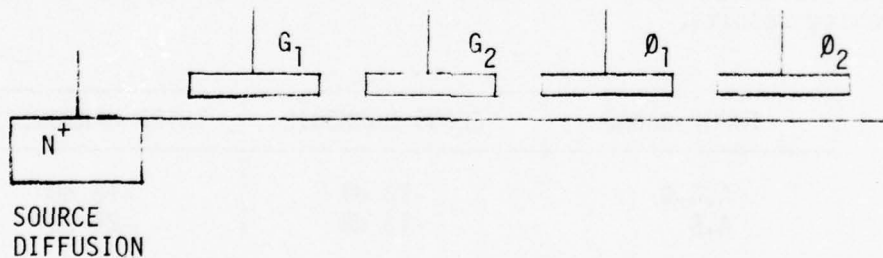


FIGURE 49.

4.6.2 Sampling Aperture

As discussed generally in Section 3, the input sampling aperture will affect the bandwidth performance of the CCD. This is analogous to the sampling aperture-resolution requirements of A/D converters. The accuracy

of the sampling process will be determined to a large extent by the width of the sampling aperture. In specifying sampling aperture in an A/D converter, a conventional approach is to limit the signal excursion to less than one-half the least significant bit during the sampling aperture. This specification sets the aperture size limit, δ , to approximately $(T_p/2^{N-1})$ where T_p is the period of the highest frequency to be sampled and N is the number of quantization bits.

If we consider only the bandwidth capabilities of the sampling aperture, the 3 dB bandwidth can be determined by the frequency response:

$$S_f = \frac{\sin \frac{2\pi\delta}{T_p}}{\frac{2\pi\delta}{T_p}} = .707$$

This yields $\delta/T_p = .22$. It is thus apparent that the bandwidth criterion is much less restrictive of the sampling aperture than the conventional sampling noise criterion for A/D converters. The key issue is the magnitude of the uncertainty in the sample amplitude created by the sampling aperture. If the aperture acts as a pure signal average, no noise is introduced. However, if the charge injection varies depending upon, for example, whether the slope of the signal is positive or negative, then a sampling error signal will occur. This error signal will act as a noise added to the signal and if high enough could degrade the signal-to-noise ratio of the processor. No sampling error signal was derived during the study and none was included in the CCD simulation.

4.6.3 CCD Input Model

The CCD input model used for the simulation included the effect of nonlinearities and sampling aperture. A piecewise linear approximation to the input, based upon measured values, is shown in Figure 50. Harmonic analysis of signals passed through the input with the two distortion conditions gave the following results.

INPUT RANGE	SECOND HARMONIC	THIRD HARMONIC
A,B,C	-13 dB	-18 dB
A,B	-13 dB	-24 dB

These distortion levels were too high to consider anything other than the linear operating range, A. With the linear region covering only $4/28 = 14\%$ of the full well, the total dynamic range is limited. For the simulations, a 2.0 percent background bias charge was used, further reducing the signal range.

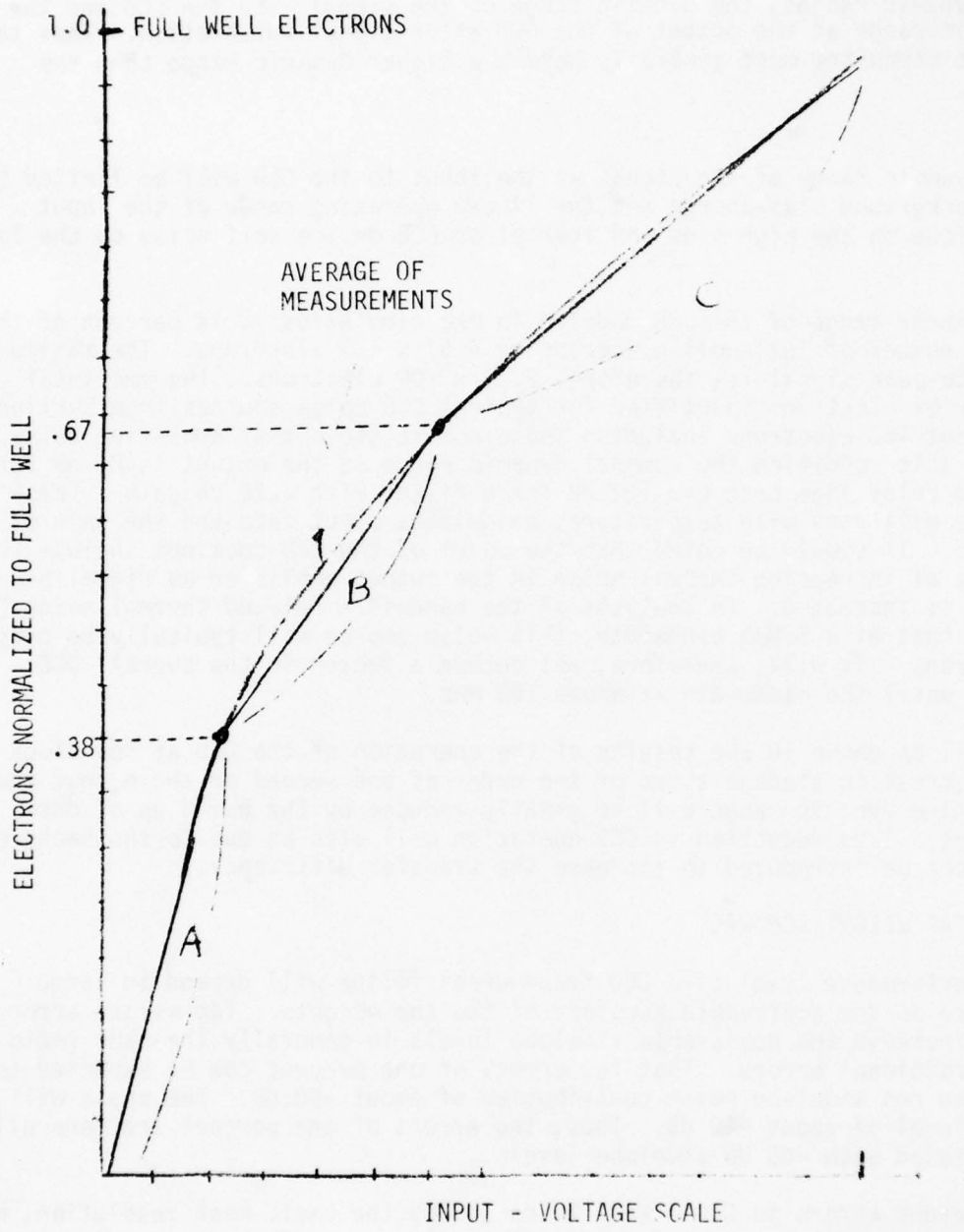


FIGURE 50. MEASURED INPUT TRANSFER CHARACTERISTICS

4.7 DYNAMIC RANGE

The dynamic range of a device can be defined as the ratio of the peak to peak signal before saturation to noise. In a CCD processor one can define two dynamic ranges, the dynamic range of the signal into the CCD and the dynamic range at the output of the CCD after signal integration. Thus the output circuitry must generally handle a higher dynamic range than the input.

The dynamic range of the signal at the input to the CCD will be limited by the background bias charge and the linear operating range of the input technique on the high side and thermal or CCD device self noise on the low side.

The linear range of the CCD modeled in the simulation is 14 percent of the total number of full-well electrons or 4.57×10^6 electrons. The maximum peak-to-peak signal is, therefore, 2.28×10^6 electrons. The rms total number of electrons identified for typical CCD noise sources from Section 4.4 is about 160 electrons including those due to the output amplifier noise. Under this condition the nominal dynamic range at the output is 83 dB for a tapped delay line case and 103 dB for a filter with a 20 dB gain. These values will vary with temperature, bandwidth, clock rate and the gain of the filter. It should be noted that the model of the CCD does not include the effect of increasing thermal noise in the output amplifier as signal bandwidth is increased. An analysis of the bandwidth related thermal noise [8-17] shows that at a 5 MHz bandwidth, this noise source will typically be only 6 electrons. It will, therefore, not become a factor in the overall CCD noise until the bandwidth is above 100 MHz.

It will be shown in the results of the operation of the CCD at low clock rates, creating storage times of the order of one second or above, that the effective dynamic range will be greatly reduced by the build up of dark current. Some reduction in CCD operation will also be due to the background bias charge introduced to increase the transfer efficiency.

4.8 TAP WEIGHT ACCURACY

The performance level of a CCD transversal filter will depend in large measure on the achievable accuracy of the tap weights. Tap weight errors will increase the achievable sidelobe levels in generally the same ratio of the fractional errors. That is, errors of one percent can be expected to have an rms sidelobe noise contribution of about -50 dB. The peaks will be at a level of about -40 dB. Thus, tap errors of one percent are generally associated with -40 dB sidelobe levels.

Tap weight errors in CCD's will be caused by the basic mask resolution, mask misalignment, charge transfer efficiency and non-uniform charge distribution. Non-uniform charge distribution is due to the non-ideal nature of a split-gate tap. That is, the computation of gate dimension assumes a square gate size, but edge effects on the gates effectively rounds the edges creating a slight error in gate capacitance. The latter three causes are not generally considered to be of major importance. However, measurements of tap weight

errors on a split-gate transversal filter at RCA showed tap weight errors which ranged up to a maximum of 6 percent with a standard deviation of 1.75 percent. The simulation has included consideration of tap weight errors from .1 to 10 percent.

4.9 SIGNAL ISOLATION

4.9.1 Potential Well Isolation

It is important that the charge stored in a potential well is influenced only by its own and neighboring control gates to prevent crosstalk and undesirable losses. This is assured by surrounding the CCD channel with a potential barrier preventing the leaking of charge from the well in the transverse direction as shown in Figure 51. This barrier also prevents clock busses from interfering with the signals in the wells. Well to well isolation along the CCD channel is controlled by the gate clock signals.

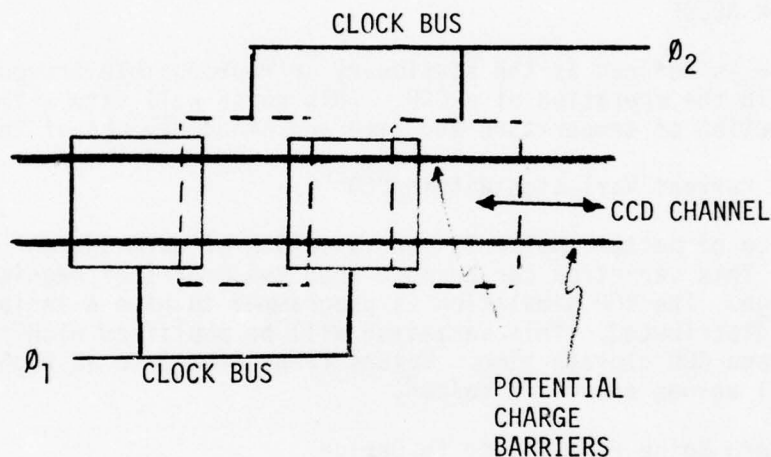


FIGURE 51. CCD CHANNEL ISOLATION

4.9.2 Input-Output Feedthrough

CCD delay lines often exhibit direct coupling from the input signal to the output. This can be due to two causes. If the clock signals and input sampling pulse are not timed properly, it may allow the input charge to propagate directly through the CCD. This is an unusual condition and will only be observed with a control/clock timing drift or failure. Parasitic capacitance on the CCD package, wire bonds or external circuitry can provide a direct coupling from the input to the output. This problem can be aggravated by the use of dual-in-line packages which have parallel closely spaced leads.

4.9.3 Clock Feedthrough

The CCD output structure whether a signal is developed from the drain or a floating gate is such that clock feedthrough is inherent in the process. No

output technique has been reported which eliminates feedthrough. The clock signal must, therefore, be cancelled or filtered. These processes may be aided by the incorporation of clock drivers and controls on the CCD chip.

The problem of clock filtering is relatively straightforward in applications where the sample rate is much greater than the signal bandwidth. However, in applications such as binary coded correlators the clock signal may be identical to the code rate. In these cases, the clock can only be removed by cancellation. Experiments have been performed [28] using sine wave clocks for operation of CCD's at frequencies as high as 100 MHz. The sine wave clocks may not provide maximum transfer efficiency but since they contain no significant spectral components beyond the fundamental they are relatively easy to cancel. On-chip cancellation can also improve performance since the on-off chip driving creates slight mismatches in the clock signals which lead to high clock spikes. A sample-and-hold operation after clock cancellation can be used to remove the spikes.

4.10 PATTERN NOISE

Pattern noise is defined as the stationary or reproducible irregularities encountered in the operation of a CCD. This noise will vary within a given CCD as a function of temperature and time and among devices of the same type.

4.10.1 Dark Current Variation Within CCD

A large source of pattern noise is the variation of dark current among the CCD stages. This variation can be more than two orders of magnitude from stage to stage. The CCD simulation is programmed to give a variation which is Rayleigh distributed. This variation will be amplified with increasing temperature and CCD storage time. Values range from 2 to as high as 100 na/cm² which typical values around 10 na/cm².

4.10.2 Pattern Noise From Device to Device

Variations in characteristics from device to device can adversely affect the performance of a system where multiple CCD's are used or when devices are replaced due to failures. CCD parameters which can be expected to vary from device to device include the input structure linearity, tap weight errors, charge transfer efficiency and temperature coefficients.

4.11 CCD CHARACTERISTICS - SUMMARY

Tables 28 and 30 list a summary of key CCD developments reported in the literature. A short summary of extremes is listed in Table 28, and a more complete listing is given in Table 30. The CCD simulation program results have been correlated with these general results to assure conformity. Table 29 summarizes the noise sources with their mean, variance and distribution as incorporated in the CCD simulation.

TABLE 28. SUMMARY OF REPORTED CCD CHARACTERISTICS

◦ Maximum Number of Stages	910
◦ Minimum Transfer Inefficiency	$1 * 10^{-5}$
◦ Maximum Sample Rate	180 MHz
◦ Minimum Dark Current Density	$1.5 \frac{nA}{CM^2} @ 25^{\circ}C$
◦ Maximum Dynamic Range	75 dB
◦ Minimum Harmonic Distortion	-45 dB

TABLE 29. CCD NOISE SOURCES IN SIMULATION

<u>Noise Source</u>	<u>Mean</u>	<u>Variance</u>	<u>Distribution</u>
Input/Output	0	$2K_3 K TC_i/g^2$	Gaussian
Shot	0	$J_D A K_2/g f_c$	Gaussian
Trap	0	$.7K T N_{SS} A$	Gaussian
Filter Tap Weights	Weight Value	(Percent Error) ²	Gaussian
Transfer	0	$2 e N_S$	Gaussian
Dark Current*	$J=J_{gd}+J_{gn}+J_{gs}$	$J^2/(\pi/2)$	Rayleigh (J_{gs} Term Only)

* See Section 4.5 for Expanded Equation.

TABLE 30. SUMMARY OF REPORTED CCD CHARACTERISTICS

TYPE	STAGES	CLOCK PHASE	SAMPLE RATE	TRANSFER INEFFICIENCY	DARK CURRENT	MASK ACCURACY	DYNAMIC RANGE	S/N	HARMONIC DISTORTION	APPLICATION	REFERENCE
SCCD	500	4	200 KHZ	3×10^{-4}	2 NA/CM ²	.05 MILS	75 dB		-45 dB	BANDPASS FILTER	R. W. Broderick, et al., "500-STAGE CCD TRANSVERSAL FILTER FOR SPECTRAL ANALYSIS" IEEE VOL. ED-23 FEB. '76
SCCD	500	4	500 HZ-100 KHZ	1×10^{-4}	2 NA/CM ²	.05 MILS	75 dB		-45 dB	CHIRP FILTER	
SCCD	63	2	80 KHZ			.05 MILS		62 dB	-40 dB	LOWPASS FILTER	R. D. Baertsch, et al., "DESIGN & OPERATION OF PRACTICAL CHARGE TRANSFER TRANSVERSAL FILTERS", IEEE VOL. ED-23, 2/76
SCCD	256	3	8 MHZ	5×10^{-5}	10 NA/CM ²			60 dB	-40 dB	ANALOG DELAY	
SCCD	13	3	10 KHZ-5 MHZ	1×10^{-3}						MATCHED FILTER	D. A. Sealer, et al., "ANALOG & CHARACTERIZATION OF CCD'S FOR ANALOG SIGNAL PROCESSING", IEEE '75 COMMUNICATION CONF.
SCCD	21	3	60 KHZ	5×10^{-3}						CHIRP FILTER	
SCCD	250	2	250 KHZ-8 MHZ					62 dB	-40 dB	ANALOG DELAY	D. R. Collins, et al., "ANALOG MATCHED FILTERS USING CCD'S" NEREM '72
SCCD	500	3	1 MHZ							ANALOG DELAY	
SCCD	100	3	3 KHZ-3 MHZ	3×10^{-4} 9×10^{-4}	10-100 NA/CM ²					ANALOG DELAY	M. F. Tomsett, et al., "USE OF CCD'S FOR DELAYING ANALOG SIGNALS", IEEE VOL. SC-8, APR '73
SCCD	40	2	1-2 MHZ	5×10^{-4}						ANALOG DELAY	
SCCD	40	2	20 MHZ	1×10^{-4}						ANALOG DELAY	D. J. Butt, "PERFORMANCE LIMITATIONS OF CCD'S" INTER. CONF. ON TECHNOLOGY & APPLICATIONS OF CCD'S, SEPT. '74
SCCD	100x100	2	500 KHZ				52 dB			IMAGER	
PCCD	128	4	100 KHZ-135 MHZ	5×10^{-5}	2 NA/CM ² 25°C .6 NA/CM ² -6°C .1 NA/CM ² -20°C .01 NA/CM ² -60°C					ANALOG DELAY	R. H. Dyck, et al., "LOW LIGHT LEVEL PERFORMANCE OF A CHARGE-COUPLED AREA IMAGING DEVICE", INTER. CONF. ON TECH. & APPLICATIONS OF CCD'S, SEPT. '74
SCCD	24	3	8 KHZ-20 KHZ					70 dB	.02-.3%	ANALOG DELAY	
SCCD	48	3	8 KHZ-20 KHZ					70 dB		ANALOG DELAY	D. A. Sealer, et al., "A DUAL DIFFERENTIAL CHARGE-COUPLED ANALOG DELAY DEVICE", IEEE, VOL. ED-23, FEB '76
BCCD	150	4	25 KHZ-1 MHZ	2×10^{-5}	3-8 NA/CM ²					ANALOG DELAY	

TABLE 30. SUMMARY OF REPORTED CCD CHARACTERISTICS (CONTINUED)

TYPE	STAGES	CLOCK PHASE	SAMPLE RATE	TRANSFER INEFFICIENCY	DARK CURRENT	MASK ACCURACY	DYNAMIC RANGE	S/N	HARMONIC DISTORTION	APPLICATION	REFERENCE
S _{CCD}	800	3	100 KHz- 1 MHz	2.4x10 ⁻⁴						BANDPASS FILTER	C. R. Hemes, "A Self Contained 800 Stage CCD Transversal Filter", CCD Conference '75, San Diego
B _{CCD}	150	4	500 KHz	1*10 ⁻⁵	3-8 NA/CM ²					ANALOG DELAY	R. N. Brodersen & S. P. Emmons, "The Measurement of Noise in BCCD", CCD Conference '75, San Diego
P _{CCD}	130	4	10 KHz- 105 MHz	1*10 ^{-3@27°C} 5.5*10 ^{-4@-196°C} 1*10 ^{-3@-243°C} 1*10 ^{-2@-255°C} 2*10 ^{-2@-268°C}						ANALOG DELAY	A. J. Steckl, "Low Temperature Silicon CCD Operation", CCD Conference '75, San Diego
S _{CCD}	100	4	10 KHz	7.5*10 ^{-4@27°C} 4*10 ^{-4@-196°C} 1.4*10 ^{-3@-268°C}						IR SIGNAL PROC.	
B _{CCD}	128	2	1 MHz- 50 MHz	1.8@10 ⁻⁴ -9.34*10 ⁻⁴						ANALOG DELAY	L. J. Micastrro, Internal RCA Report
S _{CCD}	64	3		2*10 ⁻⁴ -1.2*10 ⁻³	1.5 NA/CM ² -5 NA/CM ²					ANALOG DELAY	G. J. Declerck, et al, "Low Dark Current CCD", CCD Conference '76, Edinburgh
P _{CCD}	128	4	180 MHz	2*10 ⁻⁵						ANALOG DELAY	L. J. Esser in "Solid State Imaging", Jespers, De Wiele, & White, Noordhoff, 1976

*TRANSFER GATES IN ACCUMULATION

GLOSSARY OF CCD TERMS

a_T	trap capture cross section
A	active area of potential well (mil^2)
\AA	angstrom (10^{-10} meter)
BCCD	buried channel CCD
C	gate capacitance
C_i	CCD input capacitance
C_{ox}	MOS gate oxide capacitance per unit area
CCD	charge coupled device
CTE	charge transfer efficiency
CTI	charge transfer inefficiency
d_{ch}	effective thickness of channel implant
d_{ox}	oxide thickness
ΔV	two phase clock voltage bias
e	charge transfer inefficiency CTI
eV	electron volt
ϵ_{ox}	permittivity of silicon dioxide
ϵ_{si}	permittivity of silicon
f_c	clock frequency
F	Faraday
J_D	dark current density ($\text{amperes}/\text{cm}^2$)
J_{gd}	dark current density from bulk depletion
J_{gn}	dark current density from neutral bulk
J_{gs}	dark current density from Si-SiO_2 interface
k	Boltzmann's constant ($8.617 \times 10^{-5} \text{ eV}/^\circ\text{K}$)
K_1	electrons per coulomb (6.28×10^{18})
K_2	Faraday's per coulomb (1.036×10^{-5})
K_3	coulombs per electron (1.602×10^{-19})
L_n	carrier diffusion length
MOS	metal oxide semiconductor
μ	micron
n_i	intrinsic carrier concentration
nm	nanometer
N_R	density of recombination - regeneration centers
N_S	number of carriers in a charge packet

N_{SS}	density of fast states
N_{st}	concentration of recombination - regeneration centers at the interface
pf	picofarad
q	electron charge (1.602×10^{-19} coulomb, 1.64×10^{-24} F)
Q_S	charge stored in CCD potential well (electrons)
$S_i-S_iO_2$	silicon-silicon dioxide
SCCD	surface channel CCD
σ_{IN}	rms input noise
σ_{SN}	rms shot noise
σ_{TP}	rms trap noise
σ_{TR}	rms transfer noise
t_d	carrier lifetime
T	temperature ($^{\circ}K$)
v_{th}	carrier thermal velocity
V	volts
V_p	pulse potential applied to CCD gate with respect to adjacent gate
x_d	carrier lifetime

5. SIMULATION DEVELOPMENT

5.1 SIMULATION SOFTWARE ORGANIZATION

The simulation software was written in modular form with over 21 subroutines for each device simulation. The reason for a large number of subroutines is that the program was designed to be run on a mini-computer with at most 28K of memory. This modularity allows for extensive overlaying as well as ease of debugging and changing of the program. Figure 52 is the block diagram of the overlay structure (i.e., the subroutines residing in an overlay) for the delay line and tapped delay line. The main program is responsible for calling in the overlays and maintaining the integrity of common areas. Table 31 is a brief description of each subroutine referenced in Figure 52.

Figure 53 is a block diagram of a linear FM matched filter which was simulated. Figure 54 is the corresponding block diagram of the overlay structure for Figure 53. Table 32 is the brief descriptions of each subroutine referenced in Figure 54.

The random variables used by the program were generated offline onto a mass storage device (magnetic tape). Only standard normal random variates were generated using the direct approach [29]. The random variates used by the program were read from the device and transformed to the appropriate distributions.

Table 33 is a listing of the program questions to the user for the delay line and Table 34 is the corresponding prompting for the linear FM matched filter. Appendix A and B are the listings of the programs for each device.

The devices that can be simulated by the two programs are a delay line, a tapped delay line, and a matched filter. The delay line represents a transformation of the form:

$$g(nT) = af(nT-NT)$$

where NT is the delay (time spent in the device), T the sampling rate and a the perturbation due to the device ($a=1$ correspondence to a lossless device). The tapped delay line (the number of stages is equal to number of taps) represents the samples of a signal being weighted and summed,

$$g(nT) = \sum_{i=1}^N a_i f(nT-iT)$$

where a_i 's are the weights, iT the i th sample of the signal and $g(nT)$ the n th output of a summer. The matched filter (convolver) is made up of four tapped delay lines whose weights have been chosen to be samples of the expected receive signal (weights are correlated/matched in some manner with the expected signal samples). Examples of weights are ± 1 for derivative phase and binary phase waveforms, and linear FM weights (samples of \sin/\cos).

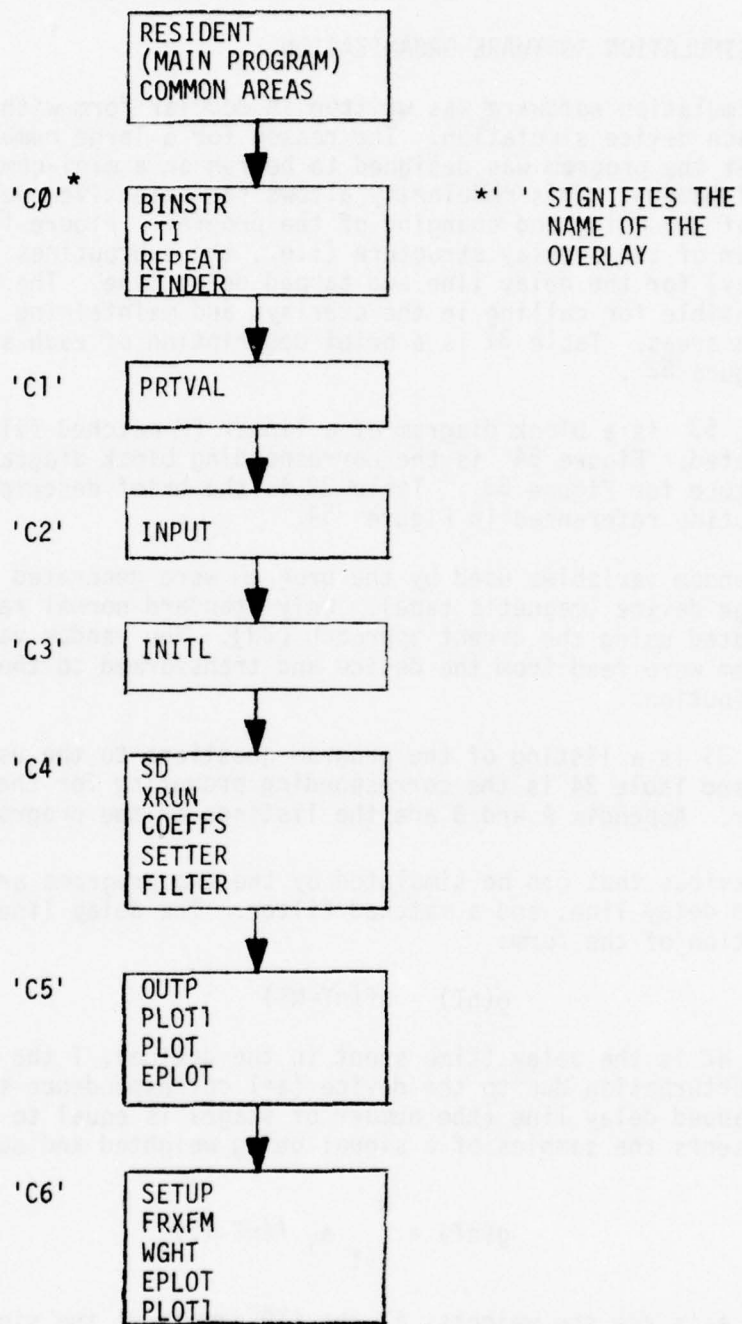
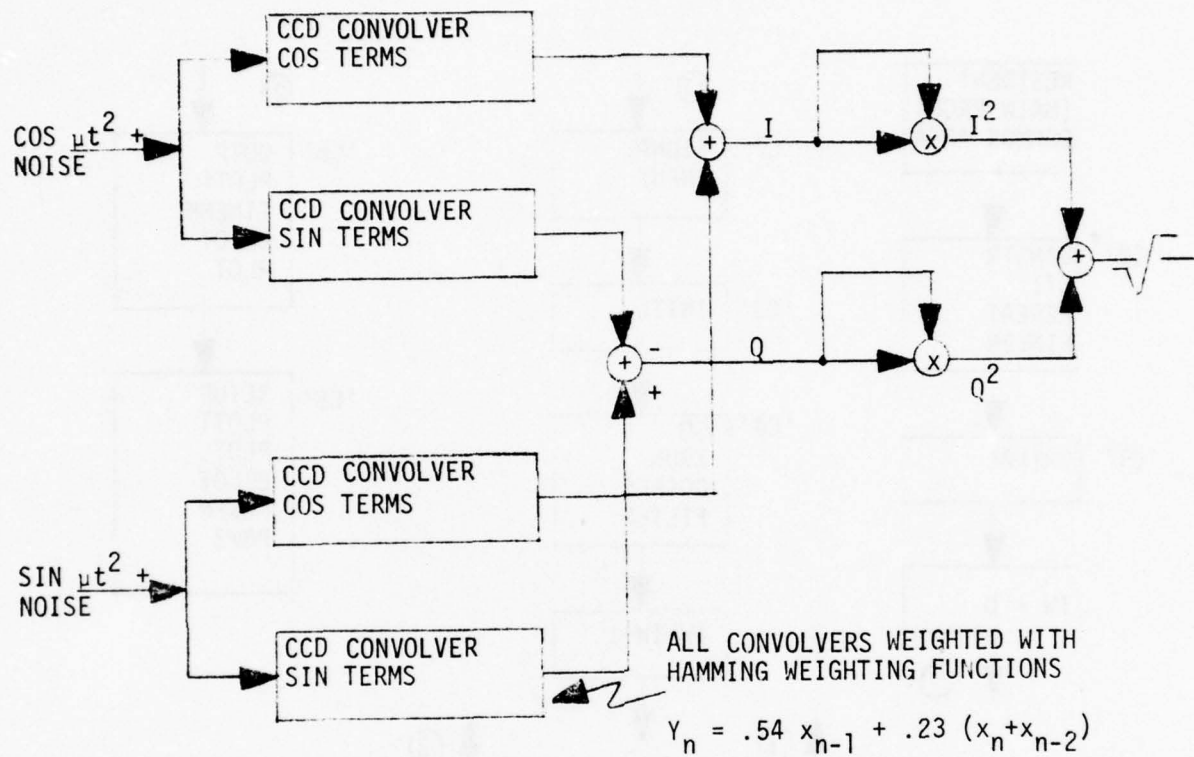


FIGURE 52. BLOCK DIAGRAM OF OVERLAY STRUCTURE FOR SIMULATION MODEL OF DELAY LINE AND TAPPED DELAY LINE

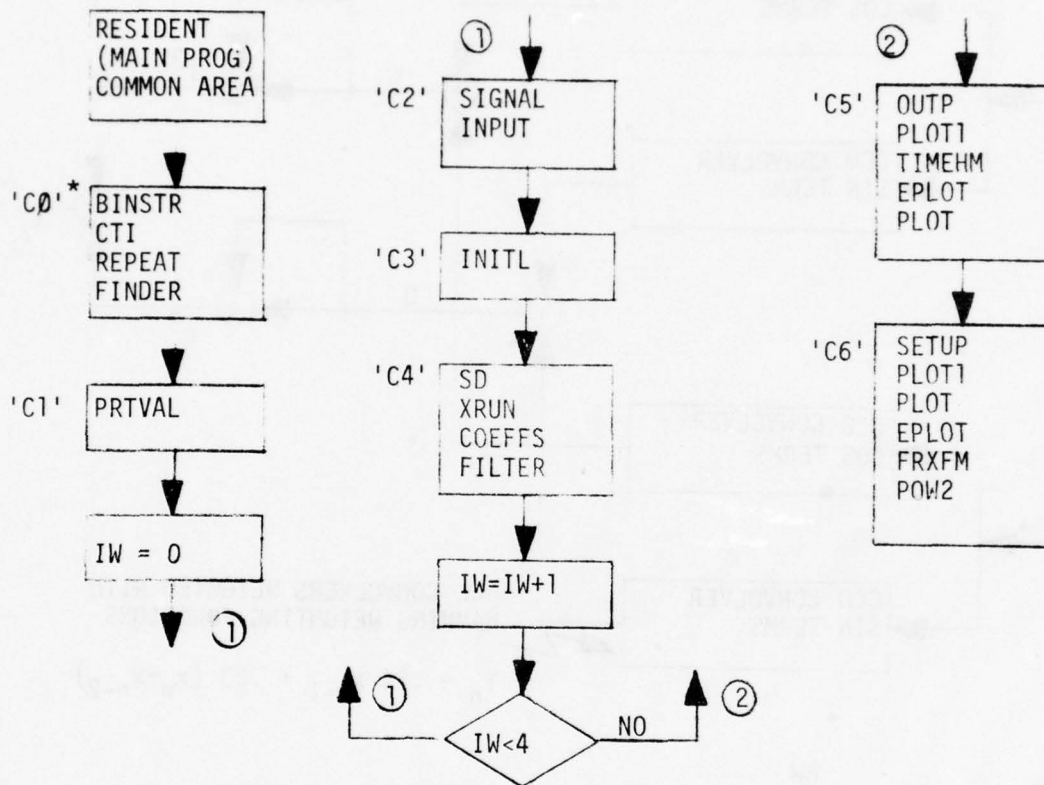


$$\mu = \frac{BW}{2T_p}$$

BW = BANDWIDTH OF THE SIGNAL

T_p = LENGTH OF THE SIGNAL

FIGURE 53. BLOCK DIAGRAM OF LINEAR FM MATCHED FILTER



* ' ' SIGNIFIES THE NAME OF THE OVERLAY

FIGURE 54. BLOCK DIAGRAM OF OVERLAY STRUCTURE FOR SIMULATION MODEL OF LINEAR FM MATCHED FILTER

TABLE 31. A BRIEF DESCRIPTION OF THE SUBROUTINES REFERENCED IN FIGURE 52

BINSTR - Is responsible for interrogating the user as to the structure of the CCD (area, length, temperature, etc.), the input waveform (duration, amplitude, pulse/sinusoids, etc.), and the outputs desired for each run. Table 33 gives the questions asked by the subroutine.

COEFFS - Either computes the tap weights for a CW signal or reads in the tap weights from .DAT slot +4 for an arbitrary transversal filter. Appendix C gives the listing of a design program developed in [30].

CTI - Computes the Charge Transfer Inefficiency (CTI) for either buried or surface devices. The CTI is a function of background charge.

EPLOT - Is a general plot routine which plots an array of values on a scale of 0 to 100 dB normalized to the maximum value of the array.

FILTER - Computes the filter response by summing the weighted outputs of each cell on the second clock pulse.

FINDER - Performs bookkeeping needed for multiple runs. That is, the program has the ability to alter two of six variables.

FRXFM - Performs a decimation in frequency FFT.

INITL - Initializes the CCD before the device sees the input signal.

INPUT - Forms the input waveform. The user has the option of no signal, pulse of given length and amplitude, sinusoidal of given length and amplitude. The subroutine changes the formed input from voltage to electrons with either a linear transformation or a non-linear transform.

OUTP - Converts the output of the device from electrons to voltage storing the results on .DAT Slot +2. The subroutine is also responsible for the addition of the output noise.

PLOT - Is a general plot routine which plots out linearly a given array of data on a 132 column line printer. It is used in the program to plot the input and output responses versus time.

PLOT1 - Is a bookkeeping routine which calculates the sampled mean, variance, minimum and maximum for a specified array of data.

PRTVAL - Calculates the means and standard deviations for the CCD noise sources.

REPEAT - Performs bookkeeping for multiple runs. See subroutine FINDER.

SD - Calculates the cumulative means and standard deviations for the normal noise sources.

SETUP - Is responsible for putting the data in proper form so that different outputs maybe obtained (i.e., FFT, weighting, etc.).

TABLE 31. CONTINUED

WGHT - Performs either Hamming or Hanning weighting on a specified array of data. The weighting is in the time domain to allow suppression of the sidelobes in the frequency domain.

XRUN - Performs the bookkeeping of transferring the electrons from well to well and stage to stage. The bookkeeping includes the addition of the different noise sources and dark current.

TABLE 32. A BRIEF DESCRIPTION OF THE SUBROUTINE REFERENCED IN FIGURE 54

BINSTR - Is responsible for interrogating the user as to the structure of the CCD (area, length, temperature, etc.), the input waveform (bandwidth, duration phase, amplitude, etc.), and the outputs desired for each run. Table 34 gives the questions asked by the subroutine.

COEFFS - Computes the tap weights to match a linear FM signal.

CTI - Computes the Charge Transfer Inefficiency (CTI) for either surface or buried devices. The CTI is a function of background charge.

EPlot - Is a general plot routine which plots out an array of values on a scale of 0 to 100 dB normalized to the maximum value of the array.

FILTER - Computes the filter response by summing the weighted outputs of each cell on the second clock pulse.

FINDER - Performs bookkeeping needed for multiple runs. That is, the program has the ability to alter two of six variables of the CCD.

FRXFM - Performs a decimation in frequency FFT.

INITL - Initializes the CCD before the device sees the input signal.

INPUT - Forms the input waveform. The user has the options of signal-to-noise, bandwidth, pulse length, phase of the return, noise only and target only. The subroutine changes the formed input to electrons from voltage with either a linear or non-linear transformation.

OUTP - Converts the output to voltage from electrons. The subroutine also combines the four separate signals from the four match filters, squares the Inphase and Quadrature channels.

PLOT - Is a general plot routine which prints out linearly a given array of data on a 132 column line printer. It is used in the program to plot the input and output responses versus time.

PLOT1 - Is a bookkeeping routine which calculates the samples mean and variance, and also finds the minimum and maximum values for a specified array of data.

POW2 - Computes the power of 2 which is greater than or equal to a specified number. Is a utility program for the FFT program.

PRTVAL - Calculates the means and standard deviations for the CCD noise sources.

REPEAT - Performs bookkeeping for multiple runs. See subroutine FINDER.

SD - Calculates the cumulative mean and standard deviations for the normal noise sources.

TABLE 32. CONTINUED

SETUP - Is responsible for putting the data in proper form so that different outputs may be obtained (i.e., FFT, weighting, etc.).

TIMEHM - Performs Hamming weighting on a specified array of data. The weighting is done on the frequency domain to suppress the time response sidelobes.

XRUN - Performs the bookkeeping of transferring the electrons from well to well and stage to stage. The bookkeeping includes the addition of the different noise sources and dark current.

TABLE 33. QUESTIONS ASKED BY THE DELAY LINE AND TAPPED DELAY LINE SIMULATION

CREATE NEW FILE ON DAT SLOT +2 Y = 0 N = 1

If user wants the output saved for later use, response should be a 0. If not, then 1. The data will be stored on file TEMP02.DAT for a response of 1.

NAME OF FILE XXXXXX.DAT

If response to above was a 0, then user must give the name of the file. Only restrictions are that the file name cannot begin with a numeric and all spaces must be filled in with a character or a blank.

THE NUMBER OF STAGES IN THE CCD (F10.0)

User specifies the number of stages from 1 to 600. The upper limit is only restricted by core size.

SD OF THE INITIAL STATE (F10.0)
IF < 0, THEN NO BACKGROUND VOLTAGE ADDED

The user specifies the number of electrons for the standard deviation of the initial state of the CCD. If a negative number is given, the system will not add in background charge to the input signal.

SURFACE OR BURIED DEVICE (0 OR 1)

The user specifies a 0 for surface device and a 1 for buried device.

AREA OF THE WELL IN MIL**2

The user specifies the area of each gate.

% OF BACKGROUND CHARGE
< 0, THEN SPECIFY TRANSFER LOST

The user specifies the % of background charge which determines the charge transfer inefficiency. If the number specified is < 0, then the next question will ask for the lost.

FRACTION LOST EACH TIME .XXXX

If the response to the above question was negative, then user specifies the fraction lost on each transfer.

CLOCK SAVING VOLTAGE

Self explanatory.

TABLE 33. CONTINUED

PLOT OF INPUT AND OUTPUT Y=0 N=1

If user wants a plot of input and output signals, response is a zero.
If not, then a 1.

FFT OF OUTPUT Y=1 N=0

If user specifies a 1, then an FFT of the output signal is plotted. If
he specifies a 0, then no FFT is performed.

CLOCK FREQUENCY (F10)

User responds with the sampling frequency of the device.

THE LENGTH OF TIME OF THE RUN < 1201

The number of samples from the input signal that are processed by the
CCD.

PRINT OUT INTERMEDIATE VALUES NO = 0 YES = 1

For debugging purposes, the user has the option of examining the
contents of the wells.

FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N = 0 Y = 1

A DC component corresponding to feedthrough voltage is added if
response is a 1. If a 0, none is added.

DURATION OF THE SIGNAL MIN = 0 MAX = 1200

The number of samples of the input which will contain a signal versus
noise only.

TYPE OF SIGNAL PULSE = 0 SIN = 1

User has option of two types of signals: a pulse (response 0) or
sinusoidals (response 1).

** If response to above is 0, then next question is:

INPUT LEVEL OF SIGNAL MAX = VALUE VOLTS

User specifies the amplitude of the pulse in volts.

** If response to above is 1, then the next question is:

OF SINUSOIDALS F10 < 5

User can specify up to 5 sinusoidals input.

TABLE 33. CONTINUED

FREQUENCY OF THE i SIGNAL (HERTZ)

User specifies in hertz the frequency of the i^{th} sinusoidal.

AMPLITUDE (% OF WELL) OF THE i SIGNAL

User specifies in terms of % of full well the amplitude of the i^{th} sinusoidal.

DC BIAS (% OF WELL) TERM ADDED TO INPUT #10

User responds with a DC bias added to input signal in terms of % of a full well.

NON-LINEAR INPUT WARPING Y=0 N=1

User has option of using a linear input structure (1) or a non-linear input response to the CCD.

FILTER RESPONSE COMPUTED N=0 Y=1

User has option of obtaining the output of a delay line (0) or the output from a tapped delay line (1). (Coefficients read in from DAT Slot +4 in E15.8 format.)

DARK CURRENT ADDED Y=0 N=1

Dark current added Yes = 0 No = 1.

** If response to above is 0, then next 4 questions below are asked. If a 1, then next 4 questions are omitted.

AMBIENT TEMPERATURE IN DEGREES °C

Self explanatory.

DO YOU WANT TO HOLD THE SIGNAL FOR ANY TIME Y=0 N=1

User has option of obtaining the response when the signal has been put in storage mode.

** If response to above question is 0, then the next 2 questions are asked. If not, then they are shipped.

TIME (SEC) LEFT IN DELAY LINE

Number of seconds left in delay line.

FREQUENCY CLOCK SIGNAL OUT

Output clock frequency after the storage time has been completed.

TABLE 33. CONTINUED

MULTIPLE RUN Y=# OF CHANGES N=0

User has option of changing a parameter between runs. If response is > 0, then number of runs with this variable changed. If 0, then none.

** If response to above is = 0, then the next 5 questions are omitted.

WHICH INPUT IS TO BE CHANGED

1 = NUMBER OF STAGES, 2 = SURFACE/BURIED
3 = AREA OF WELL, 4 = STORAGE TIME (SEC)
5 = CLOCK FREQUENCY, 6 = AMBIENT TEMPERATURE

Response is the variable to be changed.

INPUT THE i VALUE

Response is to input the value for the ith run.

SECOND VARIABLE CHANGING Y = NUMBER N = 0

Response is the number of times the second variable is to be changed. If 0, then none.

** If response to above 0, then skip next 2 questions.

WHICH INPUT

The variable number to be changed.

INPUT THE i VALUE

The value for the ith change of second variable.

RUN WITH NOISE Y=0 N=1

Run with the noise sources or not. Yes = 0 No = 1.

** If response to above is 1, then the program begins a run.

SELECT THE PARTICULAR NOISE INPUTS N=0 Y=1

User has option of keeping all noise sources in the program (0) or selecting which noise sources are to be input (1).

** If response to above is 0, then the program begins a run.

ADD IN INPUT NOISE Y = 0 N = 1

Yes = 0, No = 1.

TABLE 33. CONTINUED

ADD IN SHOT NOISE $Y = 0 \ N = 1$

Self explanatory.

ADD IN TRANSFER NOISE $Y = 0 \ N = 1$

Self explanatory.

ADD IN THE OUTPUT NOISE $Y = 0 \ N = 1$

Self explanatory.

ADD IN THE FILTER NOISE $Y = 0 \ N = 1$

Self explanatory.

ADD IN THE TRAP NOISE $Y = 0 \ N = 1$

Self explanatory.

** Program begins a run.

TABLE 34. QUESTIONS ASKED BY THE LINEAR FM FILTER SIMULATION

CREATE NEW FILE ON DAT SLOT +2 Y = 0 N = 1

If user wants the output saved for later use, response should be a 0. If not, then a 1. The data will be stored on file TEMP02.DAT for a response of 1.

NAME OF FILE XXXXXX.DAT

If response to above was a 0, then user must give the name of the file. Only restrictions are that the file cannot begin with a numeric and all spaces must be filled in with a character or a blank.

THE NUMBER OF STAGES IN CCD (F10.0)

User specifies the number of stages from 1 to 600. The upper limit is only restricted by core size.

SD OF THE INITIAL STATE (F10.0)

IF < 0, THEN NO BACKGROUND VOLTAGE ADDED

The user specifies the number of electrons for the standard deviation of the initial state of the CCD. If a negative number is given, the system will not add in background charge to the input signal.

NOISE + TARGET 0

NOISE 1

TARGET 2

The user response with the input configuration. A = 0, the user wishes a target and noise as an input. If response is a 1, only noise injected at input and finally, if response is a 2, then only a target with no noise at input to CCD.

SURFACE OR BURIED (0 OR 1)

The user specifies a 0 for surface device and a 1 for buried device.

AREA OF THE WELL IN MIL**2

The user specifies the area of each gate.

% OF BACKGROUND CHARGE

< 0, THEN SPECIFY TRANSFER LOSS

The user specifies the % of background charge which determines the charge transfer inefficiency. If the number specifies is less than 0, then the next question will ask for the loss.

TABLE 34. CONTINUED

FRACTION LOSS EACH TIME .XXXX

If the response to the above question was negative, then the user specifies the fraction loss on each transfer.

CLOCK SWING VOLTAGE

The user specifies the clock swing voltage of the device.

PLOT OF INPUT AND OUTPUT Y=0 N=1

If user wants a plot of input and output signals, response is a zero. If not, then a 1.

HAMMING WEIGHTING TO OUTPUT Y=0 N=1

If user wants Hamming weighting applied such that the time sidelobes are suppressed, then a 0 is response. If not, then a 1.

FFT OF OUTPUT Y=1 N=0

User responses with a 0 if no FFT of output is wanted and with a 1 if it is wanted.

CLOCK FREQUENCY (F10.0)

User responds with the sampling frequency of the device.

THE LENGTH OF TIME OF THE RUN < 1201

The number of samples from the input signal that are processed by the CCD.

PRINT OUT INTERMEDIATE VALUES NO=0 YES=1

For debugging purposes, the user has the option of examining the contents of the wells.

FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1

A DC component corresponding to feedthrough voltage is added if response is a 1. If a 0, none is added.

DURATION OF THE SIGNAL MIN=0 MAX=1200

The number of samples of the input which will contain a signal versus number of samples with no signal. The signal samples are centered about the middle of the sampling window.

TABLE 34. CONTINUED

BANDWIDTH OF THE LINEAR FM (HERTZ)

The bandwidth of the linear FM signal is specified by the user in hertz (< sampling frequency bandwidth).

SIGNAL TO NOISE RATIO AT IF (dB)

The user specifies the signal to noise ratio of the target at input to the device.

PHASE ANGLE OF TARGET DEGREES

The user specifies the phase angle of the target in degrees (0-360).

DC BIAS (% OF WELL) TERM ADDED TO INPUT F10

User responds with a DC bias added to input signal in terms of % of a full well.

MEAN ERROR IN TAP WEIGHTS

User specifies the mean tap weight accuracy.

SD OF THE TAP ERROR

User specifies the standard deviation about the above mean value.

AMBIENT TEMPERATURE IN DEGREES °C

User specifies the ambient temperature that the device will operate at.

DARK CURRENT ADDED Y=0 N=1

Dark current added Yes = 0 No = 1.

MULTIPLE RUN Y=# OF CHANGES N=0

User has option of changing a parameter between runs. If response is > 0, then number of runs with this variable changed. If 0, then none.

** If response to above is 0, then the next 5 questions are omitted.

WHICH INPUT IS TO BE CHANGED

1 = NUMBER OF STAGES, 2 = SD OF THE TAP WEIGHTS
3 = AREA OF WELL, 4 = MEAN OF THE TAP WEIGHTS
5 = CLOCK FREQUENCY, 6 = AMBIENT TEMPERATURE

User response is the variable to be changed.

TABLE 34. CONTINUED

INPUT THE i VALUE

Response is to input the value for the i^{th} run.

SECOND VARIABLE CHANGING $Y = \text{NUMBER } N = 0$

Response is the number of times the second variable is to be changed.
If \emptyset , then none.

** If response to above \emptyset , then skip next 2 questions.

WHICH INPUT

The variable number to be changed.

INPUT THE i VALUE

The value for the i^{th} change of second variable.

RUN WITH NOISE $Y=0$ $N=1$

Run with the noise sources or not. Yes = 0 No = 1.

** If response to above is 1, then the program begins a run.

SELECT THE PARTICULAR NOISE INPUTS $N=0$ $Y=1$

User has option of keeping all noise sources in the program (0) or selecting which noise sources are to be input (1).

** If response to above is 0, then the program begins a run.

ADD IN INPUT NOISE $Y = 0$ $N = 1$

Yes = 0, No = 1.

ADD IN SHOT NOISE $Y = 0$ $N = 1$

Self explanatory.

ADD IN TRANSFER NOISE $Y = 0$ $N = 1$

Self explanatory.

ADD IN THE OUTPUT NOISE $Y = 0$ $N = 1$

Self explanatory.

ADD IN THE FILTER NOISE $Y = 0$ $N = 1$

Self explanatory.

TABLE 34. CONTINUED

ADD IN THE TRAP NOISE $Y = 0$ $N = 1$

Self explanatory.

** Program begins a run.

5.2 SIMULATION OPERATIONAL CAPABILITIES

The simulation was designed to model the transfer of electrons from stage to stage in a CCD delay line. The simulation accomplishes this by transforming an input voltage to an electron packet. The packet is then moved through the various stages of the device with the appropriate noise perturbations added to the packet of charge at each clock pulse. The noise sources that have been incorporated in the model are the input, output, trap, shot, transfer and filter coefficient inaccuracies. Dark current has also been incorporated in the model. The noise sources have been made functions of device (surface or buried), area, clock voltage, clock frequency, temperature.

The simulation has the capabilities of operating in two modes: delay line and tapped delay line. The delay line can be operated in either a continuous mode or a storage mode. The continuous mode corresponds to clocking the data through the device at one clock rate. The storage mode corresponds to clocking the data into the device, storing for a given length of time and then clocking the data out.

These modes enable a user to simulate a single device, such as a delay line, FIR filter or more complex devices such as chirp filters or doppler filter banks by interconnecting the simple devices by relatively minor programming connections of the individual modules of the computer programs. This would thus enable the user to test the critical parameters of a CCD in a system with relative ease.

6.0 SIMULATION RESULTS

6.1 DELAY LINE TESTS - STORAGE AND CONTINUOUS MODES

6.1.1 Effects of Charge Transfer Inefficiencies on Device Non-Linearities

The Charge Transfer Inefficiency (CTI) leaves behind at each transfer a packet of charge which is signal dependent. In the simulation model this CCD characteristic was modeled as a percentage of the charge being subtracted off from the charge packet which is being transferred from well to well. Transferred electrons = electrons to be transferred - the percent of the electrons being transferred, and the electrons left behind (residue) = the percent of the electrons being transferred. The possible non-linear distortions of the CTI on a signal were examined by inputting a 1500 Hz sine wave with a 1.3 volt amplitude riding on a 1.4 volt bias. A full well of the CCD has a corresponding voltage of 2.8 volts. The peak value of the input signal is approximately 97% of a full well. The length of the CCD line was 310 stages with operating characteristics of 6 KHz clock, a gate area of 2 mil², a clock swing voltage of 10 volts, and a temperature of 27°C. The dark current and the other noise sources were not added. Figure 55 is a plot of the Hamming weighted power spectrum of the CCD's output. An extreme value of the CTI (1×10^{-3}) was used. As can be seen in Figure 55, the harmonics generated are more than 100 dB down from the peak representing 1.5 KHz. (In all the following figures, the curves on the power spectrums were normalized to the peak of that curve.) The sharp spike in Figure 55 is caused by the Hamming weighting which spreads the DC term thus not allowing complete cancellation when the mean is subtracted before finding the power spectrum. (In Figures 55 and 56, the 128 frequency sample corresponds to the sampling rate.) In conclusion, since the level of non-linear distortion observed in Figure 55 is so low for even an extreme value of the CTI, the CTI can be ruled out in the model as a possible contributor to non-linear distortions.

6.1.2 Non-Linear Effects of Dark Current

Having observed that the CTI does not contribute to the non-linearity of the device, the remaining possible contributor in the model is the dark current. The dark current distortion would arise when the signal is clipped due to the potential wells filling up with dark current. The effect of clipping should be analogous to amplitude clipping in a limiter. To examine the possible distortions, a 7 Hz sine wave with a 1.3 volt amplitude riding on a 1.4 volt bias (full well corresponds to 2.8 volts) was inputted into a 600 stage CCD delay line. The operating characteristics of the device were a clock swing voltage of 10 volts, a temperature of 27°C, and a gate area of 2 mil². The CTI was set equal to zero (no loss due to charge transfer inefficiency) and the noise sources were not added in. The sampling rate of the device was 30 Hz which corresponds to each sample of the input being in the device for 20 seconds. Figure 56 is a plot of the power spectrum of the output with Hamming weighting. As can be seen from Figure 56, the second harmonics were approximately only 13 dB down from the peak spectrum component at 7 Hz. (As in Figure 55, the Hamming weighting spread the DC term thus not allowing full cancellation; and the spike near DC is the result). Thus, the distortions due to dark current can become severe if clipping is allowed to

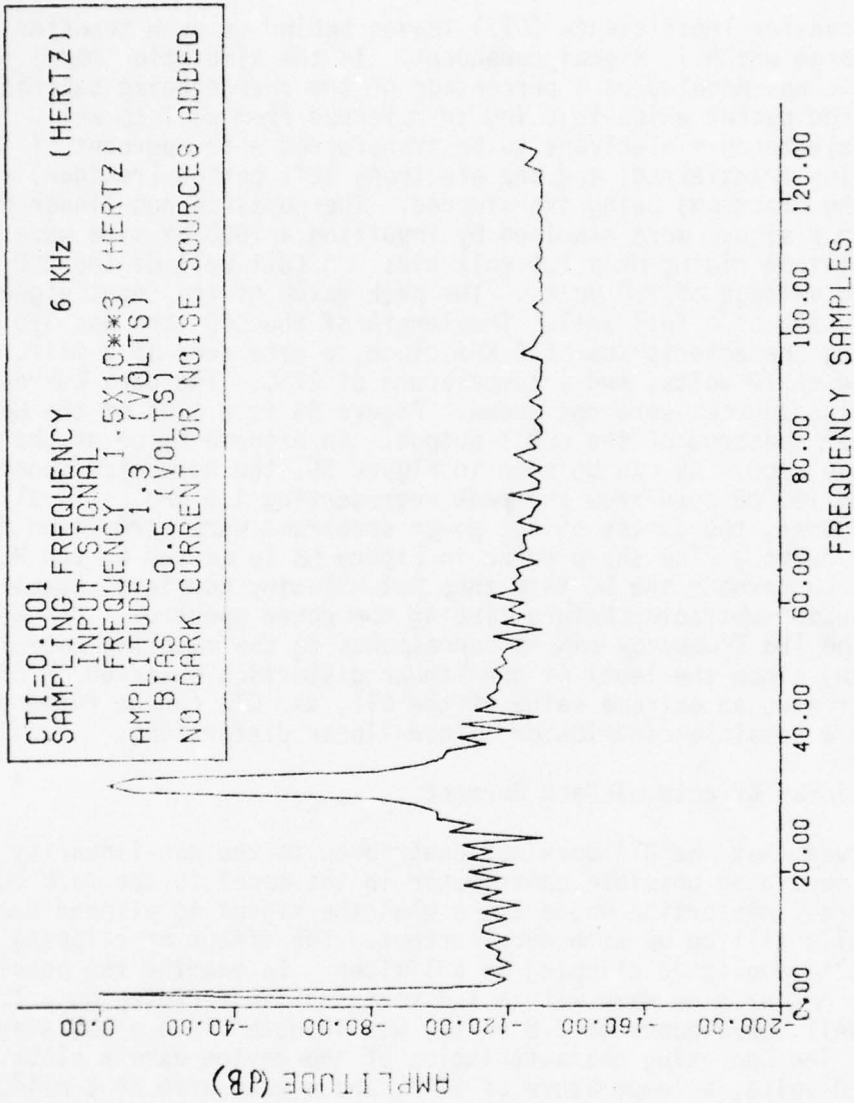


FIGURE 55. AMPLITUDE VERSUS CLOCK RATE OF THE OUTPUT OF A CCD DELAY LINE WITH A SINUSOIDAL INPUT FOR A LARGE CHARGE TRANSFER INEFFICIENCY (CTI = 0.001)

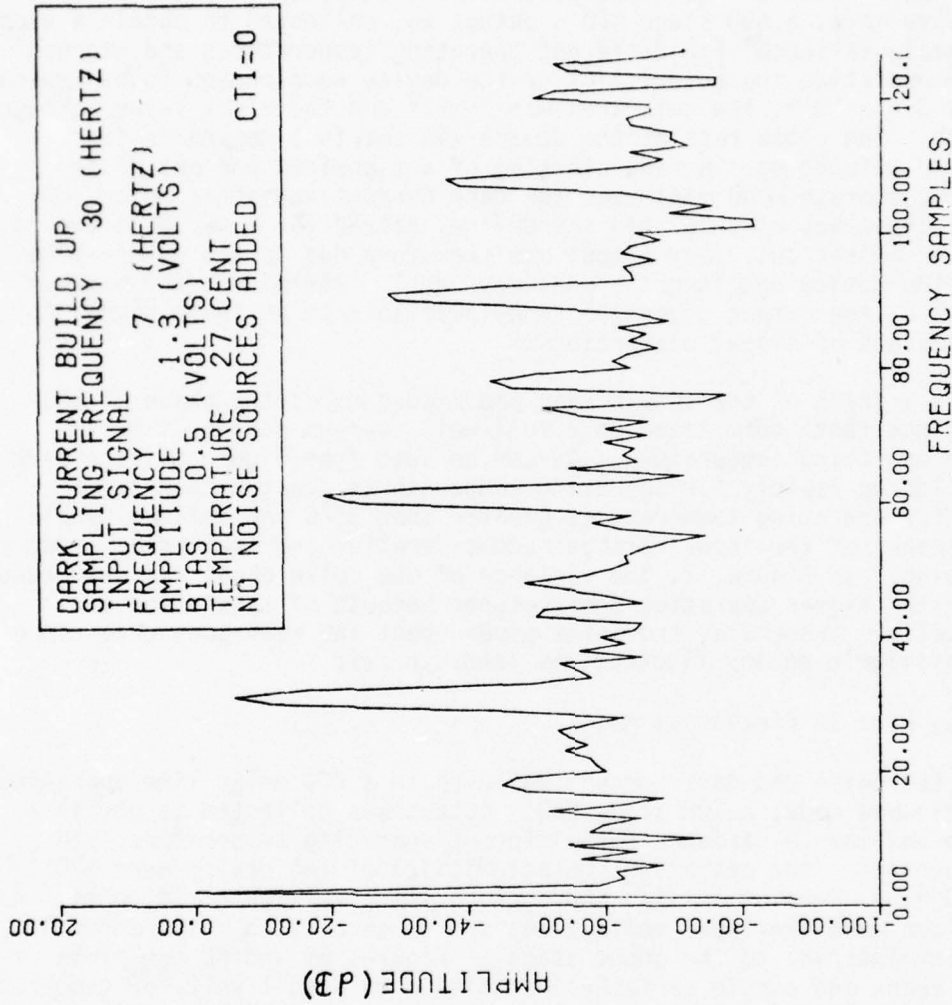


FIGURE 56. AMPLITUDE VERSUS CLOCK RATE OF THE OUTPUT OF A CCD DELAY LINE WITH A SINUSOIDAL INPUT WITH DARK CURRENT BUILD-UP

occur. The degree of clipping and its frequency is related to the operating parameters of the device and the input signal. In the discussion below, the operating parameters are examined.

6.1.3 Delay Line In Storage Mode

To examine the effects of noise and dark current build-up in a CCD delay line in the storage mode, a 600 stage CCD's output was collected to obtain a sample mean and sample variance* for different operating temperatures and storage times. The operating characteristics of the device were chosen to be typical. The CTI was 3.6×10^{-4} , the gate area was 2 mil^2 and the clock swing voltage was 10 volts. The clock rate of the device was set to 1 Megahertz for inputting and outputting. A fast clocking of a signal in and out of the device in the storage mode minimizes the dark current and other noise sources. A zero volt input was clocked into the device, stored for a variable amount of time, and clocked out. Any output was therefore due to the internal noise sources of the device and is not signal dependent. Therefore, the measure of the noise at the output gives the range available to an input signal for different amounts of signal distortions.

Figure 57 is a graph of the sample mean and Figure 58 is the graph of the sample variance (both normalized to a full well) versus storage time in seconds and operating temperature. As can be seen from Figure 57, the dark current builds up rapidly for operating temperatures greater than 35°C . Therefore, for operating temperatures greater than 35°C the maximum usable amplitude (peak) of the input voltage becomes smaller and smaller in order to avoid clipping. In Figure 58, the variance of the noise about the mean tends to zero for the higher operating temperatures because of saturation of potential wells. Therefore, the noise power about the mean goes zero since the range available to any fluctuations tends to zero.

6.1.4 Delay Line In Continuous Mode

To examine the noise and dark current build-up in a CCD delay line operating in the continuous mode, a 128 stage CCD's output was collected to obtain a sample mean and sample variance for different operating temperatures and clock frequencies. The operating characteristics of the device were a CTI of 3.6×10^{-4} , an area of 2 mil^2 , and a clock swing voltage of 10 volts. As in the storage mode the input voltage was set to zero (zero volts added at each sampling interval to the input stage). Figures 59 and 60 are plots of the sample means and sample variances normalized to a full well for temperatures in the range of -55°C to $+125^\circ\text{C}$ and clock frequencies of 5 to $5 \times 10^5 \text{ Hz}$. As

*
$$\text{Sample Mean} = \sum_{i=1}^N x_i / N \text{ where } x_i \text{ are the data samples and } N \text{ is the number to be averaged.}$$

$$\text{Sample Variance} = \sum_{i=1}^N (x_i - \bar{X})^2 / (N-1) \text{ where } x_i \text{ and } N \text{ are same as for sample mean and } \bar{X} \text{ is the sample mean defined above.}$$

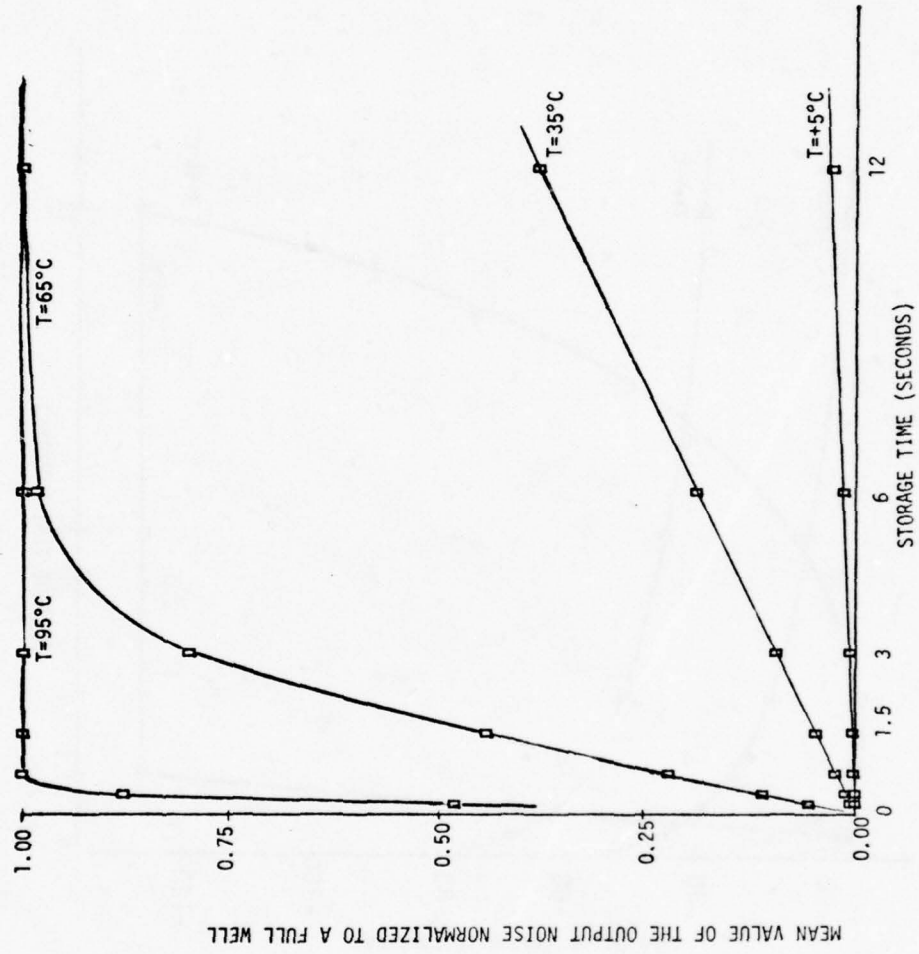


FIGURE 57. MEAN VALUE OF OUTPUT NOISE NORMALIZED TO FULL WELL VERSUS STORAGE TIME VERSUS TEMPERATURE FOR A CCD DELAY LINE IN STORAGE MODE

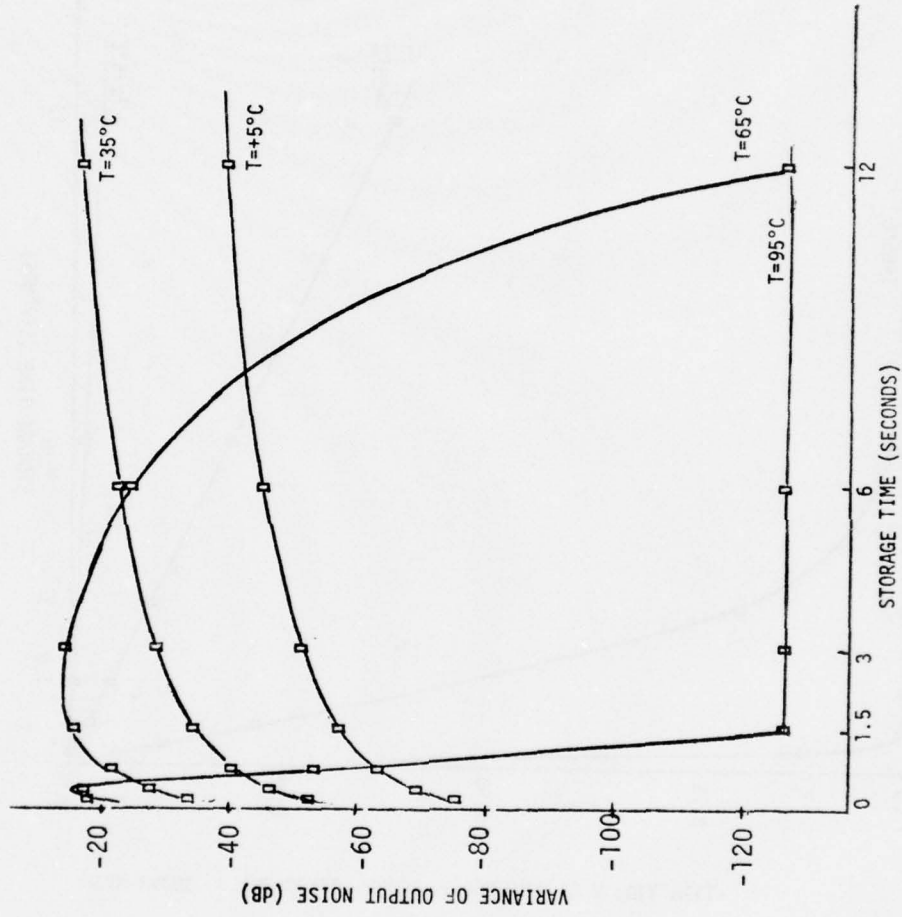


FIGURE 58. VARIANCE OF THE OUTPUT NOISE VERSUS STORAGE TIME VERSUS TEMPERATURE FOR A CCD DELAY LINE IN STORAGE MODE

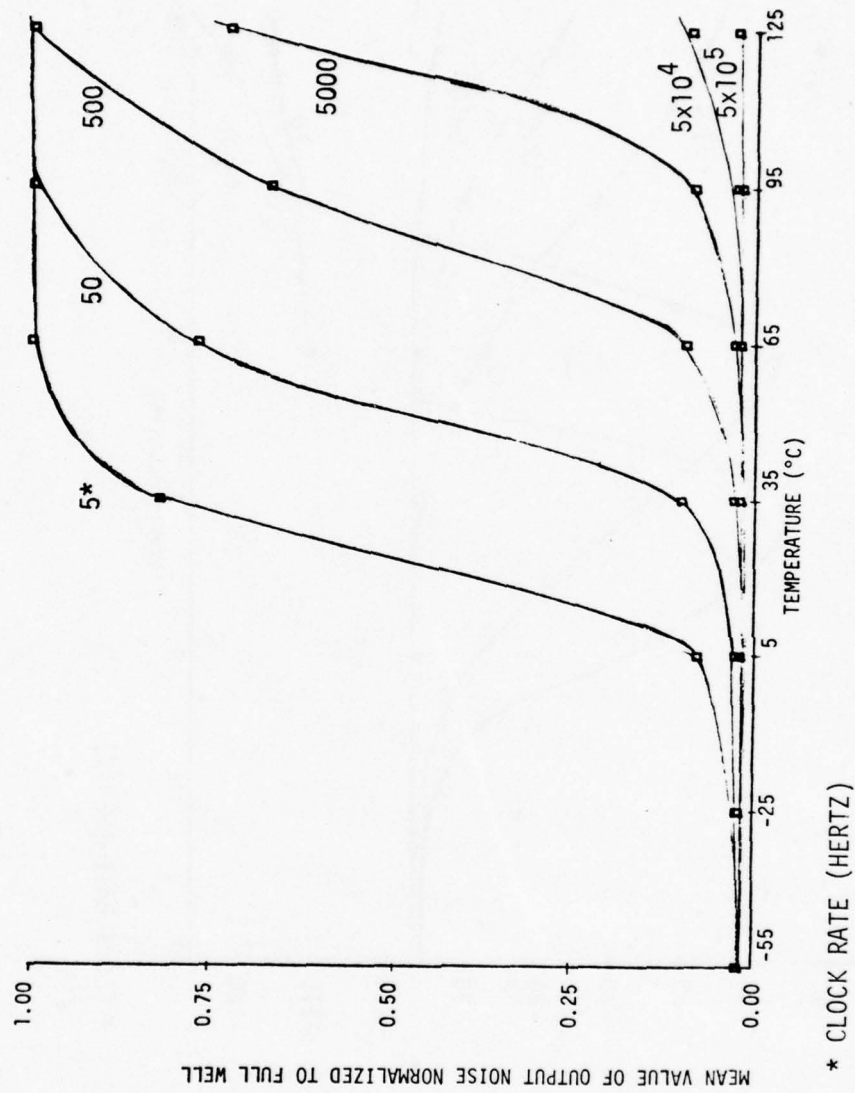


FIGURE 59. MEAN VALUE OF OUTPUT NOISE NORMALIZED TO FULL WELL VERSUS TEMPERATURE VERSUS CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE

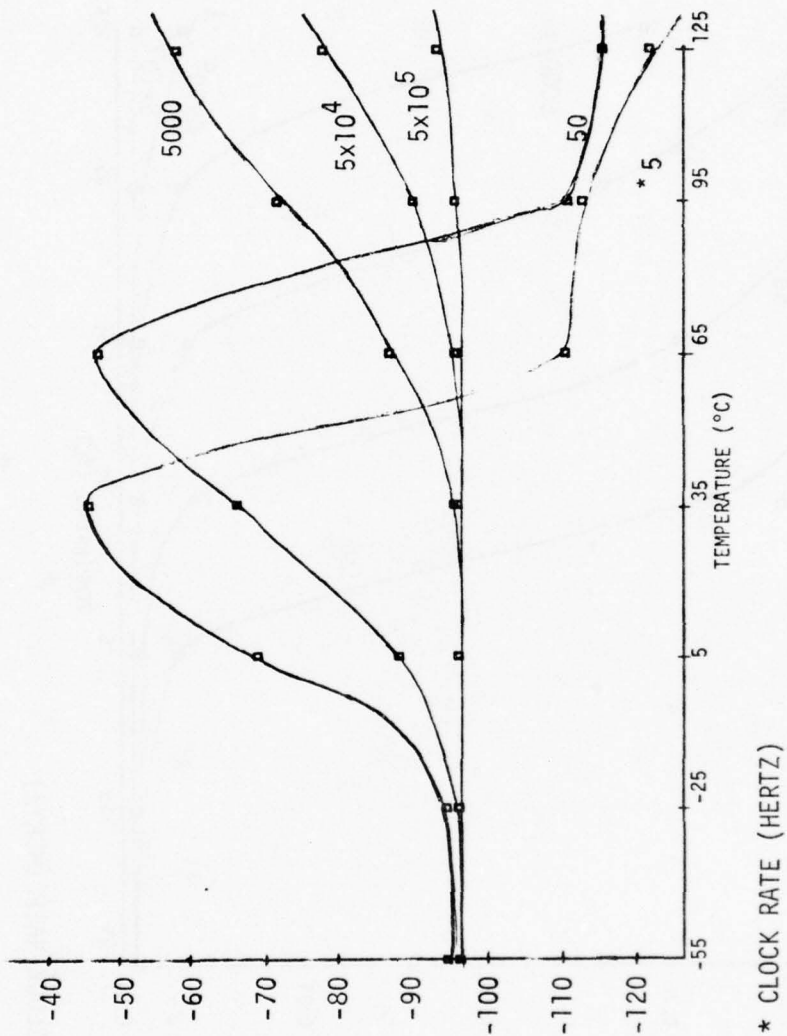


FIGURE 60. VARIANCE OF OUTPUT NOISE VERSUS TEMPERATURE VERSUS CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE

observed in the storage mode, the dark current and noise builds up to occupy the full well which causes the variance to go to zero. For a given set of parameters, the variances for the continuous mode are not as large as the storage mode. This is due to the dark current contributions in the continuous mode being averaged over a large number of independent wells while in the storage mode each output sample contains the dark current build-up of a different well.

6.1.5 Number of Stages, Temperature and Clock Rate

To examine the noise and dark current build-up in a CCD delay line operating in the continuous mode for different number of stages and clock rates, the output was collected and the sample mean and variance were computed for a CCD operating at a temperature of 27°C, CTI of 3.6×10^{-4} , an area of 2 mil², and a clock swing voltage of 10 volts. As in the discussion above, zero input voltage was added to the input structure. Figures 61 and 62 are plots of the sample mean and variance normalized to a full well for delay lines of length 16 to 512 and clock frequencies from 50 to 50,000 Hz.

As can be seen from Figure 61, at low clock frequencies, the clock rate must be increased in order to maintain a given noise level for the same number of stages. This effect holds up to a clock rate of about 1500 Hz for the CCD parameters used.

6.2 LINEAR FM MATCHED FILTER SIMULATIONS

The foregoing simulations have examined the CCD operation as a delay line either in the storage mode or the continuous mode. In order to evaluate the CCD operating as a tapped delay line, the device was configured in a linear FM matched filter system. This called for the simulation of four different tapped delay lines (Figure 63) for the complex I and Q channels of the filter. The coefficients of the delay line were modified with Hamming weighting to reduce the time sidelobes of the output.

In Figures 64 through 108, the number of input samples was 512 with the length of the individual CCD tapped delay lines set at 129. The matched weights on each tapped delay line were modified by Hamming weighting to reduce the time sidelobes. The Time*Bandwidth product was a constant 64.5 in all the figures. That is, the argument of the sine or cosine waveform at each tapped delay line was $\text{Bandwidth} * \text{Time}^2 / 2 * \text{Length of the signal}$ where the length of the signal was 129/clock frequency which gives a Time * Bandwidth product of $\text{Bandwidth} * 129/\text{clock frequency}$ (Figure 63). The ratio of Bandwidth to clock frequency was fixed in order to keep the desired product of 64.5. The operating characteristics of the devices were 2 mil² for gate area and a clock swing voltage of 10 volts.

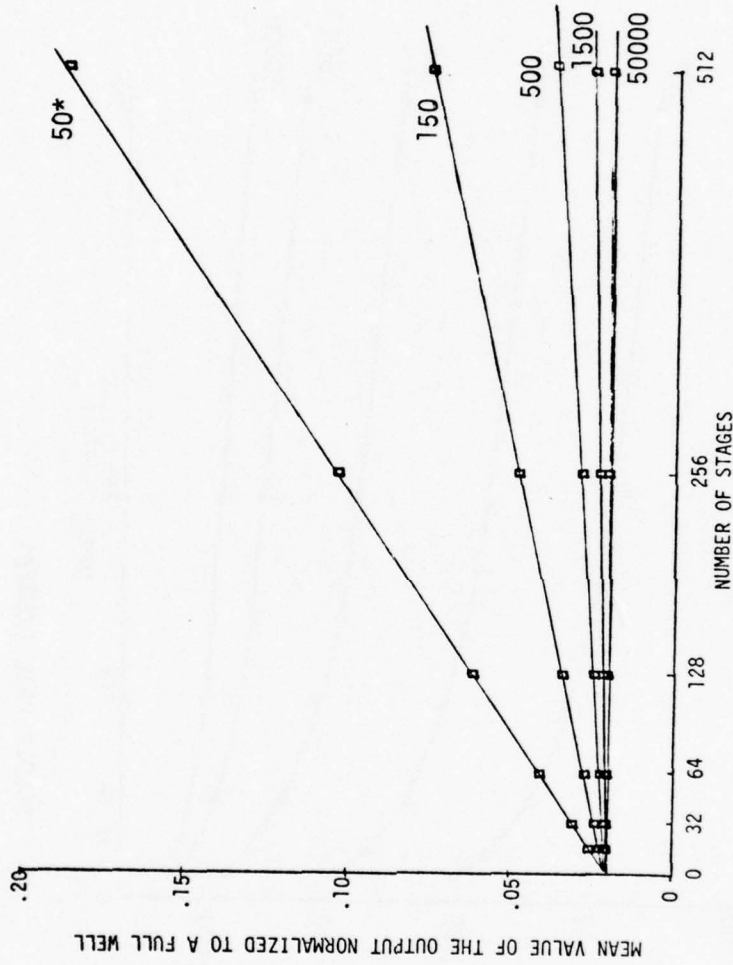
In Figures 66 - 108, the plots are normalized to the peak time response. The reason for including the actual time plots is that in comparing different operating temperatures, clock frequencies, and CTI's on the outputs, the actual data better reflects the degree of spreading and sidelobe levels than a tabular summary.

Figure 64 is a plot of the sidelobe level of the output of the matched filter versus temperature in the ranges of -55°C to 125°C and clock rates from 50 to 150 KHz. The sidelobe level for temperatures less 5°C is fairly constant. However as the temperature is increased, the clock frequency must be increased in order to keep the sidelobe levels down. As can also be observed in the actual time plots, the noise level rises and falls with temperature and frequency. (In Figure 66, the noise is -90 dB from the peak while for Figure 69 it is only -30 dB.)

Figure 65 is a graph of the sidelobe level of the output of the matched filter for coefficient inaccuracies in range of 0 to 10%. The tap weights were allowed to have an error with zero mean and standard deviation of a given percent for a normal distribution. Figure 65 shows that out to 6% there is no system degradation due to tap weight inaccuracy.

Figures 66 through 99 are the outputs from the matched filter for different sampling frequencies and temperatures. The specific case is given in the box on each figure. The plots are normalized to the peak of the time function.

Figures 100 - 108 are plots of the response of linear FM matched filter as Charge Transfer Inefficiency is varied with frequency for a CCD operating at 0°C . (In our model, due to the lack of theoretical and experimental data, we were not able to incorporate CTI as a function of temperature.) Figures 100, 113, and 106 show to a marked extent the broadening of the mainlobe and sidelobes of the return. Also observed is the raising of the sidelobe levels and a time shift of the mainlobe when the clock rate is constant while the CTI is varied. These effects are caused by the signal being smeared as it is shifted through the delay line. Finally, as the frequency is increased, no appreciable difference can be observed with regard to width and level of the sidelobes and mainlobe. That is, as frequency is increased, the dark current level decreases, but the effects due to CTI are not diminished.



*CLOCK RATE (HERTZ)

FIGURE 61. MEAN VALUE OF OUTPUT NOISE NORMALIZED TO FULL WELL VERSUS THE NUMBER OF STAGES AND CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE

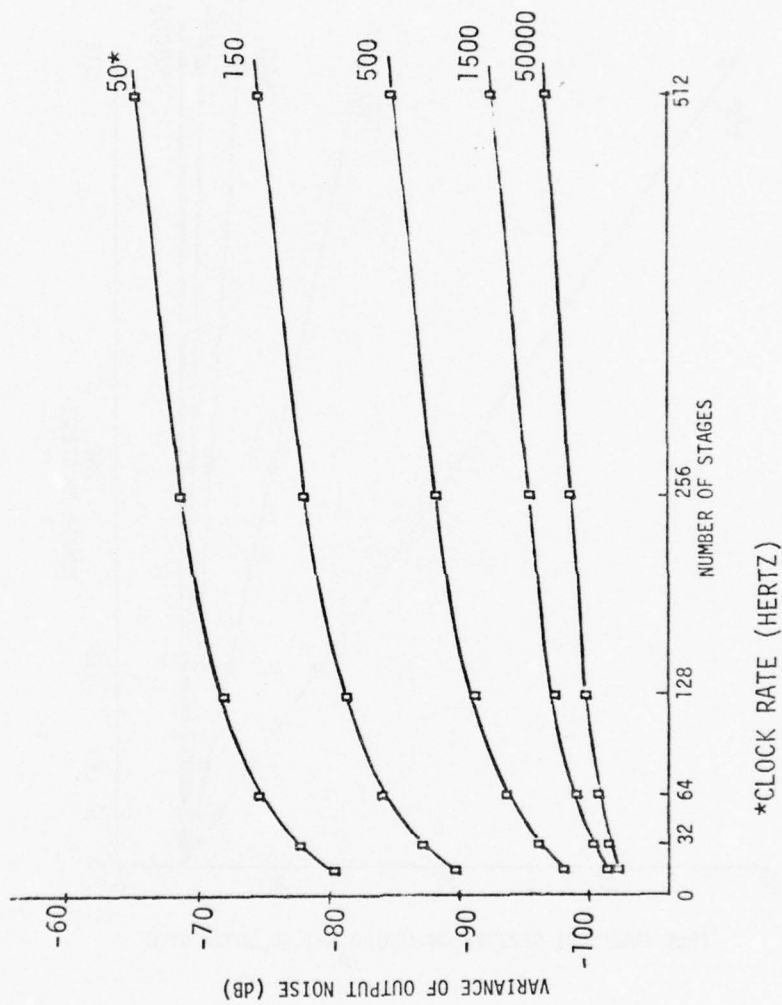
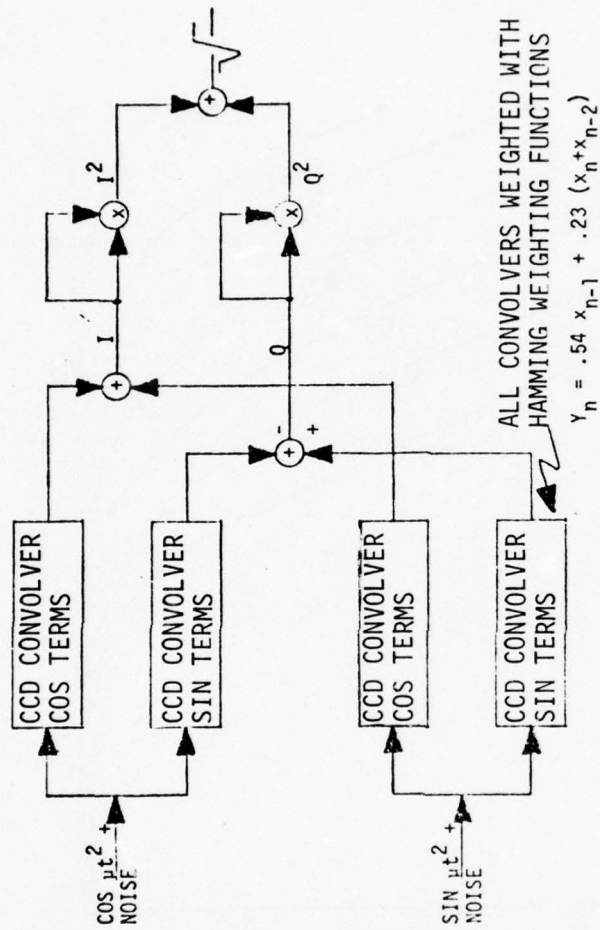


FIGURE 62. VARIANCE OF OUTPUT NOISE VERSUS THE NUMBER OF STAGES AND CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE



$$\nu = \frac{BW}{2T_p}$$

BW = BANDWIDTH OF THE SIGNAL

T_p = LENGTH OF THE SIGNAL

ALL CONVOLVERS WEIGHTED WITH
HAMMING WEIGHTING FUNCTIONS
 $Y_n = .54 x_{n-1} + .23 (x_n + x_{n-2})$

FIGURE 63. BLOCK DIAGRAM OF LINEAR FM MATCHED FILTER

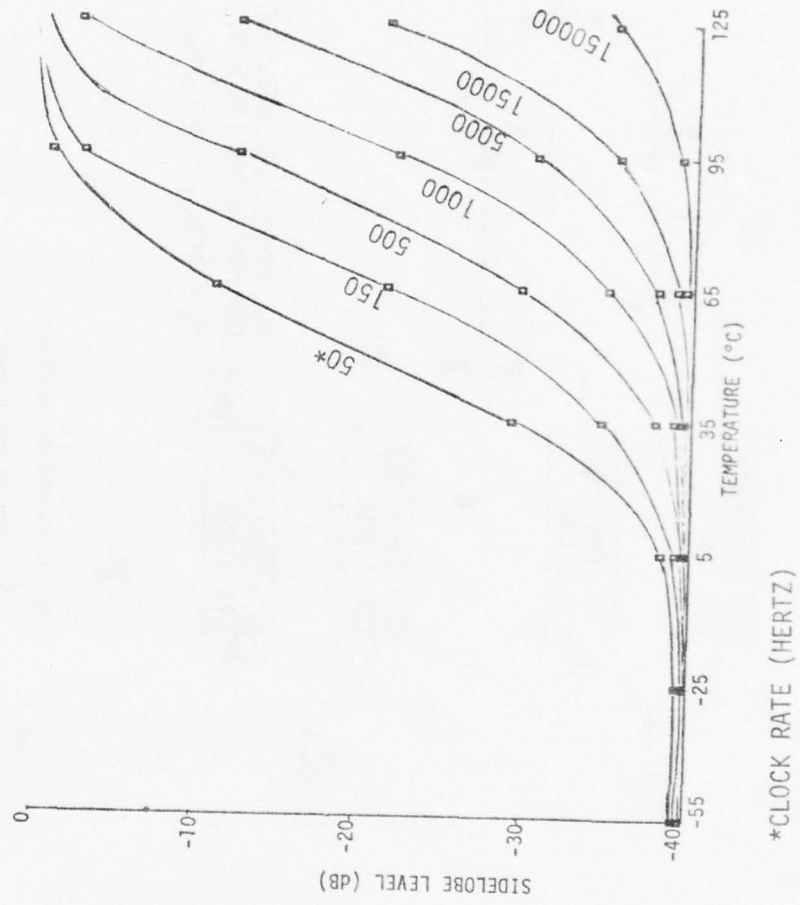


FIGURE 64. SIDELOBE LEVEL OF LINEAR FM MATCHED FILTER VERSUS TEMPERATURE AND CLOCK RATE

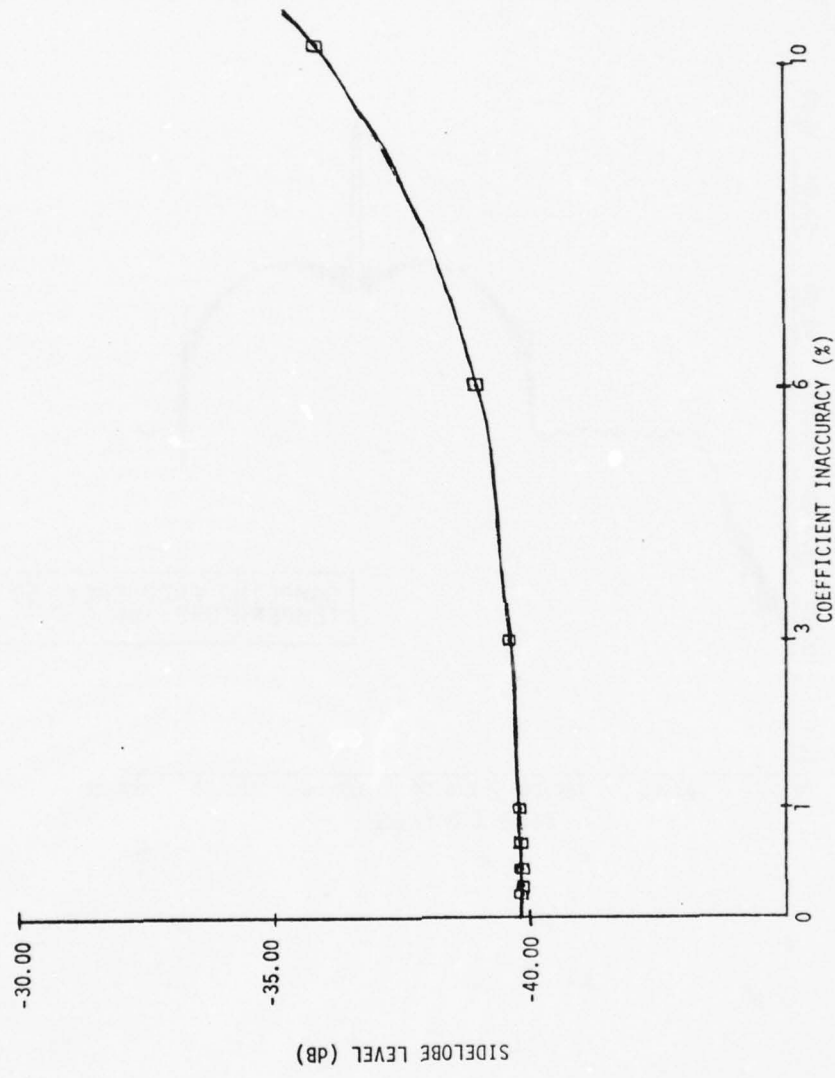


FIGURE 65. SIDELOBE LEVEL OF A LINEAR FM MATCHED FILTER VERSUS COEFFICIENT INACCURACY

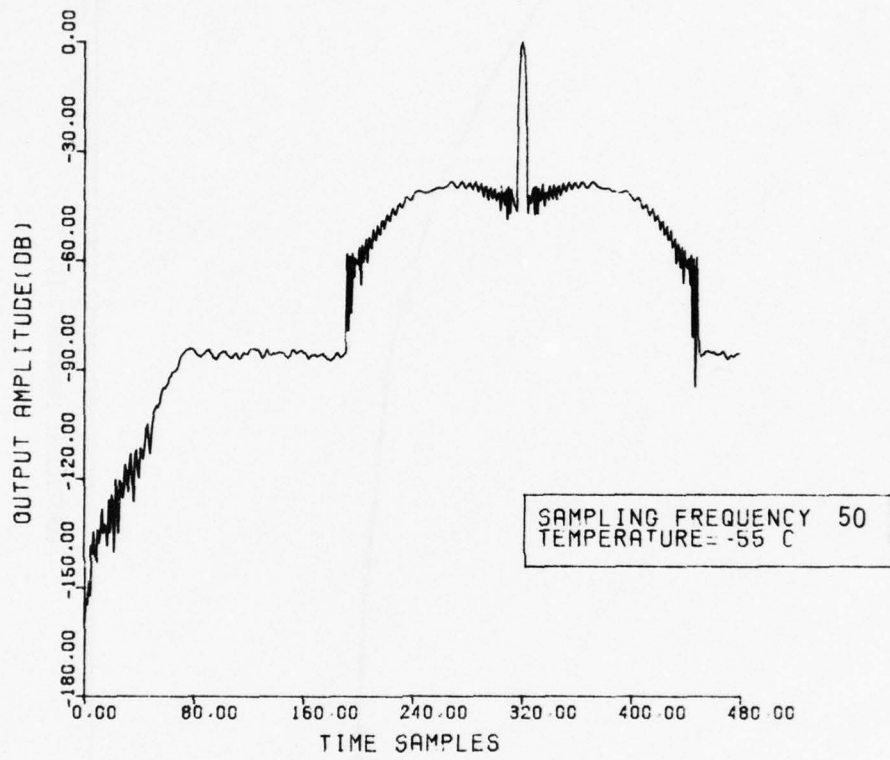


FIGURE 66. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF -55°C

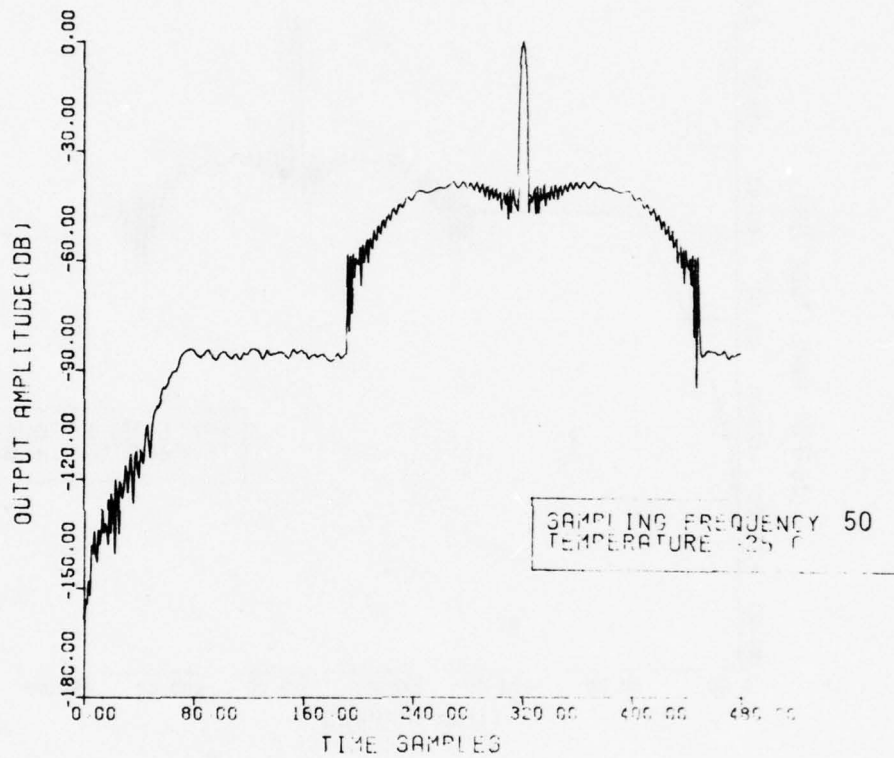


FIGURE 67. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF -25°C

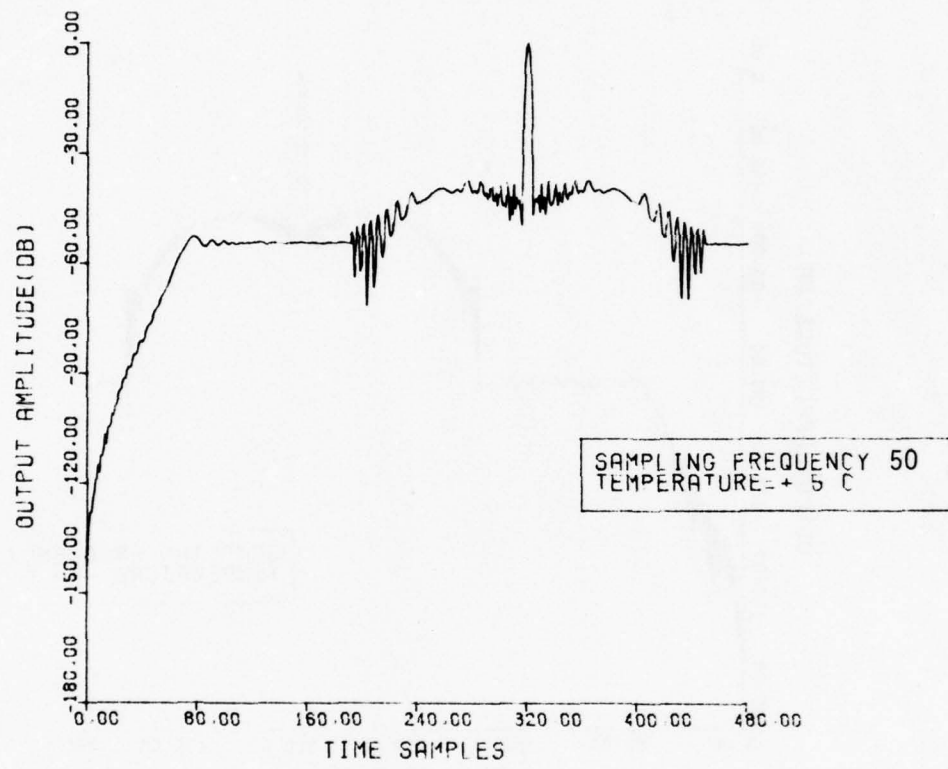


FIGURE 68. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +5°C

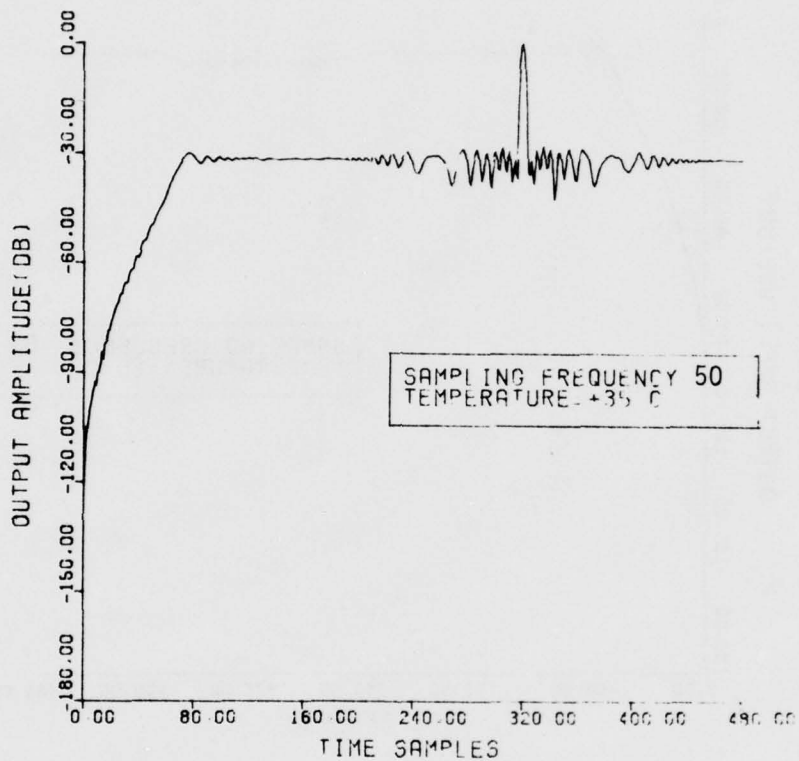


FIGURE 69. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +35°C

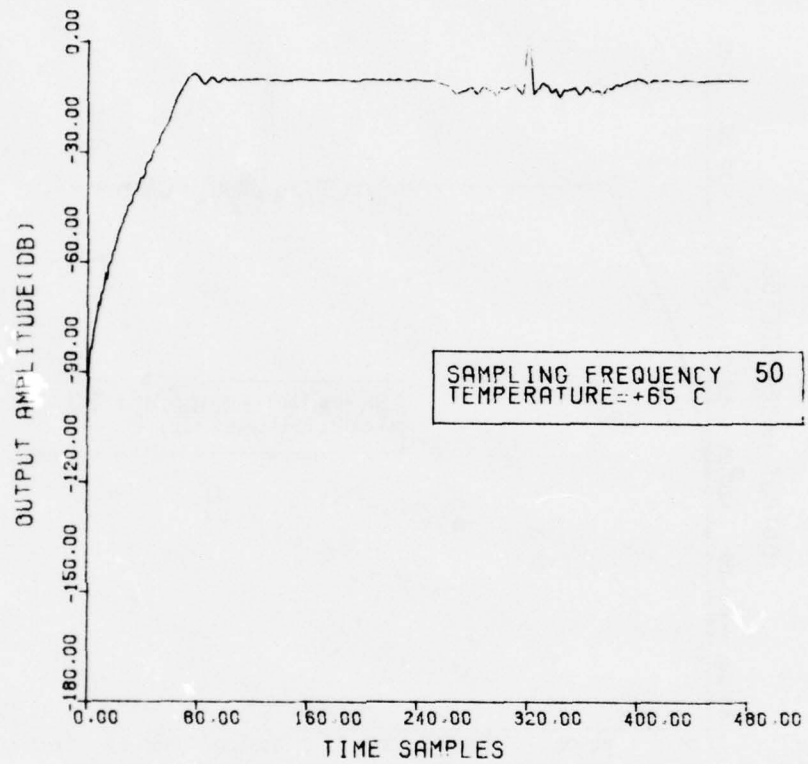


FIGURE 70. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +65°C

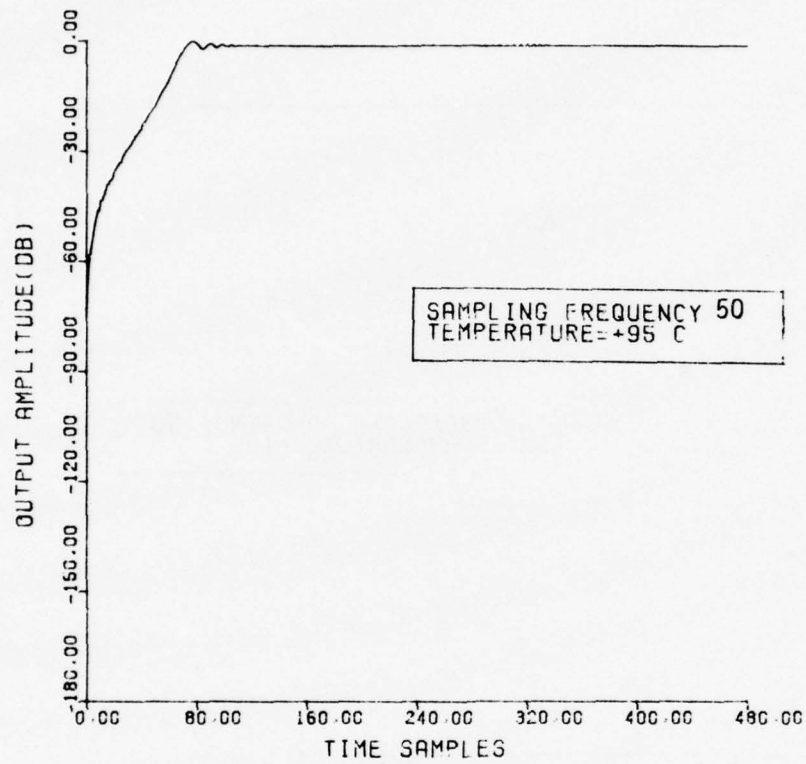


FIGURE 71. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +95°C

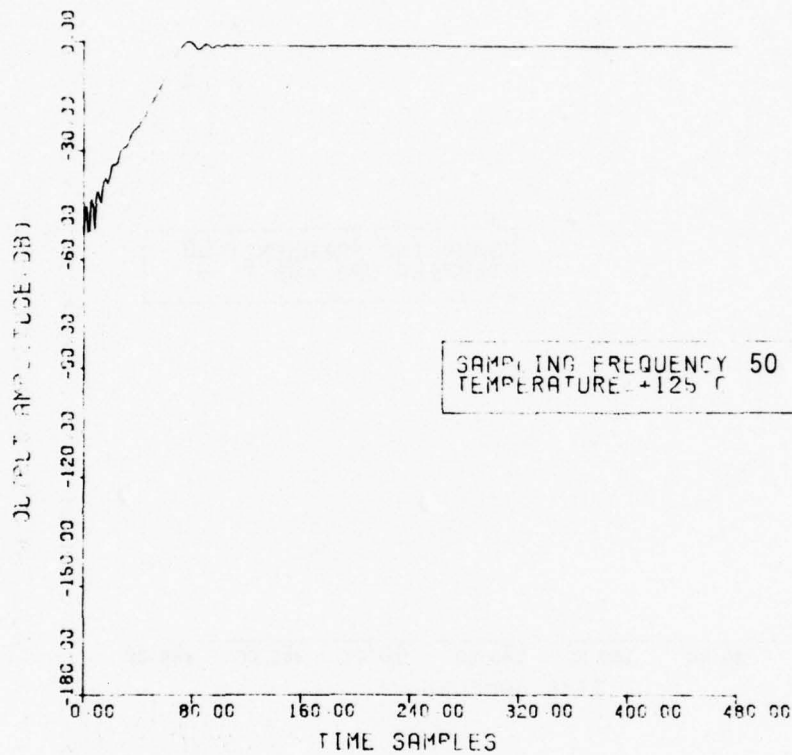


FIGURE 72. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +125°C

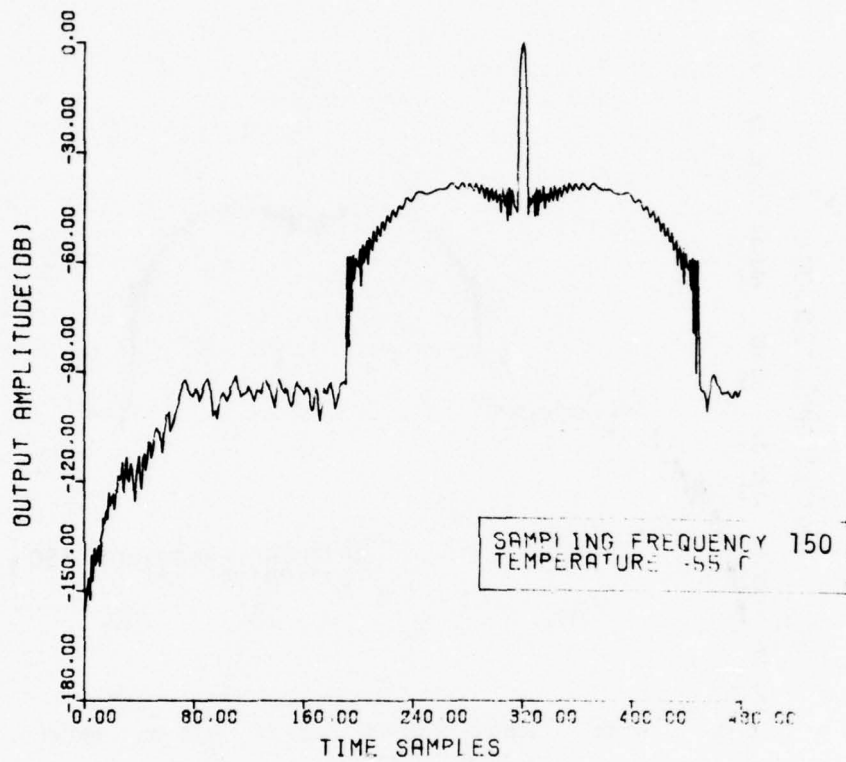


FIGURE 73. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF -55°C

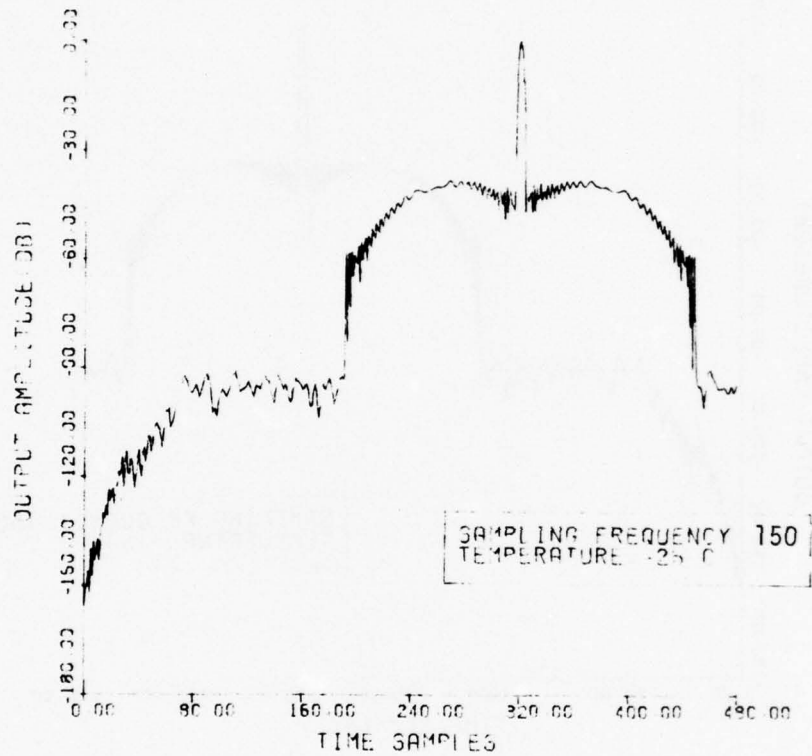


FIGURE 74. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF -25°C

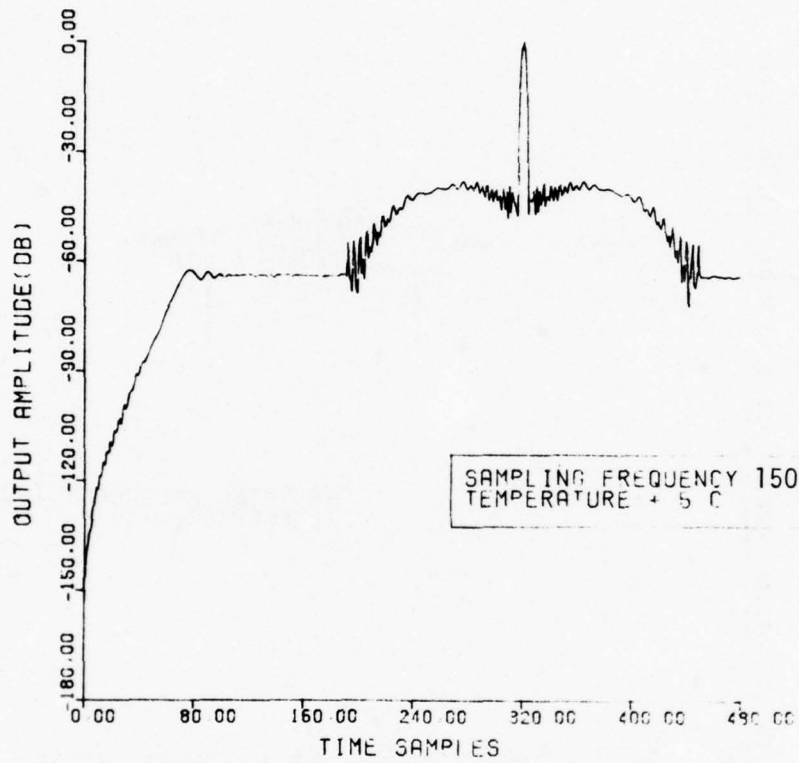


FIGURE 75. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +5°C

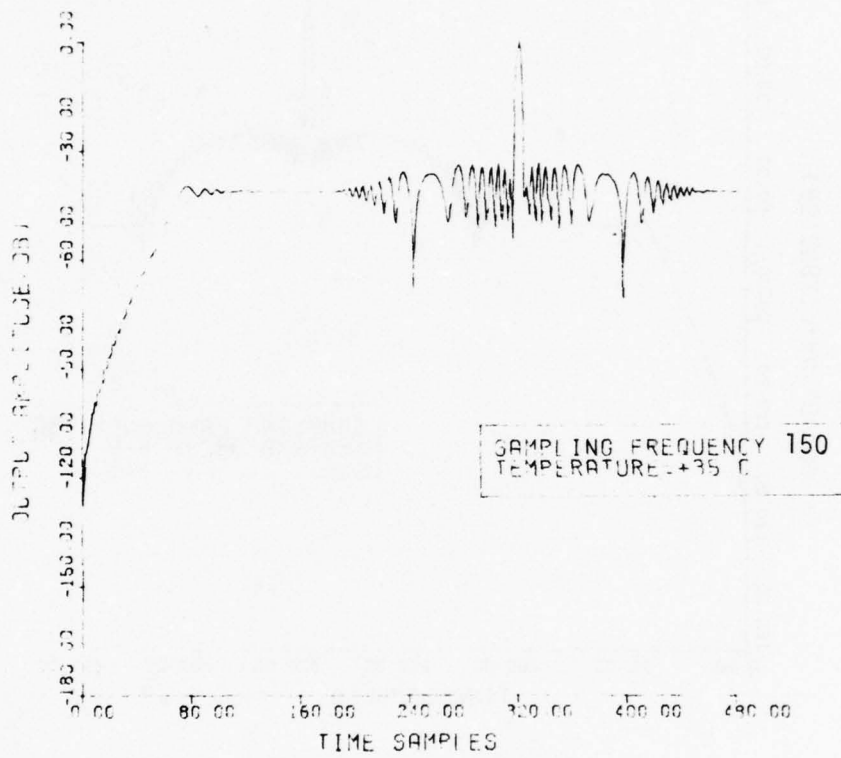


FIGURE 76. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +35°C

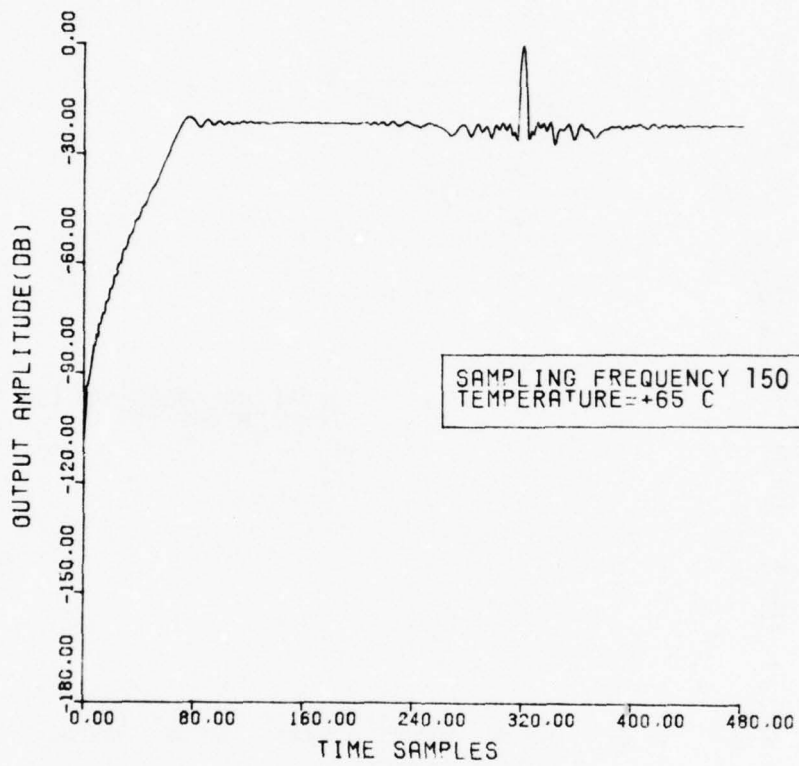


FIGURE 77. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +65°C

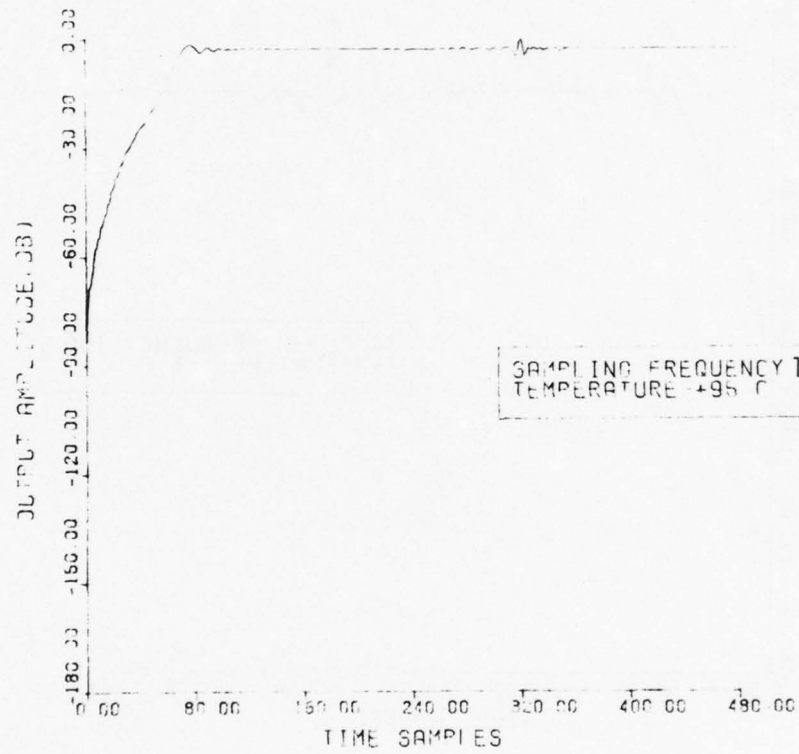


FIGURE 78. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +95°C

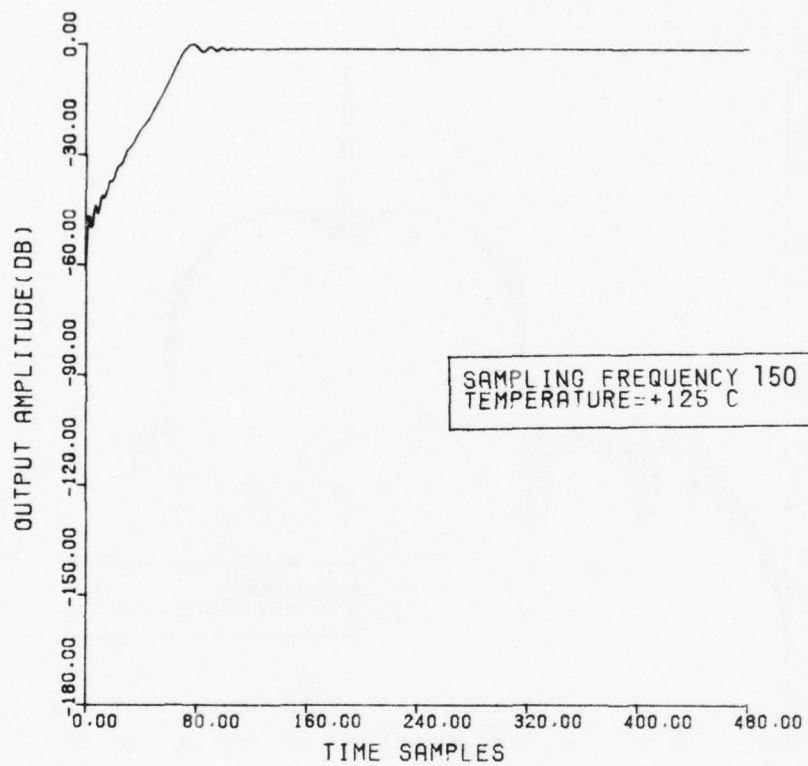


FIGURE 79. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +125°C

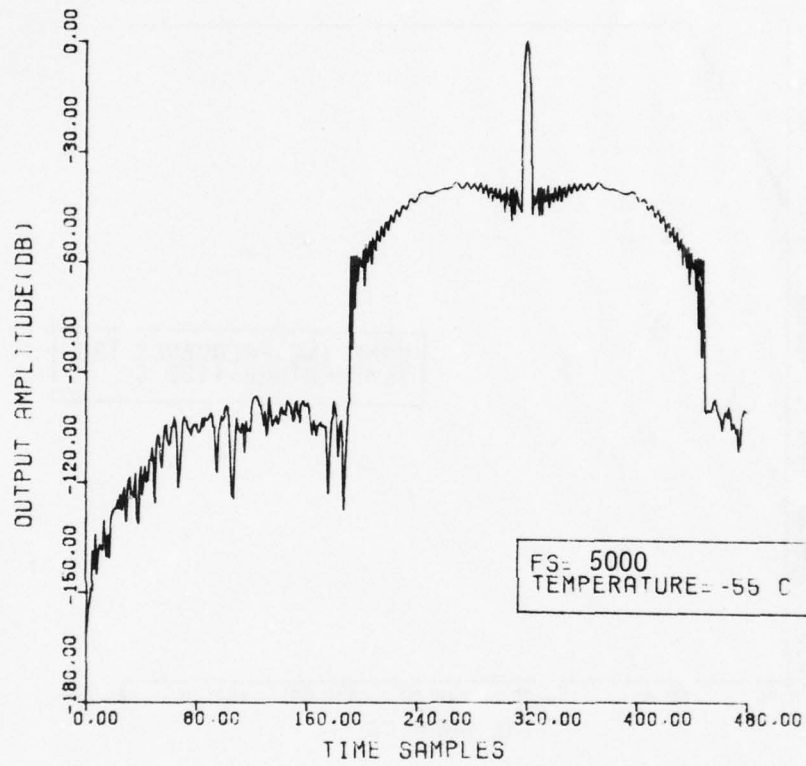


FIGURE 80. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF -55°C

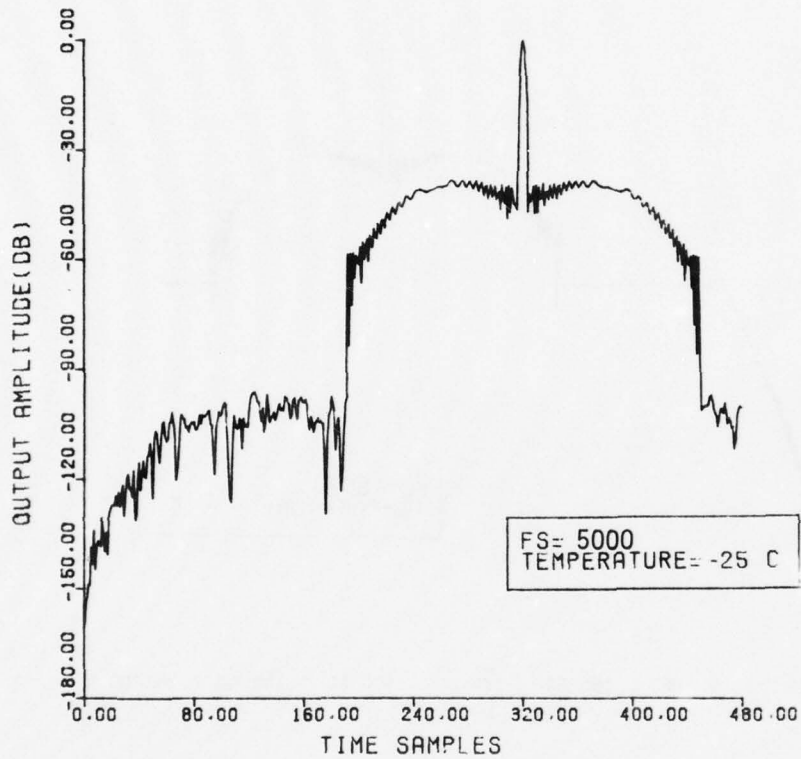


FIGURE 81. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF -25°C

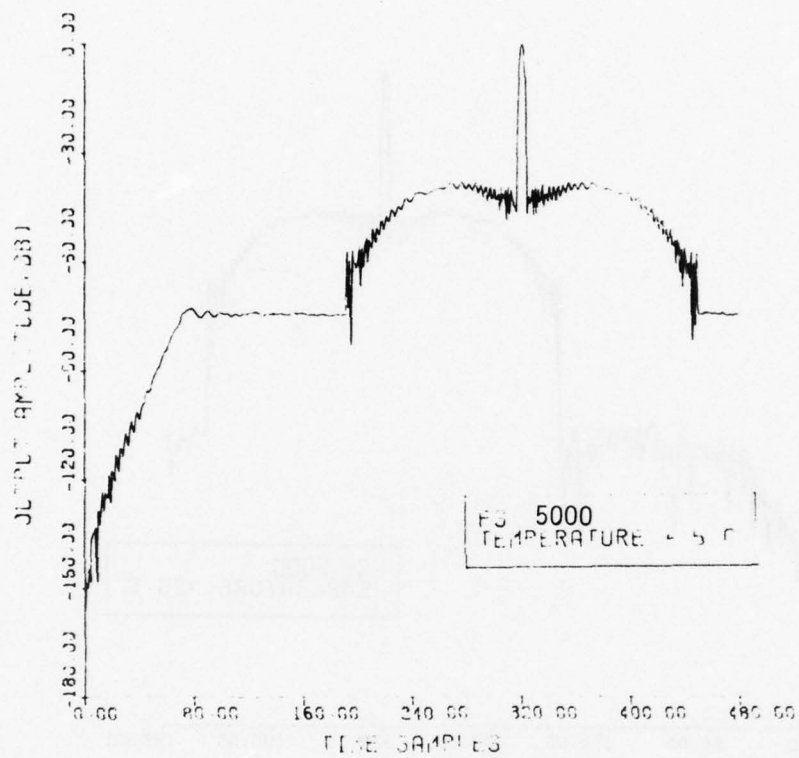


FIGURE 82. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR
 CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +5°C

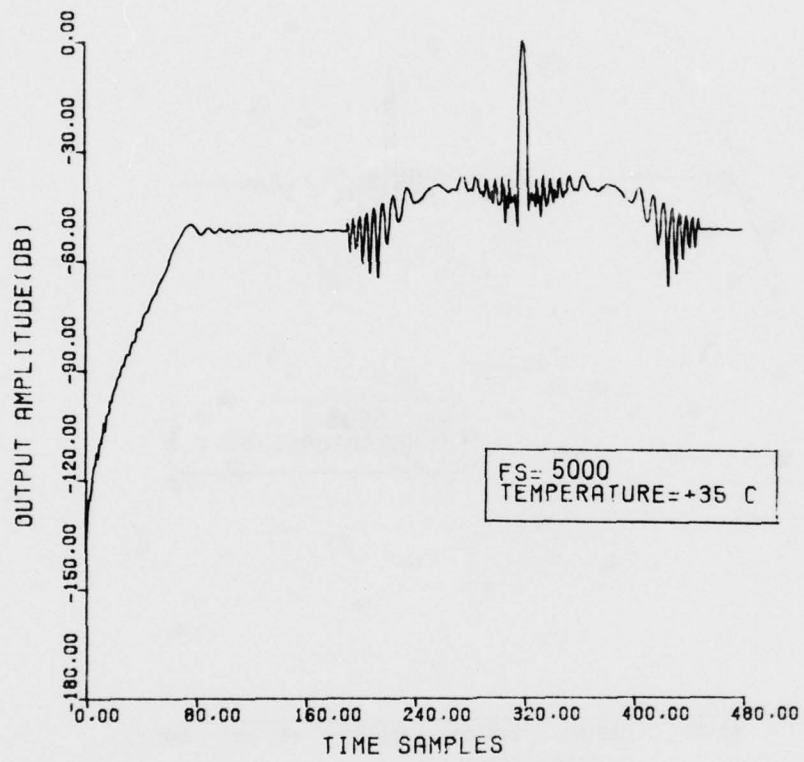


FIGURE 83. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +35°C

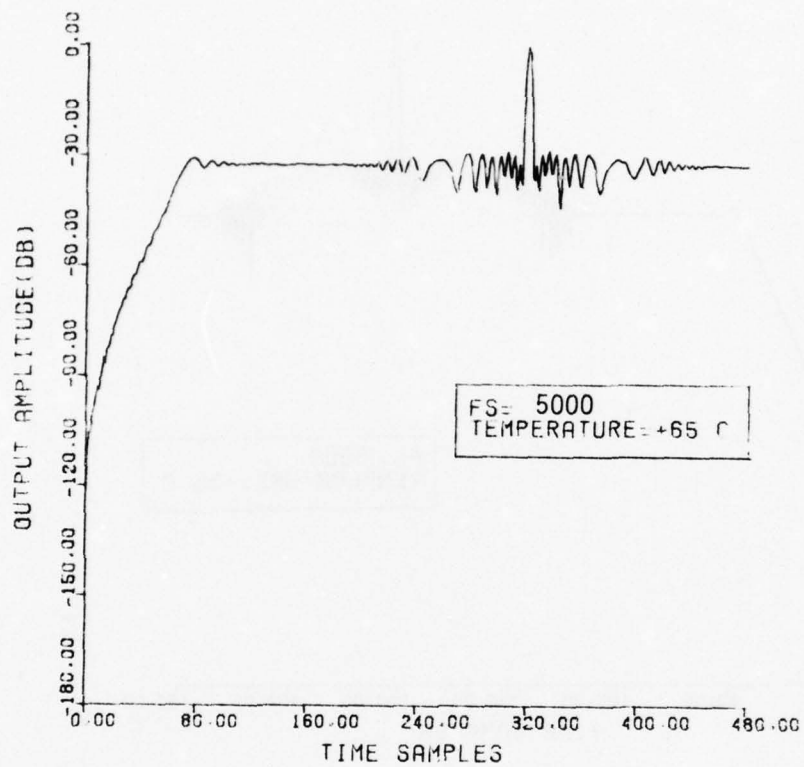


FIGURE 84. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR
CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +65°C

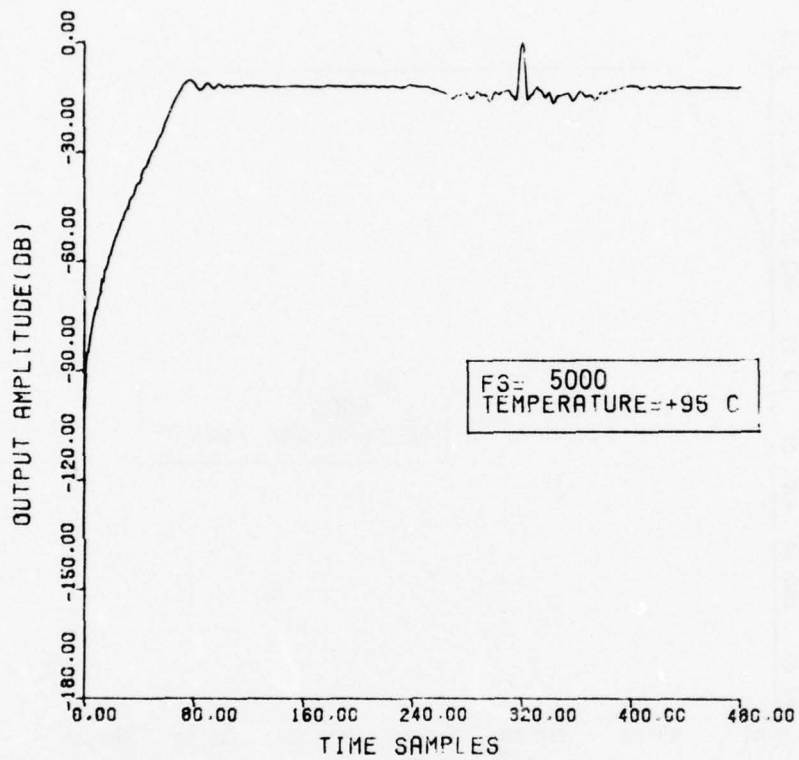


FIGURE 85. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +95°C

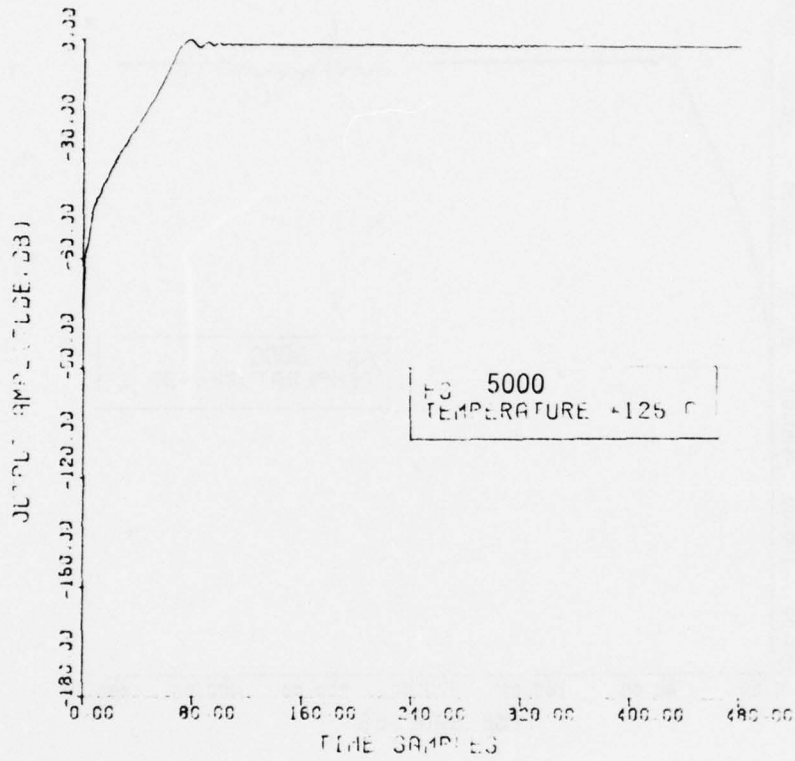


FIGURE 86. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +125°C

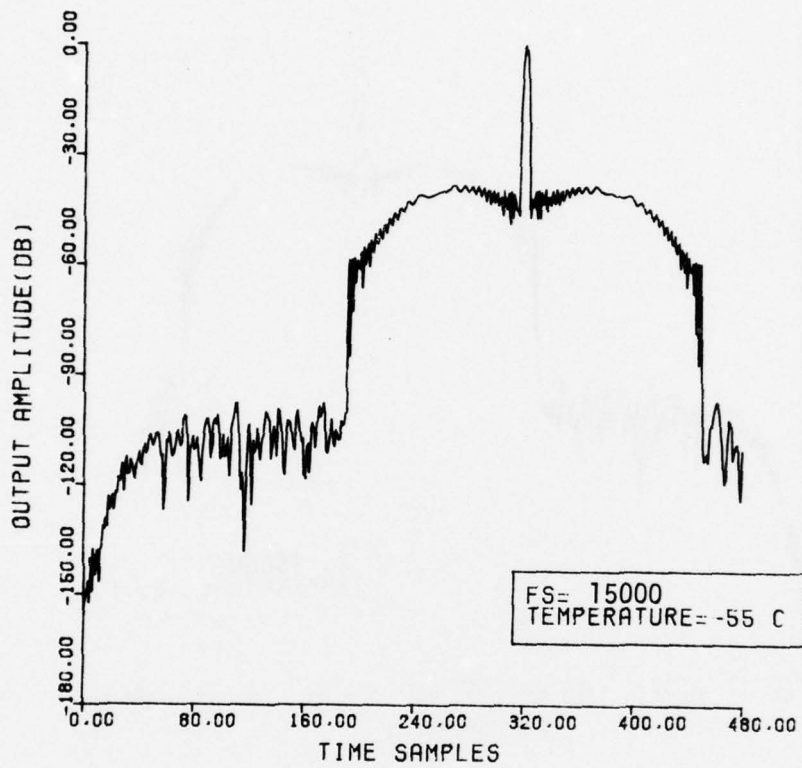


FIGURE 87. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF -55°C

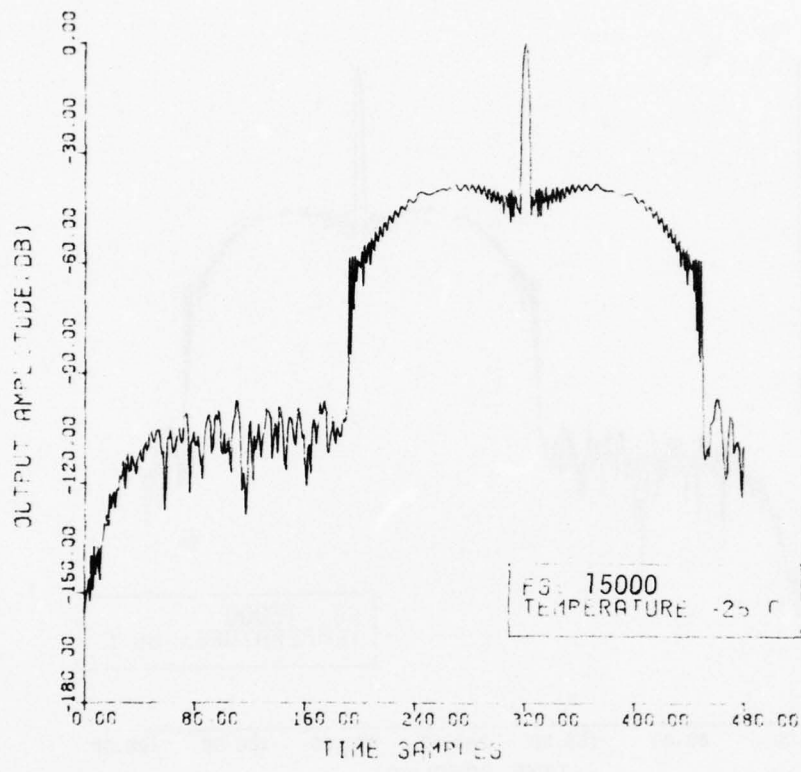


FIGURE 88. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF -25°C

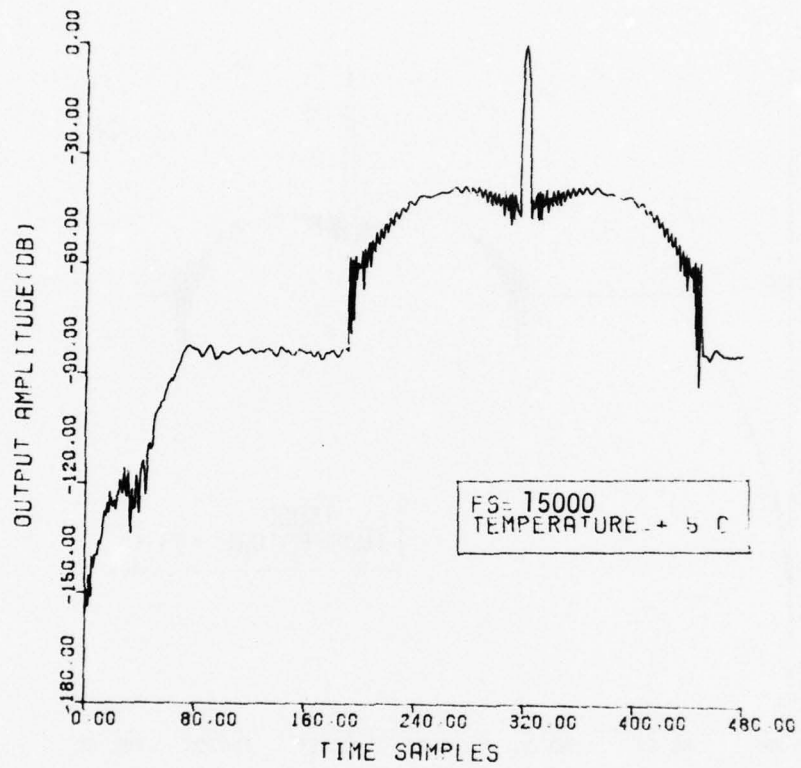


FIGURE 89. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +5°C

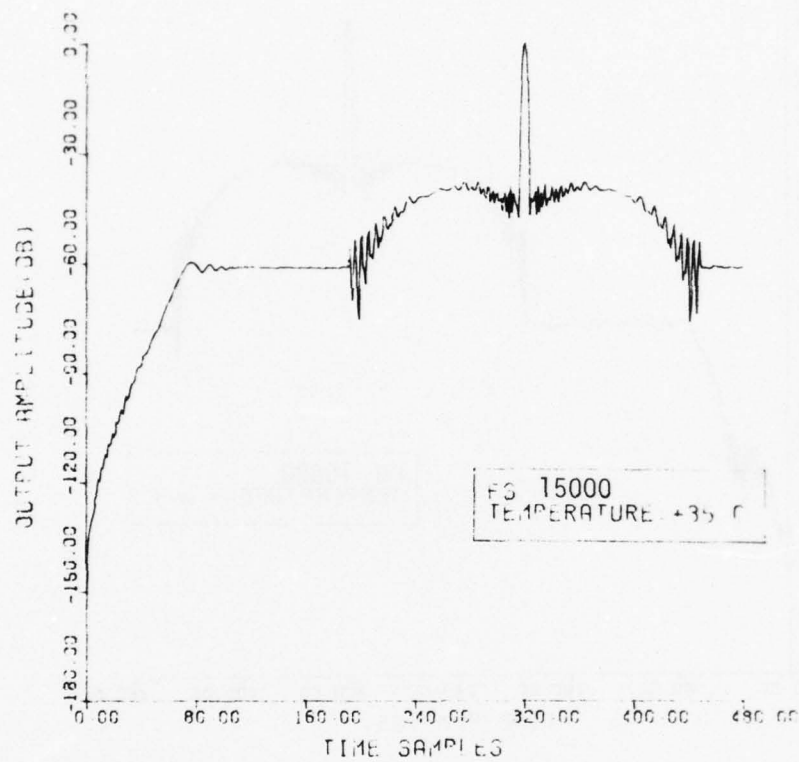


FIGURE 90. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +35°C

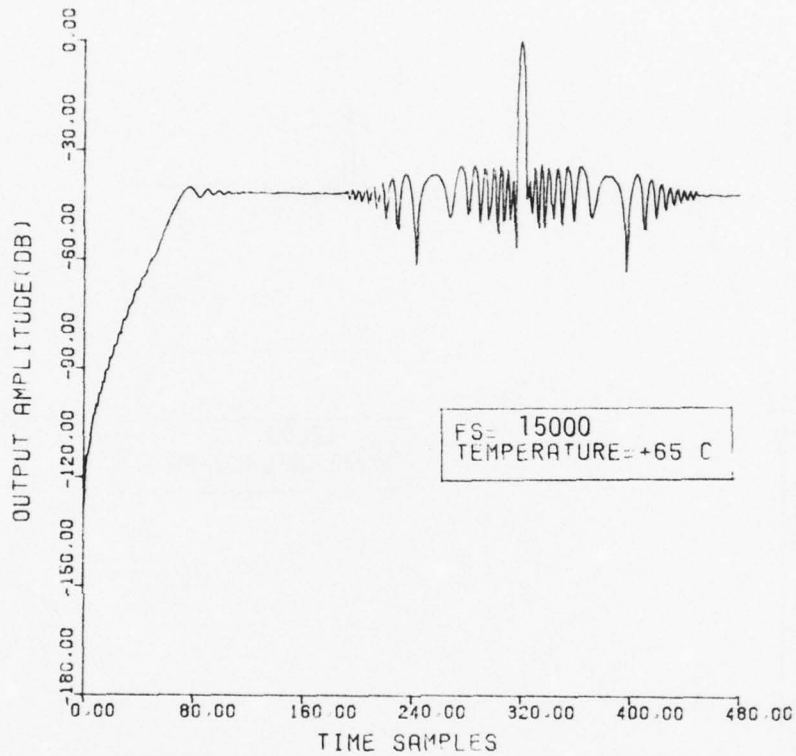


FIGURE 91. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +65°C

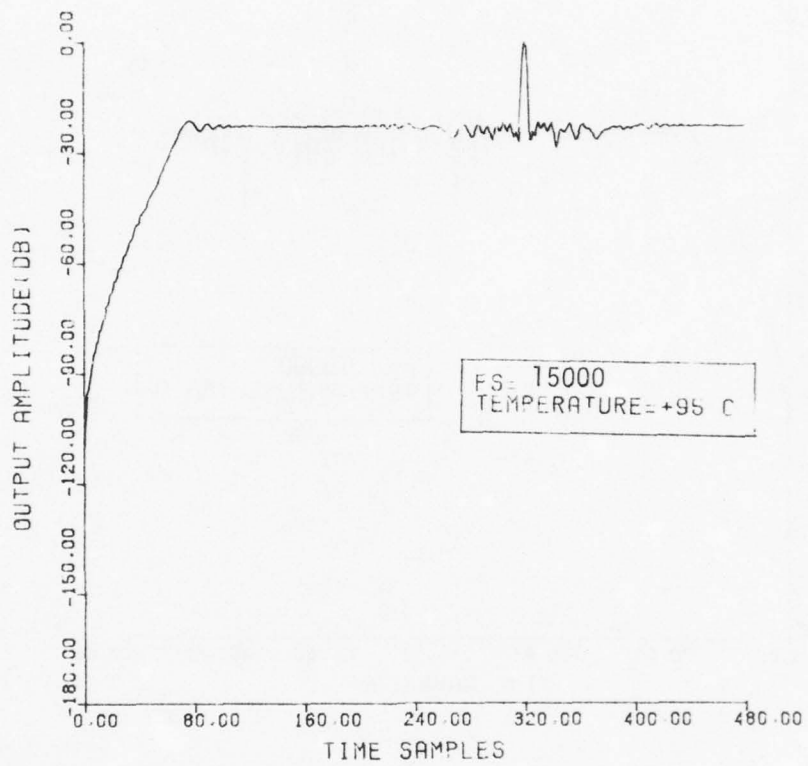


FIGURE 92. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +95°C

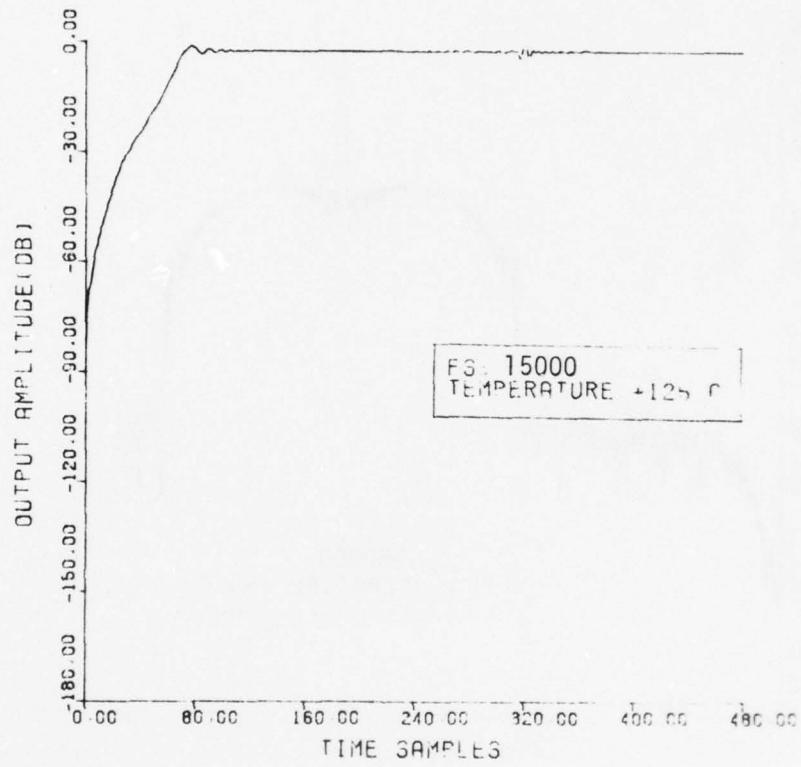


FIGURE 93. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +125°C

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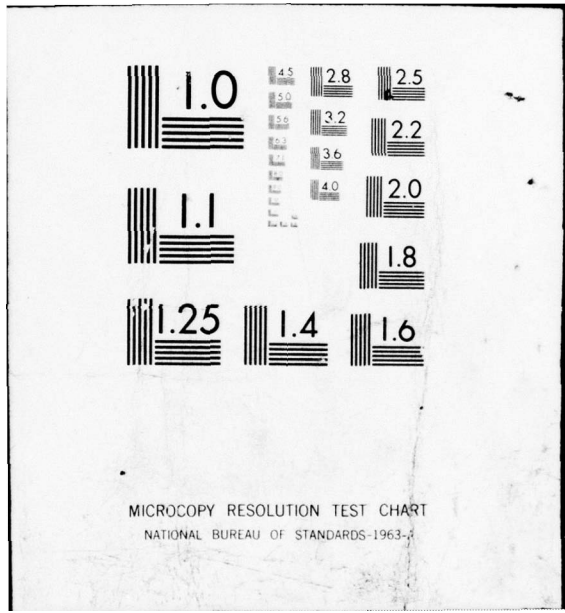
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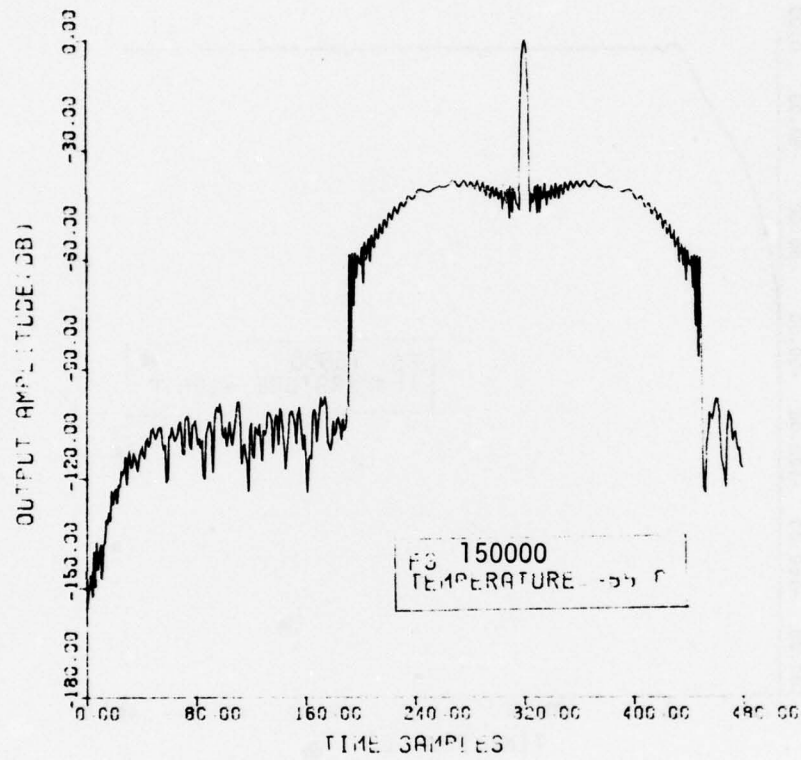


FIGURE 94. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF -55°C

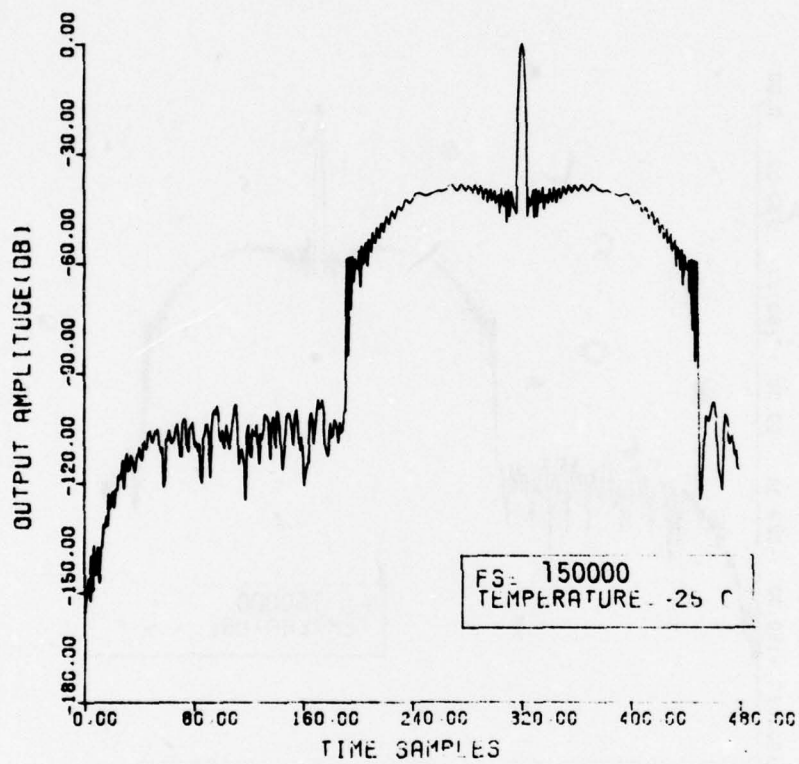


FIGURE 95. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF -25°C

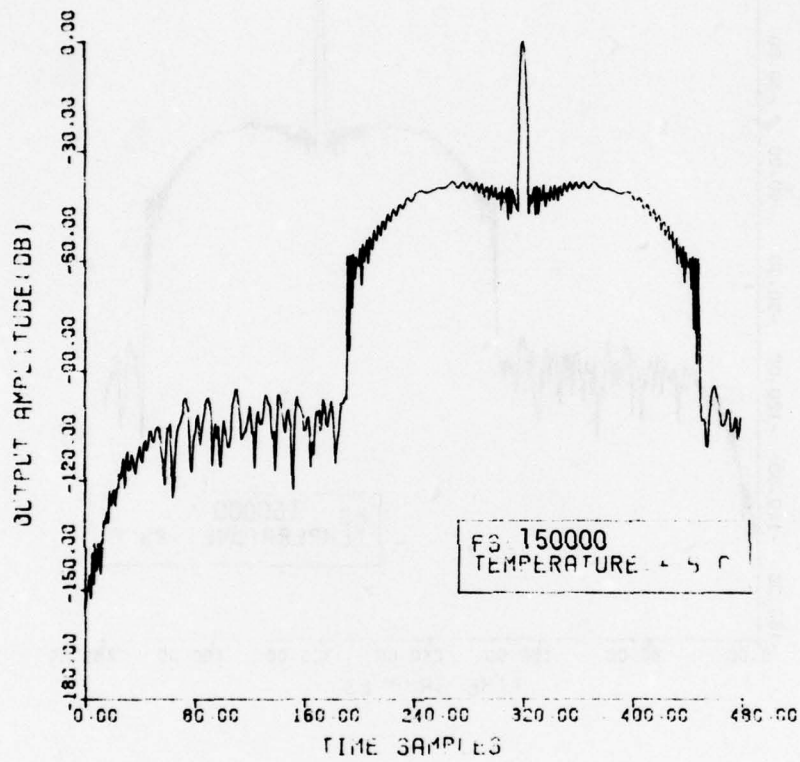


FIGURE 96. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +5°C

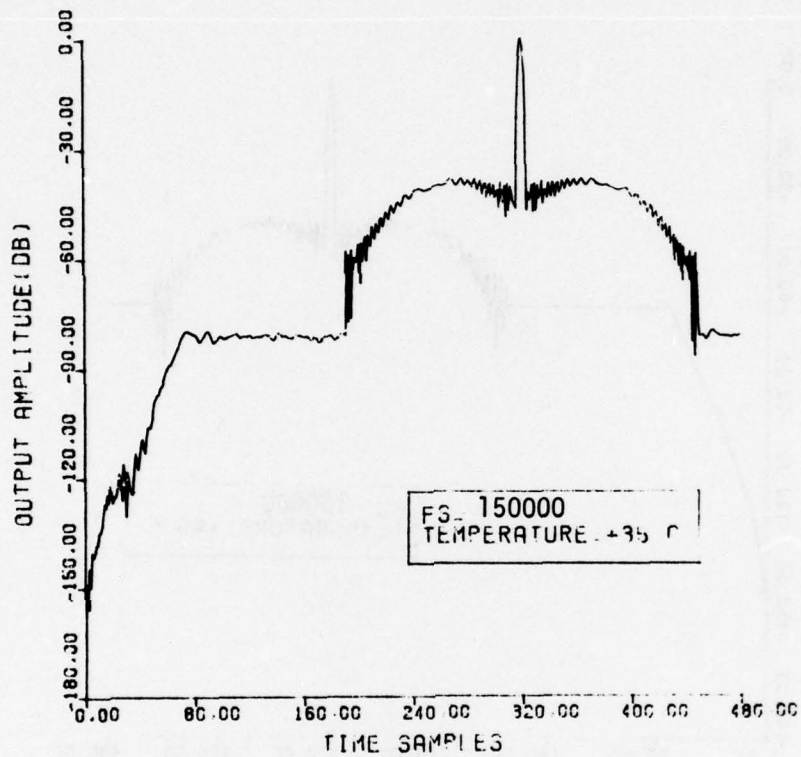


FIGURE 97. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +35°C

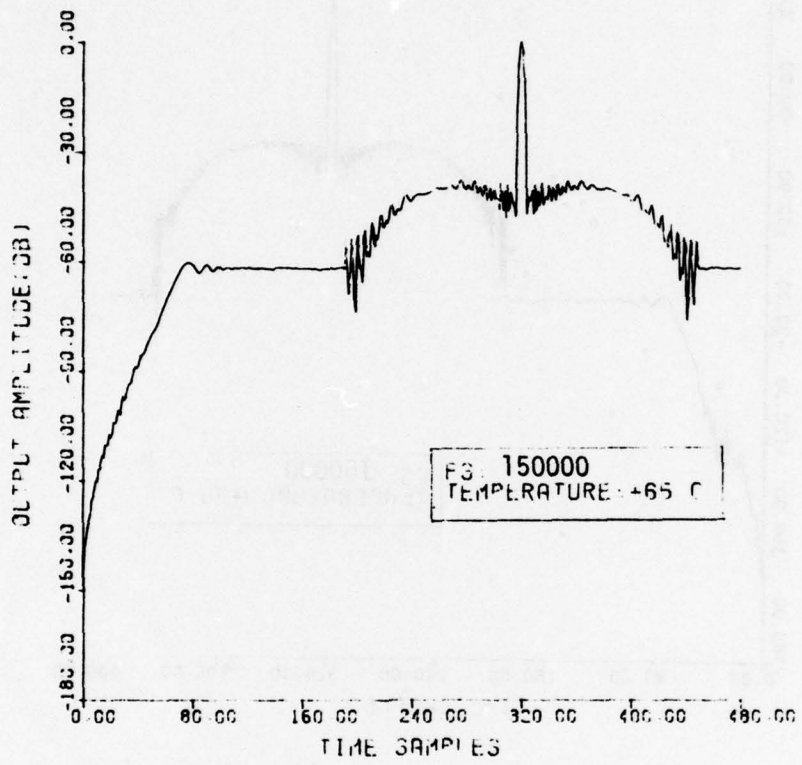


FIGURE 98. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +65°C

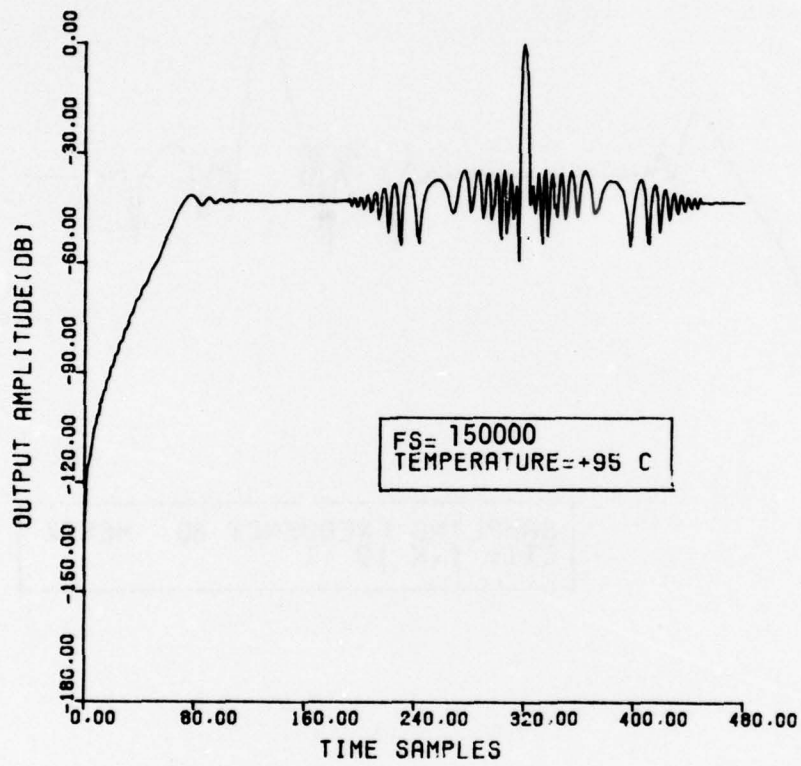


FIGURE 99. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +95°C

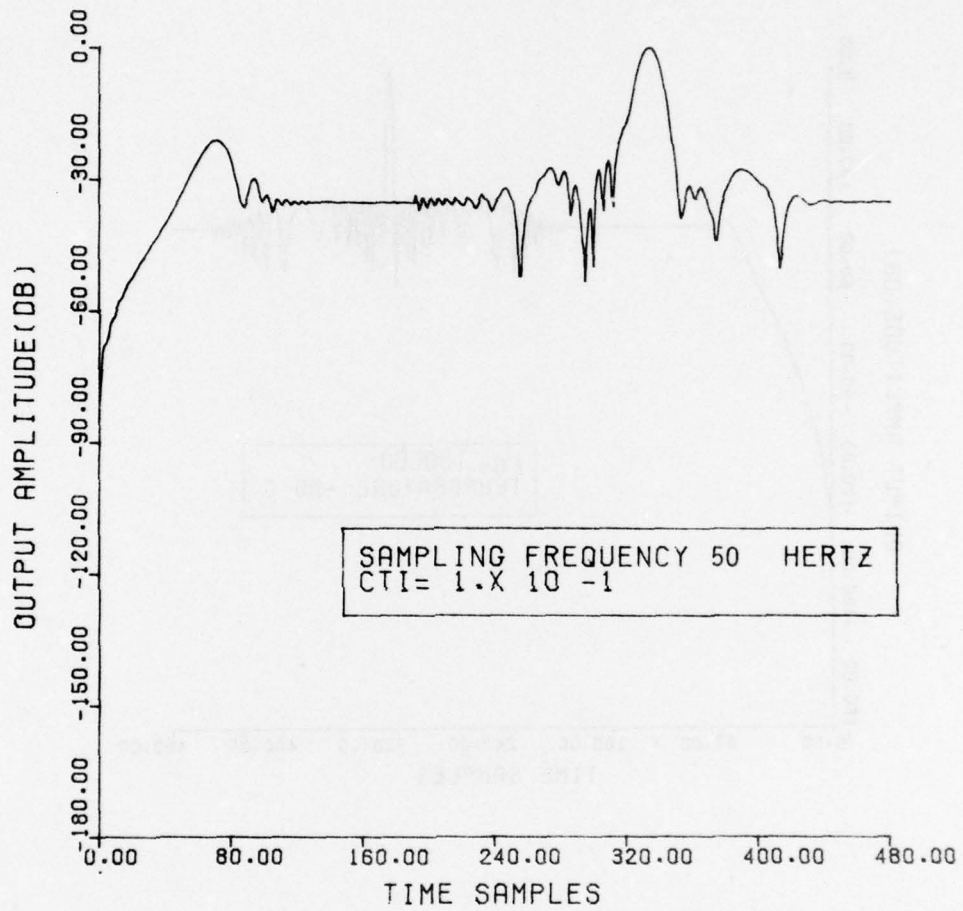


FIGURE 100. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR
CLOCK RATE OF 100 HERTZ AND CTI = 0.1

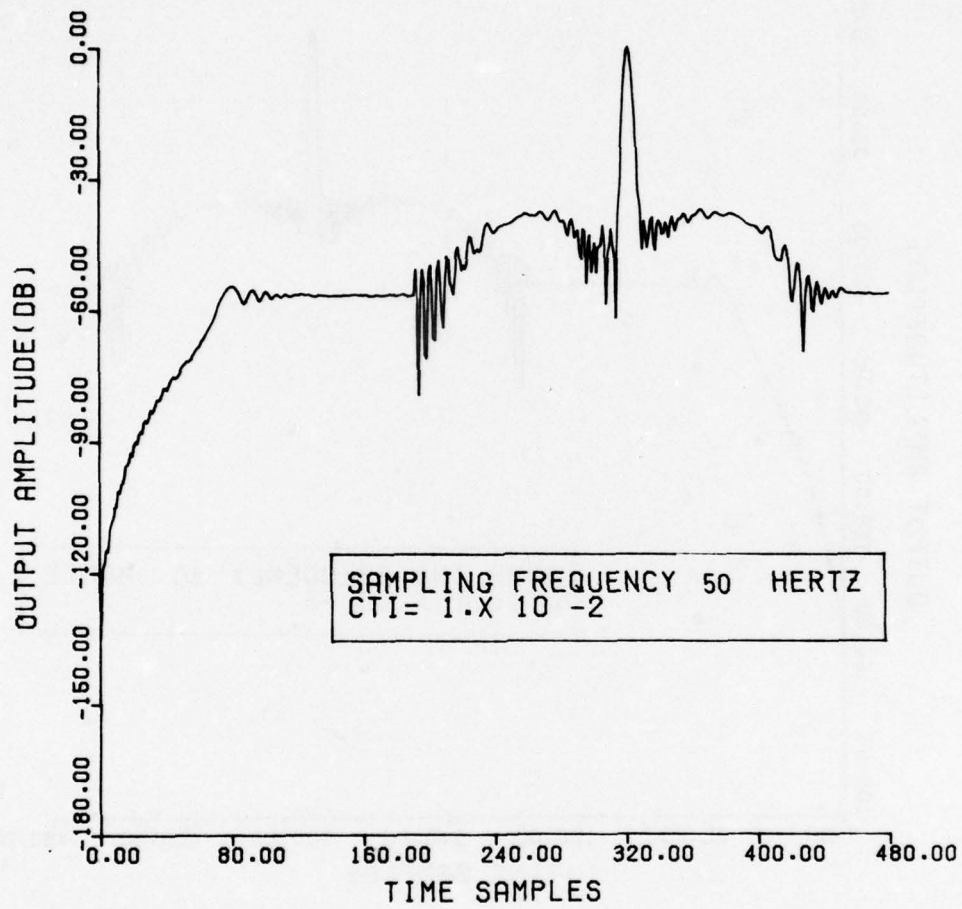


FIGURE 101. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR
CLOCK RATE OF 100 HERTZ AND CTI = 0.01

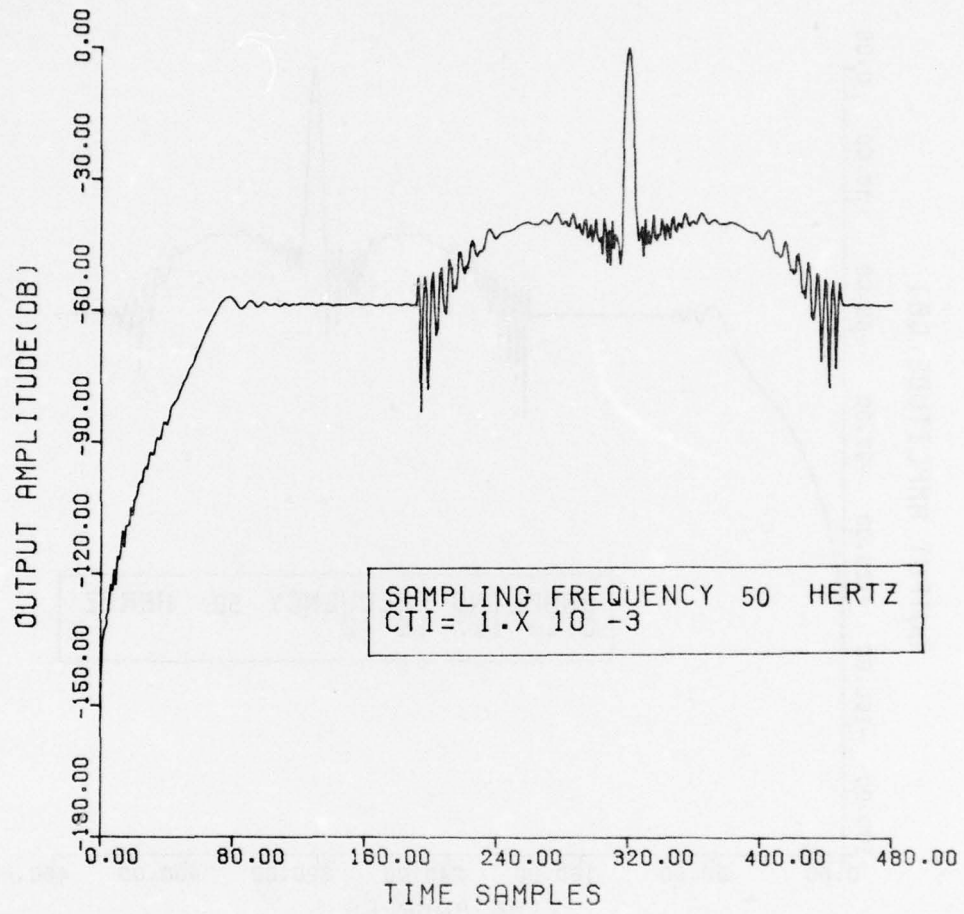


FIGURE 102. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR
CLOCK RATE OF 100 HERTZ AND CTI = 0.001

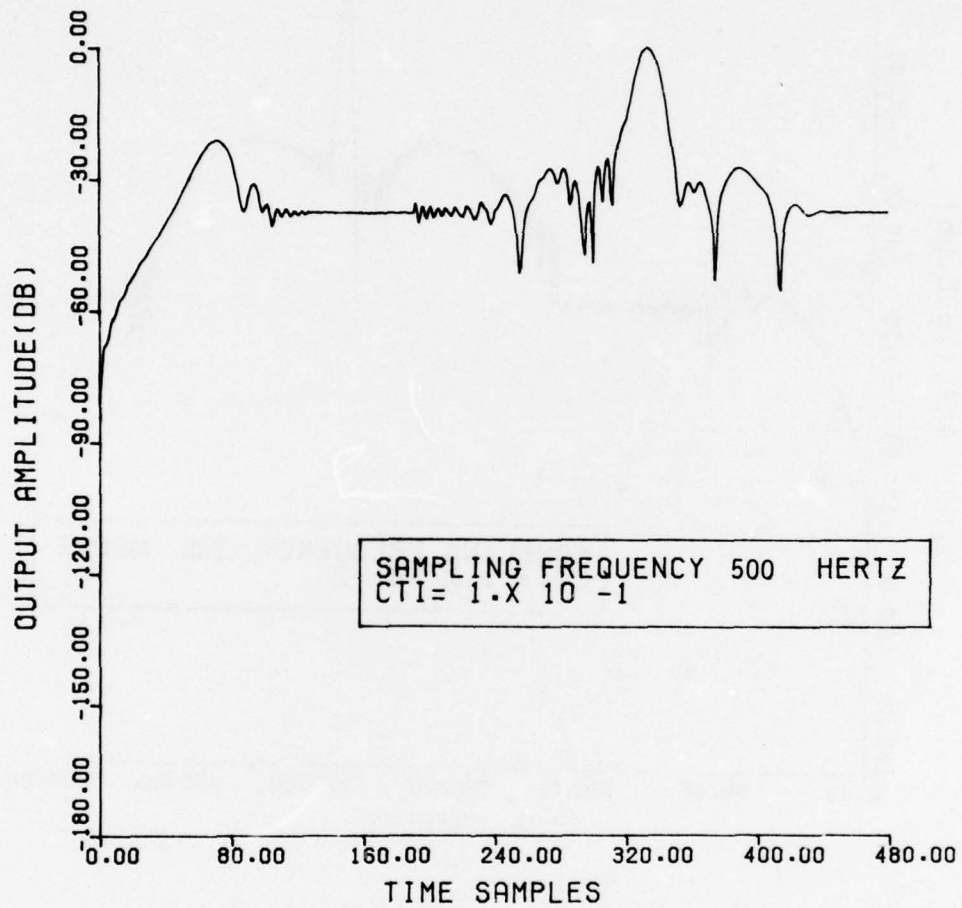


FIGURE 103. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 1,000 HERTZ AND CTI = 0.1

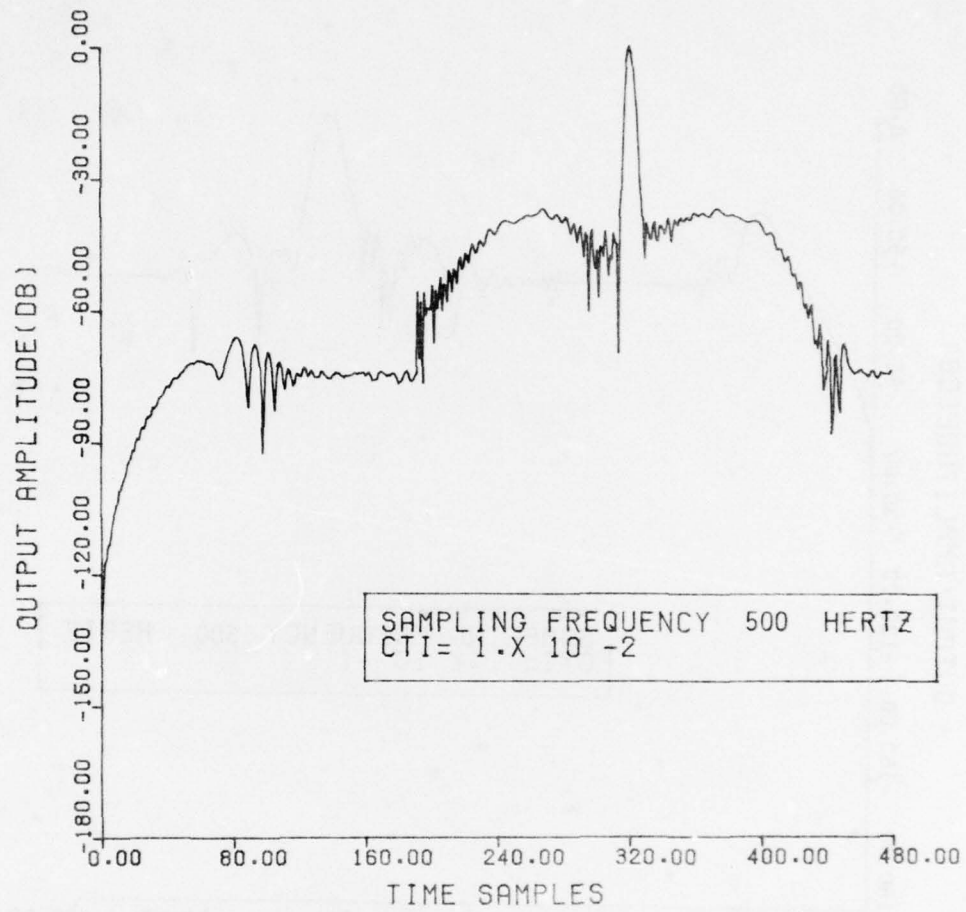


FIGURE 104. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR
CLOCK RATE OF 1,000 HERTZ AND CTI = 0.01

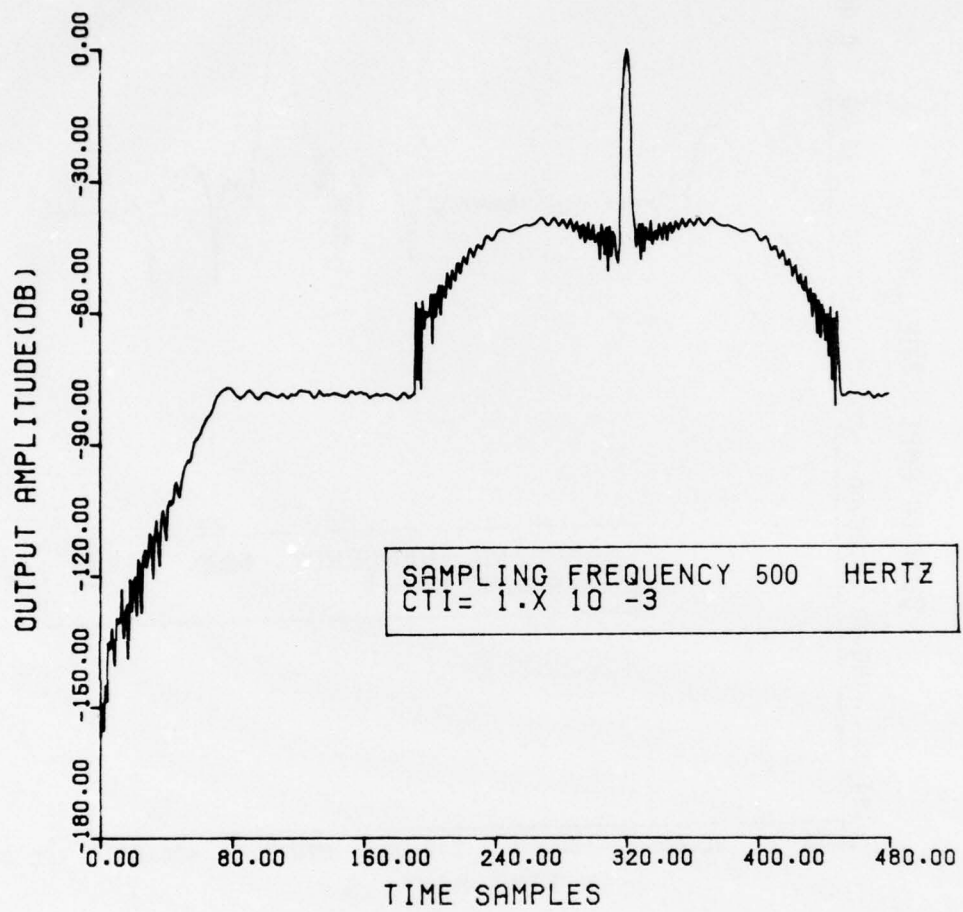


FIGURE 105. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 1,000 HERTZ AND CTI = 0.001

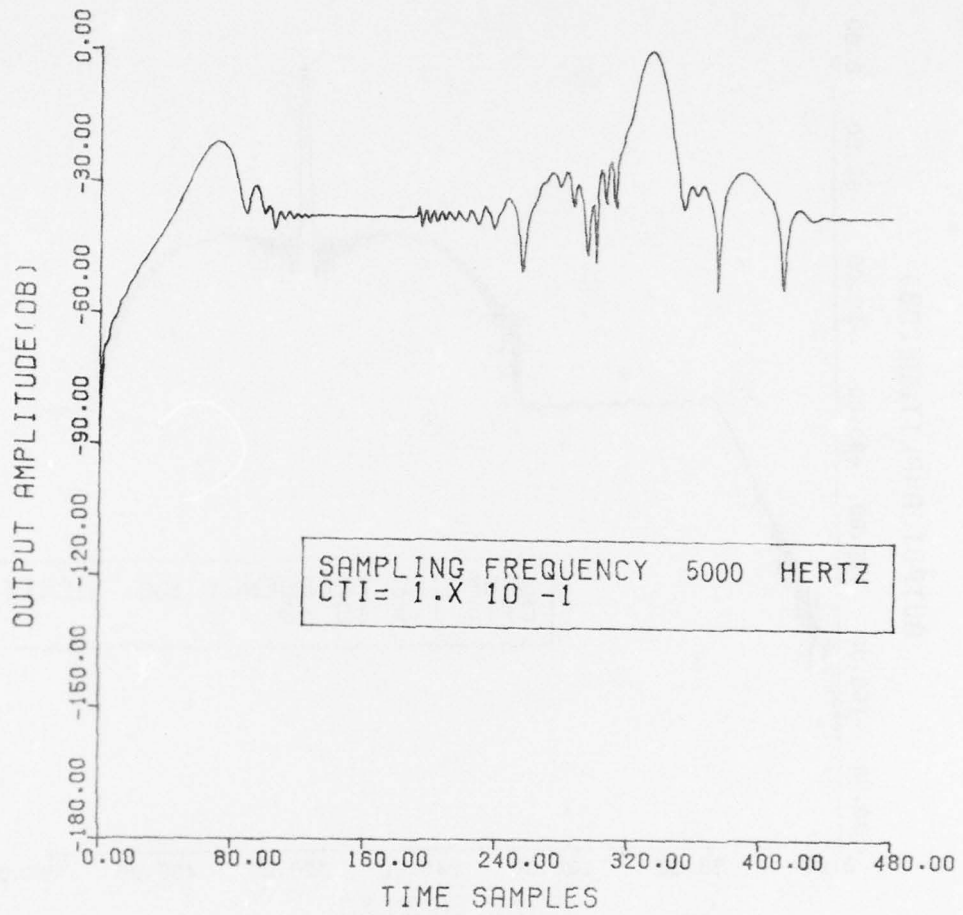


FIGURE 106. OUTPUT AMPLITUDE OF LINEAR MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND CTI = 0.1

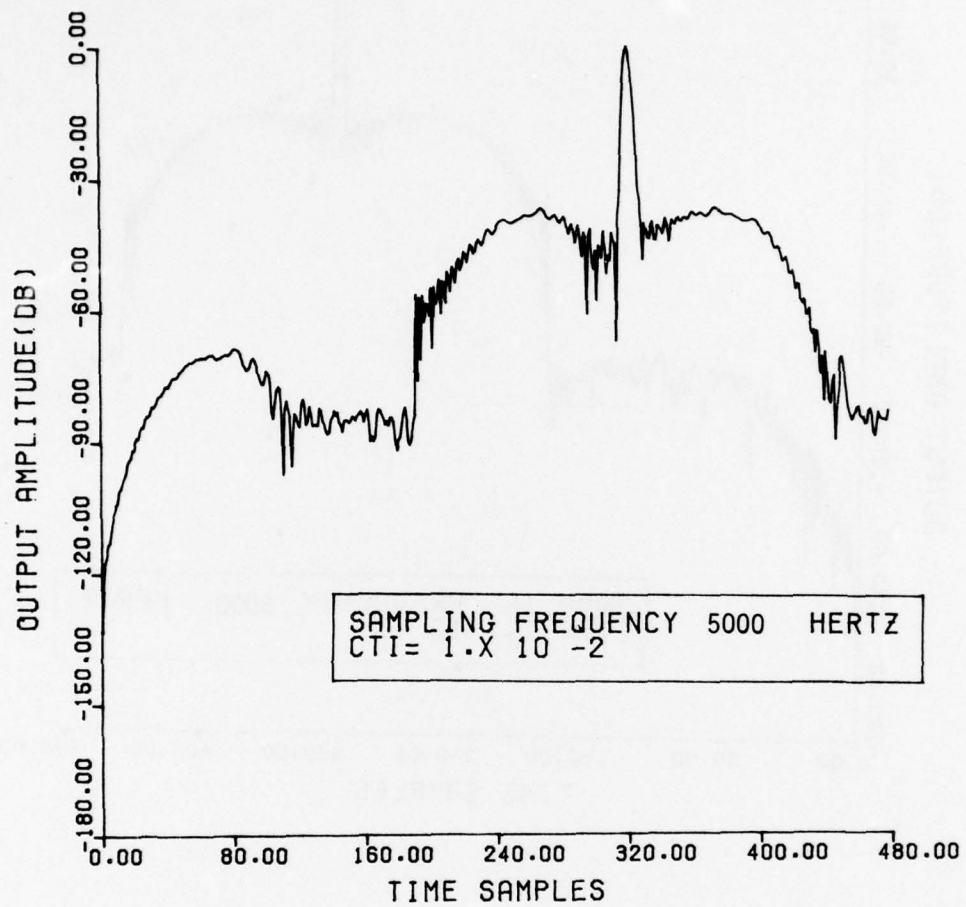


FIGURE 107. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND CTI = 0.01

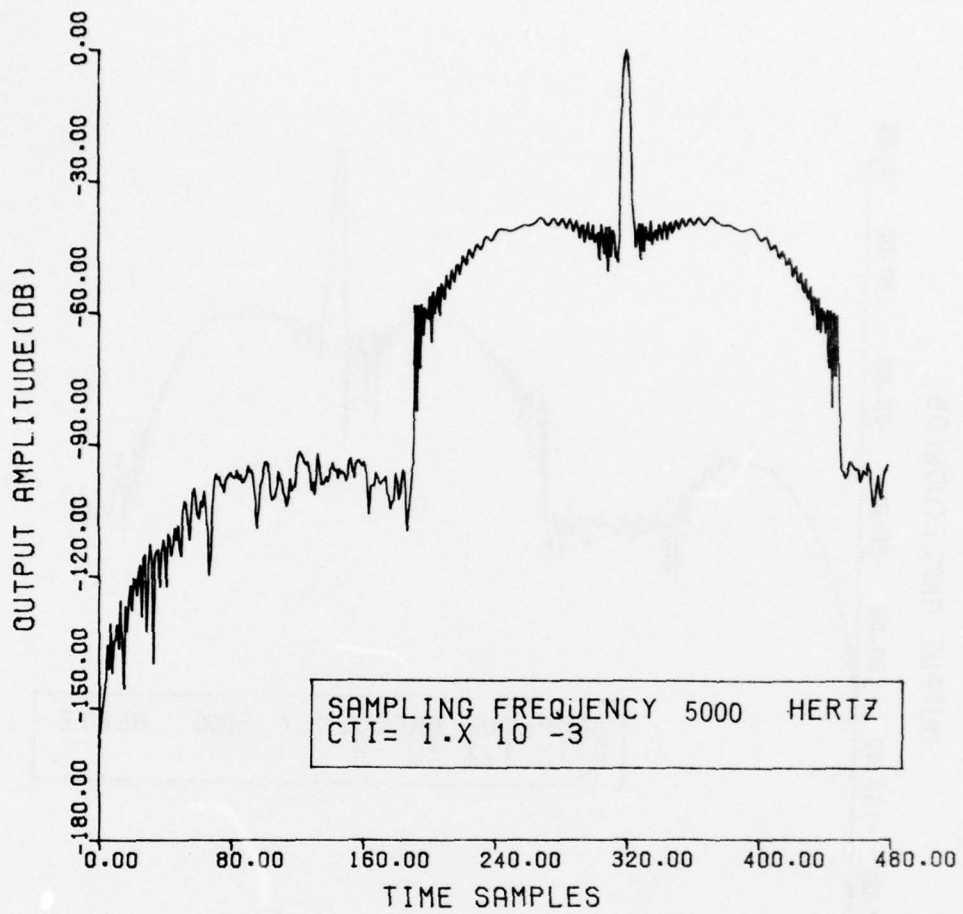


FIGURE 108. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND CTI = 0.001

7.0 CCD COST/PERFORMANCE IMPLEMENTATION PROJECTIONS

7.1 PROGRAMMABILITY - ADAPTIVE, FLEXIBLE WAVEFORM PROCESSING

7.1.1 Objectives of Programmability

The desirability of programmability in radar signal processing functions stems from two basic desires. First for a given radar, the system operating parameters are generally developed analytically and their appropriateness to specific situations may be limited. The ability to change the waveform to match the radar task would provide the capability to use the basic radar resources of energy and bandwidth to their maximum efficiency in any given environment. This programmability will generally encompass variations in bandwidth, pulse length and waveform type. More elaborate programmability would involve changing the basic mode structure of the radar such as from pulse compression-MTI to a pulse-doppler mode with coherent MTD (moving target detection) processing.

A second objective of programmability is to provide interchangeability of signal processor units among different radar systems. While cost would be a factor here an even more important advantage would be performance upgrading. Programmable signal processing units could be tailored to any specific radar's requirements even though they were not originally designed for that application.

7.1.2 Programmability With CCD's

To achieve full programmability with CCD's it is necessary to have a reliable technique for switching and moving charge in opposing directions. While this would at first seem to be a straight-forward operation, consideration of a typical CCD structure will indicate the problems. Figure 109 shows a CCD delay line structure with the overlapping gates connected to clock busses. In order to contain charge within the limits defined by the gates and prevent clock bus coupling to the wells, charge barriers are introduced along the line. If it is desired to switch charge from moving down one line to another a means must be provided to tap the line through the barrier in a manner which transfers charge efficiently without crosstalk effects. As shown in Figure 109 this can be done by use of a transfer gate which serves as the barrier function when the gate is turned off. In the particular concept shown, charge can flow in either direction depending on the clock and control signal sequence. Thus the unit could also serve as a 2 to 1 multiplexer if the control busses are separated properly.

The fact that the charge moves through the substrate prevents one charge path from crossing another with both being operated simultaneously. This greatly restricts the complexity of functions. For example, one cannot easily construct a simple lattice network.

Table 35 lists a number of functions which can be considered for CCD processor programmability together with the means of achieving them and the general status of development.

Electrically variable tap weights are one of the most desirable features for

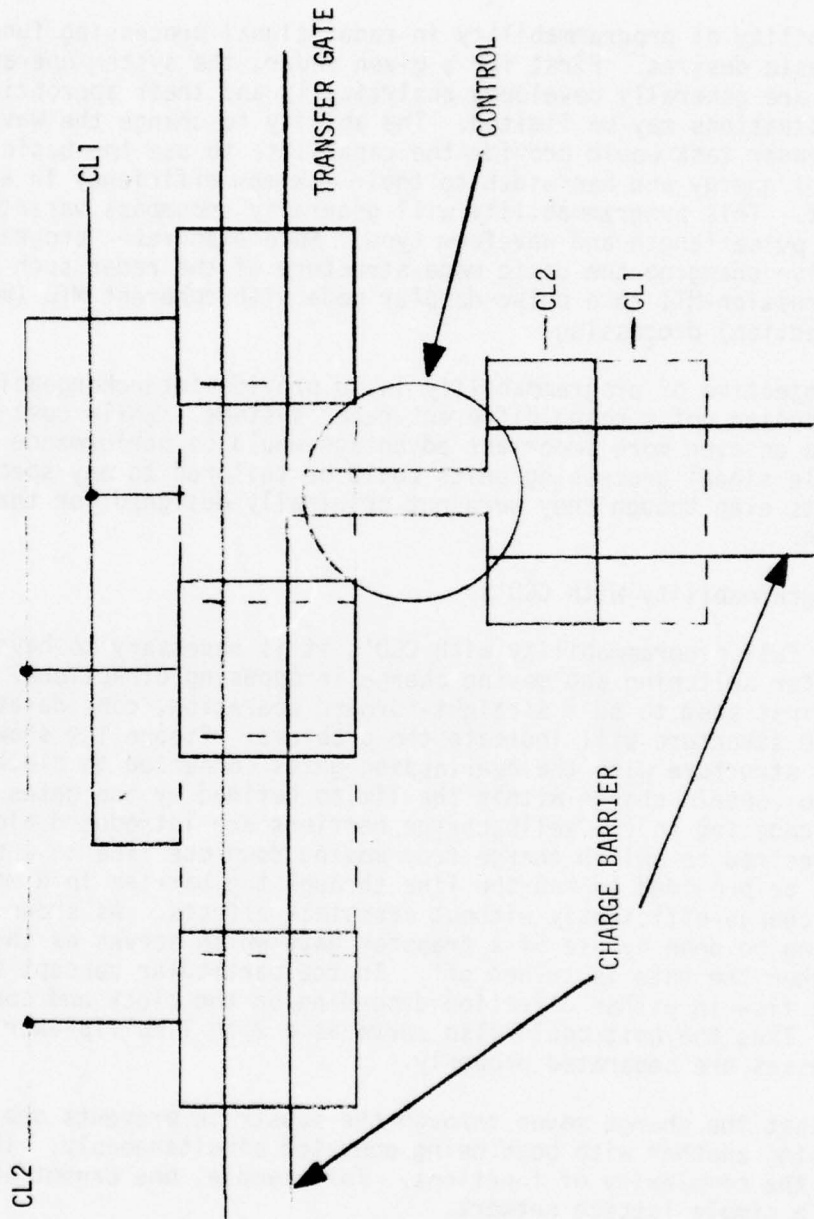


FIGURE 109. CONCEPTUAL CCD CHARGE TAP

TABLE 35. CCD PROGRAMMABILITY CONSIDERATIONS

TECHNIQUE CATEGORY	TECHNIQUES	TECHNOLOGY STATUS
Electrically Variable Weights	<ul style="list-style-type: none"> ◦ Floating Gate Taps ◦ Integrated Multipliers ◦ Analog Storage 	<ul style="list-style-type: none"> ◦ Storage Time is Limited ◦ Multiplier is Problem ◦ Floating Gate Taps are Developed
Semi-Programmable Weights	<ul style="list-style-type: none"> (a) Split Gate Weighting (b) Electrically Programmed Permanent Weights 	<ul style="list-style-type: none"> (a) Established But Not Truly Programmable (b) Technique Not Developed
Switching and Shifting Charge	Use of Transfer Gates and Barrier Controls	<ul style="list-style-type: none"> ◦ Developed for Binary Signals ◦ Analog Technology Not Established
Variable Length	<ul style="list-style-type: none"> ◦ Setting Weights to Zero ◦ Control Length by Switching 	Requires Switching or Programmable Weights
Function Select	◦ Reconfiguration of Chip	Requires Extensive Development
Digital Logic Approach	Basic Digital Gate Functions Implemented with CCD Controls	<ul style="list-style-type: none"> ◦ Maybe in Laboratory Stage ◦ Suitable for Pipelined Functions such as Digital Filters and FFT's

CCD transversal filters. The basic floating gate tap technique allows CCD delay registers to be non-destructively sensed. However, the multiplication of two signals stored on separate CCD registers with a multiplier integrated on the circuit has presented problems. The difficulty is in part due to the nature of the signals stored on the CCD. Each analog sample must have sample values about a bias level in order to retain a general bipolar form. In this case, each sample will have the form $x_j = b + x(t_j)$. A general filter function with the bias factors takes the form:

$$\int (b_1 + x(t)) [b_2 + y(t-\tau)] dt$$

The foregoing integral will have four terms; the integral of the product of the two bias terms, the integral of each bias times the opposite signal and the integral of the product of the two signals. This is of course undesirable unless the spectrum of the signal products can be separated from the other terms. The CCD multiplier must, therefore, eliminate the bias cross products in the multiplication operation. Techniques for achieving this have been suggested [31, 32] which essentially cancel the bias terms of the two functions prior to or during multiplication. The techniques are, however, not well established with the latter reference [32] in 1975 describing a 32 tap filter with 32 multipliers whose output dynamic range was 20 dB, in part limited by external circuitry.

An electrically programmable filter by implication requires charge storage of a reasonable length of time. Dark current will limit this application just as it does general memory storage to storage times of 1 second or less unless the CCD is cooled.

A programmable feature which would greatly enhance the flexibility of CCD filters would be the ability to program fixed filter weights after fabrication in the manner of a PROM in digital memories. This would eliminate the costs of custom tailoring the weights for every CCD filter desired and would greatly reduce the cost of any particular CCD filter made in small to moderate quantities. This, however, is a need looking for an invention. No devices of this nature are known at this time.

The achievement of electrically variable lengths for CCD transversal filters and delay times will follow the development of programmable weights and methods of switching charge paths. Following along this same line would be the ability to change the signal processing function by reconfiguration of the CCD chip.

A final technique for programmability in CCD's should be mentioned and that is the implementation of digital logic devices with CCD's. Calculations [33] indicate that CCD's can provide a logic density improvement of a factor of 16 and attendant power improvement of 18 at a 5 MHz clock rate over I²L technology. Applications are primarily suited for pipeline computation operations such as found with the FFT.

7.2 BANDWIDTH LIMITATIONS

The bandwidth capability or limitations of CCD signal processors fall into two categories; those due to the CCD device itself and those which involve

the peripheral circuitry required to operate the CCD.

7.2.1 CCD Bandwidth Limitations

Bandwidth handling capability of a CCD is essentially determined by the clock rate at which it can be operated. In considering wide-bandwidth application, concentration must necessarily be placed on buried channel, or peristaltic, CCD's since their charge transfer rates are much higher than surface channel CCD's.

A basic question is whether the inherent performance characteristics of CCD's will vary as a function clock rate. It has been shown in the simulation results reported in Section 6.0 that at low clock frequencies, performance is adversely affected because of dark current build-up. The maximum time that a signal can be held in a CCD prior to dark current build-up causing saturation effects is indicated in Table 36. The low frequency limitation for delay line applications will not be a factor in most radar applications. This does not include application where long storage times are involved.

TABLE 36. LOW FREQUENCY LIMITATIONS OF CCD DELAY LINES
(DARK CURRENT FILTERING 20% OF WELL)

<u>Temperature</u>	<u>Max Storage Time (Seconds)</u>
- 55°C	>12 Seconds
- 25°C	>12 Seconds
+ 5°C	>12 Seconds
+ 35°C	6 Seconds
+ 65°C	0.75 Seconds
+ 95°C	< 0.1875 Seconds
+125°C	< 0.1875 Seconds

The CCD model developed for the simulation on this program has no noise or degradation sources which degrade the performance of a CCD as the clock rate is increased. Two recent studies [34, 35] have been reported regarding the measured performance of CCD's at high clock rates. Chan, et al [34] conducted an interesting test on a 130 cell buried channel CCD. By initially loading the CCD at rates up to 105 MHz, holding the data, and reading it out at the lower rate of 100 kHz, the effects of higher frequency operation were examined. This fixed low output speed prevented degradations due to the output circuitry itself from being a factor. Linearity of the input structure was verified to give second and third harmonic distortion levels of about -54 dB. The transfer efficiency (>.999) was found to be constant over all operating frequencies and no other performance measures could be seen as a function of frequency other than that due to dark current build up at very low frequencies.

7.2.2 Clock, Control and Packaging Considerations

Although the CCD itself has not exhibited any important operating degradations up to the limitation imposed by charge mobility, the practical use of CCD's at high frequencies is a problem. The CCD has been developed in large measure by use of the circuit technology of digital logic. The analysis of CCD's follows the sampled data nature of digital signals. However, a CCD is a low-

noise analog device and optimum operation cannot be achieved unless very careful analog design and packaging procedures are followed. One rather obvious manifestation of the problem is apparent in the packaging of CCD's in dual-in-line packages. This packaging method, which was developed in conjunction with the growth of digital logic, is characterized by leads running closely parallel to each other over relatively large distances from the chip to package pins. The problems of cross coupling of clocks and signals in such a device are large. Recall that 100 MHz is a higher frequency than television channel 6 (84-88 MHz) and an appreciation of the shielding and lead lengths required in television tuners may give an insight into the packaging requirements for CCD's where 10 volt clocks are in close proximity to millivolt signals.

The design of clock drivers, output amplifiers and drivers are difficult problems and the high frequency performance of a CCD device will very likely fail due to efficiencies in these areas before CCD device limits are reached.

7.3 POST PROCESSING FUNCTIONS

The post processing functions in a radar signal processor generally refer to those following the basic matched filtering operation. Doppler processing is generally considered with the pulse compression system since it forms a matched filter for a target with a specific doppler. Post processing functions include: thresholding, range and angle estimation, bulk filtering, constant false alarm rate (CFAR) processing, interpolation, predictors and various pattern recognition procedures. Many of the functions are identified in Figure 2. The application of CCD's is possible in those cases where the computations can be pipelined. Implementation of many post processing functions with CCD's is even more dependent on achieving programmability and adaptability than the pre-post processor functions. An important consideration relative to the appropriateness of CCD processing is the processing rate requirements of specific functions and whether digital microprocessor based techniques will ultimately be the best approach.

7.3.1 Processing Rate Requirements

The question of potential competitive advantages for implementation of post processing functions with CCD's depends upon the computation rates and the functions required. Table 37 lists conventional post processing functions together with their relative computational rates and general architecture. Those in which a CCD-analog implementation is projected to perform at a lower cost than a microprocessor based digital system are indicated. In general, functions which are related to threshold detection such as interpolation and CFAR are candidates for CCD processing. Pattern recognition functions are CCD candidates because even though the duty factor is low relative to the pulse interval, the bandwidth will be high and computation rates similar to the thresholding functions are likely to be required.

7.3.2 Interpolation

Sampled data systems are characterized by non-optimum time sampling of the input data which causes a range straddling and an error in the estimate of the true target position. This effect is illustrated in Figure 110. The

TABLE 37. POST PROCESSOR CCD CANDIDATES

POST PROCESSING FUNCTION	COMPUTATION RATE	DUTY CYCLE	PRINCIPAL PROCESSING ELEMENTS (ARCHITECTURE)	REMARKS RE CCD IMPLEMENTATION	ADVANTAGE TO	
					CCD	MICRO-PROCESSOR
Threshold Detection	Video Sample Rate	100%	Amplitude Comparison	Peripheral CCD, Analog Circuitry	X	
Normal Threshold Computation	<< Sample Rate	~ 1%	Weighting & Adding Several Sensor Inputs	Requires Programmability		X
Interpolation	Sample Rate or Greater	100%	Transversal Filter	Programmability of Weights is Desirable	X	
CFAR	Sample Rate or Greater	100%	Transversal Filter	Programmable Weights for Adaptive CFAR	X	
Range & Angle Estimation	<< Sample Rate	< 1%	Add, Subtract, Mult., Divide, Small Delays	Specialized Analog Functional Would Do Mult. & Divide Operation		X
Pattern Recognition (Correlation, 2D Transform)	High	< 1%	Programmable Transversal Filter for 2D Transform	Computation Rates Are High Since Waveforms are Wideband	X	
Predictors, Coordinate Conversion, Kalman Filters	<< Sample Rate	Small	General Arithmetic Operations	Required Wide Programmability		X

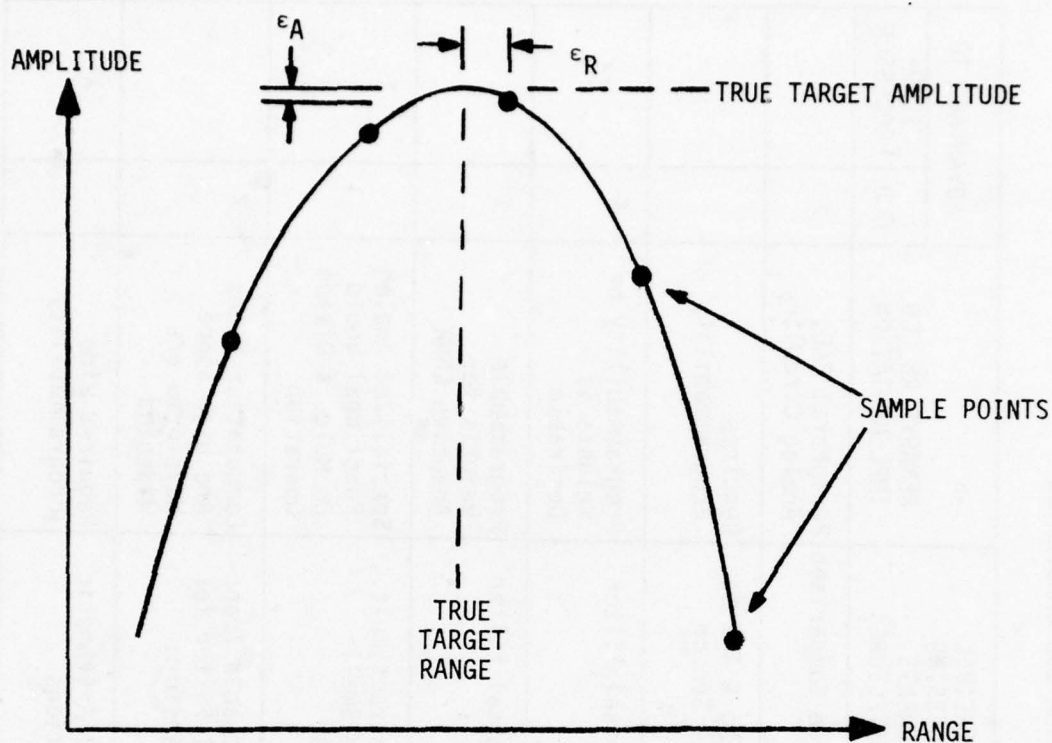


FIGURE 110. TARGET STRADDLING WITH SAMPLED DATA SYSTEM

problem can be avoided by sampling at a rate much higher than that required by the Nyquist sampling criteria. Figure 111 shows the straddling loss versus sampling rate.

Interpolation between samples which effectively increase the sampling rate can be achieved by a number of filter approaches. An optimum filter can be derived which is closely matched to the spectrum of the compressed pulse. A typical configuration is the 4-point polynomial interpolator shown in Figure 112. This is virtually a standard transversal filter and it can be readily implemented with CCD's. One filter is necessary for each inter-sample interpolated point.

7.3.3 CFAR Processing

The objective of a constant false-alarm rate (CFAR) process is to adaptively adjust the target detection threshold to the environment. A situation is depicted in Figure 113 where a large clutter return is present. If a fixed threshold were used, it would have to be set above the clutter return. However, if the threshold is made to adapt to the clutter return, the small target outside the clutter return can be detected. An implementation of a CFAR system designed to accomplish the required adaptivity is shown in Figure 114. In this case, the sidelobe levels of the compressed pulse output are measured in the

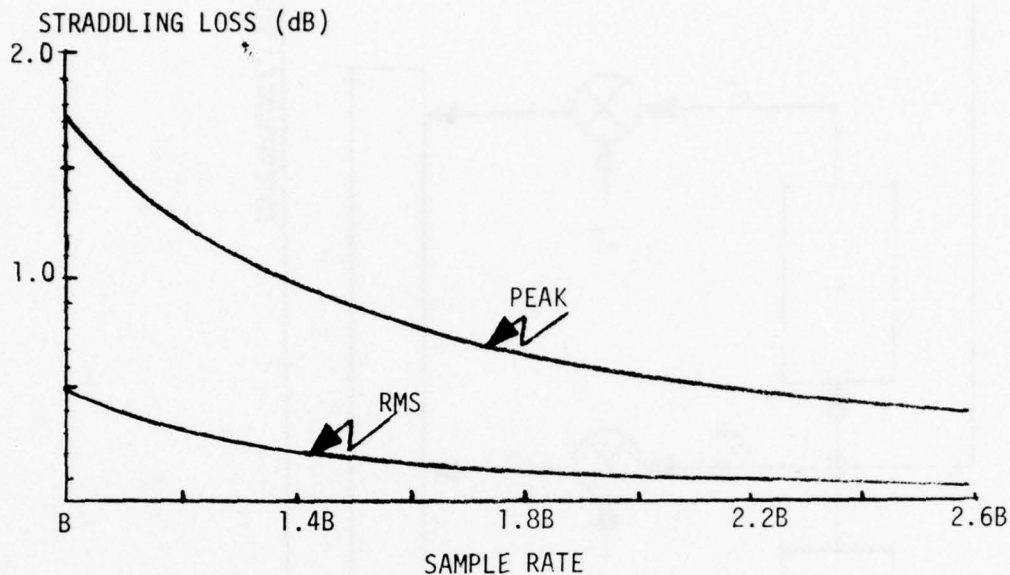


FIGURE 111. STRADDLING LOSS VERSUS SAMPLING RATE FOR HAMMING WEIGHTED COMPRESSED LINEAR FM PULSE OF BANDWIDTH, B

vicinity of the range sample of interest and these levels are used to adjust the threshold level. This entire function can be implemented with CCD's.

7.4 PRACTICAL CCD IMPLEMENTATIONS

7.4.1 Peripheral CCD Circuitry

A principal feature of CCD's is their small size and power dissipation in relation to their functional capability. However, in ascertaining the total cost of a CCD system, the peripheral circuitry necessary to operate the devices must be included. This aspect of CCD's is perhaps the most critical problem, or deterrent, to more widespread application. The operation of CCD's involve multiple phase, multiple level clock signals, bias levels for the input gates, output amplifiers, and finally the cancellation or filtering of the clock signal from the output. The amount of control circuitry required will vary among the CCD devices and with the sophistication of the designer, but an example will illustrate the situation. A commercially available CCD, a dual 455 stage (1H) delay line, is marketed by Fairchild. This unit, designated the CCD 321, is offered with a design development module containing all required control signals. The component count of the module (type CCD 32M) includes:

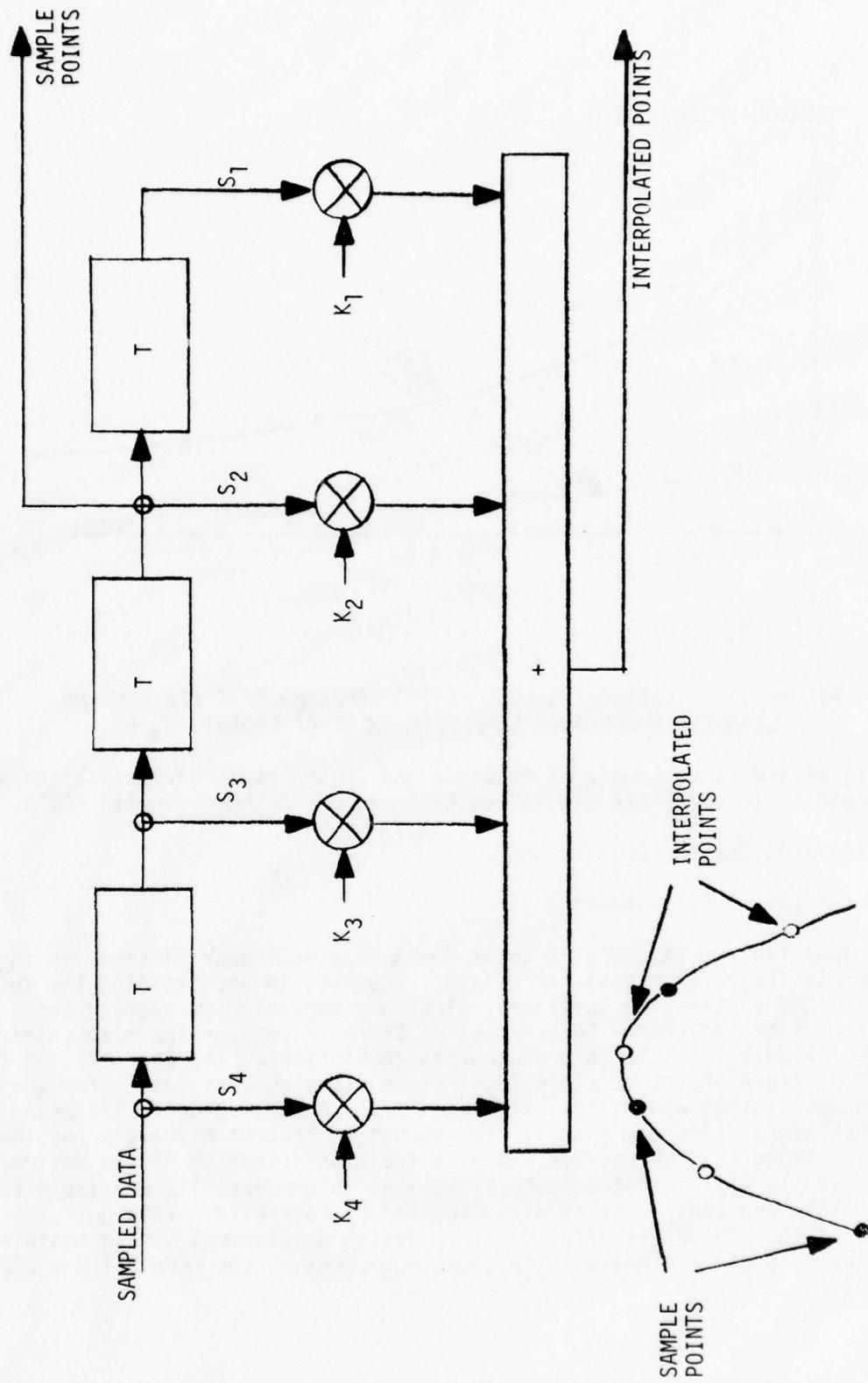


FIGURE 112. 4-POINT POLYNOMIAL INTERPOLATOR

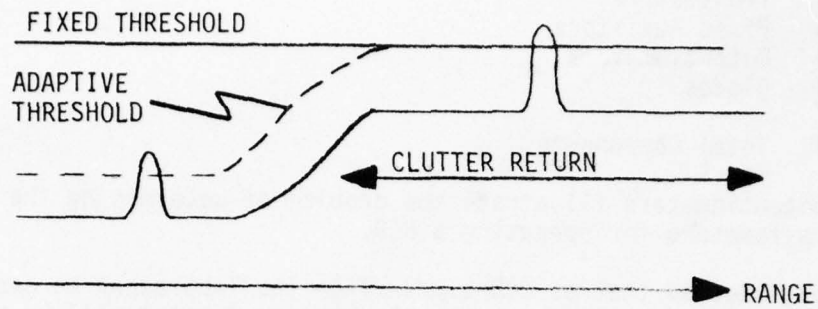


FIGURE 113. VARIABLE THRESHOLD ENVIRONMENT

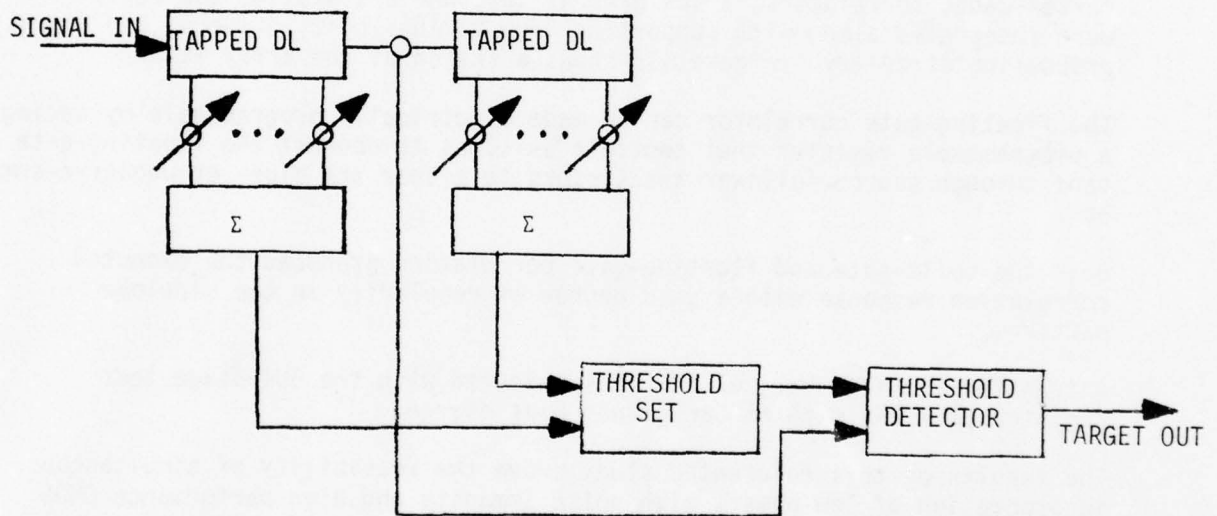


FIGURE 114. TYPICAL CFAR IMPLEMENTATION

9	Integrated Circuits
44	Capacitors
14	Transistors
39	Fixed Resistors
10	Potentiometers
<u>23</u>	Diodes
139	Total Components

The 10 potentiometers illustrate the problem of determining the optimum control parameters for operating a CCD.

It can be expected that as CCD's move from the laboratory to systems, the needs relative to precise operational characterization will be met. The other development which can be expected to improve the hardware implementation of CCD's will be the integration of control signals on the CCD chip.

7.4.2 On-Chip CCD Controls

The integration of CCD control signals on the CCD circuit is a target of CCD development effort at this time. The most extensive program of this reported thus far appears to be a program of RCA for the US Army Electronics Command [36]. A complex CCD array comprised of split-gate and floating-gate 13-bit Barker-coded correlators, a low pass filter, and a 504-stage CCD register were integrated along with supporting CMOS timing/logic, drivers, and signal processing circuitry. Figure 115 shows a sketch of the array layout.

The floating-gate correlator can be made electrically programmable by adding a programmable register that controls switches to connect the floating-gate taps through source follower transistors to either the plus- or negative-sum bus.

Both the split-gate and floating-gate correlators produced the expected correlation response with a good degree of regularity in the sidelobe patterns.

A transfer inefficiency of 10^{-5} was measured with the 504-stage test register at 1 MHz with no background bias charge.

The results on this referenced study prove the feasibility of simultaneous incorporation of low power, high noise immunity and high performance CMOS on-chip with high efficiency CCD devices to achieve self-contained signal processing components such as analog delay and transversal filters which do not require complex external support circuitry.

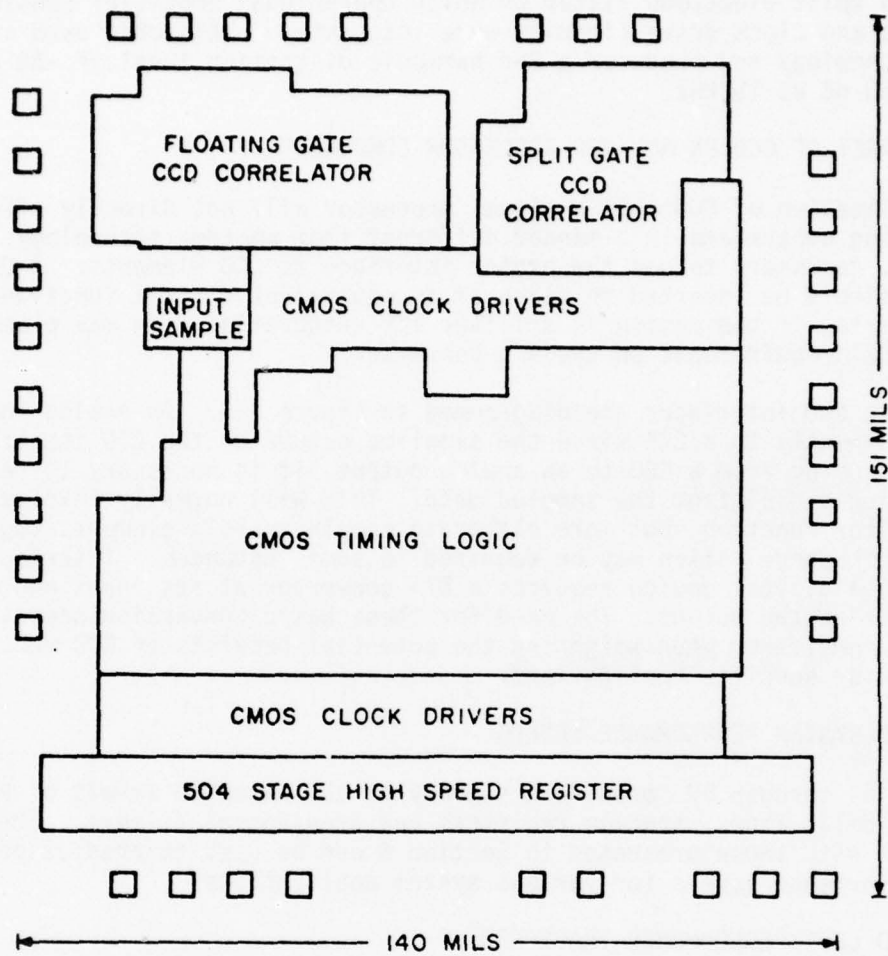


FIGURE 115. LAYOUT OF CMOS/CCD TEST CHIP

A recent paper [37] by researchers at Bell Labs discussed the development of a 55 tap split electrode filter on which operational amplifier sensing circuits and clock drive circuits were integrated. This chip used silicon NMOS technology and produced a 2nd harmonic distortion level of -50 dB and a S/N of 60 dB at 15 kHz.

7.5 IMPACT OF CCD ON NON-CCD PROCESSOR COMPONENTS

The application of CCD's in a signal processor will not directly affect other processing subsystems in a manner different from another technology. It is, however, necessary to use the proper interface to CCD elements. A CCD unit cannot simply be inserted in place of an equivalent digital function since, for example, if the device is a filter its integration gain may place additional requirements on the A/D converter.

The basic CCD interfaces are diagrammed in Figure 116. An analog input can be fed directly to a CCD since the sampling occurs on the CCD itself. However, in going from a CCD to an analog output, it is necessary to recover the analog signal from the sampled data. This will normally involve a low pass filter function, but more elaborate sample-on-hold elements together with clock cancellation may be required in some instances. Interfacing a CCD with a digital device requires a D/A converter at its input and an A/D converter at the output. The need for these basic conversion operations must be considered when weighting the potential benefits of CCD versus digital for specific applications.

7.6 SUB-SYSTEM PERFORMANCE LEVELS

Tables 38 through 40 provide a summary of the expected levels of performance for CCD delay lines, storage registers and transversal filters. These charts together with those presented in Section 6 can be used to predict potential CCD performance levels for various system applications.

7.7 CCD COST/PERFORMANCE TRADEOFFS

General projections on CCD system costs relative to other technologies can be made, but specific tradeoffs will depend on the application and the competing technology. For low data rate applications, microprocessor techniques will prevail as most cost-effective. As the data rates and processing requirements increase to the hundreds of kilohertz up to 10 MHz, CCD's will find increasing application. Buried channel CCD's operate up to and beyond 100 MHz. Figure 117 indicates general speed performance categories for various technologies. The line of demarcation between different approaches will fluctuate depending on the specific application. Note that every category of processor can be built with special purpose digital hardware. This involves paralleling at the very high rates.

Costs can be expected to follow the basic pattern of Figure 118. A standard implementation using MSI digital technology will be relatively low in cost but as the number of units to be constructed increases, the parts cost will become dominant. Thus initial investments in either LSI or CCD development will produce substantial savings in the end. Since fewer chip designs are required for CCD's and fewer parts will be required in the system, the CCD

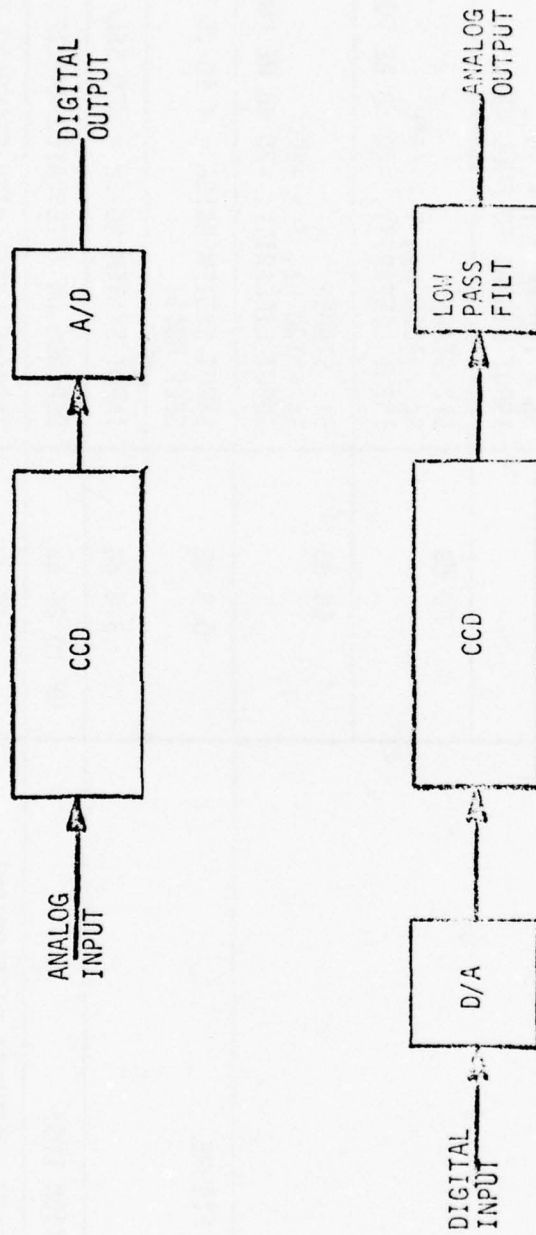


FIGURE 116. CCD - ANALOG - DIGITAL INTERFACE

TABLE 38 . EXPECTED CCD DELAY LINE PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE	115 dB	512 STAGES SR = 100 kHz, T = +5°C INPUT LINEAR TO FULL WELL
	80 dB	512 STAGES SR = 1000 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
	60 dB	512 STAGES SR = 100 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
NOISE FIGURE	0.3 dB	INPUT SYSTEM NOISE = + 10 dB RE TO CCD SELF NOISE
	3.0 dB	INPUT SYSTEM NOISE = CCD SELF NOISE
INSERTION LOSS	UP TO 26 dB	DEPENDS ON INTEGRATED AMPLIFIERS
LINEARITY (HARMONIC DISTORTION)	-45 dB	TYPICAL LEVEL WITH STANDARD INPUT TECHNIQUE (MEASURED RESULTS)

TABLE 39. EXPECTED CCD STORAGE REGISTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE*	52 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, RE FULL WELL
	24 dB	STORAGE TIME = 12 SEC TEMPERATURE = 35°C, RE FULL WELL
	73 dB	STORAGE TIME = 1 SEC TEMPERATURE = 5°C, RE FULL WELL
	32 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, -20 dB RE FULL WELL
NOISE FIGURE INSERTION LOSS LINEARITY	SAME AS DELAY LINE CASE	

* THE DYNAMIC RANGE FOR CCD'S IN A STORAGE MODE IS LOW BECAUSE OF THE BUILD-UP OF DARK CURRENT VARIATIONS WHICH ARE AVERAGED OUT IN THE DELAY LINE CASE.

TABLE 40. EXPECTED CCD TRANSVERSAL FILTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC*	MEASURE	CONDITIONS
MAX SIDELobe LEVEL (IDEAL = -39.6, TW PRODUCT = 65)	-39.5 dB	TAP ERRORS = 1% T = 5°C CLOCK RATE (f_s) = 105 Hz
	-39.3 dB	TAP ERRORS = 3%
	-35.6 dB	TAP ERRORS = 10%
	-36 dB	f_s = 10 kHz TEMP. = 95°C
	-38.5 dB	f_s = 10 kHz TEMP. = 65°C
DYNAMIC RANGE (OUTPUT) CCD FILTER = 129 STAGES, TW = 65	80 dB	f_s = 100 Hz TEMP. = -25°C
	60 dB	f_s = 100 Hz TEMP. = 5°C
	60 dB	f_s = 300,000 Hz TEMP. = 65°C
	110 dB	f_s = 3000 Hz TEMP. = -25°C
		RE FULL WELL
NOISE FIGURE	0.3 dB	INPUT SYSTEM NOISE = +10 dB RE TO CCD SELF NOISE
	3.0 dB	INPUT SYSTEM NOISE = CCD SELF NOISE
INSERTION LOSS	UP TO 26 dB	DEPENDS ON INTEGRATED AMPLIFIERS
LINEARITY (HARMONIC DISTORTION) CCD FILTER = 129 STAGES, TW = 65	-63 dB	RE OUTPUT
	-45 dB	RE INPUT

* THESE MEASUREMENTS APPLY TO CORRELATORS, CONVOLVERS, MATCHED FILTERS AND CZT SPECTRUM ANALYZERS IN SO FAR AS FUNDAMENTAL CCD IMPOSED LIMITATIONS.

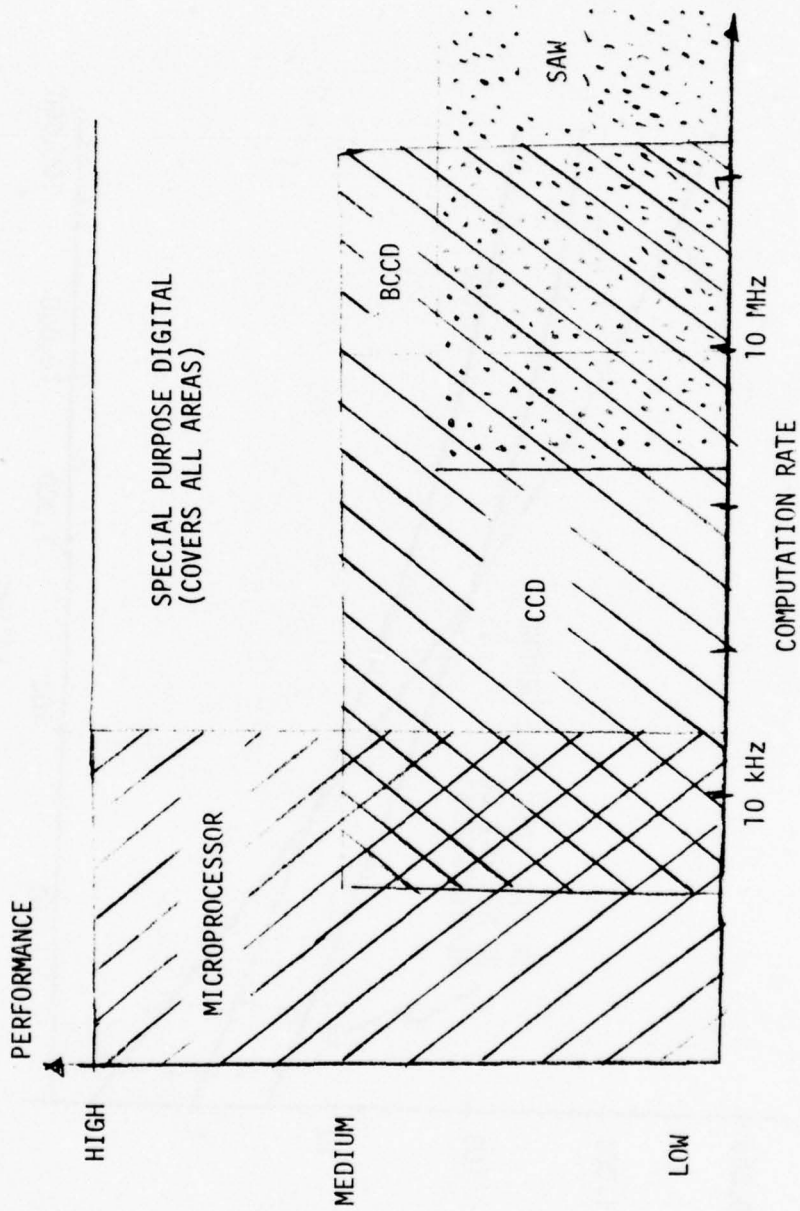


FIGURE 117. TECHNOLOGY CATEGORIES

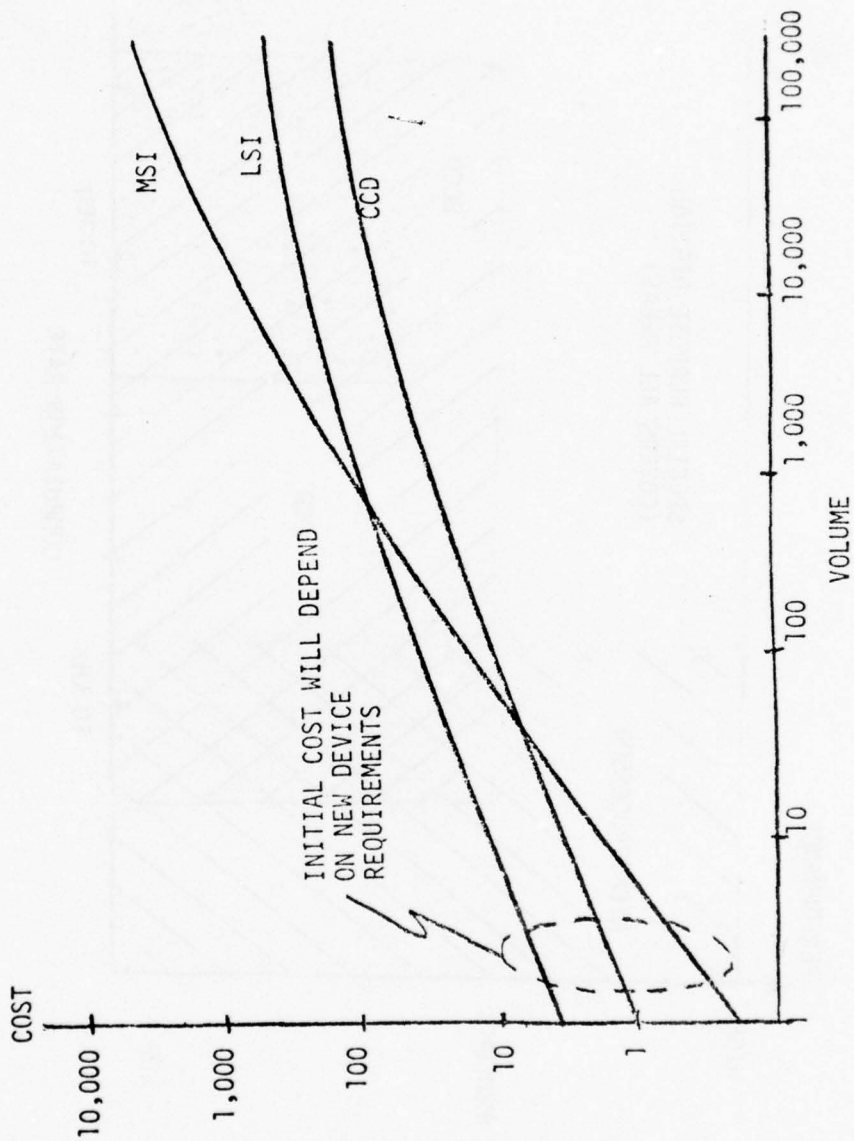


FIGURE 118. TECHNOLOGY COST TRENDS

unit costs will be lowest for large volumes. The crossovers of "break-even" costs indicated in Figure 118 can not be assumed to hold in general. Each application will produce a different tradeoff.

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APPENDIX A. COMPUTER LISTING OF DELAY LINE

```

C
C      CCD1,FTN
C
C
C      CCD STUDY   MODELING AND SIMULATION OF THE DEVICE
C
C
C*****
C*****
C
0001      REAL A(2),B(3)
0002      COMMON /RAND/G0(10)
0003      COMMON /BINSTR/G(50)
0004      COMMON /CCD/G1(1202)
0005      COMMON /INPUT/G2(1200)
0006      COMMON /VOLTS/G5(10)
0007      COMMON /PASS/GG(50)
0008      COMMON /COEFF/COEFF(600)
0009      10      CONTINUE
0010      WRITE(5,100)
0011      100     FORMAT(1H1'   CCD STUDY   TEST RUN'//)
0012      CALL TIME(A)
0013      CALL DATE(B)
0014      WRITE(5,101) B,A
0015      101     FORMAT(5X,'DATE: ',3A4,5X,'TIME: ',2A4//)
0016      CALL LINK('C0')
0017      CALL LINK('C1')
0018      CALL LINK('C2')
0019      CALL LINK('C3')
0020      CALL LINK('C4')
0021      CALL LINK('C5')
0022      CALL LINK('C6')

C*
C*
C*      THE FOLLOWING CODE IS USED TO FORCE THE
C*      MAIN MODULE TO CARRY THE I/O ROUTINES
C*      SEE DESCRIPTION IN FORTRAN OR LINK
C*      MANUALS
C*
C*
0023      IDUM=0
0024      IF(IDUM,EQ,0) GOTO 10
0025      READ(1,'INDEX) A
0026      WRITE(1,'INDEX) A
0027      READ(6,1001) II,A
0028      WRITE(6,1001) II,A
0029      1001     FORMAT(15,E15.8,F10.0)
0030      END

```

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```

C*
C*
C*      CCD LINK STRUCTURE
C*
C*      CCD,CCD,CCD<CCD1,FTNLIB/L/U/E
C*
C*
C*      C0 LINK STRUCTURE
C*
C*      C0,C0<CCD.STB,C0,CCD6,CCD19,CCD31,FTNLIB/L/U/E
C*
C*
COMMON /BINSTR/XX(30),IJ(30)
COMMON /PASS/STAD(20),ISTAD(22),ROW(7),IRW(4)
1  CONTINUE
   IF(IJ(9),NE.9998) CALL INSTR
   IF(IJ(21).GT.0) CALL REPEAT
   IF(IJ(9).LT.0) GOTO 1
   IJ(21)=IJ(21) + 1
   CALL RETURN
   END

C*
C*
C*      C1 LINK STRUCTURE
C*
C*      C1,C1<CCD.STB,C1,CCD5,FTNLIB/L/U/E
C*
COMMON /RAND/PI,PII
   PI=4.*ATAN(1.)
   PII=2.*PI
   CALL PRVAL
   CALL RETURN
   END

C*
C*
C*      C2 LINK STRUCTURE
C*
C*      C2,C2<CCD.STB,C2,CCD2,FTNLIB/L/U/E
C*
CALL INPUT
CALL RETURN
END

C*
C*
C*      C3 LINK STRUCTURE
C*
C*      C3,C3<CCD.STB,C3,CCD3,FTNLIB/L/U/E
C*
CALL INITL
CALL RETURN
END

```

C*
C*
C*
C*
C*
C*
C*

C4 LINK STRUCTURE

C4,C4<CCD,STB,C4,CCD7,CCD17,CCD18,CCD20,CCD30,FTNLIB/L/U/E

CALL SD
CALL XRUN
CALL RETURN
END

C*
C*
C*
C*
C*
C*
C*

C5 LINK STRUCTURE

C5,C5<CCD,STB,C5,CCD8,FTNLIB/L/U/E

CALL OUTP
CALL RETURN
END

C*
C*
C*
C*
C*
C*
C*

C6 LINK STRUCTURE

C6,C6<CCD,STB,C6,CCD26,CCD27,CCD28,CCD29,CCD16,FTNLIB/L/U/E

CALL SETUP
CALL RETURN
END

C
C
C
C
C
C

CCD6,PTN

SUBROUTINE READS IN THE INSTRUCTIONS FOR A RUN

```
      SUBROUTINE INSTR
      REAL A(3)
      COMMON /CCD/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(4),XLEV,
2      ZL(20),ISTAGE,IPRINT,I LENGT,IFILT,NRVS,IJ(20)
      COMMON /BINSTR/XXZ(30),IJL(30)
      COMMON /VOLTS/WW1,WW2,ITIME
      COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
      COMMON /RAND/R1(4),RR(6)
      DATA A/4HTEMP,4H02.0,4HAT00/
      IJL(21)=0
      IRW(3)=0
      IJL(9)=9998
7000  WRITE(6,7000)
      FORMAT(' CREATE NEW FILE ON DAT SLOT 2 Y=0 N=1 '/')
      READ(6,91) I
      IF(I.NE.0) GOTO 7005
      WRITE(6,7001)
7001  FORMAT(' NAME OF FILE XXXXXX.D '/')
      READ(6,7002) A(1),A(2)
7002  FORMAT(2A4)
7003  WRITE(5,7003) A
7004  FORMAT(' NAME OF FILE FOR THIS RUN ',3A4//)
      CALL SETFIL(2,A,IER2,'DK',0)
      DEFINE FILE 2(50,64,U,IVAR)
1      WRITE(6,100)
100   FORMAT(' THE NUMBER OF STAGES IN THE CCD (F10.0)')//
      READ(6,101) X
101   FORMAT(F10.0)
      IUPPER=600
      ILOWER=0
      ISTAGE=X
      IF((ISTAGE.GT.ILOWER).AND.(ISTAGE.LE.IUPPER)) GOTO 3
      WRITE(6,201) ISTAGE,ILOWER,IUPPER
201   FORMAT(' ERROR MESSAGE # OF STAGES TO SMALL OR TO LARGE'/
2' # OF STAGES: ',I4,' LOWER LIMIT: ',I4,' UPPER: ',I4//)
      GOTO 1
3      WRITE(6,103)
103   FORMAT(' SD OF THE INITIAL STATE (F10.0) '/')
2' IF < 0 THEN NO BACKGROUND VOLTAGE ADDED '/')
      READ(6,101) XSD
C*
C*
C*   CHANGE 02/22/77
C*
      XXZ(3)=XSD
      IJL(1)=ISTAGE
4      WRITE(6,104)
104   FORMAT(' SURFACE OR BURIED DEVICE (0 OR 1.)')//
      READ(6,101) ZZ1
      IJ(1)=ZZ1
      IJL(6)=IJ(1)
      IF((IJ(1).LT.0).OR.(IJ(1).GT.1)) GOTO 4
```

```

WRITE(6,108)
108  FORMAT(' AREA OF WELL IN MIL**2 '/')
      READ(6,101) ZL(5)
      WRITE(6,107)
107  FORMAT(' % OF BACKGROUND CHARGE %/
2     ' <0 THEN SPECIFY TRANSFER LOST '/')
      READ(6,101) ZL(6)
      IF(ZL(6).LT.0.) WRITE(6,7891)
7891  FORMAT(' FRACTION LOST EACH TIME ,XXXX'/)
      IF(ZL(6).LT.0.) READ(6,101) XPERC
      IF(ZL(6).GE.0.) CALL CTI(ZL,XPERC,IJ)
      WRITE(6,109)
109  FORMAT(' CLOCK SWING VOLTAGE '/')
      READ(6,101) ZL(8)
      XXZ(1)=XPERC
      XXZ(15)=ZL(5)
      XXZ(16)=ZL(6)
      XXZ(18)=ZL(8)
      WRITE(6,9050)
9050  FORMAT(' PLOT OF INPUT AND OUTPUT Y=0 N=1 '/')
      READ(6,91) IJL(7)
      WRITE(6,7011)
7011  FORMAT(' FFT OF OUTPUT Y=1 N=0 '/')
      READ(6,91) IJL(30)
5     WRITE(5,1000) IJL(30),XPERC,ZL(6),ZL(8)
1000  FORMAT(' # OF STAGES IN THE CCD ',I5/
3     ' CTI OF DEVICE ',1PE15.8/
4     ' % OF THE BACKGROUND CHARGE ',1PE15.8/
4     ' AREA OF THE WELL (MIL**2)',1PE15.8//)
6     WRITE(6,206)
206  FORMAT(' CLOCK FREQUENCY (F10) '/')
      CLCKMX=1.E10
      READ(6,101) FCLOCK
      IF((FCLOCK.GT.0.).AND.(FCLOCK.LE.CLCKMX)) GOTO 60
      WRITE(6,1006) CLCKMX
1006  FORMAT(' CLOCK RATE OUTSIDE OF RANGE OF 0. TO 'F10.0//)
      GOTO 6
60    CONTINUE
      WRITE(5,701) FCLOCK
701  FORMAT(' CLOCK RATE ',1PE15.8/)
80    WRITE(6,800)
800  FORMAT(' THE LENGTH OF TIME OF THE RUN < 1201 '/')
      READ(6,101) ZZ1
      ITIME=ZZ1
      IF((ITIME.LT.0).OR.(ITIME.GT.1200)) GOTO 80
      WRITE(6,90)
90    FORMAT(' PRINT OUT INTERMEDIATE VALUES NO=0 YES=1/')
      READ(6,91) IPRINT
91    FORMAT(I1)
      WRITE(6,9008)
9008  FORMAT(' FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1/')
C*
C*  MAXIMUM INPUT VOLTAGE IS 2.8 VOLTS
C*
C*
      XYZ(4)=FCLOCK
      IJL(2)=IPRINT
      XMAXV=2.8
      WW1=XMAXV
      READ(6,91) NHVS

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96      WRITE(6,93)
93      FORMAT(' DURATION OF THE SIGNAL MIN=0 MAX=1200')
      READ(6,101) ZZ1
      ILENGT=ZZ1
      WRITE(6,7020)
7020    FORMAT(' TYPE OF SIGNAL PULSE =0 SIN = 1 ')
      READ(6,91) IJL(29)
      IF(IJL(29).EQ.0) GOTO 95
7022    WRITE(6,7021)
7021    FORMAT(' # OF SINUSOIDALS F10, < 5')
      READ(6,101) ZZ1
      IJL(28)=ZZ1
      IF((IJL(28).LE.0).OR.(IJL(28).GT.4)) GOTO 7022
      IKK=IJL(28)
      IKL=30
      DO 7023 I=1,IKK
      WRITE(6,7024) I
7024    FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL(HERTZ)')
      READ(6,101) ZZ1
      XXZ(IKL)=ZZ1
      WRITE(6,8025) I
8025    FORMAT(' AMPLITUDE (% OF WELL) OF THE ',I3,' SIGNAL')
      READ(6,101) STAD(I)
      STAD(I)=WW1*STAD(I)/100.
      WRITE(6,7030) I,ZZ1,STAD(I)
7030    FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL ',1PE15.8/
2        ' AMPLITUDE (VOLTS) OF THE SIGNAL ',1PE15.8/)
      IKL=IKL - 1
7023    CONTINUE
      WRITE(6,8053)
8053    FORMAT(' DC BIAS (% OF WELL) TERM ADDED TO INPUT F10 ')
      READ(6,101) XXZ(5)
      XXZ(5)=WW1*XXZ(5)/100.
      GOTO 9918
95      CONTINUE
      WRITE(6,92) XMAXV
92      FORMAT(' INPUT LEVEL OF SIGNAL MAX= ',F10.3,' VOLTS')
      READ(6,101) XLEV
      IF((XLEV.LE.0.).OR.(XLEV.GT.XMAXV)) GOTO 95
9918    CONTINUE
      IJL(3)=ILENGT
      IJL(5)=NRVS
      XXZ(10)=XLEV
      WRITE(6,8010)
8010    FORMAT(' NON LINEAR INPUT WARPING Y=0 N=1')
      READ(6,91) IJ(12)
      WRITE(6,97)
97      FORMAT(' FILTER RESPONSE COMPUTED? N=0 Y=1')
      READ(6,101) ZZ1
      IFILY=ZZ1
      IJL(20)=1
      WRITE(6,9033)
9033    FORMAT(' DARK CURRENT ADDED Y=0 N=1 ')
      READ(6,91) IJ(13)
      IF(IJ(13).EQ.1) GOTO 9036
      WRITE(6,9034)
9034    FORMAT(' AMBIENT TEMPERATURE DEGREES C ')
      READ(6,101) Z71
      XXZ(26)=Z71 + 275.
      WRITE(6,9035) ZZ1,XXZ(26)

```

```

9035  FORMAT(' AMBIENT TEMPERATURE (C) ',F10.4,' (K) ',F10.4/)
      WRITE(6,1701)
1701  FORMAT(' DO YOU WANT TO HOLD THE SIGNAL FOR ANY ' /
2     ' OF TIME Y=0 N=1 ' /)
      READ(6,91) IJL(20)
      IF(IJL(20).EQ.1) GOTO 9036
      WRITE(6,1702)
1702  FORMAT(' TIME(SEC) LEFT IN DELAY LINE ' /)
      READ(6,101) XXZ(21)
      WRITE(6,1703)
1703  FORMAT(' FREQUENCY CLOCK SIGNAL OUT AT ' /)
      READ(6,101) XXZ(22)
      WRITE(5,1704) XXZ(4),XXZ(21),XXZ(22)
1704  FORMAT(' INPUT SAMPLING RATE ',1PE15.8,
2     ' TIME LEFT IN DEVICE ',1PE15.8,
3     ' OUTPUT SAMPLING RATE ',1PE15.8/)
9036  CONTINUE
      IJL(4)=IFILT
      IJL(17)=IJ(12)
      IJL(18)=IJ(13)
      WRITE(6,6011)
6011  FORMAT(' MULTIPLE RUN Y=# OF CHANGES N=0 F10° /)
      READ(6,101) ZZ1
      IJL(19)=ZZ1
      IF(IJL(19).EQ.0) GOTO 8000
      WRITE(6,6012)
6012  FORMAT(' WHICH INPUT IS TO BE CHANGED ' /
2     ' 1= # OF STAGES, 2= SURFACE/BURIED ' /
3     ' 3= AREA OF WELL, 4= STORAGE TIME (SEC) ' /
4     ' 5= CLOCK FREQUENCY, 6= AMBIENT TEMPERATURE ' / /)
      READ(6,91) IJL(22)
      K=IJL(19)
      DO 6019 I=1,K
        WRITE(6,6013) I
6013  FORMAT(' INPUT THE ',I6,' VALUE ' /)
      READ(6,101) RR(I)
6019  CONTINUE
      WRITE(5,6015) (I,RR(I),I=1,K)
6015  FORMAT(' MULTIPLE RUNS ' / / (1X,I2,2X,1PE15.8))
      WRITE(6,8717)
8717  FORMAT(' SECOND VARIABLE CHANGING Y=# N=0 ' /)
      READ(6,91) IRW(1)
      IF(IRW(1).EQ.0) GOTO 8000
      WRITE(6,6012)
      READ(6,91) IRW(2)
      K=IRW(1)
      DO 8718 I=1,K
        WRITE(6,6013) I
      READ(6,101) ROW(I)
8718  CONTINUE
      WRITE(5,6015) (I,ROW(I),I=1,K)
8000  WRITE(6,8001)
8001  FORMAT(' RUN WITH NOISE Y=0 N=1 ' /)
      READ(6,91) IJ(3)
      IJL(8)=IJ(3)
      IF((IJ(3).LT.0).OR.(IJ(3).GT.1)) GOTO 8000
      IF(IJ(3).EQ.1) RETURN
      K=10
      DO 9000 I=5,11
        IJ(I)=0

```

```

      IJL(K)=0
      K=K + 1
9000  CONTINUE
      WRITE(6,8003)
8003  FORMAT(' SELECT THE PARTICULAR NOISE INPUTS N=0,Y=1'/)
      READ(6,91) IJ(5)
      IJL(10)=IJ(5)
      IF(IJ(5).EQ.0) RETURN
      WRITE(6,8004)
8004  FORMAT(' ADD IN INPUT NOISE Y=0 N=1 '/)
      READ(6,91) IJ(6)
      WRITE(6,8005)
8005  FORMAT(' ADD IN THE SHOT NOISE Y=0 N=1'/)
      READ(6,91) IJ(7)
      WRITE(6,8006)
8006  FORMAT(' ADD IN THE TRANSFER NOISE Y=0 N=1'/)
      READ(6,91) IJ(8)
      WRITE(6,8007)
8007  FORMAT(' ADD IN THE OUTPUT NOISE Y=0 N=1'/)
      READ(6,91) IJ(9)
      WRITE(6,8008)
8008  FORMAT(' ADD IN THE FILTER NOISE Y=0 N=1'/)
      READ(6,91) IJ(10)
      WRITE(6,8009)
8009  FORMAT(' ADD IN INTERFACE NOISE '/)
      READ(6,91) IJ(11)
      K=11
      DO 57 I=6,11
      IJL(K)=IJ(I)
      K=K + 1
57    CONTINUE
      RETURN
      END

```

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C*
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C*

CCD19.FTN

COMPUTES CTI FOR SURFACE AND BURIED DEVICES

02/22/77

```
      SUBROUTINE CTI(ZL,ZPERC,IJ)
      INTEGER IJ(5)
      REAL ZL(20)
      X=ZL(6)
      IF(IJ(1).EQ.1) GOTO 100
      IF(X.GT.4.) GOTO 1
      ZPERC=3.6E-4
      RETURN
1     IF(X.GT.5.) GOTO 2
      ZPERC=-2.7E-4*X + 1.4E-3
      RETURN
2     IF(X.GT.10.) GOTO 3
      ZPERC=-1.E-5*X + 1.4E-4
      RETURN
3     ZPERC=3.9E-5
      RETURN
100   IF(X.GT.4.) GOTO 101
      ZPERC=-1.6E-5*X + 1.1E-4
      RETURN
101   IF(X.GT.13.5) GOTO 102
      ZPERC=-2.1E-6*X + 5.0E-5
      RETURN
102   ZPERC=2.8E-5
      RETURN
      END
```

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C*
C*
C*
C*
C*
C*

CC031.FTN

```
      SUBROUTINE REPEAT
REAL A(3)
COMMON /BINSTR/XX(30),IJ(30)
COMMON /RAND/R1(4),RR(6)
COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
DATA A/4HTEMP,4H02.0,4HAT00/
      CALL SETFIL(2,A,IER2,"DK",0)
      DEFINE FILE 2(50,64,U,IVAR)
      IF(IJ(21).GT.IJ(19)) GOTO 1000
         K=IJ(22)
         KK=IJ(21)
      CALL FINDER(RR,Y,K,KK)
      IF((IJ(21).EQ.1).AND.(IRW(3).EQ.0)) ROW(7)=Y
      RETURN
1000  CONTINUE
      IRW(3)=IRW(3) + 1
      IF(IRW(3).GT.IRW(1)) GOTO 2000
         K=IRW(2)
         KK=IRW(3)
      CALL FINDER(ROW,Y,K,KK)
         K=IJ(22)
         KK=7
         IJ(21)=0
      CALL FINDER(ROW,Y,K,KK)
      RETURN
2000  CONTINUE
      IJ(9)=-10000
      RETURN
      END
```

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C*
C*
C*
C*
C*
C*

CC032,PTN

```
      SUBROUTINE FINDER(A,Y,K,KK)
      REAL A(2)
      COMMON /BINSTR/XX(30),IJ(30)
      X=A(KK)
      WRITE(5,1010) K,KK,A(KK)
1010  FORMAT(' VARIABLE CHANGES ',2(I6,1X),1PE15.8)
      GOTO (10,20,30,40,50,60),K
      WRITE(6,1000) K
1000  FORMAT(' ERROR MESSAGE IN REPEAT ',I6)
      STOP
10    Y=IJ(1)
      IJ(1)=A(KK)
      RETURN
20    Y=IJ(6)
      IJ(6)=A(KK)
      RETURN
30    Y=XX(15)
      XX(15)=A(KK)
      RETURN
40    Y=XX(21)
      XX(21)=A(KK)
      RETURN
50    Y=XX(4)
      XX(4)=A(KK)
      RETURN
60    Y=XX(26) + 273.
      XX(26)=A(KK) + 273
      RETURN
      END
```

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```

C*
C*      CC05,PTN
C*
C*
C*      SUBROUTINE PRINTS OUT MEANS AND SD OF THE
C*      VARIOUS NOISE RANDOM VARIABLES
C*
0001      SUBROUTINE PRTVAL
0002      REAL JD,NSS
0003      COMMON /BINSTR/XX(30),IJL(30)
0004      COMMON /RAND/PI,PI1,II1,II2
0005      COMMON /PASS/STAD(20)
C*
C*
C*      NOISE ADDED OR NOT
C*
0006      INOISE=IJL(8)
0007      IDARK=IJL(18)
C*
C*
C*      CONSTANTS NEED IN CALCULATIONS
C*
0008      XKB=8.617E-5
0009      AREA=XX(15)*6.4516E-6
0010      Q=1.602E-19
0011      NSS=1.E10
0012      C=1.E-13
0013      QQ=1.6498E-24
0014      TU=100.E-6
0015      XD=1.E-4
0016      SIGMA=1.E-15
0017      VTH=8.E5
0018      XNST=5.E9
0019      XNNN=5.E14
0020      XLN=0.05609
0021      TEMP=XX(26)
0022      FCLOCK=XX(4)
0023      FCLOCK2=XX(22)
C*
C*
C*      INPUT NOISE
C*
C*      MEAN=0
C*
C*      VAR= XKB*TEMP*C/Q**2
C*
C*
0024      X=XKB*TEMP
0025      XX(6)=SQRT(2.*X*C/(3.*Q))
C*
C*
C*      OUTPUT NOISE
C*
C*      SAME AS ABOVE
C*

```

```

0026      C*      XX(9)=XX(6)
          C*
          C*
          C*      FAST INTERFACE
          C*
          C*
          C*      MEAN=0
          C*      SD=SQRT(0.7*K*TEMP*NSS*AREA)
          C
0027      C*      XX(19)=SQRT(0.7*X*NSS*AREA)
          C*
          C*
          C*      FILTER NOISE
          C*
          C*      MEAN = 0.0061
          C*      SD = 0.07
          C*
0028      C*      XX(20)=0.0061
0029      C*      XX(17)=0.07
          C*
          C*
          C*      DARK CURRENT
          C*
0030      IF (XX(26).LT.250.) GOTO 50
0031      XNI=1.21/(8.617E-5*TEMP)
0032      XNI=EXP(-XNI)
0033      XNI=XNI*1.5E33
0034      XNI=XNI*TEMP**3
0035      XNI=SQRT(XNI)
0036      GOTO 51
0037      50 CONTINUE
0038      XNI=53228827.58
0039      51 CONTINUE
0040      GBI=XNI*XNI*XLN/(XNNN*TD)
0041      GSI=0.5*XNI*SIGMA*VTH
0042      GDI=XNI*X0/(2.*TD)
0043      XX(25)=10000.
0044      STAD(20)=GBI
0045      STAD(19)=GSI
0046      STAD(18)=GDI
0047      STAD(17)=AREA/(FCLOCK*2.)
0048      XX(24)=AREA
0049      STAD(16)=XNST
0050      STAD(15)=00/1.0363E-5
0051      IF (IDARK.EQ.1) XX(25)=0.
0052      IF (IDARK.EQ.2) WRITE(5,8010) GBI,GSI,GDI,TOTALI
0053      8010 FORMAT(' INDIVIDUAL SOURCES OF DARK CURRENT '/
          2 6(3X,1PE15.8))
          C*
          C*      SHOT NOISE
          C*

```

```

C*      MEAN=0.
C*
C*      SD= SQRT(JD*AREA/Q*FCLOCK)
C*
C*
0054      JD=GBI + GSI* $XNST$  + GDI
0055      JD=JD*STAD(15)
0056      XX(7)=SQRT(JD*AREA/(Q*FCLOCK))
0057      IF(IJL(20).EQ.0) XX(23)=SQRT(JD*AREA/(Q*FCLOCK2))

C*
C*      PRINT OUT THE MEANS AND SD
C*
C*
0058      IF(INOISE.EQ.1) RETURN
0059      WRITE(5,9088) XX(25)
0060      9088  FORMAT(' DARK CURRENT ELECTRONS ADDED PER '
2 'TRANSFER ',1PE15.8//)

C*
0061      Z=0.
0062      WRITE(5,2) Z,XX(6)
0063      WRITE(5,3) Z,XX(7)
0064      WRITE(5,5) Z,XX(9)
0065      WRITE(5,6) XX(20),XX(17)
0066      WRITE(5,10) Z,XX(19)
0067      WRITE(5,7) (IJL(I),I=10,16)
0068      7  FORMAT(' STATUS OF THE NOISE SOURCES'//
2' SELECT THE NOISE INPUTS Y=1 N=0 ',I2/
3' ADD IN INPUT NOISE Y=0 N=1 ',I2/
4' ADD IN SHOT NOISE Y=0 N=1 ',I2/
5' ADD IN TRANSFER NOISE Y=0 N=1 ',I2/
6' ADD IN OUTPUT NOISE Y=0 N=1 ',I2/
7' ADD IN FILTER NOISE Y=0 N=1 ',I2/
8' ADD IN INTERFACE NOISE Y=0 N=1 ',I2//)

0069      2  FORMAT(' MEAN OF THE INPUT NOISE ',1PE15.8,
' SD ',1PE15.8/)
0070      3  FORMAT(' MEAN OF THE SHOT NOISE ',1PE15.8,
' SD ',1PE15.8/)
0071      4  FORMAT(' MEAN OF THE TRANSFER NOISE ',1PE15.8,
' SD ',1PE15.8/)
0072      5  FORMAT(' MEAN OF THE OUTPUT NOISE ',1PE15.8,
' SD ',1PE15.8/)
0073      6  FORMAT(' MEAN OF THE FILTER ERROR ',1PE15.8,
' SD ',1PE15.8/)
0074      10  FORMAT(' MEAN OF THE INTERFACE NOISE ',1PE15.8,
' SD ',1PE15.8/)

0075      RETURN
0076      END

```

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CCD2,FTN

SUBROUTINE GENERATES THE INPUT SIGNAL TO THE CCD

ASSUMES THAT MAXIMUM VOLTAGE IS 2 VOLTS (XMAXV)
WHICH CORRESPONDS TO 100000 ELECTRONS (XMAXEL)

ITIME IS THE CCD RUN TIME

SUBROUTINE INPUT

REAL A(30)
COMMON /INPUT/ELECTR(1200)
COMMON /BINSTR/XZ(30),IJ(30)
COMMON /VOLTS/XMAXV,XMAXEL,ITIME
COMMON /CCD/HOLD(1200)
COMMON /RAND/PI,PII
COMMON /PASS/STAD(20)

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TRIAL RUN IMPULSE AT TIME ZERO

02/18/77 CHANGE IN FULL WELL ELECTRON COUNT

CLOCK SWING

CS=XZ(10)
AREA=XZ(15)
COUL=2.625E-13
ELECTR=6.281E+18
XMAXEL=AREA*COUL*ELECTR*CS
IF(IJ(6),EQ,1) XMAXEL=XMAXEL/2.
XZ(2)=XZ(16)*XMAXEL/100.
WRITE(5,1000) XMAXV,XMAXEL,CS,IJ(6)
1000 FORMAT(' MAXIMUM INPUT VOLTAGE ',1PE15.8,
25X,'CORRESPONDS TO MAXIMUM NO. OF ELECTRONS ',1PE15.8/
31X,'CLOCK SWING VOLTAGE ',1PE15.8/
4' SURFACE(FAT ZERO) 0 OR BURIED(SLIM ZERO) 1 ',I2//)
CONST=XMAXEL/XMAXV
CC2=1./CONST
WRITE(5,2000) XZ(10),IJ(3),XZ(5)
2000 FORMAT(' VOLTAGE OF THE SIGNAL ',F10.4,' LENGTH ',
2'OF THE SIGNAL ',16/
3' BIAS VOLTAGE ADDED TO INPUT ',F10.4//)
AVE=XZ(2)
SD=XZ(3)
IF(SD,LT,0.) GOTO 10
K=31
DO 4 1=1,ITIME
IF(K,LE,30) GOTO 1
K=1
6001 CONTINUE
READ(1,END=8000,ERR=8000) A

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1      CONTINUE
      ELECTR(I)=A(K)*SD + AVE
          K*K + 1
4      CONTINUE
      GOTO 20
10     DO 15 I=1,ITIME
      ELECTR(I)=0.
15     CONTINUE
20     CONTINUE
      IF(IJ(3).EQ.0) RETURN
          I1=IJ(3)
          VOLT=XZ(10)
      IF(IJ(29).EQ.1) GOTO 7000
      IF(IJ(17).EQ.1) GOTO 26
C*
C*   NON LINEAR INPUT CHARACTERISTIC
C*
C*   03/29/77
      IF(VOLT.GT.0.420) GOTO 22
          VOLT=2.783*VOLT - 0.082
          GOTO 26
22     IF(VOLT.GT.1.280) GOTO 24
          VOLT=0.98*VOLT + 0.666
          GOTO 26
24     VOLT=0.572*VOLT + 1.183
26     CONTINUE
      DO 25 I=1,I1
          ELECTR(I)=VOLT*CONST + ELECTR(I)
          IF(ELECTR(I).GT.XMAXEL) ELECTR(I)=XMAXEL
25     CONTINUE
      IF(IJ(17).EQ.0) WRITE(5,1050) VOLT
1050   FORMAT(' NON LINEAR INPUT VOLTAGE ',1PE15.8/)
      RETURN
7000   CONTINUE
          VOLT2=XZ(5)
          IK=IJ(28)
          SAMPL=1./XZ(4)
          TIME=0.
      DO 7050 II=1,I1
          HOLD(II)=0.
          IK2=30
          DO 7040 I=1,IK
              FREQ=XZ(IK2)*PII*TIME
              HOLD(II)=HOLD(II) + STAD(I)*SIN(FREQ)
              IK2=IK2 - 1
7040   CONTINUE
          TIME=TIME + SAMPL
7050   CONTINUE
      DO 7060 II=1,I1
          VOLT=HOLD(II) + VOLT2
          VOLT=VOLT + ELECTR(II)*CC2
          IF(IJ(17).EQ.1) GOTO 7059
          IF(VOLT.GT.0.420) GOTO 7051
          VOLT=VOLT*2.783 - 0.082
          GOTO 7059
7051   IF(VOLT.GT.1.280) GOTO 7052
          VOLT=VOLT*0.98 + 0.666
          GOTO 7059
7052   VOLT=VOLT*0.572 + 1.183

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```
7059 CONTINUE
      ELECTR(II)=VOLT*CONST
      IF(ELECTR(II).GT.XMAXEL) ELECTR(II)=XMAXEL
7060 CONTINUE
      STAD(5)=XZ(5)*CONST
      RETURN
8000 REWIND 1
      GOTD 8001
      END
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CC03,FTN

SUBROUTINE INITIALIZES CCD FOR INPUT DATA

```
      SUBROUTINE INITL
      REAL AA(30)
      COMMON /CCD/CCDW(2,601)
      COMMON /BINSTR/XJ(30),IJ(30)
      COMMON /VOLTS/XMAXV,XMAXE
      COMMON /PASS/STAD(20)
      ISTAGE=IJ(1)
      IPRINT=IJ(2)
      INOISE=IJ(8)
      IF(IJ(29).EQ.1) GOTO 7000
      AVE=XJ(2)
      SD=XJ(3)
      IF(SD.LT.0.) GOTO 100
      WRITE(5,505) AVE,SD
505      FORMAT(' MEAN VALUE OF THE INITIAL STATES ',1PE15.8/
2        ' SD OF THE INITIAL STATES ',1PE15.8/)
      I=1
1      READ(1,END=8000,ERR=8000) AA
      K=1
2      CONTINUE
      CCDW(2,I)=AA(K)*SD + AVE
      RES=CCDW(2,I)*XJ(1)
      CCDW(1,I)=RES
      CCDW(2,I)=RES
      I=I + 1
      K=K + 1
      IF(I.GT.ISTAGE) GOTO 3
      IF(K.GT.30) GOTO 1
      GOTO 2
3      CONTINUE
      IF(IPRINT.NE.1) RETURN
      WRITE(5,1000) (I,I=1,ISTAGE)
1000     FORMAT(15X,'STAGES '(13I10))
      WRITE(5,1001) (CCDW(1,I),CCDW(2,I),I=1,ISTAGE)
1001     FORMAT(12(1X,F10.2))
      RETURN
100     DO 110 I=1,ISTAGE
      CCDW(1,I)=0.
      CCDW(2,I)=0.
110     CONTINUE
200     WRITE(5,201)
201     FORMAT(' NO BACKGROUND VOLTAGE ADDED '/')
      RETURN
7000    CONTINUE
      BIAS=STAD(5)
      RES=BIAS*XJ(1)
      BIAS=BIAS - RES
      DO 701 I=1,ISTAGE
      CCDW(1,I)=RES
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A18

```
      CCDW(2,1)=RES  
7001 CONTINUE  
      WRITE(5,7010) RES,BIAS  
7010 FORMAT(' BIAS TERMS ADDED TO WELLS ',2(2X,1PE15.8)/)  
      RETURN  
8000 REWIND 1  
      GOTO 1  
      END
```

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C*
C*      CCD7.FTN
C*
C*
C*
C*      SUBROUTINE DOES THE BOOKKEEPING FOR THE CCD2 ARRAY
C*      VERSUS TIME
C*
C*
C*      SUBROUTINE XRUN
0001      REAL A(30),B(30)
0002      COMMON /VOLTS/G1,G2,ITIM
0003      COMMON /CCD/CCDW(2,601)
0004      COMMON /INPUT/ELECTR(1200)
0005      COMMON /BINSTR/XPERC,XMEAN,XSQ,FCLOCK,FBAND,XZ(25),ISTAGE
0006      COMMON /BINSTR/XPERC,XMEAN,XSQ,FCLOCK,FBAND,XZ(25),ISTAGE
2          ,IPRINT,ILENGT,IFILT,ILJ(3),INOISE,IJJ(20)
0007      COMMON /PASS/STAD(20),ISTAD(20),IVAR
0008      LL=ISTAGE + 1

C*
C*      SHOT NOISE
C*      INPUT NOISE
C*      TRANSFER NOISE CHANGED 03/23/77
C*      INTERPACE NOISE ADDED 03/24/77
C*
C*
0009      ISTART=1
0010      IPP=1
0011      I3=0
0012      I4=0
0013      IJJ(17)=0
0014      DARK=XZ(20)
0015      IF(DARK,EQ,0.) GOTO 5000
0016      I3=31
0017      GBI=STAD(20)
0018      GSI=STAD(19)
0019      GDI=STAD(18)
0020      GG=GBI + GDI
0021      CONST=STAD(17)
0022      XNST=STAD(16)
0023      CUR=STAD(15)
0024      G1=CUR*GBI
0025      G2=CUR*GSI
0026      G3=CUR*GDI
0027      5000 CONTINUE
0028      IF(INOISE,EQ,1) GOTO 8000
0029      SDINPT=STAD(1)
0030      SDMIOL=STAD(2)
0031      SDTRAN=SQRT(2.*XPERC)
0032      INPT=ISTAD(1)
0033      IMIDL=ISTAD(2)
0034      I3=31
0035      8000 CONTINUE
0036      IF(IFILT,EQ,1) CALL COEFFS
0037      ILL=ITIM
0038      ITIME=ITIM + ISTAGE
0039      IF(IJJ(12),EQ,0) ITIME=ISTAGE
0040      IEND=1
0041      IPR=GIN=0
0042      2329 CONTINUE

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```

0043      DO 1 I=ISTART,ITIME
0044          IF(I.EQ.1) GOTO 7002
0045          IBEGIN=I - 1
0046          IEND=I - ILL
0047          IF(IBEGIN.GT.ISTAGE) IBEGIN=ISTAGE
0048          IF(IEND.GT.ISTAGE) IEND=ISTAGE
0049          IF(IEND.LE.0) IEND=1
0050          CCDW(1,LL)=0.
0051          J=IBEGIN
0052          IF(IPRINT,NE,1) GOTO 25
0053          WRITE(5,1001) I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
0054      1001  FORMAT(I4,(6(1X,E15.8)))
0055      25    CONTINUE
0056          DO 2 K=1,ISTAGE
0057              JJ=J + 1

C*
C*      FIND RESIDUE AT CLOCK PULSE 2 IN EACH WELL
C*      TRANSFER REMAINING CHARGE TO WELL AT CLOCK 1
C*      LEAVE RESIDUE IN OLD WELL AT CLOCK 2
C*
0058          RES=XPERC*CCDW(2,J)
0059          CCDW(1,JJ)=CCDW(1,JJ) + CCDW(2,J) - RES
0060          IF(DARK.EQ.0.) GOTO 5010
0061          IF(I3.LE.29) GOTO 5001
0062          I3=1
0063      3001  CONTINUE
0064          READ(1,END=3000,ERR=3000) A
0065      5001  CONTINUE
0066          RAY=SQRT(A(I3)**2 + A(I3 + 1)**2)
0067          RAYY=XNST*RAY
0068          RAY=RAYY*G2
0069          DARKK=CONST*(GSI*RAYY + GG)
0070          CCDW(1,JJ)=CCDW(1,JJ) + DARKK
0071          GSUM=RAY + G1 + G3
0072          IF(I.LT.3) WRITE(5,5002) I,G1,RAY,G3,GSUM
0073      5002  FORMAT(' CURRENT DENSITIES ',I6,6(1X,E15.8))
0074          IF(I.LT.6) WRITE(5,5003) I,DARKK
0075      5003  FORMAT(' ELECTRONS ADDED PER CLOCK ',I6,1X,E15.8)
0076          I3=I3 + 2
0077      5010  CONTINUE
0078          IF(IJJ(5).EQ.0) XRES=CCDW(2,J)
0079          CCDW(2,J)=RES
0080          IF(INOISE.EQ.1) GOTO 8001
0081          IF(IMIDL.EQ.2) GOTO 8001

C*
C*      ADD IN NOISE SOURCES OF MIDDLE REGION
C*      SHOT INTERACE*2
C*
0082          IF(I3.LE.30) GOTO 10
0083          I3=1
0084      3011  CONTINUE
0085          READ(1,END=3010,ERR=3010) A
0086          CONTINUE
0087          CCDW(1,JJ)=CCDW(1,JJ) + A(I3)*SDMIDL
0088          I3=I3 + 1
0089      8001  CONTINUE

C*
C*      TRANSFER NOISE ADDED IN ONE PER TRANSFER
C*

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0090          IF(INOISE,EQ,1) GOTO 8005
0091          IF(IJJ(5),EQ,1) GOTO 8005
0092          IF(I3,LE,30) GOTO 11
0093          I3=1
0094 3021      CONTINUE
0095          READ(1,END=3020,ERR=3020) A
0096 11          CONTINUE
0097          RES=XRES
0098          IF(RES,LT,0.) RES=-RES
0099          XRES=SQRT(RES)*SDTRAN*A(I3)
0100          I3=I3 + 1
0101          CCDW(2,JJ)=CCDW(2,JJ) + XRES
0102          CCDW(1,JJ)=CCDW(1,JJ) - XRES
0103 8005      CONTINUE
0104          IF(CCDW(1,JJ),GT,Q2) CCDW(1,JJ)=Q2
0105          IF(J,LE,IEND) GOTO 7001
0106          J=J - 1
0107 2          CONTINUE
0108 7001      CONTINUE
0109          IF(I,LE,ISTAGE) GOTO 7002
0110          IF(IFILT,EQ,1) GOTO 7002
0111          I4=I4 + 1
0112          B(I4)=CCDW(1,LL)
0113          IJJ(17)=IJJ(17) + 1
0114          IF(I4,LT,30) GOTO 7002
0115          WRITE(2,'1PP) B
0116          IPP=IPP + 1
0117          I4=0
0118 7002      CONTINUE
0119          IF(I,GT,ILL) GOTO 21
0120          CCDW(1,1)=CCDW(1,1) + ELECTR(I)
0121          IF(INOISE,EQ,1) GOTO 8002
0122          IF(INPT,EQ,0) GOTO 8002

C*
C*          ADD IN INPUT NOISE SOURCES
C*          SHOT INPUT INTERFACE
C*
C*
0123          IF(I3,LE,30) GOTO 20
0124          I3=1
0125 3031      CONTINUE
0126          READ(1,END=3030,ERR=3030) A
0127 20          CONTINUE
0128          CCDW(1,1)=CCDW(1,1) + A(I3)*SDINPT
0129          I3=I3 + 1
0130 8002      CONTINUE
0131          IF(CCDW(1,1),GT,Q2) CCDW(1,1)=Q2
0132          IF(IPRINT,NE,1) GOTO 21
0133          WRITE(5,1001) I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
0134 21          CONTINUE
0135          J=I
0136          IF(IBEGIN,GE,ILL) IEND=IEND + 1
0137          IF(J,GT,ISTAGE) J=ISTAGE
0138          IF(I,EQ,ITIME) GOTO 1
0139          DO 3 K=1,ISTAGE

C*
C*
C*          FIND RESIDUE AT CLOCK 1 WELLS
C*          TRANSFER REMAINING TO CLOCK 2 WELLS
C*          LEAVE THE RESIDUE IN CLOCK 1 WELL

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C*
C*
0140      RES=XPERC*CCDW(1,J)
0141      CCDW(2,J)=CCDW(2,J) + CCDW(1,J) - RES
0142      IF(IJJ(5),EQ,0) XRES=CCDW(1,J)
0143      CCDW(1,J)=RES
0144      IF(DARK,EQ,0.) GOTO 5020
0145      IF(I3,LE,29) GOTO 5021
0146      I3=1
0147 3041  CONTINUE
0148      READ(1,END=3040,ERR=3040) A
0149 5021  CONTINUE
0150      RAY=SQRT(A(I3)**2 + A(I3+1)**2)
0151      RAYY=RAY*XNST
0152      DARK=CONST*(GSI*RAYY + GG)
0153      CCDW(2,J)=CCDW(2,J) + DARK
0154 5020  CONTINUE
0155      IF(INOISE,EQ,1) GOTO 8003
0156      IF(IMIDL,EQ,0) GOTO 8003

C*
C*      ADD IN MIDDLE NOISE SOURCES
C*      SHOT 2*INTERFACE
C*
C*
0157      IF(I3,LE,30) GOTO 30
0158      I3=1
0159 3051  CONTINUE
0160      READ(1,END=3050,ERR=3050) A
0161 30    CONTINUE
0162      CCDW(2,J)=CCDW(2,J) + A(I3)*SDMIDL
0163      I3=I3 + 1
0164 8003  CONTINUE

C*
C*      ADD IN TRANSFER NOISE
C*
0165      IF(INOISE,EQ,1) GOTO 8006
0166      IF(IJJ(5),EQ,1) GOTO 8006
0167      IF(I3,LE,30) GOTO 35
0168      I3=1
0169 3061  CONTINUE
0170      READ(1,END=3060,ERR=3060) A
0171 35    CONTINUE
0172      RES=XRES
0173      IF(RES,LT,0.) RES=-RES
0174      XRES=SQTRAN*SQRT(RES)*A(I3)
0175      I3=I3 + 1
0176      CCDW(2,J)=CCDW(2,J) - XRES
0177      CCDW(1,J)=CCDW(1,J) + XRES
0178 8006  CONTINUE
0179      IF(CCDW(2,J),GT,02) CCDW(2,J)=02
0180      IF(J,LE,IEND) GOTO 99
0181      J=J -1
0182 3    CONTINUE
0183 99    CONTINUE
0184      IF(IPRINT,NE,1) GOTO 22
0185      WRITE(5,1000) (CCDW(1,J),CCDW(2,J),J=1,ISTAGE)
0186 1000  FORMAT(6(2X,E15,8))
0187 22    CONTINUE
0188      IF(((IFILT,EQ,1).AND.(I,GE,ISTAGE)) CALL FILTER(A,8,I3,I4,I,IPP)
0189 1     CONTINUE

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0190      IF(IJJ(12),EQ,1) GOTO 2330
0191      IF(ISTART,NE,1) GOTO 2330
0192      CALL SETTER(XNST, GSI, GG, CONST, ITIME, ISTART, ISTAGE, ITIM)
0193      GOTO 2329
0194      2330      CONTINUE
0195      IF(I4,NE,0) WRITE(2*IPP) B
0196      RETURN
0197      3000      REWIND 1
0198      GOTO 3001
0199      3010      REWIND 1
0200      GOTO 3011
0201      3020      REWIND 1
0202      GOTO 3021
0203      3030      REWIND 1
0204      GOTO 3031
0205      3040      REWIND 1
0206      GOTO 3041
0207      3050      REWIND 1
0208      GOTO 3051
0209      3060      REWIND 1
0210      GOTO 3061
0211      END

```

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C*
C*
C*      CCD17.FTN
C*
C*      SUBROUTINE LOADS UP THE WEIGHTS FOR A FILTER
C*
C*

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```

0001      SUBROUTINE COEFFS
0002      COMMON /BINSTR/ZL(30), ISTAGE
0003      COMMON /COEFF/COEFF(600)
0004      WRITE(5,1000)
0005      1000      FORMAT(1H1/'      FILTER WEIGHTS '/')
0006      DO 1 I=1, ISTAGE
0007      READ(4,1001) COEFF(I)
0008      1001      FORMAT(E15,8)
0009      WRITE(5,1003) I, COEFF(I)
0010      1003      FORMAT(16,3X,E15,8)
0011      1      CONTINUE
0012      WRITE(5,1002) ZL(11)
0013      1002      FORMAT(' % ERROR PER WEIGHT 'F10.3//)
0014      RETURN
0015      END

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C*
C*      CCD18,FTN
C*
C*
C*      SUBROUTINE COMPUTES THE FILTER RESPONSE PER PULSE
C*
C*
0001      SUBROUTINE FILTER(A,B,I1,I4,J,IPP)
0002      REAL A(1),B(1)
0003      COMMON /BINSTR/XL(30),ISTAGE,IJJ(6),INOISE,IJ(20)
0004      COMMON /CCD/CCDW(2,601)
0005      COMMON /COEFF/COEFF(600)
0006      SD=XL(17)
0007      ERR=1. + XL(11)
0008      XSUM=0.
0009      DO 5 I=1,ISTAGE
0010          XSUM=XSUM + CCDW(2,I)*COEFF(I)*ERR
0011          IF(INOISE.EQ.1) GOTO 5
0012          IF(IJ(7).EQ.1) GOTO 5
0013          IF(I1.LE.30) GOTO 1
0014      2      CONTINUE
0015          I1=1
0016          READ(1,END=1000,ERR=1000) A
0017      1      CONTINUE
0018          XSUM=XSUM + A(I1)*SD*CCDW(2,I)
0019          I1=I1 + 1
0020      5      CONTINUE
0021          IF(J.LE.ISTAGE) RETURN
0022          I4=I4 + 1
0023          B(I4)=XSUM
0024          IJ(17)=IJ(17) + 1
0025          IF(I4.LT.30) RETURN
0026          I4=0
0027          WRITE(2*IPP) B
0028          IPP=IPP + 1
0029          RETURN
0030      1000  CONTINUE
0031          REWIND 1
0032          GOTO 2
0033          END

```

```

C*
C*
C*   CCD20,PTN
C*
C*   SUBROUTINE SD
COMMON /BINSTR/XX(30),IJ(20)
COMMON /PASS/STAD(20),ISTAD(20)
C*
C*   LOADS APPROPRIATE NOISE SOURCES IN SDS
C*
C*   IF(IJ(8),EQ,1) RETURN
SDINPT=XX(6)
SDSHOT=XX(7)
SDOUTP=XX(9)
SDINTR=XX(19)
C*
C*   CHECK TO SEE IF ALL SOURCES ARE ADDED IN
C*
C*       ISTAD(1)=0
C*       ISTAD(2)=0
C*       ISTAD(3)=0
IF(IJ(10),EQ,1) GOTO 10
S1=SDSHOT*SDSHOT
S2=SDINTR*SDINTR
C*
C*   INPUT SD
C*
C*       STAD(1)=SQRT(SDINPT*SDINPT + S1 + S2)
C*       ISTAD(1)=1
C*
C*   MIDDLE NOISE SOURCES MINUS TRANSFER
C*
C*       STAD(2)=SQRT(S1 + 2.*S2)
C*       ISTAD(2)=1
C*
C*   OUTPUT NOISE SOURCES
C*
C*       STAD(3)=SQRT(S1 + S2 + SDOUTP*SDOUTP)
C*       ISTAD(3)=1
C*       RETURN
10   CONTINUE
C*
C*   COMPUTE INPUT IF NEEDED
C*
C*       VAR=0.
IF(IJ(11),EQ,1) GOTO 15
VAR=SDINPT*SDINPT
ISTAD(1)=1
15   IF(IJ(12),EQ,1) GOTO 20
VAR=VAR + SDSHOT*SDSHOT
ISTAD(1)=1
20   IF(IJ(16),EQ,1) GOTO 25
VAR=VAR + SDINTR*SDINTR
ISTAD(1)=1
25   IF(ISTAD(1).EQ,1) VAR=SQRT(VAR)
STAD(1)=VAR

```

```

C*
C*
C*      COMPUTE MIDDLE SD IF NEEDED
C*
      VAR=0.
      IF(IJ(12),EQ,1) GOTO 30
      VAR=SDSHOT*SDSHOT
      ISTD(2)=1
30     IF(IJ(16),EQ,1) GOTO 35
      VAR=VAR + 2.*SDINTR*SDINTR
      ISTD(2)=1
35     IF(ISTAD(2),EQ,1) VAR=SQRT(VAR)
      STAD(2)=VAR

```

```

C*
C*
C*      COMPUTE OUTPUT SD IF NEEDED
C*
      VAR=0.
      IF(IJ(12),EQ,1) GOTO 40
      VAR=SDSHOT*SDSHOT
      ISTD(3)=1
40     IF(IJ(14),EQ,1) GOTO 45
      VAR=VAR + SDOUTP*SDOUTP
      ISTD(3)=1
45     IF(IJ(16),EQ,1) GOTO 50
      VAR=VAR + SDINTR*SDINTR
      ISTD(3)=1
50     IF(ISTAD(3),EQ,1) VAR=SQRT(VAR)
      STAD(3)=VAR
      RETURN
      END

```

```

C*
C*
C*      CCD50.FTN
C*
C*

```

```

0001      SUBROUTINE SETTER(XNST,GS1,GG,CON,ITIME,ISTART,ISTAGE,ITIM)
0002      REAL A(50)
0003      COMMON /BINSTR/XX(30),IJ(30)
0004      COMMON /CCO/CCDW(2,601)
0005      CONST=XX(24)*XX(21)
0006      I4=51
0007      DO 100 I=1,ITIME
0008      IF(I4,LE,29) GOTO 1
0009      I4=1
0010      READ(1) A
0011      1      CONTINUE
0012      RV=SQRT(A(I4)**2 + A(I4+1)**2)
0013      RV=RV*XNST
0014      DARK=CONST*(GS1*RV+GG)
0015      CCDW(2,I)=CCDW(2,I) + DARK
0016      I4=I4 + 2
0017      100   CONTINUE
0018      ISTART=ISTAGE + 1
0019      ITIME=ITIM + ISTAGE
0020      IF(XX(4),EQ,XX(22)) RETURN
0021      CON=XX(24)/(XX(22)*2.)
0022      IF(IJ(12),EQ,1) RETURN
0023      XX(7)=XX(23)
0024      CALL SD
0025      RETURN
0026      END

```


C
C
C
C
C
C

CCDB,FTN

SUBROUTINE PRINTS OUT INITIAL AND FINAL ARRAYS

SUBROUTINE OUTP

REAL A(30),BB(30)
COMMON /INPUT/ELECTR(1200)
COMMON /VOLTS/XMAXV,XMAXEL,ITIME
COMMON /BINSTR/XZ(30),IJ(2),ILT,IFILT,ILL(3),INOISE,IJL(20)
COMMON /PASS/STAD(20),ISTAD(20)
COMMON /CCD/A,HB,XMAX,XMIN,AVE,VAR,X1,XXIN,VMAXO,XXOUT,SD

C*
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C*
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C*
C*
C*

MAX OUTPUT VOLT IS 100 MILLEVOLTS
THIS INCLUDES THE CLOCK VOLTAGE
SO MAKE THE MAXIMUM NON CLOCK VOLTAGE
48 MILLEVOLTS

NUMB=IJL(17)
J=1
I2=31
XXIN=XMAXV/XMAXEL
VMAXO=48,E=3
XXOUT=VMAXO/XMAXEL
K=31
SD=STAD(3)

C*
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C*
C*

FOLLOWING CODE IS WRITEN THIS WAY SINCE THERE
IS NO OVERSTRIKE ON THE LINEPRINTER

IF(IFILT.NE.1) WRITE(5,500)
IF(IFILT.EQ.1) WRITE(5,501)
500 FORMAT(1H1/' (OUTPUT MINUS THE CLOCK VOLTAGE) '//
2 16X,'VOLTS',28X,'ELECTRONS'/
3 11X,'INPUT',5X,'OUTPUT',19X,'INPUT',6X,'OUTPUT'/
4 1X,60(1H-))
501 FORMAT(1H1/' (OUTPUT MINUS THE CLOCK VOLTAGE) '//
2 16X,'VOLTS',28X,'ELECTRONS',32X,'FILTER'/
3 11X,'INPUT',5X,'OUTPUT',19X,'INPUT',6X,'OUTPUT',22X,'VOLTS',
4 6X,'ELECTRONS'/
5 1X,104(1H-))
IPP=0
DO 100 I=1,NUMB
X1=ELECTR(I)*XXIN
IF(I2.LE.30) GOTO 1
I2=1
IF(IPP.GT.0) WRITE(2'IPP) BB
IPP=IPP + 1
READ(2'IPP) BB
1 CONTINUE
IF(INOISE.EQ.1) GOTO 3
IF(ISTAD(3).EQ.0) GOTO 3
IF(K.LE.30) GOTO 2
3001 CONTINUE

```

      K=1
      READ(1,END=3000,ERR=3000) A
2     CONTINUE
      BB(I2)=BB(I2) + A(K)*SD
3     CONTINUE
      X2=BB(I2)*XXOUT
      IF(ILL(3),EQ.1)      GOTO 7053
      IF(IFILT,NE.1) WRITE(5,1000) I,X1,X2,ELECTR(I),BB(I2)
1000  FORMAT(15,2(1X,F10.4),10X,2(1X,F12.2))
      IF(IFILT,EQ.1) WRITE(5,1001) I,X1,X2,ELECTR(I),
2     BB(I2),X3
1001  FORMAT(15,2(1X,F10.4),10X,2(1X,F12.2),16X,F10.4,3X,F12.2)
7053  CONTINUE
      ELECTR(I)=X1
      BB(I2)=X2
      I2=I2 + 1

C*
C*
C*   ADD IN THE FEED FOR CLOCK 1
C*       55 MILLEVOLTS
C*   SUBTRACT THE FEED FOR CLOCK 2
C*       55 MILLEVOLTS
C*
C*
C*       CLOCK=55,E=3
C+
C+
C+   ADD IN THE DIRECT FEEDTHROUGH
C+   MAXIMUM INPUT VOLTAGE CORRESPONDS
C+   TO 2 MILLEVOLTS AT OUTPUT
C+
C+
100  CONTINUE
      CALL PLOT1(ELECTR,XMIN,XMAX,AVE,VAR,VARI,NUMB)
      WRITE(5,8099) NUMB,AVE,VAR,VARI
8099  FORMAT(' INPUT ',I6,' AVE ',1PE15.8,' SD ',1PE15.8,1X,1PE15.8/)
      AVE=1.
      IF(ILL(3),EQ.0) CALL PLOT(ELECTR,NUMB,XMIN,XMAX,AVE,AVE,AVE)
      XZ(12)=VMAXO
      XZ(13)=CLOCK
      REWIND 1
      ENDFILE 1
      WRITE(2*IPP) BB
      WRITE(6,8010) IPP
8010  FORMAT(' DONE WITH OUTP' ,I6//)
      IPP=1
      AVE=0.
      AVE1=0.
      VAR=0.
      VARI=0.
      NUMBB=NUMB/2 + 1
      I2=31
      DO 8079 I=1,NUMB
      IF(I2.LE.30) GOTO 8078
      I2=1
      READ(2*IPP) BB
      IPP=IPP + 1
8078  CONTINUE
      ELECTR(I)=BB(I2)
      I2=I2 + 1

```

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```

AVE=AVE + ELECTR(I)
X1=ELECTR(I)**2
VAR=VAR + X1
IF(I.LT,NUMB) GOTO 8079
AVE1=AVE1 + ELECTR(I)
VAR1=VAR1 + X1
8079 CONTINUE
X1=FLOAT(NUMB)
VAR=X1*VAR - AVE*AVE
IF(VAR.GT.0.) VAR=SQRT(VAR/(X1*(X1-1.)))
AVE=AVE/X1
X1=FLOAT(NUMB/2)
VAR1=X1*VAR1 - AVE1*AVE1
IF(VAR1.GT.0.) VAR1=SQRT(VAR1/(X1*(X1-1.)))
AVE1=AVE1/X1
WRITE(5,8075) NUMB,AVE,VAR,AVE1,VAR1
8075 FORMAT(" OUTPUT ",I6," AVE ",1PE15.8," SD ",1PE15.8/
2 " HALF THE OUTPUT AVE ",1PE15.8," SD ",1PE15.8//)
CALL PLOT1(ELECTR,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
WRITE(5,8075) NUMB,AVE,VAR1
AVE=1.
IF(ILL(3).EQ.0) CALL PLOT(ELECTR,NUMB,XMIN,XMAX,AVE,AVE,AVE)
ENDFILE 2
RETURN
3000 REWIND 1
GOTO 3001
END

```

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C*
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C*
C*
C*

LITTLE BOOKKEEPING
CC026,FTN

```
      SUBROUTINE SETUP
      REAL ARR(30)
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /CCO/B(1200)
      COMMON /INPUT/A(1200)
      IW=0
      IF (IJ(30),EQ,0) RETURN
      ICC=1
800   CONTINUE
      NUMB=IJ(25)
      K=0
      NUMBB=NUMB/2 + 1
      DO 110 I=NUMBB,NUMB
      K=K + 1
      A(K)=A(I)
110   CONTINUE
      NUMB=K
      CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
      WRITE(5,8080) NUMB,AVE,VAR,VAR1
8080  FORMAT(1H1' # MEAN SD ',I6,4(1X,1PE15.8)/)
      IF (IW,EQ,1) GOTO 77
      J=1
      IND=2
2     NUM=NUMB/IND
      IF (NUM,EQ,0) GOTO 5
      IND=IND*2
      J=J + 1
      GOTO 2
5     CONTINUE
      IF (NUMB,EQ,(IND/2)) J=J - 1
      IF (IW,EQ,0) GOTO 6
77    CONTINUE
      CALL WGHT(A,IW,NUMB)
      CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
6     CONTINUE
      DO 18 I=1,NUMB
      A(I)=A(I) - AVE
18    CONTINUE
      IND=2**J
      IPP=IND - NUMB
      IF (IPP,EQ,0) GOTO 10
      K=NUMB + 1
      DO 7 I=K,IND
7     A(I)=0.
10    DO 20 I=1,IND
      B(I)=0.
20    CONTINUE
      CALL FRXFM(J,A,B)
      IND=IND/2
      DO 30 I=1,IND
      D=A(I)**2 + B(I)**2
```

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```
      D=SQRT(D)
      A(I)=D
30    CONTINUE
      CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,IND)
           I=1
      CALL EPLOT(A,XMAX,IND,I,I)
           ICC=ICC + 1
           IW=1
      IF((IPP.EQ.0).AND.(ICC.LT.3)) GOTO 800
      RETURN
      END
```

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```

C*
C*
C*   LITTLE BOOKKEEPING
C*
C*   CCO27,FTN
C*
C*
C*   SUBROUTINE FRXFM(N2POW,XT,YT)
C*
C*   DECIMATION IN FREQUENCY FFT ALGORITHM
C*
C*
C*   DIMENSION XT(2),YT(2)
C*   N=2**N2POW
C*   M=N2POW
C*   DO 600 L0=1,M
C*     LMX=2**(M-L0)
C*     LIX=2*LMX
C*     SCL=6.2831853072/FLOAT(LIX)
C*     DO 600 LM=1,LMX
C*       ARG=FLOAT(LM-1)*SCL
C*       C=COS(ARG)
C*       S=SIN(ARG)
C*       DO 600 LI=LIX,N,LIX
C*         J1=LI-LIX+LM
C*         J2=J1+LMX
C*         T1=XT(J1) -XT(J2)
C*         T2=YT(J1) - YT(J2)
C*         XT(J1)=XT(J1) + XT(J2)
C*         YT(J1)=YT(J1) + YT(J2)
C*         XT(J2)=C*T1 + S*T2
C*         YT(J2)=C*T2 - S*T1
C*
600   CONTINUE
C*
C*   BIT REVERSAL
C*
C*
C*     NV2=N/2
C*     NM1= N -1
C*     J=1
C*     DO 635 I=1,NM1
C*       IF(1,GE,J) GOTO 631
C*       T1=XT(J)
C*       T2=YT(J)
C*       XT(J)=XT(I)
C*       YT(J)=YT(I)
C*       XT(I)=T1
C*       YT(I)=T2
C*
631   K=NV2
620   CONTINUE
C*       IF(K,GE,J) GOTO 635
C*       J=J -K
C*       K=K/2
C*       GOTO 620
C*
635   J=J+K
C*       RETURN
C*       END

```

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```

C*
C*
C*   CCO28,FTN
C*
      SUBROUTINE WGHT(A,IW,NUMB)
REAL A(2)
COMMON /RAND/PI,PII
C*
C*
C*   N=NUMB - 1
      IF(NUMB.NE.2*(NUMB/2)) N=NUMB
      N=N/2 - 1
      CONST=PII/FLOAT(NUMB)
      ALPHA=0.54
      IF(IW.EQ.2) ALPHA=0.5
      C1=1. - ALPHA
      DO 1 I=1,NUMB
          T1=CONST*FLOAT(I+N)
          A(I)=A(I)*(ALPHA + C1*COS(T1))
1      CONTINUE
          RETURN
          END

```

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```

C*
C*
C*      CCD29.FTN
C*
C*      SUBROUTINE EPLOT(XT,XMAX,LNUMB,LSTRT,LINT)
C      FOR PLOTTING RESULTS ON A SCALE 0 TO 50 DB
C      ASSUMES THAT CAPTIONING IS PROVIDED, AND POINTS EXIST (UP TO LEND)
C      NORMALIZES POINTS TO XMAX BEFORE PLOTTING
C*
C*
C*      XT VECTOR OF STORED POINTS TO BE PLOTTED
C*      XMAX MAX VALUE IN VECTOR XT
C*      LNUMB NUMBER OF POINTS TO BE PLOTTED
C*      LSTRT INDEX OF FIRST POINT TO BE PLOTTED
C*      LINT INTERVAL BETWEEN PLOTTED POINTS IN ARRAY
C*
C*      OUTPUT OF 999 MEAN THAT POINT WAS LESS THEN
C*      OR EQUAL TO ZERO
C*
C*****M27- LATEST REVISION DATED: 21, APR, 77
      REAL AKAR(5)
      REAL XT(2)
      COMMON /CCD/ALINE(101)
      DATA AKAR/' ',' ',' ',' ',' ',' ',' ',' ',' '
      LEND=LSTRT+(LNUMB-1)*LINT
      KOUNT=0
      WRITE(5,15)
15      FORMAT(/59X,'DB DOWN'/)
      WRITE(5,17)
17      FORMAT(/1X,'PT # VALUE 100 ','17X','80','18X','60','18X','40',
1          '18X','20','18X','0 INDEX')
      DO 20 I=LSTRT,LEND,LINT
      TEST=XT(I)/XMAX
      IF(TEST) 24,24,26
24      DB=999.
      GO TO 30
26      DB=-20.*ALOG10(TEST)
30      IF( MOD(KOUNT,10).NE.0 ) GO TO 50
C      EVERY TENTH LINE
      DO 35 J=1,101
35      ALINE(J)=AKAR(1)
      DO 40 J=1,101,5
40      ALINE(J)=AKAR(3)
      GO TO 70
C      ALL OTHER LINES
50      DO 55 J=1,101
55      ALINE(J)=AKAR(4)
      DO 60 J=1,101,10
60      ALINE(J)=AKAR(2)
C      LINE READY FOR INSERTION OF POINT
70      KOUNT=KOUNT+1
      L=101-IFIX(DB+.5)
      IF(L.LT.1) GO TO 90
      ALINE(L)=AKAR(5)
90      WRITE(5,95) I,DB,(ALINE(J),J=1,101),KOUNT
95      FORMAT(1X,I4,F7.2,1X,101A1,15)
22      CONTINUE
      WRITE(5,17)
      RETURN
      END

```



```

REVAVE=AIN(T(AVE/XIN)*XIN
XMIN=REVAVE-60.*XIN
XS(1)=REVAVE-50.*XIN
XS(2)=REVAVE-25.*XIN
XS(3)=REVAVE
XS(4)=REVAVE+25.*XIN
XS(5)=REVAVE+50.*XIN
WRITE(5,1000)DELT,TINTL,XS
1000 FORMAT(/5X24HABSCISSA IS IN UNITS OF 1PE13.7,
1 * INITIAL VALUE ',1PE13.7/
2 61X21H-----AMPLITUDE-----//2X8HABSCISSA5X
3 1PE11.4,4(14X1PE11.4)/1X,132(1H,))
C*
C* BY PASS CODE AFTER GOTO 6
C*
KNT=1
IF(TINTL.GT.1.) KNT=TINTL
IF(KNT.GT.0) GOTO 6
TSAVE=TINTL
KNT=1
4 KNTCHK=(TINTL-TSAVE)/DELT+.1
IF(KNTCHK-KNT)5,6,5
5 WRITE(5,1001)
1001 FORMAT(/2H */)
KNT=KNTCHK
6 DO 7 I=1,NELMNT
AVE=AVE + ARRAY(I)
VAR=VAR + ARRAY(I)*ARRAY(I)
K=((ARRAY(I)-XMIN)/XIN+2.5)
IF(K.GT.122)K=123
IF(K.LT.1)K=1
TEMP=STRING(K)
STRING(K)=STAR
WRITE(5,1002)KNT,(STRING(J),J=2,123)
1002 FORMAT(110,1X123A1)
KNT=KNT + 1
7 STRING(K)=TEMP
TINTL=FLOAT(KNT)*DELT+TSAVE
XIN=NELMNT
XMIN=(XIN - 1.)*XIN
VAR=XIN*VAR + AVE*AVE
IF(VAR.GT.0.) VAR=SQRT(VAR/XMIN)
AVE=AVE/XIN
WRITE(5,8000) NELMNT,AMIN,AMAX,AVE,VAR
8000 FORMAT(' * OF ELEMENTS ',I5/
2* MINIMUM VALUE ',1PE15.8/
3* MAXIMUM VALUE ',1PE15.8/
4* MEAN OF ELEMENTS',1PE15.8/
5* SD OF THE ELEMENTS',1PE15.8//)
RETURN
END

```

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```

C*
C*
C*
C**1 KEY TO CCD STUDY ARRAY BINSTR
C*
C*
COMMON /BINSTR/XX(30),IJ(30)
C*
C*
C* IJ(1) # OF STAGES IN CCD
C* IJ(2) DEBUGGING AID PRINTS OUT INTERMEDIATE VALUES
C* NO 0 YES 1
C* IJ(3) LENGH OF INPUT PULSE
C* IJ(4) COMPUTE TAPPED DELAY LINE RESPONSE
C* NO 0 YES 1
C* IJ(5) FEEDTHROUGH VOLTAGE ADDED N=0 Y=1
C* IJ(6) SURFACE OR BURIED DEVICE
C* IJ(7) PLOT OUTPUT AND INPUT Y=0 N=1
C* IJ(8) NOISE INJECTED OR NOT Y=0 N=1
C* IJ(10) SELECT NOISE SOURCES N=0, Y=1
C* IJ(11) INPUT NOISE ADDED
C* IJ(12) SHOT NOISE ADDED
C* IJ(13) TRANSFER NOISE ADDED
C* IJ(14) OUTPUT NOISE ADDED
C* IJ(15) FILTER NOISE ADDED
C* IJ(16) INTERFACE NOISE ADDED
C* IJ(17) NON LINEAR INPUT CHARACTERISTIC
C* YES= 0 NO = 1
C* IJ(18) DARK CURRENT NOISE
C* IJ(20) HOLD SIGNAL FOR ANY TIME Y=0 N=1
C* IJ(27) # OF ELEMENTS IN FILE ON DAT SLOT 2
C* IJ(28) # OF SINUSODIAL SIGNALS ADDED AT INPUT
C* IJ(29) TYPE OF SIGNAL 0 PULSE 1 SIN
C* IJ(30) FFT OF OUTPUT
C*
C*
C* XX(1) TRANSFER INEFFICIENCY
C* XX(2) MEAN VALUE OF THE INITIAL STATE OF DEVICE
C* XX(3) SD OF INITIAL STATE
C* XX(4) CLOCK FREQUENCY
C* XX(6) SD OF INPUT NOISE
C* XX(7) SD OF SHOT NOISE
C* XX(8) SD OF TRANSFER NOISE
C* XX(9) SD OF OUTPUT NOISE
C* XX(10) INPUT LEVEL OF INPUT PULSE 0 TO 2 VOLTS
C* XX(11) % ERROR OF THE TAP WEIGHTS
C* XX(12) MAXIMUM OUTPUT VOLTAGE
C* XX(13) OUTPUT VOLTAGE OF CLOCK
C* XX(14) FEEDTHROUGH VOLTAGE LEVEL
C* XX(15) AREA OF WELL
C* XX(16) BACKGROUND CHARGE 0 TO 35 %
C* XX(17) SD OF FILTER NOISE
C* XX(18) CLOCK SWING VOLTAGE
C* XX(19) SD OF INTERFACE NOISE
C* XX(20) MEAN OF INTERFACE NOISE
C* XX(21) TIME SIGNAL HELD IN DEVICE
C* XX(22) OUTPUT SAMPLING RATE
C* XX(23) SHOT NOISE FOR OUTPUT FREQUENCY
C* XX(24) CONSTANT A FOR DARK CURRENT MULTIPLY
C* XX(25) NUMBER OF ELECTRONS ADDED FOR DARK CURRENT
C* XX(26) AMBIENT TEMPERATURE READ IN DEGREES C
C* CONVERTED TO KELVIN
C* XX(27) FREQUENCY OF 4TH INPUT
C* XX(28) FREQUENCY OF 3TH INPUT
C* XX(29) FREQUENCY OF 2TH INPUT

```

APPENDIX B. COMPUTER LISTING OF MATCHED LINEAR FM FILTER

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CCD1.FTN

CCD STUDY MODELING AND SIMULATION OF THE MATCHED FILTER


```

REAL A(2),B(3)
COMMON IW
COMMON /RAND/G0(10)
COMMON /RINSTR/G(50)
COMMON /CCD/G1(1202)
COMMON /INPUT/G2(1200)
COMMON /VOLTS/G5(100)
COMMON /PASS/GG(50)
COMMON /FILTER/FILT(600)
10  CONTINUE
    WRITE(S,100)
100  FORMAT(1H1'   CCD STUDY   TEST RUN'//)
    CALL TIME(A)
    CALL DATE(B)
    WRITE(S,101) B,A
101  FORMAT(SX,'DATE: ',3A4,5X,'TIME: ',2A4//)
    CALL LINK('C0')
    CALL LINK('C1')
    IW=0
30  CONTINUE
    CALL LINK('C2')
    CALL LINK('C3')
    CALL LINK('C4')
    IW=IW + 1
    IF(IW.LT.4) GOTO 30
    CALL LINK('C5')
    CALL LINK('C6')

```

```

C*
C*
C*  THE FOLLOWING CODE IS USED TO FORCE THE
C*  MAIN MODULE TO CARRY THE I/O ROUTINES
C*  SEE DESCRIPTION IN FORTRAN OR LINK
C*  MANUALS
C*
C*

```

```

        IDUM=0
1001 IF(IDUM.EQ.0) GOTO 10
        READ(1,INDEX) A
        WRITE(1,INDEX) A
        READ(6,1001) II,A
        WRITE(6,1001) II,A
        FORMAT(15,E15.8,F10.0)
        END

```

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C
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C

CC06.FTN

SUBROUTINE READS IN THE INSTRUCTIONS FOR A RUN

```

SUBROUTINE INSTR
REAL A(3)
COMMON /CCD/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(4),XLEV,
2      ZL(20),ISTAGE,IPRINT,I LENGT,IFILT,NRVS,IJ(20)
COMMON /BINSTR/XXZ(30),IJL(30)
COMMON /VOLTS/WW1,WW2,ITIME
COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
COMMON /RAND/R1(4),RR(6)
DATA A/4HTEMP,4H02,0,4MAT00/
      IJL(21)=0
      IRW(3)=0
      IJL(9)=9998
7000 WRITE(6,7000)
      FORMAT(' CREATE NEW FILE ON DAT SLOT 2 Y=0 N=1 '/')
      READ(6,91) I
      IF(I.NE.0) GOTO 7005
      WRITE(6,7001)
7001 FORMAT(' NAME OF FILE XXXXXX.D '/')
      READ(6,7002) A(1),A(2)
7002 FORMAT(2A4)
7005 WRITE(5,7003) A
7003 FORMAT(' NAME OF FILE FOR THIS RUN ',3A4//)
      CALL SETFIL(2,A,IER2,'DK',0)
      DEFINE FILE 2(200,64,U,IVAR)
1      WRITE(6,100)
100  FORMAT(' THE NUMBER OF STAGES IN THE CCD (F10.0)')
      READ(6,101) X
101  FORMAT(F10.0)
      IUPPER=600
      ILOWER=0
      ISTAGE=X
      IF((ISTAGE.GT.ILOWER).AND.(ISTAGE.LE.IUPPER)) GOTO 3
201  WRITE(6,201) ISTAGE,ILOWER,IUPPER
      FORMAT(' ERROR MESSAGE # OF STAGES TO SMALL OR TO LARGE'
2* # OF STAGES: ',I4,' LOWER LIMIT: ',I4,' UPPER: ',I4//)
      GOTO 1
3      WRITE(6,103)
103  FORMAT(' SD OF THE INITIAL STATE (F10.0)')
2* IF < 0 THEN NO BACKGROUND VOLTAGE ADDED')
      READ(6,101) XSD
C*
C*
      WRITE(6,5123)
5123 FORMAT(' NOISE + TARGET 0')
2      ' NOISE          1'
3      ' TARGET          2')
      READ(6,91) IJL(28)
C*
      XXZ(3)=XSD
      IJL(1)=ISTAGE
4      WRITE(6,104)
104  FORMAT(' SURFACE OR BURIED DEVICE (0 OR 1)')
      READ(6,91) IJ(1)
      IJL(6)=IJ(1)
      IF((IJ(1).LT.0).OR.(IJ(1).GT.1)) GOTO 4
      WRITE(6,108)

```

B2

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```

106   FORMAT(' AREA OF WELL IN MIL**2 '/')
      READ(6,101) ZL(5)
      WRITE(6,107)
107   FORMAT(' % OF BACKGROUND CHARGE '/')
      2 * '<0 THEN SPECIFY TRANSFER LOST '/')
      READ(6,101) ZL(6)
      IF(ZL(6).LT.0.) WRITE(6,7891)
7891  FORMAT(' FRACTION LOST EACH TIME ,XXXX'/)
      IF(ZL(6).LT.0.) READ(6,101) XPERC
      IF(ZL(6).GE.0.) CALL CTI(ZL,XPERC,IJ)
      WRITE(6,109)
109   FORMAT(' CLOCK SWING VOLTAGE '/')
      READ(6,101) ZL(8)
      XXZ(1)=XPERC
      XXZ(15)=ZL(5)
      XXZ(16)=ZL(6)
      XXZ(18)=ZL(8)
      WRITE(6,9050)
9050  FORMAT(' PLOT OF INPUT AND OUTPUT Y=0 N=1 '/')
      READ(6,91) IJL(7)
      WRITE(6,8151)
8151  FORMAT(' HAMMING WEIGHTING TO OUTPUT Y=0 N=1'/)
      READ(6,91) IJL(4)
      WRITE(6,7011)
7011  FORMAT(' FFT OF OUTPUT Y=1 N=0 '/')
      READ(6,91) IJL(30)
5     WRITE(6,1000) ISTAGE,XPERC,ZL(6),ZL(5)
1000  FORMAT(' # OF STAGES IN THE CCD ',I5/
3     ' CTI OF DEVICE ',1PE15.8/
4     ' % OF THE BACKGROUND CHARGE ',1PE15.8/
4     ' AREA OF THE WELL (MIL**2)',1PE15.8//)
6     WRITE(6,206)
206   FORMAT(' CLOCK FREQUENCY (F10) '/')
      CLCKMX=1.E10
      READ(6,101) FCLOCK
      IF((FCLOCK.GT.0.),AND.(FCLOCK.LE.CLCKMX)) GOTO 60
      WRITE(6,1006) CLCKMX
1006  FORMAT(' CLOCK RATE OUTSIDE OF RANGE OF 0. TO 'F10.0/')
      GOTO 6
60    CONTINUE
      WRITE(5,701) FCLOCK
701   FORMAT(' CLOCK RATE ',1PE15.8/)
80    WRITE(6,800)
800   FORMAT(' THE LENGTH OF TIME OF THE RUN < 1201 '/')
      READ(6,101) ZZ1
      ITIME=ZZ1
      IF((ITIME.LT.0).OR.(ITIME.GT.1200)) GOTO 80
      WRITE(6,90)
90    FORMAT(' PRINT OUT INTERMEDIATE VALUES NO=0 YES=1'/)
      READ(6,91) IPRINT
91    FORMAT(I1)
      WRITE(6,9008)
9008  FORMAT(' FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1'/)
C*
C*   MAXIMUM INPUT VOLTAGE IS 2.8 VOLTS
C*
C*
      XXZ(4)=FCLOCK
      IJL(2)=IPRINT
      XMAXV=2.8
      WW1=XMAXV
      READ(6,91) NRVS
96    WRITE(6,93)
95    FORMAT(' DURATION OF THE SIGNAL MIN=M MAX=1200'/)
      READ(6,101) ZZ1
      ILENGT=771

```

```

WRITE(6,7024)
7024  FORMAT(' BANDWIDTH OF THE LINEAR FM (HERTZ) '//)
      READ(6,101)  XXZ(30)
      XXZ(8)=XXZ(30)/XXZ(4)
      WRITE(6,8025)
8025  FORMAT(' SIGNAL TO NOISE RATIO AT IF(DB) '//)
      READ(6,101)  XXZ(29)
      WRITE(6,7028)
7028  FORMAT(' PHASE ANGLE OF TARGET DEGREES '//)
      READ(6,101)  XXZ(28)
      WRITE(5,7030)  XXZ(30),XXZ(29),XXZ(28)
7030  FORMAT(' BANDWIDTH OF SIGNAL '1PE15.0/
2  ' SIGNAL TO NOISE OF SIGNAL(DB) '1PE15.0/
3  ' PHASE ANGLE OF THE SIGNAL '1PE15.0//)
      WRITE(6,8053)
8053  FORMAT(' DC BIAS (% OF WELL) TERM ADDED TO INPUT F10 '//)
      READ(6,101)  XXZ(5)
      XXZ(5)=WW1*XXZ(5)/100.
95    CONTINUE
      IJL(3)=ILENGT
      IJL(5)=NRVS
      WRITE(6,8010)
8010  FORMAT(' NON LINEAR INPUT WARPING Y=0 N=1 '//)
      READ(6,91)  IJ(12)
      WRITE(6,97)
97    FORMAT(' MEAN ERROR IN TAP WEIGHTS '//)
      READ(6,101)  XXZ(20)
      WRITE(6,7128)
7128  FORMAT(' SD OF THE TAP ERROR (.0061 .07) '//)
      READ(6,101)  XXZ(17)
      IJL(20)=1
      WRITE(6,9034)
      READ(6,101)  ZZ1
      XXZ(26)=ZZ1 + 273.
      WRITE(5,9035)  ZZ1,XXZ(26)
      WRITE(6,9033)
9033  FORMAT(' DARK CURRENT ADDED Y=0 N=1 '//)
      READ(6,91)  IJ(13)
      IF(IJ(13).EQ.1) GOTO 9036
9034  FORMAT(' AMBIENT TEMPERATURE DEGREES C '//)
9035  FORMAT(' AMBIENT TEMPERATURE (C) ',F10.4,' (K) ',F10.4//)
9036  CONTINUE
      IJL(17)=IJ(12)
      IJL(18)=IJ(13)
      WRITE(6,6011)
6011  FORMAT(' MULTIPLE RUN Y=# OF CHANGES N=0 F10 '//)
      READ(6,91)  IJL(19)
      IF(IJL(19).EQ.0) GOTO 8000
      WRITE(6,6012)
6012  FORMAT(' WHICH INPUT IS TO BE CHANGED '//)
2  ' 1= # OF STAGES, 2=SD OF THE TAP WEIGHTS '//
3  ' 3= AREA OF WELL, 4=BACKGROUND CHARGE '//
4  ' 5=CLOCK FREQUENCY,6=AMBIENT TEMPERATURE '//)
      READ(6,91)  IJL(22)
      K=IJL(19)
      DO 6019 I=1,K
      WRITE(6,6013)  I
6013  FORMAT(' INPUT THE ',I6,' VALUE '//)
      READ(6,101)  RR(I)
6019  CONTINUE
      WRITE(5,6015)  (I,RR(I),I=1,K)
6015  FORMAT(' MULTIPLE RUNS '//7(1X,I2,2X,1PE15.0))
      WRITE(6,8717)
8717  FORMAT(' SECOND VARIABLE CHANGING Y=# N=0 '//)
      READ(6,91)  IRW(1)
      IF(IRW(1).EQ.0) GOTO 8000

```

```

WRITE(6,6012)
READ(6,91) IRW(2)
K=IRW(1)
DO 8718 I=1,K
WRITE(6,6013) I
READ(6,101) ROW(I)
8718 CONTINUE
WRITE(5,6015) (I,ROW(I),I=1,K)
8000 WRITE(6,8001)
8001 FORMAT(' RUN WITH NOISE Y=0 N=1 '/')
READ(6,91) IJ(3)
IJL(8)=IJ(3)
IF((IJ(3).LT.0).OR.(IJ(3).GT.1)) GOTO 8000
IF(IJ(3).EQ.1) RETURN
K=10
DO 9000 I=5,11
IJ(I)=0
IJL(K)=0
K=K + 1
9000 CONTINUE
WRITE(6,8003)
8003 FORMAT(' SELECT THE PARTICULAR NOISE INPUTS N=0,Y=1/')
READ(6,91) IJ(5)
IJL(10)=IJ(5)
IF(IJ(5).EQ.0) RETURN
WRITE(6,8004)
8004 FORMAT(' ADD IN INPUT NOISE Y=0 N=1 '/')
READ(6,91) IJ(6)
WRITE(6,8005)
8005 FORMAT(' ADD IN THE SHOT NOISE Y=0 N=1/')
READ(6,91) IJ(7)
WRITE(6,8006)
8006 FORMAT(' ADD IN THE TRANSFER NOISE Y=0 N=1/')
READ(6,91) IJ(8)
WRITE(6,8007)
8007 FORMAT(' ADD IN THE OUTPUT NOISE Y=0 N=1/')
READ(6,91) IJ(9)
WRITE(6,8008)
8008 FORMAT(' ADD IN THE FILTER NOISE Y=0 N=1/')
READ(6,91) IJ(10)
WRITE(6,8009)
8009 FORMAT(' ADD IN INTERFACE NOISE '/')
READ(6,91) IJ(11)
K=11
DO 57 I=6,11
IJL(K)=IJ(I)
K=K + 1
57 CONTINUE
RETURN
END

```

```

C*
C*
C*      C1 LINK STRUCTURE
C*
C*      C1,C1<CCD,ST0,C1,CCDS,FTNLIB/L/U/E
C*

```

```

COMMON /RAND/PI,PII
COMMON /VOLTS/Q1,Q2,ITIM,IPP
PI=4.*ATAN(1.)
PII=2.*PI
CALL PRTVAL
IPP=1
CALL RETURN
END

```



```

C*
C* CCDS.FTN
C*
C*
C* SUBROUTINE PRINTS OUT MEANS AND SD OF THE
C* VARIOUS NOISE RANDOM VARIABLES
C*
C*
C* SUBROUTINE PRTVAL
REAL JD,NSS
COMMON IBIT
COMMON /3INSTR/XX(30),IJL(30)
COMMON /RAND/PI,PII,II1,II2
COMMON /PASS/STAD(20)

C*
C*
C* NOISE ADDED OR NOT
C*
C* INOISE=IJL(8)
C* IDARK=IJL(18)

C*
C*
C* CONSTANTS NEED IN CALCULATIONS
C*
C*
C* XKB=8.517E-5
C* AREA=XX(15)*6.4516E-6
C* Q=1.602E-19
C* NSS=1.E10
C* C=1.E-13
C* QQ=1.6498E-24
C* TD=100.E-6
C* XD=1.E-4
C* SIGMA=1.E-15
C* VTH=8.25
C* XNST=5.E9
C* XNNN=5.E14
C* XLN=0.05609
C* TEMP=XX(26)
C* FCLOCK=XX(4)

C*
C*
C* INPUT NOISE
C*
C* MEAN=0
C*
C* VAR= XKB*TEMP*C/Q**2
C*
C*
C* X=XKB*TEMP
C* XX(6)=SQRT(2.*X*C/(3.*Q))

C*
C*
C* OUTPUT NOISE
C*
C* SAME AS ABOVE
C*
C*
C* XX(7)=XX(6)
C*
C*

```

```

C*
C* FAST INTERFACE
C*
C*
C*
C* MEAN=0
C* SD=SQRT(0.7*K*TEMP*NSS*AREA)
C*
C*
C* XX(19)=SQRT(0.7*X*NSS*AREA)
C*
C*
C* DARK CURRENT
C*
C*
C* IF (XX(26),LT,250,) GOTO 50
C* XNI=1.21/(8.617E-5*TEMP)
C* XNI=EXP(-XNI)
C* XNI=XNI*1.5E33
C* XNI=XNI*TEMP**3
C* XNI=SQRT(XNI)
C* GOTO 51
50 CONTINUE
C* YNI=53228827.58
51 CONTINUE
C* GBI=XNI*XNI*XLN/(XNNN*TD)
C* GSI=0.5*XNI*SIGMA*VTH
C* GDI=XNI*XD/(2.*TD)
C* XX(25)=10000.
C* STAD(20)=GBI
C* STAD(19)=GSI
C* STAD(18)=GDI
C* STAD(17)=AREA/FCLOCK
C* XX(24)=AREA
C* STAD(16)=XNST
C* STAD(15)=QQ/1.0363E-5
C* IF (IDARK.EQ.1) XX(25)=0.
C* IF (IDARK.EQ.0) WRITE(5,8010) GBI,GSI,GDI,TOTALI
8010 2 FORMAT(' INDIVIDUAL SOURCES OF DARK CURRENT '/
C* 2 6(3X,1PE15.8))
C*
C* SHOT NOISE
C*
C* MEAN=0.
C*
C* SD= SQRT(JD*AREA/Q*FCLOCK)
C*
C*
C* JD=GBI + GSI*XNST + GDI
C* JD=JD*STAD(15)
C* XX(7)=SQRT(JD*AREA/(Q*FCLOCK))
C*
C* PRINT OUT THE MEANS AND SD
C*
C*
C* IF (INOISE,EQ,1) RETURN
C* IF (IBIT.GT.0) RETURN
C* WRITE(5,9088) XX(25)
9088 2 FORMAT(' DARK CURRENT ELECTRONS ADDED PER
C* 2 'TRANSFER ',1PE15.8//)
C*
C*
C* Z=0.
C* WRITE(5,2) Z,XX(6)
C* WRITE(5,3) Z,XX(7)
C* WRITE(5,4) Z,XX(8)

```

```

WRITE(5,6) XX(20),XX(17)
WRITE(5,10) Z,XX(19)
WRITE(5,7) (IJL(I),I=10,16)
7  FORMAT(" STATUS OF THE NOISE SOURCES"//
2  " SELECT THE NOISE INPUTS Y=1 N=0 ",I2/
3  " ADD IN INPUT NOISE Y=0 N=1 ",I2/
4  " ADD IN SHOT NOISE Y=0 N=1 ",I2/
5  " ADD IN TRANSFER NOISE Y=0 N=1 ",I2/
6  " ADD IN OUTPUT NOISE Y=0 N=1 ",I2/
7  " ADD IN FILTER NOISE Y=0 N=1 ",I2/
8  " ADD IN INTERFACE NOISE Y=0 N=1 ",I2//)
2  FORMAT(" MEAN OF THE INPUT NOISE      ",1PE15.8,
2  " SD      ",1PE15.8/)
3  FORMAT(" MEAN OF THE SHOT NOISE      ",1PE15.8,
2  " SD      ",1PE15.8/)
4  FORMAT(" MEAN OF THE TRANSFER NOISE  ",1PE15.8,
2  " SD      ",1PE15.8/)
5  FORMAT(" MEAN OF THE OUTPUT NOISE    ",1PE15.8,
2  " SD      ",1PE15.8/)
6  FORMAT(" MEAN OF THE FILTER ERROR    ",1PE15.8,
2  " SD      ",1PE15.8/)
10 FORMAT(" MEAN OF THE INTERFACE NOISE  ",1PE15.8,
2  " SD      ",1PE15.8/)
      RETURN
      END

```

```

C*
C*
C*      C2,FTN
C*
C*      C2 LINK STRUCTURE
C*C
C*
C*      C2,C2<FILT,STB,C2,MOD4,CCD2,FTNL18/L/U/E
C*
C*
C*

```

```

COMMON IW
CALL SIGNAL
CALL INPUT
CALL RETURN
END

```

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C*
C*
C*
C*
C*
C*
C*
C*
C*

MOD4.FTN

COMBINES SIGNAL PLUS THE NOISE

SUBROUTINE SIGNAL

COMMON IW
COMMON /FILTER/A(30)
COMMON /INPUT/ARRAY(1200)
COMMON /VOLTS/WW1,WW2,ITIME,IPP
COMMON /BINSTR/XX(30),IJ(30)
COMMON /RAND/PI,PII

WRITE(6,8000)
8000 FORMAT(' SIGNAL'//)
NSIGNAL=IJ(28)
ASI=SQRT(2.*10.**(XX(29)/10.))

C
C*
C*
C*
C*
C

PLACE THE TARGET IN THE MIDDLE OF THE SAMPLES
FROM - THE LENGTH OF THE SIGNAL PULSE
TO + THE LENGTH OF THE SIGNAL PULSE

ISTART=ITIME/2 - IJ(3)/2 + 1
JEND=ISTART + IJ(3) - 1

C
C*
C

BANDWIDTH OF THE LINEAR FM BW=XX(30)

BW=XX(30)

C
C
C

PHASE IS AN INPUT PARAMETER

PHASE=XX(28)
RADS=PHASE*PI/180.

C
C
C

SAMPLING FREQUENCY

FS=XX(4)
TS=1./FS
TIMEPL=FLOAT(IJ(3))*TS
SLOPE=BW*PII/TIMEPL
SLOPE=SLOPE/2.
XX(27)=SLOPE
TIME=-FLOAT(ITIME/2)*TS
JJ=1
J=0

1
5

IF(NSIGNAL.EQ.2) GOTO 5

READ(1,END=9000,ERR=9000)A

J=0

IF(NSIGNAL.NE.2) J=J + 1

IF(JJ.GT.ITIME) GOTO 20

IF(J.GT.30) GOTO 1

XSING=0.

IF(JJ.LT.ISTART) GOTO 10

IF(JJ.GT.JEND) GOTO 10

ARG=PII*(IJJ-ISTART) + RADS

IF(IW.GT.1) XSING=ASI*SIN(ARG)

IF(IW.GT.2) XSING=ASI*COS(ARG)

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```
IF(NSIGNL,EQ,0) ARRAY(JJ)=XSING + A(J)
IF(NSIGNL,EQ,1) ARRAY(JJ)=A(J)
IF(NSIGNL,EQ,2) ARRAY(JJ)= XSING
JJ=JJ + 1
TIME=TIME + TS
      GOTO 5
20  CONTINUE
      RETURN
9000 REWIND 1
      GOTO 1
      END
```

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C
C
C
C
C
C
C
C
C
C
C

CC02,FTN

SUBROUTINE GENERATES THE INPUT SIGNAL TO THE CCD

ASSUMES THAT MAXIMUM VOLTAGE IS 2 VOLTS (XMAXV)
WHICH CORRESPONDS TO 100000 ELECTRONS (XMAXEL)

ITIME IS THE CCD RUN TIME

SUBROUTINE INPUT

REAL A(30)
COMMON IBIT
COMMON /INPUT/ELECTR(1200)
COMMON /BINSTR/XZ(30),IJ(30)
COMMON /VOLTS/XMAXV,XMAXEL,ITIME
COMMON /CCD/HOLD(1200)
COMMON /RAND/PI,PII
COMMON /PASS/STAD(20)

C
C
C
C
C
C*
C*
C*
C*

TRIAL RUN IMPULSE AT TIME ZERO

02/18/77 CHANGE IN FULL WELL ELECTRON COUNT

CLOCK SWING

CS=XZ(18)
AREA=XZ(15)
COUL=2.625E-13
ELECTR=6.281E+18
XMAXEL=AREA*COUL*ELECTR*CS
IF(IJ(6).EQ.1) XMAXEL=XMAXEL/2.
XZ(2)=XZ(16)*XMAXEL/100.
IF(XZ(2).LT.0.) XZ(2)=0.
IF(IBIT.GT.0) GOTO 8181
WRITE(5,1000) XMAXV,XMAXEL,CS,IJ(6)
1000 FORMAT(' MAXIMUM INPUT VOLTAGE ',1PE15.8,
25X,'CORRESPONDS TO MAXIMUM NO. OF ELECTRONS ',1PE15.8/
31X,'CLOCK SWING VOLTAGE ',1PE15.8/
4' SURFACE(FAT ZERO) 0 OR BURIED(SLIM ZERO) 1 ',I2//)
WRITE(5,2000) IJ(3),XZ(5)
2000 FORMAT(' LENGTH OF THE SIGNAL ',I6/
3' BIAS VOLTAGE ADDED TO INPUT ',F10.4//)
8181 CONTINUE
CONST=XMAXEL/XMAXV
AVE=XZ(2)
SU=XZ(3)
BIAS=XZ(5)
BIAS=BIAS*CONST
K=31
IF(AVE.GT.BIAS) BIAS=AVE
DO 4 I=1,ITIME
ELECTR(I)=ELECTR(I)*CONST + BIAS
K=K + 1
IF(BIAS.LE.0.) GOTO 4
IF(ELECTR(I).GT.XMAXEL) ELECTR(I)=XMAXEL

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```
4      IF (ELECTR(I).LT.0.) ELECTR(I)=0.  
      CONTINUE  
      STAD(5)=BIAS  
      RETURN  
      END
```

```
C*  
C*  
C*  
C*  
C*  
C*  
C*  
C*  
C*  
C*
```

```
C3,FTN
```

```
C3,C3<FILT.STB,C3,CC03,FTNLIB/L/U/E
```

```
COMMON IW  
CALL INITL  
CALL RETURN  
END
```

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00000000

CC03,FTN

SUBROUTINE INITIALIZES CCD FOR INPUT DATA

```

SUBROUTINE INITL
REAL AA(30)
COMMON IBIT
COMMON /CCD/CCDW(2,601)
COMMON /BINSTR/XJ(30),IJ(30)
COMMON /VOLTS/XMAXV,XMAXE
COMMON /PASS/STAD(20)
CONST=XMAXE/XMAXV
ISTAGE=IJ(1)
IPRINT=IJ(2)
INOISE=IJ(8)
BIAS=STAD(5)
SD=XJ(3)
IF((SD.LT.0.).AND.(XJ(5).LE.0.)) GOTO 100
IF(IBIT.EQ.0) WRITE(5,505) AVE,SD,BIAS
505  FORMAT(' MEAN VALUE OF THE INITIAL STATES ',1PE15.8/
2  ' SD OF THE INITIAL STATES ',1PE15.8/
3  ' NUMBER OF ELECTRONS ADDED ',1PE15.8/)
      I=1
      K=1
      IF(SD.LE.0.) GOTO 2
1      READ(1,END=8000,ERR=8000) AA
      K=1
2      CONTINUE
      CCDW(2,I)=BIAS
      IF(SD.LE.0.) GOTO 5
      CCDW(2,I)=CCDW(2,I) + AA(K)*SD
      K=K + 1
5      CONTINUE
      RES=CCDW(2,I)*XJ(1)
      CCDW(1,I)=RES
      CCDW(2,I)=RES
      I=I + 1
      IF(I.GT.ISTAGE) GOTO 3
      IF(K.GT.30) GOTO 1
      GOTO 2
3      CONTINUE
      IF(IPRINT.NE.1) RETURN
      WRITE(5,1000) (I,I=1,ISTAGE)
1000  FORMAT(15X,'STAGES'/'(13I10))
      WRITE(5,1001) (CCDW(1,I),CCDW(2,I),I=1,ISTAGE)
1001  FORMAT(12(1X,F10.2))
      RETURN
100  DO 110 I=1,ISTAGE
      CCDW(1,I)=0.
      CCDW(2,I)=0.
110  CONTINUE
200  WRITE(5,201)
201  FORMAT(' NO BACKGROUND VOLTAGE ADDED (/)
      RETURN
7000  CONTINUE
      BIAS=STAD(5)
      RES=BIAS*XJ(1)

```

B13

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```
BIAS=BIAS - RES
DO 7001 I=1,1STAGE
  CCDW(1,I)=RES
  CCDW(2,I)=RES
7001 CONTINUE
  WRITE(5,7010) RES,BIAS
7010 FORMAT(" BIAS TERMS ADDED TO WELLS ",2(2X,1PE15.8)/)
  RETURN
8000 REWIND 1
  GOTO 1
  END
```

```
C*
C*
C*      C4 LINK STRUCTURE
C*
C*      C4,C4<CCD,ST0,C4,CCD7,CCD17,CCD18,CCD20,CCD30,FTNL18/L/U/E
C*
COMMON IW
COMMON /VOLTS/Q1,Q2,ITIME,IPP
IF(IPP.EQ.1) CALL SD
CALL XRUN
CALL RETURN
  END
```

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C*
C*
C*
C*
C*
C*
C*

CCD7.FTN

SUBROUTINE DOES THE BOOKKEEPING FOR THE CCD2 ARRAY
VERSUS TIME

SUBROUTINE XRUN
REAL A(30),B(30)
COMMON IBIT
COMMON /VOLTS/Q1,Q2,ITIM
COMMON /CCD/CCDW(2,601)
COMMON /INPUT/ELECTR(1200)
COMMON /BINSTR/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(25),ISTAGE
2 ,IPRINT,ILENGT,IFILT,ILJ(3),INOISE,IJJ(20)
COMMON /PASS/STAD(20),ISTAD(20),IVAR
LL=ISTAGE + 1

C*
C*
C*
C*
C*
C*
C*

SHOT NOISE
INPUT NOISE
TRANSFER NOISE CHANGED 03/23/77
INTERFACE NOISE ADDED 03/24/77

ISTART=1
I3=0
I4=0
IJJ(17)=0
DARK=XZ(20)
IF(DARK.EQ.0.) GOTO 5000
I3=31
GHI=STAD(20)
GSI=STAD(19)
GDI=STAD(18)
GG=GSI + GDI
CONST=STAD(17)
XNST=STAD(16)
CUR=STAD(15)
G1=CUR*GSI
G2=CUR*GDI
G3=CUR*GDI
5000 CONTINUE
IF(INOISE.EQ.1) GOTO 8000
SDINPT=STAD(1)
SDMIDL=STAD(2)
SOTRAN=SQRT(2.*XPERC)
INPT=ISTAD(1)
IMIDL=ISTAD(2)
I3=31
8000 CONTINUE
CALL COEFS
ILL=ITIM
ITIME=ITIM
IEND=1
IREGIN=0
2329 CONTINUE
DO 1 I=ISTART,ITIME
IF(I.EQ.1) GOTO 7002
IBEGIN=I - 1
IEND=I - ILL
IF(IBEGIN.GT.ISTAGE) IBEGIN=ISTAGE

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```

      IF(IEND.GT.ISTAGE) IEND=ISTAGE
      IF(IEND.LE.0) IEND=1
      CCDW(1,LL)=0.
      J=IBEGIN
      IF(IPRINT.NE.1) GOTO 25
      WRITE(5,1001) I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
1001  FORMAT(I4,(6(1X,E15.8)))
25    CONTINUE
      DO 2 K=1,ISTAGE
      JJ=J + 1

C*
C*   FIND RESIDUE AT CLOCK PULSE 2 IN EACH WELL
C*   TRANSFER REMAINING CHARGE TO WELL AT CLOCK 1
C*   LEAVE RESIDUE IN OLD WELL AT CLOCK 2
C*
C*
      RES=XPERC*CCDW(2,J)
      CCDW(1,JJ)=CCDW(1,JJ) + CCDW(2,J) - RES
      IF(DARK.EQ.0.) GOTO 5010
      IF(I3.LE.29) GOTO 5001
      I3=1
3001  CONTINUE
      READ(1,END=5000,ERR=3000) A
5001  CONTINUE
      RAY=SQRT(A(I3)**2 + A(I3 + 1)**2)
      RAYY=XNST*RAY
      RAY=RAY*G2
      DARKK=CONST*(GSI*RAYY + GG)
      CCDW(1,JJ)=CCDW(1,JJ) + DARKK
      GSUM=RAY + G1 + G3
      IF(IBIT.GT.0) GOTO 8181
      IF(I.LT.3) WRITE(5,5002) I,G1,RAY,G3,GSUM
5002  FORMAT(' CURRENT DENSITIES ',I6,6(1X,E15.8))
      IF(I.LT.6) WRITE(5,5003) I,DARKK
5003  FORMAT(' ELECTRONS ADDED PER CLOCK ',I6,1X,E15.8)
8181  CONTINUE
      I3=I3 + 2
5010  CONTINUE
      IF(IJJ(5).EQ.0) XRES=CCDW(2,J)
      CCDW(2,J)=RES
      IF(INOISE.EQ.1) GOTO 8001
      IF(IMIDL.EQ.0) GOTO 8001

C*
C*   ADD IN NOISE SOURCES OF MIDDLE REGION
C*   SHOT INTERACE*2
C*
      IF(I3.LE.30) GOTO 10
      I3=1
3011  CONTINUE
      READ(1,END=3010,ERR=3010) A
10    CONTINUE
      CCDW(1,JJ)=CCDW(1,JJ) + A(I3)*SDMIDL
      I3=I3 + 1
8001  CONTINUE

C*
C*   TRANSFER NOISE ADDED IN ONE PER TRANSFER
C*
      IF(INOISE.EQ.1) GOTO 8005
      IF(IJJ(5).EQ.1) GOTO 8005
      IF(I3.LE.30) GOTO 11
      I3=1
3021  CONTINUE
      READ(1,END=3020,ERR=3020) A
11    CONTINUE
      RES=XRES
      IF(RES.LT.0.) RES=-RES

```

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```

      XRES=SQRT(RES)*SDTRAN*A(I3)
      I3=I3 + 1
      CCDW(2,JJ)=CCDW(2,JJ) + XRES
      CCDW(1,JJ)=CCDW(1,JJ) - XRES
8005  CONTINUE
      IF(CCDW(1,JJ).GT,Q2)  CCDW(1,JJ)=Q2
      IF(CCDW(2,JJ).GT,Q2)  CCDW(2,JJ)=Q2
      IF(J.LE,IEND)  GOTO 7001
      J=J - 1
2     CONTINUE
7001  CONTINUE
7002  CONTINUE
      IF(I.GT,ILL)  GOTO 21
      CCDW(1,1)=CCDW(1,1) + ELECTR(I)
      IF(INOISE.EQ,1)  GOTO 8002
      IF(INPT,EQ,0)  GOTO 8002

C*
C*  ADD IN INPUT NOISE SOURCES
C*  SHUT INPUT INTERFACE
C*
C*
      IF(I3.LE,30)  GOTO 20
      I3=1
3031  CONTINUE
      READ(1,END=3030,ERR=3030)  A
20    CONTINUE
      CCDW(1,1)=CCDW(1,1) + A(I3)*SDINPT
      I3=I3 + 1
8002  CONTINUE
      IF(CCDW(1,1).GT,Q2)  CCDW(1,1)=Q2
      IF(IPRINT.NE,1)  GOTO 21
      WRITE(5,1001)  I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
21    CONTINUE
      J=I
      IF(IBEGIN.GE,ILL)  IEND=IEND + 1
      IF(J.GT,ISTAGE)  J=ISTAGE
      DO 3  K=1,ISTAGE

C*
C*
C*  FIND RESIDUE AT CLOCK 1 WELLS
C*  TRANSFER REMAINING TO CLOCK 2 WELLS
C1   LEAVE THE RESIDUE IN CLOCK 1 WELL
C*
C*
      RES=XPERC*CCDW(1,J)
      CCDW(2,J)=CCDW(2,J) + CCDW(1,J) - RES
      IF(IJJ(5).EQ,0)  XRES=CCDW(1,J)
      CCDW(1,J)=RES
      IF(DARK,EQ,0.)  GOTO 5020
      IF(I3.LE,29)  GOTO 5021
      I3=1
3041  CONTINUE
      READ(1,END=3040,ERR=3040)  A
5021  CONTINUE
      RAY=SQRT(A(I3)**2 + A(I3+1)**2)
      RAYY=RAY*XNST
      DARK=CONST*(GSI*RAYY + GG)
      CCDW(2,J)=CCDW(2,J) + DARK
      I3=I3 + 2
5020  CONTINUE
      IF(INOISE.EQ,1)  GOTO 8003
      IF(IMIDL,EQ,0)  GOTO 8003

C*
C*  ADD IN MIDDLE NOISE SOURCES  B17
C*  SHOT 2*INTERFACE
C1

```

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```

C*          IF(I3.LE.30) GOTO 30
           I3=1
3051      CONTINUE
           READ(1,END=3050,ERR=3050) A
30        CONTINUE
           CCDW(2,J)=CCDW(2,J) + A(I3)*SDMIDL
           I3=I3 + 1
8003      CONTINUE
C*
C*          ADD IN TRANSFER NOISE
C*
           IF(INOISE.EQ.1) GOTO 8006
           IF(IJJ(5).EQ.1) GOTO 8006
           IF(I3.LE.30) GOTO 35
           I3=1
3061      CONTINUE
           READ(1,END=3060,ERR=3060) A
35        CONTINUE
           RES=XRES
           IF(RES.LT.0.) RES=-RES
           XRES=SDTRAN*SQRT(RES)*A(I3)
           I3=I3 + 1
           CCDW(2,J)=CCDW(2,J) - XRES
           CCDW(1,J)=CCDW(1,J) + XRES
8006      CONTINUE
           IF(CCDW(1,J).GT.Q2) CCDW(1,J)=Q2
           IF(CCDW(2,J).GT.Q2) CCDW(2,J)=Q2
           IF(J.LE.IEND) GOTO 99
           J=J + 1
3        CONTINUE
99        CONTINUE
           IF(IPRINT.NE.1) GOTO 22
           WRITE(5,1000) (CCDW(1,J),CCDW(2,J),J=1,ISTAGE)
1000     FORMAT(6(2X,E15.8))
22        CONTINUE
1056     CONTINUE
           CALL FILTER(I,IEND)
1        CONTINUE
           RETURN
3000     REWIND 1
           GOTO 3001
3010     REWIND 1
           GOTO 3011
3020     REWIND 1
           GOTO 3021
3030     REWIND 1
           GOTO 3031
3040     REWIND 1
           GOTO 3041
3050     REWIND 1
           GOTO 3051
3060     REWIND 1
           GOTO 3061
           END

```

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C*
C*
C*
C*
C*
C*

CCD17,FTN

SUBROUTINE LOADS UP THE WEIGHTS FOR A FILTER

SUBROUTINE COEFFS

COMMON IW
COMMON /FILTER/COEFF(600)
COMMON /VOLTS/Q1,Q2,ITIME,IPP,B(30),I2
COMMON /BINSTR/ZL(30),IJ(30)
COMMON /RAND/PI,PII

I2=1

ISTAGE=IJ(1)

TS=1./ZL(4)

TIME=FLOAT(ITIME/2)*TS

ISTART=ITIME/2 - IJ(3)/2 + 1

JJ=1

DO 8080 I=1,ITIME

IF(JJ.GE,ISTART) GOTO 8081

JJ=JJ + 1

TIME=TIME + TS

8080

CONTINUE

8081

CONTINUE

SLOPE=ZL(27)

DO 1 I=1,ISTAGE

ARGG=SLOPE*TIME**2

IF((IW.EQ.0).OR.(IW.EQ.2)) COEFF(I)=COS(ARGG)

IF((IW.EQ.1).OR.(IW.EQ.3)) COEFF(I)=SIN(ARGG)

TIME=TIME + TS

1

CONTINUE

IF(IJ(4).EQ.1) RETURN

CALL MMWGH(COEFF,ISTAGE)

RETURN

END

AD-A051 333

RCA GOVERNMENT SYSTEMS DIV MOORESTOWN N J MISSILE AND--ETC F/G 17/9
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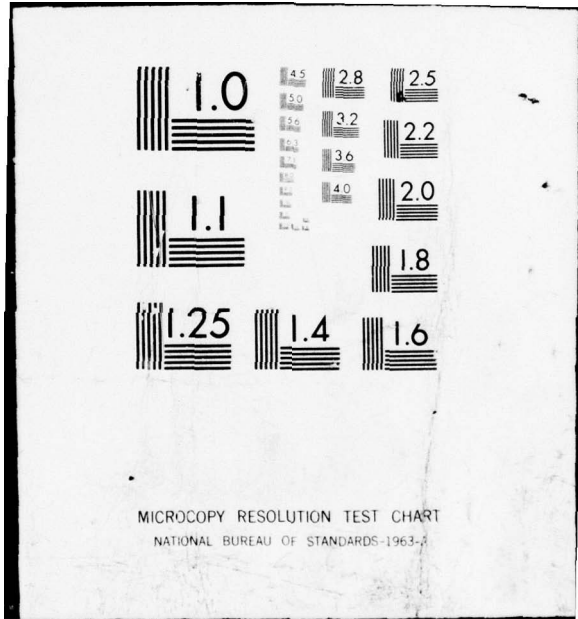
END

DATE

FILMED

4-78

DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

C*
C*
C*
C*
C*
C*
C*

CCD18.FTN

SUBROUTINE COMPUTES THE FILTER RESPONSE PER PULSE

SUBROUTINE FILTER(J,IEND)

```
REAL AA(30)
COMMON /FILTER/COEFF(600)
COMMON /BINSTR/XL(30),IJ(30)
COMMON /RAND/PI,PII
COMMON /VOLTS/Q1,Q2,ITIME,IPP,B(30),I2
COMMON /CCD/CCDW(2,601)
COMMON /PASS/STAD(20)

C*
BIAS=STAD(5) + STAD(5)*XL(1)
ISTAGE=IJ(1)
INOISE=IJ(8)
ERR=1. + XL(20)
SD=XL(17)
CS=0.
    I1=31
    IK=ISTAGE
    IBEGIN=J
    IF(IBEGIN.GT.ISTAGE) IBEGIN=ISTAGE
DO 10 I=IEND,IBEGIN
    WELL=CCDW(2,I) - BIAS
    IF(INOISE.EQ.1) GOTO 9
    IF(SD.LE.0.) GOTO 9
    IF(I1.LE.30) GOTO 7
    I1=1
5    READ(1,END=1000,ERR=1000) AA
7    CONTINUE
    CS=CS + WELL*COEFF(IK)*(ERR + AA(I1)*SD)
    I1=I1 + 1
    GOTO 1010
9    CONTINUE
    CS=CS + WELL*COEFF(IK)
1010    IK=IK - 1
10    CONTINUE
    B(I2)=CS
    I2=I2 + 1
    IF((I2.LT.31).AND.(J.LT.ITIME)) RETURN
    I2=1
    WRITE(2,IPP) B
    IPP=IPP + 1
    RETURN
1000    REWIND 1
        GOTO 5
        END
```

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```

C*
C*
C*      CCD20.FTN
C*
C*
C*      SUBROUTINE SD
COMMON /BINSTR/XX(30),IJ(20)
COMMON /PASS/STAD(20),ISTAD(20)
C*
C*
C*      LOADS APPROPRIATE NOISE SOURCES IN SDS
C*
C*
C*      IF (IJ(8).EQ.1) RETURN
SDINPT=XX(6)
SDSHOT=XX(7)
SDOUTP=XX(9)
SDINTR=XX(19)
C*
C*
C*      CHECK TO SEE IF ALL SOURCES ARE ADDED IN
C*
C*
C*      ISTAD(1)=0
C*      ISTAD(2)=0
C*      ISTAD(3)=0
C*      IF (IJ(10).EQ.1) GOTO 10
C*      S1=SDSHOT*SDSHOT
C*      S2=SDINTR*SDINTR
C*
C*
C*      INPUT SD
C*
C*
C*      STAD(1)=SQRT(SDINPT*SDINPT + S1 + S2)
C*      ISTAD(1)=1
C*
C*
C*      MIDDLE NOISE SOURCES MINUS TRANSFER
C*
C*
C*      STAD(2)=SQRT(S1 + 2.*S2)
C*      ISTAD(2)=1
C*
C*
C*      OUTPUT NOISE SOURCES
C*
C*
C*      STAD(3)=SQRT(S1 + S2 + SDOUTP*SDOUTP)
C*      ISTAD(3)=1
C*      RETURN
10      CONTINUE
C*
C*
C*      COMPUTE INPUT IF NEEDED
C*
C*
C*      VAR=0.
C*      IF (IJ(11).EQ.1) GOTO 15
C*      VAR=SDINPT*SDINPT
C*      ISTAD(1)=1
15      IF (IJ(12).EQ.1) GOTO 20
C*      VAR=VAR + SDSHOT*SDSHOT
C*      ISTAD(1)=1
20      IF (IJ(16).EQ.1) GOTO 25
C*      VAR=VAR + SDINTR*SDINTR
C*      ISTAD(1)=1
25      IF (ISTAD(1).EQ.1) VAR=SQRT(VAR)
C*      STAD(1)=VAR
C*
C*
C*
C*      COMPUTE MIDDLE SD IF NEEDED

```

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```

      VAR=0.
      IF(IJ(12),EQ,1) GOTO 30
      VAR=SDSHOT*SDSHOT
      ISTD(2)=1
30    IF(IJ(14),EQ,1) GOTO 35
      VAR=VAR + 2.*SDINTR*SDINTR
      ISTD(2)=1
35    IF(ISTAD(2),EQ,1) VAR=SQRT(VAR)
      STAD(2)=VAR

C*
C*
C*      COMPUTE OUTPUT SD IF NEEDED
C*
      VAR=0.
      IF(IJ(12),EQ,1) GOTO 40
      VAR=SDSHOT*SDSHOT
      ISTD(3)=1
40    IF(IJ(14),EQ,1) GOTO 45
      VAR=VAR + SDOUTP*SDOUTP
      ISTD(3)=1
45    IF(IJ(16),EQ,1) GOTO 50
      VAR=VAR + SDINTR*SDINTR
      ISTD(3)=1
50    IF(ISTAD(3),EQ,1) VAR=SQRT(VAR)
      STAD(3)=VAR
      RETURN
      END

C*
C*
C*      C5 LINK STRUCTURE
C*
C*      C5,C5<CCD,STB,C5,CCD8,FTNLIG/L/U/E
C*
      CALL OUTP
      CALL RETURN
      END

```

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C
C
C
C
C
C

CC08,FTN

SUBROUTINE PRINTS OUT INITIAL AND FINAL ARRAYS

SUBROUTINE OUTP

REAL A(30),BB(30)
COMMON /INPUT/ELECTR(1200)
COMMON /VOLTS/XMAXV,XMAXEL,ITIME,IPP
COMMON /BINSTR/XZ(30),IJ(2),ILT,IFILT,ILL(3),INOISE,IJL(20)
COMMON /PASS/STAD(20),ISTAD(20)
COMMON /CCD/ZL(1200)
COMMON /FILTER/ARRY(600)

C*
C*
C*
C*
C*
C*
C*
C*
C*
C*
C*
C*
C*
C*
C*
C*

N = # STAGES
VMAX0 MAXIMUM OUTPUT VOLTAGES
VMIN0 MINIMUM OUTPUT VOLTAGES
F FULL WELL OF ELECTRONS

OUTPUT OF FILTER CAN HAVE A RANGE OF
VALUES OF + TO = N*F*STAGES

VOLTAGE OUT=SLOPE*(ELECTONS + F*STAGES)

ELECTRONS IS # ELECTRONS FOR THAT SAMPLE
SLOPE=(VMAX0 - VMIN0)/(2*F*STAGES)

I2=31
VMAX0=46.E-3
VMIN0=1.E=6
X3=FLOAT(IJ(1))*XMAXEL
X4=X3
X6=VMAX0/X4
7845 CONTINUE
IJLL=0
IPP=0
10 CONTINUE
J=0
DO 100 I=1,ITIME
IF(I2.LE.30) GOTO 1
I2=1
IF(IPP.GT.0) WRITE(2*IPP) BB
IPP=IPP + 1
READ(2*IPP) BB
1 CONTINUE
IF((XZ(3).LE.0.).AND.(XZ(5).LE.0.)) GOTO 5555
IF(BB(I2).GT.X4) BB(I2)=X4
IF(BB(I2).LT.-X4) BB(I2)=-X4
X2=BB(I2)*X6
BB(I2)=X2
5555 CONTINUE
I2=I2 + 1
100 CONTINUE
WRITE(6,8010) IPP
8010 FORMAT(' DONE WITH OUTP' ,I6//)
I2=31
IJLL=IJLL + 1
IF(IJLL.LT.4) GOTO 10
WRITE(2*IPP) BB

```

REWIND 1
ENDFILE 1
  IPP=1
  I2=31
30  IJLL=0
CONTINUE
  I2=31
DO 8079 I=1,ITIME
IF(I2.LE.30) GOTO 8078
  I2=1
READ(2*IPP) 88
  IPP=IPP + 1
8078 CONTINUE
IF(IJLL.EQ.0) ELECTR(I)=88(I2)
IF(IJLL.EQ.3) ELECTR(I)=ELECTR(I) + 88(I2)
IF(IJLL.EQ.1) ZL(I)=-88(I2)
IF(IJLL.EQ.2) ZL(I)=ZL(I) + 88(I2)
  I2=I2 + 1
8079 CONTINUE
  IJLL=IJLL + 1
IF(IJLL.LT.4) GOTO 30
  IJR=ITIME
DO 9157 I=1,ITIME
ELECTR(I)=SQRT(ELECTR(I)**2 + ZL(I)**2)
9157 CONTINUE
CALL PLOT1(ELECTR,XMIN,XMAX,AVE,VAR,VAR1,IJR)
WRITE(5,8075) IJR,AVE,VAR,XMAX,XMIN
8075 FORMAT(' OUTPUT #',I6,' AVE ',1PE15.8,' SD ',1PE15.8/
2 ' HALF THE OUTPUT AVE ',1PE15.8,' SD ',1PE15.8//)
ENDFILE 2
IF(ILL(5).NE.0) RETURN
  JK=1
CALL EPLOT(ELECTR,XMAX,IJR,JX,JK)
  RETURN
  END

```

C*
C*
C*
C*
C*
C*
C*

C6 LINK STRUCTURE
C6,C6<CCD,STB,C6,CCD26,CCD27,CCD28,CCD29,CCD16,FYNLIB/L/U/E

CALL SETUP
CALL RETURN
END

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C*
C*
C*
C*
C*
C*
C*

LITTLE BOOKKEEPING

CCD26.FTN

```
      SUBROUTINE SETUP
      REAL ARR(30)
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /CCD/B(1200)
      COMMON /INPUT/A(1200)
      COMMON /VOLTS/Q1,Q2,ITIME
      IF(IJ(30).EQ.0) RETURN
      ICC=1
800   CONTINUE
      NUMB=ITIME
      CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
      WRITE(5,8080) NUMB,AVE,VAR,VAR1
8080  FORMAT(1H1' # MEAN SD ',I6,4(1X,1PE15.6)/)
      CALL POW2(NUMB,J)
      77  CONTINUE
      6   CONTINUE
      CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
      DO 18 I=1,NUMB
      A(I)=A(I) - AVE
      18  CONTINUE
      CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
      WRITE(5,8080) NUMB,AVE,VAR,VAR1
      AVE=1.
      CALL PLOT(A,NUMB,XMIN,XMAX,AVE,AVE,AVE)
      K=1
      CALL EPLOT(A,XMAX,NUMB,K,K)
      IND=2**J
      IPP=IND * NUMB
      IF(IPP.EQ.0) GOTO 10
      K=NUMB + 1
      DO 7 I=K,IND
      7   A(I)=0.
      10  DO 20 I=1,IND
      B(I)=0.
      20  CONTINUE
      CALL FRXFM(J,A,B)
      IND=IND/2
      DO 30 I=1,IND
      D=A(I)**2 + B(I)**2
      D=SQRT(D)
      A(I)=D
      30  CONTINUE
      CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,IND)
      I=1
      CALL EPLOT(A,XMAX,IND,I,I)
      ICC=ICC + 1
      IW=1
      RETURN
      END
```

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```

C*
C*
C*      LITTLE BOOKKEEPING
C*
C*      CC027.FTN
C*
C*
C*      SUBROUTINE PRXFM(N2POW,XT,YT)
C*
C*      DECIMATION IN FREQUENCY FFT ALGORITHM
C*
C*
C*      DIMENSION XT(2),YT(2)
C*      N=2**N2POW
C*      M=N2POW
C*      DO 600 L0=1,M
C*          LMX=2**(M-L0)
C*          LIX=2*LMX
C*          SCL=6.2831853072/FLOAT(LIX)
C*      DO 600 LM=1,LMX
C*          ARG=FLOAT(LM-1)*SCL
C*          C=COS(ARG)
C*          S=SIN(ARG)
C*      DO 600 LI=LIX,N,LIX
C*          J1=LI-LIX+LM
C*          J2=J1+LMX
C*          T1=XT(J1) -XT(J2)
C*          T2=YT(J1) - YT(J2)
C*          XT(J1)=XT(J1) + XT(J2)
C*          YT(J1)=YT(J1) + YT(J2)
C*          XT(J2)=C*T1 + S*T2
C*          YT(J2)=C*T2 - S*T1
600      CONTINUE
C*
C*      BIT REVERSAL
C*
C*      NV2=N/2
C*      NM1= N -1
C*      J=1
C*      DO 635 I=1,NM1
C*          IF(I.GE.J) GOTO 631
C*          T1=XT(J)
C*          T2=YT(J)
C*          XT(J)=XT(I)
C*          YT(J)=YT(I)
C*          XT(I)=T1
C*          YT(I)=T2
631      K=NV2
620      CONTINUE
C*          IF(K.GE.J) GOTO 635
C*          J=J -K
C*          K=K/2
C*          GOTO 620
635      J=J+K
C*          RETURN
C*          END

```

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C1
C*
C*
C*
C*

CCD28,FTN

 SUBROUTINE WGHT(A,IW,NUMB)
REAL A(2)
COMMON /RAND/PI,PII

C*
C*
C*

 N=NUMB - 1
 IF (NUMB.NE.2*(NUMB/2)) N=NUMB
 N=N/2 - 1
 CONST=PII/FLOAT(NUMB)
 ALPHA=0.54
 IF (IW.EQ.2) ALPHA=0.5
 C1=1. - ALPHA
 DO 1 I=1,NUMB
 T1=CONST*FLOAT(I+N)
 A(I)=A(I)*(ALPHA + C1*COS(T1))
1 CONTINUE
 RETURN
 END

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BEST AVAILABLE COPY


```

0*
C*
C*      CCD29.FTN
C*
C*      SUBROUTINE EPLOTT(XT,XMAX,LNUMB,LSTRT,LINT)
C*      FOR PLOTTING RESULTS ON A SCALE 0 TO 50 DB
C*      ASSUMES THAT CAPTIONING IS PROVIDED, AND POINTS EXIST (UP TO LEND)
C*      NORMALIZES POINTS TO XMAX BEFORE PLOTTING
C*
C*      XT VECTOR OF STORED POINTS TO BE PLOTTED
C*      XMAX MAX VALUE IN VECTOR XT
C*      LNUMB NUMBER OF POINTS TO BE PLOTTED
C*      LSTRT INDEX OF FIRST POINT TO BE PLOTTED
C*      LINT INTERVAL BETWEEN PLOTTED POINTS IN ARRAY
C*
C*      OUTPUT OF 999 MEAN THAT POINT WAS LESS THEN
C*      OR EQUAL TO ZERO
C*
C*****M27- LATEST REVISION DATED: 21, APR, 77
      REAL AKAR(5)
      REAL XT(2)
      COMMON /CCD/ALINE(101)
      DATA AKAR/' ',' ',' ',' ',' ',' ',' ',' ',' '0'/
      LEND=LSTRT+(LNUMB-1)*LINT
      KOUNT=0
      WRITE(5,15)
15      FORMAT(/59X,'DB DOWN'/)
      WRITE(5,17)
17      FORMAT(/1X,'PT # VALUE 100 ',17X,'80',18X,'60',18X,'40',
1          18X,'20',18X,'0 INDEX')
      DO 20 I=LSTRT,LEND,LINT
      TEST=XT(I)/XMAX
      IF(TEST) 24,24,26
24      DB=999.
      GO TO 30
26      DB=-20.*ALOG10(TEST)
30      IF( MOD(KOUNT,10).NE.0 ) GO TO 50
C          EVERY TENTH LINE
      DO 35 J=1,101
35      ALINE(J)=AKAR(1)
      DO 40 J=1,101,5
40      ALINE(J)=AKAR(3)
      GO TO 70
C          ALL OTHER LINES
50      DO 55 J=1,101
55      ALINE(J)=AKAR(4)
      DO 60 J=1,101,10
60      ALINE(J)=AKAR(2)
C          LINE READY FOR INSERTION OF POINT
70      KOUNT=KOUNT+1
      L=101-IFIX(DB+.5)
      IF(L.LT.1) GO TO 90
      ALINE(L)=AKAR(5)
90      WRITE(5,95) I,DB,(ALINE(J),J=1,101),KOUNT
95      FORMAT(1X,I4,F7.2,1X,101A1,15)
20      CONTINUE
      WRITE(5,17)
      RETURN
      END

```

C*
C*
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SUBROUTINE PLOTS OUT AN ARRAY ON LINEPRINTER

CCD16.FTN

SUBROUTINE PLOT(ARRAY,NELMNT,AMIN,AMAX,CONT,DELT,TINTL)

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ARRAY IS THE ARRAY OF DATA TO BE PLOTTED FROM THE THE 1ST
ELEMENT TO THE ELEMENT NUMBER GIVEN BY NELMNT.
AMIN IS THE MINIMUM VALUE THE PLOT COULD REACH.
AMAX IS THE MINIMUM VALUE THE PLOT COULD REACH.
CONT IS A SWITCH THAT TELLS THE SUBROUTINE IF THE INPUT
ARRAY IS A CONTINUATION OF THE LAST PLOT.
CONT GREATER THAN 1.0 IMPLIES A CONTINUATION.
DELT IS THE INCREMENT TO BE USED ALONG THE ABSCISSA.
TINTL IS THE INITIAL VALUE OF THE ABSCISSA.

NOTE

TINTL IS CHANGED BY THE SUBROUTINE. IT IS RESET TO THE VALUE
THAT IS EXPECTED AS THE INITIAL VALUE OF THE NEXT CALL IF THE
CONTINUATION OPTION IS USED.
IF THE CONTINUATION OPTION IS USED AND THE INITIAL TIME IS CHANGED
FROM THE EXPECTED VALUE, THE OUTPUT WILL BE FLAGED WITH A *.
THE TIMING WILL BE RESEQUENCED TO AGREE WITH THE NEW VALUE.

DIMENSION ARRAY(5),XS(5),STRING(123)
DATA SPACE/' '/,STAR/'0'//,GRID/'+'//

AVE=0.
VAR=0.
TINTL=ABS(TINTL)
DO 1 I=1,123
1 STRING(I)=SPACE
DO 2 I=12,112,25
2 STRING(I)=GRID
IF (CONT-1.)3,3,4
3 X=1.001*(AMAX-AMIN)/120.
4 KR GIVES X ROUNDED TO KR SIGNIFICANT DIGITS EQUALS XIN.
KR=6
ZP=-69.0775
Z=AMAX1(ABS(X),EXP(ZP))
LOG10F=ALOG(Z)/2.302585
K1=INT(LOG10F+50.)
PWRK=10.** (50+KR-K1)
SIGK=AIN(T(X*PWRK))
PWRKM1=10.** (49+KR-K1)
SIGKM1=AIN(T(X*PWRKM1))
Y=10.**SIGKM1
YP=SIGK-Y
NY=INT(YP)
NY=((NY)/5+1)*5
YP=AIN(T((NY+Y)/10.))
ROUNDF=YP/PWRKM1
XIN=ROUNDF
XIN=Y
AVE=(AMAX+AMIN)/2.
REVAVE=AIN(T(AVE/XIN)*YTN
XMIN=REVAVE-62.*XIN
XS(1)=REVAVE-50.*XIN
XS(2)=REVAVE-25.*XIN

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XS(3)=REVAVE
XS(4)=REVAVE+25.*XIN
XS(5)=REVAVE+50.*XIN
WRITE(S,1000)DELT,TINTL,XS
1000 FORMAT(/5X24HABSCISSA IS IN UNITS OF 1PE13.7,
1 ' INITIAL VALUE ',1PE13.7/
2 61X21H-----AMPLITUDE-----/2X8HABSCISSASX
3 1PE11.4,4(14X1PE11.4)/1X,132(1H,))
C*
C* BY PASS CODE AFTER GOTO 6
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KNT=1
IF(TINTL.GT.1.) KNT=TINTL
IF(KNT.GT.0) GOTO 6
TSAVE=TINTL
KNT=1
4 KNTCHK=(TINTL-TSAVE)/DELT+.1
IF(KNTCHK=KNT)5,6,5
5 WRITE(S,1001)
1001 FORMAT(/2H */)
KNT=KNTCHK
6 DO 7 I=1,NELMNT
AVE=AVE + ARRAY(I)
VAR=VAR + ARRAY(I)*ARRAY(I)
K=((ARRAY(I)-XMIN)/XIN+2.5)
IF(K.GT.122)K=123
IF(K.LT.1)K=1
TEMP=STRING(K)
STRING(K)=STAR
1002 WRITE(S,1002)KNT,(STRING(J),J=2,123)
FORMAT(I10,1X123A1)
KNT=KNT + 1
7 STRING(K)=TEMP
TINTL=FLOAT(KNT)*DELT+TSAVE
XIN=NELMNT
XMIN=(XIN - 1.)*XIN
VAR=XIN*VAR - AVE*AVE
IF(VAR.GT.0.) VAR=SQRT(VAR/XMIN)
AVE=AVE/XIN
8000 WRITE(S,8000) NELMNT,AMIN,AMAX,AVE,VAR
FORMAT(' # OF ELEMENTS ',I5/
2' MINIMUM VALUE ',1PE15.8/
3' MAXIMUM VALUE ',1PE15.8/
4' MEAN OF ELEMENTS ',1PE15.8/
5' SD OF THE ELEMENTS ',1PE15.8//)
RETURN
END

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CCD LINK STRUCTURE

CCD,CCO,CCD<CCO1,FTNLIB/L/U/E

C0 LINK STRUCTURE

C0,C0<CCO,STB,C0,CCO6,CCO19,CCO31,FTNLIB/L/U/E

COMMON /BINSTR/XX(30),IJ(30)
COMMON /PASS/STAD(20),ISTAD(22),ROW(7),IRW(4)

1

CONTINUE
IF(IJ(9).NE.9998) CALL INSTR
IF(IJ(21).GT.0) CALL REPEAT
IF(IJ(9).LT.0) GO TO 1
IJ(21)=IJ(21) + 1
CALL RETURN
END

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CCD6.FTN

SUBROUTINE READS IN THE INSTRUCTIONS FOR A RUN

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      SUBROUTINE INSTR
      REAL A(3)
      COMMON /CCD/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(4),XLEV,
2      ZL(20),ISTAGE,IPRINT,I LENGT,IFILT,NRVS,IJ(20)
      COMMON /BINSTR/XXZ(30),IJL(30)
      COMMON /VOLTS/WW1,WW2,ITIME
      COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
      COMMON /RAND/R1(4),RR(6)
      DATA A/4HTEMP,4H02.0,4HAT00/
      IJL(21)=0
      IRW(3)=0
      IJL(9)=9998
      WRITE(6,7000)
7000  FORMAT(' CREATE NEW FILE ON DAT SLOT 2 Y=0 N=1 '/')
      READ(6,91) I
      IF(I.NE.0) GOTO 7005
      WRITE(6,7001)
7001  FORMAT(' NAME OF FILE XXXXXX.D '/')
      READ(6,7002) A(1),A(2)
7002  FORMAT(2A4)
7005  WRITE(5,7003) A
7003  FORMAT(' NAME OF FILE FOR THIS RUN ',3A4//)
      CALL SETFIL(2,A,IER2,'DK',0)
      DEFINE FILE 2(50,64,U,IVAR)
1      WRITE(6,100)
100   FORMAT(' THE NUMBER OF STAGES IN THE CCD (F10.0)')//)
101   READ(6,101) X
101   FORMAT(F10.0)
      IUPPER=600
      ILOWER=0
      ISTAGE=X
      IF((ISTAGE.GT.ILOWER).AND.(ISTAGE.LE.IUPPER)) GOTO 3
      WRITE(6,201) ISTAGE,ILOWER,IUPPER
201   FORMAT(' ERROR MESSAGE # OF STAGES TO SMALL OR TO LARGE'/
2*   '# OF STAGES: ',I4,' LOWER LIMIT: ',I4,' UPPER: ',I4//)
      GOTO 1
3      WRITE(6,103)
103   FORMAT(' SD OF THE INITIAL STATE (F10.0)')//
2*   IF < 0 THEN NO BACKGROUND VOLTAGE ADDED')//
      READ(6,101) XSD
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      CHANGE 02/22/77
      XXZ(3)=XSD
      IJL(1)=ISTAGE
4      WRITE(6,104)
104   FORMAT(' SURFACE OR BURIED DEVICE (0 OR 1.)')//
      READ(6,101) ZZ1
      IJ(1)=ZZ1
      IJL(6)=IJ(1)
      IF((IJ(1).LT.0).OR.(IJ(1).GT.1)) GOTO 4
      WRITE(6,108)
108   FORMAT(' AREA OF WELL IN MIL**2')//
100   READ(6,101) ZL(5)
      WRITE(6,107)

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107   FORMAT(' % OF BACKGROUND CHARGE %/
      2   ' <0 THEN SPECIFY TRANSFER LOST %/)
      READ(6,101) ZL(6)
      IF(ZL(6).LT.0.) WRITE(6,7891)
7891  FORMAT(' FRACTION LOST EACH TIME ,XXXX'/)
      IF(ZL(6).LT.0.) READ(6,101) XPERC
      IF(ZL(6).GE.0.) CALL CTI(ZL,XPERC,103)
      WRITE(6,109)
109   FORMAT(' CLOCK SWING VOLTAGE %/)
      READ(6,101) ZL(8)
      XXZ(1)=XPERC
      XXZ(15)=ZL(5)
      XXZ(16)=ZL(6)
      XXZ(18)=ZL(8)
      WRITE(6,9050)
9050  FORMAT(' PLOT OF INPUT AND OUTPUT Y=0 N=1 %/)
      READ(6,91) IJL(7)
      WRITE(6,7011)
7011  FORMAT(' FFT OF OUTPUT Y=1 N=0 %/)
      READ(6,91) IJL(30)
      WRITE(5,1000) ISTAGE,XPERC,ZL(16),ZL(13)
1000  FORMAT(' # OF STAGES IN THE CCD ',I3/)
      3* CTI OF DEVICE ',1PE15.8/
      4* % OF THE BACKGROUND CHARGE ',1PE15.0/
      4* AREA OF THE WELL (MIL**2)',1PE15.0//)
      WRITE(6,206)
      6
206   FORMAT(' CLOCK FREQUENCY (F10) %/)
      CLCKMX=1.E10
      READ(6,101) FCLOCK
      IF((FCLOCK.GT.0.).AND.(FCLOCK.LE.CLCKMX)) GOTO 60
      WRITE(6,1006) CLCKMX
1006  FORMAT(' CLOCK RATE OUTSIDE OF RANGE OF 0. TO *F10.0/)
      GOTO 6
      60
      CONTINUE
      WRITE(5,701) FCLOCK
      701  FORMAT(' CLOCK RATE ',1PE15.8/)
      80   WRITE(6,800)
      800  FORMAT(' THE LENGTH OF TIME OF THE RUN < 1201 %/)
      READ(6,101) ZZ1
      ITIME=ZZ1
      IF((ITIME.LT.0).OR.(ITIME.GT.1200)) GOTO 80
      WRITE(6,90)
      90   FORMAT(' PRINT OUT INTERMEDIATE VALUES NO=0 YES=1'/)
      READ(6,91) IPRINT
      91   FORMAT(I1)
      WRITE(6,9008)
9008  FORMAT(' FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1'/)
      C*
      C*   MAXIMUM INPUT VOLTAGE IS 2.8 VOLTS
      C*
      C*
      XXZ(4)=FCLOCK
      IJL(2)=IPRINT
      XMAXV=2.8
      WW1=XMAXV
      READ(6,91) NRVS
      WRITE(6,93)
      93   FORMAT(' DURATION OF THE SIGNAL MIN=0 MAX=1200'/)
      READ(6,101) ZZ1
      ILENGT=ZZ1
      WRITE(6,7020)
      7020 FORMAT(' TYPE OF SIGNAL PULSE =0 SIN = 1 %/)
      READ(6,91) IJL(29)
      IF(IJL(29).EQ.0) GOTO 95
      7022 WRITE(6,7021)
      7021 FORMAT(' # OF SINUSOIDALS F10. * 5'/)

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READ(6,101) ZZ1
IJL(28)=ZZ1
IF((IJL(28).LE.0).OR.(IJL(28).GT.4)) GOTO 7022
IKK=IJL(28)
IKL=30
DO 7023 I=1,IKK
WRITE(6,7024) I
7024 FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL(HERTZ)')
READ(6,101) ZZ1
XXZ(IKL)=ZZ1
WRITE(6,8025) I
8025 FORMAT(' AMPLITUDE (% OF WELL) OF THE ',I3,' SIGNAL')
READ(6,101) STAD(I)
STAD(I)=WW1*STAD(I)/100.
WRITE(5,7030) I,ZZ1,STAD(I)
7030 FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL ',1PE15.8/
2 ' AMPLITUDE (VOLTS) OF THE SIGNAL ',1PE15.8/)
IKL=IKL + 1
7023 CONTINUE
WRITE(6,8053)
8053 FORMAT(' DC BIAS (% OF WELL) TERM ADDED TO INPUT F10 ')
READ(6,101) XXZ(5)
XXZ(5)=WW1*XXZ(5)/100.
GOTO 9918
95 CONTINUE
WRITE(6,92) XMAXV
92 FORMAT(' INPUT LEVEL OF SIGNAL MAX= ',F10.3,' VOLTS')
READ(6,101) XLEV
IF((XLEV.LE.0.).OR.(XLEV.GT.XMAXV)) GOTO 95
9918 CONTINUE
IJL(3)=ILENGT
IJL(5)=NRVS
XXZ(10)=XLEV
WRITE(6,8010)
8010 FORMAT(' NON LINEAR INPUT WARPING Y=0 N=1')
READ(6,91) IJ(12)
WRITE(6,97)
97 FORMAT(' FILTER RESPONSE COMPUTED? N=0 Y=1')
READ(6,101) ZZ1
IFILT=ZZ1
IJL(20)=1
WRITE(6,9033)
9033 FORMAT(' DARK CURRENT ADDED Y=0 N=1 ')
READ(6,91) IJ(13)
IF(IJ(13).EQ.1) GOTO 9036
WRITE(6,9034)
9034 FORMAT(' AMBIENT TEMPERATURE DEGREES C ')
READ(6,101) ZZ1
XXZ(26)=ZZ1 + 273.
WRITE(5,9035) ZZ1,XXZ(26)
9035 FORMAT(' AMBIENT TEMPERATURE (C) ',F10.4,' (K) ',F10.4/)
WRITE(6,1701)
1701 FORMAT(' DO YOU WANT TO HOLD THE SIGNAL FOR ANY '
2 ' OF TIME Y=0 N=1 ')
READ(6,91) IJL(20)
IF(IJL(20).EQ.1) GOTO 9036
WRITE(6,1702)
1702 FORMAT(' TIME (SEC) LEFT IN DELAY LINE ')
READ(6,101) XXZ(21)
WRITE(6,1703)
1703 FORMAT(' FREQUENCY CLOCK SIGNAL OUT AT ')
READ(6,101) XXZ(22)
WRITE(5,1704) XXZ(4),XXZ(21),XXZ(22)
1704 FORMAT(' INPUT SAMPLING RATE ',1PE15.8,
2 ' TIME LEFT IN DEVICE ',1PE15.8,
3 ' OUTPUT SAMPLING RATE ',1PE15.8/)

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9036 CONTINUE
      IJL(4)=IFILT
      IJL(17)=IJ(12)
      IJL(18)=IJ(13)
      WRITE(6,6011)
6011  FORMAT(' MULTIPLE RUN Y=# OF CHANGES N=0 F10')
      READ(6,101) ZZ1
      IJL(19)=ZZ1
      IF(IJL(19).EQ,0) GOTO 8000
      WRITE(6,6012)
6012  FORMAT(' WHICH INPUT IS TO BE CHANGED ')
      2  ' 1= # OF STAGES, 2=SURFACE/BURIED '
      3  ' 3= AREA OF WELL, 4=STORAGE TIME (SEC) '
      4  ' 5=CLOCK FREQUENCY,6=AMBIENT TEMPERATURE '
      READ(6,91) IJL(22)
      K=IJL(19)
      DO 6019 I=1,K
        WRITE(6,6013) I
6013  FORMAT(' INPUT THE ',I6,' VALUE ')
      READ(6,101) RR(I)
6019  CONTINUE
      WRITE(5,6015) (I,RR(I),I=1,K)
6015  FORMAT(' MULTIPLE RUNS '///7(1X,I2,2X,1PE15.8))
      WRITE(6,8717)
8717  FORMAT(' SECOND VARIABLE CHANGING Y=# N=0 ')
      READ(6,91) IRW(1)
      IF(IRW(1).EQ,0) GOTO 8000
      WRITE(6,6012)
      READ(6,91) IRW(2)
      K=IRW(1)
      DO 8718 I=1,K
        WRITE(6,6013) I
      READ(6,101) ROW(I)
8718  CONTINUE
      WRITE(5,6015) (I,ROW(I),I=1,K)
8000  WRITE(6,8001)
8001  FORMAT(' RUN WITH NOISE Y=0 N=1 ')
      READ(6,91) IJ(3)
      IJL(8)=IJ(3)
      IF((IJ(3).LT,0).OR.(IJ(3).GT,1)) GOTO 8000
      IF(IJ(3).EQ,1) RETURN
      K=10
      DO 9000 I=5,11
        IJ(I)=0
        IJL(K)=0
        K=K + 1
9000  CONTINUE
      WRITE(6,8003)
8003  FORMAT(' SELECT THE PARTICULAR NOISE INPUTS N=0,Y=1')
      READ(6,91) IJ(5)
      IJL(10)=IJ(5)
      IF(IJ(5).EQ,0) RETURN
      WRITE(6,8004)
8004  FORMAT(' ADD IN INPUT NOISE Y=0 N=1 ')
      READ(6,91) IJ(6)
      WRITE(6,8005)
8005  FORMAT(' ADD IN THE SHOT NOISE Y=0 N=1')
      READ(6,91) IJ(7)
      WRITE(6,8006)
8006  FORMAT(' ADD IN THE TRANSFER NOISE Y=0 N=1')
      READ(6,91) IJ(8)
      WRITE(6,8007)
8007  FORMAT(' ADD IN THE OUTPUT NOISE Y=0 N=1')
      READ(6,91) IJ(9)
      WRITE(6,8008)
8008  FORMAT(' ADD IN THE FILTER NOISE Y=0 N=1')

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      READ(6,91) IJ(10)
      WRITE(6,8009)
8009  FORMAT(' ADD IN INTERFACE NOISE '/')
      READ(6,91) IJ(11)
           K=11
      DO 57 I=6,11
      IJL(K)=IJ(I)
      K=K + 1
57    CONTINUE
           RETURN
           END

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COMPUTES CTI FOR SURFACE AND BURIED DEVICES

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      SUBROUTINE CTI(ZL,ZPERC,IJ)
      INTEGER IJ(5)
      REAL ZL(20)
      X=ZL(6)
      IF(IJ(1).EQ.1) GOTO 100
      IF(X.GT.4.) GOTO 1
      ZPERC=3.6E-4
      RETURN
1     IF(X.GT.5.) GOTO 2
      ZPERC=-2.7E-4*X + 1.4E-3
      RETURN
2     IF(X.GT.10.) GOTO 3
      ZPERC=-1.E-5*X + 1.4E-4
      RETURN
3     ZPERC=3.9E-5
      RETURN
100   IF(X.GT.4.) GOTO 101
      ZPERC=-1.6E-5*X + 1.1E-4
      RETURN
101   IF(X.GT.13.5) GOTO 102
      ZPERC=-2.1E-6*X + 5.8E-5
      RETURN
102   ZPERC=2.8E-5
      RETURN
      END

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SUBROUTINE REPEAT

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REAL A(3)
COMMON /BINSTR/XX(30),IJ(30)
COMMON /RAND/R1(4),RR(6)
COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
DATA A/4HTEMP,4H02.D,4HAT00/
  CALL SETFIL(2,A,IER2,'DK',0)
  DEFINE FILE 2(50,64,U,IVAR)
  IF(IJ(21).GT.IJ(19)) GOTO 1000
  K=IJ(22)
  KK=IJ(21)
  CALL FINDER(RR,Y,K,KK)
  IF((IJ(21).EQ.1).AND.(IRW(3).EQ.0)) ROW(7)=Y
  RETURN
1000 CONTINUE
  IRW(3)=IRW(3) + 1
  IF(IRW(3).GT.IRW(1)) GOTO 2000
  K=IRW(2)
  KK=IRW(3)
  CALL FINDER(ROW,Y,K,KK)
  K=IJ(22)
  KK=7
  IJ(21)=0
  CALL FINDER(ROW,Y,K,KK)
  RETURN
2000 CONTINUE
  IJ(9)=-10000
  RETURN
  END
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